HVDC-AC System Interaction From AC Harmonics

Volume 1: Harmonic Impedance Calculations

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**HVDC-AC System Interaction From AC
Harmonics,
Volume 1. Harmonic Impedance Calculations**

**EL-2583, Volume 1
Research Project 1138-1**

Final Report, September 1982

Prepared by

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Schenectady, New York

ABSTRACT

Improved methods are needed to characterize ac system harmonic behavior for ac filter design for HVDC systems. The purpose of this General Electric Company RP1138 research is to evaluate the present filter design practice and to investigate methods for calculating system harmonic impedances.

~~An overview of ac filter design for HVDC systems~~ and a survey of literature related to filter design have been performed. Two methods for calculating system harmonic impedances have been investigated. In the measurement method, an instrumentation system for measuring system voltage and current has been assembled. Different schemes of using the measurements to calculate system harmonic impedances have been studied. In the analytical method, a procedure to include various operating conditions has been proposed. Computer programs for both methods have been prepared, and the results of the measurement and analytical methods analyzed.

A conclusion of the project is that the measurement and analytical methods both provided reasonable results. There are correlations between the measured and analytical results for most harmonics, although there are discrepancies between the assumptions used in the two methods. A sensitivity approach has been proposed to further correlate the results.

From the results of the analysis, it is recommended that both methods should be tested further. For the measurement method, more testing should be done to cover different system operating conditions. In the analytical method, more detailed models for representing system components should be studied. In addition, alternative statistical and sensitivity approaches should be attempted.

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

Over the years many improvements have been made in high-voltage direct-current (HVDC) converter design concepts, but not much progress has been made in optimizing the design of alternating-current (ac) harmonic filters. In this report for RP1138-1, impedance-frequency characteristics measured on an ac system serving an HVDC converter were compared with values obtained using a digital model. The principal emphasis was on improving a utility's ability to specify ac filter designs for future HVDC projects. Complementary work covering interference at carrier communication frequencies was carried out under RP1427 and is described in EPRI Final Report EL-2545. Additional work concerning distribution voltages is being carried out under RP1024 (which is presented in EPRI Final Report EL-1627) and under RP2017.

PROJECT OBJECTIVES

The objectives of this project were to evaluate past harmonic filter design practices and to investigate methods for calculating system harmonic impedances at frequencies ranging from 120 to 3000 Hz. The calculation of harmonic impedances has two aspects: (1) the development of a digital model to accurately represent the system and (2) the assembly of an instrumentation package for measuring harmonic voltages and currents so that the reliability of the modeling method can be assessed. An additional task was to write a guide book on ac filter design.

PROJECT RESULTS

Past filter design practices were evaluated. An instrument package was developed, and the measured impedances were compared with those calculated from a digital model; they showed substantial agreement at most harmonics between the measured and the analytic results. Agreement was improved by performing a sensitivity analysis with respect to frequency. Digital programs for calculating harmonic components of the measured signals and system impedance were developed.

The project was much more complicated than originally anticipated. The work completed is a step toward understanding the impedance-frequency characteristics of ac systems. There is a need, however, for more measured data for systems under different loading conditions, more detailed models for system components and loads, and a better understanding of the higher-order harmonic currents and voltages and their effects on power system equipment.

The results of this project are published in two volumes. Volume 1 reports on the technical approaches and the results. Volume 2 documents the computer programs.

Gil Addis, Project Manager
Electrical Systems Division

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General Electric Company has completed EPRI research project RP1138-1, "HVDC-AC System Interaction From AC Harmonics." The RP1138-1 work was managed by Glenn D. Breuer of the Electric Utility Systems Engineering Department (EUSED). The work was performed by Joe H. Chow, Carl B. Lindh, Nicholas W. Miller, William W. Price, Anne E. Turner and Robert R. Whitney of EUSED and Fred H. Numrich of the General Electric Company's Turbine Technology Laboratory. Two other investigators, Thomas J. Gentile (A. D. Little, Inc.) and Dr. Robert H. Lasseter (University of Wisconsin), had also contributed.

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SUMMARY

Current practice of ac filter design for HVDC systems has incorporated conservative assumptions of system characteristics leading to either overdesign or, at best, varying margins of voltage and current stresses on equipment. Improved methods are needed to characterize the ac system harmonic behavior in order to incorporate this information into the filter design and performance assessment process. The purpose of this project has been to evaluate the present filter design practice and to investigate methods for calculating system harmonic impedances.

BACKGROUND

Historically, the application of HVDC transmission systems has involved the study of the effects of the harmonic currents generated by converter operation and injected into ac systems and the mitigation of harmonic effects by filters. Data on the ac system impedance at the various harmonic frequencies have been sought by measurement and calculation. While some information about the system impedance can be determined, it varies with time, system contingencies and system growth. As a consequence, conservative assumptions of system impedances have provided the basis of ac filter design and performance. Coupled with often arbitrary levels of required telephone influence criteria, this has resulted in more costly filters than would be required if a better understanding of the system harmonic behavior was available.

This project addressed the need for the system harmonic impedance information and methods to determine it by test and/or calculation for a present or future system. The project undertook research to measure harmonic impedances and sources on a power system and to modify existing analytical techniques to more closely match the field test measurements. The information will improve the ability of a utility to describe the ac system for future filter design.

OBJECTIVES

The objectives of the research and development effort of this project were as follows:

1. To design an instrumentation system, conduct field tests and use the test data to provide information on the ac system impedance-frequency characteristics.
2. To develop computer models for calculating impedance-frequency characteristics and compare with the field tests.
3. To develop a basis for characterizing a utility ac network by test and/or calculation prior to a dc application in a manner to improve ac filter design.
4. To report on the completion of these study areas and prepare an overview on the influence of system harmonic characteristics on ac filter design.

FILTER DESIGN SURVEY

The existing literature of published and unpublished information in relation to the definition of ac system frequency characteristics and ac filter design was reviewed. A detailed state-of-the-art survey on how utilities defined ac system frequency characteristics and how filters were designed was written.

MEASUREMENT METHOD

Data Acquisition System

To measure a harmonic voltage as low as one volt in a system with 136,000 volts line-to-ground voltage, a measurement system with a dynamic range approaching 100 dB is required. The main component of the measurement instrumentation system was the Transient Monitor System developed under EPRI RP751. To overcome the limited dynamic range of the EPRI system, notch filters were installed such that one measured signal would be recorded on two digital channels, one with all the frequencies and the other with the 60 Hz removed.

Bonneville Power Administration (BPA) was the host utility for the field tests at the Celilo substation. BPA supplied special voltage dividers for voltage measurement and current transformers for current measurement. The current transformers also contained "bushing taps" which were built-in capacitive voltage dividers. Special toroids called "Maxwell Worms" or Rogowski Coils were installed

at the neutral end of shunt impedances to measure current. The sensors used eventually were the current transformers and the bushing taps.

The measured signals were transmitted to the instrumentation system with twisted pair telephone cables installed in conduits. An optical fiber link was also installed but not used due to distortion.

The instrumentation system, the sensors and the data links comprised the data acquisition system.

An automatic data logging system was installed to monitor the filter currents above a preset limit. The intent was to use the filter currents as level indicators during the test periods.

Testing

Tests were first performed to determine the adequacy of the data acquisition system. They consisted of measuring the voltages across and the currents in known shunt impedances. By comparing the calculated harmonic impedances to the known impedances specified by the manufacturers, the accuracy of the data acquisition system was found to be adequate.

The objective of the testing was to measure system voltages and currents for a variety of system operating conditions. The testing included the HVDC system in operation and not in operation, and system configurations with single-phase shunt impedance and three-phase shunt impedance switchings. These tests were performed on two different days. The different types of measurements allowed the use of different schemes in impedance calculations. The schemes complemented each other and offered a consistency check in themselves.

Impedance Calculation

The voltage and current measurements were processed using Fourier transform techniques to obtain their harmonic components from the 2nd to the 50th harmonic.

Four different schemes of impedance calculations were considered. They were the dc-off single-phase switchings (DCOFF1P), the dc-off three-phase switchings (DCOFF3P), the dc-on one measurement (DCON1M), and the dc-on two measurement

(DCON2M) schemes. The system configuration in which a particular scheme was applicable is listed in Table 1. The DCON1M scheme did not require shunt impedance switchings.

Table 1
Application of Measurement Schemes

DC Status	Shunt Impedance Switchings	Schemes
Off	Single-Phase	DCOFF1P
Off	Three-Phase	DCOFF3P
On	With or Without Shunt Impedances	DCON1M
On	Single- or Three-Phase	DCON2M

The dc-off schemes used the ac system harmonics as the only harmonic sources in the system. The DCON1M scheme assumed that the harmonic generation by the converter operation was dominant and neglected the ac system harmonics. The DCON2M scheme took both the dc and ac harmonics into account.

A statistical approach was used to analyze the measurement results obtained from various tests.

ANALYTICAL METHOD

Digital Program for System Harmonic Impedance Calculation

The generally accepted approach is to compute for each harmonic, a Thevenin equivalent of the ac system as seen from the converter terminals. Such an equivalent requires the determination of a Thevenin impedance and a voltage source for the system at the subject harmonic frequency. A digital computer program called System Impedance Scanning Program (SISP) has been prepared for estimating the Thevenin impedance. That program utilizes bus shunt and branch data as normally input to a conventional load flow program, and constructs the nodal-admittance matrix of the network under study. To determine the driving point impedance at a specific node (converter bus for example), the program reduces the admittance matrix down to that one node and inverts the resulting admittance. That procedure is repeated for each frequency of interest with the individual shunt and branch element admittances inputted for that frequency.

Computer Models

The shunt and branch elements were represented by frequency dependent impedances. Transmission lines were modeled with distributed parameters and skin effect. Shunt connected reactors and capacitors were represented by $Y_L = 1/\omega L$ and $Y_C = \omega C$, respectively. Shunt connections to ground representing loads were neglected since no suitable admittance model was hypothesized.

Analysis Procedure

The SISF program was used to estimate the positive sequence impedance of the ac system as viewed from the Celilo converter station. Computations were made with the actual system conditions in effect during the tests. Extreme care was exercised to know the state of the system network during the test period. Hard copy records of real time data were obtained from the BPA operating center. Flows into some lower voltage networks consisting of "loads" to the ac system were monitored. These data would be useful if, in the future, load models were studied.

To estimate the system impedance, an approach that progressively modeled a larger portion of the system was taken. The approach started out with a model which includes all branches and shunts up to a certain tier of buses. The system impedances were calculated with the terminal buses open circuited and then short circuited. If the results for two successive tiers were roughly the same, then sufficient detail of the system had been included. On the other hand, if the results were different, the model was enlarged by including branches and shunts for an extra tier of buses, and the impedances were recalculated with open and short circuit termination. In this study, no convergence was observed. Thus a statistical processing was performed using the impedance values for different tiers which were interpreted as representative of the impedance characteristics for a variety of operating conditions.

CORRELATION OF MEASURED AND ANALYTICAL RESULTS

The measured and analytical results were compared as a check of the methods. Comparisons were made using individual data points as well as mean impedances and standard deviations. A sensitivity approach was also used to further correlate the results.

CONCLUSIONS

The measurement and analytical methods both provided consistent results. The measurement and analytical results were correlated for most harmonics. The discrepancies were attributed to the system components not modeled in the SISP and not captured by the statistical approach.

In the measurement method, the data acquisition system was adequate, as shown by the measured values of known shunt impedances. All the schemes except the DCOM1M scheme provided consistent results above the 5th harmonic, although the dc-on schemes were better than the dc-off schemes because of larger signals. The DCON1M scheme which neglected the ac system harmonics was not reliable especially for the lower harmonics (2nd to 7th) where the dc and ac system harmonics were roughly of the same order of magnitude. For the 5th and lower harmonics, the measurement method provided poor results. One of the reasons was that not all the nonlinearities in the ac system were accounted for. Thus, these measurement schemes were a valid method for calculating certain system impedances at particular operating conditions. They provided less conservative results since they included the damping effects of loads and other equipments, thus requiring less expensive filters.

In the analytical method, the results obtained from a statistical approach correlated with most of the measured results. At some harmonics where the discrepancies were substantial, a sensitivity analysis performed with respect to frequency further correlated the results. Although SISP was valid, it needed to be improved both in terms of modeling and analysis because its results were conservative and would lead to overdesign of filters.

RECOMMENDATIONS

How to Use the Results of this Project

The results of this project are contained in two volumes of the final report. Volume 1 reports on the technical approaches and the results, and Volume 2 documents the computer programs. Volume 1 can be organized into five parts. Section 1 is an introduction to Volume 1. Section 2 is an overview of the present ac filter design practice in the electric power industry. Sections 3 to 6 discuss the measurement method and Section 7 presents the analytical method to calculating

system harmonic impedances. Section 8 is a comparison of the measurement and analytical methods using the Bonneville Power Administration's system as viewed from the Celilo substation.

The final report can be used in several ways. For power engineers interested in ac filter design, Section 2, Volume 1, serves as an introduction. It explains the process of combining the knowledge of system harmonics generation and harmonic impedances to design filters for meeting certain performance and reactive power requirements. For those who want to pursue the subject further, a bibliography on harmonic generation and filter design in Appendix A, Volume 1, provides an extensive list of references and their synopses.

For ac filter designers who need to know system harmonic impedances, the project has provided two sets of digital computer programs. The first set is to be used with actual system voltage and current measurements. Although no instrumentation system evolved as a final product of this project, a prototype was constructed and the design criteria were documented. It can serve as a model for future system designs. Four measurement schemes were tested. The dc-off schemes are applicable when there is no nearby dc harmonic source, and will be useful in the design phase before a dc terminal is built. The dc-on schemes are applicable when there is an available nearby dc harmonic source, and will be useful for monitoring the harmonic impedance changes due to system expansions after a dc terminal has been built. These schemes are flexible in that they can accommodate both single phase and three phase shunt impedance switchings. Test procedures for obtaining the measurements are given, which can be used as guidelines for future tests. Digital programs (DATARD, HARMAP, etc.) for calculating harmonic components of the measured signals and system impedances are available to the filter designers. The structure and usage, including data forms, of the programs are given in Volume 2. The data conversion program is applicable to the instrumentation system used in this project only and has to be modified if a different instrumentation system is used. However, the other programs will still be applicable with a few input statement changes.

When it is inconvenient to perform actual system measurements, an analytical approach can be used to calculate system harmonic impedances. This approach has the advantages of being able to investigate effects of contingencies and study

future system configurations. The extent of the system to be modeled can be obtained by examining tiers of buses. In case of no convergence, a statistical approach with a sensitivity analysis is suggested. A digital program (SISP) is available, and its structure and usage with data forms are given in Volume 2. The program is currently dimensioned to 400 buses, 600 lines, and can be easily expanded. New models can also be added easily if needed.

Future Work

This project is a first step toward understanding the impedance-frequency characteristics of ac systems. It uncovers several issues which need to be addressed.

In the measurement method, more tests should be performed to obtain data for systems at different loading conditions. Perhaps the tests could be performed on a smaller or isolated system to make the validation with the analytical method easier. Schemes that account for unbalanced impedances such as the one outlined in Appendix B of Volume 1, and nonlinearities in ac system harmonic generation should be considered.

In the analytical method, more detailed models for system components such as transformers and loads should be studied. Alternative analysis techniques for determining the extent of the system to be modeled should be developed. The three-phase calculation method should be considered to account for imbalance close to the bus of interest.

In the general area of harmonics, a better understanding of the higher order harmonic currents and voltages and their effects on power system equipment is required. For example, a present concern is the effect of harmonics in generators which are close to harmonic generating devices. In view of the imminent installation of many dc transmission systems and other nonconventional generating and storage devices such as photovoltaic cells, fuel cells and wind turbines by the utilities, it constitutes an urgently needed research area.

Section 1

INTRODUCTION

Current practice of ac filter design for HVDC systems has incorporated conservative assumptions of system characteristics leading to either overdesign or, at best, varying margins of voltage and current stresses on equipment. Improved methods are needed to characterize the ac system harmonic behavior in order to incorporate this information into the filter design and performance assessment process. The purpose of this project has been to evaluate the present filter design practice and to investigate methods for calculating system harmonic impedances.

An overview of ac filter design for HVDC systems and a survey of references related to filter design have been performed.

Two methods for calculating system harmonic impedances have been investigated and computer programs for both methods have been prepared. In the measurement method, an instrumentation system for measuring system voltage and current has been assembled and shown to have the required accuracy. Different schemes for using the voltage and current measurements in impedance calculations have been studied. In the analytical method, a procedure to include various operating conditions has been proposed. The results of the measurement and analytical methods have been compared.

Both the measurement and analytical methods provided consistent results. There were correlations between the measured results and the calculated results at most harmonics. The correlations were improved by performing a sensitivity analysis. It is recommended that the methods be further tested with more measurement data and accurate computer models for equipments.

1.1 Summary of Report

The report is in two volumes. This volume, Volume 1, reports on the technical approaches and the results. Volume 2 documents the computer programs used in this project. Preliminary results of this project have also been described in [1,2]. The harmonics measured at BPA's Big Eddy Substation are documented separately in [3]. The following is a summary of Volume 1.

Section 2 is an overview of ac filter design for HVDC systems. It reports on the present practice of system impedance-frequency specifications. The filter configurations and their design criteria are discussed. Other factors such as reactive power supply are also considered.

Section 3 describes the techniques for calculating system harmonic impedances from voltage and current measurements. It contains four schemes, the dc-on two measurements (DCON2M), dc-on one measurement (DCON1M), dc-off three-phase switching (DCOFF3P) and dc-off single-phase switching (DCOFF1P) schemes. The assumptions used in the schemes are also stated.

Section 4 describes the design of the data acquisition system. The components of the systems, namely, the instrumentation system, the voltage and current sensors, and the data links, and their integration are discussed in detail.

Section 5 describes the tests performed to obtain the measurements. The configuration at Celilo and the procedure used in the tests are given. The harmonics measured at Big Eddy during the tests are in [3].

Section 6 contains the measurement results. It gives an overview of the Fourier transform technique used in processing the test data. It analyzes the measured harmonic voltages and currents, and discusses the accuracy of the data based on the comparison of the measured values of shunt impedances to manufacturers' specifications. It describes the results of using a statistical approach in processing the impedances calculated from the different schemes. Recommendations for the different schemes are given.

Section 7 contains the analytical results. It describes the models available in SISP and a statistical approach to analyze the SISP results. The use of SISP is illustrated with the calculation of system harmonic impedances from Celilo.

Section 8 compares the analytical results to the test results. A sensitivity analysis is performed to include effects of frequency changes. Conclusions and recommendations for improving the correlation of the results are given.

Appendix A is a compilation in reverse chronological order of the literature on system harmonic generation and ac filter design from 1949 to 1980. Each publication is followed by its synopsis.

Appendix B describes impedance calculation methods from voltage and current measurements that do not require a balanced impedance assumption.

Appendix C is a description of the harmonic current monitoring system installed at Celilo and Big Eddy.

Appendix D contains the measured impedances obtained from the various tests.

References

1. G.D. Breuer, J.H. Chow, T.J. Gentile, C.B. Lindh, F.H. Numrich, R.H. Lasseter, G. Addis, and J.J. Vithayathil, "HVDC-AC Harmonic Interaction, Part I: Development of a Harmonic Measurement System Hardware and Software," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, March 1982, pp. 701-708.
2. G.D. Breuer, J.H. Chow, T.J. Gentile, C.B. Lindh, R.H. Lasseter, G. Addis and J.J. Vithayathil, "HVDC-AC Harmonic Interaction, Part II: AC System Harmonic Model with Comparison of Calculated and Measured Data," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, March 1982, pp. 709-718.
3. P.E. Eichin, "Harmonic Analysis Data Manually Recorded at BPA's Big Eddy Substation During Celilo HVDC Operation and Capacitor/Harmonic Filter Switching Tests," EPRI RP-1138-1 Project Report, April 1979.

Section 2

STATE-OF-THE-ART OF AC FILTER DESIGN

In the sections below ac filter design considerations will be discussed. Topics to be discussed include the harmonic generation, system harmonic impedance models, filter configurations, performance values, reactive power considerations and filter component design. It is believed that the general design procedure will be the same regardless of HVDC manufacturers; the primary distinction is in the programs used for the filter design. References to the topics discussed in this section can be found in Appendix A, which is a bibliography on harmonic generation and ac filter design.

2.1 Generation of Harmonics by Converters

The modern HVDC station consists of 12-pulse converter sections as indicated in Figure 2.1-1. As seen in this illustration the 12-pulse connection consists of two 6-pulse groups, one group having a Y-Y connected converter transformer and the other group having a Y- Δ connected converter transformer. A series connection of the two 6-pulse groups constitutes a 12-pulse connection. These 12-pulse groups can also be connected in series on the dc side (if required for voltage), or in parallel (if required for current); the converter transformers are in parallel on the ac side. This is illustrated in Figure 2.1-2 which is a one-line diagram of two series connected 12-pulse bridges per pole.

2.1.1 Six Pulse Harmonic Generation

In Figure 2.1-1 a Y-Y connected and a Y- Δ connected 6-pulse group were illustrated. Since harmonic generation is of interest we will determine the wave shapes of the primary currents i_A , i_B and i_C for the Y-Y connected converter and i'_A , i'_B and i'_C for the Y- Δ connected converter. In Figure 2.1-3 currents i_A , i_B and i_C are indicated to show the firing sequencing of the thyristors marked 1, 3 and 5 in the upper portion of the 6-pulse thyristors bridge and 4, 6 and 2 in the lower portion of the thyristor bridge. Only i'_A and the summation of i_A and i'_A have been indicated

Figure 2.1-1 12 Pulse Bridge Connection

Figure 2.1-2 One-Line of a HVDC Station

Figure 2.1-3 Primary Side Currents

because the remaining currents are merely displaced by the 120° relation between phases as indicated by currents i_B and i_C . In Figure 2.1-3 the solid lines show the currents with the overlap $\mu = 0$, with no dc current ripple, for a perfect sinusoidal ac wave shape. The dashed curve illustrates the current wave shape when overlap is considered. These wave shapes are deduced from the firing sequence of the valves (which is sequential as follows - 1,1',2,2',3,3',4,4',5,5',6,6'); and the fact that 1 P.U. current flows through the valves. Also, consideration must be given to the firing delay α and the fact that the Y- Δ converter transformer introduces a 30 electrical degrees phase shift in the secondary line-to-line voltage in relation to the line-to-line voltage provided by the Y-Y connected converter transformer.

If commutation overlap is neglected and if the smoothing reactor is assumed to be very large, the current waves are essentially square as indicated by the solid line waveforms in Figure 2.1-3. In this case the Fourier series for the ac currents are as follows:

$$i_A = K \left(\cos \theta - \frac{1}{5} \cos 5 \theta + \frac{1}{7} \cos 7 \theta - \frac{1}{11} \cos 11 \theta + \frac{1}{13} \cos 13 \theta \dots \right) \quad (2.1)$$

$$i'_A = K \left(\cos \theta + \frac{1}{5} \cos 5 \theta - \frac{1}{7} \cos 7 \theta - \frac{1}{11} \cos 11 \theta + \frac{1}{13} \cos 13 \theta + \dots \right) \quad (2.2)$$

In either case the generated harmonics are:

$$n = kP \pm 1 \quad (2.3)$$

where n is the harmonic order, P is the pulse number and k is an integer 1,2,3... These are known as the characteristic 6 pulse harmonics.

2.1.2 Twelve Pulse Harmonic Generation

Inspection of the wave shapes $i_A + i'_A$, as shown in Figure 2.1-3, indicates that its Fourier series will be the sum of the Fourier series for i_A and i'_A :

$$i_A + i'_A = 2K \left(\cos \theta - \frac{1}{11} \cos 11 \theta + \frac{1}{13} \cos 13 \theta - \frac{1}{23} \cos 23 \theta + \frac{1}{25} \cos 25 \theta \dots \right) \quad (2.4)$$

The equation continues to apply where P is 12 and the harmonics are of order 11, 13, 23, 25, etc.

In practical applications, the constant 2K or the amplitude is determined by the no-load direct voltage and the direct current since the rms value of (2.4) is

$$I_A = \frac{I_d U_{do}}{\sqrt{3} U_{L-L}} \left(\cos \theta - \frac{1}{11} \cos 11\theta + \frac{1}{13} \cos 13\theta \dots \right) \quad (2.5)$$

where I_d = direct current
 U_{do} = no-load direct voltage for a 12-pulse bridge
 U_{L-L} = ac systems line-to-line voltage

From the above discussion it can be concluded that the maximum values of fundamental and harmonic currents will be

$$I_1 = \frac{I_d U_{do}}{\sqrt{3} U_{L-L}} \quad (2.6)$$

and

$$I_n = \frac{I_1}{n} \quad (2.7)$$

These maximum harmonic currents are not normally generated because of the overlap in the commutation which is related to delay angle (α), direct current (I_d) and commutating reactances (ϵ_x) of the converter transformers. For practical cases the harmonic current generation can be expressed as

$$I_n = k_n I_1$$

where k_n is indicated in Table 2.1-1 for common values of α , ϵ_x and rated dc current.

Table 2.1-1

Factor k_n as a function of α and ϵ_x

n	$\alpha = 15^\circ$		$\alpha = 20^\circ$		$\alpha = 30^\circ$	
	$\epsilon_x = 0.8$	$\epsilon_x = .10$	$\epsilon_x = .08$	$\epsilon_x = .10$	$\epsilon_x = 0.8$	$\epsilon_x = .10$
11	.47	.37	.56	.42	.69	.57
13	.32	.19	.42	.26	.57	.44
23	.21	.19	.16	.21	.07	.14
25	.21	.15	.20	.20	.06	.13

It should be noted that the converter appears to be a current source for the fundamental as well as the characteristic harmonics.

2.1.3 Noncharacteristic Harmonic Generation

The main harmonic generation of a HVDC converter station will be the characteristic harmonics which for the present 12-pulse types of converter connections will be of the order

$$n = 12k \pm 1 \quad (2.9)$$

where k is an integer 1, 2, 3...

Minor magnitude of other harmonic orders is generated mainly due to firing angle errors and unbalances in the converter transformer reactance and the supply voltage to the converters. The unbalances generate odd harmonic orders while the firing angle error of the converters will also generate even harmonics. The present phase lock loop control system which all manufacturers employ results in a random control angle variation of a few tenths of a degree. This random control variation generates very low values of harmonics which can be neglected in harmonic studies.

2.1.4 Higher Pulse Arrangements

In industrial converter applications it is quite common to use higher pulse numbers than 12. For instance, in rectifiers for aluminum pot lines, 36-pulse or even 72-pulse operation is employed. These pulse connections are accomplished by extra windings and taps on the converter transformers.

HVDC power transmission studies have shown that pulse numbers higher than 12 are not economical. A pulse number of 24 could be accomplished by using a 15 degree

phase shift between converter transformers. The primary side for one 12-pulse group would be shifted forward 7 1/2 degrees by the use of a modified delta or an equivalent zig-zag wye transformer. The other 12-pulse group would be shifted backward 7 1/2 degrees in a similar manner to accomplish the 15 degree shift between the 12-pulse groups required for the 24-pulse connection. With this arrangement the characteristic harmonic generation would be 23rd, 25th, 47th, 49th, and the 11th and 13th harmonic filters could be eliminated. However, filters are also a source for the vars consumed by the converter and only the elimination of the reactors of the 11th and 13th filter plus the extra rating in the capacitors from the harmonic currents could offset the cost for the complication in converter transformer windings. At present, this cannot be accomplished economically and manufacturers will use the 12-pulse connection as the basic module in HVDC installations.

2.1.5 Other Harmonic Sources

Any ac system contains harmonic currents and voltages to a certain degree even when the ac system does not include converter HVDC.

Conventional generators are harmonic voltage sources. Conventional power transformers due to nonlinearity in excitation characteristics are harmonic current sources, particularly if operating close to saturation. In distribution systems, harmonics appear because many loads such as light dimmers and household equipments having variable speed motors produce harmonics. For instance, in England substantial 2nd harmonic produced by the power circuits of television receivers could be measured on the high voltage ac systems.

In filter design for HVDC systems, consideration must be given to these system harmonics by arbitrarily increasing the effective harmonic generation or by recognition of harmonic currents or existing distortion voltages.

2.1.6 Harmonic Models

The one-line diagram of a HVDC converter station is indicated in Figure 2.1-4 and the corresponding model is illustrated in Figure 2.1-5. The ac system to the right of point A is represented in the model by the harmonic impedance of the system ($Z_{S,n}$). The filters indicated below point A are represented in the model by the total impedance ($Z_{F,n}$). These harmonic impedances, $Z_{S,n}$ and $Z_{F,n}$, will be considered in the following subsections. Although the model appears to be quite simple, hand calculations of harmonic currents and voltages

Figure 2.1-4 One-Line Diagram of a HVDC Station

Figure 2.1-5 Harmonic Model of a HVDC Station

are time consuming due to the complex representation of impedances and the large number of harmonics needed to be considered. However, these calculations are conveniently performed using computer programs.

2.2 System Harmonic Impedance

The harmonic impedance of a system is quite difficult to determine. Filter designers would like to work with impedances obtained from measurements. Harmonic impedances could also be obtained from measurements on scale models, from calculations based on system data or from use of realistic assumptions of system harmonic impedance values. Each method has its advantages and disadvantages and will be discussed below.

2.2.1 Measured System Harmonic Impedance

The difficulty in measuring the harmonic impedance on an actual system results from the need for instrumentation with a dynamic range of 100 dB and good phase angle measuring accuracy. These requirements can be met using a digital recording system.

Measurements with a digital recording system use the intrinsic system harmonic voltages as the source and provide the harmonic impedance for the conditions existing during the test. Different system conditions could be created by switching of lines. Also measurement of different loading of the system in the form of day, night and weekend measurements could be obtained. There would be some uncertainty in the data since the effect of future system expansion on harmonic system impedance could not be considered.

In the scale model, measurements accounting for future expansion could be made provided that confidence in the scale model was obtained by a satisfactory comparison between the scale model and the actual system harmonic impedance measurements.

2.2.2 Calculated System Harmonic Impedance

Attempts to calculate the harmonic impedance of systems have been made in the past. The design of the filters for the Pacific HVDC system was based on calculated system harmonic impedances provided in the form of a sector, with minimum and maximum impedance and angle for each harmonic. Different load models and system configurations were used to arrive at this data. Normally only the

positive sequence impedance is calculated. The problem with these calculations is to arrive at proper representation of loads and resistive components in equipment. For example, in the calculation of the harmonic impedance of a particular ac system it was found that if the system was represented five buses away for each line emerging from the point of interest, not significantly different impedances were obtained regardless if the far end buses were shorted or opened. For close-by load points, load representations would also be required.

2.2.3 Different Types of Generalized Network Assumptions

Utilities have used several different approaches to characterize the harmonic impedance of the ac system for harmonic specifications of the HVDC or static var control systems. Some of these are discussed in more detail below.

General Sector Model

This general sector model has been used by manufacturers of HVDC equipment and by utilities in HVDC specifications. The objective of this model shown in Figure 2.2-1 is to create a boundary enveloping the actual harmonic impedances. This boundary is related to the minimum and maximum short circuit impedance of the system. The outer curved boundary of the sector is the harmonic order times the maximum short circuit impedance; the inner boundary arc of the sector is the square root of the harmonic order times the minimum short circuit impedance. The sectors are bounded between specified impedance angles. Bounding impedance angles for several ranges of harmonic orders are described in Figure 2.2-1. The model lends itself conveniently for smaller subdivisions for the calculation of performance values as defined in Subsection 2.4. With this model, maximum, minimum and mean value of performance parameters can be calculated along with other useful statistics. The model itself has no direct relation to the physical system except for the lower harmonics which may be related to the short circuit impedance of the ac system.

General Circle Model

A few utilities have been using a Circle Model in one form or another. The general form of these models is illustrated in Figure 2.2-2 where R_1 , R_2 and the impedance angle θ are determined from system characteristics.

This model has a close resemblance to the physical characteristic of a system impedance; since it is not related to the harmonic order it tends to cover too

Figure 2.2-1 System Impedance Characteristic General Sector Model

Figure 2.2-2 System Impedance Characteristic General Circle Model

broad an area for the lower harmonics. Therefore, it is important to properly describe the radius for the circle section. The selection of the intercept (R_1) with the abscissa is also of importance since an abnormally low value will make it difficult to design the filters to limit the flow of harmonic currents to the ac system.

X/R Ratio Model

In some cases a specified X/R ratio for the harmonic impedance of the ac system has been used for some performance and component rating calculations. The objective has been to determine maximum performance values or filter component currents along the specified system harmonic impedance line.

This model is valid for lower harmonics, but deviates from physical reality for the higher harmonics.

Infinite Impedance Model

This model has been used for performance calculations, and demonstrates that the performance will be completely dependent on the impedance of the filters. All parallel resonances which might occur will not be simulated in an actual system and unrealistic results are obtained.

Mixed Models

In some cases mixed models have been used. For example, one model may be used for performance calculations and another model used for determination of harmonic currents through filter components.

From the above discussion it can be seen that a unified characterization of a systems harmonic impedance does not exist. From a filter design standpoint, standardization of system harmonic impedance models or a reliable means of calculating the harmonic characteristics of a system certainly would be very desirable.

2.3 Harmonic Filter Configurations

It was indicated in Subsection 2.1 that the modern HVDC station operates with a pulse number of 12 and that the characteristic harmonics generated would be 11th, 13th, 23rd, 25th, 35th, 37th, 47th and 49th. Since the harmonic generation is inversely proportional to the harmonic order, 11th and 13th harmonic would have about twice the magnitude of the rest of the harmonics. The present practice is,

at least for larger stations, to provide tuned, band pass filters for the 11th and 13th harmonics; damped, high-pass filters are provided for the higher harmonic current generation. It is possible for some HVDC installations to provide only high-pass filters. This, however, depends on the performance criteria selected for the station (to be discussed in Subsection 2.4).

It should be mentioned that the filters provided in a HVDC station, in addition to providing a low impedance path for the generated harmonics, will also provide var support for the converter. Since the var support would be required in any case, the additional cost for the filter is the inclusion of the reactor, resistors, and the protection equipment. This must be taken into account when economic comparisons or cost evaluations are made.

A discussion of the different types of filters used in HVDC stations will follow.

2.3.1 Band Pass Filters

The band pass filter consists of a capacitor (C) in series with a reactor (L) tuned at a specific harmonic (n). For low quality factor (Q) filters, a resistor (R) may also be included in the series circuit. Figure 2.3-1 indicates the arrangement where R_n will consist of the loss component in the capacitor (R_C) and the resistance of the reactor (R_L) plus the external resistance (R), if needed, to bring the Q of the circuit down to desired value

$$R_n = R_C + R_L + R \quad (2.10)$$

and Q at tuned frequency would be

$$Q = \frac{n X_{L,1}}{R_n} \quad (2.11)$$

where $X_{L,1} = 2\pi f_1 L$ is the reactance of the reactor at fundamental frequency (f_1).

At the tuned harmonic (n_o) the reactance of the reactor is equal to the reactance of the capacitor

$$n_o X_{L,1} = \frac{X_{C,1}}{n_o} \quad (2.12)$$

Figure 2.3-1 Band Pass Filter

Figure 2.3-2 Impedance Characteristic of a Band Pass Filter as a Function of Frequency

and the filter will exhibit a resistive characteristic (R_n). The band pass filter impedance characteristic is indicated in Figure 2.3-2.

Sometimes the characteristics of a filter are plotted using X-R coordinates or polar coordinates. The characteristics of the band pass filter in X-R coordinates are illustrated in Figure 2.3-3. Below the resonance harmonic (n_o) the band pass filter has a capacitive reactance. Above n_o the reactance is inductive and at n_o the reactance is zero and the filter impedance is resistive with the value R_n .

Detuning

A vital factor in the design of band pass filters is the difference between the filter resonant frequency and the frequency of the harmonic current to be absorbed. This disparity can be caused by variation in power system frequency or by change in inductance or capacitance of the filter circuit. In the past, automatic tuning schemes have been employed but they have not been entirely satisfactory. More recently the component variation has been controlled or switching has been employed. In any case the following discussion of detuning is an important part of the design process.

The filter impedance Z_F is defined by

$$Z_F = R_n + j \left(n X_{L,1} - \frac{X_{C,1}}{n} \right) \quad (2.13)$$

The substitution of (2.11) and (2.12) into (2.13) yields

$$Z_F = \frac{X_{C,1}}{n_o Q} + j \left(n \frac{X_{C,1}}{n_o^2} - \frac{X_{C,1}}{n} \right) \quad (2.14)$$

which simplifies to

$$Z_F = \frac{X_{C,1}}{n_o} \left\{ \frac{1}{Q} + j \left(\frac{n}{n_o} - \frac{n_o}{n} \right) \right\} \quad (2.15)$$

If we define a relative detuning δ as

$$\delta = \frac{n - n_o}{n_o} \quad (2.16)$$

Figure 2.3-3 X-R Characteristic of a Band Pass Filter

the band pass filter impedance can then be expressed as

$$Z_F = \frac{X_{C,1}}{n_o} \left(\frac{1}{Q} + j \frac{2 + \delta}{1 + \delta} \delta \right) \quad (2.17)$$

$$K = \left(\frac{1}{Q} + j \frac{2 + \delta}{1 + \delta} \delta \right) \quad (2.18)$$

The quantity K is given in Table 2.3-1 for different Q values as a function of δ , within the normal detuning range. The magnitude of K is plotted in Figure 2.3-4. Using the curves in Figure 2.3-4 the absolute value of the band pass filter impedance will be

$$|Z_F| = \frac{X_{C,1}}{n_o} |K| \quad (2.19)$$

The detuning of a band pass filter is caused by variations in the ac system's fundamental frequency, variation in the capacitor's capacitance due to dielectric temperature variations and to the accuracy of the initial tuning of the filter. The above detuning influence will be discussed in more detail below.

Table 2.3-1

Quantity $K = \left(\frac{1}{Q} + j \frac{2 + \delta}{1 + \delta} \delta \right)$ as a function of detuning for different

Q values

δ	Q = ∞	Q=125	Q=100	Q=75
0.015	0.0298 /90	0.0308 /75.0	0.0314 /71.4	0.0326 /65.9
0.010	0.0199 /90	0.0214 /68.1	0.0223 /63.3	0.0240 /56.2
0.005	0.0100 /90	0.0128 /51.3	0.0141 /44.9	0.0167 /36.8
0	0 /0	0.0080 /0	0.0100 /0	0.0133 /0
-0.005	0.0100 /-90	0.0128 /-51.4	0.0142 /-45.1	0.0167 /-36.9
-0.010	0.0201 /-90	0.0216 /-68.3	0.0225 /-63.6	0.0241 /-56.4
-0.015	0.0302 /-90	0.0313 /-75.2	0.0318 /-71.7	0.0330 /-66.2

Frequency Variation

Normally during steady-state conditions the frequency of the American utility networks is held fairly constant at 60Hz. However, minor frequency variations do occur and a ± 0.1 Hz frequency variation has often appeared in specifications for harmonic filters. If we use a frequency variation of ± 0.1 Hz the contribution to the detuning (δ_F) from frequency will be

Figure 2.3-4 Quantity $|K|$ vs. Detuning

$$\delta_F = \frac{\pm 0.1}{60} \quad (2.20)$$

The frequency variation during transient conditions can, however, be quite larger and a filter designer also has to consider this variation.

Component Variation

The only component in the band pass filter exhibiting some significant variation with the temperature is the capacitor. Depending on the dielectric used in the capacitor, its capacitance variation (α) can be from 0.00025 - 0.0007 per unit per degree Celsius change in temperature. The following expression for the capacitance (C) can be written

$$C = C_o \{1 - \alpha (T - T_o)\} \quad (2.21)$$

where C_o is the capacitance at T_o . The capacitance of a capacitor has a negative variation as a function of the dielectric temperature. An increased temperature will give reduced capacitance.

If we look at the effect of this capacitance variation, we note that the tuned frequency for a LC circuit is

$$f = \frac{1}{2\pi} \frac{1}{\sqrt{LC}} \quad (2.22)$$

Taking the total derivative of equation (2.22) we obtain

$$\frac{df}{f} = -\frac{1}{2} \left(\frac{dC}{C} + \frac{dL}{L} \right) \quad (2.23)$$

This shows that the relative frequency variation is essentially one half of the sum of the relative capacitance and inductance variations.

The contribution to detuning δ_C due to variation in capacitance will therefore be

$$\delta_C = -\frac{1}{2} \frac{C - C_o}{C_o} \quad (2.24)$$

which can also be expressed as:

$$\delta_C = \alpha(T - T_o)/2 \quad (2.25)$$

where T_0 is chosen to be the center of the dielectric temperature range.

The contribution to detuning due to the inductance variation for fixed reactors can be neglected since it is practically independent of frequency or temperature variations.

On-Site Tuning

Many different approaches can be used in the initial tuning of the band pass filters. Adjustments in the inductance of the reactor, and addition of series capacitors or adjustment of the parallel capacitance in the series sections of the capacitor bank are all means of tuning the filter bank. Of the methods mentioned, the adjustment of the parallel capacitance is most convenient. This method consists of removing or adding capacitor units and changing some with lower capacitance but of the same voltage rating. This can be achieved so that the capacitor bank can be within $\pm 0.25\%$ of a desired value. The allowance in calculations for the initial tuning in frequency variation (δ_{IT}) will therefore be

$$\delta_{IT} = \frac{\pm 0.0025}{2} = \pm 0.0013. \quad (2.26)$$

The total relative frequency deviation (δ) will therefore be:

$$\delta = \delta_F + \delta_C + \delta_{IT} \quad (2.27)$$

Assuming a ± 0.1 Hz frequency variation, a temperature variation of 34°C and a temperature coefficient α of .0007, the variations are

$$\begin{aligned} \delta_F &= \pm 0.0017 \\ \delta_C &= \pm 0.0119 \\ \delta_{IT} &= \pm 0.0013 \\ \delta &= \pm 0.0149 \end{aligned}$$

If we also assume that the Q of the filters is 125 at tuned harmonic frequency, the band pass filter would have an impedance angle according to Table 2.3-1 of about ± 75 degrees for the extreme frequency, temperature and initial detuning conditions.

2.3.2 Double Tuned Filters

It is possible to combine two band pass filters into one filter bank as indicated in Figure 2.3-5. This filter would have low impedance for selected harmonics and a high impedance between the two.

This type of filter was used on one of the first HVDC installations, the cross-channel link between England and France, but has not been used in subsequent HVDC installations. This is mainly due to the complexity of the filter and the interaction between components. A fault or change in one component affects both tuning points. Economy and reliability consideration tend not to favor this arrangement.

2.3.3 High Pass Filters

A high pass filter is used to provide a low impedance path for the higher harmonics generated in a HVDC station. It consists of a capacitor (C) in series with a parallel branch of a reactor (L) and a resistor (R_{HP}) as indicated in Figure 2.3-6. This type of filter is also called a second order damped shunt filter. A third order damped shunt filter has also been used in some installations. It includes a capacitor in series with the resistor branch (R_{HP}). The impedance characteristic, as a function of frequency of the high pass filter indicated in Figure 2.3-6, is shown in Figure 2.3-7. The corresponding characteristic in the X-R coordinate is illustrated in Figure 2.3-8. If 11th and 13th tuned filters are provided, the high pass filter is usually designed to have a minimum impedance at the 24th harmonic thereby presenting a low impedance to the characteristic 23rd and 25th harmonics. The higher harmonics will see an impedance which includes substantial damping.

Advantages of the high pass filter includes the following:

- No sharp tuning is required.
- It tolerates relatively large steady state frequency excursion.
- Its high resistances and damped impedances characteristics reduce transient voltages.

Its disadvantages, especially if used for the 11th and 13th harmonics, are higher losses and lower harmonic filtering performance.

Figure 2.3-5 Double Tuned Filter

Figure 2.3-6 High Pass Filter

Figure 2.3-7 Impedance Characteristic of a High Pass Filter as a Function of Frequency

Figure 2.3-8 X-R Characteristic of a High Pass Filter

Figure 2.3-9 High Pass Filter with Low Fundamental Loss

A variant of the high pass filter is illustrated in Figure 2.3-9. The reactor (L_1) capacitor (C_2) branch in parallel with the resistor (R_1) can be tuned for the fundamental frequency, obtaining low impedance, and practically diverting the fundamental currents away from the resistor.

2.3.4 Total Harmonic Filter Impedance

As an example, the total harmonic impedance of a filter for a HVDC installation is indicated in Figure 2.3-10. The impedance is quite capacitive for harmonics up to the 10th harmonic. Since a band-pass filter for the 11th harmonic is used, the impedance at the 11th harmonic should be resistive and at a low value. As the frequency, or harmonic order, is increased, the 11th harmonic filter branch becomes inductive and will form a parallel resonance circuit with the remainder of the filters which are still capacitive at a frequency between harmonic order 11 and 12. At the parallel resonance the impedance is resistive at a large value. The impedance then loops into the capacitor region and will again be resistive at a low value for the 13th harmonic. At higher harmonics another parallel resonance between the inductive 11th and 13th filters and the capacitive high pass filters is formed at a frequency between the 14th and 15th harmonics. At higher than 15th harmonic the characteristics of the high pass filter will provide a well damped impedance for harmonics ≥ 23 rd.

2.4 Performance Values

The prime objective of the filters is to provide a low impedance path for the harmonics generated in the HVDC station resulting in a tolerable harmonic current flow into the network.

The performance criteria used in U.S.A., Canada and in some other countries will be discussed in more detail. The International Telegraph and Telephone Consultative Committee (C.C.I.T.T.) has issued "directives concerning the protection of telecommunication lines against harmful effects from electricity lines" and published by The International Telecommunication Union, 1963, which defines criteria commonly used in Europe.

There are basically three filter performance criteria appearing in specifications for HVDC stations. The first relates to the harmonic voltage distortion on the ac system. Individual harmonic limits and overall harmonic distortion limits are

Figure 2.3-10 Total Harmonic Impedance of Filter Bank

included in specifications. The second performance criterion relates to the TIF (Telephone Influence Factor) on the converter bus of the ac system. The third criterion is the IT product on the connection between the HVDC converter and the ac system.

2.4.1 Definition of Harmonic Distortion

Two definitions of distortion have appeared in HVDC filter specifications. The first is an arithmetic summation of all harmonic voltages expressed in percent of the line to neutral fundamental voltage.

$$D = \frac{\sum_{n=2}^{n=m} I_{S,n} \times Z_{S,n}}{E_1} \times 100 \quad [\%] \quad (2.28)$$

where $I_{S,n}$ is the harmonic current of the n th harmonic flowing to the system. $Z_{S,n}$ is the harmonic impedance of the system at the n th harmonic and m is the highest harmonic considered, usually 49th or 50th; E_1 is the fundamental line to neutral voltage.

A definition which has a closer relation to physical phenomenon is the RSS summation of the harmonic voltages, also expressed in the percent of the line to neutral fundamental voltage.

$$D_{RSS} = \frac{\left(\sum_{n=2}^{n=m} (I_{S,n} \times Z_{S,n})^2 \right)^{\frac{1}{2}}}{E_1} \times 100 \quad [\%] \quad (2.29)$$

In some cases an upper limit for any individual harmonic voltage is specified. Often this limit has been selected to be one percent of the fundamental voltage.

2.4.2 Definition of TIF

The TIF performance criterion is an index of possible telephone influence and is the RSS of weighted per unit harmonic voltages appearing at the interface between the converter and the ac systems:

$$TIF = \frac{\left(\sum_{n=1}^{n=m} (I_{S,n} \times Z_{S,n} \times F_n)^2 \right)^{\frac{1}{2}}}{E_1} \quad (2.30)$$

where F_n is the telephone influence factor defined in EEI publication 60-63, September, 1960 and shown graphically in Figure 2.4-1.

2.4.3 Definition of IT

The IT product is the performance criterion which has caused filter designers the most difficulty. The IT is the RSS of weighted harmonic currents flowing from the HVDC station to the converter bus:

$$IT = \left(\sum_{n=1}^{n=m} (I_{S,n} \times F_n)^2 \right)^{\frac{1}{2}} \quad (2.31)$$

(Sometimes the IT product is called kIT which is IT/1000.)

From the past experience of utilities and telephone companies an IT product of about 10,000 has been acceptable. This value has therefore appeared in specifications of HVDC filters. Expensive series filters would be required to meet this low value. Such a value of IT might be a reasonable maximum for a single line but a converter connected to more than one line should be allowed to generate more than this value. Figure 2.4-2 describes a system where five lines are connected to the converter bus and a converter IT generation of $\sqrt{5} \times 10000$ probably should be permitted.

2.4.4 Performance Limitations

It is not the intent of this report to propose a specific performance value because different ac systems may have different requirements or different exposures of the telephone communications lines. The intent is merely to discuss the performance values from a filter design standpoint.

In [1], a range of performance values was indicated. For instance, it was indicated that TIF values lower than 25 were considered good and should not cause any telecommunications problems. The range between 25 and 50 was considered to

Figure 2.4-1 Telephone Influence Factor

$$I_{Tc} \leq \left(\sum_{m=1}^5 (I_{Tm})^2 \right)^{\frac{1}{2}}$$

Figure 2.4-2 IT Product Distribution

belong to an uncertain area where interference conditions could exist. A TIF value above 50 was likely to cause telephone interference. Telephone communications systems have improved since the referenced article was published (1946) and the guidelines indicated in Table 2.4-1 were upgraded. The distortion expression in RSS values has been added. Suggested performance values which do not make the filter design for a HVDC station too expensive are also included.

Table 2.4-1
Performance Criteria

	Excellent	Good	Bad	Suggested
TIF	< 25	25-50	>50	35
KIT	< 25	25-100	>100	
D _{RSS} (%)	< 2	2-5	<5	2
D _{individual} (%)				1

The IT performance value has not been included in the suggested values since it is credible only if calculated with actual system impedances and line configurations.

2.5 Combination of Generation, System and Filters

Previous sections have discussed the harmonic generation of the HVDC converters, filter configurations and approaches used for the representation of the harmonic impedance of a system; and the definition of some performance values which may be acceptable from a telephone interference and filter design standpoint. Having completed these discussions, the pieces to the model can now be combined. Figure 2.5-1 indicates the overall mathematical model that the ac filter designer will employ and possible design approaches will now be discussed.

2.5.1 No Filter

Only in special situations will it be possible to operate a HVDC station with no ac filters without exceeding acceptable performance values. Such situations may occur if the rating of the HVDC station is extremely small in relation to the short circuit capacity of the ac system. Another situation is metropolitan ac cable systems where harmonics may be absorbed by cable capacitance and shielded from contact with telephone circuits.

Figure 2.5-1 General Harmonic Model

2.5.2 High Pass Filter Only

There is a trend among ac filter designers to use only the high pass filters if adequate performance can be achieved. The reason is that the high pass filter with its damped characteristic does not change its impedance substantially with normal frequency variations or with capacitance variations due to temperature change. One filter can do the job of two band pass filters. Furthermore, the filtering function is not completely lost for extended frequency variations due to dynamic swings in the system. Due to the increased cost of losses, this approach may not always be economical.

2.5.3 Full Set of Filters

Traditionally, the filters in the 12 pulse HVDC station consist of 11th and 13th band pass filters plus a high-pass filter. The combined impedance characteristics are illustrated in Figure 2.3-10. As shown in this figure, the 11th and the 13th harmonic filter impedances are resistive at resonance but can exhibit large phase angles under detuned conditions. If the ac system has a large phase angle of opposite sign and about the same magnitude large resonant currents will circulate between filters and system, with resultant increase in losses in the filter and decreases in performance.

The advantage with the full set of filters is that losses are low and reasonable performance values can be met with a reasonable filter component rating.

2.5.4 Filter System Resonance

By examining the total impedance of a filter bank in Figure 2.3-10, it becomes apparent that the harmonic impedance of the filter system for the lower harmonics (2nd to the 10th) is quite capacitive with very little damping. If the systems harmonic impedance of the system in the same frequency range is inductive, which is quite likely, the resonant situation which is illustrated in Figure 2.5-2 will exist. The filter impedance is represented by a capacitor, which is a preferable representation for the lower harmonics, and the system impedance is represented by a reactor. In Figure 2.5-3, the capacitive reactance of the filter and the inductive reactance of the ac system are illustrated with respect to frequency. At the parallel resonant point the resulting impedance is high and is resistive in nature.

Figure 2.5-2 Filter System Resonance

Figure 2.5-3 Filter System Reactance as a Function of Frequency

Figure 2.5-4 Filter System Impedance as a Function of Frequency

The total impedance of the circuit is illustrated in Figure 2.5-4. Since a constant current source (I_n) is applied to the large impedance a high harmonic voltage will occur. Normally the harmonic generation for the 10th harmonic and below is of noncharacteristic nature and is of lower magnitude than the characteristic generation. However, the total impedance at resonance can be so high that a significant harmonic voltage is developed requiring filters.

2.6 Reactive Power Considerations

As previously indicated, the objectives of the ac filters are the provision of a low impedance path for the converter generated harmonics and the provision of var support for the converters. At high dc system load levels this dual function works out satisfactorily; but at low load levels more reactive power may be generated by the filter than is absorbed by the converters, forcing too much capacitive vars to the ac system. The reactive power balance in the ac system is disturbed and overvoltage may result.

The next consideration is the reactive consumption of the converters and techniques by which the var generation of the filters is matched to the var consumption of the converters and var capabilities of the ac system.

2.6.1 Reactive Power Absorption of Converters

Reactive power is absorbed at both rectifier and inverter and can be calculated with engineering accuracy by the following expression:

$$Q = U_d I_d \left(\left(\frac{U_{do}}{U_d} \right)^2 - 1 \right)^{\frac{1}{2}} \quad (2.32)$$

where U_d is the dc voltage
 I_d is the dc current
 U_{do} is the dc no load voltage.

The relation between the voltage (U_d) and dc no load voltage (U_{do}) is

$$U_d = U_{do} \cos \alpha - \epsilon_x \frac{I_d}{I_{dH}} U_{doH} \quad (2.33)$$

where α is the delay angle for rectifiers (the extinction angle γ applies for inverters)

I_{dH} is the rated dc load current

ϵ_x is half of the converter transformers reactance (X_T)

U_{doH} is the rated no load voltage of the converter

If we assume a delay angle (α) or extinction angle (γ) of 18 degrees and a converter transformer reactance of 20% ($\epsilon_x = 0.1$), we can calculate the var requirement of the converter. Table 2.6-1 illustrates the ratio U_{do}/U_d and the per unit converter var requirement for various values of load currents.

Table 2.6-1
Converter Per Unit Var Requirement

$\frac{I_d}{I_{dH}}$	$\frac{U_{do}}{U_d}$	$\frac{Q}{U_d I_{dH}}$
1.0	1.18	0.62
0.9	1.16	0.53
0.8	1.15	0.45
0.7	1.14	0.38
0.6	1.12	0.31
0.5	1.11	0.24
0.4	1.10	0.18
0.3	1.09	0.13
0.2	1.07	0.08

The present var requirement is plotted in Figure 2.6-1. By multiplying the P.U. value for the desired load level with the converter stations rating in MW, the converters reactive power requirement is obtained.

2.6.2 Var Generation From Filters and Shunt Banks

At fundamental frequency the filter banks are almost purely capacitive and the var generation of the bank is approximately equal to the var rating of the capacitors in the filter. Due to the fact that the band-pass and high-pass filters contain reactors in the circuit, a minor increase in the var generation

Figure 2.6-1 Converter Var Requirement

below capacitor capability occurs; this increase is related to the tuned frequency. The actual var generation (Q_F) for band-pass filters will be

$$Q_F = \frac{(U_{L-L})^2 n^2}{X_C (n^2 - 1)} \quad (2.34)$$

If the ac line to line voltage (U_{L-L}) is in kV and the band pass filters capacitor reactance (X_C) is in ohms and (n) is the tuned harmonic to which the filter is tuned, (Q_F) will be expressed in Mvars.

Equation (2.34) is approximately valid for high-pass filters, as illustrated in Figure 2.3-6, provided that (n) is the harmonic order for which the high pass filter has its minimum impedance.

The var generation for a shunt bank will be

$$Q_{CB} = \frac{(U_{L-L})^2}{X_{SB}} \quad (2.35)$$

The total var generation from filters and capacitor banks will therefore be

$$Q_T = 2 (Q_{11} + Q_{13} + Q_{HP}) + mQ_{SB} \quad (2.36)$$

assuming one complete filter set (11th and 13th band pass filters plus a high-pass filter) per pole and m number of shunt banks.

The challenge for the filter designer is to match the var generation from the filters and shunt bank throughout the converter load range and at the same time meet the performance values expected by the customer. This should, of course, be accomplished without excessive var flow to or from the ac system. No hard rules exist as far as the division of vars between the shunt banks and the filters. This division depends on individual conditions such as the harmonic impedance of the ac system, the type of filters used, required performance values, economic evaluation, etc. An approximate division may be 40-50 percent of var requirement in filters and the remainder in shunt banks. Figure 2.6-2 illustrates the var

Figure 2.6-2 Coordination of Var Consumption and Generation

Figure 2.6-3 Var Flow to or from AC System

generation from shunt banks and filters superimposed on the var consumption of the converters.

2.6.3 Var Flow to or from System

The ability of an ac system to deliver or absorb vars to or from an HVDC converter station depends basically on its short circuit impedance and the voltage variation acceptable on the converter bus. Normally it is the practice to switch capacitor banks at certain points to minimize var flow to or from the system. This is indicated in Figure 2.6-3 which shows the net var flow to or from the system based on the var conditions indicated in Figure 2.6-2. At a certain load point on the HVDC station it may also be necessary to switch some of the filter banks. Since the harmonic generation for some characteristic harmonics is not reduced in direct proportion to the load reduction, the worst performance values may occur at the load point where a complete set (one 11th, one 13th, and one high-pass filter) has been switched out.

From the above discussion it is clear that the limits of the var flow to or from the ac system will have an influence on filter design and cost. Too tight a limit will reduce individual bank size and introduce several switching points, making filters and shunt banks unnecessarily costly.

2.7 Filter Component Design

This section covers the filter design process leading to the component specifications. This process should start only when it has been determined that the filter design meets all performance requirements. The process may be separated for different filter alternatives to determine the least expensive filter design which exhibits adequate performance.

2.7.1 Specifications for Capacitors

An important parameter for capacitors in filter circuits is the maximum steady state voltage. This voltage is determined by an arithmetic summation of the fundamental voltage plus the harmonic voltages across the capacitor. Since the fundamental voltage is much larger than the harmonic voltages the maximum capacitor voltage will normally occur at the maximum system voltage. For a band-pass filter the capacitor voltage will be

$$V_c = V_{s,MAX} \frac{n^2}{n^2-1} + \sum_{n=2}^{n=m} I_{F,n} Z_{F,n} \quad (2.37)$$

where $V_{s,MAX}$ is the maximum system voltage, $I_{F,n}$ is the harmonic filter current, $Z_{F,n}$ is the harmonic impedance of the filter and m is the highest harmonic considered.

The harmonic current and harmonic filter impedance values correspond to the worst harmonic voltage condition for the detuning range. The correction $n^2/(n^2-1)$ for the fundamental voltage is due to the influence of the filter reactor.

In similar manner the maximum capacitor voltage for the high-pass filter and shunt banks are obtained.

In determination of the maximum detuning range the loss of capacitor cans should be considered.

Normally in filter design the var capability of the capacitors (Q)

$$Q = \frac{(U_{s,MAX} \frac{n^2}{n^2-1})^2}{X_c} + \sum_{n=2}^{n=m} (I_{F,n})^2 \frac{X_c}{n} \quad (2.38)$$

is not a design limiting factor.

In addition to capacitance values, the specification for filter capacitors will contain the maximum harmonic voltages or maximum harmonic currents encountered by the capacitors in the application as filter components.

2.7.2 Specification for Reactors

An important parameter for reactors is the maximum currents flowing through the reactor. An equivalent fundamental current ($I_{1,EQ}$) can be calculated as follows

$$I_{1,EQ} = (I_1^2 + \sum_{n=2}^{n=m} I_n^2 (1 + \frac{E}{100} n^2))^{\frac{1}{2}} \quad (2.39)$$

where I_1 and I_n are the current through the reactor and E is the eddy loss in percent.

The contribution of the harmonics in this equivalent fundamental current dominates the fundamental current (I_1) and hence, this calculation should be performed using harmonics at minimum system voltage, giving the largest harmonic currents generated by the HVDC converters.

The calculation of the voltage across the reactor is also important since the voltage across the reactor will determine whether dry type or oil filled reactors will be required. Filter designs attempt to use the dry type reactor construction if possible due to its lower cost.

In addition to the required inductance value the specifications for the reactor will include an equivalent fundamental current rating or an indication of maximum harmonic currents through the reactor.

2.7.3 Specifications for Resistors

Since it is possible to provide enough resistance in the reactor elements for the band-pass filters to obtain an acceptable Q (in order of 100 - 125) it is only the resistors in the high-pass filter which are of concern.

The parameters which will be of interest are the ohmic value (R) of the resistor and the effective current (I_{EF}) through the resistor.

$$I_{EF} = \left(\sum_{n=1}^{n=m} I_n^2 \right)^{\frac{1}{2}} \quad (2.40)$$

The power rating (P) of the resistor will therefore be

$$P = I_{EF}^2 R \quad (2.41)$$

2.7.4 General Considerations

In the filter component design there are other factors to consider, such as filter protection, insulation coordination, short term frequency swings, etc.,

all having an impact on the filter performance. To discuss this in more detail would go beyond the intent of this report. Considerations on these factors can be found in the references cited in Appendix A.

Reference

1. AIEE Committee Report, "Inductive Coordination Aspects of Rectifier Installations," AIEE Transactions, Vol. 65, pp. 417-436, 1946.

Section 3

TECHNIQUES OF SYSTEM IMPEDANCE CALCULATIONS FROM MEASUREMENTS

3.1 Introduction

This section discusses methods for calculating equivalent system impedance using voltage and current measurements. The advantages of the methods are:

1. They only use local measurements.
2. They do not require any transmission line data.

The methods consist of three steps:

1. Measuring the voltage and current signals;
2. Calculating the harmonic components of the voltage and current signals;
3. Calculating the harmonic impedances using the results of step 2.

Four different schemes of step 3, each intended for a different system configuration, are considered in this section. The instrumentation required for the voltage and current measurements in step 1 is discussed in the next section. Step 2 will be discussed in Section 6.

In the calculation of the harmonic impedance, the system is assumed to be linear and thus can be represented by a three phase Thevenin equivalent circuit (Figure 3.1-1). The harmonic voltage E is the Thevenin voltage source of all the harmonic generating sources in the system, and the impedance Z is the Thevenin impedance of all the harmonic impedances in the system. The impedance Z consists of self-impedances Z_{xx} , $x=a,b,c$, and mutual impedances Z_{xy} , $x,y=a,b,c$, $x \neq y$. The voltage V is the voltage at the measurement point, that is, the bus of interest, and the current I flowing into the bus is zero if there is no shunt impedance or current source at the bus.

Figure 3.1-1 Thevenin Equivalent Representation of a System.

A second assumption is that the system impedance is balanced, that is, the self and mutual impedances satisfy

$$Z_{aa} = Z_{bb} = Z_{cc} = Z_s \quad (3.1)$$

$$Z_{ab} = Z_{ba} = Z_{ac} = Z_{ca} = Z_{bc} = Z_{cb} = Z_m. \quad (3.2)$$

Thus, the voltage-current relationship is

$$\begin{bmatrix} E_a - V_a \\ E_b - V_b \\ E_c - V_c \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (3.3)$$

which can be rewritten as

$$\begin{bmatrix} E_a - V_a \\ E_b - V_b \\ E_c - V_c \end{bmatrix} = \begin{bmatrix} I_a & I_b + I_c \\ I_b & I_a + I_c \\ I_c & I_a + I_b \end{bmatrix} \begin{bmatrix} Z_s \\ Z_m \end{bmatrix} = A \begin{bmatrix} Z_s \\ Z_m \end{bmatrix}. \quad (3.4)$$

Note that in (3.4), the voltages \$E\$ and \$V\$ are not required to be balanced. A measurement method that does not require balanced impedances is described in Appendix B.

The objective is to use measurements of V and I to calculate Z_s and Z_m , from which the positive sequence impedance

$$Z_p = Z_s - Z_m \quad (3.5)$$

can be obtained [2]. Four different schemes are considered:

1. DC-on with two measurements (DCON2M).
2. DC-on with one measurement (DCON1M).
3. DC-off with three phase switching (DCOFF3P).
4. DC-off with single phase switching (DCOFF1P).

Computer programs for these schemes are documented in Volume 2 of the final report, and their names are given in the brackets. In schemes 1 and 2, a harmonic source is present at the measurement point, whereas in schemes 3 and 4, no harmonic source is present at the measurement point. Scheme 4 was proposed by Crevier and Mercier in [1]. These schemes will be discussed in the following subsections, and their applications to the measurement data at Celilo will be discussed in Section 6.

3.2 DC-On Impedance Calculation with Two Measurements

The DC-on impedance calculation scheme is applicable when a dc terminal is operating at the measurement point (Figure 3.2-1). The advantage of this scheme is that dc terminals generate large currents at the characteristic harmonics, which result in more accurate measurements.

Figure 3.2-1 DC-On System Configuration

This technique requires one set of measurements of voltages and currents without the shunt impedances and another set of measurements of voltages and currents with the shunt impedances connected. With two different sets of measurements, the Thevenin voltage source E can be eliminated. The shunt impedances can be connected to one phase or to all three phases. The measurement with the shunt impedances yields

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} - \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{b1} \\ I_{c1} \end{bmatrix} \quad (3.6)$$

and the measurement without the shunt impedances yields

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} - \begin{bmatrix} V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_{a2} \\ I_{b2} \\ I_{c2} \end{bmatrix}. \quad (3.7)$$

Assuming that E does not change during the switching, the subtraction of (3.6) from (3.7) results in

$$\begin{bmatrix} V_{a1} - V_{a2} \\ V_{b1} - V_{b2} \\ V_{c1} - V_{c2} \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_{a2} - I_{a1} \\ I_{b2} - I_{b1} \\ I_{c2} - I_{c1} \end{bmatrix} \quad (3.8)$$

which can be rearranged into

$$\begin{bmatrix} V_{a1} - V_{a2} \\ V_{b1} - V_{b2} \\ V_{c1} - V_{c2} \end{bmatrix} = \begin{bmatrix} I_{a2} - I_{a1} & (I_{b2} - I_{b1}) + (I_{c2} - I_{c1}) \\ I_{b2} - I_{b1} & (I_{a2} - I_{a1}) + (I_{c2} - I_{c1}) \\ I_{c2} - I_{c1} & (I_{a2} - I_{a1}) + (I_{b2} - I_{b1}) \end{bmatrix} \begin{bmatrix} Z_s \\ Z_m \end{bmatrix}. \quad (3.9)$$

Denoting (3.9) by

$$u = A_1 \begin{bmatrix} Z_s \\ Z_m \end{bmatrix}, \quad (3.10)$$

the self and mutual impedances can be solved by using the least square method

$$\begin{bmatrix} Z_s \\ Z_m \end{bmatrix} = (A_1^* A_1)^{-1} A_1^* u \quad (3.11)$$

to filter measurement noises. The positive sequence impedance can be obtained from (3.5). The * denotes complex conjugate transposition.

3.3 DC-On Impedance Calculation with One Measurement

The harmonic currents generated by the dc terminals at the characteristic harmonics are, in general, much larger than the system Thevenin voltage source E. Thus, as a first approximation, E can be neglected, which simplifies the system impedance calculations by requiring only one set of measurements. It will be shown in Section 6 that for the measurements obtained at Celilo, this approximation is not valid for the 7th and lower harmonics.

Neglecting E, (3.6) or (3.7) reduces to

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = - \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (3.12)$$

Note that (3.12) is valid with or without the shunt impedances connected. Equation (3.12) can be rewritten as

$$\begin{aligned} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} &= - \begin{bmatrix} I_a & I_b + I_c \\ I_b & I_a + I_c \\ I_c & I_a + I_b \end{bmatrix} \begin{bmatrix} Z_s \\ Z_m \end{bmatrix} \\ &= - A \begin{bmatrix} Z_s \\ Z_m \end{bmatrix} \end{aligned} \quad (3.13)$$

Then, a least square approximation

$$\begin{bmatrix} Z_s \\ Z_m \end{bmatrix} = -(A^* A)^{-1} A^* \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3.14)$$

provides for the averaged Z_s and Z_m , from which the averaged Z_p can be calculated from (3.5).

3.4 DC-Off Impedance Calculation with Three Phase Switchings

Without any harmonic sources at the measurement point, voltage and current measurements with and without shunt impedances are necessary to calculate the harmonic impedances (Figure 3.4-1). This subsection discusses the technique for three phase shunt impedance switchings and the next subsection discusses the technique for single phase switchings.

Figure 3.4-1 DC-Off System Configuration

The measurement without the shunt impedances yields

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = 0, \quad \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix}, \quad (3.15)$$

that is, the voltage at the measurement point is equal to the system harmonic voltage.

With the shunt impedances connected, the measurement yields

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}, \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix}. \quad (3.16)$$

Assuming that E remains unchanged during the switching, the measurements with and without the shunt impedances are related by

$$\begin{bmatrix} V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} - \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}, \quad (3.17)$$

which can be rearranged as

$$\begin{bmatrix} V_{a1} & - & V_{a2} \\ V_{b1} & - & V_{b2} \\ V_{c1} & - & V_{c2} \end{bmatrix} = \begin{bmatrix} I_a & I_b + I_c \\ I_b & I_a + I_c \\ I_c & I_a + I_b \end{bmatrix} \begin{bmatrix} Z_s \\ Z_m \end{bmatrix}. \quad (3.18)$$

Denoting (3.18) by

$$u = A \begin{bmatrix} Z_s \\ Z_m \end{bmatrix}, \quad (3.19)$$

the self and mutual impedances can be solved with a least square approximation as

$$\begin{bmatrix} Z_s \\ Z_m \end{bmatrix} = (A^* A)^{-1} A^* u. \quad (3.20)$$

from which Z_p can be obtained.

3.5 DC-Off Impedance Calculation with Single Phase Switchings

When only one phase, say phase c, is connected to a shunt impedance, (3.18) reduces to

$$\begin{bmatrix} V_{a1} - V_{a2} \\ V_{b1} - V_{b2} \\ V_{c1} - V_{c2} \end{bmatrix} = \begin{bmatrix} 0 & I_c \\ 0 & I_c \\ I_c & 0 \end{bmatrix} \begin{bmatrix} Z_s \\ Z_m \\ Z_c \end{bmatrix}. \quad (3.21)$$

The self and mutual impedance can be calculated as

$$Z_s = (V_{c1} - V_{c2})/I_c, \quad (3.22)$$

$$Z_m = (V_{a1} - V_{a2})/I_c = (V_{b1} - V_{b2})/I_c, \quad (3.23)$$

and the positive sequence impedance can be obtained from (3.5). The values of Z_m from two different phases can be used to verify the balanced impedance assumption.

To account for measurement noises, the least square method in [1] is used. Using the relationship

$$V_{c1} = I_c (Z_s + Z_c), \quad (3.24)$$

(3.23) is rewritten as

$$\begin{bmatrix} (V_{a2} - V_{a1}) & V_{c1} & (V_{a2} - V_{a1}) \\ (V_{b2} - V_{b1}) & V_{c1} & (V_{b2} - V_{b1}) \\ V_{c2} & 0 & (V_{c2} - V_{c1}) \end{bmatrix} \begin{bmatrix} Z_s \\ Z_m \\ Z_c \end{bmatrix} = 0. \quad (3.25)$$

The combination of (3.23), (3.25), and the shunt impedance current-voltage relation

$$Z_c I_c = V_{c2}, \quad (3.26)$$

yields

$$\begin{bmatrix} 0 & I_c & 0 \\ 0 & I_c & 0 \\ I_c & 0 & 0 \\ 0 & 0 & I_c \\ V_{a2} - V_{a1} & V_{c1} & V_{a2} - V_{a1} \\ V_{b2} - V_{b1} & V_{c1} & V_{b2} - V_{b1} \\ V_{c2} & 0 & V_{c2} - V_{c1} \end{bmatrix} \begin{bmatrix} Z_s \\ Z_m \\ Z_c \end{bmatrix} = \begin{bmatrix} V_{a1} - V_{a2} \\ V_{b1} - V_{b2} \\ V_{c1} - V_{c2} \\ V_{c2} \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (3.27)$$

which is denoted by

$$A_2 \begin{bmatrix} Z_s \\ Z_m \\ Z_c \end{bmatrix} = u \quad (3.28)$$

A least square estimate would yield

$$\begin{bmatrix} Z_s \\ Z_m \\ Z_c \end{bmatrix} = (A_2^* A_2)^{-1} A_2^* u \quad (3.29)$$

The method in [1] assumes that the system impedances are balanced. A method without using the balanced impedance assumption is given in Appendix B. It requires single phase switching measurements on all three phases. The method in Appendix B, however, has not been used in this project.

3.6 Summary

Four schemes for calculating system harmonic impedances from local voltage and current measurements have been discussed. The dc-on methods are more attractive at the characteristic harmonics than the dc-off methods due to the large signals. However, the dc-off methods provide good results in the lower harmonics, as shown in Section 6. Both the dc-on and dc-off methods are based on

the assumptions that the system is represented by a Thevenin equivalent and the system impedances are balanced. The instrumentations described in Sections 4 and 5 are implemented based on these methods.

References

1. D. Crevier and A. Mercier, "Estimation of Higher Frequency Network Equivalent Impedances by Harmonic Analysis of Natural Waveforms," IEEE Transactions on Power Apparatus and Systems, Vol. 97, Mar/Apr 1978, pp. 424-431.
2. General Electric Company, Transmission Line Reference Book 345 kV and Above, EPRI, 1975.

Section 4

DATA ACQUISITION SYSTEM

Measurement of harmonic voltages and currents in a high voltage system requires extremely careful techniques. For impedance calculations using the relatively small difference between two voltage measurements, the requirements are particularly difficult to meet. For some test conditions, the largest harmonic component was at least 40 dB below the level of the fundamental and the levels of the higher harmonics generally fall off at approximately $1/n$ or worse. Consequently, a dynamic range of 100 dB became one of the objectives of the measurement system.

In order to measure harmonic impedance, phase angle accuracy is also necessary. This, together with the dynamic range requirement, led to a requirement for a digital recording system as the only practical approach to achieve these goals. At the time the project was started, no vendor had a suitable off-the-shelf digital system available and the project did not allow time or funding to procure a new system. Fortunately, a recording system, the Transient Monitor System, developed by EPRI for RP751, was loaned for use on the project.

4.1 Limitations of EPRI Recording System

The EPRI recording system has a capability of digital recording for 15 data channels. Of these, six are 12 bit channels and nine are eight bit channels. In a binary digital system, each bit is equivalent to six dB of dynamic range (2:1 ratio). Consequently, a 12 bit channel has 72 dB of dynamic range which is considerably less than the 100 dB objective.

Measurement of a three phase system usually involves three voltages and three currents for a total of six data channels. Since the EPRI recording system had additional channels (at lower resolution) available, it was possible to employ a divide and conquer approach previously used with analog recording systems. In this approach, each signal is divided into two channels, one having all frequency components and the other having only the harmonics, the fundamental component

being removed by a notch filter. With separate level controls of these two parts, a two channel equivalent of 100 dB dynamic range can be achieved for each sensor.

4.2 Functional Description of Instrumentation System

The system approach previously described is shown as a block diagram in Figure 4.2-1. A dashed box labeled "external" indicates portions of the system which are not part of the EPRI digital recording system. The numbers in parentheses in the diagram indicate the number of signal channels between the blocks. Individual blocks will be described in later sections of the report.

The equipment in the "external" box is actually scattered over a considerable area as shown in Figure 4.2-2. In this sketch, the dashed lines represent signal cables between sensors and electronics and between the instrument enclosures. The block labeled EPRI Van is the digital recording system, while the BPA van (a small trailer) and the instrument house (a little larger than a telephone booth) contain the "external" electronics. The signal leads were run in non-metallic underground conduit, some existing at the station and some installed specifically for the tests by BPA. Photographs of the instrumentation system are shown in Figures 4.2-3 to 4.2-9.

4.3 Sensors for Voltage and Current Measurement

In order to measure voltages and currents on the 230 kV line, it was initially assumed that BPA, the host utility, would furnish a suitable set of potential transformers and current transformers. An additional method of measuring currents flowing to ground was planned using induction coils also known as Maxwell Worms or Rogowski coils (Figure 4.2-11).

When the measurement system was finally installed, BPA supplied three high voltage precision voltage dividers (Haefley) instead of potential transformers (Figure 4.2-10). The current transformers also contained "bushing taps" which were built-in capacitive voltage dividers (Figure 4.2-10). Consequently, two types of sensors for voltage and two types of sensors for current were available.

Figure 4.2-1 Instrumentation System Functional Block Diagram

Figure 4.2-2 Physical Location of Measurement System Components

Figure 4.2-3 Location of EPRI Van in HV Yard

Figure 4.2-4 EPRI Van Electronics

Figure 4.2-5 Digital Recording System

Figure 4.2-6 BPA Trailer (Remote Electronics)

Figure 4.2-7 Electronics in BPA Van

Figure 4.2-8 Instrument House (Remote Electronics)

Figure 4.2-9 Electronics in Instrument House

Figure 4.2-10 Voltage Dividers and Current Transformers

Figure 4.2-11 Maxwell Worm Installation on HP Filter

4.3.1 Voltage Sensors

Haefley Voltage Dividers

The Haefley voltage dividers were huge units approximately 18 feet tall. Each divider consisted of three porcelain columns in series with internal RC networks and a fourth RC network in the base. Large corona rings were used at the top and at the next lower junction. Each contained an internal RC network of approximately 200 megohms in parallel with approximately 600 picofarads. With a 0.53 microfarad capacitor and approximately 220 kilohms from base to ground, this resulted in a frequency compensated RC divider with a nominal 2500:1 ratio. Each divider had a triaxial cable connected to a terminating circuit box located in the BPA van. Special circuit boxes constructed by BPA provided an additional 100:1 division to reduce the voltage to instrument levels and to match the amplifier impedance. The overall divider was claimed to have a flat frequency response from dc to well beyond 1 MHz. However, in a checkout test using the measurement system to determine the harmonic impedance of a known capacitor (one of the VAR banks), the impedance plot (log amplitude vs. log frequency) changed its slope from - to + at approximately 900 Hz. This was proved to be caused by erroneous data from the voltage dividers and the Haefley dividers were not used in later tests. No explanation for their poor performance is known to date.

Bushing Taps

The bushing taps were actually capacitive dividers built into the current transformers. Their capacitance values were not known and so they were calibrated against the Haefley dividers (at 60 Hz). The bushing taps gave excellent results in the impedance test described in Subsection 4.9 and their nominal division ratio was 60,000:1. Consequently, all voltages used in the subsequent test data were obtained using the bushing taps as voltage sensors.

4.3.2 Current Sensors

Current Transformers

The current transformers provided by BPA were rated at 500 kV and had a ratio of 3000:5A. Their secondaries were each connected to a precision non-inductive resistor of 0.200 ohm $\pm$ 0.1% as their only load, giving a conversion value of 3000 amperes per volt. This signal was sent to the BPA van by twisted pair shielded telephone cable.

Maxwell Worms

The Maxwell Worms (or Rogowski coils) are essentially air core toroidal induction coils. They are made by winding, in a constant pitch, two layers of fine wire on a piece of plastic tubing slipped over a steel rod mandrel. The resulting long helical coil is then coated removed from the steel mandrel and filled with a silicone rubber compound and the ends are fitted with a pin and socket arrangement so that the cylinder can be formed into a locked circle. Both ends of the winding come off one end of the assembly and are connected to an output lead of twisted pair shielded wire. The sensitivity of the coil is proportional to its cross sectional area, the winding pitch and the number of turns. It is independent of the coil length when formed into a single turn circle. When the coil is mounted around a current carrying conductor, the output voltage is proportional to the derivative of the current in the conductor. This property is particularly useful in measuring harmonic currents since the output voltage increases with frequency, which tends to compensate for the decreasing levels of higher harmonic currents usually encountered.

For this project, the worms were formed into two turn coils, doubling the sensitivity and lessening any effects of discontinuity at the joint (approximately 1/8" between the ends of the coil). The coils are calibrated using a pure sinusoidal current at 400 Hz and computing the sensitivity at 60 Hz. For this project, the two turn configuration coils had a nominal sensitivity of 3000 ampere per volt at 60 Hz. Exact measured values for each particular coil were used in the data reduction and analysis of the test data.

The coils were built to measure currents in the grounded end of the capacitor banks and filters. However, since these grounded points can assume high voltages during a possible fault condition, special insulators were fabricated by BPA for safe mounting of the coils. In addition, the insulators were made with large flanges which had holes drilled at angular increments. This enabled a calibration coil of 10 turns of #14 insulated wire to be threaded through the coil. This feature was used in a calibration test described in a later section. The Maxwell Worms were installed by BPA personnel and the shielded leads were routed through non-metallic conduit to their respective amplifiers.

4.4 Harmonic Separation Filters

In order to provide sufficient dynamic range for the harmonic components of the sensor signals, the fundamental component is suppressed by the harmonic separation filters. Figure 4.4-1 shows a block diagram of one of the filter channels. The input stage is simply a differential follower with unity gain. This is followed by amplifier A which is used to adjust the signal to approximately ± 10 volts to optimize signal to noise ratios. The output of amplifier A drives the notch filter and also the data transmission cable to the digital recording system. For the notch filter, a bridged T circuit is used to produce a sharp null at 60 Hz, usually greater than -40 dB. However, to accommodate small changes in line frequency and component drift, the notch filters were purposely detuned symmetrically to widen the notch while retaining at least 30 dB attenuation of the fundamental component. A reduced fundamental component remains in the output signal, but is not used in subsequent data reduction. The signal from the notch filter is amplified by amplifier B, usually by 20 dB, and transmitted by cable to the digital recording system.

Figure 4.4-1 Harmonic Separation Filter

Although the harmonic separation filters have a differential input circuit, a separate differential amplifier (Tektronix AM502) was used between the sensors and the filters to provide a significantly higher common mode rejection. This was essential for operation with long sensor leads in the high electromagnetic interference fields at the site.

4.5 Data Links

Transmitting signals for long distances under 230 kV power lines was expected to be a problem. For this reason, a fiber optic data link had been developed in a previous EPRI contract for use with the digital recording system. Permission to

use the fiber optic link was given and the fiber optic cables were installed in conduits at the site. However, since no performance data for the optical link was available at the time, a backup system of several sets of six pair telephone lines (shielded) was also installed in the same conduits.

4.5.1 Optical Data Link

Basically, the optical data link consisted of a light emitting diode (LED) at the source end of a fiber optic cable and a photodiode at the receiving end. At the source end, the light from the LED was modulated by an FM system operating at approximately 5 MHz. At the receiving end, the signal from the photodiode was demodulated to recover the signal.

In order to evaluate the system, one channel was set up inside the EPRI van, using a 100 meter length of optical cable still on its reel. In this manner, the input and output signals could be compared conveniently. A high quality oscillator was connected to the input and the input and output signals were compared on a dual channel oscilloscope and by a real time spectrum analyzer. Some distortion was noticed on the oscilloscope and the linearity control of the FM modulator was adjusted for minimum distortion. However, the control could vary the position of the distortion on the displayed sine wave, but could not eliminate it. When the input and output signals were checked by the spectrum analyzer, it became obvious that the harmonics generated by the modulator distortion were greater than the expected magnitude of the power system harmonics to be measured.

Since the fiber optic cables were already installed, the transmitting and receiving electronics were installed for all channels for further evaluation. The test signal was sent to the remote locations by the telephone cables and also returned by cable as well as the optical data links for comparison. Further testing showed the following results:

1. The power supplies intended to supply three modulators each had inadequate voltage regulation and required 130 V input for proper operation.
2. Distortion levels were unacceptable for most of the channels with 5th and 11th harmonics at -50 dB.

3. For a given setting of the distortion control, the amount and type of distortion varied with supply voltage and temperature. Therefore, it could not be corrected by software in the data conversion.

4.5.2 Twisted Pair Cable Links

With the realization that the optical data links were not useable for the purpose, the backup system of telephone cable was investigated. For optimum performance, the cable should be fed and terminated in a balanced configuration matched to the 600 ohm cable impedance. However, no equipment of this type was available, so the cable was excited single ended and the receiving end was connected unterminated to a differential amplifier at hand. The common mode voltage measured as high as ± 4 volts, which was not surprising since the cable runs under the 230 kV lines for almost half its distance. A Tektronix AM502 amplifier was connected at the receiving end. Tests showed that the common mode rejection at 60 Hz was 70 dB and no significant distortion was introduced by the wire data link. Additional amplifiers were shipped to provide an AM502 for each data channel to the digital recording system.

4.6 Data Recording System

Figure 4.2-1 showed the overall system functional block diagram. In this diagram, all blocks except those enclosed in the dashed line (labeled "EXTERNAL") are part of the data recording system, or the EPRI van loaned to GE for the project.

The data recording system is a fully digital system having a final output on nine track digital magnetic tape. Input signals in the form of analog voltages are received by the differential amplifiers described in the previous section. These signals then pass through the anti-alias filters, which are preset to match the data bandwidth to be recorded.

The system can record up to 15 data channels, with six channels of 12 bit resolution and nine channels of eight bit resolution. Each channel has its own A/D converter and 8192 word memory. Basically, the purpose is to record signals corresponding to the three voltages and three currents in a three phase system. However, in order to achieve a dynamic range of 100 dB (which would require a 16 bit system for each channel), each of the signals was split into channels by the harmonic filters as described in Subsection 4.4. The harmonic

portions of the signals were recorded on the 12 bit channels and the fundamental portions were recorded on eight bit channels.

The anti-alias filters were set for 5 kHz bandwidth, which also set the sampling rate at 20,000 samples per second. In this system, all A/D converters (one for each channel) are clocked simultaneously. The equipment was used in the manual mode by pressing a start button. This causes 8192 digital words to be stored in each channel memory, which covers a little over 0.4 second or 24 cycles at 60 Hz.

The contents of each memory can be displayed, four channels at a time, on a CRT monitor display. This was done whenever a set of data was taken to verify that all channels were operating before transferring the data to the magnetic tape. Upon command, transfer of data is accomplished by the formatter which first records header information, then transfers one channel of data at a time to the digital tape recorder. The tape recorder uses 1/2 inch tape at 37.5 inches per second with a recording density of 800 bits per inch. This is compatible with standard tape playback units, but the data must be reformatted in a predetermined manner before entering it in a computer for analysis. The output tapes were transported to GE at Schenectady for validation, reformatting, and data analysis.

4.7 System Checkout and Calibration

Initial system checkouts of the EPRI van were performed at Waltz Mill, Pennsylvania before the van was shipped to Oregon. These tests involved recording of known sine waves and square waves on various channels to verify accuracy, frequency response, noise, crosstalk, etc. Similar checks were conducted at Celilo after the shipment damages were repaired.

The fiber optic data links were tested as described in Subsection 4.5.1. Because of their inadequacy, the twisted pair links were tested as described in Subsection 4.5.2.

The Maxwell Worms were calibrated in the Materials and Processes Laboratory of GE at Schenectady. At the request of BPA, a special system was set up to verify their calibration after installation at Celilo. For this purpose, the support insulators for the worms had uniformly spaced holes drilled so that 10 turns of number 14 wire could be threaded through each worm. These excitation windings were then connected in series by a heavy wire routed through the non-metallic

conduit, forming a loop approximately 1/4 mile in length. A constant current amplifier was used to excite the loop with known levels and frequencies of current, using both sinusoidal and triangular waveforms. Output signals from the Maxwell Worms were transmitted to the data recording system through the normal amplifiers, filters, and twisted-pair data links. The signals were recorded on the tape which was then sent to Schenectady for analysis. Some on-site measurements were also made for preliminary information. The calibration method performed well despite the harsh environment of the 230 kV lines.

The Heafley voltage dividers were calibrated by BPA personnel. When it was determined that they were unusable for harmonic measurement, the bushing taps were calibrated against the Heafley dividers which were accurate at 60 Hz. For the CTs, BPA data were used since it was impractical to calibrate the CTs on site.

As an overall check on amplifiers, filters, etc., known signals were injected into all channels and data recorded on magnetic tape. In addition to on-site checks, these data were computer processed for validation.

Finally, as an overall check, sets of data were recorded to measure the voltages and currents of a capacitor bank. These data were processed to yield the capacitance at each harmonic frequency. This was the test which indicated the problem with the Heafley dividers. Subsequent tests using the bushing taps gave excellent results.

4.8 Test Procedure

For a complex test of this nature, one of the most important aspects is record keeping since there are well over 100 knobs and dials involved. To simplify this problem, check lists and log sheets were prepared in advance. The data runs were taken between 10:00 and 14:00 hours. All equipment had been checked the previous evening and left on for thermal stability. Preset items, such as the amplifiers at each end of the twisted pair data links, were compared to a check list to verify correct gain, bandwidth setting, etc.

The station equipment was set to the prescribed configuration for a data point. Then the signals were checked for proper levels on oscilloscopes at the remote locations and gain settings adjusted as needed and logged.

Communications were maintained by headset intercom and by telephone between the two remote locations, the data recording center, and the Celilo control room. When all signals were verified and control settings recorded, a data sample was captured in the digital memory, checked on the monitor, and recorded on digital tape. Then a second set of data, at the same conditions, was recorded redundantly.

Additional data points were recorded at the end of a sequence. For example, in switching a capacitor bank as a known impedance, the data sequence was:

1. Open circuit condition.	}	Two records each.
2. Load circuit closed.		
3. Open circuit condition.		

A comparison of steps 1 and 3 verified that external conditions on the transmission system had not changed during the test sequence.

4.9 System Performance

Overall system performance can best be judged by the analysis of the measurement data given in Section 6. However, the performance of portions of the system is described for possible use in future work.

Comparison of current measurements using the Maxwell Worms and CTs shows that both methods are usable at similar accuracy within some limitations. The Maxwell Worm or Rogowski Coil has advantages at frequencies beyond 2 kHz where the performance of the CT is usually unknown. However, in these tests, data from the worms had more scatter than data from the CTs. This is attributed to the fact that the worms were not electrostatically shielded and were located in high level electric fields. Although differential amplifiers were used, electrostatic pickup could not be fully cancelled.

The bushing taps (part of the CTs) are actually capacitive voltage dividers and performed well over the bandwidth of interest. The Heafley dividers had problems as described in Subsection 4.3.1. These units were located in a straight line under the 230 kV bus. Each divider had three sections in series with corona rings at the top and one section down. It is suspected that some cross-coupling may have been introduced by the capacitance between corona rings of adjacent phases, but this would require a special test to verify.

Signal cables installed in non-metallic conduit by BPA provided better results than expected in the difficult environment under the 230 kV lines. One of the factors contributing to their good performance was the inclusion of heavy ground leads (dual 4/0 cables) in each of the signal conduits. The fiber optic cables were installed and removed from the conduits without incident despite their fragile nature. The optical portions of the links performed well, but the FM modulators (an old technology) were inadequate.

The data recording system (EPRI van) suffered considerable damage in transit and required both mechanical and electronic repairs. When the system had been repaired, it performed very well except for some formatter problems in header data which were not serious.

The Data Acquisition System for this project was indeed a challenge. Considering the fact that it was spread out under roughly 10 acres of 230 kV lines, a severe electromagnetic interference environment, its performance was adequate for the intended task.

Section 5

TEST PROCEDURE

5.1 Basic System Configuration

The complete data acquisition system has been described and evaluated in Section 4. In the final analysis, the twisted pair system was proved to be more than adequate and due to the harmonics produced by the optical system, the twisted pair system was preferred. Figure 5.1-1 shows a one-line diagram of the ac-yard at the Big Eddy substation and the dc-yard at the Celilo substation. The distance between Big Eddy and Celilo is one mile. During all tests, the 5th and 7th harmonic filters at Big Eddy were not used.

5.2 Limitations and Problems Within the Acquisition System

During all the testing, preliminary switching was performed to be absolutely sure that the measured voltages did not exceed the maximum input voltages allowed by the data acquisition system.

During some routine checks on the playback of data tapes, it became evident that there was a problem within the data acquisition system. Fortunately, after a concerted effort it was ascertained that the problem was within the "header" portion of each data file. The data portion of each file was not affected and because of this, the data was usable. By careful analysis of the header information, it was possible to identify the number and date and time of each data file. After all testing was accomplished, the data tapes were returned to Schenectady for data analysis.

5.3 Test Schedule

All testing was done on January 20 and 21, 1979. For each data point, three data files were obtained. The tests performed are listed in Tables 5.3-1 and 5.3-2. Figure 5.3-1 is a three phase drawing showing the physical location (and electrical) of all the parameters measured. The labeled items agree with those actually used and with the labels in Tables 5.3-1 and 5.3-2.

Figure 5.1-1 One-Line Diagram of Big Eddy and Celilo

Table 5.3-1
January 20, 1979 Test Sequence

SYSTEM CONFIGURATION											MEASUREMENT POINTS														REMARKS
TEST NUMBER	DATE	POLE 3 1 PHASE CAP BK 8A	POLE 3 3 PHASE CAP BK	POLE 3 11 & 13 FLT	POLE 3 HP FLT	POLE 4 1 PHASE CAP BK 8B	POLE 4 1 PHASE CAP BK 8C	POLE 4 11 & 13 FLT	POLE 4 HP FLT	POLE 3 TO POLE 4 230 kV BUS TIE	CT'S A, B, C POLE 3 230 kV BUS FEED	BUSH TAPS A, B, C POLE 3 230 kV BUS FEED	801 802 803 MW POLE 3 A, B, C CAP BK 2	804 MW POLE 3 A CAP BK 1	805 806 807 MW POLE 3 A, B, C 11 & 13 FLT	808 MW POLE 4 A CAP BK 2	809 MW POLE 4 B CAP BK 2	810 MW POLE 4 A CAP BK 1	811 MW POLE 4 C CAP BK 1	812 813 814 MW POLE 4 A, B, C 11 & 13 FLT	DC STATUS	DC PWR IN MW	DC DIR.		
1	1/20		0									X	X								OFF			Tests 1 & 2 Repeated	
2	1/20		X									X	X								OFF			4 More Times	
3	1/20			X							X	X									OFF			Tests 3 & 4 Repeated	
4	1/20			0							X	X									OFF			1 More Time	
5	1/20			0								X			X						OFF			Tests 5 & 6 Repeated	
6	1/20			X								X			X						OFF			1 Time	
7	1/20	X				0	0			X	X	X									OFF			Tests 7 thru 15 Re-	
8	1/20	0				0	0			X	X	X									OFF			peated 2 More Times	
9	1/20	0				X	0			X	X	X									OFF				
10	1/20	0				0	0			X	X	X									OFF				
11	1/20	0				0	X			X	X	X									OFF				
12	1/20	0				0	0			X	X	X									OFF				
13	1/20	0				0	0			X	X	X									OFF				
14	1/20	X				X	X			X	X	X									OFF				
15	1/20	0				0	0			X	X	X									OFF				
16	1/20	0				0	0			X		X		X			X		X		OFF			Tests 16 thru 24 Re-	
17	1/20	X				0	0			X		X		X			X		X		OFF			peated 1 Time	
18	1/20	0				0	0			X		X		X			X		X		OFF				
19	1/20	0				X	0			X		X		X			X		X		OFF				
20	1/20	0				0	0			X		X		X			X		X		OFF				
21	1/20	0				0	X			X		X		X			X		X		OFF				
22	1/20	0				0	0			X		X		X			X		X		OFF				
23	1/20	X				X	X			X		X		X			X		X		OFF				
24	1/20	0				0	0			X		X		X			X		X		OFF				
25	1/20		0							X		X		X							ON	200	S/N	Tests 25 & 26 Re-	
26	1/20		X							X		X		X							ON	200	S/N	peated 1 Time	
27	1/20		0							X	X	X									ON	200	S/N	Tests 27 & 28 Re-	
28	1/20		X							X	X	X									ON	200	S/N	peated 1 Time	
29	1/20	0				0	0			X	X	X									ON	200	S/N	Tests 29 thru 37 Re-	
30	1/20	X				0	0			X	X	X									ON	200	S/N	peated 1 Time	
31	1/20	0				0	0			X	X	X									ON	200	S/N		
32	1/20	0				X	0			X	X	X									ON	200	S/N		
33	1/20	0				0	0			X	X	X									ON	200	S/N		
34	1/20	0				0	X			X	X	X									ON	200	S/N		
35	1/20	0				0	0			X	X	X									ON	200	S/N		
36	1/20	X				X	X			X	X	X									ON	200	S/N		
37	1/20	0				0	0			X	X	X									ON	200	S/N		
38	1/20			X						X	X	X									ON	200	S/N	Tests 38 & 39 Re-	
39	1/20			0						X	X	X									ON	200	S/N	peated 1 Time	
40	1/20				X					X	X	X									ON	200	S/N	Tests 40 & 41 Re-	
41	1/20				0					X	X	X									ON	200	S/N	peated 1 Time	

Table 5.3-2
January 21, 1979 Test Sequence

SYSTEM CONFIGURATION											MEASUREMENT POINTS														REMARKS
TEST NUMBER	DATE	POLE 3 1 PHASE CAP BK 0A	POLE 3 3 PHASE CAP BK	POLE 3 11 & 13 FLT	POLE 3 HP FLT	POLE 4 1 PHASE CAP BK 0B	POLE 4 1 PHASE CAP BK 0C	POLE 4 11 & 13 FLT	POLE 4 HP FLT	POLE 3 TO POLE 4 220 kV BUS TIE	CT'S A, B, C POLE 3 220 kV BUS FEED	BUSH TAPS A, B, C POLE 3 220 kV BUS FEED	801 802 803 MW POLE 3 A, B, C CAP BK 2	804 805 806 MW POLE 3 A CAP BK 1	807 808 809 MW POLE 3 A, D, C 11 & 13 FLT	810 811 812 MW POLE 4 A CAP BK 2	813 814 815 MW POLE 4 B CAP BK 2	816 817 818 MW POLE 4 C CAP BK 1	819 820 821 MW POLE 4 A CAP BK 1	822 823 824 MW POLE 4 B CAP BK 1	825 826 827 MW POLE 4 C CAP BK 1	DC STATUS	UC PWR IN MW	DC DIR.	
1	1/21		0									X	X									OFF			Tests 1 & 2 Repeated
2	1/21		X									X	X									OFF			1 Time
3	1/21		0								X	X										OFF			Tests 3 & 4 Repeated
4	1/21		X								X	X										OFF			1 Time
5	1/21			X							X	X										OFF			Tests 5 & 6 Repeated
6	1/21			0							X	X										OFF			1 Time
7	1/21			0								X			X							OFF			Tests 7 & 8 Repeated
8	1/21			X								X			X							OFF			1 Time
9	1/21	0				0	0			X	X	X										OFF			Tests 9 thru 17 Repeated 1 Time
10	1/21	X				0	0			X	X	X										OFF			
11	1/21	0				0	0			X	X	X										OFF			
12	1/21	0				X	0			X	X	X										OFF			
13	1/21	0				0	0			X	X	X										OFF			
14	1/21	0				0	X			X	X	X										OFF			
15	1/21	0				0	0			X	X	X										OFF			
16	1/21	X				X	X			X	X	X										OFF			
17	1/21	0				0	0			X	X	X										OFF			
18	1/21	0				0	0			X		X		X								OFF			Tests 18 thru 26 Repeated 1 Time
19	1/21	X				0	0			X		X		X								OFF			
20	1/21	0				0	0			X		X		X								OFF			
21	1/21	0				X	0			X		X		X								OFF			
22	1/21	0				0	0			X		X		X								OFF			
23	1/21	0				0	X			X		X		X								OFF			
24	1/21	0				0	0			X		X		X								OFF			
25	1/21	X				X	X			X		X		X								OFF			
26	1/21	0				0	0			X		X		X								OFF			
27	1/21	0		X						X	X	X										ON	200	S/N	Tests 27 & 28 Repeated 1 Time
28	1/21	X		X						X	X	X										ON	200	S/N	
29	1/21	0		X		0	0			X	X	X										ON	200	S/N	Tests 29 thru 37 Repeated 1 Time
30	1/21	X		X		0	0			X	X	X										ON	200	S/N	
31	1/21	0		X		0	0			X	X	X										ON	200	S/N	
32	1/21	0		X		X	0			X	X	X										ON	200	S/N	
33	1/21	0		X		0	0			X	X	X										ON	200	S/N	
34	1/21	0		X		0	X			X	X	X										ON	200	S/N	
35	1/21	0		X		0	0			X	X	X										ON	200	S/N	
36	1/21	X		X		X	X			X	X	X										ON	200	S/N	
37	1/21	0		X		0	0			X	X	X										ON	200	S/N	
38	1/21		0	X						X	X	X										ON	200	S/N	Tests 38 thru 41 Repeated 1 Time
39	1/21		X	X						X	X	X										ON	200	S/N	
40	1/21		0	X						X		X	X									ON	200	S/N	Tests 40 & 41 Repeated 1 Time
41	1/21		X	X						X		X	X									ON	200	S/N

Figure 5.3-1 Electrical Location of Components and Sensors

Tests 1 and 2 consisted of first measuring the system using bushing taps A, B, C and Maxwell Worms 801, 802 and 803 first with no filters and capacitors banks and then adding a three phase capacitor bank on Pole 3. Pole 3 only was energized. This sequence was repeated 4 times.

Tests 3 and 4 was done first with no filters and no capacitors on Pole 3 and then adding three phase 11th and 13th harmonic filters. Measurements were taken on bushing taps A, B, and C and CT's (current transformers) A, B, and C. This series was repeated once.

Tests 5 and 6 consisted of measuring bushing taps A, B, and C and Maxwell Worms 805, 806 and 807 (on Pole 3 11th and 13th harmonic filters) first without the filters and then with them on. This was repeated one time.

In the next series of tests (7 through 15) the bus tie was closed so that Pole 4 was also energized. The sequence went as follows:

Test 7 Pole 3 single phase capacitor bank on. (ØA)

Test 8 No capacitor banks on.

Test 9 Pole 4 single phase capacitor bank on. (ØB)

Test 10 No capacitor banks on.

Test 11 Pole 4 single phase capacitor bank on. (ØC)

Test 12 No capacitor banks on.

Test 13 No capacitor banks on.

Test 14 Pole 3 Phase A, Pole 4 Phase B and Pole 4 Phase C capacitor banks on.

Test 15 No capacitor banks on.

For tests 7 though 15 the measured parameters were the bushings taps A, B, and C and CT's A, B, and C. The above sequence was repeated one time.

Tests 16 through 24 are a repeat of 7 through 15 except the measured parameters were the bushings taps A, B, C and Maxwell Worms 804 (Pole 3 capacitor bank A), 809 (Pole 4 capacitor bank B) and 811 (Pole 4 capacitor bank C). This sequence was repeated once.

NOTE: For tests 1 through 24 the DC was off. For tests 25 through 41 the DC was on at 200 megawatts - South to North (Los Angeles to The Dalles in Oregon).

Tests 25 and 26 consisted first of measuring bushing taps A, B, and C and Maxwell Worms 801, 802, and 803 on Pole 3 without any filter or capacitor banks on and then with a three phase capacitor bank on Pole 3. This sequence was repeated one time.

Tests 27 and 28 were a repeat of 25 and 26 except the measured parameters were the bushing taps A, B, and C and the CT's A, B, and C. Again this was repeated one time.

Tests 29 through 37 consisted of measuring the bushing taps A, B, and C and the CT's A, B, and C during the following sequence.

29. No capacitor banks on.
30. Pole 3 Phase A capacitor bank on.
31. No capacitor banks on.
32. Pole 4 Phase B capacitor bank on.
33. No capacitor banks on.
34. Pole 4 Phase C capacitor bank on.
35. No capacitor banks on.
36. Pole 3 Phase A, Pole 4 Phase B, and Pole 4 Phase C capacitor banks on.
37. No capacitor banks on.

All of the above were repeated one time.

Tests 38 and 39 consisted of having the 11th and 13th filters on Pole 3 on and then off while measuring the bushing taps A, B, and C and the CT's A, B, and C. This was repeated once.

In tests 40 and 41 the high pass filter on Pole 3 was turned on and off while measuring the bushing taps A, B, and C and CT's A, B, and C. This sequence was repeated one time.

This concluded the testing done on January 20, 1979.

On January 21, 1979 testing was resumed with test 1 and 2 being done first without any capacitor banks on and then with a three phase capacitor bank put on Pole 3. Pole 3 only was energized and the measured parameters were the bushing taps A, B, and C and Pole 3 Maxwell Worms 801, 802 and 803 (on 3Ø capacitor bank). This sequence was repeated once.

Tests 3 and 4 were identical to 1 and 2 except the measurement points were the bushing taps A, B, and C and CT's A, B, and C. This was also repeated one time.

Tests 5 and 6 consisted of measuring the bushing taps A, B, and C and the CT's A, B, and C first with Pole 3 11th and 13th harmonic filters on and then off. This was repeated once.

Test 7 was identical to 6 and test 8 was identical to 5 except measured points were the bushing taps A, B, and C and maxwell worms 805, 806 and 807 which were on the Pole 3 11th and 13th harmonic filters. Again this was repeated one time.

During tests 9 through 17 measurements on the bushing taps A, B, and C and the CT's A, B, and C were connected. During this sequence and all that followed, Pole 4 was energized via the bus tie. The sequence of testing was as follows:

9. No capacitor banks on.
10. Pole 3 Phase A capacitor bank on.
11. No capacitor banks on.
12. Pole 4 Phase B capacitor bank on.
13. No capacitor banks on.
14. Pole 4 Phase C capacitor bank on.
15. No capacitor banks on.
16. Pole 3 Phase A, Pole 4 Phase B, and Pole 4 Phase C capacitor banks on.
17. No capacitor banks on.

The above sequence was repeated once.

Tests 18 through 26 are a repeat of tests 9 through 17 except the measured parameters were the bushing taps A, B, and C and Maxwell Worms 804, 809 and 811. This series of tests was repeated one time.

For tests 27 and 28 and all subsequent tests, the DC was on at the 200 megawatt level with the power flow from south to north. For tests 27 and 28, the bushing taps A, B, and C and CT's A, B and C were measured first without any capacitor banks and then with the three phase Pole 3 capacitor bank on. This sequence was repeated once.

Tests 29 through 37 consisted of measuring the bushing taps A, B, and C and the CT's A, B, and C in the following sequence:

29. No capacitor banks on.
30. Pole 3 Phase A cap bank on.
31. No capacitor banks on.
32. Pole 4 Phase B cap bank on.
33. No capacitor banks on.
34. Pole 4 Phase C cap bank on.
35. No capacitor banks on.
36. Pole 3 Phase, Pole 4 Phase B, and Pole 4 Phase C capacitor banks on.
37. No capacitor banks on.

This series was repeated one time.

Tests 38 and 39 was done first with no capacitor banks on but with the Pole 3, 11th and 13th harmonic filters on, then with both the Pole 3 three phase capacitor bank and Pole 3 11th and 13th harmonic filters on. The measured points during this sequence were the bushing taps A, B, and C and CT's A, B, and C.

Tests 40 and 41 were identical to 38 and 39 except the measured points were the bushing taps A, B, and C and the Pole 3 three capacitor bank maxwell worms 801, 802, and 803.

This concluded the testing for January 21, 1979.

5.4 Preliminary (On-Site) Checks on Data Acquired

After all the data was acquired each day, the "tape" was played back to be sure all of the data was satisfactory. It was at this time that the header data was analyzed and the "key" derived for identification of each record. By having a monitor system alongside the data acquisition system, it became readily apparent that all of the acquisition system was operating properly.

Section 6

MEASUREMENT DATA ANALYSIS AND SYSTEM IMPEDANCE CALCULATIONS

The data acquired from the actual testing are processed to obtain the harmonic contents of the voltages and currents, so that the schemes discussed in Section 3 can be used to calculate the system harmonic impedances. The discrete Fourier Transform technique is used to compute the harmonic contents of the voltage and current measurements. Almost all of the measurement data obtained on January 20 and 21, 1979 using CT's were processed. As a first step, the voltage and current components are examined. Then the data accuracy is examined by calculating the impedances of capacitor and filter banks and comparing the results to the impedances provided by the manufacturers. The four schemes described in Section 3 are used to calculate the system impedances. A statistical approach is taken to analyze the available data which can be classified according to operating conditions (dc-on and dc-off), switching procedures (single phase and three phase), and the time of measurements (first day and second day).

In Subsection 6.1, the Fourier Transform technique and its practical usage are discussed. The signals are examined in Subsection 6.2 and the data accuracy is assessed in Subsection 6.3 with the capacitor and filter impedance calculations. The system harmonic impedances are in Subsection 6.4.

6.1 Fourier Transform Technique

The measured voltage and current waveforms, $u(t)$, are composed of sinusoidal signals whose frequencies are multiples of the fundamental 60 Hz, that is,

$$\begin{aligned} u(t) &= \sum_{i=1}^n R_i \sin(i\omega_0 t + \phi_i) \\ &= \sum_{i=1}^n (\alpha_i \sin i\omega_0 t + \beta_i \cos i\omega_0 t) \end{aligned} \quad (6.1)$$

where

$$\alpha_i = R_i \cos \theta_i, \beta_i = R_i \sin \theta_i. \quad (6.2)$$

Since $u(t)$ is sampled at discrete intervals, the discrete Fourier Transform technique is used to find α_i and β_i . The Fast Fourier Transform technique is not used because the requirement here is to determine only the harmonic frequency components, with no need to compute any signals between the harmonic frequencies.

6.1.1 Calculation of α_i and β_i

The Fourier Transform of the measured sampled signal $u(t_k)$, $k=1, \dots, m$ at the harmonic frequency $\omega=i\omega_0$ is computed as

$$\begin{aligned} U(i\omega_0) &= \sum_{k=1}^m (\cos i\omega_0 t_k - j \sin i\omega_0 t_k) u(t_k) \Delta t \\ &= \alpha_i^* + j\beta_i^*, \end{aligned} \quad (6.3)$$

where α_i^* is the sum of the real components, β_i^* is the sum of the imaginary components, and

$$\Delta t = T_\omega / m. \quad (6.4)$$

In (6.4), T_ω is the length of the sampled signal, m is the number of sampled points, and i is the harmonic number.

The Fourier Transform of the waveform (6.1) is

$$\begin{aligned} U(\omega) &= \int_0^{T_\omega} \left\{ \sum_{i=1}^n (\alpha_i \sin i\omega_0 t + \beta_i \cos i\omega_0 t) (\cos \omega t - j \sin \omega t) \right\} dt \\ &= \sum_{i=1}^n -Sx_i [\alpha_i S_i - \beta_i C_i] + j(\alpha_i C_i - \beta_i S_i), \end{aligned} \quad (6.5)$$

where

$$\begin{aligned}
S_i &= \sin [(\omega - i\omega_o) T_\omega/2] , \\
C_i &= \cos [(\omega - i\omega_o) T_\omega/2] , \\
Sx_i &= (T_\omega/2) S_i / [(\omega - i\omega_o) T_\omega/2] .
\end{aligned} \tag{6.6}$$

When ω is close to $i\omega_o$, (6.5) can be approximated by

$$U(\omega) \approx -(Sx_i)[(\alpha_i S_i - \beta_i C_i) + j(\alpha_i C_i - \beta_i S_i)], \tag{6.7}$$

because the Sx_k terms for $k \neq i$ are negligible. At $\omega = i\omega_o$, $U(i\omega_o)$ reduces to $-(T_\omega/2)(-\beta_i - j\alpha_i)$. Then equating the real and imaginary parts of (6.3) and (6.7), we obtain

$$\begin{bmatrix} \alpha_i \\ \beta_i \end{bmatrix} = (2/T_\omega) \begin{bmatrix} -\beta_i^* \\ \alpha_i^* \end{bmatrix} . \tag{6.8}$$

Thus knowing α_i^* and β_i^* for each harmonic, the sinusoidal components of $u(t)$ can be computed. The Harmonic Analysis Program HARMAP which calculates α_i , β_i from (6.8) is documented in Volume 2.

6.1.2 Practical Considerations

A few necessary steps are taken to avoid some of the pitfalls in analyzing discrete data. They are described as follows.

Aliasing effects occur when the sampling rate is too low, resulting in the high frequency components of a time series impersonating low frequencies [2]. To avoid this uncertainty, the sampling rate must be higher than twice the highest frequency present in the signal. In this study, the voltage and current signals are sampled at 20 kHz, and passed through an anti-alias filter, which is a 5 kHz low pass filter, thus retaining the 3 kHz (50th harmonic) bandwidth of interest. Therefore, there is no significant aliasing of the signals to produce erroneous results.

In the Fourier analysis of a finite data record, an impulse function at frequency f_1 is "leaked" or spread out into the adjacent frequencies (see Figure 6.1-1). The frequency spectrum in Figure 6.1-1 consists of a main lobe and many sidelobes. The height of the main lobe is $RT_\omega/2$ where R is the amplitude of the impulse function and T_ω is the length of the processed data record in

seconds. The width of the main lobe is $2/T_{\omega}$, whereas those of the sidelobes are $1/T_{\omega}$. To obtain an accurate value of R, an accurate estimate of the fundamental frequency is required.

Any small deviation of the fundamental frequency from 60 Hz can be calculated from the measurements. Of all the voltage and current measurements, only the phase a, b, c reference voltages measured with 8-bit channels are not passed through 60 Hz notched filters. The voltage of phase a is used to find a complete number of periods of the 60 Hz signal by locating the positive zero crossing points, that is, the transition of the data value from negative to positive. The zero crossing point for both the beginning and the end of the record is found when the number of negative data points among the 20 immediate preceding points is equal to the number of positive data points among the 20 immediate succeeding points. This technique would locate the "best" zero crossing point in the presence of noise. Then the fundamental frequency is calculated by

$$f_o = \left(\frac{\text{Number of points} \times \Delta t}{\text{Number of periods}} \right)^{-1} \quad (6.9)$$

where $\Delta t = (\text{sampling frequency})^{-1} = (1/20,000)$ sec. This technique is used in the HARMAP program.

The zero crossing point, that is, the first point in the data sequence, is not necessarily zero due to the discretization. This results in a phase shift. Thus, the phase of the fundamental frequency voltage component is calculated and compensated in the higher harmonics. The elimination of the phase shift is important in impedance calculations using more than one measurement set, because it ensures that all the measurements start from the same reference.

Figure 6.1-1 Discrete Fourier Transform of an Impulse Function at f_1 .

Since the sampling frequency of 20 kHz is not an integer multiple of 60 Hz, the number of periods must be multiples of three in order to obtain a complete number of periods. For example, three periods of 60 Hz would require exactly 1000 data points. The total number of data points in a single record is 8092. Taking into account the zero crossing point searching, the largest number of periods that can be used is 21. The larger the number of periods processed, the more accurate the fundamental frequency estimation and the harmonic component calculations will be. However, the computation becomes more costly. Experience with the data indicates that 12 periods are adequate. This selection also allows the searching of zero crossing points starting from the 2001 data point, thus avoiding possible transients in the first 2000 points due to measurement equipment switchings. For this condition, $T_w = .2$ sec and the width of a main lobe is 10 Hz. Beside the narrowing of sidelobe widths, taking a large number of periods also averages out the effect of finite word length of the digital recording equipment. Further noise reduction in the data is obtained by averaging the results of three measurement sets taken at slightly different times.

6.1.3 Other Considerations

Crevier and Mercier [3] suggested the use of a least square estimation scheme to calculate α_1 and β_1 . They eliminated the white noise in the spectrum by calculating the Fourier Transform for several frequencies about the harmonic. Although the least square method has been implemented in HARMAP, it was not found useful in this study because of the leakage effect: the component of one harmonic may be so large that it penetrates and corrupts the components of the

adjacent harmonics. A potentially useful approach to reduce the leakage effect is to weigh the data through windows [2]. If the fundamental frequency is exactly 60 Hz, the leakage effect causes no problem because the sidelobes are zero at the harmonics. However, the fundamental frequency usually differs slightly from 60 Hz. With a good windowing technique to eliminate the effect of sidelobes, the least square method in [3] can be extended to find the true harmonics as well. These are future research topics.

6.2 Analysis of Measurement Data

A summary of the data processed with HARMAP is given in Table 6.2-1. The test numbers in Table 6.2-1 correspond to the test numbers in Tables 5.3-1 and 5.3-2. Almost all the tests with CT measurements were processed. Multiple records of each data set are denoted by events. The data were taken over a period of two days, and in the following discussion, January 20, 1979 will be referred to as the first day and January 21, 1979 as the second day. The test was performed within a three-hour time span in the morning of each day. Both the dc-off and dc-on operating conditions were measured.

Two types of switchings were used: a balanced switching where shunt impedances were switched onto all three phases and an unbalanced switching where a shunt impedance was switched onto only a single phase. The shunt impedances consist of capacitor banks in Poles 3 and 4, and 11th and 13th, and HP filter banks. Of these impedances, only one set of capacitor banks can be used for single phase switchings. For data sets 1-15, 17 and 18, the current into the system was measured with current transformers (CT). For data set 16, the current in the capacitors was measured with Maxwell Worms (MW), which are also known as Rogowski Coils.

The harmonic contents of the current and voltage were obtained by processing the current and voltage measurements over a period of 0.2 second with the program HARMAP. The total length of each measurement is 0.4 second and the 0.2 second period (4000 data points) processed skips the first 0.1 second (2000 data points) of measurement. For data sets 1 to 7, all the harmonic components up to the 49th harmonic have been calculated. For data sets 8 to 18, only the odd harmonic components have been calculated. Each event consists of three separate

Table 6.2-1
Data Sets Processed

Data Set	Event No.	Date	DC Status	Celilo Pole 3			Celilo Pole 4			Current Measuring Device	Test Number	Impedance Calculation
				3 Phase Cap Bk	11 & 13 Flt	HP Flt	1 Phase Cap Bk ØA	1 Phase Cap Bk ØB	1 Phase Cap Bk ØC			
1	1,2	1/20	OFF	X						CT	1,2	DCOFF3P
2	1,2	1/20	OFF		X					CT	3,4	DCOFF3P
17	1	1/20	OFF				X			CT	7,8	DCOFF1P
17	2	1/20	OFF					X		CT	9,10	DCOFF1P
17	3	1/20	OFF						X	CT	11,12	DCOFF1P
3	1,2	1/20	OFF				X	X	X	CT	14,15	DCOFF3P
4	1,2	1/20	ON	X						CT	27,28	DCON2M
18	1	1/20	ON				X			CT	29,30	DCON1M
18	2	1/20	ON					X		CT	31,32	DCON1M
18	3	1/20	ON						X	CT	33,34	DCON1M
5	1,2	1/20	ON				X	X	X	CT	35,36	DCON2M
6	1,2	1/20	ON		X					CT	38,39	DCON2M
7	1,2	1/20	ON			X				CT	40,41	DCON2M
8	1,2	1/21	OFF	X						CT	3,4	DCOFF3P
9	1,2	1/21	OFF		X					CT	5,6	DCOFF3P
10	1,4	1/21	OFF				X			CT	9,10	DCOFF1P
10	2,5	1/21	OFF					X		CT	11,12	DCOFF1P
10	3,6	1/21	OFF						X	CT	13,14	DCOFF1P
11	1,2	1/21	OFF				X	X	X	CT	16,17	DCOFF3P
12	1,2	1/21	ON	X	ON					CT	27,28	DCON2M
13	1,4	1/21	ON		ON		X			CT	29,30	DCON2M
13	2,5	1/21	ON		ON			X		CT	31,32	DCON2M
13	3,6	1/21	ON		ON				X	CT	33,34	DCON2M
14	1,2	1/21	ON		ON		X	X	X	CT	36,37	DCON2M
15	1	1/21	ON	X	ON					CT	38,39	DCON2M
16	1	1/21	ON	X	ON					MW	40,41	

X - denotes a switching of the shunt impedance from on to off.

DCOFF3P = DC-Off Three Phase Switching Program
DCOFF1P = DC-Off One Phase Switching Program
DCON2M = DC-On Two Measurements Program
DCON1M = DC-On One Measurement Program

recordings. The results of these recordings are averaged to reduce measurement noises. Four events, out of a total of 44 events, had data conversion problems and were not processed.

The first day dc-off data indicate that the harmonic components of the system are small. In general, the harmonic current components are less than 6A and the harmonic voltage components are less than 500 V. The currents are mostly lagging the voltages, a result of the fact that the system impedance is mostly inductive. The even harmonic components are smaller than the odd harmonic components, and the magnitude of the components decreases rapidly as the harmonic number increases. Table 6.2-2 lists the harmonic analysis results for data set 17, event 1 (phase a capacitor switching). Figures 6.2-1 to 6.2-4 are plots of phase a voltages and currents with and without capacitor. Note that the CT's detected some currents when no capacitor was connected, but these stray signals were very small.

The first day dc-on data indicate that a substantial amount of current is generated by the dc operation at the characteristic harmonics which are the 11th, 13th, 23rd, 25th, 35th, 37th, 47th and 49th harmonics. The 11th and 13th harmonic current components are of the order of 60A, which cause the 11th and 13th harmonic voltage components to be of the order of 2 kV. Table 6.2-3 lists the harmonic analysis results for data set 18, event 1 (phase a capacitor switching). Figures 6.2-5 and 6.2-6 are plots of phase a voltages and currents with capacitor on phase a.

Table 6.2-2 shows that there are strong harmonic signals generated by the system in the lower harmonics. For example, the voltage levels of the 3rd to the 7th harmonic range from 300 volts to 500 volts. These voltage signals are comparable to those measured when dc is on (see Table 6.2-3). This negates the assumption of the dominance of the dc harmonic source used in Section 3 which allows impedance calculations using only one measurement.

The 11th and 13th filters reduce the magnitude of the voltage component for the 11th and 13th harmonics. The magnitude of the voltage at the 11th harmonic decreased about 94%. Table 6.2-4 shows the phase signals of data set 2, event 1, without any filters and Table 6.2-5 shows the phase signals with the filters connected. Figures 6.2-7 to 6.2-10 show the phase a signals when switching the

Table 6.2-2
Data Set 17, Event 1
dc off, capacitor connected to Phase A
AVERAGE OF 3 SEQUENCES

	CHANNEL	HARMONICS							
		3	5	7	9	11	13	15	17
v _{ref}	7 MAG	0.47268	0.33645	0.46512	0.07037	0.18586	0.01994	0.01126	0.01018
	PHASE	-173.405	-129.645	-134.568	62.470	-39.961	-46.500	28.988	-36.732
i _a	10 MAG	1.66289	2.56470	3.75777	1.45992	3.45051	0.38069	0.10555	1.02180
	PHASE	-81.850	-31.480	-47.492	129.699	50.323	70.014	-116.319	83.732
i _b	11 MAG	0.04000	0.03159	0.03581	0.00689	0.04515	0.00388	0.01090	0.01681
	PHASE	-175.725	50.854	-152.091	-144.439	-149.076	-172.054	-52.431	100.416
i _c	12 MAG	0.02470	0.03940	0.02281	0.00503	0.03816	0.00225	0.00447	0.00870
	PHASE	-110.733	-166.740	85.069	163.066	-9.520	23.670	-63.493	67.495
v _a	13 MAG	0.33964	0.30976	0.48487	0.09192	0.18156	0.01658	0.00396	0.03352
	PHASE	-168.103	-126.280	-137.707	41.375	-40.023	-19.649	157.114	-6.479
v _b	14 MAG	0.17758	0.28205	0.25993	0.01368	0.20070	0.00663	0.00469	0.01325
	PHASE	80.444	5.782	103.943	111.310	119.884	133.603	97.197	-103.136
v _c	15 MAG	0.05453	0.24620	0.29542	0.02306	0.17779	0.00966	0.00491	0.02817
	PHASE	-59.923	122.691	-2.090	115.730	-84.709	-57.210	108.974	-8.997

	CHANNEL	HARMONICS							
		19	21	23	25	27	29	31	33
v _{ref}	7 MAG	0.01152	0.01555	0.00921	0.00994	0.00828	0.02249	0.01219	0.02053
	PHASE	-101.112	131.139	42.919	-169.102	160.550	149.380	161.835	59.781
i _a	10 MAG	0.35165	0.15601	0.11509	0.45663	0.04429	0.21537	0.23184	0.07277
	PHASE	-83.165	115.910	-171.384	-12.688	-6.471	-5.208	102.380	171.751
i _b	11 MAG	0.02150	0.01164	0.01497	0.01272	0.00410	0.01081	0.01217	0.00135
	PHASE	102.258	86.950	-29.580	10.664	160.414	-120.196	80.887	-59.824
i _c	12 MAG	0.00261	0.00364	0.00527	0.00974	0.00256	0.00904	0.00795	0.00264
	PHASE	169.885	88.182	186.908	-114.931	-141.343	-4.773	-21.239	89.590
v _a	13 MAG	0.01063	0.00601	0.00272	0.01010	0.00114	0.00396	0.00397	0.00129
	PHASE	-156.399	28.692	95.843	-102.304	-89.750	-100.258	14.344	92.801
v _b	14 MAG	0.00508	0.00848	0.00997	0.02593	0.00052	0.01488	0.02512	0.00326
	PHASE	-179.148	-21.702	-100.742	-92.781	165.500	148.463	23.583	-29.586
v _c	15 MAG	0.01076	0.00365	0.02153	0.02024	0.00300	0.02398	0.01219	0.00337
	PHASE	-170.177	53.767	70.994	161.482	-131.652	-94.417	-108.187	25.050

	CHANNEL	HARMONICS							
		35	37	39	41	43	45	47	49
v _{ref}	7 MAG	0.01173	0.02333	0.02688	0.03123	0.04787	0.03260	0.04702	0.02852
	PHASE	-87.852	68.369	-144.123	22.802	-149.125	39.137	-144.750	35.177
i _a	10 MAG	0.30940	0.39004	0.01280	0.05897	0.05082	0.03706	0.09792	0.04502
	PHASE	47.419	-112.486	-163.111	-172.195	12.744	-102.439	42.546	-33.527
i _b	11 MAG	0.00941	0.02955	0.00410	0.00173	0.00497	0.00179	0.00313	0.00178
	PHASE	-130.801	-102.783	165.323	-166.471	170.838	83.238	-73.424	-56.047
i _c	12 MAG	0.01627	0.02386	0.00190	0.00226	0.00441	0.00048	0.00512	0.00597
	PHASE	21.164	118.507	-168.466	48.516	-31.457	83.402	65.601	-120.827
v _a	13 MAG	0.00434	0.00513	0.00015	0.00053	0.00057	0.00043	0.00080	0.00048
	PHASE	-43.686	158.420	172.896	87.367	-106.652	164.199	-59.538	-145.094
v _b	14 MAG	0.01409	0.04785	0.00119	0.00334	0.00383	0.00180	0.00593	0.00566
	PHASE	163.042	167.458	-110.676	67.738	81.270	136.274	-103.907	-64.638
v _c	15 MAG	0.03408	0.04259	0.00191	0.00355	0.00871	0.00187	0.00988	0.00702
	PHASE	-69.067	31.950	47.716	11.524	-117.329	136.329	-41.151	181.808

V_{ref} is phase A voltage without 60 Hz components filtered.

Currents are in amperes.

Voltages are in kilovolts.

HVDC - AC HARMONICS	TEST WHIT08	SEQ. 04-06
EPRI RP 1138-1 TASK 5A	JANUARY 20, 1979	
PHASE A CAP SWITCHING - DC OFF - CT - CAP OFF

Figure 6.2-1 Voltage Magnitude and Phase Plot of Phase A with
DC Off and No Capacitor

HVDC - AC HARMONICS	TEST WHIT08	SEQ. 04-06
EPRI RP 1138-1 TASK 5A	JANUARY 20, 1979	
PHASE A CAP SWITCHING - DC OFF - CT - CAP OFF

Figure 6.2-2 Current Magnitude and Phase Plot of Phase A with
DC Off and No Capacitor

HVDC - AC HARMONICS	TEST WHIT08	SEQ. 07-09
EPRI RP 1138-1 TASK 5A	JANUARY 20, 1979	
PHASE A CAP SWITCHING - DC OFF - CT - CAP ON

Figure 6.2-3 Voltage Magnitude and Phase Plot of Phase A with
DC Off and Capacitor Connected

HVDC - AC HARMONICS	TEST WHIT08	SEQ. 07-09
EPRI RP 1138-1 TASK 5A	JANUARY 20, 1979	
PHASE A CAP SWITCHING - DC OFF - CT - CAP ON

Figure 6.2-4 Current Magnitude and Phase Plot of Phase A with
DC Off and Capacitor Connected

Table 6.2-3
Data Set 18, Event 1
dc on, capacitor connected to Phase A

AVERAGE OF 3 SEQUENCES									
	CHANNEL			HARMONICS					
	7	9	11	13	15	17	19	21	23
v_{ref}	MAG 0.48847	0.33275	0.39820	0.14079	3.45342	2.43702	0.10516	0.02986	
	PHASE -172.020	-136.919	-132.835	-175.935	-49.342	-137.565	-70.891	-165.822	
i_a	MAG 5.12009	3.38487	1.39000	2.40106	66.10758	57.86686	1.80584	0.84010	
	PHASE -83.594	-85.974	-0.479	-45.769	-118.130	-45.801	64.541	1.633	
i_b	MAG 2.26580	3.40936	1.51297	2.84388	68.95583	56.38296	2.25152	0.96780	
	PHASE -94.347	-38.689	-142.020	-49.476	-0.937	-168.408	-39.264	-154.093	
i_c	MAG 3.91969	3.29457	0.62728	2.18551	69.96352	53.60080	1.89003	0.52879	
	PHASE -18.680	157.333	141.958	-163.413	121.563	75.677	179.939	-74.478	
v_a	MAG 0.36407	0.31988	0.41880	0.10040	3.43768	2.41581	0.07012	0.03236	
	PHASE -164.253	-132.357	-136.935	-175.935	-50.748	-139.101	-65.668	-157.812	
v_b	MAG 0.19682	0.34933	0.36419	0.13705	4.39981	3.21270	0.05718	0.04011	
	PHASE 88.978	-0.960	98.342	-63.333	-172.558	6.116	-139.855	39.363	
v_c	MAG 0.08902	0.31477	0.36554	0.16272	3.41237	2.18764	0.05536	0.01398	
	PHASE -93.824	118.381	-11.427	74.800	-48.911	-135.775	82.971	-117.050	

	CHANNEL			HARMONICS					
	19	21	23	25	27	29	31	33	
v_{ref}	MAG 0.13539	0.07919	1.59709	1.64610	0.20303	0.08253	0.05627	0.04673	
	PHASE -32.287	-72.156	-171.963	-91.393	-20.309	-128.214	-79.895	-135.888	
i_a	MAG 1.94227	1.33190	25.32432	23.45717	1.03999	1.24386	0.85592	0.51038	
	PHASE 113.629	25.749	-42.153	32.577	153.720	59.868	-153.585	28.109	
i_b	MAG 1.50826	2.19836	27.45248	23.27548	1.37857	1.21987	0.45641	0.51630	
	PHASE -26.532	131.145	75.657	-89.185	-19.934	-166.439	-98.140	-157.038	
i_c	MAG 1.28366	1.95631	27.36842	21.90982	1.39384	1.04539	0.88988	0.88869	
	PHASE -107.151	-93.197	-160.158	154.039	-108.377	-50.966	4.304	-2.660	
v_a	MAG 0.12151	0.11038	1.56972	1.65355	0.21250	0.08727	0.07657	0.04451	
	PHASE -18.373	-85.020	-172.013	-91.363	-13.846	-109.067	-85.825	-151.038	
v_b	MAG 0.06564	0.13334	1.31673	1.18252	0.16935	0.09500	0.04316	0.00406	
	PHASE -169.279	4.777	-50.013	157.051	-120.818	49.874	-17.197	82.707	
v_c	MAG 0.06652	0.16465	1.70140	1.49665	0.22945	0.06471	0.07716	0.06701	
	PHASE 149.620	134.029	-36.497	-43.990	115.605	-158.923	-117.172	-142.971	

	CHANNEL			HARMONICS					
	35	37	39	41	43	45	47	49	
v_{ref}	MAG 0.20430	0.49225	0.02742	0.04892	0.03811	0.07423	0.09453	0.11898	
	PHASE -152.870	-8.432	-160.808	-106.045	-79.685	-104.032	-173.849	-157.423	
i_a	MAG 3.74030	8.03992	0.85963	0.65848	0.33475	0.81864	3.25304	2.36070	
	PHASE -1.117	140.800	-80.163	74.141	-54.933	48.681	-46.464	-73.031	
i_b	MAG 5.37657	7.84640	0.55886	0.52437	0.50246	0.56548	2.55388	3.12025	
	PHASE 120.758	23.231	130.435	-160.179	-157.703	95.338	80.791	162.885	
i_c	MAG 4.60858	7.80499	1.06055	0.48817	0.52015	0.14763	2.98201	2.48355	
	PHASE -103.107	-94.314	16.427	-48.718	77.270	131.809	-174.982	33.911	
v_a	MAG 0.20342	0.50001	0.09429	0.04112	0.02505	0.06098	0.11431	0.11332	
	PHASE -154.471	-8.393	145.519	-74.258	115.898	-77.640	174.451	151.627	
v_b	MAG 0.32343	0.56595	0.00774	0.03512	0.04320	0.04190	0.07866	0.14746	
	PHASE -12.641	-115.173	-19.519	75.576	51.241	-32.288	-54.453	58.789	
v_c	MAG 0.23729	0.51313	0.07386	0.02688	0.05345	0.03029	0.14528	0.13174	
	PHASE 108.247	100.156	-122.898	143.291	-107.168	-27.406	36.069	-90.386	

v_{ref} is Phase A voltage without 60 Hz components filtered.

Currents are in amperes.

Voltages are in kilovolts.

HVDC - AC HARMONICS	TEST WHIT10	SEQ. 34-36
EPRI RP 1138-1 TASK 5A	JANUARY 20, 1979	
PHASE A CAP SWITCHING - DC ON - CT - CAP OFF

Figure 6.2-5 Voltage Magnitude and Phase Plot of Phase A with
DC On and No Capacitor

HVDC - AC HARMONICS	TEST WHIT10	SEQ. 34-36
EPRI RP 1138-1 TASK 5A	JANUARY 20, 1979	
PHASE A CAP SWITCHING - DC ON - CT - CAP OFF

Figure 6.2-6 Current Magnitude and Phase Plot of Phase A with DC On and No Capacitor

Table 6.2-4
Data Set 2, Event 1
dc off, no filter

AVERAGE OF 3 SEQUENCES

	CHANNEL	HARMONICS							
		3	5	7	9	11	13	15	17
v _{ref}	7 MAG	0.37291	0.28313	0.26359	0.03950	0.20289	0.02173	0.05688	0.06258
	PHASE	-169.847	-132.746	-126.859	156.757	0.599	-138.849	2.530	159.262
i _a	10 MAG	0.08137	0.04860	0.03076	0.00432	0.00212	0.00856	0.00972	0.01299
	PHASE	-121.020	64.607	-66.422	129.710	136.746	151.672	122.560	71.804
i _b	11 MAG	0.03033	0.01035	0.01912	0.00493	0.00737	0.01476	0.00980	0.01678
	PHASE	-148.591	-7.796	-82.787	48.834	-54.031	-104.163	148.027	85.892
i _c	12 MAG	0.03131	0.02682	0.01546	0.00181	0.01117	0.00721	0.00457	0.00784
	PHASE	-115.570	156.023	-7.664	-146.405	-74.910	170.967	141.733	81.786
v _a	13 MAG	0.26854	0.24113	0.30841	0.02452	0.16036	0.01054	0.00194	0.03454
	PHASE	-160.726	-123.919	-134.551	72.239	-2.092	-10.864	-135.405	106.961
v _b	14 MAG	0.18964	0.26716	0.26742	0.01229	0.20263	0.05484	0.00535	0.01121
	PHASE	94.039	0.508	103.747	46.552	129.677	174.839	109.306	-106.752
v _c	15 MAG	0.03455	0.21975	0.29034	0.01323	0.16137	0.04651	0.00292	0.03418
	PHASE	-71.290	126.756	-7.440	98.437	-105.432	-12.354	67.099	-58.333

	CHANNEL	HARMONICS							
		19	21	23	25	27	29	31	33
v _{ref}	7 MAG	0.06315	0.05362	0.04638	0.02318	0.04616	0.04517	0.02400	0.03791
	PHASE	-1.591	-163.719	12.041	-174.517	3.964	-165.945	39.829	-161.883
i _a	10 MAG	0.00406	0.00601	0.00940	0.01365	0.01271	0.01270	0.00604	0.00091
	PHASE	33.019	-130.506	-172.134	131.531	94.140	78.071	46.723	5.752
i _b	11 MAG	0.00254	0.00408	0.00351	0.00352	0.00460	0.00555	0.00882	0.00209
	PHASE	174.592	-150.490	-78.601	107.509	31.352	162.347	115.440	-177.011
i _c	12 MAG	0.00162	0.00374	0.01027	0.04464	0.00839	0.00730	0.00283	0.00153
	PHASE	-47.246	-133.490	-164.406	162.426	121.262	70.477	42.916	-175.712
v _a	13 MAG	0.01345	0.00489	0.00560	0.02779	0.00375	0.01328	0.01941	0.00519
	PHASE	-33.103	156.889	166.521	75.331	2.909	14.942	141.589	120.581
v _b	14 MAG	0.00703	0.00697	0.01526	0.02244	0.00215	0.02213	0.02219	0.00279
	PHASE	101.279	-50.317	-116.141	-86.429	146.556	139.187	14.721	-20.007
v _c	15 MAG	0.01102	0.00432	0.02078	0.02450	0.00318	0.02068	0.01267	0.00374
	PHASE	-165.372	58.546	46.822	157.338	-146.558	-93.111	-128.111	-78.781

	CHANNEL	HARMONICS							
		35	37	39	41	43	45	47	49
v _{ref}	7 MAG	0.04616	0.05434	0.01961	0.01467	0.00887	0.00015	0.00956	0.01737
	PHASE	-6.742	-124.530	-10.928	-131.380	39.689	141.345	-106.726	47.967
i _a	10 MAG	0.00478	0.00522	0.01042	0.01222	0.01304	0.00685	0.00432	0.00825
	PHASE	116.294	87.708	87.743	62.186	42.482	33.650	60.395	53.019
i _b	11 MAG	0.00632	0.00053	0.00218	0.00522	0.01068	0.00211	0.00217	0.00536
	PHASE	65.465	-96.113	-162.113	72.296	44.473	-48.746	-173.257	35.105
i _c	12 MAG	0.00441	0.01093	0.00874	0.00877	0.00569	0.00371	0.00509	0.00712
	PHASE	147.675	89.739	92.193	68.716	41.896	60.570	75.055	86.418
v _a	13 MAG	0.00519	0.03003	0.00254	0.00345	0.00209	0.00285	0.00417	0.00159
	PHASE	-16.824	-148.652	147.075	170.181	17.131	-65.599	57.043	12.079
v _b	14 MAG	0.01970	0.03790	0.00195	0.00004	0.00397	0.00131	0.00335	0.00357
	PHASE	61.641	107.181	59.074	117.957	58.689	162.464	-177.924	-52.312
v _c	15 MAG	0.01493	0.03859	0.00315	0.00528	0.00667	0.00092	0.00714	0.00416
	PHASE	-164.220	-36.795	-76.640	-6.893	-147.825	65.814	-65.725	193.023

v_{ref} is Phase A voltage without 60 Hz components filtered.

Currents are in amperes.

Voltages are in kilovolts.

Table 6.2-5

Data Set 2, Event 1
dc off, filter bank connected

AVERAGE OF 3 SEQUENCES										
	CHANNEL			HARMONICS						
	7	10	11	12	13	14	15	16	17	18
v_{ref}	MAG 0.47905	0.26649	0.50549	0.07506	0.05189	0.05017	0.03160	0.02928		
	PHASE -173.617	-173.001	-142.505	27.678	-178.470	21.307	-157.783	75.356		
i_a	MAG 0.79980	1.51173	4.84310	1.71011	3.05374	0.14239	0.01940	0.25526		
	PHASE -79.674	-28.959	-51.526	115.410	9.827	-46.971	155.866	35.009		
i_b	MAG 0.58016	1.70400	4.14026	0.99507	2.93308	1.04306	0.07189	0.10325		
	PHASE 175.740	99.391	-175.125	139.788	121.831	-176.478	24.171	158.143		
i_c	MAG 0.09618	1.34502	4.31732	2.26876	3.25820	0.91439	0.02676	0.22860		
	PHASE 33.995	-138.406	79.183	118.689	-113.447	7.782	16.997	-111.118		
v_a	MAG 0.27973	0.27684	0.47537	0.07194	0.00587	0.00074	0.00103	0.01711		
	PHASE -164.773	-124.661	-141.221	26.268	40.916	10.294	-94.137	121.980		
v_b	MAG 0.18335	0.30017	0.39979	0.08170	0.00915	0.00366	0.00318	0.00713		
	PHASE 92.799	7.340	97.166	57.252	173.517	-135.011	120.188	-101.150		
v_c	MAG 0.03987	0.25426	0.44396	0.10447	0.00991	0.00375	0.00126	0.01693		
	PHASE -71.925	126.407	-11.517	30.989	-77.341	30.146	92.914	-25.818		

	CHANNEL			HARMONICS						
	19	21	23	25	27	29	31	33		
v_{ref}	MAG 0.03505	0.03540	0.04703	0.06377	0.05919	0.04149	0.07263	0.05054		
	PHASE -152.875	6.015	-156.603	31.808	-164.320	36.281	-179.238	29.395		
i_a	MAG 0.08632	0.02302	0.03569	0.11911	0.03488	0.06932	0.06850	0.03374		
	PHASE -104.548	100.047	99.130	-43.860	-43.229	-62.216	67.243	46.085		
i_b	MAG 0.06082	0.04897	0.08463	0.10633	0.02084	0.04469	0.09071	0.01429		
	PHASE 23.789	-138.400	162.712	-175.698	-74.556	45.287	-64.891	-155.422		
i_c	MAG 0.07709	0.01663	0.04047	0.11691	0.00200	0.08499	0.04680	0.01121		
	PHASE 119.644	19.481	-21.614	71.124	-170.583	-157.374	157.640	-129.003		
v_a	MAG 0.00835	0.00213	0.00316	0.01975	0.00327	0.01064	0.01568	0.00690		
	PHASE -16.870	163.021	179.864	37.619	40.826	35.822	157.393	128.941		
v_b	MAG 0.00463	0.00418	0.01081	0.01672	0.00142	0.01746	0.01942	0.00392		
	PHASE 109.256	-35.231	-104.366	-80.447	-149.491	155.087	29.735	-49.588		
v_c	MAG 0.00763	0.00275	0.01400	0.01705	0.00291	0.01765	0.01154	0.00413		
	PHASE -155.856	90.583	50.906	156.744	-106.012	-79.103	-119.594	-37.263		

	CHANNEL			HARMONICS						
	35	37	39	41	43	45	47	49		
v_{ref}	MAG 0.04838	0.02730	0.04760	0.01457	0.02610	0.01967	0.00549	0.00683		
	PHASE -156.968	14.756	-141.670	27.317	-157.111	-15.961	-174.735	-92.297		
i_a	MAG 0.02706	0.07924	0.00873	0.00739	0.01099	0.01009	0.01540	0.00907		
	PHASE 166.888	117.743	0.821	28.259	-65.261	-110.822	-34.888	-91.090		
i_b	MAG 0.07217	0.10312	0.00727	0.00476	0.00827	0.00081	0.00381	0.00421		
	PHASE -52.042	15.073	-23.289	-53.079	-45.730	32.490	81.918	-137.204		
i_c	MAG 0.07287	0.10244	0.01123	0.02411	0.01134	0.00756	0.01934	0.00248		
	PHASE 61.196	-108.738	-90.537	-71.703	147.336	-34.450	-125.873	88.969		
v_a	MAG 0.00903	0.02297	0.00224	0.00381	0.00222	0.00263	0.00364	0.00184		
	PHASE -95.024	-149.172	161.718	170.892	30.307	-60.409	49.820	-10.897		
v_b	MAG 0.01904	0.02773	0.00208	0.00084	0.00228	0.00183	0.00222	0.00283		
	PHASE 40.890	111.588	85.282	-73.076	54.362	178.736	-170.360	-29.444		
v_c	MAG 0.01712	0.03044	0.00240	0.00532	0.00486	0.00091	0.00530	0.00321		
	PHASE 151.012	-30.718	-59.106	2.321	-144.636	79.352	-68.980	163.344		

V_{ref} is Phase A voltage without 60 Hz components filtered.

Currents are in amperes.

Voltages are in kilovolts.

HVDC - AC HARMONICS	TEST WHIT07	SEQ. 31-33
EPRI AP 1138-1 TASK 5A	JANUARY 20, 1979	
FILTER SWITCHING - DC OFF - CT - FILTER OFF

Figure 6.2-7 Voltage Magnitude and Phase Plot of Phase A
with Filter Bank Switched Off

HVDC - AC HARMONICS TEST WHIT07 SEQ. 31-33
EPRI RP 1138-1 TASK SA JANUARY 20, 1979
FILTER SWITCHING - DC OFF - CT - FILTER OFF

Figure 6.2-8 Current Magnitude and Phase Plot of Phase A
with Filter Bank Switched Off

HVDC - AC HARMONICS	TEST WHIT07	SEQ. 34-36
EPRI RP 1138-1 TASK 5A	JANUARY 20, 1979	
FILTER SWITCHING - DC OFF - CT - FILTER ON

Figure 6.2-9 Voltage Magnitude and Phase Plot of Phase A
with Filter Bank Switched On

HVDC - AC HARMONICS	TEST WHIT07	SEQ. 34-36
EPRI RP 1136-1 TASK 5A	JANUARY 20, 1979	
FILTER SWITCHING - DC OFF - CT - FILTER ON

Figure 6.2-10 Current Magnitude and Phase Plot of Phase A
with Filter Bank Switched On

filters in and out with dc off. When dc is on, switching on the filter reduces the 11th and 13th harmonic currents to about 5A and voltages to 150 volts.

Table 6.2-4 shows that the system voltages are fairly balanced when dc is off. Table 6.2-3 shows that the dc operation results in fairly balanced voltages and currents, even though the capacitor is switched onto one phase. Only the phase c voltage measurements at the 3rd harmonic are significantly different from phases a and b measurements. The reason for this discrepancy is probably due to the tuning of the 60 Hz notched filter on measurement channel 15.

Unusually high phase a even harmonic voltage components in the range of 100 V to 200 V are obtained when the three single phase capacitors are switched onto the system (data set 5, see Figure 6.2-11). The even harmonic voltage components in phases b and c are much smaller. This phenomenon does not occur in the three single phase capacitor switching when dc is off, or in any other dc-on measurements. It is attributed to the location of the capacitors. The phase b and c capacitors are located at Pole 4 while the phase a capacitor is located at Pole 3. With the instrumentation grounded at Pole 4, the voltage buildup across the ground path between the two poles due to the harmonic currents showed up on the phase a measurement.

The second day dc-off data are similar to the first day dc-off data. The second day dc-on data were measured with the 11th and 13th filter connected to the system. Thus the harmonic components are, in general, smaller than those of the first day data. An exception is the 7th harmonic current components which increase from about 7A to about 30A when the capacitor banks are switched in, due to a possible resonance between the system and the filter bank.

The Maxwell Worm results are not as accurate (data set 16) as the CT results. The worms which measured the current in the capacitors showed a significant amount of current signal even though the capacitors were disconnected. This is probably due to the fact that the worms were not shielded and hence would pick up stray signals.

6.3 Capacitor and Filter Impedance Calculations

Before calculating the system impedance, the accuracy of the data recorded was examined by calculating the capacitor impedances from the single phase capacitor

HVDC - AC HARMONICS	DATA SET 5-B TEST 35-36
BPA HARMONIC ANALYSIS	JANUARY 20, 1979
3-1 PH. CAP SWITCHING - DC ON - NO MW

Figure 6.2-11 Voltage Magnitude and Phase Plot of Phase A with Three Single Phase Capacitor Banks Connected

switching tests (data set 17, events 1, 2 and 3) and comparing the results to the impedance data of the capacitor supplied by the manufacturer (rated at 82 MVAR-three phase at 60 Hz) at different harmonics. Figures 6.3-1 to 6.3-3 are bar plots of the magnitude and phase of the impedances of the phases a, b and c capacitor, respectively. On this plot, marked with an X, is the capacitor impedance calculated from measurements. Figure 6.3-1 shows that the measured capacitor impedance compared to the capacitor impedance obtained from the manufacturer's data, up to about the 27th harmonic, has a maximum magnitude deviation of 16 percent and a phase deviation of 5.8 degrees. The average magnitude deviation is about 11.5 percent and the average phase deviation is about 2.2 degrees.

The measured capacitor impedances for the phases b and c capacitors, shown in Figures 6.3-2 and 6.3-3, are similar to the phase a results.

Another check on the accuracy of the recorded data is to examine the impedance of the 11th and 13th filters used in three phase switchings. Figure 6.3-4 shows the one line diagram of the 11th and the 13th filters.

HVDC - AC HARMONICS	TEST WHIT08	SEQ. 04-09
EPRI RP 1138-1 TASK SA	JANUARY 20, 1979	
PHASE A CAP SWITCHING - POLE 3 DC OFF - CT		

X - CAPACITOR IMPEDANCE FROM
MANUFACTURER'S DATA

| - MEASURED CAPACITOR IMPEDANCE

Figure 6.3.1 Impedance Plot of Phase A Capacitor

HVDC - AC HARMONICS EPRI RP 1135-1 TASK 5A PHASE B CAP SWITCHING - PBLE 3 DC BFF - CT B1	TEST WHIT08 JANUARY 20, 1979	SEQ. 10-15
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X - CAPACITOR IMPEDANCE FROM
MANUFACTURER'S DATA

| - MEASURED CAPACITOR IMPEDANCE

Figure 6.3-2 Impedance Plot of Phase B Capacitor

HVDC - AC HARMONICS TEST WHIT08 SEQ. 16-21
 EPRI RP 1138-1 TASK 5A JANUARY 20, 1979
 PHASE C CAP SWITCHING - POLE 3 DC OFF - CT C1

X - CAPACITOR IMPEDANCE FROM
 MANUFACTURER'S DATA

| - MEASURED CAPACITOR IMPEDANCE

Figure 6.3-3 Impedance Plot of Phase C Capacitor

Figure 6.3-4 One Line Diagram of the 11th and 13th Filter

The 11th and 13th filters are located at the Celilo substation. Figure 6.3-5 shows the plot of the calculated impedance and the measured impedance of phase a versus the harmonic number. The results for the filter switchings are similar to those for the capacitor switchings. The agreement is excellent up to the 19th harmonic. Due to the small signals, the agreement deteriorates rapidly above the 19th harmonic.

The impedance comparison results show that the measurement data are valid for most harmonics, although the filter switching results are less accurate at the higher harmonics.

6.4 System Impedance

The four different impedance calculation schemes described in Section 3 are used to compute the system impedance from the measurements. The schemes used for the different data sets are shown in Table 6.2-1. The results of the computation are tabulated in Appendix D.1.

Figure 6.3-5 Impedance Plot of Filter

The first step of the impedance analysis is to investigate the consistency of the impedances calculated from different methods and operating conditions. Three investigations are performed: first, the consistency between different events in a data set; second, the consistency between data sets using the same measurement scheme; and third, the consistency between different schemes.

The mean and standard deviation of the impedances calculated from the different events of a data set are listed in Appendix D.2. The mean $R_m + jX_m$ of n impedances $R_i + jX_i$, $i = 1, 2, 3, \dots, n$, is calculated as

$$R_m = (\sum_{i=1}^n R_i)/n, \quad X_m = (\sum_{i=1}^n X_i)/n, \quad (6.4.1)$$

and the standard deviation S is given by

$$S = \sqrt{\{\sum_{i=1}^n [(R_i - R_m)^2 + (X_i - X_m)^2]/n\}}. \quad (6.4.2)$$

A smaller standard deviation or variance indicates that the impedances are more consistent. In general, the impedances are more consistent when the harmonic currents and voltages are large. Thus, the dc-on results are more consistent than the dc-off results, and the odd harmonic impedances are more consistent than the even harmonic impedances. Furthermore, the dc-on results with the 11th and 13th filters on or switching have large variances, since the filters reduce the level of harmonic currents and hence the accuracy of the measurements. Another observation is that the single phase capacitor switching results are not as consistent as the three phase switching results. A possible explanation is that the capacitors are in separate banks whose neutrals are connected only through the ground mat.

Table 6.4-1
Data Sets Combined According to Day, DC Status, and Switching

Data Set	Day	DC	Switching	Combination of Data Sets
21	1	ON	1Ø	18
22	1	ON	3Ø	4, 5, 6, 7
23	1	OFF	1Ø	17
24	1	OFF	3Ø	1, 2, 3
25	2	ON	1Ø	13
26	2	ON	3Ø	12, 14, 15
27	2	OFF	1Ø	10
28	2	OFF	3Ø	8, 9, 11

The mean impedances of data sets 1-15, 17 and 18 are combined as in Table 6.4-1 according to the measurement day, dc status and switching techniques. For convenience, the new data sets are numbered as 21 to 28. The mean and standard deviation of the new data sets are listed in Appendix D.3. For single phase switching, there is only one data set in each category and the averaged impedances are the original impedances. In the other data sets the standard deviations are, in general, small, although they become larger at the higher harmonics of the dc-off data sets. The small variances indicate that the three phase switching measurements can be performed using any of the switching devices available at Celilo. It is also of interest to note that the variances of the even harmonic impedances of the new data sets are smaller with dc-off than with dc-on, which are to be expected.

The impedances from data set 21 which are calculated using one dc-on measurement do not account for harmonic sources within the system. As shown in Subsection 6.2, the system harmonic voltages are significant for the lower harmonics such as the 3rd, 5th and 7th. For these harmonics, two measurement techniques are required. For example, the 7th harmonic impedance of data set 5, event 1 calculated using one measurement is $237.3 + j230.9$ ohms while that calculated using two measurements is $3.4 + j34.9$ ohms, which is consistent with the dc off results. Thus, the one measurement dc-on method is unreliable except for the characteristic harmonics. Data set 21 will be dropped from further consideration.

The mean impedances of data sets 22-28 are then used to examine the consistency between the different methods and different day of measurements, as shown in Table 6.4-2. The mean and standard deviation of these comparisons are shown in the tables indicated. In general, the variances of the comparisons are small compared to the magnitude of the mean impedances. A large variance occurs at the 3rd harmonic when data set 23 is used, which is a bad data point.

Table 6.4-2
Consistency Between Data Sets 22-28

	Table
1. First day dc on.	6.4-3
2. First day dc off.	6.4-4
3. Second day dc on.	6.4-5
4. Second day dc off.	6.4-6
5. First day single phase switching.	6.4-7
6. First day three phase switching.	6.4-8
7. Second day single phase switching.	6.4-9
8. Second day three phase switching.	6.4-10
9. All first day data.	6.4-11
10. All second day data.	6.4-12
11. All dc on data.	6.4-13
12. All dc off data.	6.4-14
13. All single phase switching.	6.4-15
14. All three phase switching.	6.4-16
15. All data sets.	6.4-17
16. All first day even harmonics.	6.4-18

The results in Tables 6.4-3 to 6.4-18 further substantiate some of the observations made earlier that the dc-on method (two measurements) yields more consistent results than dc-off methods, three phase switchings yield more consistent results than single phase switchings, and the first day results are more consistent than the second day results.

Table 6.4-3

AVERAGE OF FIRST DAY DC ON DATA SETS EXCEPT DC ON
SINGLE PHASE SWITCHING

DATA SETS PROCESSED :
(22,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION *
3	17.26	87.51	0.75	17.24	0.00
5	16.72	92.66	-0.70	16.70	0.00
7	35.46	81.08	5.50	35.03	0.00
9	48.29	68.28	17.87	44.86	0.00
11	47.10	11.20	46.21	9.15	0.00
13	45.23	-8.89	44.68	-6.99	0.00
15	31.44	67.39	12.09	29.02	0.00
17	61.04	70.59	20.28	57.57	0.00
19	54.66	51.84	33.77	42.98	0.00
21	62.31	58.89	32.19	53.35	0.00
23	55.83	47.35	37.83	41.07	0.00
25	62.14	61.66	29.50	54.69	0.00
27	150.24	29.06	131.32	72.97	0.00
29	67.06	16.34	64.35	18.87	0.00
31	79.47	50.01	51.08	60.88	0.00
33	53.01	10.98	52.04	10.10	0.00
35	59.45	39.77	45.69	38.03	0.00
37	57.06	34.12	47.24	32.00	0.00
39	51.49	31.52	43.90	26.92	0.00
41	48.68	40.70	36.91	31.74	0.00
43	75.25	15.38	72.56	19.96	0.00
45	70.25	31.45	59.93	36.66	0.00
47	40.35	39.84	30.99	25.85	0.00
49	47.47	60.31	23.51	41.24	0.00

*Standard deviation is zero since there is only one data set.

Table 6.4-4

AVERAGE OF FIRST DAY DC OFF
DATA SETS

DATA SETS PROCESSED :
(23,0) (24,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	287.25	-127.16	-173.50	-228.93	296.55
5	20.34	74.14	5.56	19.57	3.56
7	35.27	79.98	6.14	34.74	1.31
9	48.78	70.84	16.01	46.08	3.47
11	52.76	4.05	52.63	3.73	1.37
13	47.13	3.97	47.02	3.27	10.46
15	30.14	55.85	16.92	24.95	4.64
17	64.91	56.60	35.73	54.19	1.44
19	54.62	65.04	23.05	49.51	5.14
21	57.43	52.34	35.09	45.46	2.29
23	56.73	51.91	35.00	44.65	3.64
25	61.66	67.77	23.33	57.08	3.21
27	144.33	25.80	129.95	62.82	10.75
29	61.91	11.70	60.63	12.56	3.76
31	80.29	49.82	51.80	61.35	16.14
33	46.91	11.32	46.00	9.21	14.82
35	31.06	83.80	3.36	30.88	23.46
37	34.67	45.90	24.13	24.90	13.71
39	57.56	15.35	55.51	15.24	7.99
41	36.47	15.68	35.11	9.85	14.65
43	66.17	41.19	49.80	43.58	15.82
45	56.31	22.46	52.03	21.51	16.05
47	32.32	17.22	30.87	9.56	9.88
49	50.26	48.41	33.36	37.59	26.90

Table 6.4-5

AVERAGE OF SECOND DAY DC ON
DATA SETS

DATA SETS PROCESSED :
(25,0) (26,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	16.28	112.66	-6.27	15.02	11.63
5	41.32	97.61	-5.47	40.96	23.44
7	35.95	80.45	5.97	35.46	0.44
9	54.04	67.97	20.27	50.10	2.57
11	20.28	61.09	9.81	17.76	9.77
13	44.21	-13.31	43.02	-10.18	13.39
15	34.42	52.28	21.06	27.23	2.09
17	55.66	63.88	24.51	49.98	1.46
19	56.31	55.09	32.23	46.18	2.85
21	68.75	56.46	37.99	57.31	2.62
23	56.35	47.96	37.74	41.85	0.50
25	63.07	64.92	26.74	57.13	0.07
27	158.22	30.81	135.90	81.03	4.45
29	64.61	7.98	63.99	8.98	1.14
31	76.35	48.01	51.08	56.75	1.41
33	45.01	8.10	44.56	6.35	13.47
35	58.34	32.45	49.12	31.48	0.75
37	56.81	37.60	45.01	34.67	1.97
39	79.78	47.05	54.36	58.40	25.86
41	54.13	42.60	39.85	36.65	3.60
43	58.40	3.29	58.30	3.35	5.52
45	57.13	27.25	50.79	26.16	2.27
47	44.32	42.09	32.89	29.70	2.27
49	49.31	58.45	25.80	42.02	1.43

Table 6.4-6

AVERAGE OF SECOND DAY DC OFF
DATA SETS

DATA SETS PROCESSED :
(27,0) (28,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	36.00	46.59	24.74	26.16	24.35
5	24.70	100.18	-4.37	24.31	10.53
7	40.75	78.02	8.46	39.86	1.46
9	58.63	67.91	22.05	54.33	6.42
11	56.20	-8.64	55.56	-8.45	1.95
13	36.93	-22.62	34.09	-14.20	2.67
15	25.33	72.19	7.75	24.12	6.33
17	59.35	62.69	27.23	52.74	12.79
19	46.18	52.53	28.09	36.65	13.07
21	66.60	65.33	27.80	60.53	11.94
23	32.67	78.63	6.44	32.03	16.85
25	67.33	64.48	29.00	60.76	5.27
27	157.35	27.66	139.37	73.04	11.17
29	65.58	8.13	64.93	9.28	2.94
31	75.59	40.26	57.68	48.85	8.15
33	56.00	27.21	49.80	25.61	9.53
35	36.82	13.21	35.85	8.42	40.50
37	59.33	25.46	53.56	25.50	33.86
39	52.66	-2.69	52.60	-2.47	42.76
41	48.66	36.83	38.94	29.17	3.64
43	69.75	8.57	68.97	10.40	12.72
45	40.73	38.91	31.69	25.59	18.84
47	51.96	61.72	24.61	45.76	40.65
49	25.37	142.62	-20.16	15.40	25.06

Table 6.4-7

AVERAGE OF FIRST DAY SINGLE PHASE SWITCHING DATA SETS EXCEPT
DC ON SINGLE PHASE SWITCHING

DATA SETS PROCESSED :
(23,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION *
3	9.46	63.42	4.23	8.46	0.00
5	19.11	83.83	2.05	19.00	0.00
7	34.50	81.72	4.97	34.14	0.00
9	51.75	68.79	18.72	48.25	0.00
11	51.60	3.24	51.52	2.92	0.00
13	45.99	-8.84	45.44	-7.07	0.00
15	33.77	50.66	21.41	26.12	0.00
17	66.14	55.97	37.02	54.81	0.00
19	53.05	59.82	26.67	45.86	0.00
21	59.21	53.75	35.01	47.75	0.00
23	58.32	48.65	38.53	43.77	0.00
25	62.39	64.88	26.49	56.49	0.00
27	141.14	21.68	131.16	52.13	0.00
29	61.36	15.16	59.22	16.05	0.00
31	73.06	39.01	56.77	45.99	0.00
33	33.86	21.46	31.52	12.39	0.00
35	7.60	82.16	1.04	7.53	0.00
37	47.95	41.10	36.13	31.53	0.00
39	49.58	15.65	47.74	13.37	0.00
41	42.39	-3.95	42.29	-2.92	0.00
43	56.29	29.57	48.96	27.78	0.00
45	49.67	6.58	49.34	5.69	0.00
47	30.73	35.01	25.17	17.63	0.00
49	59.63	75.05	15.39	57.61	0.00

*Standard deviation is zero since there is only one data set.

Table 6.4-8

AVERAGE OF FIRST DAY 3 PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(22,0) (24,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	13.09	79.03	2.49	12.85	4.72
5	17.86	87.96	0.63	17.85	1.82
7	34.98	81.39	5.24	34.58	0.52
9	50.02	68.55	18.30	46.56	1.75
11	49.24	7.04	48.87	6.03	4.09
13	45.61	-8.87	45.06	-7.03	0.38
15	32.26	58.72	16.75	27.57	4.88
17	63.07	62.98	28.65	56.19	8.48
19	53.73	55.77	30.22	44.42	3.83
21	60.70	56.39	33.60	50.55	3.13
23	57.07	48.01	38.18	42.42	1.39
25	62.24	63.27	28.00	55.59	1.75
27	145.38	25.48	131.24	62.55	10.42
29	64.20	15.78	61.78	17.46	2.93
31	75.92	44.74	53.93	53.44	7.97
33	43.27	15.06	41.78	11.25	10.32
35	32.63	44.27	23.36	22.78	27.04
37	52.41	37.31	41.69	31.77	5.56
39	50.05	23.73	45.82	20.15	7.04
41	42.14	20.00	39.60	14.41	17.54
43	65.28	21.45	60.76	23.87	12.43
45	58.59	21.18	54.64	21.17	16.37
47	35.51	37.75	28.08	21.74	5.04
49	53.11	68.52	19.45	49.43	9.14

Table 6.4-9

AVERAGE OF SECOND DAY SINGLE PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(25,0) (27,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	33.61	55.02	19.27	27.54	29.67
5	38.96	102.53	-8.45	38.03	24.67
7	38.16	80.38	6.38	37.63	2.63
9	59.28	67.93	22.27	54.94	5.84
11	38.76	6.38	38.53	4.31	22.81
13	48.16	-20.34	45.16	-16.74	9.10
15	31.41	59.22	16.08	26.99	3.49
17	55.88	68.75	20.25	52.09	6.16
19	44.66	53.90	26.32	36.08	11.38
21	72.07	59.06	37.06	61.81	4.07
23	34.77	59.94	17.42	30.10	23.55
25	66.02	62.51	30.47	58.56	3.98
27	163.01	28.71	142.96	78.32	10.31
29	67.08	8.35	66.37	9.74	1.44
31	79.67	44.67	56.65	56.01	6.95
33	44.44	28.01	39.23	20.87	3.04
35	28.50	12.91	27.78	6.37	33.49
37	42.24	41.81	31.49	28.16	13.29
39	78.41	19.61	73.86	26.32	57.69
41	49.93	40.78	37.81	32.61	6.93
43	56.13	6.05	55.82	5.92	7.11
45	40.59	29.25	35.42	19.83	18.90
47	67.16	54.55	38.95	54.72	26.15
49	33.36	107.54	-10.05	31.81	36.11

Table 6.4-10

AVERAGE OF SECOND DAY 3 PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(26,0) (28,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	13.66	93.36	-0.80	13.64	9.60
5	27.27	92.90	-1.38	27.24	10.36
7	38.54	77.95	8.05	37.69	2.62
9	53.40	67.95	20.05	49.49	2.63
11	27.31	10.56	26.84	5.00	30.01
13	32.85	-13.46	31.95	-7.64	4.80
15	27.49	62.41	12.73	24.36	10.80
17	59.62	58.12	31.49	50.63	8.44
19	57.31	53.97	34.01	46.75	4.09
21	62.96	62.85	28.73	56.02	11.77
23	51.31	58.57	26.76	43.78	11.42
25	64.48	66.93	25.27	59.33	2.70
27	152.46	29.79	132.31	75.75	4.04
29	63.12	7.75	62.55	8.52	0.52
31	71.93	43.58	52.11	49.59	6.48
33	56.23	11.37	55.13	11.09	16.97
35	66.29	30.38	57.19	33.52	8.50
37	74.33	25.50	67.09	32.01	20.28
39	44.41	41.82	33.10	29.62	13.67
41	52.74	39.01	40.98	33.20	1.14
43	71.89	6.25	71.46	7.83	9.97
45	56.87	34.14	47.07	31.92	6.68
47	27.84	48.20	18.56	20.75	18.76
49	30.04	58.50	15.69	25.62	19.63

Table 6.4-11

ALL FIRST DAY DATA SETS EXCEPT DC ON SINGLE PHASE
SWITCHING

DATA SETS PROCESSED :
(22,0) (23,0) (24,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	186.80	-128.16	-115.42	-146.88	280.79
5	18.93	79.51	3.45	10.61	4.38
7	35.33	80.35	5.92	34.83	1.12
9	48.60	69.99	16.63	45.67	3.02
11	50.79	6.25	50.49	5.53	4.11
13	46.24	-0.19	46.24	-0.15	9.87
15	30.43	59.80	15.31	26.30	4.82
17	63.20	61.07	30.58	55.32	7.54
19	54.31	60.65	26.62	47.34	7.26
21	58.97	54.64	34.12	48.09	4.38
23	56.40	50.41	35.94	43.46	3.67
25	61.74	65.72	25.39	56.28	4.08
27	146.24	26.91	130.40	66.20	10.02
29	63.58	13.33	61.87	14.66	4.62
31	80.02	49.88	51.56	61.19	13.18
33	48.94	11.20	48.01	9.51	12.44
35	37.57	62.30	17.47	33.26	27.87
37	41.91	40.58	31.83	27.27	15.97
39	55.07	20.33	51.64	19.13	10.14
41	39.61	25.65	35.71	17.15	15.82
43	67.58	31.89	57.38	35.70	20.15
45	60.78	25.91	54.67	26.56	15.38
47	34.35	25.88	30.91	14.99	11.13
49	49.10	52.22	30.08	38.81	22.52

Table 6.4-12

ALL SECOND DAY DATA SETS

DATA SETS PROCESSED :

(25,0) (26,0) (27,0) (28,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	22.56	65.84	9.24	20.59	25.21
5	33.00	98.57	-4.92	32.64	19.99
7	38.34	79.16	7.21	37.66	2.75
9	56.34	67.94	21.16	52.21	5.40
11	33.01	8.11	32.69	4.66	27.29
13	40.43	-17.55	38.55	-12.19	10.82
15	29.44	60.71	14.40	25.68	8.30
17	57.50	63.27	25.87	51.36	9.31
19	51.24	53.94	30.16	41.42	10.79
21	67.48	60.83	32.89	58.92	10.16
23	43.04	59.12	22.09	36.94	20.28
25	65.20	64.69	27.87	58.94	4.30
27	157.72	29.24	137.63	77.04	9.56
29	65.10	8.06	64.46	9.13	2.28
31	75.80	44.16	54.38	52.80	7.79
33	49.81	18.71	47.18	15.98	15.35
35	46.93	25.15	42.48	19.95	31.58
37	57.74	31.40	49.29	30.08	24.79
39	60.35	27.61	53.48	27.97	46.65
41	51.33	39.87	39.40	32.91	5.22
43	64.01	6.17	63.64	6.88	11.71
45	48.69	32.10	41.24	25.87	16.47
47	47.44	52.69	28.75	37.73	30.17
49	28.85	84.39	2.82	28.71	31.94

Table 6.4-13

ALL DC ON DATA SETS EXCEPT FIRST DAY SINGLE PHASE
SWITCHING

DATA SETS PROCESSED :
(22,0) (25,0) (26,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	16.24	104.00	-3.93	15.76	10.11
5	33.10	96.78	-3.91	32.07	22.40
7	35.79	80.66	5.81	35.31	0.47
9	52.12	68.06	19.47	48.35	3.43
11	26.51	34.16	21.94	14.89	19.35
13	44.52	-11.82	43.57	-9.12	11.06
15	33.18	57.00	18.07	27.83	4.64
17	57.36	66.26	23.10	52.51	4.27
19	55.74	54.03	32.74	45.11	2.87
21	66.59	57.22	36.05	55.99	3.94
23	56.18	47.76	37.77	41.59	0.56
25	62.74	63.84	27.66	56.31	1.74
27	155.54	30.24	134.37	78.34	5.69
29	65.27	10.84	64.11	12.27	4.76
31	77.38	48.69	51.08	58.13	2.26
33	47.66	9.17	47.05	7.60	11.69
35	58.61	35.05	47.98	33.66	3.54
37	56.87	36.44	45.75	33.78	2.30
39	69.88	43.28	50.87	47.91	26.27
41	52.31	42.01	38.87	35.01	3.99
43	63.68	8.02	63.05	8.89	11.26
45	61.47	28.85	53.84	29.66	6.82
47	42.99	41.38	32.26	28.42	2.75
49	48.69	59.06	25.04	41.76	1.63

Table 6.4-14

ALL DC OFF DATA SETS

DATA SETS PROCESSED :

(23,0) (24,0) (27,0) (28,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	125.75	-126.26	-74.38	-101.39	265.26
5	21.95	88.44	0.60	21.94	9.59
7	38.00	78.93	7.30	37.30	3.14
9	53.69	69.24	19.03	50.20	7.26
11	54.15	-2.50	54.09	-2.36	6.48
13	40.92	-7.68	40.55	-5.47	13.28
15	27.46	63.31	12.34	24.53	7.21
17	62.04	59.51	31.48	53.47	10.07
19	50.10	59.31	25.57	43.08	12.10
21	61.62	59.32	31.45	52.99	12.00
23	43.58	61.61	20.72	38.34	19.81
25	64.47	66.05	26.17	58.92	5.52
27	150.82	26.77	134.66	67.93	12.98
29	63.72	9.87	62.78	10.92	4.32
31	77.67	45.19	54.74	55.10	14.53
33	50.96	19.98	47.90	17.41	15.03
35	27.75	45.07	19.60	19.65	38.54
37	46.31	32.97	38.85	25.20	29.73
39	54.43	6.73	54.06	6.38	32.04
41	41.85	27.78	37.03	19.51	14.52
43	65.23	24.44	59.39	26.99	23.94
45	48.03	29.36	41.87	23.55	20.34
47	39.18	44.92	27.74	27.66	34.82
49	27.31	76.01	6.60	26.49	38.92

Table 6.4-15

ALL SINGLE PHASE SWITCHING DATA SETS EXCEPT FIRST DAY
DC ON

DATA SETS PROCESSED :
(23,0) (25,0) (27,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	172.21	-127.25	-104.23	-137.08	292.05
5	32.17	94.66	-2.61	32.07	23.35
7	37.46	79.72	6.69	36.86	2.44
9	54.76	69.38	19.28	51.26	8.23
11	43.81	5.74	43.59	4.38	19.96
13	46.78	-8.14	46.30	-6.63	16.20
15	29.87	60.17	14.86	25.91	3.66
17	58.21	64.59	24.98	52.58	8.40
19	48.19	60.10	24.02	41.78	12.72
21	66.47	56.77	36.43	55.60	9.44
23	41.60	57.91	22.10	35.24	21.60
25	64.23	65.11	27.04	58.27	5.86
27	158.08	29.03	138.22	76.71	11.00
29	65.61	8.34	64.92	9.52	2.38
31	82.51	49.68	53.38	62.91	12.20
33	48.97	18.98	46.31	15.92	12.46
35	30.25	47.56	20.41	22.32	36.95
37	35.28	44.80	25.03	24.86	14.93
39	74.07	18.29	70.33	23.24	47.57
41	45.26	40.31	34.52	29.28	8.71
43	59.07	23.69	54.09	23.74	25.97
45	49.09	31.52	41.85	25.66	19.72
47	53.13	44.10	38.16	36.98	32.96
49	28.99	68.96	10.41	27.06	41.85

Table 6.4-16

ALL 3 PHASE SWITCHING DATA SETS

DATA SETS PROCESSED :

(22,0) (24,0) (26,0) (28,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	13.27	86.35	0.84	13.24	7.75
5	22.55	90.95	-0.37	22.54	8.85
7	36.74	79.59	6.64	36.14	2.82
9	51.71	68.24	19.17	48.02	2.81
11	38.26	8.30	37.85	5.52	24.09
13	39.20	-10.79	38.51	-7.34	7.39
15	29.86	60.42	14.74	25.97	8.77
17	61.29	60.62	30.07	53.41	9.02
19	55.76	54.84	32.11	45.59	4.54
21	61.73	59.68	31.17	53.28	9.36
23	53.96	53.01	32.47	43.10	9.96
25	63.33	65.13	26.63	57.46	3.24
27	148.82	27.69	131.77	69.15	10.31
29	63.51	11.80	62.17	12.99	4.96
31	73.92	44.18	53.02	51.51	7.57
33	49.72	12.98	48.46	11.17	15.55
35	49.14	34.95	40.28	28.15	26.76
37	63.04	30.38	54.39	31.89	19.55
39	46.65	32.23	39.46	24.88	13.46
41	46.80	30.58	40.29	23.81	15.59
43	67.98	13.48	66.11	15.85	14.83
45	57.36	27.56	50.85	26.55	14.12
47	31.54	42.34	23.32	21.25	14.54
49	41.43	64.90	17.57	37.52	19.49

Table 6.4-17

ALL DATA SETS EXCEPT FIRST DAY DC ON SINGLE
PHASE SWITCHING

DATA SETS PROCESSED :
(22,0) (23,0) (24,0) (25,0) (26,0) (27,0) (28,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	67.62	-130.80	-44.19	-51.18	211.72
5	26.66	92.87	-1.33	26.62	17.38
7	37.05	79.64	6.66	36.45	2.69
9	53.01	68.75	19.22	49.41	6.01
11	40.63	7.11	40.31	5.03	22.60
13	42.43	-9.54	41.85	-7.03	12.60
15	29.87	60.31	14.79	25.94	7.05
17	59.94	62.27	27.89	53.05	9.12
19	52.46	56.91	28.64	43.95	10.04
21	63.74	58.38	33.42	54.28	9.81
23	48.62	54.80	28.03	39.73	17.27
25	63.72	65.12	26.81	57.80	4.58
27	152.77	28.28	134.53	72.39	11.69
29	64.38	10.29	63.35	11.50	4.61
31	77.51	46.69	53.17	56.40	11.33
33	49.34	15.52	47.54	13.20	14.54
35	40.83	38.93	31.76	25.65	33.16
37	50.31	34.63	41.81	28.88	23.18
39	57.97	24.65	52.69	24.18	36.16
41	45.98	34.67	37.82	26.15	13.67
43	63.92	17.51	60.96	19.23	21.57
45	53.79	29.11	47.00	26.17	17.34
47	40.79	43.32	29.68	27.99	26.48
49	36.08	66.30	14.50	33.04	31.73

Table 6.4-18

ALL FIRST DAY DATA SETS EVEN HARMONICS

DATA SETS PROCESSED :
(22,0) (24,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	26.32	116.01	-11.54	23.66	9.31
4	24.09	72.14	7.38	22.93	2.93
6	44.66	49.15	29.21	33.78	39.80
8	39.46	74.07	10.83	37.94	6.39
10	73.92	55.10	42.29	60.63	1.72
12	58.55	34.58	48.21	33.23	10.56
14	12.26	21.15	11.44	4.43	4.10
16	35.89	66.42	14.36	32.90	1.27
18	68.93	21.87	64.01	25.70	30.71
20	63.38	61.39	30.35	55.64	11.26
22	75.33	40.82	57.01	49.24	17.30
24	76.67	10.26	75.44	13.66	34.48
26	105.96	42.49	78.13	71.57	21.67
28	110.78	-29.54	96.39	-54.62	5.53
30	89.52	33.69	74.49	49.67	53.08
32	64.37	-12.03	62.96	-13.41	6.89
34	59.13	21.86	54.88	22.02	11.91
36	50.57	75.79	12.41	49.02	57.85
38	61.23	-27.69	54.22	-28.45	35.32
40	83.84	24.78	76.12	35.14	17.74
42	81.58	-6.22	81.10	-8.84	19.86
44	49.85	-2.07	49.82	-1.80	1.61
46	53.48	38.60	41.80	33.37	15.08
48	62.86	148.27	-53.47	33.06	57.62

The difference between the first and second day impedances is small. The most significant one is at the 11th harmonic, which seems to be very sensitive. The first day results indicate that the 11th harmonic impedance is $50.5 + j5.6$ ohms, the second day dc-on results show that it is $9.8 + j17.8$ ohms and the second day dc-off results show that it is $55.6 - j8.5$ ohms.

The harmonic impedances in Tables 6.4-17 and 6.4-18 are plotted in Figure 6.4-1. The 2nd, 3rd, 5th and 48th harmonic impedances have negative resistance and hence are not plotted. An attempt was made to recalculate the impedances by eliminating the zero sequence voltage and current components. However, the negative resistances did not change significantly. This is a subject for future investigation. The harmonic impedances are mostly inductive. The harmonic impedance goes from inductive to capacitive when there is a parallel resonance condition in the system, and from capacitive to inductive where there is a series resonance condition. Some of the resonance circles are easily detectable, such as those formed by the 12th, 13th and 14th harmonics, and the 26th, 27th, 28th and 29th harmonics. These impedances can be enclosed in the sector bounded by 12 and 150 ohms, and -29 and 80 degrees. The information is useful for filter design.

Figure 6.4-1 Measured System Harmonic Impedances

6.5 Conclusions

The overall consistency of the results obtained from the measurement data confirms the feasibility of calculating system harmonic impedances from measured voltages and currents. However, great care in the measurement and analysis is required due to the small harmonic components. The assumption of a Thevenin equivalent harmonic source in the system, which remains constant during the test period, has proven acceptable. The harmonic source should not be neglected in the dc-on method even though the dc signals are large. Although it is not possible, from the discrete frequency points measured, to construct a complete impedance versus frequency characteristic of the system, it is possible to infer some of the system resonant points from the available data.

Although the data sets are extensive, they represent only about a six hour period. Further tests would be desirable to examine the system impedance under various loading and generation levels (e.g., summer and winter), and network configurations and to further verify the analysis methods.

References

1. J.H. Chow, D.W. Durbak, W.W. Price, A.E. Turner, "Harmonic Analysis of the Celilo Test Data," Final Report, BPA Contract DC-AC79-81BP31116, March, 1982.
2. G.D. Bergland, "A Guided Tour of the Fast Fourier Transforms," IEEE SPECTRUM, Vol. 6, 1969, pp. 41-52.
3. D. Crevier and A. Mercier, "Estimation of Higher Frequency Network Equivalent Impedances by Harmonic Analysis of Natural Waveforms," IEEE PAS, Vol. 97, Mar/Apr 1978, pp. 424-431.

Section 7

SYSTEM IMPEDANCE CALCULATIONS FROM ANALYTICAL DATA

7.1 Introduction

The calculation of system harmonic impedances from analytical data is discussed in this section. The intent is to establish a method of analysis for evaluating system harmonic impedances and to validate the System Impedance Scanning Program (SISP) designed to execute this analysis.

The use of SISP to model system components is explained in Subsection 7.2. A technique to calculate system harmonic impedance for large systems is proposed in Subsection 7.3. The modeling of the system and the calculation of the impedance from the Celilo substation are given in Subsection 7.4.

7.2 System Impedance Scanning Program (SISP)

The SISP digital computer program determines the driving point impedance of a system as a function of frequency from a given point in the network. The bus admittance matrix of the system is constructed at each frequency step and reduced to a single complex number by assuming zero current injection at all but the driving point bus.

System elements are modeled in SISP in three different ways, selectable by the user.

Table 7.2-1
System Element Models

Type	R	X	Y	Uses
0	Constant	ωL	ωC	Shunt Devices, Loads
1	Constant	Distributed Parameter		Transmission Lines
2	$R=R(\sqrt{f}/r_{dc})$	Distributed Parameter		Transmission Lines

7.2.1 Transmission Line Models

For this study Type 2 models are used to represent all the transmission lines included in the system data. A discussion of the determination of the line parameters follows.

Line Resistance

For Type 2 representations, the skin effect on the resistance of the line is included. The basic reference on skin effect is Rosa and Grover [1], which presents a solution of the equations for skin effect for a straight cylindrical wire and a table of values of the resulting Bessel function solutions. The parameter x used in this table and in other skin effect formulas is given by:

$$x = \sqrt{2\pi f \mu r^2 / \rho} \quad (7.1)$$

where

f = frequency (Hz)

r = radius (m)

ρ = resistivity (ohm-meters)

μ = permeability = 1.257×10^{-6} henries/meter for non-magnetic material.

However, the dc resistance of a cylindrical conductor can be expressed as

$$r_{dc} = \rho / (\pi r^2) \text{ ohms/meter} . \quad (7.2)$$

Therefore, for non-magnetic material (7.1) becomes

$$x = .001585 \sqrt{f/r_{dc}}, \text{ for } r_{dc} \text{ in ohms/meter} \quad (7.3)$$

or

$$x = .0636 \sqrt{f/r_{dc}}, \text{ for } r_{dc} \text{ in ohms/mile.} \quad (7.4)$$

The procedure in SISP is to calculate the parameter x using an assumed value for r_{dc} (.07 ohm/mile). Then, equations which approximate the Rosa and Grover tabulated values are used to compute the ratio of ac resistance to dc

resistance. These equations were obtained, with slight modification from Magnusson [2] as follows:

for $x < 2.4$,

$$r_{ac}/r_{dc} = .035x^2 + 0.938 , \quad (7.5)$$

for $x \geq 2.4$,

$$r_{ac}/r_{dc} = .35x + 0.3 . \quad (7.6)$$

The total line resistance is the product of the resistance ratio and the total dc resistance. This value of total dc resistance is calculated assuming the true input value of resistance is the true 60 Hz resistance.

Distributed Parameters

As frequency and the length of a line increase, a constant L and C pi-section no longer represents satisfactorily the impedance. The use of hyperbolic functions to obtain modified pi-section parameters will produce a more accurate model. The modified pi-section has the following form:

$$Z' = Z \frac{\sinh \sqrt{ZY}}{\sqrt{ZY}}$$

$$\frac{Y'}{2} = \frac{Y}{2} \frac{\tanh \sqrt{ZY}/2}{\sqrt{ZY}/2}$$

where $Z = R + j\omega L$
 $Y = G^* + j\omega C$

* IN SISP, G is zero.

The hyperbolic functions are implemented in SISP using the complex sine and tangent functions.

$$\sinh \sqrt{ZY} = -j \sin (j\sqrt{ZY}) \quad (7.7)$$

$$\tanh \frac{\sqrt{ZY}}{2} = -j \tan (j\sqrt{ZY}/2). \quad (7.8)$$

In using the hyperbolic parameter representation pi-section equivalents of long lines, the argument of the hyperbolic functions assumes a linear increase in the reactive terms of the series impedance and shunt admittance with frequency. This assumption can be justified by a comparison of the line reactance and charging determined in field testing and the linear reactance calculated here ($X = j\omega L$). Actual test data taken from the Transmission Line Reference Book [3], and the SISP model are plotted in Figure 7.2-1. The deviation of the test data from the linear approximation is insignificant. Thus, the effect of increasing frequency on the linear impedances is the same as if the length of the line is increased since L and C are both linear functions of line length [4].

7.2.2 Modeling of Other System Elements

Transformer Model

The transformers represented in the system data are represented with the Type 0 model of Table 7.2-1: a constant resistance and a linearly increasing reactance, $Z = R + j\omega L$. This model is a fairly simple representation of a transformer, which ignores the frequency dependent nature of the eddy current losses in the core and the turn to turn capacitance of the windings. These simplifications still allow for a reasonably accurate representation of the harmonic behavior of the transformer.

Shunt Devices

Discrete shunt devices in the system, such as capacitors, reactors and filters are represented with Type 0 models, connected from bus to ground. The reactance of the reactors and susceptance of the capacitors vary linearly with frequency. The resistance of shunt devices is assumed to remain constant with frequency. The shunt devices modeled in the system data were represented without real loss terms.

The harmonic impedance of filters is modeled with the series combination of two Type 0 models, one for the capacitor and one for the tuned reactor, connected to ground. The quality of the filter is dictated by the amount of resistance

Figure 7.2-1 Comparison of SISP Model with Data from the Transmission Line Reference Book [3]

included in the two elements. In this study, no filters were on line at the time of the tests, and consequently were not included in the system representation.

Series Capacitors

Series capacitors are also modeled with Type 0 representations. The series capacitor can be spliced into the line which it is compensating by recognizing the two intermediate buses on either side of the compensation and including the capacitor, with any constant resistive losses, between the buses.

Generator Model

The harmonic behavior of a generator for frequencies of interest in the SISP analysis are represented by a Type 0 model to ground, using a simple resistance and reactance. The subtransient reactance of the generator is representative of the harmonic driving point impedance. The armature resistance may be included, but represents a relatively insignificant effect. In this study, the subtransient reactance of the machines represented in the SISP data was obtained using twenty percent per unit impedance on the machine's MVA base. No armature losses were included.

Load Modeling

The harmonic behavior of loads is dependent on the composition of the load. The composition will generally be different from site to site, with little information available regarding specific load composition. This makes modeling of a "typical" load difficult. A load could be represented using the Type 0 model, with a constant resistance and linearly increasing impedance to ground. No attempt was made in this study to represent the loads, which were left open circuited.

7.3 SISP Modeling of Large Systems

The representation of large power systems for harmonic preformance analysis requires that many system configurations be considered. The intent of investigating many system representations is to identify a range of possible system harmonic impedances, which may be encountered during actual operations. Changes in system configurations may include equipment outages and model parameter variations.

For each system configuration, the harmonic impedance should be calculated for a proper termination on the final tier or level of representation. These tiers are a measure of the remoteness of system buses from the bus at which the driving point impedance is being calculated. For example, all the buses which are two buses away from the driving point bus, that is, which have two branches in series connecting them to the driving point bus, are on the second tier. Figure 7.3-1 demonstrates this tier or level concept for a generic system topology. Admittances to ground are included on each bus in the system which has shunt devices or loads. If the system representation is to stop at some tier, an appropriate termination on the buses at the last tier is required. To obtain bounds of the terminating impedance, the last tier buses are short circuited and then open circuited, since the actual impedance is somewhere between zero and infinity. Another reasonable choice of a terminating impedance is to use the impedances of the lines out to the next tier of buses. As the model is extended to include progressively more tiers, the impact of opening and shorting the terminating buses is expected to decrease, with the impedances calculated at each tier converging to some single value for each harmonic. This convergence would suggest that additional detail in the system representation is unnecessary. As the representation of the system is changed, a range of possible driving point impedances is calculated at each level, which will in some statistical sense yield a usable range of driving point impedances for each harmonic, if the results fail to converge in the expected manner.

7.4 System Harmonic Impedance from the Celilo Bus

The system representation used in the evaluation of the harmonic driving point impedance from HVDC station at Celilo is based on data assembled from a number of sources. The line, transformer and generator characteristics were extracted from a WSCC load flow data set. The connections and parameters included in this representation were traced out and verified from the Celilo bus into the BPA and adjacent systems using data tables and system one line diagrams provided by BPA. The connections in the area nearest to the test site were further checked against operator records and hard copies of operator computer displays for the periods during the tests. The final data set includes representations out to the seventh tier, as described in the previous section. Figure 7.4-1 shows the geographic location and extent of the system included in the system representation. Detailed one line diagrams of the system as modeled are shown in Figures 7.4-2 to 7.4-5. The system comprises 244 buses, and 506 lines, transformers, series capacitors, shunt devices and generators. Voltage levels

Figure 7.3-1 Illustration of Tiers

Figure 7.4-1 Extent of System Modeled in SISP

Figure 7.4-2 One-Line Diagram of BPA'S 500kV System Modeled in SISP

Figure 7.4-3 One-Line Diagram of BPA'S 345kV System Modeled in SISP

Figure 7.4-4 One-Line Diagram of BPA'S 230kV System Modeled in SISP
(Page 1 of 2)

Figure 7.4-5 One-Line Diagram of BPA'S 230kV System Mdeled in SISP
(Page 2 of 2)

include 500 kv, 345 kv, 230 kv and generator voltages. The operator log sheets from the time of the tests, January 20 and 21, 1979, indicate that the system configurations of BPA for both days during the tests were the same and that the 5th and 7th filters located at Big Eddy were all disconnected during the tests.

The process of analytically determining the harmonic impedance from Celilo involved executing a number of cases, using the termination options discussed in the previous section. For each tier, SISP was executed for both open and short circuit terminations. This process was performed from the first to seventh tiers. The results of these cases are shown in Tables 7.4-1 to 7.4.14, with the per unit quantities on a 230 kV and 100 MVA base.

To gain some insight into the significance of each of these harmonic scans, the resistance-reactance, and the magnitude-phase angle of the impedances are plotted for all frequencies from the second to the fiftieth harmonic in Figures 7.4-6 to 7.4-19, for the fourth tier representation with short circuit terminations. The resistance-reactance plots show the magnitude and phase together as the impedances swing clockwise through each resonance circle with increasing frequency. The frequencies at which parallel resonances occur are most easily seen in the magnitude plots. These relative maxima of driving point impedance tend to be most sensitive to the accuracy and precision of system data. This is probably true in actual practice as well, meaning that frequencies of high driving point impedance will generally tend to shift with relatively small changes in system topology and operating conditions.

Since results of the scans of harmonic impedances did not exhibit the expected convergence to a single value for each harmonic, the variation of system harmonic impedances was investigated with a statistical approach. In this study, the mean and standard deviation of the driving point impedances for the fourth to the seventh tier with open and circuit terminations were calculated (Table 7.4-15). Figure 7.4-20 is a resistance-reactance plot of the mean harmonic impedances. The mean impedances can be included in a sector bounded by 6 and 180 ohms, and -33 and 85 degrees, with most of the harmonic impedances being inductive. Figure 7.4-21 is a magnitude-phase angle plot of the mean impedances. The magnitude plot includes two sidebands, representing plus and minus one standard deviation from the mean values. This information is useful for ac filter design.

Table 7.4-1 Short Circuit

Termination - Tier 1

FREQ HERTZ	RESISTANCE PER UNIT	REACTANCE PER UNIT	RESISTANCE OHMS	REACTANCE OHMS	MAGNITUDE OHMS	ANGLE DEGREES
180.000	8.09089E-05	4.20007E-03	0.04280	2.22183	2.22225	88.89641
240.000	9.07934E-05	5.60016E-03	0.04803	2.96248	2.96287	89.07117
300.000	9.95099E-05	7.00031E-03	0.05264	3.70316	3.70354	89.18559
360.000	1.07374E-04	8.40053E-03	0.05680	4.44388	4.44424	89.26770
420.000	1.14632E-04	9.80084E-03	0.06064	5.18465	5.18500	89.32990
480.000	1.21351E-04	1.12013E-02	0.06419	5.92547	5.92581	89.37930
540.000	1.27721E-04	1.26018E-02	0.06756	6.66635	6.66669	89.41932
600.000	1.33703E-04	1.40025E-02	0.07073	7.40730	7.40764	89.45293
660.000	1.39395E-04	1.54033E-02	0.07374	8.14833	8.14867	89.48151
720.000	1.44816E-04	1.68043E-02	0.07661	8.88945	8.88978	89.50625
780.000	1.50056E-04	1.82054E-02	0.07938	9.63066	9.63099	89.52776
840.000	1.55126E-04	1.96068E-02	0.08206	10.37197	10.37230	89.54670
900.000	1.59965E-04	2.10083E-02	0.08462	11.11340	11.11372	89.56374
960.000	1.64653E-04	2.24101E-02	0.08710	11.85494	11.85526	89.57905
1020.000	1.69272E-04	2.38121E-02	0.08954	12.59660	12.59692	89.59271
1080.000	1.73681E-04	2.52144E-02	0.09188	13.33840	13.33872	89.60535
1140.000	1.78032E-04	2.66169E-02	0.09418	14.08034	14.08066	89.61678
1200.000	1.82184E-04	2.80197E-02	0.09638	14.82243	14.82274	89.62747
1260.000	1.86286E-04	2.94228E-02	0.09855	15.56467	15.56498	89.63725
1320.000	1.90343E-04	3.08262E-02	0.10069	16.30708	16.30739	89.64622
1380.000	1.94212E-04	3.22300E-02	0.10274	17.04966	17.04997	89.65475
1440.000	1.98115E-04	3.36341E-02	0.10480	17.79242	17.79273	89.66251
1500.000	2.01835E-04	3.50385E-02	0.10677	18.53538	18.53568	89.66996
1560.000	2.05521E-04	3.64433E-02	0.10872	19.27852	19.27883	89.67689
1620.000	2.09175E-04	3.78485E-02	0.11065	20.02187	20.02218	89.68336
1680.000	2.12707E-04	3.92541E-02	0.11252	20.76543	20.76574	89.68954
1740.000	2.16229E-04	4.06601E-02	0.11439	21.50922	21.50952	89.69531
1800.000	2.19725E-04	4.20666E-02	0.11623	22.25323	22.25353	89.70073
1860.000	2.23122E-04	4.34735E-02	0.11803	22.99748	22.99778	89.70594
1920.000	2.26423E-04	4.48808E-02	0.11978	23.74196	23.74226	89.71095
1980.000	2.29701E-04	4.62887E-02	0.12151	24.48670	24.48701	89.71568
2040.000	2.32957E-04	4.76970E-02	0.12323	25.23170	25.23200	89.72016
2100.000	2.36193E-04	4.91058E-02	0.12495	25.97698	25.97728	89.72442
2160.000	2.39337E-04	5.05152E-02	0.12661	26.72252	26.72282	89.72855
2220.000	2.42463E-04	5.19250E-02	0.12826	27.46835	27.46865	89.73247
2280.000	2.45571E-04	5.33355E-02	0.12991	28.21447	28.21477	89.73620
2340.000	2.48590E-04	5.47465E-02	0.13150	28.96090	28.96120	89.73985
2400.000	2.51666E-04	5.61581E-02	0.13313	29.70762	29.70792	89.74324
2460.000	2.54654E-04	5.75703E-02	0.13471	30.45467	30.45497	89.74656
2520.000	2.57555E-04	5.89831E-02	0.13625	31.20204	31.20233	89.74982
2580.000	2.60515E-04	6.03965E-02	0.13781	31.94974	31.95004	89.75287
2640.000	2.63389E-04	6.18106E-02	0.13933	32.69778	32.69808	89.75585
2700.000	2.66251E-04	6.32253E-02	0.14085	33.44616	33.44646	89.75873
2760.000	2.69101E-04	6.46407E-02	0.14235	34.19492	34.19522	89.76140
2820.000	2.71940E-04	6.60568E-02	0.14386	34.94403	34.94432	89.76413
2880.000	2.74694E-04	6.74736E-02	0.14531	35.69351	35.69381	89.76675
2940.000	2.77438E-04	6.88911E-02	0.14676	36.44338	36.44368	89.76926
3000.000	2.80173E-04	7.03093E-02	0.14821	37.19363	37.19392	89.77169

Table 7.4-2 Short Circuit

Termination - Tier 2

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	1.37050E-04	6.38654E-03	0.07250	3.37848	3.37926	88.77068
180.000	1.55518E-04	9.60387E-03	0.08227	5.08044	5.08111	89.07228
240.000	1.71679E-04	1.28530E-02	0.09082	6.79922	6.79983	89.23474
300.000	1.86804E-04	1.61482E-02	0.09882	8.54238	8.54295	89.33723
360.000	2.01796E-04	1.95082E-02	0.10675	10.31984	10.32039	89.40735
420.000	2.17795E-04	2.29595E-02	0.11521	12.14555	12.14610	89.45651
480.000	2.36591E-04	2.65426E-02	0.12516	14.04104	14.04160	89.48930
540.000	2.62394E-04	3.03277E-02	0.13881	16.04336	16.04396	89.50429
600.000	3.06852E-04	3.44563E-02	0.16232	18.22738	18.22811	89.48977
660.000	4.18019E-04	3.92964E-02	0.22113	20.78782	20.78900	89.39054
720.000	1.00633E-03	4.64488E-02	0.53235	24.57143	24.57720	88.75887
780.000	3.32641E-02	3.54362E-02	17.59673	18.74573	25.71084	46.81086
840.000	2.73730E-03	5.06479E-02	1.44803	26.79275	26.83185	86.90643
900.000	9.15482E-03	3.33075E-02	4.84290	17.61965	18.27309	74.63132
960.000	1.87719E-03	5.42745E-02	0.99304	28.71119	28.72836	88.01910
1020.000	1.12549E-02	8.57562E-02	5.95383	45.36504	45.75407	82.52309
1080.000	4.18014E-03	3.96637E-02	2.21129	20.98210	21.09830	83.98383
1140.000	3.62328E-03	6.26993E-02	1.91671	33.16792	33.22326	86.69267
1200.000	1.33732E-02	3.47186E-02	7.07440	18.36612	19.68150	68.93394
1260.000	1.74837E-03	5.70853E-02	0.92489	30.19815	30.21231	88.24573
1320.000	1.15230E-03	6.60608E-02	0.60956	34.94616	34.95147	89.00070
1380.000	1.13877E-03	7.39011E-02	0.60241	39.09366	39.09830	89.11718
1440.000	1.56037E-03	8.29863E-02	0.82543	43.89975	43.90751	88.92281
1500.000	4.36337E-03	9.85410E-02	2.30822	52.12819	52.17927	87.46461
1560.000	7.97018E-02	5.86207E-02	42.16224	31.01036	52.33829	36.33452
1620.000	4.85853E-03	7.97119E-02	2.57016	42.16759	42.24584	86.51208
1680.000	4.05142E-03	1.00464E-01	2.14320	53.14526	53.18846	87.69067
1740.000	2.63707E-02	1.44637E-01	13.42108	76.51324	77.68140	80.05104
1800.000	1.43218E-02	6.31448E-02	7.57622	33.40361	34.25201	77.22103
1860.000	4.04766E-03	9.64913E-02	2.14121	51.04390	51.08879	87.59794
1920.000	3.67855E-03	1.17112E-01	1.94596	61.95227	61.98283	88.20090
1980.000	6.44971E-03	1.46018E-01	3.41190	77.24371	77.31902	87.47086
2040.000	4.19664E-02	2.42561E-01	22.20024	128.31479	130.22110	80.18421
2100.000	4.21892E-02	-1.73304E-02	22.31811	-9.16781	24.12772	-22.33182
2160.000	7.88625E-03	8.35737E-02	4.17183	44.21051	44.40691	84.60938
2220.000	8.50507E-03	1.27699E-01	4.49918	67.55283	67.70250	86.18959
2280.000	4.71185E-02	2.14900E-01	24.92569	113.68207	116.38257	77.63315
2340.000	6.51743E-02	-2.46910E-03	34.47722	-1.30615	34.50195	-2.16958
2400.000	1.84908E-02	6.28801E-02	9.78161	33.26356	34.67195	73.61330
2460.000	7.13509E-03	1.04183E-01	3.77446	55.11263	55.24173	86.08215
2520.000	7.32443E-03	1.34574E-01	3.87462	71.18974	71.29510	86.88466
2580.000	1.65456E-02	1.80638E-01	8.75264	95.55761	95.95763	84.76658
2640.000	2.91708E-01	1.67556E-01	154.31367	88.63705	177.95851	29.87286
2700.000	2.11905E-02	9.46214E-02	11.20980	50.05470	51.29457	77.37685
2760.000	1.30707E-02	1.56698E-01	6.91438	82.89325	83.18112	85.23182
2820.000	2.19762E-02	2.27364E-01	11.62543	120.27578	120.83631	84.47915
2880.000	1.10032E-01	4.28338E-01	58.20717	226.59058	233.94736	75.59322
2940.000	3.39648E-01	-4.12713E-01	179.67395	-218.32529	282.75195	-50.54684
3000.000	3.24547E-02	-6.63327E-02	17.16853	-35.09000	39.06490	-63.92883

Table 7.4-3 Short Circuit
Termination - Tier 3

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	2.93154E-04	1.12709E-02	0.15508	5.96230	5.96431	88.51009
180.000	3.57392E-04	1.72802E-02	0.18906	9.14124	9.14320	88.81518
240.000	4.57975E-04	2.40153E-02	0.24227	12.70411	12.70642	88.90750
300.000	8.26782E-04	3.31102E-02	0.43737	17.51532	17.52078	88.56959
360.000	3.43789E-02	7.56855E-02	18.18643	40.03761	43.97450	65.57085
420.000	1.74206E-03	3.04411E-02	0.92155	16.10333	16.12968	86.72470
480.000	1.08647E-03	4.27764E-02	0.57474	22.62873	22.63603	88.54507
540.000	1.35632E-03	5.42570E-02	0.71749	28.70196	28.71092	88.56802
600.000	6.78632E-03	7.54717E-02	3.58996	39.92451	40.08558	84.86185
660.000	5.22326E-03	6.44953E-02	2.76311	34.11802	34.22973	85.36991
720.000	5.64306E-03	9.72965E-02	2.98518	51.46983	51.55632	86.68065
780.000	7.17113E-02	2.26060E-01	37.93528	119.58556	125.45832	72.39979
840.000	2.53514E-02	1.12032E-03	13.41088	0.59265	13.42397	2.53036
900.000	1.75034E-02	3.93921E-02	9.25930	20.83843	22.80295	66.04261
960.000	1.19391E-02	9.13359E-02	6.31577	48.31668	48.72771	82.55275
1020.000	2.84696E-02	-1.64411E-02	15.06043	-8.69736	17.39139	-30.00631
1080.000	6.22911E-03	6.55788E-02	3.29520	34.69119	34.84734	84.57395
1140.000	1.29991E-01	3.56900E-02	68.76524	18.88003	71.30998	15.35269
1200.000	5.57241E-03	6.14989E-02	2.94780	32.53290	32.66618	84.82258
1260.000	3.47360E-03	8.63388E-02	1.83754	45.67325	45.71019	87.69611
1320.000	3.61619E-03	1.07481E-01	1.91296	56.85727	56.88945	88.07301
1380.000	4.95753E-03	1.33081E-01	2.62253	70.39987	70.44870	87.86661
1440.000	9.67641E-03	1.74379E-01	5.11882	92.24664	92.38855	86.82388
1500.000	4.63482E-02	2.89579E-01	24.51818	153.18748	155.13719	80.90674
1560.000	2.00005E-01	-1.65677E-01	105.80241	-87.64315	137.38803	-39.63720
1620.000	3.07058E-02	8.49842E-02	16.24338	44.95664	47.80111	70.13461
1680.000	2.95870E-01	1.60995E-01	156.51535	85.16654	178.18639	28.55246
1740.000	3.51122E-02	1.15569E-01	18.57436	61.13601	63.89537	73.10016
1800.000	1.18691E-01	2.46133E-02	62.78738	13.02044	64.12321	11.71557
1860.000	2.08943E-01	3.09781E-01	110.53098	163.87410	197.66591	56.00084
1920.000	6.29808E-02	3.57661E-03	33.31683	1.89203	33.37051	3.25028
1980.000	3.13339E-01	1.91389E-01	165.75639	101.24466	194.23094	31.41675
2040.000	2.15510E-02	4.81495E-04	11.40051	0.25471	11.40335	1.27989
2100.000	1.55798E-02	1.00960E-01	8.24170	53.40793	54.04010	81.22755
2160.000	8.50537E-02	1.80699E-01	44.99340	95.58989	105.64957	64.79401
2220.000	5.35073E-01	-2.09755E-01	283.05377	-110.96027	304.02570	-21.40574
2280.000	3.25789E-02	-1.43808E-02	17.23422	-7.60745	18.83857	-23.81738
2340.000	6.19868E-02	1.00145E-01	32.79101	52.97649	62.30377	58.24362
2400.000	2.69066E-02	1.01274E-01	14.23358	53.57371	55.43228	75.12126
2460.000	4.74493E-02	2.21380E-01	25.10070	117.11009	119.76985	77.90259
2520.000	7.64557E-01	4.79671E-01	404.45050	253.74573	477.45905	32.10350
2580.000	7.04049E-02	-1.48708E-01	37.24420	-78.66657	87.03769	-64.66508
2640.000	4.42651E-02	3.19970E-02	23.41623	16.92640	28.89329	35.86125
2700.000	1.54623E-01	-5.72947E-02	01.79582	-30.30892	87.23065	-20.33186
2760.000	6.75791E-02	-1.17495E-01	35.74936	-62.15495	71.70254	-60.09399
2820.000	1.62872E-02	-1.13711E-02	8.61591	-6.01533	10.50800	-34.92141
2880.000	2.48551E-02	5.02326E-02	13.14832	26.57303	29.64801	63.67382
2940.000	7.98116E-02	-4.36433E-02	42.22036	-23.08731	48.12051	-28.67111
3000.000	1.34800E-02	3.79913E-02	7.13094	20.09739	21.32500	70.46434

Table 7.4-4 Short Circuit

Termination - Tier 4

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	4.01046E-04	8.23505E-03	0.21215	4.35634	4.36150	87.21191
180.000	3.76948E-04	1.69451E-02	0.19941	8.96395	8.96617	88.72565
240.000	5.08343E-04	2.47032E-02	0.26891	13.06800	13.07077	88.82114
300.000	1.27020E-03	3.64267E-02	0.67193	19.26972	19.28144	88.00291
360.000	1.71138E-02	-8.21002E-04	9.05319	-0.43431	9.06360	-2.74655
420.000	1.56405E-03	3.44485E-02	0.82738	18.22325	18.24203	87.40041
480.000	4.33002E-03	3.91903E-02	2.29058	20.73168	20.85784	83.69514
540.000	1.39713E-03	5.36639E-02	0.73908	28.38819	28.39781	88.50866
600.000	2.00957E-03	6.90552E-02	1.06306	36.53020	36.54567	88.33311
660.000	6.82896E-03	1.01074E-01	3.61252	53.46813	53.59003	86.13474
720.000	9.08291E-02	-3.78379E-02	48.04862	-20.01624	52.05113	-22.61578
780.000	1.75725E-02	8.58563E-02	9.29585	45.41796	46.35951	78.43284
840.000	3.13837E-02	6.10103E-02	16.59142	32.27444	36.28932	62.79354
900.000	3.06225E-02	6.69667E-02	16.19930	35.42539	38.95351	65.42637
960.000	1.49059E-01	-6.23083E-02	78.85217	-32.96110	85.46402	-22.68548
1020.000	5.18018E-03	4.42393E-02	2.74032	23.40261	23.56250	83.32140
1080.000	1.66200E-02	8.85387E-02	8.79200	46.83699	47.65504	79.36846
1140.000	4.84447E-03	7.00420E-02	2.56272	37.05224	37.14075	86.04343
1200.000	3.38052E-03	9.37109E-02	1.78829	49.57306	49.60530	87.93401
1260.000	5.76141E-03	1.14608E-01	3.04779	60.62750	60.70406	87.12213
1320.000	9.44309E-03	1.53105E-01	4.99539	80.99268	81.14658	86.47064
1380.000	3.93859E-02	1.29452E-01	20.83513	68.48025	71.57966	73.07761
1440.000	3.80522E-02	2.40896E-01	20.12962	127.43397	129.01402	81.02366
1500.000	9.34554E-01	-2.29757E-01	494.37900	-121.54148	509.10016	-13.81206
1560.000	3.18129E-02	-2.75932E-02	16.82901	-14.59681	22.27740	-40.93705
1620.000	4.63321E-02	6.16987E-02	24.50968	32.63861	40.81671	53.09561
1680.000	1.84891E-02	9.72827E-02	9.78073	51.46254	52.38374	79.23898
1740.000	9.63135E-02	1.84328E-01	50.94983	97.50944	110.01807	62.41240
1800.000	2.40872E-02	8.59616E-02	12.74214	45.47366	47.22516	74.34664
1860.000	4.17346E-02	1.45060E-01	22.07758	76.73659	79.84937	73.94916
1920.000	4.03814E-02	2.22853E-01	21.36176	117.88905	119.80882	79.72932
1980.000	3.53684E-01	6.23294E-01	187.09879	329.72244	379.10794	60.42755
2040.000	7.06582E-02	-1.81288E-01	37.37819	-95.90121	102.92798	-68.70629
2100.000	2.03364E-02	2.11851E-02	10.75798	11.20694	15.53478	46.17095
2160.000	1.02886E-01	1.03761E-01	54.42695	54.88969	77.29922	45.24253
2220.000	2.32161E-01	-1.12003E-01	122.81318	-59.24978	136.35840	-25.75444
2280.000	8.41979E-02	1.59592E-01	44.54071	84.42410	95.45315	62.18465
2340.000	6.18245E-02	-3.85292E-02	32.70514	-20.38194	38.53633	-31.93128
2400.000	5.36208E-02	1.00972E-01	28.36538	53.41404	60.47855	62.02959
2460.000	6.02529E-02	4.58207E-02	31.87377	24.23913	40.04338	37.25200
2520.000	1.57460E-01	2.34161E-01	83.29624	123.87106	149.27258	56.08141
2580.000	9.30863E-02	-5.41118E-02	49.24263	-28.62513	56.95818	-30.16977
2640.000	2.06607E-01	2.51803E-02	109.29511	13.32040	110.10383	6.94868
2700.000	5.07351E-02	6.16353E-02	26.83889	32.60506	42.23051	50.54046
2760.000	2.20722E-01	2.44857E-01	116.76202	129.52959	174.38831	47.96751
2820.000	8.06507E-02	-8.87679E-02	42.66423	-46.95821	63.44534	-47.74305
2880.000	9.35072E-02	3.00331E-02	49.46530	15.88749	51.95410	17.80622
2940.000	2.38385E-02	-4.99773E-02	12.61055	-26.43801	29.29154	-64.49954
3000.000	1.16690E-02	7.68279E-03	6.17290	4.06420	7.39069	33.36066

Table 7.4-5 Short Circuit
Termination - Tier 5

FREQ HERTZ	RESISTANCE PER UNIT	REACTANCE PER UNIT	RESISTANCE OHMS	REACTANCE OHMS	MAGNITUDE OHMS	ANGLE DEGREES
120.000	3.76947E-04	1.40958E-02	0.19940	7.45666	7.45932	88.46818
180.000	5.12696E-04	2.25191E-02	0.27122	11.91260	11.91569	88.69576
240.000	1.10104E-03	3.48897E-02	0.58245	18.45665	18.46584	88.19247
300.000	3.85769E-03	5.47147E-02	2.04072	28.94405	29.01591	85.96700
360.000	9.15558E-03	-3.25295E-03	4.84330	-1.72081	5.13992	-19.55999
420.000	4.02342E-03	4.17316E-02	2.12839	22.07604	22.17841	84.49305
480.000	9.91594E-03	6.50641E-02	5.24553	34.41890	34.81633	81.33465
540.000	4.45190E-03	3.71188E-02	2.35506	19.63587	19.77659	83.16082
600.000	7.29355E-03	6.11012E-02	3.85829	32.32253	32.55200	83.19292
660.000	7.06238E-02	3.42743E-02	37.36000	18.13112	41.52718	25.88768
720.000	7.62512E-03	5.45822E-02	4.03369	28.87399	29.15438	82.04726
780.000	2.21017E-02	7.71136E-02	11.69182	40.79310	42.43555	74.00702
840.000	3.63758E-02	8.07143E-02	19.24282	42.69784	46.83366	65.74014
900.000	3.07185E-02	6.45403E-02	16.25008	34.14184	37.81177	64.54752
960.000	1.32610E-01	2.31749E-03	70.15072	1.22595	70.16143	1.00120
1020.000	8.70278E-03	5.04186E-02	4.60377	26.67145	27.06586	80.20665
1080.000	2.00620E-02	8.63991E-02	10.61278	45.70515	46.92112	76.92754
1140.000	1.92350E-02	5.77173E-02	10.17529	30.53246	32.18335	71.56876
1200.000	1.34577E-02	6.94299E-02	7.11914	36.72842	37.41202	79.03027
1260.000	4.23942E-02	5.70020E-02	22.42652	30.15406	37.57946	53.36066
1320.000	5.01906E-02	1.18158E-01	26.55083	62.50565	67.91100	66.98544
1380.000	3.97500E-02	8.26673E-02	21.02773	43.73102	48.52388	64.31978
1440.000	3.55709E-02	1.26730E-01	18.81701	67.04043	69.63116	74.32156
1500.000	4.88074E-01	2.94801E-01	258.19125	155.94995	301.63409	31.13237
1560.000	1.10070E-01	1.00767E-01	58.22697	53.30581	78.94231	42.47358
1620.000	2.83055E-02	6.21523E-02	14.97361	32.87856	36.12767	65.51447
1680.000	6.07330E-02	1.34001E-01	32.12778	70.88670	77.82749	65.61868
1740.000	1.02506E-01	1.17952E-01	54.22574	62.39662	82.66662	49.00775
1800.000	8.70305E-02	7.36504E-02	46.03912	38.96106	60.31223	40.23990
1860.000	5.64147E-02	1.48738E-01	29.84340	78.68256	84.15208	69.22884
1920.000	1.11615E-01	3.27933E-01	59.04425	173.47641	183.24925	71.20354
1980.000	1.25385E-01	-1.99403E-01	66.32860	-105.48409	124.60488	-57.83825
2040.000	7.56737E-02	2.24919E-02	40.03137	11.89822	41.76216	16.55314
2100.000	1.85622E-02	2.40302E-02	9.81942	12.71196	16.06284	52.31553
2160.000	3.73383E-02	9.28849E-02	19.75194	49.13613	52.95751	68.10066
2220.000	9.69526E-02	1.85957E-01	51.28791	98.37151	110.93874	62.46384
2280.000	2.00852E-01	9.09830E-02	106.25044	48.13002	116.64328	24.36989
2340.000	5.16928E-02	-2.15401E-02	27.34549	-11.39470	29.62457	-22.62120
2400.000	2.70624E-02	8.79303E-02	14.31601	46.51512	48.66831	72.89315
2460.000	1.34578E-01	2.57439E-01	71.19202	136.18527	153.67085	62.40130
2520.000	9.08960E-02	-4.11261E-02	48.08401	-21.75568	52.77671	-24.34445
2580.000	2.26145E-01	1.89364E-01	119.63074	100.17342	156.03279	39.94130
2640.000	5.53131E-02	1.34336E-02	29.26061	7.10639	30.11120	13.65087
2700.000	6.11757E-02	7.00071E-02	32.36197	37.03378	49.18127	48.85142
2760.000	1.07252E-01	9.74879E-02	56.73651	51.57111	76.67210	42.26953
2820.000	1.70560E-01	-1.20149E-01	90.22612	-63.55862	110.36509	-35.16228
2880.000	3.75921E-02	2.74979E-02	19.88624	14.54638	24.63858	36.18472
2940.000	8.96507E-02	-2.74645E-02	47.42524	-14.52873	49.60078	-17.03246
3000.000	1.96725E-02	1.68075E-02	10.40674	8.89117	13.68770	40.50945

Table 7.4-6 Short Circuit
Termination - Tier 6

FREQ HERTZ	RESISTANCE PER UNIT	REACTANCE PER UNIT	RESISTANCE OHMS	REACTANCE OHMS	MAGNITUDE OHMS	ANGLE DEGREES
120.000	4.07836E-04	1.54936E-02	0.21575	8.19612	8.19896	88.49216
180.000	6.91962E-04	2.64351E-02	0.36605	13.98415	13.98894	88.50058
240.000	8.14286E-03	7.02577E-02	4.30757	37.16635	37.41514	83.38892
300.000	2.09028E-03	2.30594E-02	1.10576	12.19844	12.24846	84.82044
360.000	1.10589E-02	6.43463E-03	5.85016	3.40392	6.76839	30.19301
420.000	5.15552E-03	3.68476E-02	2.72727	19.49239	19.68226	82.03519
480.000	3.02047E-02	7.93233E-02	15.97831	41.96203	44.90121	69.15416
540.000	1.73067E-02	6.54617E-02	9.15523	34.62925	35.81903	75.19106
600.000	8.13579E-03	6.00210E-02	4.30383	31.75113	32.04149	82.28067
660.000	2.48192E-02	2.05847E-02	13.12936	10.88929	17.05745	39.61178
720.000	1.20472E-02	8.52094E-02	6.37297	45.07578	45.52407	81.95266
780.000	4.60374E-02	5.40907E-02	24.35378	28.61399	37.57482	49.59841
840.000	1.29190E-01	3.26778E-02	68.34148	17.28657	70.49386	14.19489
900.000	2.38335E-02	5.63689E-02	12.60793	29.81915	32.37501	67.08071
960.000	1.02981E-01	-2.23434E-02	54.47690	-11.81967	55.74439	-12.24154
1020.000	4.34328E-02	8.79716E-02	22.97595	46.53699	51.89977	63.72382
1080.000	4.53092E-02	5.80010E-02	23.96858	30.68250	38.93468	52.00373
1140.000	1.44428E-02	5.74795E-02	7.64027	30.40665	31.35184	75.89532
1200.000	1.18857E-02	8.47494E-02	6.28753	44.83243	45.27118	82.01662
1260.000	4.42504E-02	7.54120E-02	23.40844	39.89296	46.25368	59.59639
1320.000	3.21954E-02	5.75834E-02	17.03139	30.46161	34.89954	60.79002
1380.000	1.17911E-02	1.32661E-01	6.23747	70.17760	70.45425	84.92083
1440.000	5.92774E-02	2.09635E-01	31.35774	110.89713	115.24531	74.21100
1500.000	2.43436E-01	1.37517E-01	128.77750	72.74640	147.90430	29.46210
1560.000	8.76606E-02	-1.24813E-02	46.37247	-6.60260	46.84016	-8.10342
1620.000	2.02495E-02	6.68594E-02	10.71198	35.36864	36.95521	73.15019
1680.000	4.92584E-02	1.48086E-01	26.05771	78.33772	82.55788	71.60117
1740.000	1.76128E-01	1.89145E-01	93.17184	100.05744	136.72046	47.04084
1800.000	1.62698E-01	1.02644E-01	86.06725	54.29892	101.76415	32.24739
1860.000	8.11857E-02	1.19507E-01	42.94726	63.21912	76.42725	55.81018
1920.000	1.64060E-01	2.49073E-01	86.78778	131.75972	157.77434	56.62782
1980.000	3.20697E-01	7.29067E-02	169.64874	38.56767	173.97748	12.80784
2040.000	1.30275E-01	-1.03397E-01	68.91555	-54.69676	87.98346	-38.43826
2100.000	1.91929E-02	2.71860E-02	10.15302	14.38138	17.60420	54.77853
2160.000	4.04283E-02	9.27846E-02	21.38658	49.08304	53.53999	66.45616
2220.000	4.71778E-02	1.97959E-01	24.95708	104.72011	107.65295	76.59522
2280.000	3.92757E-01	-3.33177E-02	207.76852	-17.62504	208.51477	-4.84880
2340.000	8.73685E-02	1.27200E-02	46.21796	6.72888	46.10522	8.28351
2400.000	6.00257E-02	9.81889E-02	31.75362	51.94191	60.87901	58.56133
2460.000	2.67358E-01	4.91515E-02	141.43260	26.00112	143.80278	10.41700
2520.000	6.36285E-02	9.99420E-02	33.65950	52.86932	62.67477	57.51694
2580.000	1.24450E-01	-5.99591E-02	65.83398	-31.71836	73.07645	-25.72445
2640.000	3.12760E-02	3.78107E-02	16.54499	20.00186	25.95787	50.40338
2700.000	7.25745E-02	7.93844E-02	38.39190	41.99437	56.89873	47.56597
2760.000	1.36100E-01	1.20090E-01	71.99691	63.52759	96.01723	41.42407
2820.000	8.99478E-02	-6.07075E-02	47.58237	-32.11427	57.40565	-34.01618
2880.000	1.19147E-01	7.94445E-02	63.02885	42.02612	75.75507	33.69440
2940.000	1.17387E-01	-8.77327E-03	62.09768	-4.64106	62.27087	-4.27423
3000.000	4.79703E-02	4.00798E-02	25.37631	21.20220	33.06797	39.87916

Table 7.4-7 Short Circuit
Termination - Tier 7

FREQ HERTZ	RESISTANCE PER UNIT	REACTANCE PER UNIT	RESISTANCE OHMS	REACTANCE OHMS	MAGNITUDE OHMS	ANGLE DEGREES
120.000	4.23558E-04	1.63152E-02	0.22406	8.63075	8.63366	88.51289
180.000	1.30909E-03	3.25649E-02	0.69251	17.22681	17.24073	87.69799
240.000	2.31963E-03	1.24176E-02	1.22708	6.56890	6.68253	79.41900
300.000	1.71214E-02	3.77770E-02	9.05720	19.98404	21.94071	65.61895
360.000	1.34004E-02	4.30689E-03	7.08882	2.27834	7.44595	17.81739
420.000	2.40025E-03	3.89284E-02	1.26973	20.59310	20.63220	86.47173
480.000	3.01708E-02	8.31922E-02	15.96038	44.00866	46.81342	70.06609
540.000	4.19940E-03	3.14204E-02	2.22148	16.62141	16.76921	82.38742
600.000	1.14710E-02	6.53182E-02	6.06814	34.55335	35.08214	80.03948
660.000	2.15341E-02	4.97653E-02	11.39154	26.32585	28.68480	66.60123
720.000	2.72451E-02	1.02520E-01	14.41265	54.23331	56.11573	75.11749
780.000	2.41058E-02	6.14395E-02	12.75197	32.50152	34.91363	68.57745
840.000	5.95943E-02	1.02287E-01	31.52540	54.10978	62.62363	59.77411
900.000	4.38062E-02	5.55812E-02	23.17346	29.40245	37.43679	51.75669
960.000	1.13590E-01	-4.53536E-02	60.08902	-23.99204	64.70169	-21.76559
1020.000	4.32096E-02	3.42114E-02	22.85786	18.09784	29.15499	38.37063
1080.000	4.92046E-02	9.59796E-02	26.02925	50.77319	57.05645	62.85773
1140.000	1.02089E-02	6.42800E-02	5.40052	34.00415	34.43033	80.97569
1200.000	6.37556E-03	8.66379E-02	3.37267	45.83145	45.95538	85.79128
1260.000	3.52339E-02	1.31486E-01	18.63872	69.55619	72.01017	74.99908
1320.000	1.65756E-02	8.29098E-02	8.76847	43.85926	44.72718	78.69433
1380.000	1.21476E-02	1.33671E-01	6.42609	70.71214	71.00353	84.80741
1440.000	7.88483E-02	2.63991E-01	41.71076	139.65103	145.74704	73.37025
1500.000	8.23225E-02	1.76881E-01	43.54861	93.57002	103.20771	65.04217
1560.000	1.28919E-01	-2.30302E-02	68.19801	-12.18297	69.27765	-10.12854
1620.000	2.11249E-02	6.98871E-02	11.17508	36.97030	38.62234	73.18141
1680.000	4.77218E-02	1.39744E-01	25.24482	73.92459	78.11624	71.14526
1740.000	1.40029E-01	2.19128E-01	74.07559	115.91888	137.56592	57.42023
1800.000	9.84036E-02	7.40394E-02	52.05552	39.16685	65.14460	36.95800
1860.000	6.46131E-02	1.40568E-01	34.18034	74.36040	81.83987	65.31376
1920.000	2.13462E-01	1.39109E-01	112.92157	73.58862	134.78342	33.09144
1980.000	2.14473E-01	2.27654E-01	113.45646	120.42921	165.45563	46.70764
2040.000	1.17553E-01	-4.87238E-03	62.18542	-2.57749	62.23882	-2.37346
2100.000	1.85895E-02	2.59528E-02	9.83385	13.72902	16.88759	54.38664
2160.000	3.59225E-02	9.06104E-02	19.00303	47.93292	51.56239	68.37413
2220.000	4.88489E-02	1.89868E-01	25.84106	100.44010	103.71102	75.57195
2280.000	2.84019E-01	3.51522E-02	150.24609	18.59551	151.39247	7.05545
2340.000	9.13676E-02	-8.50671E-03	48.33344	-4.50005	48.54248	-5.31914
2400.000	4.22610E-02	9.91883E-02	22.35606	52.47062	57.03471	66.92269
2460.000	3.12409E-01	9.44177E-02	165.26427	49.94695	172.64699	16.81612
2520.000	7.44957E-02	9.80295E-02	39.40825	51.85760	65.13233	52.76764
2580.000	1.09293E-01	-7.52031E-02	57.81576	-39.78244	70.18051	-34.53147
2640.000	5.49301E-02	4.76093E-02	29.05801	25.18530	38.45345	40.91629
2700.000	4.90501E-02	7.17015E-02	25.94751	37.93007	45.95610	55.62444
2760.000	1.81166E-01	1.16149E-01	95.83678	61.44268	113.84152	32.66467
2820.000	8.91199E-02	-2.14081E-02	47.14441	-11.32488	48.48555	-13.50748
2880.000	9.54324E-02	5.46039E-02	50.48375	28.88547	58.16338	29.77706
2940.000	6.03773E-02	-3.88965E-02	31.93961	-20.57627	37.99371	-32.79062
3000.000	3.50996E-02	4.30997E-02	18.56767	22.79973	29.40384	50.84127

Table 7.4-8 Open Circuit
Termination - Tier 1

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
180.000	0.00000E+00	-9.52558E+01	0.00000	-50390.32422	50390.32422	-90.00000
240.000	0.00000E+00	-7.13123E+01	0.00000	-37724.20313	37724.20313	-90.00000
300.000	0.00000E+00	-5.71867E+01	0.00000	-30251.78320	30251.78320	-90.00000
360.000	-2.70416E-04	-4.76279E+01	-0.14305	-25195.16211	25195.16211	-90.00033
420.000	0.00000E+00	-4.08197E+01	0.00000	-21593.61328	21593.61328	-90.00000
480.000	-4.55913E-04	-3.57047E+01	-0.24118	-18887.79297	18887.79297	-90.00073
540.000	-1.80190E-04	-3.17442E+01	-0.09532	-16792.70508	16792.70508	-90.00033
600.000	1.46004E-04	-2.85747E+01	0.07724	-15115.99902	15115.99902	-89.99971
660.000	-8.04013E-05	-2.59703E+01	-0.04253	-13738.27734	13738.27734	-90.00018
720.000	3.37775E-05	-2.38053E+01	0.01787	-12593.00586	12593.00586	-89.99992
780.000	0.00000E+00	-2.19717E+01	0.00000	-11623.01367	11623.01367	-90.00000
840.000	-3.72145E-05	-2.04019E+01	-0.01969	-10792.60449	10792.60449	-90.00011
900.000	2.16113E-05	-1.90415E+01	0.01143	-10072.94043	10072.94043	-89.99994
960.000	3.79824E-05	-1.78499E+01	0.02009	-9442.61133	9442.61133	-89.99988
1020.000	7.56911E-05	-1.67967E+01	0.04004	-8886.52148	8886.52148	-89.99974
1080.000	5.25046E-05	-1.58644E+01	0.02777	-8392.28809	8392.28809	-89.99981
1140.000	8.75347E-05	-1.50312E+01	0.04631	-7951.50098	7951.50098	-89.99967
1200.000	6.07554E-05	-1.42780E+01	0.03214	-7553.06006	7553.06006	-89.99976
1260.000	4.95911E-05	-1.35974E+01	0.02623	-7193.01709	7193.01709	-89.99979
1320.000	7.52942E-05	-1.29781E+01	0.03983	-6865.39746	6865.39746	-89.99967
1380.000	5.28107E-05	-1.24133E+01	0.02794	-6566.63379	6566.63379	-89.99976
1440.000	5.48237E-05	-1.18956E+01	0.02900	-6292.78809	6292.78809	-89.99974
1500.000	6.02194E-05	-1.14177E+01	0.03186	-6039.94775	6039.94775	-89.99970
1560.000	8.79998E-05	-1.09782E+01	0.04655	-5807.49121	5807.49121	-89.99954
1620.000	6.82650E-05	-1.05705E+01	0.03611	-5591.81299	5591.81299	-89.99963
1680.000	6.81073E-05	-1.01920E+01	0.03603	-5391.58203	5391.58203	-89.99962
1740.000	7.35788E-05	-9.83969E+00	0.03892	-5205.19434	5205.19434	-89.99957
1800.000	8.49156E-05	-9.51072E+00	0.04492	-5031.17139	5031.17139	-89.99949
1860.000	6.81541E-05	-9.20320E+00	0.03605	-4868.49414	4868.49414	-89.99958
1920.000	9.23682E-05	-8.91464E+00	0.04886	-4715.84619	4715.84619	-89.99941
1980.000	8.68374E-05	-8.64363E+00	0.04594	-4572.48047	4572.48047	-89.99943
2040.000	8.86018E-05	-8.38847E+00	0.04687	-4437.50244	4437.50244	-89.99940
2100.000	6.82621E-05	-8.14808E+00	0.03611	-4310.33252	4310.33252	-89.99953
2160.000	7.80683E-05	-7.92107E+00	0.04130	-4190.24854	4190.24854	-89.99944
2220.000	9.06998E-05	-7.70604E+00	0.04798	-4076.49414	4076.49414	-89.99933
2280.000	8.34550E-05	-7.50248E+00	0.04415	-3968.80957	3968.80957	-89.99937
2340.000	7.96061E-05	-7.30909E+00	0.04211	-3866.50610	3866.50610	-89.99938
2400.000	7.86860E-05	-7.12561E+00	0.04162	-3769.44653	3769.44653	-89.99937
2460.000	8.02730E-05	-6.95084E+00	0.04246	-3676.99463	3676.99463	-89.99934
2520.000	8.47106E-05	-6.78462E+00	0.04481	-3589.06177	3589.06177	-89.99928
2580.000	8.99525E-05	-6.62591E+00	0.04758	-3505.10376	3505.10376	-89.99922
2640.000	8.02635E-05	-6.47437E+00	0.04246	-3424.94165	3424.94165	-89.99929
2700.000	8.89594E-05	-6.32984E+00	0.04706	-3348.48535	3348.48535	-89.99920
2760.000	8.33912E-05	-6.19118E+00	0.04411	-3275.13647	3275.13647	-89.99923
2820.000	9.46242E-05	-6.05854E+00	0.05006	-3204.96826	3204.96826	-89.99911
2880.000	9.27987E-05	-5.93163E+00	0.04909	-3137.03276	3137.03276	-89.99911
2940.000	9.17860E-05	-5.80961E+00	0.04855	-3073.28223	3073.28223	-89.99909
3000.000	9.27143E-05	-5.69263E+00	0.04905	-3011.39917	3011.39917	-89.99907

Table 7.4-9 Open Circuit
Termination - Tier 2

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	1.24012E-03	-3.57436E-01	0.65603	-189.08374	189.08488	-89.80122
180.000	1.55210E-03	-2.19596E-01	0.82106	-116.16630	116.16920	-89.59505
240.000	1.95498E-03	-1.43515E-01	1.03419	-75.91950	75.92654	-89.21956
300.000	2.64911E-03	-8.99169E-02	1.40138	-47.56602	47.58666	-88.31245
360.000	4.94703E-03	-4.07899E-02	2.61698	-21.57785	21.73596	-83.08489
420.000	4.03179E-02	-5.83305E-02	21.32818	-30.85684	37.51048	-55.34786
480.000	1.80344E-01	-9.99366E-02	95.40203	-52.86644	109.07066	-28.99275
540.000	8.90472E-03	2.46038E-02	4.71060	13.01543	13.84164	70.10359
600.000	1.31739E-02	1.59448E-02	6.96898	8.43482	10.94134	50.43596
660.000	8.72769E-03	8.75908E-02	4.61695	46.33551	46.56496	84.30974
720.000	1.45884E-02	1.70475E-01	7.71727	90.18139	90.51099	85.10883
780.000	4.03683E-02	3.46058E-01	21.35481	183.06468	184.30603	83.34642
840.000	5.65466E-01	1.33216E+00	299.13174	704.71021	765.56921	67.00000
900.000	1.34855E-01	-7.14356E-01	71.33823	-377.89417	384.56879	-79.30961
960.000	2.39895E-02	-2.89845E-01	12.69044	-153.32779	153.85205	-85.26860
1020.000	1.09402E-02	-1.66616E-01	5.78735	-88.13988	88.32967	-86.24330
1080.000	8.00860E-03	-9.94328E-02	4.23655	-52.59995	52.77029	-85.39518
1140.000	1.04977E-02	-4.31327E-02	5.55329	-22.81719	23.48325	-76.32121
1200.000	9.16331E-02	7.70504E-02	48.47392	40.75964	63.33299	40.05904
1260.000	1.95251E-02	-8.72839E-02	10.32880	-46.17317	47.31433	-77.39069
1320.000	1.30916E-02	-1.11168E-02	6.92545	-5.88078	9.08545	-40.33639
1380.000	1.94282E-01	-1.12617E-01	102.77533	-59.57463	118.79354	-30.09910
1440.000	8.62434E-03	-3.88797E-02	4.56228	-20.56738	21.06730	-77.49310
1500.000	4.99881E-03	-1.23185E-03	2.64437	-0.65165	2.72348	-13.84354
1560.000	6.74572E-03	2.93160E-02	3.56849	15.50815	15.91341	77.04158
1620.000	7.59289E-03	5.75772E-02	4.01664	30.45833	30.72203	82.43757
1680.000	3.28338E-02	1.39992E-01	17.36908	74.05575	76.06536	76.80040
1740.000	8.69804E-02	-1.07860E-01	46.01265	-57.05817	73.29939	-51.11672
1800.000	2.26439E-02	4.03737E-02	11.97862	21.35767	24.48750	60.71377
1860.000	1.02909E-01	-8.08603E-02	54.43880	-42.77510	69.23361	-38.15837
1920.000	9.64648E-03	1.44525E-02	5.10299	7.64535	9.19195	56.27836
1980.000	5.97803E-03	4.95125E-02	3.16238	26.19210	26.38232	83.11556
2040.000	5.90422E-03	7.66934E-02	3.12333	40.57080	40.69085	85.59779
2100.000	8.31015E-03	1.07617E-01	4.39607	56.92945	57.09893	85.58441
2160.000	2.82103E-02	1.67957E-01	14.92323	88.84904	90.09359	80.46550
2220.000	6.76434E-02	1.77325E-02	35.78333	9.38047	36.99244	14.68935
2280.000	1.35363E-02	1.14429E-01	7.16070	60.53279	60.95485	83.25357
2340.000	1.44962E-02	1.72268E-01	7.66851	91.12965	91.45174	85.18993
2400.000	2.83668E-02	2.58830E-01	15.00606	136.92082	137.74068	83.74554
2460.000	1.43317E-01	5.22622E-01	75.81485	276.46729	286.67410	74.66492
2520.000	3.72935E-01	-5.58228E-01	197.28262	-295.30261	355.13953	-56.25433
2580.000	3.40002E-02	-9.37730E-02	17.98611	-49.60590	52.76595	-70.07037
2640.000	1.58726E-02	2.86799E-02	8.39659	15.17168	17.34020	61.03818
2700.000	4.27489E-02	1.35733E-01	22.61416	71.80300	75.27995	72.51833
2760.000	3.77254E-02	7.91891E-02	19.95672	41.89101	46.40181	64.52705
2820.000	3.76164E-02	1.92882E-01	19.89907	102.03457	103.95685	78.96454
2880.000	3.94004E-01	4.53314E-01	208.42790	239.80287	317.72253	49.00402
2940.000	7.33692E-02	-8.26912E-02	38.81233	-43.74363	58.47993	-48.41837
3000.000	2.86372E-02	7.10969E-02	15.14910	37.61025	40.54659	68.06083

Table 7.4-10 Open Circuit

Termination - Tier 3

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	2.18203E-02	1.69321E-01	11.54294	89.57055	90.31126	82.65678
180.000	4.02839E-01	1.89834E-01	213.10185	100.42233	235.57809	25.23174
240.000	7.31905E-03	1.17381E-02	3.87178	6.20945	7.31765	58.05524
300.000	7.12579E-03	1.35953E-03	3.76954	0.71919	3.83754	10.80169
360.000	1.02157E-01	4.10475E-02	54.04115	21.71414	58.24045	21.89063
420.000	5.20626E-03	4.79919E-02	2.75411	25.38773	25.53668	83.80865
480.000	4.29664E-02	1.36796E-01	22.72923	72.36511	75.85069	72.56297
540.000	9.46851E-03	6.52992E-02	5.00884	34.54329	34.90454	81.74951
600.000	7.95619E-02	9.85134E-02	42.08824	52.11358	66.98690	51.07478
660.000	3.70129E-02	2.50610E-01	19.57981	132.57245	134.01054	81.59865
720.000	4.56524E-01	-7.14569E-01	241.50134	-378.00714	448.56696	-57.42629
780.000	2.16687E-02	-9.77568E-02	11.46273	-51.71334	52.96851	-77.50195
840.000	2.97570E-02	3.73922E-02	15.74143	19.78046	25.27962	51.48698
900.000	6.47313E-02	-1.12917E-01	34.24285	-59.73295	68.85201	-60.17584
960.000	6.16600E-02	8.16227E-02	32.61816	43.17841	54.11395	52.93161
1020.000	7.94941E-02	-2.40482E-01	42.05241	-127.21499	133.98529	-71.70809
1080.000	6.79935E-03	-7.14544E-02	3.59685	-37.79940	37.97015	-84.56432
1140.000	3.18423E-03	-2.96785E-02	1.68446	-15.69994	15.79004	-83.87612
1200.000	3.27164E-03	-3.14113E-03	1.73070	-1.66166	2.39925	-43.83409
1260.000	1.97603E-02	4.08405E-02	10.45321	21.60463	24.00062	64.18040
1320.000	4.66957E-03	-1.00911E-02	2.47020	-5.33820	5.88203	-65.16813
1380.000	6.22828E-03	1.42228E-02	3.29476	7.52385	8.21364	66.35098
1440.000	6.97131E-04	2.45887E-02	0.36878	13.00745	13.01268	88.37601
1500.000	5.99373E-04	3.63507E-02	0.31707	19.22951	19.23213	89.05536
1560.000	1.40320E-03	4.83865E-02	0.74229	25.59644	25.60720	88.33891
1620.000	2.35078E-03	5.24709E-02	1.24356	27.75713	27.78497	87.43478
1680.000	1.43356E-03	6.49724E-02	0.75835	34.37041	34.37878	88.73603
1740.000	2.88779E-03	8.05750E-02	1.52764	42.62415	42.65152	87.94742
1800.000	5.68510E-02	6.72340E-02	30.07416	35.56680	46.57737	49.78320
1860.000	4.17597E-03	8.13024E-02	2.20909	43.00898	43.06568	87.05968
1920.000	3.43969E-03	1.02489E-01	1.81959	54.21643	54.24696	88.07778
1980.000	6.44244E-03	1.32319E-01	3.40805	69.99683	70.07975	87.21255
2040.000	5.77230E-02	2.38990E-01	30.53548	126.42595	130.06128	76.42149
2100.000	3.10565E-02	3.60624E-02	16.42890	19.07700	25.17619	49.26534
2160.000	3.67227E-02	9.77337E-02	19.42632	51.70113	55.23032	69.40667
2220.000	1.39290E-02	1.15658E-01	7.36846	61.18296	61.62506	83.13276
2280.000	4.33118E-02	2.05242E-01	22.91192	108.57303	110.96422	78.08384
2340.000	1.08041E-01	-4.67052E-02	57.15360	-24.70705	62.26541	-23.37842
2400.000	4.14896E-02	9.31408E-02	21.94798	49.27147	53.93877	65.98943
2460.000	2.04674E-02	6.77087E-02	10.82725	35.81789	37.41859	73.18066
2520.000	1.20736E-02	1.19084E-01	6.38691	62.99558	63.31853	84.21075
2580.000	4.31485E-02	1.92019E-01	22.82555	101.57805	104.11102	77.33546
2640.000	4.45540E-02	6.36585E-02	23.56909	33.67535	41.10391	55.01216
2700.000	1.76776E-02	1.46808E-01	9.35146	77.66141	78.22240	83.13390
2760.000	5.50509E-02	2.47191E-01	29.12193	130.76428	133.96785	77.44481
2820.000	1.11551E-01	1.94578E-02	59.01040	10.29320	59.90139	9.89457
2880.000	3.81709E-02	1.74714E-01	20.19243	92.42387	94.60394	77.61588
2940.000	2.78585E-01	2.83181E-01	147.37160	149.80261	210.14093	45.46870
3000.000	5.30982E-01	2.40484E-01	280.88937	127.21608	308.35492	24.36599

Table 7.4-11 Open Circuit
Termination - Tier 4

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	1.06356E-03	6.90289E-04	0.56262	0.36516	0.67074	32.98499
180.000	9.17432E-03	4.08289E-02	4.85321	21.59851	22.13705	77.33591
240.000	2.17257E-03	1.97172E-02	1.14929	10.43042	10.49355	83.71214
300.000	4.80769E-03	4.04034E-02	2.54327	21.37338	21.52416	83.21415
360.000	2.84942E-03	1.98197E-02	1.50734	10.48460	10.59240	81.81879
420.000	6.94198E-03	4.07673E-02	3.67231	21.56589	21.87632	80.33619
480.000	2.12300E-02	1.22247E-03	11.23065	0.64669	11.24925	3.29559
540.000	3.38123E-03	5.05365E-02	1.78867	26.73381	26.79358	86.17224
600.000	2.42331E-03	6.07243E-02	1.28193	32.12317	32.14874	87.71473
660.000	7.13323E-03	9.69211E-02	3.77348	51.27126	51.40993	85.79072
720.000	1.22695E-01	1.93498E-01	64.90585	102.36052	121.20414	57.62160
780.000	1.23011E-01	5.24824E-02	65.07291	27.76321	70.74800	23.10541
840.000	2.71120E-02	6.13310E-02	14.34226	32.44408	35.47280	66.15166
900.000	1.02382E-01	3.93262E-02	54.15990	20.80355	58.01796	21.01245
960.000	5.51211E-02	-8.92531E-03	29.15909	-4.72149	29.53887	-9.19761
1020.000	5.48806E-03	4.61937E-02	2.90319	24.43649	24.60835	83.22472
1080.000	1.62491E-02	1.04563E-01	8.59579	55.31408	55.97799	81.16691
1140.000	2.04588E-02	3.85275E-02	10.82272	20.38103	23.07634	62.03084
1200.000	1.14790E-02	7.42071E-02	6.07240	39.25555	39.72243	81.20667
1260.000	8.25345E-03	9.98036E-02	4.36607	52.79612	52.97635	85.27258
1320.000	3.75487E-02	1.79968E-01	19.86329	95.20300	97.25307	78.21480
1380.000	4.52903E-02	-8.77427E-03	23.95856	-4.64159	24.40403	-10.96431
1440.000	2.73995E-02	1.13667E-01	14.49435	60.12995	61.85222	76.44738
1500.000	7.57072E-02	1.45254E-01	40.04908	76.83923	86.64986	62.47120
1560.000	1.37037E-01	1.50610E-01	72.49241	79.67282	107.71680	47.70169
1620.000	2.44763E-02	7.41650E-02	12.94795	39.23369	41.31504	71.73601
1680.000	8.59357E-02	1.70391E-01	45.46000	90.13682	100.95177	63.23617
1740.000	2.99262E-01	2.13608E-01	158.30972	112.99853	194.50098	35.51854
1800.000	1.07485E-01	1.41167E-01	56.85978	74.67712	93.86004	52.71406
1860.000	2.18244E-01	-8.21502E-03	115.45121	-4.34575	115.53298	-2.15568
1920.000	1.23011E-01	2.25327E-01	65.07285	119.19798	135.80365	61.36888
1980.000	5.83082E-02	-2.57852E-02	30.84502	-13.64040	33.72649	-23.85615
2040.000	4.52321E-02	-2.14847E-02	23.92719	-11.36542	26.48984	-25.40718
2100.000	4.38479E-02	3.18529E-02	23.19552	16.85019	28.66986	35.99621
2160.000	5.04402E-02	1.16976E-01	26.68284	61.88039	67.38810	66.67428
2220.000	4.15201E-02	1.27386E-01	21.96413	67.38699	70.87615	71.94713
2280.000	4.02988E-01	1.62853E-01	213.18042	86.14922	229.92953	22.00433
2340.000	7.05246E-02	-3.47500E-02	37.30752	-18.38275	41.59058	-26.23112
2400.000	6.22568E-02	9.29711E-02	32.93386	49.18169	59.19019	56.19229
2460.000	2.04311E-01	1.61693E-01	108.08044	85.53558	137.83221	38.35833
2520.000	4.92700E-02	6.27721E-02	26.06382	33.20641	42.21361	51.87152
2580.000	5.46184E-02	1.36565E-01	28.89315	72.24266	77.80628	68.20127
2640.000	1.33008E-01	1.71327E-02	70.36130	9.06322	70.94260	7.33984
2700.000	9.24080E-02	6.90141E-02	48.88381	36.50847	61.01226	36.75391
2760.000	1.25300E-01	-8.39885E-02	66.28361	-44.42994	79.79684	-33.83397
2820.000	4.58102E-02	5.25549E-02	24.23358	27.80157	36.88080	48.92257
2880.000	5.75051E-02	4.54045E-02	30.42020	24.01896	38.75951	38.29366
2940.000	8.28978E-02	6.04483E-02	43.85293	31.97716	54.27355	36.09920
3000.000	5.95991E-02	4.05046E-02	31.52792	21.42695	38.11986	34.20075

Table 7.4-12 Open Circuit
Termination - Tier 5

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	2.28652E-02	7.56129E-03	12.09567	3.99992	12.73989	18.29856
180.000	1.65621E-02	2.45948E-03	8.76134	1.30106	8.85742	8.44673
240.000	1.39340E-03	2.81101E-02	0.73711	14.87023	14.88849	87.16220
300.000	5.05421E-03	2.97983E-02	2.67368	15.76329	15.98842	80.37345
360.000	9.56081E-03	8.93290E-03	5.05767	4.72551	6.92173	43.05543
420.000	1.72164E-02	2.37266E-02	9.10745	12.55139	15.50751	54.03486
480.000	2.65445E-03	4.28755E-02	1.40421	22.68116	22.72459	86.45731
540.000	5.67392E-03	6.51068E-02	3.00150	34.44152	34.57206	85.01939
600.000	3.17364E-02	1.10935E-01	16.78853	58.68454	61.03875	74.03519
660.000	1.01754E-01	6.35877E-02	53.82793	33.63789	63.47404	32.00188
720.000	4.12190E-02	5.87541E-02	21.80434	31.08092	37.96676	54.94839
780.000	4.22151E-02	9.04551E-02	22.33178	47.85076	52.80534	64.98170
840.000	2.87300E-02	2.08062E-02	15.19819	11.00646	18.76505	35.91188
900.000	3.11691E-02	5.73085E-02	16.48843	30.31621	34.51002	61.45905
960.000	1.66941E-01	-4.40839E-02	88.31170	-23.32038	91.33891	-14.79237
1020.000	2.71283E-02	7.70022E-02	14.35086	40.73414	43.18816	70.59236
1080.000	3.48956E-02	4.64864E-02	18.45976	24.59129	30.74889	53.10581
1140.000	1.02297E-02	8.77275E-02	5.41153	46.40784	46.72229	83.34888
1200.000	1.31568E-02	6.63002E-02	6.95993	35.07280	35.75670	78.77591
1260.000	1.74018E-02	8.29056E-02	9.20557	43.85704	44.81276	78.14574
1320.000	1.37676E-02	9.39916E-02	7.28304	49.72155	50.25212	81.66678
1380.000	1.16228E-02	1.49081E-01	6.14845	78.86401	79.10332	85.54209
1440.000	7.43987E-02	1.52137E-01	39.35691	80.48023	89.58813	63.94018
1500.000	2.63792E-01	3.36451E-01	139.54572	177.98239	226.16528	51.90205
1560.000	7.63022E-02	-2.59717E-02	40.36385	-13.73904	42.63803	-18.79753
1620.000	3.03105E-02	7.22596E-02	16.03428	38.22532	41.45206	67.24354
1680.000	8.42397E-02	1.32527E-01	44.56262	70.10691	83.07120	57.55830
1740.000	5.45264E-02	1.16394E-01	28.84447	61.57225	67.99371	64.89853
1800.000	1.33979E-01	1.16801E-01	70.87492	61.78770	94.02646	41.08144
1860.000	1.26299E-01	9.74601E-02	66.81204	51.55639	84.39141	37.65604
1920.000	6.84793E-02	5.14036E-02	36.22557	27.19249	45.29595	36.89349
1980.000	2.71470E-01	2.36126E-01	143.60785	124.91050	190.33090	41.01683
2040.000	7.75891E-02	-9.47569E-02	41.04462	-50.12640	64.78671	-50.68862
2100.000	1.88395E-02	2.86722E-02	9.96611	15.16761	18.14883	56.69248
2160.000	4.45261E-02	1.04398E-01	23.55430	55.22654	60.03978	66.90160
2220.000	5.14793E-02	2.04470E-01	27.23255	108.16449	111.53999	75.86836
2280.000	2.05796E-01	-4.01048E-02	108.86584	-21.21545	110.91378	-11.02742
2340.000	6.66889E-02	-1.07136E-02	35.27842	-5.66749	35.73076	-9.12661
2400.000	4.70365E-02	1.00149E-01	24.88230	52.97879	58.53103	64.84219
2460.000	1.77010E-01	2.09286E-01	93.63825	110.71255	145.00134	49.77619
2520.000	4.15278E-02	2.18837E-02	21.95822	11.57648	24.83179	27.78766
2580.000	8.11252E-02	-4.94273E-02	42.91524	-26.14707	50.25323	-31.35279
2640.000	2.96344E-02	5.06855E-02	15.67661	26.81261	31.05918	59.68633
2700.000	8.33135E-02	8.06320E-02	44.07282	42.65435	61.33357	44.06298
2760.000	1.27129E-01	1.36210E-01	67.25136	72.05496	98.56299	46.97491
2820.000	3.08740E-01	6.29440E-02	163.32344	33.29739	166.68314	11.52320
2880.000	1.16814E-01	9.53141E-04	61.79473	0.50421	61.79679	0.46749
2940.000	5.68604E-02	-4.64030E-02	30.07914	-24.54718	38.82420	-39.21742
3000.000	6.39538E-02	1.29392E-02	33.83157	6.84482	34.51705	11.43773

Table 7.4-13 Open Circuit
Termination - Tier 6

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	1.55437E-01	5.17008E-02	82.22592	27.34973	86.65512	18.39800
180.000	9.19328E-04	2.01027E-02	0.48632	10.63432	10.64543	87.38160
240.000	1.61718E-03	2.21006E-02	0.85549	11.69122	11.72248	85.81491
300.000	3.73663E-02	2.90920E-02	19.76679	15.38969	25.05132	37.90300
360.000	8.99502E-03	1.04171E-02	4.75836	5.51063	7.28073	49.18976
420.000	2.36526E-02	6.06266E-02	12.51222	32.07148	34.42580	68.68749
480.000	2.46817E-03	4.34744E-02	1.30566	22.99796	23.03500	86.75064
540.000	1.49418E-02	7.26741E-02	7.90419	38.44458	39.24871	78.38190
600.000	3.96694E-02	6.49215E-02	20.98510	34.34347	40.24734	58.57357
660.000	6.29117E-03	5.63776E-02	3.32803	29.82373	30.00884	83.63271
720.000	1.25200E-02	9.06950E-02	6.62310	47.97767	48.43266	82.14025
780.000	1.25102E-01	1.29986E-01	66.17870	68.76278	95.43552	46.09706
840.000	2.76172E-02	6.57230E-02	14.60951	34.76748	37.71227	67.20756
900.000	3.28198E-02	5.69912E-02	17.36167	30.14832	34.79007	60.06343
960.000	1.14215E-01	4.87009E-02	60.41952	25.76280	65.68288	23.09333
1020.000	1.21086E-02	3.15680E-02	6.40546	16.69945	17.88579	69.01453
1080.000	3.28543E-02	5.46504E-02	17.37992	28.91004	33.73206	58.98687
1140.000	1.51612E-02	7.01429E-02	8.02029	37.10559	37.96248	77.80328
1200.000	1.42296E-02	6.68528E-02	7.52747	35.36512	36.15735	77.98390
1260.000	1.29382E-02	1.19870E-01	6.84431	63.41114	63.77945	83.83961
1320.000	2.33779E-02	1.28013E-01	12.36691	67.71896	68.83892	79.65063
1380.000	1.52711E-02	1.31488E-01	8.07840	69.55737	70.02491	83.37534
1440.000	6.47562E-02	1.89641E-01	34.25603	100.32028	106.00772	71.14668
1500.000	3.97645E-01	-1.97425E-02	210.35396	-10.44379	210.61305	-2.84232
1560.000	1.28682E-01	2.85999E-02	68.07256	15.12933	69.73357	12.53049
1620.000	2.02946E-02	6.83608E-02	10.73586	36.16288	37.72284	73.46516
1680.000	3.80295E-02	1.51919E-01	20.11759	80.36501	82.84474	75.94609
1740.000	9.96107E-02	1.68756E-01	52.69408	89.27197	103.66365	59.44816
1800.000	1.00574E-01	4.05115E-02	53.20347	21.43058	57.35747	21.93978
1860.000	9.25246E-02	1.26810E-01	48.94552	67.08266	83.04063	53.88439
1920.000	3.39306E-01	1.61708E-01	179.49297	85.54358	198.83517	25.48175
1980.000	2.24212E-01	9.56062E-02	118.60799	50.57569	128.94089	23.09391
2040.000	1.53337E-01	-7.87031E-02	81.11543	-41.63396	91.17619	-27.16998
2100.000	1.72685E-02	2.45976E-02	9.13505	13.01211	15.89856	54.92953
2160.000	4.81125E-02	8.16917E-02	25.45154	43.21490	50.15285	59.50393
2220.000	5.19803E-02	1.78722E-01	27.49758	94.54415	98.46173	73.78326
2280.000	5.05676E-01	5.54853E-03	267.50244	2.93517	267.51855	0.62865
2340.000	1.04926E-01	1.39500E-03	55.50606	0.73796	55.51096	0.76171
2400.000	4.57497E-02	1.05037E-01	24.20161	55.56433	60.60621	66.46398
2460.000	7.80297E-02	4.27689E-02	41.27770	22.62474	47.07151	28.72761
2520.000	1.22064E-01	1.80661E-01	64.57201	95.56944	115.33891	55.95486
2580.000	8.10957E-02	-9.80481E-03	42.89962	-5.18675	43.21203	-6.89384
2640.000	4.38690E-02	-3.90271E-03	23.20670	-2.06453	23.29836	-5.08381
2700.000	6.07944E-02	8.71027E-02	32.16022	46.07733	56.19075	55.08643
2760.000	9.33700E-02	6.94322E-02	49.39273	36.72962	61.55247	36.63538
2820.000	8.73430E-02	1.01283E-01	46.20447	53.57852	70.74963	49.22653
2880.000	1.67204E-01	1.05979E-02	88.45093	5.60627	88.62842	3.62672
2940.000	5.08607E-02	-3.21563E-02	26.90530	-17.01067	31.83171	-32.30281
3000.000	2.91186E-02	2.55960E-02	15.40374	13.54026	20.50887	41.31626

Table 7.4-14 Open Circuit

Termination - Tier 7

FREQ	RESISTANCE	REACTANCE	RESISTANCE	REACTANCE	MAGNITUDE	ANGLE
HERTZ	PER UNIT	PER UNIT	OHMS	OHMS	OHMS	DEGREES
120.000	2.10584E-02	-3.00873E-02	11.13988	-15.91619	19.42735	-55.01147
180.000	1.77646E-03	2.23485E-02	0.93975	11.82237	11.85966	85.45517
240.000	4.41125E-03	3.62823E-02	2.33355	18.66434	18.80965	82.87344
300.000	5.53430E-03	4.08433E-02	2.92764	21.60609	21.80354	82.28338
360.000	1.06704E-02	5.69122E-03	5.64462	3.01066	6.39732	28.07402
420.000	1.43602E-02	4.72045E-02	7.59653	24.97119	26.10110	73.07962
480.000	2.51068E-03	4.16213E-02	1.32815	22.01767	22.05769	86.54799
540.000	6.76065E-03	7.70601E-02	3.57638	40.76478	40.92136	84.98616
600.000	2.13387E-02	4.65205E-02	11.28818	24.60934	27.07477	65.35931
660.000	5.49765E-03	6.13174E-02	2.90826	32.43692	32.56704	84.87663
720.000	4.42587E-02	1.28410E-01	23.41286	67.92896	71.85057	70.98263
780.000	5.59918E-02	2.78126E-02	29.61968	14.71288	33.07256	26.41482
840.000	1.17005E-01	9.33819E-02	61.89576	49.39902	79.19183	38.59338
900.000	5.33871E-02	6.46564E-02	28.24178	34.20322	44.35604	50.45333
960.000	1.52799E-01	-6.42913E-03	80.83075	-3.40101	80.90227	-2.40934
1020.000	7.19334E-03	3.66125E-02	3.80528	19.36802	19.73829	78.88456
1080.000	3.07635E-02	6.53607E-02	16.27390	34.57583	38.21424	64.74491
1140.000	6.95085E-03	7.30432E-02	3.67700	38.63985	38.81441	84.56406
1200.000	5.96681E-02	7.66671E-02	31.56445	40.55688	51.39236	52.10723
1260.000	6.68374E-02	1.18025E-01	35.35696	62.43534	71.75156	60.47725
1320.000	1.46557E-02	9.20999E-02	7.75287	48.72082	49.33382	80.95843
1380.000	1.11964E-02	1.37931E-01	5.92287	72.96530	73.20530	85.35926
1440.000	8.15745E-02	2.59962E-01	43.15292	137.51981	144.13144	72.57845
1500.000	1.16730E-01	-1.56363E-02	61.75018	-8.27158	62.30172	-7.62948
1560.000	1.49054E-01	-4.35719E-02	78.84971	-23.04955	82.14960	-16.29483
1620.000	2.26315E-02	6.80565E-02	11.97206	36.00188	37.94028	71.60598
1680.000	4.68276E-02	1.62541E-01	24.77179	85.98444	89.48165	73.92851
1740.000	1.33406E-01	1.09645E-01	70.57191	58.00205	91.34895	39.41630
1800.000	7.69207E-02	1.04695E-01	40.69106	55.38344	68.72472	53.69471
1860.000	6.93242E-02	1.22929E-01	36.67249	65.02922	74.65702	60.57967
1920.000	1.36339E-01	1.97327E-01	72.12327	104.38586	126.87857	55.35827
1980.000	4.29878E-01	-1.53808E-01	227.40547	-81.36440	241.52312	-19.68692
2040.000	8.93145E-02	-1.91997E-02	47.24737	-10.15664	48.32671	-12.13209
2100.000	1.72164E-02	2.65092E-02	9.10749	14.02338	16.72129	56.99828
2160.000	3.65107E-02	8.26140E-02	19.31417	43.70282	47.78047	66.15730
2220.000	5.08276E-02	1.90114E-01	26.88780	100.57032	104.10256	75.03187
2280.000	4.72959E-01	1.11591E-01	250.19557	59.03173	257.06531	13.27571
2340.000	8.57061E-02	2.23567E-04	45.33854	0.11827	45.33870	0.14946
2400.000	5.15146E-02	1.00346E-01	27.25122	53.08319	59.66954	62.82548
2460.000	1.82895E-01	1.60962E-01	96.75137	85.14890	128.88429	41.35035
2520.000	1.17070E-01	2.40243E-02	61.93021	12.70887	63.22078	11.59683
2580.000	1.53453E-01	-2.82320E-02	81.17646	-14.93472	82.53886	-10.42461
2640.000	5.70299E-02	-5.69853E-03	30.16883	-3.01452	30.31907	-5.70615
2700.000	4.00186E-02	8.18093E-02	21.16983	43.27711	48.17748	63.93355
2760.000	1.22341E-01	1.53284E-01	64.71851	81.08740	103.74802	51.40549
2820.000	2.60783E-01	1.00565E-02	137.95412	5.31989	138.05666	2.20839
2880.000	9.27464E-02	1.01001E-02	49.06286	5.34296	49.35293	6.21503
2940.000	5.10420E-02	-2.71257E-02	27.00123	-14.34951	30.57736	-27.98793
3000.000	5.15023E-02	3.28211E-02	27.24473	17.36236	32.30676	32.50831

EPRI HARMONICS
120 TO 420 HZ STEP 5HZ

Figure 7.4-6 RX Plot from 120 to 420 Hz

EPRI HARMONICS
420 TO 840 HZ STEP 5HZ

Figure 7.4-7 RX Plot from 420 to 840 Hz

EPRI HARMONICS
840 TO 1260 HZ STEP 5HZ

Figure 7.4-8 RX Plot from 840 to 1260 Hz

EPRI HARMONICS
1260 TO 1680 HZ STEP 5HZ

Figure 7.4-9 RX Plot from 1260 to 1680 Hz

EPRI HARMONICS
1680 TO 2100 HZ STEP 5HZ

Figure 7.4-10 RX Plot from 1680 to 2100 Hz

EPRI HARMONICS
2100 TO 2520 HZ STEP 5HZ

Figure 7.4-11 RX Plot from 2100 to 2520 Hz

EPR1 HARMONICS
2520 TO 3000 HZ STEP 5HZ

Figure 7.4-12 RX Plot from 2520 to 3000 Hz

EPRI HARMONICS
120 TO 420 HZ STEP 5HZ

Figure 7.4-13 Magnitude-Phase Plot from 120 to 420Hz

EPRI HARMONICS
420 TO 840 HZ STEP 5HZ

Figure 7.4-14 Magnitude-Phase Plot from 420 to 240 Hz

EPRI HARMONICS
840 TO 1260 HZ STEP 5HZ

Figure 7.4-15 Magnitude-Phase Plot from 840 to 1260 Hz

EPRI HARMONICS
1260 TO 1680 HZ STEP 5HZ

Figure 7.4-16 Magnitude-Phase Plot from 1260 to 1680 Hz

EPRI HARMONICS
 1680 TO 2100 HZ STEP 5HZ

Figure 7.4-17 Magnitude-Phase Plot from 1680 to 2100 Hz

EPRI HARMONICS
2100 TO 2520 HZ STEP 5HZ

Figure 7.4-18 Magnitude-Phase Plot from 2100 to 2520 Hz

EPRI HARMONICS
2520 TO 3000 HZ STEP 5HZ

Figure 7.4-19 Magnitude-Phase Plot from 2520 to 3000 Hz

Table 7.4-15 Mean & Standard Deviation of
System Harmonic Impedances

N	FREQUENCY	MEAN R	MEAN X	MEAN Z	STANDARD DEV Z
2	120.00	13.359	5.555	14.468	11.598
3	180.00	2.071	12.180	12.355	2.542
4	240.00	1.433	16.364	16.427	3.559
5	300.00	5.098	19.316	19.978	3.111
6	360.00	5.475	3.407	6.449	1.636
7	420.00	4.980	21.443	22.014	2.659
8	480.00	6.843	26.183	27.063	5.813
9	540.00	3.843	29.957	30.203	3.476
10	600.00	8.205	35.615	36.548	4.693
11	660.00	16.166	31.998	35.850	9.104
12	720.00	23.702	44.689	50.586	15.616
13	780.00	30.162	38.302	48.752	10.654
14	840.00	30.218	34.248	45.674	10.118
15	900.00	23.060	30.533	38.262	5.382
16	960.00	65.286	-9.153	65.925	9.925
17	1020.00	10.080	26.993	28.814	5.287
18	1080.00	16.264	39.674	42.878	4.976
19	1140.00	6.714	34.316	34.967	3.082
20	1200.00	8.836	40.902	41.846	4.086
21	1260.00	15.412	52.841	55.043	6.723
22	1320.00	13.077	59.898	61.309	8.453
23	1380.00	12.329	58.731	60.011	10.869
24	1440.00	30.409	102.934	107.332	12.551
25	1500.00	172.074	54.604	180.530	68.342
26	1560.00	56.176	9.742	57.014	16.130
27	1620.00	14.133	35.935	38.614	1.958
28	1680.00	28.515	75.151	80.379	6.382
29	1740.00	72.855	87.216	113.642	17.369
30	1800.00	52.317	48.897	71.610	10.209
31	1860.00	49.616	59.040	77.120	15.223
32	1920.00	79.129	104.129	130.783	24.862
33	1980.00	132.125	57.965	144.281	57.620
34	2040.00	50.231	-31.820	59.461	15.129
35	2100.00	11.496	13.885	18.027	1.908
36	2160.00	26.196	50.633	57.009	5.049
37	2220.00	41.060	76.868	87.148	24.943
38	2280.00	168.569	32.553	171.683	33.846
39	2340.00	41.004	-6.593	41.531	5.042
40	2400.00	25.758	51.894	57.934	2.463
41	2460.00	93.689	67.549	115.501	23.832
42	2520.00	47.373	44.988	65.331	19.583
43	2580.00	61.051	3.253	61.138	22.684
44	2640.00	40.447	12.051	42.204	13.087
45	2700.00	33.728	39.760	52.139	3.956
46	2760.00	73.622	56.439	92.766	20.333
47	2820.00	74.917	-4.245	75.037	24.750
48	2880.00	51.574	17.102	54.336	9.499
49	2940.00	35.239	-11.264	36.995	9.138
50	3000.00	21.066	14.516	25.584	4.679

FOR OPEN AND SHORT CKT
TERMINATIONS .M= 4 TO 7

EPRI HARMONICS
MEAN HARMONIC IMPEDENCE
120 TO 3000 HZ STEPSCHZ

Figure 7.4-20 RX Plot of Mean Harmonic Impedances

Figure 7.4-21 Magnitude-Phase Plot of Mean Harmonic Impedances

The system impedance calculated from SISP will be compared with the measured result in the next section.

References

1. Edward B. Rosa and Frederick W. Grover, "Formulas and Tables for the Calculation of Mutual and Self Inductance," Scientific Paper No. 169, Bulletin Bureau of Standards, 8, No. 1 (1912), pp. 172-179, 226-229.
2. Philip C. Magnusson, Transmission Lines and Wave Propagation, Allyn and Bacon, Boston, 1965.
3. General Electric Company, Transmission Line Reference Book 345 kV and Above, EPRI, 1975.
4. Edith Clarke, Circuit Analysis of A-C Power Systems, Vol. 1, Wiley, New York, 1943.

Section 8

COMPARISON OF MEASURED AND ANALYTICAL RESULTS

8.1 Introduction

The system harmonic impedances calculated from SISP in Section 7 are evaluated by comparing with the measured impedance results in Section 6. In particular, the ability of the statistical approach which terminates the last tiers of buses with open and short circuits to include the measured impedances is investigated. In cases when there are discrepancies between the analytical and measured results, a sensitivity analysis with respect to frequency is performed.

Before examining the measured and analytical results, the aspects of the methods which produce the differing results are summarized.

1. Although the system impedances might not be balanced, the measured results were calculated based on the assumption that they were balanced. Thus, the measured results may differ from the SISP results which use the positive sequence impedances only.
2. The measured results included all the effects of the components existing in the system. In SISP, not all the components, such as loads, were modeled and the components were represented by ideal models.
3. Not all the nonlinearities in harmonic generation are accounted for in the measurement method. For example, harmonic voltages of transformers depend on the generated harmonic currents. The SISP results disregard harmonic sources.

In the next subsection, the measured and analytical results will be compared assuming that these differences are small. A sensitivity analysis which may account for some of these differences will be discussed in Subsection 8.3.

8.2 Mean Impedances and Individual Data

Three different comparisons of the measured and analytical results will be investigated. They are the comparison of the mean impedances for all frequencies,

the mean impedances for each harmonic and the individual impedances for each harmonic.

Figure 8.2-1 is a plot of the resistance-reactance of the mean impedances of the measured results (Figure 6.4-1) and the analytical results (Figure 7.4-20). The sector of the measured results is completely enclosed by the sector of the SISP results. Thus, the measured and analytical results are roughly of the same order of magnitude. A conservative approach would be to use the SISP sector as the impedance-frequency characteristics for all harmonics, which would include the particular system operating conditions during the test period.

The mean impedances for each harmonic are also compared. The objective is to calculate the differences between the measured mean impedances Z_{mm} and the analytical mean impedances Z_{ma} with respect to the analytical standard deviations S_a and the measured standard deviations S_m . The ratios

$$r_m = |Z_{ma} - Z_{mm}| / S_a \quad (8.1)$$

$$r_a = |Z_{ma} - Z_{mm}| / S_m \quad (8.2)$$

indicate in a statistical sense the differences between of Z_{mm} and Z_{ma} . The ratios r_a and r_m are listed in Table 8.2-1. The SISP results in Table 8.2-1 are from Table 7.4-15, and the measured results are from Tables 6.4-17 and 6.4-18. The ratios r_a and r_m were not computed for harmonics with negative measured resistances. The ratios r_a , r_m range from 0.24 to 64.25, while the averaged values are

$$\text{mean of } r_m = 6.86$$

$$\text{mean of } r_a = 6.45.$$

The large values of r_a and r_m mean that on the average, the likelihood of Z_{mm} being close to Z_{ma} is very low. One reason for the pessimistic result is that r_a and r_m are very large at a few harmonics.

To further investigate the mean impedances, the sectors formed by the individual impedances from the measured and analytical results are compared. Figures 8.2-2 to 8.2-11 show the sectors for the 5th, the 7th and the characteristic harmonics; that is, the 11th, 13th, 23rd, 25th, 35th, 37th, 47th and 49th. The SISP data are the 4th to the 7th tier with open and short circuits, and the measured data are from Appendix D.3. The measured impedances with negative resistances are not included.

EPRI HARMONICS
MEAN HARMONIC IMPEDANCE
120 TO 3000 HZ STEP 60HZ

Figure 8.2-1 Sectors of Mean Impedances

Table 8.2-1 Ratios r_m and r_a

Frequency	SISP results				Measured results			
	Mean Impedances (ohm)		Standard Deviation	r_m	Mean Impedances (ohm)		Standard Deviation	r_a
	R	X			R	X		
120.	13.36	5.55	11.60	0.00	-11.54	23.66	9.31	0.00
180.	2.07	12.18	2.54	0.00	-44.19	-51.18	211.72	0.00
240.	1.43	16.36	3.56	2.49	7.38	22.93	2.93	3.02
300.	5.10	19.32	3.11	0.00	-1.33	26.62	17.38	0.00
360.	5.47	3.41	1.64	23.56	29.21	33.78	39.80	0.97
420.	4.98	21.44	2.66	5.68	6.66	36.45	2.69	5.61
480.	6.84	26.18	5.81	2.14	10.83	37.94	6.39	1.94
540.	3.84	29.96	3.48	7.13	19.22	49.41	6.01	4.13
600.	8.20	35.62	4.69	9.01	42.29	60.63	1.72	24.58
660.	16.17	32.00	9.10	3.98	40.31	5.03	22.60	1.60
720.	23.70	44.69	15.62	1.73	48.21	33.23	10.56	2.56
780.	30.16	38.30	10.65	4.39	41.85	-7.03	12.60	3.72
840.	30.22	34.25	10.12	3.48	11.44	4.43	4.10	8.59
900.	23.06	30.53	5.38	1.76	14.79	25.94	7.05	1.34
960.	65.29	-9.15	9.93	6.65	14.36	32.90	1.27	52.00
1020.	10.08	26.99	5.29	5.97	27.89	53.05	9.12	3.46
1080.	-16.26	39.67	4.98	10.00	64.01	25.70	30.71	1.62
1140.	6.71	34.32	3.08	7.77	28.64	43.95	10.04	2.39
1200.	8.84	40.90	4.09	6.38	30.35	55.64	11.26	2.32
1260.	15.41	52.84	6.72	2.69	33.42	54.28	9.81	1.84
1320.	13.08	59.90	8.45	5.35	57.01	49.24	17.30	2.61
1380.	12.33	58.73	10.87	2.27	28.03	39.73	17.27	1.43
1440.	30.41	102.93	12.55	7.97	75.44	13.66	34.48	2.90
1500.	172.07	54.60	68.34	2.13	26.81	57.80	4.58	31.72
1560.	56.18	9.74	16.13	4.07	78.13	71.57	21.67	3.03
1620.	14.13	35.94	1.96	64.25	134.53	72.39	11.69	10.76
1680.	28.51	75.15	6.38	22.95	96.39	-54.62	5.53	26.48
1740.	72.86	87.22	17.37	4.39	63.35	11.50	4.61	16.55
1800.	52.32	48.90	10.21	2.17	74.49	49.67	53.08	0.42
1860.	49.62	59.04	15.22	0.29	53.17	56.40	11.30	0.39
1920.	79.13	104.13	24.86	4.77	62.96	-13.41	6.89	17.22
1980.	132.13	57.97	57.62	1.66	47.54	13.20	14.54	6.58
2040.	50.23	-31.82	15.13	3.57	54.88	22.02	11.91	4.54
2100.	11.50	13.89	1.91	12.28	31.76	25.65	33.16	0.71
2160.	26.20	50.63	5.05	2.75	12.41	49.02	57.85	0.24
2220.	41.06	76.87	24.94	1.92	41.81	28.88	23.18	2.07
2280.	168.57	32.55	33.85	3.83	54.22	-28.45	35.32	3.67
2340.	41.00	-6.59	5.04	6.53	52.69	24.18	36.16	0.91
2400.	25.76	51.89	2.46	21.55	76.12	35.14	17.74	2.99
2460.	93.69	67.55	23.83	2.92	37.82	26.15	13.67	5.09
2520.	47.37	44.99	19.58	3.24	81.10	-8.84	19.84	3.20
2580.	61.05	3.25	22.68	0.70	60.96	19.23	21.57	0.74
2640.	40.45	12.05	13.09	1.28	49.82	-1.80	1.61	10.39
2700.	33.73	39.76	3.96	4.80	47.00	26.17	17.34	1.10
2760.	73.62	56.44	20.33	1.93	41.80	33.37	15.08	2.61
2820.	74.92	-4.24	24.75	2.24	29.68	27.99	26.48	2.10
2880.	51.57	17.10	9.50	0.00	-53.47	33.06	57.62	0.00
2940.	35.24	-11.26	9.14	5.35	14.50	33.04	31.73	1.54
3000.	21.07	14.52	4.68	0.00	0.00	0.00	0.00	0.00

5TH HARMONIC

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

Figure 8.2-2 Comparison of 5th Harmonic Impedances

7TH HARMONIC

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

REACTANCE - OHMS
20.00 10.00 0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00

Figure 8.2-3 Comparison of 7th Harmonic Impedances

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

11TH HARMONIC

Figure 8.2-4 Comparison of 11th Harmonic Impedances

13TH HARMONIC

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

Figure 8.2-5 Comparison of 13th Harmonic Impedances

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

23TH HARMONIC

Figure 8.2-6 Comparison of 23th Harmonic Impedances

25TH HARMONIC

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

Figure 8.2-7 Comparison of 25th Harmonic Impedances

35TH HARMONIC

EPR1 HARMONICS
HARMONIC IMPEDANCE
COMPARISON

Figure 8.2-8 Comparison of 35th Harmonic Impedances

37TH HARMONIC

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

REACTANCE - OHMS
-90.00 -60.00 -40.00 -20.00 0.00 20.00 40.00 60.00 80.00 100.00 120.00

Figure 8.2-9 Comparison of 37th Harmonic Impedances

47TH HARMONIC

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

Figure 8.2-10 Comparison of 47th Harmonic Impedances

Figure 8.2-11 Comparison of 49th Harmonic Impedances

For the 5th and the 23rd harmonic, the measured sectors are in the SISP sectors, indicating that the SISP analysis is able to include these system harmonic impedances during the test periods. For the 7th, 11th, 25th, 37th, 47th and 49th harmonics, the measured and SISP sectors overlap to various extents, indicating some correlation of these data. For the 35th harmonic, the SISP sector is contained in the measured sector, whose data points are scattered. There is no overlap of the 13th harmonic sectors, indicating a lack of correlation between the data.

The sector comparison of the measured and SISP data shows a better correlation than the mean and standard deviation comparison. The sectors also allow for a straightforward sensitivity analysis, as will be shown in the next subsection.

8.3 Sensitivity Analysis

The comparison of the measured and SISP results in the last subsection has not taken any parameter variations into account. As discussed in Section 7, for impedances that lie on resonance circles, a small change in system parameters may result in a large change in the impedance values. Thus, the resonance may occur at a different frequency. Figure 8.2-1 can be used to compare the possible resonance circles in the measured and calculated results. For example, the SISP results show a resonance circle at the 15th, 16th and 17th harmonics, and the measured results show a resonance circle at the 12th, 13th and 14th harmonics. Another example is that the SISP results show a resonance circle at the 33rd, 34th and 35th harmonics, while the measured results show a resonance circle at the 27th, 28th and 29th harmonics. These variations motivate a sensitivity analysis with respect to frequency.

The following procedure was used to analyze sensitivity with respect to frequency. For the n th harmonic, the SISP sectors for the $n-1$, n , $n+1$ harmonics are superimposed to form a larger sector. The new sensitivity sector would include effects of ± 60 Hz variations in frequency. The procedure was tried on 7th, 11th and 13th harmonics where the measured and analytical results did not correlate very well. The sensitivity sectors are shown in Figures 8.3-1 to 8.3-3, and are able to enclose almost all of the measured sectors; that is, they include the test periods as an operating condition.

7TH HARMONIC
SENSITIVITY

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

Figure 8.3-1 Sensitivity Analysis of 7th Harmonic

11TH HARMONIC
SENSITIVITY

EPRI HARMONICS
HARMONIC IMPEDANCE
COMPARISON

Figure 8.3-3 Sensitivity Analysis of 13th Harmonic

Similar sensitivity sectors can be constructed for the higher harmonics. At the higher harmonics, the sectors should include more than 60 Hz variations in frequency. The sensitivity analysis would provide assurances in filter design.

8.4 Conclusions

The sector formed by the analytical mean impedances correlate to a large extent with the sector formed by the measured mean impedances. As expected, the measured sector shows more damping than the analytical sector. For comparison of individual harmonic impedances, most of the measured and analytical impedance sectors overlap to a certain extent. The correlation is improved by performing a sensitivity analysis with respect to frequency. Further analysis should be performed to include some models such as loads and sources which are neglected in SISP.

Appendix A

BIBLIOGRAPHY ON HARMONICS GENERATION AND FILTER DESIGN

1980

1. Stratford, R.P., "Rectifier Harmonics in Power Systems", IEEE Transactions on Industrial Applications, Vol. IA16, No. 2, March-April 1980, pp. 271-276.

The effect of rectifier harmonic currents on power systems is described. Rectifiers and inverters require nonsinusoidal waves of current. These current waves are made up of a number of sine waves which are harmonics of the fundamental wave. These harmonic currents can excite resonant circuits causing them to "ring" and produce large oscillating currents. Criteria as to possible problem areas are discussed and illustrated with case studies. Examples of application of filters to "trap" these harmonic currents are included. In English.

2. Yacamini, R., "Harmonics in Multiple Converter Systems: A Generalized Approach", Proceeding of the Institution of Electrical Engineers, Vol. 127, No. 2, March 1980, pp. 96-106.

A method is described which was developed to calculate the harmonics associated with systems containing a large number of converters and other sources of harmonics, e.g., steel mills or large HVDC converter stations. The method is a steady-state (frequency-domain) analysis in which each converter can be individually described. The effect of the ac system impedance and harmonic filters is catered for by using an iterative procedure. By this method, voltage harmonics and unbalances caused by, for example, arc furnaces, system impedance, system unbalances, transformer saturation, firing unbalances and the effect of firing angle and load, can all be represented to give a final level of harmonic current injection into the ac system, or the voltage distortion of the ac busbars. The multiconverter aspect of the problem, involving different converter transformer phase shifts, is handled using a transformer/converter matrix method. This method is therefore useful in examining new and planned extensions to existing systems to check whether they meet the requirements of standards. In English.

3. Zezetenko, L., "Counteracting the Higher Harmonics in Electrical Networks", Wiadomsci Elektrotechniczne, Vol. 48, No. 3, February 1980, pp. 80-81.

Reviews the effect of harmonics caused by non-linear loads, particularly on capacitors for compensating the reactive power, and on converters. Power resonant harmonic filters tuned to the frequencies of the prevailing harmonics are discussed. In Polish.

4. Evers, H.W., "Mains Pollution Caused by Domestic Appliances - Harmonic Distortion", Electronic Components and Applications, Vol. 2, No. 2, February 1980, pp. 83-90.

The current popularity of phase control as a means of power regulation in domestic appliances, has led to a sharp increase in harmonic distortion of the main supply. Future regulations (particularly those being prepared by the IEC) are likely to place severe constraints on the use of phase control devices and other devices not covered by the present CENELEC Standard EN 50 006. This article discussed the major causes of harmonic distortion, and shows by way of example how it can be reduced significantly by judicious circuit design. In English.

5. Gyugyi, Laszlo and Taylor, Edgar R., Jr., "Characteristics of Static, Thyristor-Controlled Shunt Compensator for Power Transmission System Applications", IEEE Power Engineering Society Winter Meeting, Paper F80 236-0, February 1980, 10 pages.

The operating and performance characteristics of two basic types of static, thyristor-controlled shunt compensators, one with a fixed capacitor bank and the other with synchronously switchable capacitor banks, are presented with regard to power transmission system applications. The operating principles, and the similarities and differences between the performance of the two schemes are discussed in the areas of steady-state voltage versus VAR (volt-ampere reactive) characteristic, behavior under small and large system disturbances, harmonic generation, and loss versus output VAR characteristic. In English.

6. Nag Sarkar, Tusan Kanti and Rao, Chyuri Sirama, "Some Aspects of Transient Stability Improvement with Thyristor Controlled Dynamic Brake", IEEE Power Engineering Society Winter Meeting, Paper A80 004-2, February 1980, 7 pages.

Discrete supplementary control in the form of thyristor controlled dynamic brake can significantly improve the power system transient stability. The effectiveness of a thyristor controlled dynamic brake is illustrated by comparing its performance with that of an optimally switched dynamic brake. Certain operating features peculiar to the introduction of a thyristor controlled dynamic brake are also indicated. An evaluation of possible harmonic content introduced in the line currents due to induction of thyristor controlled dynamic brake in the system is also presented. In English.

7. Hoenninger, Erich, "Harmonic Conditions in Public Power Supply Systems", Osterreichische Zeitschrift fur Elektricitatswirtschaft, Vol. 33, No. 1, January 1980, pp. 1-9.

A short description of the reasons for the occurrence of harmonic oscillations and of the complex distribution of the currents in a system, and information on the present state of the relevant measurements is given. Based on a great number of results from public distribution systems, the precarious situation in respect of harmonic oscillations is shown and the necessity of fixing a compatibility level for working stock is emphasized. In German.

1979

1. Saraiva, E. deS. and Freris, L.L., "Development of Electromechanical Filter and Performance Evaluation in DC Link", Proceedings of the Institution of Electrical Engineering, Vol. 126, No. 12, December 1979, pp. 1282-1286.

The characteristics of electromechanical filters for the suppression of harmonics and the supply of reactive power of the ac side of dc-link converters are described. The problem in the design and construction of small-scale units are highlighted. Tests with the prototype filters on a model dc link show that stability margins are considerably improved when compared to operation with conventional static filters. In English.

2. Anonymous, "Review of the Harmonic Conditions in Public Power-Supply Systems", Elektrizitätswirtschaft, Vol. 78, No. 25, December 1979, pp. 1008-1017.

Sources of harmonics are reviewed and means for their elimination pointed out. It is shown that in public systems well-ordered conditions are maintained if attention is paid to the limited capacity of the systems to absorb harmonics. This is generally ensured in the range of domestic consumers by the application of DIN EN 50006/VDE 0838 (German standards). For consumers with special contracts it is necessary, particularly with high-power installations, to take special measures, e.g., to provide filter circuits. In German.

3. Thorson, John M., "Effects of Geomagnetic Storms on Power and Communication Systems", National Telecommunications Conference Record, November 1979 (Cat. No. 79CH1514-9), Vol. 1, pp. 7.3.1-7.3.5.

Solar flares can trigger severe fluctuations in the earth's magnetic field, called geomagnetic storms. These geomagnetic field fluctuations produce spurious, quasi-dc currents in power and communication systems. The currents enter through system ground points and are of sufficient magnitude to cause half-cycle saturation in power transformers and disturb voltage sensitive communication systems. Major problems are communication systems component damage, safety and service outage problems. Power system voltage, frequency and reactive excursion, generation of harmonics, protective relaying misoperation and localized internal heating in transformers are the major power system problems incurred because of these geomagnetic storms. In English.

4. Littler, G.E., "Quality of AC Supply", Institution of Engineers, Australia, Electrical Engineering Transactions, Vol. EE15, No. 2, October 1979, pp. 74-79.

With increasing non-linear loads in the utilization field associated with the advent of solidstate control equipment for industrial drives, lighting equipment, rectifier applications, arc-furnaces, etc., the harmonic content of the general supply system is expected to increase, thus affecting the quality of ac supply. Limitation of harmonic voltages in the supply could impose restrictions on the design of power equipment and filtering. A review of the effects on consumer equipment in filtering. A review of the effects on consumer equipment in the presence of harmonics and of some of the important system parameters is made. These could provide a guide to

operating conditions which would represent a reasonable technical and economic compromise. In English.

5. Anonymous, "So You Don't Think You Have a Harmonic Problem", IEEE Industry Applications Society Conference, (Cat. No. 79 CH 1484-51A) September-October 1979, pp. 1218-1224.

Power system harmonics, generated by various non-linear and discontinuous type load equipment, can create component failures, or degradation of system protection. Apparent problems are generally related to harmonic resonance which results from power factor correction capacitors resonating with the system inductance at a harmonic generated frequency. The symptoms of the problem are related to component overheating or system overvoltages. The results of an industry questionnaire are included. In English.

6. Skipp, David D., "Harmonic Analysis and Suppression for Electrical Systems Supplying Static Power Converters and Other Nonlinear Loads", IEEE Transactions on Industry Applications, Vol. IA-15, No. 5, September-October 1979, p. 453-458.

As technology has moved forward in the past 20 years, rectification of ac power to dc power has gradually been changed from the old motor-generator (MG) sets of new static rectifiers and dc drives. These new methods afford industry more precise control of the particular process. Although these rectifiers and drives are much more versatile with less maintenance requirements, when they comprise a significant portion of the system they may have detrimental effects on the quality of the subsequent ac power system. Arc furnaces also comprise loads which may have detrimental effects on the ac power system. Since a less desirable power factor is normally inherent in any static rectification or arc furnace equipment, is not uncommon to apply power-factor correction capacitor banks for compensation, especially with the cost of electric power today. Generally, it is when both capacitor banks and static rectification and/or arc furnaces exist together on a system that problems may arise in the form of system overvoltages proportional to other than fundamental frequency. The nature and control of these higher than normal frequency components called harmonics are discussed. In English.

1978

1. Chanas, Marius, "Voltage Disturbances Affecting the Operation of the Systems: Sudden Fluctuations, Flickering, Unbalances and Harmonics", Revue Generale de l'Electricite, Vol. 87, No. 12, December 1978, pp. 925-943.

Having first recalled the origin of voltage disturbances, the article examines the effects of sudden fluctuations, flickering, unbalances and harmonics. It then indicates the allowable limits of disturbances of various kinds and defines the type of facilities and compensation devices which can be used to reduce these disturbances. In French.

2. Stratford, R.P. "Rectifier Harmonics in Power Systems", IEEE Industry Applications Society Conference, (Cat. No. 78 CH 1346-6 IA), October 1978, pp. 1275-1280.

This paper describes the effect of rectifier harmonic currents on power systems. Rectifiers and inverters require non-sinusoidal waves of current. These current waves are made up of a number of sine waves which are harmonics

of the fundamental wave. These harmonic currents can excite resonant circuits causing them to "ring" and produce large oscillating currents. Criteria as to possible problem areas are discussed and illustrated with case studies. Examples of application of filters to "trap" these harmonic currents are included. In English.

3. Hardell, Alexander, "Must We Put Up with the Contamination of Our Networks by Harmonic Oscillations", Elektrizitaetswirtschaft, Vol. 77 No. 19, September 1978, pp 672-675.

In view of the increasing loading of public electricity supply systems with currents containing harmonics the future operation of these systems is considered. Contrary to optimistic forecasts which are based on the advantages of power electronics and the necessity for their unlimited application, the operational disadvantages and the additional costs which this technique involves for electricity supply undertakings are discussed. Suggestions are made as to how these harmful effects can be minimized. In German.

4. Hammad, A.E. and Mathur, R.M., "New Generalized Concept for the Design of Thyristor Phase - Controlled VAR Compensators - 1. Steady State Performance", IEEE Power Engineering Society Summer Meeting, 1978, Paper No. F78 719-7, 8 pages.

An alternative approach to the realization of an effectively variable reactor is through the control of the current in an otherwise fixed reactance inductor branch. This is accomplished by a phase control of current conduction in the reactor arm by using an antiparallel arrangement of a thyristor pair, per phase. Thyristor phase control is simple in principle, uses linear reactors which do not pose a switching inrush current problem (unlike capacitors), is very fast and with recent advances in high power thyristor technology, has become cost effective. The generalization brings out a whole new range of possible designs from which an optimum can be selected. The most attractive features of the new designs are that they produce fewer harmonics and appear cost effective due to savings possible in filtering and valve equipment. The paper develops a general analysis, and presents algebraic expressions for the harmonic magnitudes which can be readily used for the known designs. In English.

5. Frosch, Soenke and Schultz, Walter, "Digital Calculation of the Harmonic Load in Power Systems and Equipment", Siemens Review, Vol. 45, No. 6, June 1978, pp. 288-292.

A description is given of a digital computer program designed to ascertain the harmonic loading of extensive power supply systems and the equipment connected therein. The systems to be studied can be completely simulated, including voltage levels. It is possible to take account of the frequency response of each separate system-element. Application possibilities and examples are also given. In English.

6. Koknttinen, K., Ampuja, M. and Purves, S., "Ironing Out Distribution Disturbances with Harmonic Filters", Electrical Review, Vol. 202, No. 20, May 1978, pp. 28-30.

Power transmission and distribution systems are designed to operate at a constant frequency and at sinusoidal voltage and current. Non-linear loads,

however, such as thyristor drives and arc furnaces, produce excessive harmonic currents which cause both current and voltage distortion. The best solution to this problem is harmonic filtering which can be applied to low voltages as well as to the highest power transmission voltages. In English.

7. Crevier, Daniel and Mercier, Andre, "Estimation of Higher Frequency Network Equipment Impedances by Harmonic Analysis of Natural Waveforms", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, No. 2, March-April 1978, pp. 424-431.

A digital method of analyzing harmonics in a power system has been developed which permits the equivalent network impedance to be estimated by means of the switching of capacitor banks. The method records voltage and current digitally and by data processing computes the amplitude and phase of the harmonics. By comparing results before and after the switching of a capacitor bank on one phases, the equivalent network impedance is estimated at the odd harmonics. Precision of results is acceptable in amplitude but less accurate in phase. In English.

8. Kitai, Reuvers, "On-Line Measurement of Power System Harmonic Magnitude and Phase Angle", IEEE Transactions on Instrumentation and Measurement, Vol. IM-27, No. 1, March 1978, pp. 79-81.

A measurement method is described based on Walsh spectrum measurement in the first instance, with subsequent digital computation to provide the Fourier spectrum of a periodic voltage $g(t)$ in magnitude and phase. This two-step method particularly will be suited to power-frequency waveform measurements. In English.

9. Chec-Hing, D.J., Julien, K.S. King, ST.C., Quintana, V.H. and Srivastava, K.D., "A Method for Power Factor Compensation and Harmonic Current Elimination in Industrial Deterministic Power Systems", IEEE Power Engineering Society Winter Meeting, 1978, 066-3/1-8.

The classical use of reactive compensators in linear systems and the application of harmonic filters and harmonic current injection methods to nonlinear systems, are shown to be special methods of a generalized approach to power factor compensation. The complementary method which is based on the principle of waveshaping also results from the generalized approach. It is shown that for certain nonlinear deterministic cases, the described complementary method can be more effective than the traditional approach to compensation, since no knowledge of the harmonic current components is required. In English.

10. deMello, F.P. Johnson, B.K., Hannett, C.N., Birket, D. and Toulemonde, J., "Thyristor-Controlled Reactors, Analysis of Fundamental Frequency and Harmonic Effects", IEEE Power Engineering Society Winter Meeting, 1978, Paper No. A78 106-7, 8 pages.

The static var compensator is well-suited for application to transmission systems subject to abrupt changes in reactive power demands. From performance, cost and reliability points replacement for synchronous condensers. Operational characteristics of thyristor-controlled reactors are described both in terms of the instantaneous cycle-by-cycle behavior of currents and voltages as well as their fundamental frequency effects. Examples of applications on Power Systems, tests on a prototype system and digital simulation results are described. In English.

11. Sonobe, Tadashi and Masada, Eisuke, "Analysis of Harmonic Voltage Stability of HVDC Link by Impedance Matrix Method", Electrical Engineering in Japan, Vol. 98, No. 1, February 1978, pp. 106-113.

When the capacity of an ac system is not as large as that of a HVDC system, so-called harmonic voltage instability arises. This paper analyzes the harmonic voltage stability problem by the impedance matrix method. It takes into account the feedback effect of the ac system impedance. As a result of this analysis, it is shown that the stability is affected by the amplitude condition as well as by the phase condition. The amplitude condition is dependent upon the phase of harmonic voltage and control angle. The validity of the theoretical analysis is confirmed by simulation experiments. In English.

12. Hingorani, N.G., Vanders, I., Hauth, R.L., Lasseter, R.H., Lindh, C.B., Numrich, F.H., Price, N.W., "HVDC-AC System Interaction from AC Harmonics", Proceedings of the Symposium on HVDC Power Transmission, Portland, Oregon, November 28-30, 1978, pp. 151-191.

Considers instrumentation and measuring techniques to determine the harmonic impedance of a system. Calculation of the harmonic impedance of a system is also discussed. In English.

1977

1. Ibragimov, I.E., "Investigation of the Stability of Third Subharmonic Oscillations in the Compensated Line - Transformer", Izvestiya Vysshikh Uchebnykh Zavedenii, Energetika, No. 12, December 1977, pp. 10-16.

An equation in terms of deviations for any harmonic is obtained for the initial nonlinear equation describing the investigated system. This equation is transformed to a form convenient for obtaining the periodic oscillation stability condition. Calculation formulas are obtained for plotting the regions of stability of third subharmonic oscillations. They may be used in designing and operating compensated lines and networks. In Russian.

2. Stanley, C.H., J.J. Price, and G.L. Brewer, "Design and Performance of AC Filters For 12 Pulse HVDC Schemes", IEEE 2nd International Conference on Power Electronics - Power Semiconductors and Their Applications, Sept., 1977, pp. 158-161.

Considers three types of single branch filter, giving the design basis and assumptions used to achieve a reasonable harmonic performance with the minimum of complexity, cost and losses in the equipment. These assumptions are chiefly those concerning ac system harmonic impedance, maximum permitted harmonic voltages and the magnitude of the characteristic (12 pulse) and uncharacteristic harmonic currents. Particular attention is paid to often overlooked factors that affect the magnitude of uncharacteristic harmonics. The paper also describes the basis on which the filter components are rated. In English.

3. Missen, L.G., "Measurement of Power Supply System Harmonics", Electric Energy Conference, Sydney, Australia, Sept., 1977, pp. 25-32.

Instrumentation previously used for measuring waveform distortion in Sydney's power supply is briefly reviewed together with techniques now available. The

basis design and specification of a parallel filter analyser is discussed and its performance critically analyzed. Overall uncertainty in measurement of typical harmonic voltage levels is estimated, and a comparison made between results from 24 hour and weekly recordings. Limiting values for harmonic levels are now appearing in literature, but there seems to be no definition for such a limit, in relation to the constantly varying conditions found on a power supply system. A definition for a harmonic disturbance is needed, relating magnitude, duration and frequency of occurrence. This must be done before a claim of high accuracy in measurement has any meaning. In English.

4. Showers, R.M. and Kocher, C.P., "Modeling of Harmonics on Power Systems", IEEE International Electromagnetic Compatibility Symposium Record, (Cat. No. 77 CH 1231-0 EMC) August 1977, pp. 414-426.

A quantitative analytical model is described which is considered reliable for harmonic components up to at least 100 kHz. Comparisons between experimental measurements and theoretical model are quite good. The model is valuable in providing good estimates of the harmonic levels on a power system in its early stages of design and a rational basis for setting limits of conducted current emission and voltage susceptibility. In English.

5. Crevier, Daniel and Mercier, Andre, "Estimation of Higher Frequency Network Equivalent Impedances by Harmonic Analysis of Natural Waveforms", IEEE Power Engineering Society Summer Meeting, July 1977, Paper F 77 659-6, 8 pages.

A digital method of analyzing harmonics in a power system has been developed which permits the equivalent network impedance to be estimated by means of the switching of capacitor banks. The method records voltage and current digitally and by data processing computes the amplitude and phase of the harmonics. By comparing results before and after the switching of a capacitor bank on one phase, the equivalent network impedance is estimated at the odd harmonics. Precision of results is acceptable in amplitude but less accurate in phase. In English.

6. Szabados, B, and E.F. Hill, "On-Line Phase Measurement of Power System Harmonics", IEEE Transactions on Instrumentation and Measurement, Vol. IM-26, No. 2, June 1977, pp. 170-175.

A new instrument which allows on-line measurements of the phase angle of harmonics is presented. It is used in conjunction with a wave analyzer and provides amplitude and phase angle of harmonics. The principle of the measurement is an analogue null detection. Hence the accuracy depends practically only on the quality of the tuned voltmeter used. Direct digital read out is provided for the angle. Design criteria, practical implementation and actual performance are presented. The instrument has demonstrated great potential in the study of ferromagnetic devices, core-loss curves, and power system harmonics. In English.

7. Lemoine, M., "Methods of Measuring Harmonic Impedances", International Conference on Electricity Distribution, Pt. 1. Contributions, May, 1977, pp. 23-27.

Preventing harmonic pollution of networks may be achieved by limiting the disturbing apparatus harmonic voltage contribution at the point of its connection to the public network. Most of the disturbing apparatus are sources of harmonic currents; however, the harmonic voltage characterizes the

pollution disturbing effect. This voltage being the result of the two terms of Ohm's Law, it is absolutely necessary to control informations concerning the impedances of the networks. The methods presented here enable the terms R and JX of the equal assumed positive- and negative-sequence harmonic impedances, and those of the zero-sequence harmonic impedance to be measured or recorded in situ, at the connection point of a disturbing customer. In the frequency range of about 100 Hz - 1300 Hz. In English.

8. Becker, H. and W. Schultz, "Principles for the Assessment of the Feedback Effects of Harmonics in Supply Systems", Elektrotechnische Zeitschrift, Ausgabe A, Vol. 98, No. 5, May 1977, pp. 335-338.

For investigations into the harmonic loading in power- supply systems the system components are simulated in accordance with their frequency dependence. Basic relationships and figures obtained from experience are given. Using a model system investigations are made into the effect of filter circuits on voltage distortions, and of additional loadings on the operational apparatus. The contribution concludes with a few basic data on the layout of filter circuits. In German.

9. Santarius, P., "Determining Higher Harmonics in Electric Networks", Energetika, Vol. 27, No. 5, May 1977, pp. 204-207.

The authors describe the measuring apparatus employed for carrying out harmonics analysis by means of active filters. The measuring apparatus makes it possible for a continuous analysis of a current and voltage-wave over a frequency range from 50 to 100 Hz. In Czech.

10. Chanas, M. and P. Meynaud, "Influence of Short-Circuit Power on Voltage Interferences", Revue Generale de l'Electricite, Vol. 86, No. 2, Feb. 1977, pp. 97-104.

Shows that an increase of short-circuit power tends to reduce voltage interferences which can arise from the equipment of some users. The presence of capacitors intended to compensate the reactive power can give rise, in harmonic conditions, to resonance when some specific conditions are met. The study of these conditions is considered by means of theoretical series, and parallel models representing diagrammatically the systems and their loads. In French.

11. Engiver, R., "Compensation in Supply Systems with Harmonics", Elektro-Anzoiger, Vol. 30, No. 4, Feb. 1977, pp. 28-29.

The increasing use of low voltage converter controlled plant and drives produces harmonics in the systems with undesirable loading. In practice, the 5th, 7th, 11th and 13th harmonics are significant. Means of correction include the use of tuned filter-circuit capacitor batteries, fixed capacitors, automatically regulated filter-circuit capacitors, or automatically regulated untuned filter-circuit equipment. The latter method has considerable advantages. In German.

12. Madruzza, M. and E. Tironi, "Harmonics in Currents and Voltages of Fully Controlled Bridge Converters", Elettrotecnica, Vol. 64, No. 1, Jan. 1977, pp. 69-79.

The evaluation of harmonic contents of a fully controlled bridge converter is extended to all possible operations, from no-load down to short circuit, filling in a gap in the IEC Publication 84; diagrams are reported corresponding to the most significant values of per-unit voltage drop, from no phase control operation down to vanishing of rectified voltage average value. In Italian.

13. Ibragimov, I.E., "Problem of Clarifying the Possibility of Generating Fundamental Harmonic Oscillations in the Nonlinear System Compensated Line-Transformers", Izvestiya Vysshikh Uchebnykh Zavedenii Neft i Gaz, No. 3, 1977, pp. 88-90.

An expression is obtained for clarification of the possibility of generation of non-attenuating fundamental harmonic oscillations in lines with series-connected capacitors, for maintaining and controlling voltage. If it is found that nonattenuating oscillations may occur, the proposed expression can be used to determine the value of the resistance that could be connected in parallel to the capacitors to suppress these oscillations. In Russian.

14. Frosch, S. and W. Schultz, "Digital Calculation of the Harmonic Load in Power Systems and Equipment", Siemens-Zeitschrift, Vol. 51, No. 11, 1977, pp. 899-903.

A description is given of a digital computer program designed to ascertain the harmonic loading of extensive power supply systems and the equipment connected therein. The systems to be studied can be completely simulated, including all voltage levels. It is possible to take account of the frequency response of each separate system element. Application possibilities and examples are also given. In German.

15. Mohan, N., et al., "Active Filters For AC Harmonic Suppression", IEEE Power Engineering Society Winter Meeting, 1977, Paper No. A 77 026-8.

AC/DC converters used in HVDC transmission systems inject harmonics into their associated ac and dc systems. Such converters are also proposed in conjunction with wind power generation, fuel cells and some other energy storage devices. Series-tuned passive filters are used to prevent the harmonic currents from entering into the ac network. However, the passive filters get detuned if the system frequency changes or if the filter parameters change due to temperature variation or age. In this paper, a new concept of active filters is presented, which do not have the limitations mentioned above. Basic concepts and design of active filters for eliminating ac harmonics are considered and preliminary computer simulation results are presented. In English.

1976

1. Ribeiro, C.F., "Plan Power Supply for Static Rectifiers", Electrical World, Vol. 186, No. 12, Dec. 15, 1976, pp. 54-55.

Installation of a static rectifier can result in a host of maladies on a power system unless network characteristics are examined closely. Recommendations for total harmonic voltage are given. In English.

2. Anisimov, YA.F., "A Probability Method of Finding the Resonant Frequencies in Power Systems Incorporating Diode Converters", Izvestiya Vysshikh Uchebnykh Zavedenii, Energetika, No. 12, Dec. 1976, pp. 26-30.

Power systems which contain both rectifier substations and capacitor banks face the risk of resonances developing at harmonic frequencies. The author develops a probability method of predicting these resonant frequencies, showing that their distribution follows a Gaussian Law. In Russian.

3. Kucer, M., "Reduction of Harmonics - Harmonics in Industrial Power Systems and Measures for Their Reduction", Elektrotechnik, Vol. 58, No. 21, Nov. 1976, pp. 17-18.

Outlines developments in power electronics which have encouraged the increasingly wide application of converters resulting in high content of harmonics in the supply system. Discusses the manner in which these harmonics arise, the methods for calculating their frequency and amplitude, the difficulties which they can cause and technical measures for the reduction of harmonic content. In German.

4. Holm, R.K. and R.P. Stratford, "Harmonic Analysis of Typical Paper Mill Power System", TAPPI Engineering Conference, Book 2, Oct. 1976, pp. 134-143.

In the last decade paper machine drive systems have evolved from power supplies consisting mainly of motor generator sets to those of thyristor power converters. In doing so, a new phenomenon was introduced into the power system, namely, that of generated harmonic currents. This paper describes the harmonic resonant characteristics of typical paper mill power systems. The effect of distributed and lumped power factor capacitors is reported and their resultant influence on harmonic currents associated with thyristor converters. Problems that might arise due to these harmonic currents and resonance are described and solutions to them discussed. Case studies are reported. In English.

5. Malewski, R. and J. Douville, "Measuring Properties of Voltage and Current Transformers for the Higher Harmonic Frequencies", IEEE Canadian Communications and Power Conference, Oct. 1976, pp. 327-329.

Measuring properties of instrument transformers were investigated to establish the accuracy of recording higher harmonics of the power frequency voltage and current in transmission and distribution systems. In English.

6. Eichin, P.E. and D.P. Callahan, "Measurement of Induced Noise and Filter Performance of HV Direct-Current Power Systems", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-95, No. 5, Sept.-Oct. 1976, pp. 1630-1638.

This paper is a description of a "Recommended Guide for Measurement of Electrical Noise and Harmonic Filter Performance of High Voltage Direct-Current Systems" being prepared for publication by the EHV AC/DC Working Group of the Inductive Coordination and Electrical Protection (ICEP) Subcommittee of the Communications Society's Wire Communications Committee. Information provided herein and in the guide should serve as an aid to the power and the telecommunications utilities who may be involved in organizing and implementing an inductive coordination program for high voltage direct-current (HVDC) facilities with wire communications. HVDC systems designers should also find the information useful in determining AC and DC filter requirements. In English.

7. Subbarao, T. and J. Reeve, "Harmonics Caused by Imbalanced Transformer Impedances and Imperfect Twelve-Pulse Operation in HVDC Conversion", IEEE

Transactions on Power Apparatus and Systems, Vol. PAS-95, No. 5, Sept. - Oct. 1976, pp. 1732-1737.

In substituting a degree imbalance between the phase impedances of HVDC converter transformers for the usual assumption of equal impedances, the generated ac harmonics are modified and triplen (non-characteristic) harmonics are produced. They are analyzed and assessed; and are not expected to be serious provided due attention is paid to impedance balancing. Certain normal harmonics for 6-pulse operation are ideally eliminated by 12-pulse operation. An analysis is made of the extent of residual 6-pulse harmonics due to the imperfect balance of 12-pulse bridge operation. The paper provides a basis for specifying certain design tolerances. In English.

8. Ampuja, M., "Harmonic Filters in a Power Transmission Network", Saehkoe, Vol. 49, No. 7-8, July-Aug. 1976, pp. 275-277.

The article describes the principle and construction of harmonics filters in a power transmission network and examines the data required in designing a filter. In Finnish.

9. Sasu, M., et al., "Determination of the Harmonic Distribution in a Power Network with Distorting Regime", Electrotehnica, Electronica si Automatica Electrotehnica, Vol. 24, No. 5, July 1976, pp. 162-168.

The paper presents an original method for the computation on a digital computer of the current and voltage harmonic distribution in power networks working in distorting regimes. In Rumanian.

10. Mol, J., "Recommendation for Admissible Harmonic Flow with Non-Domestic Appliances", Elektrotechnik, Vol. 54, No. 6, June 1976, pp. 368-369.

This report deals with harmonic currents produced by non-linear components of non-domestic apparatus. Harmonic currents, being injected in the electrical network, lead to harmonic voltages in the electrical installation of other customers. In this report some rules are given, enabling manufacturers, customers in electricity undertakings to prevent difficulties. In Dutch.

11. Steeper, D.E. and R.P. Stratford, "Reactive Compensation and Harmonic Suppression for Industrial Power Systems Using Thyristor Converters", IEEE Transactions on Industry Applications, Vol. IA12, No. 3, May - June 1976, pp. 232-254.

This paper discusses the problems and solutions of applying reactive compensation, either static or dynamic, to industrial power systems supplying large blocks of dc power from diode or thyristor converters. The resonance between power capacitors and system reactance can produce high harmonic voltages caused by the harmonic currents, generated by converters. The interaction between these harmonic voltages and regulating systems can be minimized by the use of suitable filters. The design of these filters should eliminate the interaction between power system and load and reduce harmonic current flow. Different methods of reactive power control are also discussed. In English.

12. Lemoine, M., "Measurement of the Harmonic Impedances of an Electric Power Supply Network by Two Nonspectral Methods", Bulletin de la Direction des Etudes et Recherches, Serie B, No. 1, 1976, pp. 5-28.

Two methods are described for determining network impedances, from the information contained in the distortion of a disturbing current applied to the network and in the distortion of the disturbed voltage resulting therefrom. These methods have reached the stage of practical application to networks. In French.

13. Kline, R., "Reciprocal Influence of Rectifier and Inverter Setups and Quality of the System", Revue Generale de l'Electricite, Vol. 85, No. 3, March 1976, pp. 231-246.

Considers the influence of the rectifier and inverter sets upon the system (harmonics, voltage deformations, reactive, high frequency disturbances), and the influences of the system upon the rectifier and inverter sets (voltage variations and deformations, phase unbalance, frequency changes, transient, total or partial disappearance of one or several phases, discordance between systems, high frequency disturbances carried along by the system). Analyzes the operating mechanisms, and discusses remedies which are to be taken with regard to the cost and to the existing regulations and standards. In French.

14. Lemoine, M., "A Few Aspects of System Pollution Due to Harmonic Distortions of the Users", Revue Generale de l'Electricite, Vol. 85, No. 3, March 1976, pp. 247-255.

Discusses the permissible harmonic voltages and the influence of conventional equipment such as rectifiers. Summarizes the nature of the harmonic impedances in electric systems and describes a method for impedance measurement by experimental and mathematical processes. In French.

15. Anisimov, YA.F., "Probabilistic Evaluation of the Conditions for Occurrence of Higher Harmonic Resonances in Systems Containing Rectifier Converters", Izvestiya Vysshikh Uchebnykh Zavedenii, Energetika, No. 2, Feb. 1976, pp. 24-30.

It is shown that the distribution laws for the equivalent admittance network for the higher harmonics, including the admittances of energy sources and receivers and capacitor banks, is normal. An expression is obtained for the parameters of this distribution law. In Russian.

16. Bretschneider, G. and E. Waldmann, "Maximum Level of Harmonics in Power Systems", Elektrotechnische Zeitschrift, Ausgabe A, Vol. 97, No. 2, Feb 1976, pp. 90-96.

Using the equivalent circuit for a medium voltage network, the performance of the harmonic voltages in relationship to their harmonic number is demonstrated, the influence of these voltages on induction motors and capacitors is investigated. In German.

17. Edwin, K.W., et al., "Rated Power of Illustrations with Symmetric Semiconductor Controlled Rectifier", Elektrotechnische Zeitschrift, Ausgabe A, Vol. 97, No. 2, Feb. 1976, pp. 69-74.

Harmonic voltages and additional transmission losses are produced by full-wave ac power-control circuits. Beginning with a statistical examination of the characteristics of existing low voltage networks, the harmonic impedance depending on frequency and load, the harmonic voltages and

the additional transmission losses depending on the characteristics of the loads are determined. The affects of some important characteristics of the controlled loads are shown. The results are tested by statistic methods obtaining limits with determined probability. In this respect, the limitation of power in existing specifications the results enable a reexamination of necessary standards. In German.

18. Heikkila, H., "Harmonics in a Power System", Saehko, Vol. 49, No. 1, Jan. 1976, pp. 27-30.

The article takes a look at the problems caused by the increasing occurrence of harmonics in electricity networks, such as a deterioration in the quality of supply, telephone interferences and increasing losses in networks and consumer devices. Owing to the lack of international standards the need for national recommendations and regulations concerning devices causing harmonics is pointed out. In Finnish.

19. Prabhakara, F.S. and K.R. Shah, "A Simplified Method of Calculation of Telephone Interference From HVDC Lines", IEEE Power Engineering Society Winter Meeting; Paper A76 198-2/1-8, 1976, pp. 25-30.

Discusses a net method of calculating the harmonic current distribution along HVDC pole conductors by using ABCD constraints. The calculation procedure for all three modes of operation; namely, bipolar, monopolar earth and metallic return (with and without filters), are included. Some representative induced noise voltage profiles, and the permissible exposure lengths of telephone lines obtained from the calculated harmonic current distribution are also given. In English.

20. Zhezhenlenko, I.V., "Norming of Harmonic Levels with Regard to Economic Loss", Electric Technology, USSR, No. 2, 1976, pp. 64-76.

Considers technical and economic aspects of higher harmonics in electrical networks. A method is proposed for selection of a generalized non-sinusoidality index in actual cases for economic substantiation and with regard to constraints imposed by technical requirements. In English, translated from Russian.

21. Hodinka, M., "Problems of Quality of the Electrical Supply", Elektrie, Vol. 30, No. 10, 1976, pp. 544-545.

Recent increases in the use of power converters, measuring, regulating, control and data transmission schemes, in the number of consumers connected to polyphase supplies, in the voltage level and short circuit currents have caused problems of voltage fluctuations, harmonic content and asymmetry of the power supply and have affected its quality. Reference is made to some national and international standards. Codes of practice and reports on the general aspect of electromagnetic compatibility and electromagnetic ecology and, in particular, to a program of theoretical and experimental work in Czechoslovakia. In German.

22. Vithayathil, J.J., Melvold, D.J., Madzarevic, V., "Calculation and Measurement of Harmonics on the A-C Side of Converter Stations of the Pacific HVDC Intertie", Proceedings of the U.S. - U.S.S.R. Symposium, Leningrad, 1976, pp. 269-324.

Discusses the harmonic generation and measurement data from the HVDC stations for different modes of operations. Harmonic penetration into the ac system is discussed. Carrier frequency noise propagation from the converters to the ac side is measured and discussed. In English.

23. Yemel'yanov, V.J., Kraichik, Yu. S., "Calculation and Measurement of Harmonics at the Alternating-Current Side of Converter Stations of Volgograd - Donbass Power Transmission", Proceedings of U.S. - U.S.S.R. Symposium, Leningrad, 1976, pp. 325-358.

Presents a method of calculating harmonic generation from converters, harmonic voltage of system and current flow to system. The effect of harmonic filters and possible harmonic amplifications are discussed. In English.

1975

1. Washburn, D.C. "Thyristor Power Supplies and AC Harmonics", Conference Record of IAS Annual Meeting, Sept. Oct. 1975, pp. 122-127.

Presents a brief review of the origin of the ac harmonics and an indication of the possible effects these harmonics may have. Some of the available techniques for their analysis and mitigation are presented. In English.

2. Nikoloff, I., "Electrical Oscillations in the Feeding Mains Produced by Direct-Current Control Tractive Units", Eisenbahntechnik, Vol. 23, No. 9, Sept, 1975, pp. 394-397.

A brief consideration of the origin of oscillations in the feeding mains by direct-current control tractive units is followed by formulas determining harmonics of the resulting control current in symmetric and unsymmetric operation of the individual direct-current controls of a tractive unit. For the individual direct-current control motor coach train a resulting harmonic generator and a hum eliminator can be derived. The direct-current control circuits are divided into three groups, and are evaluated in view of harmonics generated in the mains. In German.

3. Goel, R.C. "Certain Aspects of Generation and Control of Abnormal Harmonics in EHV DC Transmission System", Journal of the Institution of Engineers (India) Electrical Engineering Division, Vol. 56, PR. EL-1, Aug. 1975, pp. 9-12.

In this paper, various causes of generation of disturbing harmonics in EHVDC transmission system are discussed. Various factors affecting the magnitude in synchronous alternators feeding the associated ac system are considered so that the level of the third, fifth, and seventh harmonics in the output wave may be as small as possible. Some salient features of the mode of control for minimizing the harmonics and use of additional filters when harmonic resonance conditions are anticipated, are also discussed. In English.

4. Waldmann, E. "System Reactions", Elektrizitaetswirtschaft, Vol. 74, No. 17, Aug. 1975, pp. 615-621.

The use of thyristors in power systems for phase control and burst firing control causes reactions on other electrical apparatus and installations, which are transmitted via the power-distribution systems. Further, increases

in power of apparatus and installations make the reactions more pronounced. The author gives a review of the extent and types of such reactions and deals with proposals and regulations for limiting them to permissible values. The problems which can be referred to by the terms flicker, harmonics and asymmetry are described. In German.

5. Germond, A.J., "Computation of Ferroresonant Overvoltages in Actual Power Systems by Galerkin's Method", Power Industry Computer Applications (PICA) Conference, June 1975, pp. 127-135.

This paper develops a numerical technique for solving the problem of periodic ferroresonant overvoltages in a power system. The system is modeled as a set of nonlinear ordinary differential equations, whose periodical solutions are found by a numerical algorithm based on Galerkin's method. It is shown that this approach takes into account the various aspects of ferroresonance phenomena, i.e., harmonic as well as even or odd order subharmonic oscillations. Results computed by this technique are presented and discussed. In English.

6. Linde, M. "Running Harmonic Analysis of Measured Samples", Biuletyn Institute Energetyki, Vol. 17, No. 5-6, May-June 1975, pp. 37-39.

The paper contains the formulas for determining the values of the Laplace transformation based on consecutive samples of the original. These formulas are useful for data processing. New values of the transform are calculated after each sample has been received. The description of counting procedure organization is given. In Polish.

7. McLure, G.K., "Harmonic Effects in Power Systems Resulting From Use of Large Static Drives", 17th IEEE Cement Industry Technical Conference, May 1975.

Harmonics and their effects are of increasing concern both in industrial plants, the power plants that supply them, and neighboring communication networks. The nature of harmonic problems that can be encountered due to the presence of static drives in an industrial plant are reviewed. Both the origin of and the solution to the problems are discussed in qualitative terms. In English.

8. Lips, H.P. and Hans Ring, "Performance of AC Systems with Predominant Power Supply by HVDC Inverters", IEEE Transactions on Power Apparatus and Systems, Vol. PAS- 94, No. 2, Mar. - Apr. 1975, pp. 408-415.

Mode tests are described which have been conducted to investigate the performance of "weak" ac systems with dc injection. It is shown that system frequency can be controlled effectively by HVDC inverter stations. Switched capacitors may be used for voltage control. It is shown that power injection into ac systems by line commutated HVDC inverters is possible down to short circuit ratios far below 1. In English.

9. Bayard, O. and J. Fox, "Pulsed Load Characteristics and Voltage Stabilization", Revue Generale de l'Electricite, Vol. 84, No. 3, March 1975, pp. 160-164.

Reports on problems raised by direct feeding of the 400 GEV CERN accelerator by the EDF supply system. Discusses the problems presented by the 148 MW pulsed load in continuous duty. Describes the characteristics of this load

and methods used in order to maintain voltage fluctuations and harmonic distortions within acceptable limits. In French.

10. Baert, D., "Interference and Distortion in Supply Mains", Bulletin de la Societe Royale Belge des Electriciens, (Belgium), Vol. 95, No. 1, Jan. - March 1975, pp. 1-11.

A general survey is given of the sources of wave form distortion in mains supply systems and of the harmonics produced by non-ohmic loads such as rectifiers and thyristors. The frequency range of the harmonics produced is indicated. A mathematical explanation of the use of filters, capacitors and inductors in suppressing harmonics is provided. Some standard artificial networks have been used to compare the distortion produced by various sources. In Dutch.

11. Freris, L.L., and J.N. De Carvelho, "Electromechanical Filter and Its Performance in DC Transmission Systems", Proceedings of the Institution of Electrical Engineers, Vol. 122, No. 1, Jan. 1975, pp. 55-60.

It is shown that a novel filter based on an electromechanical principle is superior to conventional static filters with respect to both suppression of harmonics and supply of reactive power to converters. New forms of filter are proposed on the same principle, and the design philosophy is briefly discussed. A steady-state stability analysis of a dc link between weak ac systems reveals that the stable regime is wider with the new filter than with the conventional static filters. In English.

12. Kummerly, H., "Methods for Measuring Supply Frequency Harmonics", Bulletin de l'Association Suisse des Electriciens, Vol. 66, No. 1, Jan. 1975, pp. 19-24.

Describes methods in use in Switzerland for systematically measuring and recording the harmonic disturbances produced by electronic motor control and similar equipments, and discusses the precautions to be taken to prevent excessive harmonic pollution of the networks. In German.

13. Zhezhelenko, I.V., "On Errors in the Calculation of Harmonics in Power Networks", Problemy Tekhnicheskoi Elektrodinamiki, No. 55, 1975, pp. 44-50.

Voltage waveform distortion is an important factor in power supply quality and the concept of the "nonsinusoidality factor" is one of many ways that have been used to characterize it. This factor is not linked functionally with the cost to the economy or anyone else of harmonics present in the voltage waveform. In Russian.

14. Shidlovskii, A.K., A.D. Muzychenko, and V.F. Budennyi, "Analyzing the Output Voltage of a Multiphase Rectifier with an Asymmetric Supply Voltage", Problemy Tekhnicheskoi Elektrodinamiki, No. 55, 1975, pp. 14-19.

Shows what happens to the harmonic spectrum of the output voltage when a multiphase rectifier is fed from an asymmetric three-phase supply. Relationships are derived for the direct terms of the number of phases in the rectifier and the degree of asymmetry in the supply voltage. Using their own method of measuring the negative sequence components, the authors show that when the number of rectifier phases is multiplied to nine, the amplitude of the second harmonic in the output is proportional to the amplitude of the negative-sequence component in the input. In Russian.

15. Morrow, L.D., J. Deshmukh, and D.P. Atherton, "On-Line Harmonic Analysis and Phase Measurement", International Electrical Conference, Montreal, 1975, Paper No. 75334.

This paper describes the development of a digital program, used on-line with an EAI-590 hybrid computing system, which can be used to obtain the relative phases and magnitudes of the harmonics of two periodic signals which have the same fundamental frequency. In English.

16. Karpov, I.V., "Symmetry of the Harmonic Spectra of Three-Phase Networks", Problemy Tekhnicheskoi Elektrodinamiki, No. 55, 1975, pp. 51-55.

Regardless of whether the fundamental is symmetrical or otherwise, the author shows that relatively minor asymmetry in the fundamental can be accompanied by severe asymmetries in the higher harmonics. It is possible to establish a law of distribution of the harmonic spectra of currents and voltages which takes symmetry into account. In Russian.

1974

1. Tsaregorodtsev, V.A., "Technical and Economic Evaluation of Damage Caused by the Nonsinusoidal Shape of the Current and Voltage Curves for Power System Electrical Networks", Izvestiya Vyssikh Uchebnykh Zavedenii, Energetika, No. 12, Dec. 1974, pp. 12-16.

The operation of various different components in electrical systems is affected adversely by the presence of higher harmonics - power losses are increased, the thermal conditions of the equipment deteriorate, the aging process is accelerated in the insulation, etc. A procedure for the technical and economic evaluation of damage due to the higher harmonics is proposed and the application of various measures designed to reduce the magnitude of the current and voltage harmonics in the basic networks of a power system is justified. In Russian.

2. Pedder, D.A.G., "Passive Output Filters for Use with Lightweight Waveform Synthesizing Inverters", IEEE International Conference on Power Semiconductors and Their Applications, Dec. 1974, pp. 216-221.

The use of waveform synthesis techniques enables physically small lightweight power inversion systems to be realized. Techniques for the design of power filters have been formulated, but these have, in general, been devoted to meeting electrical specifications with no attention paid to the physical dimensions of the filter components. To enable minimization of size or weight, a method for comparing the physical dimensions of filters is necessary and it is suggested that an equivalent fundamental-frequency VA rating forms a suitable basis for comparison. In English.

3. Zhezhelenko, I.V. and V.M. Sorokin, "Higher Harmonics in Electric Networks", Elektrichestvo, No. 11, Nov. 1974, pp. 23-28.

Attention is drawn to the problem of higher harmonics in regard to the problem of maintaining voltage quality. Increasingly many valve-type converters, arc furnaces, welding gear and other devices with a nonlinear Volt-Ampere characteristic cause distortion of the network current and voltage curves, characterized by a discrete spectrum of harmonic amplitudes and initial phases. In USSR and Comecon countries the permissible

non-sinusoidality is 5%, but this level is found to be far exceeded often. Amongst other considerations, the prognosis of expected harmonics in various network regimes is contemplated. Recommended apparatus of multi-purpose type for improving several qualitative criteria, besides filters is presented. In Russian.

4. Musa, E.H., "Effects of Harmonic Disturbance", Electrical Times, No. 4291, July 25, 1974, pp. 13.

It is suggested that increasing use of thyristor- controlled systems, both in the domestic and industrial fields, could result in the cumulative effects of harmonic distortion on the supply system having disastrous effects on the operation and stability of the network. Harmonic distortion on the supply system serving consumers from a common m.y. distribution network and its effects on electronic equipment such as electron microscopes, closed circuit television monitoring devices, digital clocks and analyzers, digital counters and measuring apparatus, including oscilloscopes, are discussed. In English.

5. Lendi, H., "Third Harmonic Currents in the Neutral Conductor", Bulletin de l'Association Suisse des Electriciens, Vol. 65, No. 9, May 1974, pp. 639-641.

In certain installations, e.g., stand-by power supplies with parallel-connected transformers, unwanted 3D harmonic currents occur which require special consideration. To avoid excessive heating of the neutral conductor, precautionary measures are proposed for adequate design parameters or, alternately, for a breaker arrangement in the neutral line. Also discussed are the conditions which lead to these excessive currents. In German.

6. Rowe, N.B., "The Summation of Randomly-Varying Phasors or Vectors With Particular Reference to Harmonic Levels", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 177-181.

When more than one harmonic generator is connected to a power network, the arithmetic addition of the maximum amplitudes will, in general, lead to an excessively high value at any given instant for the predicted resultant level of harmonics at a given summation point in the system. This paper gives the result of investigations, both theoretical and by computer simulation, into the summation of a number of component phasors when each is allowed to vary independently and randomly within given limits. The probability that the modulus of the vectorial sum will exceed some given value is found. In English.

7. Prebble, W.A., "Rectifier Harmonics in the Tasmanian Hydro-Electric System", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 256-260.

In the Tasmanian hydro-electric system, commencing with 50 MW of mercury arcs in 1956, the total rectifier load has increased by the addition of germanium and silicon rectifiers to 301 MW during which period the system minimum load has risen from 150 MW (three times rectifier load) to 470 MW (1.56 times rectifier load). At each stage of the expansion, harmonic generation has been limited by selecting suitable pulse numbers, and phase angle displacements for operation of the rectifier equipment. In English.

8. Lemoine, M., "Harmonic Distortions Due to Medium- Voltage Operated Alternating Direct Current Three-Phase Converters", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 246-250.

Concerning a medium voltage substation fitted with P.F. capacitors, the author intends to set about giving a boundary condition able to say whether harmonic distortion can be well suffered or not, in the primary eventuality, that is to say when no precautionary measures have been taken either by the industrialist or by the power supply authority. The aim is to protect the medium-voltage consumers against harmonic overvoltage, and the P.F. capacitors of the substation against harmonic overload, so the boundary condition is set out in a double form: connections between the short-circuit power of the network, and those of the converter and the capacitor, which can be turned into a double diagram. In English.

9. Duveau, P., "Report on the Harmonic Analyzer for the Distribution Network", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 209-213.

If simultaneous measurement of several harmonics is desired, one must have as many "wave analyzers" as there are harmonics to be studied. It therefore appeared worthwhile to study the principle of measuring devices possessing greater accuracy, adequate stability, and the ability to measure the characteristics of several harmonics at the same time. In English.

10. Brewer, G.L., R. Coates and C.D. Clarke, "Initial Operating Experience with the Filters for the Kingsnorth DC Scheme", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 156-161.

Filters are installed to limit the voltage distortion on the 132 kV busbars at the receiving terminals and the 400 kV busbars at Kingsnorth power station. In the South of England excess megavars at times of light load are more of a problem than compensation for the reactive demands of consumers and it was specified that the filters should contribute the minimum fundamental MVAR. Additionally, at the receiving sites space for filters was limited and these facts led to sulf-tuning filters being adopted at all three sites. Tuned arms were chosen for harmonics of order 5, 7, 11 and 13 with a damped arm for higher orders. In English.

11. Kidd, W.L. and K.J. Duke, "Harmonic Voltage Distortion and Harmonic Currents in the British Distribution Network, Their Effects and Limitation", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 228-234.

Harmonic levels and examples of problems on the British Distribution system are discussed along with methods of limiting harmonic contributions. In English.

12. Myles, A. and D.C. Howroyd, "Current Waveform Distortion at 25 kV Single Phase Supply Points to British Railways", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 241-245.

The 132 kV current waveform taken at the 132/25 kV substations supplying the British Railways 25 kV 50 Hz traction system is distorted, being single phase connected across two 132 kV system phases. The condition can cause difficulties of the public supply network and requires continuing investigation, since future expansion of the BR 25 kV electrified system is likely. This paper deals with the harmonic aspects of the problem. In English.

13. Barnes, H., "An Automatic Harmonic Analyzer for the Supply Industry", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 203-208.

In order to study the effects of non-linear thyristor control equipment loads, it is first necessary to be able to measure the magnitude of the distortion they cause, the resulting circulating currents and the sensitivity of the supply system to the distortion. A brief description of the analyzer's working principles is given. The two basic forms of distortion on the system to be analyzed are: one transient with random period and the other steady-state or slowly changing with a harmonic period. In automatic analysis, valuable information is obtained on the system and its loads. In English.

14. Bialkewicz, Z.S., "Reducing of Harmonics in MV Networks With LC-Filters", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 151-155.

There is a permanent rise in number and rating of converter equipments and arc furnaces installed in power systems, that leads to increase of harmonic contents. The paper deals with problems of the reduction of voltage distortion using LC filters. In English.

15. Wood, W.S., F.P. Flynn, and A. Poray, "Effects of Supply Voltage Waveform Distortion on Motor Performance", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 268-272.

The results are given in this paper from an experimental study of the effects of supply-voltage waveform on induction motor performance. Specific examples of such distortion are not used. Instead, single harmonics of selected magnitude are added to a chosen fundamental. For this purpose, a three-phase waveform synthesizer has been used which has given fundamental frequencies, to each of which can be added the first nine harmonics, odd and even, completely variable in magnitude and phase. The aim of the work is to provide basic information relating to the effect of order and magnitude of the harmonic introduced. Harmonic voltage magnitudes greatly in excess of those likely to be encountered are included. In English.

16. Brewer, G.L., "A Simple Method for Estimating Harmonic Filter Performance", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 162-167.

Harmonic filters are generally required to limit the injection of harmonic current into the supply system from larger converter installations such as HVDC transmission schemes. With the larger schemes the estimation of the harmonic impedance of the system to enable the most economic filters to be designed is a tedious and expensive process. It is possible, making certain simplifying assumptions, to assess the worst condition simply by reference to

a family of curves without the need to carry out detailed analytical studies. In English.

17. Strojny, J., "Some Problems of Harmonic Filter Construction for AC Supply Systems", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 168-171.

In the networks supplying thyristors, arc furnaces and other non-linear devices, special means for the diminution of current and voltage waveform distortion are needed. One of these are the resonant shunt circuits-harmonic filters. In English.

18. Handke, A.E., "Results of the Analysis of Current Harmonics in Power Network Supply of Monophase Thyristor Systems", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 182-187.

Such thyristor systems as single-phase, half-wave and full-wave controlled rectifiers and a single-phase alternating current controller, which will be more commonly switched onto three-phase, four-conductor electric alternating current networks, e.g., nominal voltage 380/220 V, were subject to an analysis. Attention was drawn to two characteristic cases of load, i.e., resistive load and resistive load with very high inductive load, taking into consideration the operation of discharging diodes. In English.

19. Casu, A. and V. Simoncini, "Harmonics Due to Rectifiers Connected to the Sardinian 220 kV AC Network", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 251-255.

A discussion of harmonic content in the network, filter efficiency, and the total voltage deviation dependency law. In English.

20. Corbyn, D.B. "Abnormal Harmonic Disturbances: Assessment and Mitigation", IEE International Conference on Sources and Effects of Power System Disturbances, No. 110, April 1974, pp. 235-240.

This is a general paper intended to highlight unusual industrial harmonic effects, to indicate their importance and to suggest means of mitigation. The object is to draw attention to some of the lesser known problems and assist in the rule-making now in progress in several countries. In English.

21. Reeve, J. and T. Subbarao, "Dynamic Analysis of Harmonic Interaction Between AC and DC Power Systems", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-93, No. 2, March-April 1974, pp. 640-646.

This paper describes a method of computing harmonics and waveforms in HVDC conversion, taking into account interaction with the AC system, dynamically. The performance of filters tuned at a nominal frequency is examined when the ac system frequency varies. Computed values of harmonic currents and voltages are presented and the influence of the ac system short circuit ratio is demonstrated. Harmonic magnification can occur due to resonance effects, but the system is harmonically stable. In English.

22. Salminen, P., "Harmonic Currents Generated by Thyristor Converters and Capacitors to Compensate for Reactive Power", Saehko, Vol. 47, No. 1, Jan. 1974, pp. 12-15.

Thyristor converters generate harmonic currents to an ac network and consume a substantial amount of reactive power with a partial load. Capacitor banks are the cheapest method for the compensation of reactive power. It is, however, possible that harmonic currents overload capacitors. The article deals with the overloading of capacitors and the resonance between the capacitors and the inductance of ac network. In Finnish.

23. Muller, R., "Interaction Between Harmonic Resonances in AC Networks and Current Control of an HVDC Plant", Elektrotechnische Zeitschrift, Ausgabe A, Vol. 95, No. 1, Jan. 1974, pp. 30-34.

The present general view on harmonic instability in HVDC systems is that the distortion of the ac voltage and its effect on the firing angle control apparatus is the cause. It is shown by a computer simulation based on realistic plant-data that harmonic instability is also possible without the mentioned influence on the firing control. Conditions for its occurrence and measures to avoid it are described. In German.

1973

1. Vithayathil, J.J., "Experience With Harmonic Problems At Celilo HVDC Station", IEEE International Conference on High Voltage DC and/or AC Power Transmission, Nov. 1973, pp. 6-10.

After briefly describing the design objectives and components of the harmonic filters at the Celilo terminal of the +or- 400 kV, 1440 MW, 846 mile, Pacific Northwest-Southwest intertie, the paper presents some of the field experience and special problems encountered in this area. Subjects covered include dc neutral side 6th harmonic resonance non-characteristic harmonics generated by converters, influence of ambient harmonics, excess reactive power generation by filters under light load conditions, and carrier interference from the operation of the converter station. In English.

2. Northcote-Green, J.E.D., J.A. Baron, and P. Vilks, "The Computation of Impedance Frequency Loci and Harmonic Current Penetration for AC Systems Adjacent to HVDC Conversion Equipment", IEEE International Conference on High Voltage DC and/or AC Power Transmission, Nov. 1973, pp. 97-102.

A method is proposed whereby the effect of harmonics generated by an HVDC installation and propagated into the parent ac system may be assessed. The modeling of the various power system components at harmonic frequencies is discussed, particularly with reference to transmission lines, transformers, generation and loads. The Manitoba Hydro ac system is taken as an example. The effect on the impedance-frequency locus of removing important interconnections is demonstrated. Histograms are used to illustrate the composition of waveforms at significant points within the system. The importance of filtration at the converter bus is clearly shown. In English.

3. Freris, L.L. and J. Nunes de Carvalho, "An Electromechanical Harmonic Filter", IEEE International Conference on High Voltage DC and/or AC Power Transmission, Nov. 1973, pp. 11-15.

Present static dc harmonic filters suffer from considerable shortcomings, a list of which is given in the paper. A novel filter based on a coil oscillating in a magnetic field is shown to be free of these shortcomings. This filter besides suppressing both characteristic and uncharacteristic

harmonics is potentially capable of supplying leading or lagging vars at an adjustable level. It is also expected that due to the characteristics of this filter, system stability will be improved and inverter recovery after commutation failures will be speeded up. A prototype design is described and possible future developments are discussed at length. In English.

4. Lewis, T.M., "Cancellation of Induced Power Line Harmonics On Telephone Lines", International Electrical, Electronics Conference and Exposition Digest, No 126, Oct. 1973.

Deals with a unique method of reducing hum due to induced harmonics in telephone lines caused by power lines. The harmonic to be eliminated is added to itself 180 degrees out of phase, thereby cancelling it if the amplitudes are equal. A phase locked loop is used in the circuit to ensure that the signals are always 180 degrees apart in phase. In English.

5. Stretton-Downes, J.N., "Harmonic Distortion and Notching of the Supply Voltage by Thyristor Converters", LSE Engineering Bulletin, Vol. 12, No. 4, July 1973, pp. 12-18.

The harmonic currents generated by thyristor converters are due to the non-linearities inherent in the commutation of direct current into the three-phase ac supply. Their magnitude and number depend on the converter configuration. The two most commonly used are the 6- and 12-pulse systems. Six and 12 indicate the number of dc pulses (p) through the motor armature per cycle of the supply. The harmonics generated by a particular thyristor converter arrangement of pulse number p are given by the formula $N=np+1$, where N is the harmonic number and n is any positive integer 1,2,3.... The percentage magnitude of full-load current of the Nth harmonic is given for converters of any pulse number by $I_n = 100/N$. In English.

6. Dreschsler, R., "The Power and the Power Output of Electric Current in Operation With Thyristors", Vedecko Conference, Prague, Czechoslovakia, June 1973.

Deals with a three-phase system asymmetrically loaded by nonsinusoidal currents. Suggests that the conventional power factor formula does not include the pulsating, invisible and deformation power output. Derives an equation for determining the power factor which takes into account the content of the harmonics, as well as the nonuniformity asymmetry and unbalance of the system. In Czech.

7. Young, J.B., "Prevention of Harmonic and Ferroresonance Phenomena in Shunt Capacitor Applications", Proceedings of the American Power Conference, Vol. 35, May 1973, pp. 1092-1097.

The purpose of this paper is to analyze the effects of transformer nonlinearities on the selection to nonresonant capacitor sizes. A capacitor sizing criterion is developed which does not require specific knowledge of load frequency response characteristics or transformer nonlinearities. In English.

8. Bretschnieder, G., et al., "Harmonics in the Medium and High-Voltage Networks Caused by Apparatus With Phase Control", CIREN 2nd International Conference on Electricity Distribution, Pt. 1, May 1973, pp. 216-221.

By the use of phase controlled household appliances harmonic currents are fed into the networks. The fifth harmonic is the most important one. The additional voltage of the fifth harmonic produced on the impedances of the MV/HV networks shall not exceed 1.4 to 2 percent based on the rated voltage. If those conditions are taken as a basic which can be assumed to be very likely, this value of the harmonic voltage is based on a rated power of the apparatuses in operation from 10-25 percent of the peak load of the networks. In English.

9. Melvold, D.J., "Pacific HVDC/Intertie System AC Side Harmonic Studies", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-92, No. 2, March-April 1973, pp. 690-701.

This paper presents a summary of the decisions made and methods used to optimize the design of the ac filter bank for the Sylmar terminal of the Pacific HVDC intertie system, and the statistical approach used in the test techniques employed to evaluate its performance. In English.

10. Lips, H.P. "Aspects of Multiple Infeed of HVDC Inverter Stations Into A Common AC System", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-92, No. 2, March-April, pp. 775-779.

The two important aspects, i.e., power frequency and harmonic phenomena are discussed in view of investigations on single HVDC converters published earlier by other authors. The results are extended to multiple infeed. It is shown that in contradiction to the general opinion at present, the short circuit ratio presents no limit to the rating of a single converter station, that for multiple infeed each station can be dealt with separately with regard to its rating and that increasing the number of inverter stations connected to the same system does not increase the danger of harmonic instability. In English.

11. Bausz, I., "AC-Filters for SCR Power Supply", Elektrotechnika, Vol. 66, No. 3, 1973, pp. 105-107.

The paper deals with the characteristics of different filter circuits used for obtaining practically sinusoidal voltage, special attention is paid to harmonic reducing and eliminating properties of the filters. The relationships of the filter factors are given and the course of calculating the reactors and capacitors is presented. In Hungarian.

12. Khachaturov, A.A., "Conditions for Occurrence of Electromechanical Resonance in Complex Power Systems", Electric Technology, USSR, No. 1, 1973, pp. 43-53.

A harmonic-balance method is proposed for solving nonlinear differential equations of motion of a three-machine system possessing properties of a complex power system. Resonance is found to be less likely at low loads, with appropriate damping and by quick passage through the resonance frequency regions. In English, translated from Russian.

1972

1. Merry, S.M. and E.R. Taylor, "Overvoltages and Harmonics on EHV Systems", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-91, No. 6, Nov.-Dec. 1972, pp. 2537-2544.

Steady-state overvoltages can occur on EHV transmission systems during various system operating conditions. The voltage waveforms are characterized by a periodic waveform which may be distorted by harmonics if iron saturation of equipment on the lines occurs. This paper discusses the results of digital and transient network analyzer (ANACOM) studies which analyzed system parameters with respect to their effect on harmonics in steady-state overvoltages. Special emphasis was focused on the factors influencing harmonic distortion of the steady-state voltages. In English.

2. Sherman, W.G., "Summation of Harmonics With Random Phase Angles", Proceedings of the Institution of Electrical Engineers, Vol. 119, No. 11, Nov. 1972, pp. 1643-1648.

The magnitude of the sum of a number of harmonics, of the same order but with random phase angle, is derived, subject to certain assumptions regarding the phase distribution. Computation of the net magnitude is carried out for different types of individual harmonic amplitudes. When the number of individual harmonics is greater than about ten, it is shown that simplified expressions for the sum may be used. These lead to a simple approach, based on r.m.s. values, to the problem of determining an assessed level of harmonic content which would have a specific probability of being exceeded. Consideration is also given to the situation when just one or two harmonics are dominant, and a consequent simplification of an assessed level. The main results apply for instantaneous values of the net magnitude, but some subsidiary results give an indication of the likely behavior over a continuous period of time. In English.

3. Susnjar, M., "Transmitting the Adverse Effects of Higher Harmonics in 110 kV Transmission Networks From Powerful Rectifier Equipment in Industrial Plants, Their Effects, Checking the Harmful Influences, and Experiences Gathered So Far in Our Country and in the World", Elektroprivreda (Yugoslavia), Vol. 25, No. 9-10, Sept.-Oct. 1972, pp. 358-365.

The title is the abstract. In Croatian.

4. Rumpf, E. and S. Ranade, "Comparison of Suitable Control Systems For HVDC Stations Connected to Weak AC Systems. II. Operational Behavior of the HVDC Transmission", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-91, No. 2, March-April 1972, pp. 555-564.

The performance of HVDC systems depends to a great extent on the control methods used. The performance of the control methods described in Part I of this paper is investigated under steady-state and transient conditions. Attention is also given to the problem of harmonics in the ac system. The results show that all the described methods are suitable for HVDC operation on weak ac systems. The choice of the proper control method in a given case depends on the requirements which are to be met by the HVDC system as a whole. In English.

5. Giesner, D.B. and J. Arrillaga, "Behavior of HVDC Links Under Unbalanced-AC-Fault Conditions", Proceedings of the Institution of Electrical Engineers, Vol. 119, No. 2, Feb. 1972, pp. 209-215.

A theoretical analysis is made of the production of triplen-harmonic currents by a converter bridge using symmetrical firing control when supplied with unbalanced 3-phase voltages. It is shown that these harmonic currents can

pass into the ac system regardless of the transformer connections. Results are obtained from a digital-computer program for the dynamic behavior of an ac-dc interconnected system during single- and 2-phase faults, and particular importance is given to their effect on a weak ac system. In English.

6. Bebink, J., "Network Disturbance Occasioned by Semi- Conductors", Elektrotechnik, Vol. 50, No. 3, Feb. 1972, pp. 111-116.

The effect of load control by means of thyristors on the power network is discussed. Load factor $\cos \phi$ causes extra losses and harmonics cause trouble for voltage ripple control systems. Provisional regulations for apparatus for low voltage and small power, limiting power, asymmetry and some other points, are given. Some expectations are given for medium power systems. In Dutch.

7. Markushevich, N.S., "The Waveform of the Voltage in the Basic Networks of a Power System", Elektricheskie Stantsii, No. 7, 1972, pp. 65-66.

Gives the results of measurements of harmonic components of voltage in the principal networks of a power system, showing how these vary with time. The presence of third harmonic in the line current is shown. Recommendations are given for reducing the effect of changes in the voltage waveform on the operation of network automatic control equipment. In Russian.

1971

1. Reeve, J. and J.A. Baron, "Harmonic Interaction Between HVDC Converters and AC Power Systems", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-90, No. 6, Nov.-Dec. 1971, pp. 2785-2793.

A technique is presented for calculating the harmonic interactive behavior between HVDC and ac systems. The ac system is represented by discrete impedances at harmonic frequencies, and the calculations involve the repeated iteration of a large computer program representative of the interaction of generated ac harmonic currents with the ac system impedances and filters. Examples of computed harmonic conditions are presented, and the degree to which the harmonic behavior is dependent on the ac system impedances and filters is discussed for both normal and abnormal harmonics. In English.

2. Sasaki, H. and T. Machido, "A New Method to Eliminate AC Harmonic Currents by Magnetic Flux Compensation - Considerations on Basic Design", IEEE Transactions on Power Apparatus and Systems. Vol. PAS-90, No. 5, Sept.- Oct. 1971, pp. 2009-2019.

A new method of eliminating ac harmonic current is proposed, which is based on the principle of magnetic flux compensation in a transformer core. By means of the method, abnormal as well as normal harmonics, can effectively be dealt with. Considerations on the basic design of the new method are given. In English.

3. Moltgen, G., Elektrische Bahnen, Vol. 42, No. 8, Aug. 1971, pp. 175-178.

Analyses the ideal rectification of $16 \frac{2}{3}$ Hz traction current and assuming a complete smoothing of the pulsed dc and neglecting the commutation problems. The control angle during the positive part of the cycle is slightly greater than for the negative half-wave, and the calculation results are tabulated.

This is followed by the consideration of commutation interval of finite length. In German.

4. Orkin, N., "Oscillatory Effects of EMI Power Line Filters", IEEE International Electromagnetic Compatibility Symposium Record, July 1971, pp. 20-22.

Basic analysis of power line filters generating a very high transient current at turn-on of electric power. Prediction of levels of this transient current in both time and frequency domains. General study of power turn-on interference with EMI power line filter loads. In English.

5. Schulz, W., "Harmonics in Industrial Supply Systems With Converter Loading", Elektrotechnische Zeitschrift, Ausgabe B, Vol. 23, No. 12, June 1971, pp. 288-292.

Power electronics has an increasing effect on industrial systems and this is mainly due to the mode of operation of phase-angle controlled, mains-operated converters. Phenomena occur in the supply system, in connection with reactive power and harmonics, which are generally collected together under the term "mains feedback". With a view to comprehensive treatment of the harmonic questions, reactive power is discussed only as an introduction and for comparison purposes. In German.

6. Sheppard, H.J., "The Need to Limit Harmonic Distortion of the Supply Voltage Waveform", Electrical Review, Vol. 188, No. 10, March 1971, pp. 307-308.

The constancy of voltage and frequency, and the maintenance of the sine wave of alternating voltage forms the subject of the present article and in seeking to meet their obligations in this respect, British electricity boards have the support of a statutory provision which states that if a consumer uses the energy supplied to him for any purposes or deals with it so as to interfere unduly or improperly with the efficient supply of energy to any other consumer, the electricity board may discontinue the supply of energy to his premises. It follows from this that any form of limitation on harmonic distortion should be related to the sensitivity of existing and future equipment connected to the supply system and this, of course, includes equipment forming part of the supply network itself. In English.

7. Sasaki, H., "An Elimination of AC Harmonic Currents From DC System by Magnetic Flux Compensation", Journal of the Institute of Electrical Engineers of Japan, Vol. 91, No. 1, Jan. 1971, pp. 48-55.

A new method of eliminating harmonic current from a distorted ac current which flows out to the ac system from the ac/dc converter is proposed; higher harmonic components of the current waveform detected through the current transformer are applied to the tertiary winding of the main transformer in the opposite direction to the secondary current to compensate harmonic components of the distorted magnetic flux. This method enables one to eliminate theoretical as well as nontheoretical harmonic currents, and also to reduce the filter cost considerably. In Japanese.

8. Owen, A.R., "Cycle Syncopation AC Thyristor Control", Electrical Review, Vol. 188, No. 1, Jan. 1971, pp. 15- 17.

Describes a new technique for thyristor firing which minimizes harmonic distortion injected into the public supply. In English.

9. Memedov, T.M., "A Method for Determining the Overvoltages Due to the Fifth Harmonic in Asymmetric Long Distance Power Transmission", Izvestiya Vysshikh Uchebnykh Zavedenii, Energetika, No. 8, 1971, pp. 30-35.

In order to calculate the fifth harmonic, each transformer phase is represented by a self-contained voltage source at five times system frequency, the EMF and internal impedance of which are determined by the fundamental voltage of that phase. By this means a linear equivalent circuit with asymmetric voltage source and asymmetric fault can be set up. Examples of computations are given and compared with data from a physical model of an unloaded 650 KM line with a single-phase short circuit at the far end. In Russian.

10. Bialkiewicz, Z., "The Influence of Electric Energy Receivers and of the Power System on the Values of Harmonic Voltages", Biuletyn Instytutu Energetyki, Vol. 13, No. 5-6, 1971, pp. 41-45.

Presents the universal relationship for the determination of high harmonics immittances and of characteristic frequencies for the fundamental network system. The influence of resistance and reactance of static receivers, electric motors and of the supplying system on the network system impedances has been explained. The relationship for the determination of harmonics order, the amplitudes of which are constant in spite of network system parameters changes are given. The results of comparison of measurements and calculations for the transformer station with capacitor bank supplying the railway rectifier substation are given. In Polish.

11. Kimbark, E.W., Direct Current Transmission, Volume 1, Chichester, Sussex, England: Wiley-Interscience, 1971.

This volume compares ac and dc transmission, analyzes the bridge converter, and discusses converter circuits and charts. Incorrect operation of converters, protection, harmonics and filters and ground return. A bibliography of all pertinent material published to date is included. The appendices cover the effective value of alternating current of a six-pulse converter, the fundamental current, power, and reactive power relationships of a six-pulse converter, and the inclusion of converter equations of direct-voltage drops due to resistance and arcs. In English.

1970

1. Defty, J.W. and G.C. Maples, "Harmonic-Measurement Facility For Power-Supply Systems", Proceedings of the Institution of Electrical Engineers, Vol. 117, No. 10, Oct. 1970, pp. 1993-1996.

A description is given of a harmonic-analysis measurement facility designed at the central electricity research laboratories to statistically analyze harmonic levels on the supply system. As an example of the application of this facility, typical results are given of a statistical analysis of voltage harmonics at selected points on the 275 kV grid system. In English.

2. Reeve, J. and J.A. Baron, "Harmonic DC Line Voltages Arising From HVDC Power Conversion", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 7, Sept. 1970, pp. 1619-1624.

Steady-state firing-angle control errors and ac voltage distortion lead to the production of abnormal voltage harmonics at the dc terminals of HVDC converters: these are in addition to the usually considered "normal" harmonics. This paper describes the analysis and a digital computer program by which the normal and abnormal harmonics can be calculated for both 6- and 12-pulse converter operation. Examples of computed values are presented. In English.

3. Mikhaylov, M.I. and V.F. Kalyuzhnyy, "Protection of DC Power Line Smoothing Devices Against Electromagnetic Influence on Communications Lines", Elektrosvyaz, Translation in Telecommunications and Radio Engineering, Part 1: Telecommunications, Vol. 24, No. 9, Sept. 1970, pp. 17-21.

The existing smoothing devices for harmonic suppression at the converter substation output to a high-voltage dc power line are discussed. The authors find the required smoothing factor of the audio band low-pass filter in the context of permissible HVDC influence on adjacent overground communications lines. A common smoothing factor is obtained on the basis of the factors relative to individual harmonics. In Russian.

4. Hingorani, N.G. and S.A. Annestrand, "Insulation Levels of DC Filter Reactors and Resistors for HVDC Power Transmission", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 4, April 1970, pp. 610-618.

The insulation on the dc side of HVDC converter station is concerned with the cost of these reactors and resistors which is greatly dependent on their insulation levels, and could be a substantial part of the total filter costs if their insulation levels are comparable to the insulation level of the dc busbars. It is shown to be essential to provide separate arresters across these reactors and resistors, since the dc line arrester does not provide adequate protection for these components. By diligent use of arresters, the insulation levels and thereby the costs of these components can be greatly reduced. It is also shown that arrester duties are small compared to the capabilities of standard ac arresters. The transients suppression by reduced number of dc operations is discussed, and a method of determining appropriate protective levels is presented. In English.

5. Nield, P.N., "Method of Measuring Power System Frequencies", Proceedings of the Institution of Electrical Engineers, Vol. 117, No. 1, Jan. 1970, pp. 157-160.

A method of frequency measurement is described which uses a combination of digital and analogue techniques and is particularly suitable for measurements in the range 20-500 Hz. An analysis is made of the errors inherent in the method. The design of a frequency meter covering the range 46-51 Hz with a long term accuracy within 0.5 Hz is given; a quartz crystal is used as a reference standard, and the frequency is displayed on a moving-coil meter. The design can readily be adapted for a different frequency range. In English.

6. Libratti, C., L. Malafarina, and G. Ranieri, "Some Considerations of the Economics of Harmonic Filters in Conversion Plant for HTDC Transmission", Rendiconti della Riumione Annuale dell' Associazione Elettrotecnica Italiana, Vol. 45, No. 2, 1970, 2.4.08/4 pp.

Deals with filter combinations and effects on costs and sizes of the filter systems which result. In Italian.

7. Mirandola, P., "Results of DC Harmonic Measurements of the Sa. Coi Plant", Rendiconti della Riunione Annuale dell' Associazione Elettrotecnica Italiana, Vol. 45, No. 2, 1970, 2.4.03/12 pp.

Gives objectives, assumptions and general characteristics of Sa. Coi plant, and methods of measuring and results of measurements. Goes on to determine an equivalent circuit in block form. Compares calculated harmonic figures with measured ones and gives conclusions showing the similarities of the Two types of results. In Italian.

1969

1. Ametani, A., et al., "Harmonic Components Generated From Converter on DC Transmission", Science and Engineering Review of Doshisha University, Vol. 10, No. 2, Oct. 1969, pp. 73-91.

This report describes harmonic components generated from converters and the application of filters suitable for reducing harmonic components in ac systems. As many of high voltage transmission lines in Japan are designed for untransposed single circuit, the degree of unbalance in these transmission systems will be much higher than those in the existing ac power systems. In English.

2. Abbott, J.R., "High Frequency AC Harmonics on an HVDC Transmission Line Might be Attenuated by Conductor Design", Transmission and Distribution, Vol. 21, No. 8, Aug. 1969, pp. 58-60.

Using the principle of skin effect and the difference in impedance between aluminum and steel conductors. The author presents a brief theoretical treatise on attenuating possible 60 Hz harmonics. In English.

3. Reeve, J., J.A. Baron, and P.C.S. Krishnayya, "A General Approach to Harmonic Current Generation by HVDC Converters", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-88, No. 7, July 1969, pp. 989-995.

A general approach to the computation of current harmonics is presented for the ac side of HVDC transmission installations considering both normal and abnormal harmonics that can arise from harmonic distortion of the supply waveform and perturbations in the control firing pulses. Attention is given to 12-pulse converter operation and to alternative types of automatic control. A comprehensive digital computer program is described and examples of computed harmonics are given. In English.

4. Bensimon, A., "The Analysis of the Possible Occurrence of Harmonic Resonance Over Voltage in Very High Voltage Networks", Energetica, Vol. 17, No. 6, June 1969, pp. 279-288.

A study of the amplifications or attenuations occurring at the transmission of harmonic oscillations on long power lines of maximum possible values, is presented. In Rumanian.

5. Rangaswamy, P., "Power Factor Correction Capacitors in Harmonic Filter Circuits", Electrical India, Vol. 9, No. 4, April 1969, pp. 35-38.

The application of power factor correction capacitors in steel plant network system feeding a large number of rectifier units is considered. To avoid chances of resonances at any harmonic frequency, properly dimensioned reactors are connected in series with capacitor units to form harmonic filter circuits. An attempt has been made to consider the problem with a sample case study. In English.

6. Meyer, W.S. and H.W. Dommel, "Telephone-Interference Calculation for Multiconductor Power Lines", IEEE Transactions on Power Apparatus and Systems, Vol. PAS- 88, No. 1, Jan. 1969, pp. 35-41.

Previous work on power-line-produced telephone interference has dealt with the case of a single equivalent power conductor. This paper presents the theory applicable to a multi-conductor power line excited by general, linear networks. A self-contained digital-computer program employing these techniques has been written. It rigorously handles the important case of actual communications line-power line crossings. A comparison of the computer results with experimental measurements is provided. In English.

1968

1. Reeve, J. and P.C.S. Krishnayya, "Unusual Current Harmonics Arising From High-Voltage DC Transmission", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-87, No. 3, March 1968, pp. 883-893.

Unbalance in the operation of high-voltage dc converters gives rise to unusual or uncharacteristic harmonics in the ac waveform not expected from the existing theory relating to balanced operation. Analysis of the effect of unbalances in the alternating voltages and the valve firing angles is provided together with selected characteristics illustrating the variations in the harmonics with unbalance as determined by a comprehensive digital computer program. Six-pulse and 12-pulse operation is considered. In English.

2. Phadke, A.G., and J.H. Harlow, "Generation of Abnormal Harmonics in High-Voltage AC/DC Power Systems", IEEE Transactions on Power Apparatus and Systems, Vol. PAS- 87, No. 3, March 1968, pp. 873-883.

The possibility of abnormal harmonic generation in an ac system feeding a converter load is examined from the standpoint of automatic control systems used in modern HVDC transmission systems. It is shown that with certain types of automatic controls, the firing angles of converter valves may sustain some errors, which in turn could generate abnormal harmonic currents in the three-phase ac system feeding the converter. A criterion for predetermining the type and extent of abnormal harmonic generation is defined, and numerical examples given. Methods of reducing abnormal harmonic generation are discussed, and some experimental data supporting the theoretical calculations are also included. In English.

1967

1. Ainsworth, J.D., "Harmonic Instability Between Controlled Static Converters and AC Networks", Proceedings of the Institution of Electrical Engineers, Vol. 114, No. 7, July 1967, pp. 949-958.

A controlled mercury-arc or thyristor converter with a conventional firing-pulse control system can both generate and magnify ac harmonics additional to the fifth, seventh, etc., of classical converter theory. This effect is normally of little importance if the impedance of the ac system is low, but it is shown by analysis that, if this impedance is relatively high, as may occur on the larger sizes of converter in HVDC transmission, this type of harmonic magnification may become excessive and may even prevent stable operation of the converters. The analysis is confirmed by model tests and appears to account for several reported instances of excessive abnormal harmonics associated with firing-angle unbalance in HVDC converter installations. Generation of abnormal harmonics can be substantially reduced and harmonic magnification largely eliminated by a new control system in which firing pulses are timed by a phase-locked oscillator, controlled to satisfy the usually constant-current or extinction-angle requirements. In English.

1966

1. Kraichik, Yu.S., "Non-Canonical Harmonics in Controlled Rectifier Circuits", Izvestiya Akademii Nauk SSSR Energetika i Transport, No. 5, Sept.-Oct. 1966, pp. 84- 92.

Relation between harmonics of a rectified voltage and a spread of the angles of switching of rectifying valves is investigated. The existence of harmonics which are not exact multiples of the number of phases is established. A method for estimation of these harmonics is suggested. In Russian.

2. Robinson, G.H., "Harmonic Phenomena Associated With the Benmore-Haywards HVDC Transmission Scheme", New Zealand Engineering, Vol. 21, No. 1, Jan. 1966, pp. 16-28.

Conversion of ac to dc by rectification produces harmonics of the mains frequency. In the case of high-voltage dc transmission schemes the harmonics thus produced can cause interference in the public telephone networks, and also in any control equipment associated with the power system itself that relies for its operation on the transmission of audio frequency signals. This paper is an account of the problems encountered in the New Zealand HVDC system, and the ways in which they were overcome. In English.

3. Clarke, C.D. and M.J. Johanson-Brown, "The Application of Self-Tuned Harmonic Filters to HVDC Converters", IEE Conference on High Voltage DC Transmission, Part 1, No. 22, Sept. 1966, pp. 275-276.

Filters typically consist of a few arms sharply tuned to dominant harmonic frequencies and a damped arm to filter the higher order harmonics. The filter can be maintained in tune by adjustment of the capacitor or more usually the inductor. An equipment is described whereby detuning is detected and corrected by a tap changer on the inductor or by using an infinitely variable inductor of the moving-coil type. In English.

4. Holmborn, H. and H. Mastensson, "Experience of AC Harmonics From HVDC Installations", IEE Conference on High Voltage DC Transmission, Part 1, No. 22, Sept. 1966, pp. 445-447.

HVDC converters generate certain characteristic current harmonics. If no measures are taken, these current harmonics will spread out into the feeding ac network, where they may cause various kinds of disturbances. With filters for these harmonics most interferences are avoided. Because of local circumstances, some inconveniences have arisen at different HVDC transmission despite this filtering equipment, such as interference to telephone communications and resonances in the ac network. The quality of the telephone network itself often determines the degree of interference to telephone communications. In English.

5. Huddart, K.W. and G.L. Brewer, "Factors Influencing the Harmonic Impedance of a Power System", IEE Conference on High Voltage DC Transmission, Part 1, No. 22, Sept. 1966, pp. 450-452.

The harmonic filters which are necessary at an HVDC converter to maintain the waveform of the ac system are expensive. Calculation of their performance and rating depends critically on the harmonic impedance of the ac power system. It is recommended that this impedance should be calculated using variable frequency network analyzers or digital computers, checked by high power tests on the power system. The paper describes such work which shows that substantial system resonances occur as a rule, so that harmonic impedance cannot be found by assuming the system to be a simple inductor. The effect is most noticeable at the highest transmission voltages. In English.

6. Parker, A.M., "An Analytical Study of Harmonic Filter Design", IEE Conference on High Voltage DC Transmission, Part 1, No. 22, Sept. 1966, pp. 280-283.

A general method for designing harmonic filter installations, based on a series of logical decisions which depend to a large extent upon the filter specifications. It is shown that the reactive compensation requirements of the ac system have a significant influence on the form of the filter, and the implications of these requirements are discussed fully. The essentially iterative nature of filter design makes it particularly suitable for digital computer solution, and an outline of a possible computer program for the complete design of a filter installation is given. In English.

7. Brewer, G.L., C.D. Clarke, and A. Gavrilovic, "Design Considerations for AC Harmonics Filters", IEE Conference on High Voltage DC Transmission, Part 1, No. 22, Sept. 1966, pp. 277-279.

A brief review of the factors affecting the cost and performance. The reactive power which can be supplied or accepted by the ac system and the filtering performance required are important considerations. In the rating of the filter components the worst conditions must be assumed but it would be unrealistic to assume that they occurred simultaneously for all harmonics. One method is to assume the most unfavorable network impedance at one harmonic, while at the remaining harmonics the impedance values measured on a variable frequency network analyzer are used. In English.

1964

1. Smith, R., "Harmonic Voltages in the Outputs of Controlled Rectifier Circuits", Electronic Engineering, Vol. 36, Dec. 1964, pp. 832-837.

The harmonic voltages present in the output of controlled rectifier circuits are derived mathematically. Curves of the equivalent ripple related to 800 c/s (weighted ripple) as used for telephone purposes, are also given. A table of ripple weighting factors is included. In English.

2. Ilicete, F., J.D. Ainsworth, and F.G. Goodrich, "Some Design Aspects of Harmonic Filters for HVDC Transmission Systems", Conference Internationale des Grands Reseaux Electriques a Haute Tension, Paper 405, 1964, 25 pp.

Until the advent of high power converters for HVDC transmission systems, little attention was paid to harmonics in electrical power networks, because in general harmonic levels were found to be acceptably low. Installations of HVDC converters, however, are large relative to the network to which they are connected and it becomes necessary to install filters to reduce harmonic currents and voltages produced by them. The paper is divided into two parts. The first gives a discussion of harmonic penetration in a network, and methods of defining and specifying harmonic disturbance. The second gives a description of filter designs for a particular installation, and their design basis. In English.

1950

1. Warden, S.B., E. Friedlander, and A.N. Arman, "The Influence of Rectifier Harmonics in a Railway System on the Dielectric Stability of 33 kV Cables", Institution of Electrical Engineers Paper 1025, 1950, 13 pp.

The electrified sections of the Southern Region of British Railways outside the London suburban area derive their traction current requirements from mercury-arc-rectifier substations, which, in turn, receive hv power supplies from the British Grid by means of a 33 kV railway-cable network. The earliest installation was that between Croydon and Three Bridges, which was brought into operation in July, 1932; satisfactory operation was experienced until 1944, when it became apparent that the incidence of 33 kV cable failures had risen. The paper shows that surges were not responsible for these failures, but that the harmonics generated by the rectifier equipment, together with the system resonance characteristics, were such that the waveforms of the system voltage were considerably distorted. The conditions were aggravated by irregular operation of the rectifiers. It is deduced that this waveform distortion is mainly responsible for shortening the life of the dielectric material of the impregnated supply cable. An unusual feature of the cable damage is the presence of a number of uncarbonized pinholes in the paper types in the vicinity of the fault; it is concluded that these pinholes are caused by internal discharges, accentuated by the presence of the relatively high-frequency and high-amplitude harmonic voltages in the system. An explanation is offered to show why the greater proportion of the cable failures occurred in sections where the cable was either in the ground or in a tunnel. Practical methods of reducing or avoiding similar troubles are discussed. In English.

1949

1. Whitehead, S. and W.G. Radley, "Generation and Flow of Harmonics in Transmission Systems", Proceedings of the Institution of Electrical Engineers, Part II, Vol. 96, Feb. 1949, pp. 29-48.

Discusses the magnitude and distribution of harmonic currents flowing in ac networks. The various sources of harmonics are discussed in general, and harmonics arising from the use of mercury-arc rectifiers and in hv transmission thereby are dealt with in greater detail. The flow of harmonics arising from these sources is considered from a theoretical aspect, using equivalent networks, experimental verification of these theories being given for certain simple cases. The possibility of a complete theoretical solution is shown, and certain probable practical conclusions are drawn. Various methods of reducing harmonics are discussed, and the relative importance of the various sources is considered in the light of modern trends in harmonic suppression. In English.

Appendix B
IMPEDANCE CALCULATIONS FOR UNBALANCED NETWORK

The balanced network assumption is not necessary in calculating the system harmonic impedances, but a few more sets of measurement will be required. The following describes the methods without the balanced impedance assumption for the system with dc operating and not operating.

B.1 DC-On Impedance Calculation

The equivalent network is represented by a full Z matrix

$$Z = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \quad (B.1)$$

where the diagonal elements are the self impedances and the off-diagonal elements are the mutual impedances (Figure B.1-1). For this discussion, the harmonic source is assumed to be at the dc terminal. Non-zero system harmonic sources can be incorporated easily.

The method requires voltages and current measurement of V and I for three different network configurations, which are accomplished by single phase switching of the capacity banks Z_a , Z_b , and Z_c . The measurements are as follows:

1. Capacitor bank on phase a

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a^1 \\ V_b^1 \\ V_c^1 \end{bmatrix}, \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} I_a^1 \\ I_b^1 \\ I_c^1 \end{bmatrix}. \quad (B.2)$$

Figure B.1-1 DC-On System Configuration

2. Capacitor bank on phase b

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a^2 \\ V_b^2 \\ V_c^2 \end{bmatrix}, \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} I_a^2 \\ I_b^2 \\ I_c^2 \end{bmatrix}. \quad (\text{B.3})$$

3. Capacitor bank on phase c

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a^3 \\ V_b^3 \\ V_c^3 \end{bmatrix}, \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} I_a^3 \\ I_b^3 \\ I_c^3 \end{bmatrix}. \quad (\text{B.4})$$

The voltage and current measurement are related by

$$\begin{bmatrix} V_a^i \\ V_b^i \\ V_c^i \end{bmatrix} = - \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a^i \\ I_b^i \\ I_c^i \end{bmatrix}, \quad i=1, 2, 3. \quad (\text{B.5})$$

Defining the current matrix

$$I = \begin{bmatrix} I_a^1 & I_b^1 & I_c^1 \\ I_a^2 & I_b^2 & I_c^2 \\ I_a^3 & I_b^3 & I_c^3 \end{bmatrix}, \quad (\text{B.6})$$

the nine equations in (B.5) are rewritten as

$$\begin{bmatrix} Z_{aa} \\ Z_{ab} \\ Z_{ac} \end{bmatrix} = -I^{-1} \begin{bmatrix} V_a^1 \\ V_a^2 \\ V_a^3 \end{bmatrix} \quad (B.7)$$

$$\begin{bmatrix} Z_{ba} \\ Z_{bb} \\ Z_{bc} \end{bmatrix} = -I^{-1} \begin{bmatrix} V_b^1 \\ V_b^2 \\ V_b^3 \end{bmatrix} \quad (B.8)$$

$$\begin{bmatrix} Z_{ca} \\ Z_{cb} \\ Z_{cc} \end{bmatrix} = -I^{-1} \begin{bmatrix} V_c^1 \\ V_c^2 \\ V_c^3 \end{bmatrix} \quad (B.9)$$

The error in the data measurement is

$$\Delta_{ab} = Z_{ab} - Z_{ba}, \Delta_{bc} = Z_{bc} - Z_{cb}, \Delta_{ac} = Z_{ac} - Z_{ca} . \quad (B.10)$$

which would reflect the accuracy of the measurement equipment. The self and mutual impedance values would indicate how balanced the network is.

The positive sequence impedance is calculated from the self and mutual impedances as [1]

$$Z_p = (Z_{aa} + Z_{bb} + Z_{cc})/3 - (Z_{ab} + Z_{bc} + Z_{ca})/3 . \quad (B.11)$$

B.2 DC-Off Impedance Calculations

When the dc terminals are off, the system harmonic sources are represented with the Thevenin voltage source E (Figure B.2-1).

Figure B.2-1 DC-Off System Configuration

The dc-off method requires one voltage measurement of V without any capacitors, and the voltage measurements of V with single phase switching of the capacitor banks Z_a , Z_b , Z_c . The measurements of the capacitor currents are also required. Thus, a total of four sets of measurement are required.

0. No capacitor bank switched in

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a^0 \\ V_b^0 \\ V_c^0 \end{bmatrix}, \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \quad (\text{B.12})$$

1. Capacitor bank on phase a

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a^1 \\ V_b^1 \\ V_c^1 \end{bmatrix}, \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} I_a^1 \\ 0 \\ 0 \end{bmatrix}. \quad (\text{B.13})$$

2. Capacitor bank on phase b

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a^2 \\ V_b^2 \\ V_c^2 \end{bmatrix}, \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 0 \\ I_b^2 \\ 0 \end{bmatrix}. \quad (\text{B.14})$$

3. Capacitor bank on phase c

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_a^3 \\ V_b^3 \\ V_c^3 \end{bmatrix}, \quad \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ I_c^3 \end{bmatrix}. \quad (\text{B.15})$$

Combining the measurement sets 0 and 1 and following the method for dc-off with single-phase switchings (Subsection 3.5), the voltage and current relationship is

$$\begin{bmatrix}
I_a^1 & 0 & 0 & 0 \\
0 & I_a^1 & 0 & 0 \\
0 & 0 & I_a^1 & 0 \\
0 & 0 & 0 & I_a^1 \\
V_a^1 & 0 & 0 & (V_a^1 - V_a^0) \\
(V_b^1 - V_b^0) & V_a^1 & 0 & (V_b^1 - V_b^0) \\
(V_c^1 - V_c^0) & 0 & V_a^1 & (V_c^1 - V_c^0)
\end{bmatrix}
\begin{bmatrix}
Z_{aa} \\
Z_{ba} \\
Z_{ca} \\
Z_a
\end{bmatrix}
=
\begin{bmatrix}
V_a^0 - V_a^1 \\
V_b^0 - V_b^1 \\
V_c^0 - V_c^1 \\
V_a^1 \\
0 \\
0 \\
0
\end{bmatrix} \quad (B.16)$$

Similar sets of equations can be obtained for the phase b and phase c measurements with the capacitor banks on. Each set of equations can be separately solved using the least square method.

The three sets of equations can be combined by requiring that

$$Z_{ab} = Z_{ba}, Z_{bc} = Z_{cb}, Z_{ca} = Z_{ac} \quad (B.17)$$

In this case, there are nine unknowns in 21 complex equations

$$Ax = b, \quad (B.18)$$

where the matrix A is given in Figure B.2-2,

$$x^T = (Z_{aa}, Z_{bb}, Z_{cc}, Z_{ab}, Z_{bc}, Z_{ca}, Z_a, Z_b, Z_c) \quad (B.19)$$

and

$$\begin{aligned}
b^T = & (V_a^0 - V_a^1, V_b^0 - V_b^1, V_c^0 - V_c^1, V_a^1, V_a^0 - V_a^2, \\
& V_b^0 - V_b^2, V_c^0 - V_c^2, V_b^2, V_a^0 - V_a^3, V_b^0 - V_b^3, V_c^0 - V_c^3, \\
& V_c^3, 0, 0, 0, 0, 0, 0, 0, 0). \quad (B.20)
\end{aligned}$$

The unknowns x can then be solved from (B.18) using a least square method.

I_a^1	0	0	0	0	0	0	0	0
0	0	0	I_a^1	0	0	0	0	0
0	0	0	0	0	I_a^1	0	0	0
0	0	0	0	0	0	I_a^1	0	0
0	0	0	0	I_b^2	0	0	0	0
0	I_b^2	0	0	0	0	0	0	0
0	0	0	0	I_b^2	0	0	0	0
0	0	0	0	0	0	0	I_b^2	0
0	0	0	0	I_c^3	0	0	0	0
0	0	0	0	0	I_c^3	0	0	0
0	0	0	0	0	I_c^3	0	0	0
0	0	I_c^3	0	0	0	0	0	0
0	0	0	0	0	0	0	0	I_c^3
v_a^1	0	0	0	0	0	$(v_a^1 - v_a^0)$	0	0
$(v_b^1 - v_b^0)$	0	0	v_a^1	0	0	$(v_b^1 - v_b^0)$	0	0
$(v_c^1 - v_c^0)$	0	0	0	0	v_a^1	$(v_c^1 - v_c^0)$	0	0
0	$(v_a^2 - v_a^0)$	0	v_b^2	0	0	0	$(v_a^2 - v_a^0)$	0
0	v_b^2	0	0	0	0	0	$(v_b^2 - v_b^0)$	0
0	$(v_c^2 - v_c^0)$	0	0	v_b^2	0	0	$(v_c^2 - v_c^0)$	0
0	0	$(v_a^3 - v_a^0)$	0	0	v_c^3	0	0	$(v_a^3 - v_a^0)$
0	0	$(v_b^3 - v_b^0)$	0	v_c^3	0	0	0	$(v_b^3 - v_b^0)$
0	0	v_c^3	0	0	0	0	0	$(v_c^3 - v_c^0)$

Figure B.2-2 Matrix A of (B.18)

In addition, a shift in the Thevenin voltage when the capacitor banks are switched in can be accounted for by

$$V_y^{on} = V_y^0 + \Delta V_y^n \quad (B.21)$$

where $n = 1, 2, 3$ denotes the switching of capacitor banks corresponding to steps 1, 2, 3, and $y = a, b, c$ denotes the phases. Substituting V_y^{on} for V_y^0 with appropriate n into (B.18), we obtain a set of 21 nonlinear equations in 18 unknowns due to the additional nine unknown quantities ΔV_y^n . This set of equations can be solved using a nonlinear optimization program with the initial values

$$\Delta V_y^n = 0,$$

$$Z_a = V_a^1/I_a^1, Z_b = V_b^2/I_b^2, Z_c = V_c^3/I_c^3$$

$$Z_{aa} = (V_a^0 - V_a^1)/I_a^1, Z_{bb} = (V_b^0 - V_b^2)/I_b^2,$$

$$Z_{cc} = (V_c^0 - V_c^3)/I_c^3,$$

$$Z_{ab} = ((V_b^0 - V_b^1)/I_b^1 + (V_a^0 - V_a^2)/I_a^2)/2$$

$$Z_{bc} = ((V_c^0 - V_c^2)/I_c^2 + (V_b^0 - V_b^3)/I_b^3)/2$$

$$Z_{ca} = ((V_a^0 - V_a^3)/I_a^3 + (V_c^0 - V_c^1)/I_c^1)/2. \quad (B.22)$$

Reference

1. General Electric Company, Transmission Line Reference Book 345 KV and Above, EPRI, 1975.

Appendix C

MONITORING OF FILTER CURRENTS

C.1 Introduction

Monitoring of filter currents is described in this appendix since it is not related to the determination of system harmonic impedance but it was a part of the overall project. The objectives included the monitoring of currents in the filters over a prolonged period, such as six months. To meet this objective, an automated monitoring system was developed. Basically, the system measures the currents in each filter on a continuous basis, periodically compares the result to predetermined levels, and records a complete set of data whenever one of the preset limit levels is exceeded. Since the system is microprocessor controlled, it has additional capability and can be set to record the levels of every filter at periodic intervals, such as one hour, for a continuously sampled record.

C.2 System Description

As in any measurement system, the major elements consist of sensors, signal conditioning, processing, and a readout device. The filters to be monitored included those for harmonics 5, 7, 11, 13, and a high pass filter. With the exception of the high pass filter, each filter was already equipped with a sensing device (CT) for automatic tuning control (ATC). The load resistors for these CTs were used as signal source for the current monitor. For the high pass filter, the current was sampled in the ground lead of the filter by means of a Maxwell Worm (Rogowski coil).

The overall system block diagram is shown in Figure C.2-1, which also identifies the physical location of the various components. Each section enclosed in dashed lines is described in more detail in the succeeding sections. The datalogger is a Fluke Model 2240 B which contains a microprocessor, a numeric display, and a paper tape printer. The display is used in programming (from the front panel) or to monitor a selected channel at a time. After the unit is programmed, the

Figure C.2-1 Overall System Block Diagram

controls are locked out by a key switch to prevent tampering. The datalogger has a large capability for expansion and may also be used for other purposes simultaneously or may be interconnected to a computer or control system.

C.3 Instrumentation at Celilo

Figure C.3-1 is a functional block diagram of the instrumentation at Celilo. Resistor R is the CT load resistor in the existing automatic tuning control system for the 11th and 13th harmonic filters. It samples the current in one phase of the filter but the ATC system also has provisions for switching to any of the three phases. The signal across R is attenuated by a resistive divider to reduce the signal level and provide proper scaling. Band pass filters are used to reject the 60 Hz component of the filter current. For the High Pass Filter signal, a 60 Hz notch filter is used, followed by an integrator circuit. The integrator is necessary because the output of the worm is a voltage proportional to the derivative of the current to be measured.

At this point in the description, the desired signals have been isolated and a method is needed to relay this information to the datalogger which is approximately one mile away. Since three pairs of the Pilot Wire (a telephone type cable between the two locations) were available, these were used to relay the data. However, transmission of the AC signals might be subject to electromagnetic interference and varying attenuation with temperature changes. Consequently, it was decided to transmit the data as a DC current level using a 5 to 20 mA system used in process control. This approach involves the RMS to DC voltage conversion, and a voltage-to-current line driver. The line driver is a constant current source with an output of 5 mA for the zero condition and 20 mA for the full scale value. When the line is terminated in a small precision resistor (20 ohms), the signal level is immune to thermal resistance changes in the Pilot Wire circuit.

The electronic circuitry was mounted in small aluminum boxes which were fastened to the inside of one of the panels in the existing ATC system. This provided a convenient location with simple access to the ATC sensor wiring.

C.4 Instrumentation at Big Eddy

The signal conditioning at Big Eddy for the 5th and 7th filters is similar to that described previously for the 11th and 13th at Celilo except that no line

To Big Eddy

Figure C.3-1 Harmonic Instrumentation at Celilo

drivers are required. A functional block diagram is given in Figure C.4-2, which also shows the terminations for the twisted pairs of the Pilot Wire lines. The back-to-back zener diodes (10 volt) limit the voltage excursions to +10 volts in the event of line transients or malfunction of the line drivers.

As at Celilo, the electronics are packaged in small aluminum boxes which are mounted on a panel of the ATC system. The datalogger was rack mounted in the relay rack area.

C.5 Installation and Operation

With the exception of the datalogger (a purchased item), all the equipment for the filter current monitor was designed and built at the GE Materials and Processes Laboratory in Schenectady, New York. The Maxwell Worm was shipped early and installed by BPA personnel. Electronic boxes were built and tested to a schedule which permitted installation to coincide with a meeting scheduled at Celilo on July 7, 1978. This avoided a separate trip.

The actual installation was done by BPA personnel working with a GE specialist. The equipment was turned on and checkout was completed without incident. Known signals were injected to verify preset calibrations and no changes were required. The internal clock was set to local time and the datalogger was programmed for printout at preset limits and also for a full record each hour.

Instruction manuals and drawings were delivered to the BPA personnel who were also instructed in setup and troubleshooting procedures. After practice in programming, the keyswitch was locked in the program lockout position with keys retained by BPA. The equipment has been very reliable with no known servicing other than replacement of printer paper as needed.

Figure C.4-1 Harmonic Instrumentation at Big Eddy

Appendix D
MEASURED RESULTS

D.1 Harmonic Impedances for Data Sets 1 to 15, 17 and 18

3RD HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	26.40	57.24	14.29	22.20
1	2	12.00	-11.62	11.75	-2.42
2	1	23.40	15.79	22.52	6.37
2	2	1.70	56.81	0.93	1.42
17	1	54.87	54.20	32.10	44.50
17	2	71.15	153.72	-63.80	31.50
17	3	1794.47	-124.72	-1022.00	-1475.00
3	1	12.80	128.93	-8.04	9.96
3	2	20.80	140.50	-16.05	13.23
4	1	39.70	65.01	16.77	35.98
4	2	25.70	61.17	12.39	22.51
18	1	78.39	110.77	-27.80	73.30
18	2	84.06	107.87	-25.80	80.00
18	3	199.55	157.99	-185.00	74.80
5	1	22.60	64.71	9.65	20.43
5	2	31.60	114.28	-12.99	28.80
6	1	6.10	117.24	-2.79	5.42
7	1	17.80	-128.63	-11.12	-13.90
7	2	33.40	95.36	-3.12	33.25
8	1	31.10	45.84	21.67	22.31
8	2	6.70	106.74	-1.93	6.42
9	1	62.80	105.31	-16.58	60.57
9	2	35.70	82.55	4.63	35.40
10	1	77.40	33.83	64.30	43.09
10	2	64.30	155.94	-58.71	26.21
10	3	64.80	15.52	62.44	17.34
10	4	92.00	48.77	60.64	69.19
10	5	26.50	136.03	-19.09	18.38
10	6	183.80	0.25	183.80	0.80
11	1	7.40	106.86	-2.15	7.08
12	1	8.60	29.91	7.45	4.29
12	2	25.00	76.01	6.04	24.26
13	1	27.30	103.05	-6.16	26.59
13	2	30.20	111.65	-11.14	28.07
13	3	26.00	107.63	-7.87	24.78
13	4	29.00	112.99	-11.33	26.70
13	5	28.00	123.18	-15.32	23.43
14	1	4.70	-19.35	4.43	-1.56
15	1	17.70	-178.91	-17.70	-0.34

5TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
.1	1	19.50	72.79	5.77	18.63
.1	2	13.20	85.27	1.09	13.16
2	1	24.50	80.65	3.98	24.17
2	2	25.10	101.10	-4.83	24.63
17	1	21.32	60.19	10.60	18.50
17	2	19.92	76.94	4.50	19.40
17	3	25.55	61.73	12.10	22.50
3	1	22.40	78.39	4.51	21.94
3	2	11.60	81.10	1.79	11.46
4	1	20.00	124.33	-11.28	16.52
4	2	13.00	138.21	-9.69	8.66
18	1	96.00	137.87	-71.20	64.40
18	2	105.87	146.52	-88.30	58.40
18	3	102.95	146.25	-85.60	57.20
5	1	16.00	97.25	-2.02	15.87
5	2	27.50	94.15	-1.99	27.43
6	1	16.00	85.55	1.24	15.95
7	1	21.00	62.69	9.63	18.66
7	2	16.00	65.37	6.67	14.54
8	1	37.50	96.20	-4.05	37.28
8	2	15.50	75.05	4.00	14.98
9	1	20.60	83.70	2.26	20.48
9	2	86.60	130.20	-55.90	66.14
10	1	22.70	115.61	-9.81	20.47
10	2	13.40	-6.88	13.30	-1.61
10	3	9.20	-121.06	-4.75	-7.88
10	4	19.10	94.10	-1.37	19.05
10	5	39.10	64.69	16.72	35.35
10	6	27.30	107.40	-8.16	26.05
11	1	30.80	94.29	-2.30	30.71
12	1	40.40	48.50	26.77	30.26
12	2	15.60	27.80	13.80	7.28
13	1	43.20	119.73	-21.42	37.51
13	2	157.10	132.12	-105.36	116.53
13	3	54.20	66.65	21.48	49.76
13	4	67.70	93.08	-3.64	67.60
13	5	38.10	59.28	19.46	32.75
14	1	30.10	44.04	21.64	20.92
15	1	31.60	131.75	-21.04	23.58

7TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	33.10	80.17	5.65	32.61
1	2	36.10	83.68	3.97	35.88
2	1	35.10	79.72	6.26	34.54
2	2	35.50	81.70	5.12	35.13
17	1	33.78	72.42	10.20	32.20
17	2	32.28	79.11	6.10	31.70
17	3	42.47	82.42	5.60	42.10
3	1	34.30	80.64	5.58	33.84
3	2	33.00	84.38	3.23	32.84
4	1	35.30	81.63	5.14	34.92
4	2	36.00	85.20	3.01	35.87
18	1	297.06	47.52	200.60	219.10
18	2	354.74	47.99	237.40	263.60
18	3	319.31	48.14	213.10	237.80
5	1	35.10	84.43	3.41	34.93
5	2	35.00	82.84	4.36	34.73
6	1	35.90	79.09	6.79	35.25
7	1	35.00	78.49	6.98	34.30
7	2	35.80	77.89	7.51	35.00
8	1	40.80	74.89	10.64	39.39
8	2	37.70	79.80	6.68	37.10
9	1	40.90	76.95	9.24	39.84
9	2	45.60	72.59	13.64	43.51
10	1	41.40	81.74	5.95	40.97
10	2	38.60	78.63	7.61	37.84
10	3	45.80	80.06	7.91	45.11
10	4	40.40	86.19	2.68	40.31
10	5	39.20	71.47	12.46	37.17
10	6	40.00	82.03	5.55	39.61
11	1	39.90	76.13	9.56	38.74
12	1	35.50	79.85	6.26	34.94
12	2	35.10	79.65	6.31	34.53
13	1	36.90	82.88	4.57	36.62
13	2	31.30	84.94	2.76	31.18
13	3	36.30	78.84	7.03	35.61
13	4	36.30	79.63	6.53	35.71
13	5	37.10	77.92	7.76	36.28
14	1	36.80	80.38	6.15	36.28
15	1	37.00	80.40	6.17	36.48

9TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	51.60	68.71	18.74	48.08
1	2	63.50	64.35	27.49	57.24
2	1	53.40	71.67	16.79	50.69
2	2	52.10	63.49	23.26	46.62
17	1	56.02	74.57	14.90	54.00
17	2	29.24	84.31	2.90	29.10
17	3	53.39	65.55	22.10	48.60
3	1	41.60	73.59	11.75	39.91
3	2	49.10	73.09	14.28	46.98
4	1	45.50	68.23	16.88	42.25
4	2	46.10	70.37	15.49	43.42
18	1	28.01	9.87	27.60	4.80
18	2	51.36	57.89	27.30	43.50
18	3	53.94	59.97	27.00	46.70
5	1	50.00	65.38	20.83	45.45
5	2	51.60	68.69	18.75	48.07
6	1	47.30	67.93	17.77	43.83
7	1	49.30	67.14	19.15	45.43
7	2	49.40	70.69	16.34	46.62
8	1	38.50	55.88	21.60	31.87
8	2	58.10	74.08	15.94	55.87
9	1	80.10	83.06	9.68	79.51
9	2	41.50	49.03	27.21	31.33
10	1	85.70	41.26	64.42	56.52
10	2	60.90	88.53	1.56	60.88
10	3	74.10	65.40	30.85	67.37
10	4	59.10	70.54	19.69	55.72
10	5	44.30	67.68	16.82	40.98
10	6	76.10	69.56	26.58	71.31
11	1	52.50	73.26	15.12	50.28
12	1	54.60	67.41	20.97	50.41
12	2	52.00	65.91	21.22	47.47
13	1	55.20	67.24	21.36	50.90
13	2	59.30	69.33	20.93	55.48
13	3	54.20	74.41	14.57	52.21
13	4	51.20	73.84	14.25	49.18
13	5	51.00	68.87	18.38	47.57
14	1	54.80	64.98	23.18	49.66
15	1	54.20	64.10	23.67	48.76

11TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	49.40	5.77	49.15	4.97
1	2	52.70	3.93	52.58	3.61
2	1	53.70	0.15	53.70	0.14
2	2	51.40	0.05	51.40	0.04
17	1	45.21	1.01	45.20	0.80
17	2	63.78	8.38	63.10	9.30
17	3	53.02	3.79	52.90	3.50
3	1	51.40	7.98	50.90	7.14
3	2	51.40	1.78	51.38	1.60
4	1	56.10	11.12	55.05	10.82
4	2	55.90	10.81	54.91	10.48
18	1	54.11	3.60	54.00	3.40
18	2	55.51	4.96	55.30	4.80
18	3	55.90	6.88	55.50	6.70
5	1	55.70	10.59	54.75	10.24
5	2	57.40	9.13	56.67	9.11
6	1	37.90	12.61	36.99	8.27
7	1	37.90	11.95	37.08	7.85
7	2	38.10	12.31	37.22	8.12
8	1	49.40	-6.30	49.10	-5.42
8	2	49.80	-13.52	48.42	-11.64
9	1	55.40	-8.61	54.78	-8.29
9	2	56.10	-5.50	55.84	-5.38
10	1	61.90	-15.37	59.69	-16.41
10	2	72.40	4.57	72.17	5.77
10	3	56.80	-11.24	55.71	-11.07
10	4	41.40	-21.19	38.60	-14.96
10	5	71.20	0.77	71.19	0.96
10	6	49.80	-16.72	47.69	-14.33
11	1	57.70	-10.26	56.78	-10.28
12	1	14.40	-77.05	3.23	-14.03
12	2	17.80	-20.77	16.64	-6.31
13	1	16.10	-93.17	-0.89	-16.08
13	2	24.30	-147.54	-20.50	-13.04
13	3	46.50	83.70	5.10	46.22
13	4	98.30	51.36	61.38	76.78
13	5	53.40	-9.83	52.62	-9.12
14	1	78.40	104.15	-19.17	76.02
15	1	13.90	-47.11	9.46	-10.18

13TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	53.60	-12.40	52.35	-11.51
1	2	48.80	-4.72	48.63	-4.02
2	1	49.00	-16.09	47.08	-13.58
2	2	51.00	-10.41	50.16	-9.22
17	1	30.88	6.14	30.70	3.30
17	2	62.93	17.86	59.90	19.30
17	3	58.12	18.25	55.20	18.20
3	1	35.40	-0.85	35.40	-0.53
3	2	39.20	-5.15	39.04	-3.52
4	1	45.40	-6.80	45.08	-5.38
4	2	45.60	-7.00	45.26	-5.56
18	1	45.15	-8.92	44.60	-7.00
18	2	45.15	-8.92	44.60	-7.00
18	3	45.34	-8.88	44.80	-7.00
5	1	45.30	-7.01	44.96	-5.53
5	2	45.80	-7.91	45.36	-6.30
6	1	45.80	-11.29	44.91	-8.97
7	1	44.00	-9.86	43.35	-7.53
7	2	44.30	-9.99	43.63	-7.68
8	1	30.10	-22.61	27.79	-11.57
8	2	34.00	-21.38	31.66	-12.39
9	1	35.10	-11.41	34.41	-6.94
9	2	34.20	-20.01	32.14	-11.70
10	1	32.10	0.57	32.10	0.32
10	2	58.70	-37.92	46.31	-36.07
10	3	45.80	-15.96	44.03	-12.59
10	4	24.00	-12.92	23.39	-5.37
10	5	49.70	-31.24	42.49	-25.78
10	6	32.60	-30.05	28.22	-16.32
11	1	36.90	-25.74	33.24	-16.03
12	1	32.50	-20.48	30.45	-11.37
12	2	36.90	-10.46	36.29	-6.70
13	1	33.60	0.63	33.60	0.37
13	2	115.00	-42.05	85.39	-77.02
13	3	42.90	6.83	42.59	5.14
13	4	71.60	-9.31	70.66	-11.58
13	5	39.10	-6.53	38.85	-4.45
14	1	32.00	30.61	27.54	16.29
15	1	38.00	-24.57	34.56	-15.80

15TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	33.40	47.78	22.44	24.74
1	2	35.40	44.56	25.22	24.84
2	1	35.60	56.34	19.73	29.63
2	2	33.80	48.19	22.53	25.19
17	1	26.87	60.57	13.20	23.40
17	2	24.22	67.67	9.20	22.40
17	3	29.53	59.70	14.90	25.50
3	1	33.20	48.87	21.84	25.01
3	2	32.00	58.58	16.68	27.31
4	1	33.60	63.92	14.77	30.18
4	2	34.40	60.94	16.71	30.07
18	1	28.75	70.49	9.60	27.10
18	2	29.06	67.76	11.00	26.90
18	3	27.67	68.81	10.00	25.80
5	1	30.60	71.35	9.79	28.99
5	2	30.80	69.31	10.88	28.81
6	1	31.60	68.98	11.33	29.50
7	1	29.80	69.49	10.44	27.91
7	2	29.50	67.17	11.45	27.19
8	1	21.20	45.73	14.80	15.18
8	2	32.90	73.88	9.13	31.61
9	1	12.50	144.45	-10.17	7.27
9	2	19.30	148.08	-16.38	10.20
10	1	31.40	65.94	12.80	28.67
10	2	51.10	69.75	17.69	47.94
10	3	34.90	59.71	17.60	30.14
10	4	28.40	48.98	18.64	21.43
10	5	14.00	104.64	-3.54	13.55
10	6	29.50	63.31	13.25	26.36
11	1	30.10	71.43	9.59	28.53
12	1	34.60	57.73	18.47	29.26
12	2	32.80	60.44	16.18	28.53
13	1	31.60	55.73	17.79	26.11
13	2	35.80	48.64	23.66	26.87
13	3	30.50	54.89	17.54	24.95
13	4	38.20	47.78	25.67	28.29
13	5	26.60	62.27	12.38	23.54
14	1	42.00	34.76	34.50	23.95
15	1	36.50	63.50	16.29	32.67

17TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	65.30	57.15	35.42	54.86
1	2	60.70	57.79	32.35	51.36
2	1	74.80	51.14	46.93	58.25
2	2	71.30	55.64	40.24	58.86
17	1	63.24	55.96	35.40	52.40
17	2	58.41	77.84	12.30	57.10
17	3	75.58	42.64	55.60	51.20
3	1	64.00	58.65	33.30	54.66
3	2	61.10	56.33	33.87	50.85
4	1	55.80	76.63	12.90	54.29
4	2	56.40	79.55	10.23	55.46
18	1	32.83	54.42	19.10	26.70
18	2	29.00	52.14	17.80	22.90
18	3	32.24	63.67	14.30	28.90
5	1	72.00	80.00	12.50	70.91
5	2	68.60	72.72	20.38	65.50
6	1	63.60	55.51	36.01	52.42
7	1	56.10	72.74	16.65	53.57
7	2	58.70	72.56	17.59	56.00
8	1	56.50	53.92	33.27	45.66
8	2	66.10	40.38	50.35	42.82
9	1	54.00	54.40	31.43	43.91
9	2	96.60	52.01	59.46	76.13
10	1	39.20	71.52	12.43	37.18
10	2	68.50	85.43	5.46	68.28
10	3	70.40	49.63	45.60	53.64
10	4	66.20	117.12	-30.18	58.92
10	5	55.70	76.76	12.76	54.22
10	6	68.20	52.83	41.21	54.34
11	1	58.70	56.40	32.48	48.89
12	1	55.80	65.07	23.52	50.60
12	2	55.70	64.95	23.58	50.46
13	1	55.10	57.25	29.81	46.34
13	2	54.80	75.13	14.06	52.96
13	3	55.70	57.93	29.57	47.20
13	4	56.30	75.50	14.10	54.51
13	5	63.70	48.49	42.22	47.70
14	1	56.20	67.81	21.23	52.04
15	1	53.90	63.09	24.39	48.06

19TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	57.60	60.75	28.14	50.26
1	2	56.30	57.92	29.90	47.70
2	1	55.40	52.28	33.89	43.82
2	2	44.30	65.86	18.12	40.43
17	1	61.54	52.93	37.10	49.10
17	2	55.01	83.95	5.80	54.70
17	3	57.79	74.54	15.40	55.70
3	1	60.40	57.63	32.34	51.01
3	2	45.50	67.20	17.63	41.94
4	1	55.40	54.78	31.95	45.26
4	2	56.60	55.99	31.66	46.92
18	1	53.12	51.04	33.40	41.30
18	2	52.70	50.39	33.60	40.60
18	3	52.70	52.48	32.10	41.80
5	1	55.80	49.73	36.07	42.58
5	2	55.90	45.36	39.28	39.77
6	1	55.00	54.50	31.94	44.78
7	1	52.40	48.72	34.57	39.38
7	2	52.00	50.93	32.77	40.37
8	1	58.80	52.81	35.54	46.84
8	2	52.00	42.13	38.56	34.88
9	1	51.60	54.74	29.79	42.13
9	2	80.60	51.05	50.67	62.68
10	1	51.40	64.17	22.40	46.26
10	2	60.60	61.15	29.24	53.08
10	3	60.90	47.52	41.13	44.91
10	4	39.90	-106.10	-11.06	-38.34
10	5	56.90	67.66	21.63	52.63
10	6	11.40	53.87	6.72	9.21
11	1	56.10	49.70	36.28	42.79
12	1	58.40	57.36	31.50	49.18
12	2	57.40	57.74	30.64	48.54
13	1	59.00	49.93	37.98	45.15
13	2	51.40	53.13	30.84	41.12
13	3	58.00	48.59	38.36	43.50
13	4	55.90	52.76	33.83	44.50
13	5	55.80	56.93	30.45	46.76
14	1	54.30	59.92	27.22	46.99
15	1	58.30	56.48	32.19	48.60

21ST HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	55.70	51.47	34.70	43.57
1	2	60.30	54.99	34.60	49.39
2	1	79.10	52.64	48.00	62.87
2	2	59.40	66.25	23.92	54.37
17	1	52.05	44.38	37.20	36.40
17	2	60.01	48.58	39.70	45.00
17	3	55.96	59.26	28.60	48.10
3	1	49.50	51.06	31.11	38.50
3	2	53.40	45.05	37.73	37.79
4	1	62.60	53.92	36.87	50.59
4	2	63.60	55.21	36.29	52.23
18	1	70.59	53.99	41.50	57.10
18	2	69.03	54.03	40.50	55.90
18	3	68.77	54.23	40.20	55.80
5	1	63.10	60.82	30.76	55.09
5	2	60.10	63.90	26.44	53.97
6	1	62.70	58.78	32.50	53.62
7	1	62.70	61.39	30.02	55.04
7	2	61.70	58.59	32.16	52.66
8	1	49.10	61.88	23.14	43.30
8	2	63.20	60.07	31.53	54.77
9	1	56.20	117.12	-25.62	50.02
9	2	71.20	83.91	7.55	70.80
10	1	36.00	65.95	14.67	32.87
10	2	45.80	41.82	34.13	30.54
10	3	97.30	59.57	49.28	83.90
10	4	122.80	57.48	66.02	103.55
10	5	57.10	61.02	27.67	49.95
10	6	100.80	66.61	40.02	92.52
11	1	65.70	60.25	32.60	57.04
12	1	70.80	56.42	39.16	58.98
12	2	68.90	56.11	38.42	57.19
13	1	69.90	56.71	38.37	58.43
13	2	59.50	61.55	28.35	52.31
13	3	76.00	52.33	46.44	60.16
13	4	61.70	62.66	28.34	54.81
13	5	73.90	60.92	35.92	64.58
14	1	70.90	49.52	46.03	53.93
15	1	68.30	57.55	36.65	57.64

23RD HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	58.90	45.90	40.99	42.30
1	2	57.70	48.97	37.88	43.53
2	1	72.70	48.72	47.96	54.63
2	2	51.50	71.23	16.57	48.76
17	1	25.92	29.33	22.60	12.70
17	2	64.74	55.89	36.30	53.60
17	3	78.75	63.21	35.50	70.30
3	1	47.10	34.41	38.86	26.62
3	2	67.70	43.73	48.92	46.80
4	1	55.60	46.69	38.14	40.46
4	2	55.60	46.74	38.10	40.49
18	1	56.37	46.22	39.00	40.70
18	2	56.58	46.29	39.10	40.90
18	3	56.30	46.15	39.00	40.60
5	1	55.20	46.44	38.04	40.00
5	2	56.20	45.78	39.19	40.28
6	1	56.20	48.08	37.55	41.82
7	1	55.60	48.42	36.90	41.59
7	2	56.10	48.56	37.13	42.06
8	1	56.50	56.10	31.51	46.90
8	2	75.30	63.93	33.09	67.64
9	1	30.50	30.36	26.32	15.42
9	2	68.20	123.08	-37.22	57.15
10	1	49.90	19.08	47.16	16.31
10	2	31.70	3.46	31.64	1.91
10	3	60.40	79.20	11.32	59.33
10	4	73.70	82.70	9.36	73.10
10	5	66.20	71.07	21.48	62.62
10	6	173.40	-142.30	-137.20	-106.04
11	1	49.20	66.12	19.92	44.99
12	1	56.50	47.46	38.20	41.63
12	2	56.30	47.51	38.03	41.52
13	1	61.40	45.55	43.00	43.83
13	2	51.10	56.00	28.57	42.36
13	3	59.50	47.63	40.10	43.96
13	4	51.80	54.69	29.94	42.27
13	5	60.50	40.38	46.09	39.20
14	1	55.70	47.73	37.47	41.22
15	1	56.30	47.27	38.20	41.36

25TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	58.60	64.29	25.42	52.80
1	2	63.50	59.74	32.00	54.85
2	1	65.60	64.49	28.25	59.20
2	2	68.20	83.82	7.34	67.80
17	1	64.65	49.83	41.70	49.40
17	2	50.53	74.97	13.10	48.80
17	3	75.02	85.64	5.70	74.80
3	1	61.20	53.88	36.08	49.44
3	2	62.40	61.45	29.82	54.81
4	1	61.80	63.55	27.53	55.33
4	2	61.50	63.45	27.49	55.01
18	1	62.70	63.48	28.00	56.10
18	2	62.79	63.31	28.20	56.10
18	3	62.70	63.27	28.20	56.00
5	1	61.40	62.92	27.95	54.67
5	2	60.80	65.26	25.44	55.22
6	1	63.70	59.39	32.44	54.82
7	1	62.70	59.69	31.64	54.13
7	2	61.90	59.88	31.06	53.54
8	1	66.60	71.71	20.90	63.24
8	2	64.90	57.82	34.56	54.93
9	1	69.80	72.86	20.57	66.70
9	2	54.40	82.28	7.31	53.91
10	1	74.20	58.13	39.18	63.01
10	2	50.60	81.50	7.48	50.04
10	3	95.20	50.91	60.03	73.89
10	4	78.10	42.40	57.67	52.66
10	5	59.50	86.32	3.82	59.38
10	6	71.10	58.56	37.09	60.66
11	1	71.80	65.55	29.72	65.36
12	1	62.80	64.98	26.56	56.91
12	2	62.70	64.94	26.56	56.80
13	1	70.10	60.18	34.86	60.82
13	2	54.60	73.92	15.12	52.46
13	3	71.80	60.39	35.48	62.42
13	4	56.30	73.77	15.74	54.06
13	5	64.90	60.00	32.45	56.21
14	1	63.40	64.77	27.02	57.35
15	1	62.90	64.95	26.63	56.98

27TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	128.50	33.39	107.29	70.72
1	2	147.10	28.90	128.78	71.09
2	1	95.50	-12.90	93.09	-21.32
2	2	230.70	38.66	180.15	144.12
17	1	155.44	1.29	155.40	3.50
17	2	142.12	52.20	87.10	112.30
17	3	177.80	36.08	143.70	104.70
3	1	117.20	9.16	115.71	18.66
3	2	164.60	10.34	161.93	29.54
4	1	154.10	30.20	133.18	77.52
4	2	150.10	30.84	128.88	76.95
18	1	154.57	33.90	128.30	86.20
18	2	156.26	32.56	131.70	84.10
18	3	152.12	35.53	123.80	88.40
5	1	144.90	26.93	129.19	65.63
5	2	143.60	27.37	127.52	66.02
6	1	148.40	29.09	129.68	72.15
7	1	155.50	30.30	134.26	78.45
7	2	157.20	28.45	138.22	74.89
8	1	137.90	42.76	101.25	93.62
8	2	136.00	24.76	123.50	56.96
9	1	132.50	39.60	102.09	84.46
9	2	197.40	15.77	189.97	53.65
10	1	186.80	16.40	179.20	52.74
10	2	139.30	33.09	116.71	76.05
10	3	163.40	19.46	154.07	54.44
10	4	177.80	22.71	164.02	68.64
10	5	200.90	51.03	126.35	156.19
10	6	163.00	6.65	161.90	18.88
11	1	150.00	32.41	126.64	80.40
12	1	153.20	28.11	135.13	72.18
12	2	153.90	27.99	135.90	72.23
13	1	177.50	26.57	158.75	79.39
13	2	159.20	49.50	103.39	121.06
13	3	183.60	20.99	171.42	65.77
13	4	140.10	55.30	79.76	115.18
13	5	170.70	15.61	164.40	45.93
14	1	158.80	32.68	133.66	85.74
15	1	157.00	27.22	139.61	71.81

29TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	58.30	14.97	56.32	15.06
1	2	58.50	7.54	57.99	7.68
2	1	89.20	29.98	77.27	44.57
2	2	56.10	8.83	55.44	8.61
17	1	64.82	3.45	64.70	3.90
17	2	65.35	21.26	60.90	23.70
17	3	60.50	-0.38	60.50	-0.40
3	1	51.90	9.91	51.13	8.93
3	2	58.30	11.32	57.17	11.44
4	1	64.00	13.40	62.26	14.83
4	2	68.70	14.25	66.59	16.91
18	1	69.19	25.60	62.40	29.90
18	2	66.77	26.60	59.70	29.90
18	3	66.95	27.29	59.50	30.70
5	1	66.90	25.05	60.61	28.33
5	2	71.10	22.24	65.81	26.91
6	1	64.10	12.37	62.61	13.73
7	1	71.30	15.15	68.82	18.63
7	2	67.90	15.26	65.51	17.87
8	1	65.00	15.80	62.54	17.70
8	2	50.80	-15.85	48.87	-13.87
9	1	43.60	49.20	28.49	33.00
9	2	102.00	6.55	101.33	11.64
10	1	69.70	23.40	63.97	27.68
10	2	55.90	40.30	42.63	36.16
10	3	60.90	-12.69	59.41	-13.38
10	4	117.40	-1.89	117.34	-3.87
10	5	67.60	23.72	61.89	27.19
10	6	61.40	-10.30	60.41	-10.98
11	1	66.10	0.03	66.10	0.03
12	1	62.00	10.12	61.04	10.89
12	2	62.60	9.09	61.81	9.89
13	1	62.30	3.82	62.16	4.15
13	2	68.00	10.32	66.90	12.18
13	3	71.80	6.56	71.33	8.20
13	4	73.20	14.20	70.96	17.96
13	5	54.30	2.70	54.24	2.56
14	1	66.50	6.19	66.11	7.17
15	1	61.70	8.64	61.00	9.27

31ST HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	77.00	49.15	50.36	58.24
1	2	76.60	38.06	60.31	47.22
2	1	70.10	25.36	63.34	30.02
2	2	69.90	48.98	45.88	52.74
17	1	105.65	56.90	57.70	88.50
17	2	69.16	45.59	48.40	49.40
17	3	98.41	69.54	34.40	92.20
3	1	73.30	45.04	51.79	51.87
3	2	77.70	27.48	68.93	35.85
4	1	75.60	51.90	46.65	59.49
4	2	83.30	50.57	52.91	64.34
18	1	88.72	58.69	46.10	75.80
18	2	87.10	57.19	47.20	73.20
18	3	89.89	56.66	49.40	75.10
5	1	77.20	43.80	55.72	53.43
5	2	78.30	46.34	54.06	56.65
6	1	81.10	51.30	50.71	63.29
7	1	79.40	53.89	46.79	64.15
7	2	80.60	50.71	51.04	62.38
8	1	72.20	40.12	55.21	46.53
8	2	75.00	41.60	56.08	49.79
9	1	49.00	42.19	36.31	32.91
9	2	69.00	40.38	52.56	44.70
10	1	82.10	42.33	60.69	55.29
10	2	81.90	26.61	73.22	36.68
10	3	95.20	48.43	63.17	71.22
10	4	42.50	38.25	33.38	26.31
10	5	74.80	54.26	43.69	60.71
10	6	131.70	35.96	106.60	77.34
11	1	69.90	37.31	55.60	42.37
12	1	77.60	45.97	53.93	55.79
12	2	79.40	45.94	55.22	57.06
13	1	82.10	43.70	59.36	56.72
13	2	63.80	46.28	44.09	46.11
13	3	94.90	53.63	56.28	76.41
13	4	70.90	58.50	37.05	60.45
13	5	70.80	42.17	52.47	47.53
14	1	69.20	49.16	45.25	52.35
15	1	82.40	46.13	57.11	59.40

33RD HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	42.20	50.17	27.03	32.41
1	2	35.80	51.15	22.46	27.88
2	1	76.60	-71.97	23.71	-72.84
2	2	64.50	46.59	44.33	46.86
17	1	76.48	-20.35	71.70	-26.60
17	2	144.38	175.83	-144.00	10.50
17	3	255.99	7.68	253.70	34.20
3	1	55.70	24.37	50.74	22.98
3	2	26.90	39.30	20.82	17.04
4	1	56.10	21.18	52.31	20.27
4	2	38.30	39.53	29.54	24.38
18	1	51.03	25.66	46.00	22.10
18	2	43.07	18.27	40.90	13.50
18	3	44.46	17.95	42.30	13.70
5	1	49.60	11.56	48.59	9.94
5	2	40.00	-5.32	39.83	-3.71
6	1	61.70	12.12	60.32	12.95
7	1	56.00	-0.12	56.00	-0.12
7	2	69.50	3.37	69.38	4.09
8	1	61.10	21.36	56.90	22.25
8	2	52.40	-0.16	52.40	-0.15
9	1	48.60	28.02	42.90	22.83
9	2	133.40	35.69	108.35	77.83
10	1	76.10	53.11	45.68	60.86
10	2	100.40	42.34	74.21	67.62
10	3	54.10	-5.00	53.89	-4.72
10	4	26.00	-17.71	24.77	-7.91
10	5	42.30	81.99	5.89	41.89
10	6	41.60	-22.52	38.43	-15.93
11	1	51.70	24.39	47.09	21.35
12	1	64.10	16.33	61.51	18.02
12	2	21.20	26.05	19.05	9.31
13	1	50.10	32.62	42.20	27.01
13	2	22.60	61.16	10.90	19.80
13	3	71.40	4.00	71.23	4.98
13	4	30.80	55.05	17.64	25.25
13	5	49.80	15.67	47.95	13.45
14	1	73.80	-23.79	67.53	-29.77
15	1	45.60	-0.15	45.60	-0.12

35TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	65.90	61.49	31.45	57.91
1	2	73.70	66.71	29.14	67.69
2	1	156.20	-150.93	-136.52	-75.89
2	2	83.80	-5.17	83.46	-7.55
17	1	51.50	-0.56	51.50	-0.50
17	2	47.09	171.70	-46.60	6.80
17	3	156.87	85.58	12.10	156.40
3	1	19.60	-145.15	-16.08	-11.20
3	2	20.50	43.96	14.76	14.23
4	1	57.00	43.60	41.28	39.31
4	2	62.00	37.06	49.48	37.36
18	1	55.39	37.74	43.80	33.90
18	2	60.91	38.60	47.60	38.00
18	3	60.08	37.29	47.80	36.40
5	1	58.40	37.53	46.31	35.58
5	2	69.10	40.78	52.32	45.13
6	1	56.50	34.67	46.47	32.14
7	1	56.50	47.15	38.42	41.42
7	2	60.80	42.58	44.77	41.14
8	1	97.10	27.60	86.05	44.99
8	2	64.70	-147.14	-54.35	-35.11
9	1	262.70	50.92	165.61	203.93
9	2	107.70	-6.42	107.02	-12.04
10	1	146.90	-68.47	53.91	-136.65
10	2	109.50	-162.24	-104.28	-33.40
10	3	31.10	7.78	30.81	4.21
10	4	11.70	0.83	11.70	0.17
10	5	73.70	77.98	15.35	72.08
10	6	39.10	-36.57	31.40	-23.30
11	1	44.20	10.49	43.46	8.05
12	1	56.80	35.24	46.39	32.77
12	2	48.90	34.90	40.11	27.98
13	1	55.80	27.78	49.37	26.01
13	2	68.30	41.31	51.30	45.09
13	3	55.30	23.75	50.62	22.27
13	4	57.10	42.34	42.21	38.46
13	5	59.60	29.42	51.91	29.28
14	1	51.80	32.05	43.90	27.49
15	1	69.40	29.64	60.32	34.32

37TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	70.10	33.67	58.34	38.86
1	2	62.10	48.17	41.42	46.27
2	1	90.40	72.71	26.87	86.32
2	2	20.10	-79.53	3.65	-19.77
17	1	47.06	-31.09	40.30	-24.30
17	2	55.52	168.99	-54.50	10.60
17	3	85.16	53.55	50.60	68.50
3	1	58.90	11.52	57.71	11.76
3	2	38.60	41.73	28.81	25.69
4	1	64.10	31.25	54.80	33.25
4	2	65.50	32.60	55.18	35.29
18	1	65.37	29.31	57.00	32.00
18	2	64.47	30.06	55.80	32.30
18	3	64.81	30.40	55.90	32.80
5	1	67.50	32.13	57.16	35.90
5	2	56.30	36.01	45.54	33.10
6	1	51.80	34.12	42.88	29.06
7	1	49.80	37.49	39.51	30.31
7	2	50.00	36.93	39.97	30.04
8	1	93.00	24.61	84.55	38.73
8	2	25.90	57.59	13.88	21.87
9	1	327.80	13.44	318.82	76.19
9	2	45.00	29.31	39.24	22.03
10	1	112.70	48.64	74.47	84.59
10	2	63.30	-127.95	-38.93	-49.92
10	3	41.90	39.12	32.51	26.44
10	4	28.00	14.19	27.15	6.86
10	5	79.30	79.00	15.13	77.84
10	6	18.70	-60.46	9.22	-16.27
11	1	34.50	14.83	33.35	8.83
12	1	59.20	35.79	48.02	34.62
12	2	58.60	40.24	44.73	37.86
13	1	59.90	31.60	51.02	31.39
13	2	56.10	49.39	36.52	42.59
13	3	47.50	35.72	38.56	27.73
13	4	60.00	50.00	38.57	45.96
13	5	56.80	27.22	50.51	25.98
14	1	59.50	42.09	44.15	39.88
15	1	57.50	28.78	50.40	27.68

39TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	46.00	47.35	31.17	33.83
1	2	42.10	38.87	32.78	26.42
2	1	118.30	9.86	116.55	20.26
2	2	61.00	-45.95	42.41	-43.84
17	1	107.20	26.18	96.20	47.30
17	2	63.24	-52.84	38.20	-50.40
17	3	77.64	44.48	55.40	54.40
3	1	45.30	46.61	31.12	32.92
3	2	34.10	18.17	32.40	10.63
4	1	55.90	41.97	41.56	37.38
4	2	54.90	36.17	44.32	32.40
18	1	54.45	44.26	39.00	38.00
18	2	55.81	43.33	40.60	38.30
18	3	54.06	42.90	39.60	36.80
5	1	41.20	18.99	38.96	13.41
5	2	37.60	25.27	34.00	16.05
6	1	54.40	31.74	46.26	28.62
7	1	60.90	28.02	53.76	28.61
7	2	55.10	33.34	46.03	30.28
8	1	59.30	45.89	41.28	42.58
8	2	42.00	35.21	34.32	24.22
9	1	38.20	126.34	-22.64	30.77
9	2	10.80	-158.66	-10.06	-3.93
10	1	142.50	-17.89	135.61	-43.77
10	2	55.00	-25.20	49.77	-23.42
10	3	68.70	32.87	57.70	37.29
10	4	267.60	-60.98	129.82	-234.00
10	5	55.00	63.82	24.27	49.36
10	6	118.10	16.17	113.43	32.89
11	1	48.60	36.88	38.87	29.17
12	1	52.80	34.84	43.34	30.16
12	2	53.90	33.77	44.81	29.96
13	1	56.10	27.66	49.69	26.04
13	2	140.90	50.63	89.38	108.92
13	3	64.40	35.07	52.71	37.00
13	4	215.00	70.22	72.76	202.31
13	5	63.10	39.59	48.63	40.21
14	1	68.10	40.73	51.61	44.43
15	1	50.50	32.59	42.55	27.20

41ST HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	57.70	34.89	47.33	33.00
1	2	51.70	26.19	46.39	22.82
2	1	49.00	-26.06	44.02	-21.53
2	2	97.10	-68.47	35.63	-90.32
17	1	37.43	-63.50	16.70	-33.50
17	2	64.32	71.51	20.40	61.00
17	3	61.75	40.86	46.70	40.40
3	1	43.70	21.43	40.68	15.97
3	2	45.60	29.61	39.65	22.53
4	1	53.90	42.63	39.66	36.50
4	2	55.80	36.47	44.87	33.17
18	1	59.64	34.76	49.00	34.00
18	2	61.12	30.80	52.50	31.30
18	3	59.87	30.29	51.70	30.20
5	1	35.00	54.12	20.51	28.36
5	2	30.90	58.66	16.07	26.39
6	1	54.00	38.01	42.55	33.25
7	1	52.90	35.88	42.86	31.00
7	2	56.20	34.70	46.20	31.99
8	1	60.60	30.29	52.33	30.57
8	2	50.70	26.59	45.34	22.69
9	1	33.20	76.26	7.89	32.25
9	2	52.30	45.72	36.51	37.44
10	1	46.80	29.29	40.82	22.90
10	2	47.30	53.76	27.96	38.15
10	3	60.50	16.31	58.07	16.99
10	4	28.10	-50.81	17.76	-21.78
10	5	70.70	79.31	13.11	69.47
10	6	75.30	22.14	69.75	28.38
11	1	61.00	36.73	48.89	36.48
12	1	54.00	35.72	43.84	31.53
12	2	53.10	35.66	43.14	30.96
13	1	55.80	21.78	51.82	20.70
13	2	50.70	70.71	16.75	47.85
13	3	63.60	36.41	51.18	37.75
13	4	63.80	75.75	15.70	61.84
13	5	60.80	29.11	53.12	29.58
14	1	53.60	44.88	37.98	37.82
15	1	54.90	35.90	44.47	32.19

43RD HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	67.70	19.90	63.66	23.04
1	2	64.70	15.36	62.39	17.14
2	1	121.20	67.39	46.60	111.88
2	2	78.70	134.57	-55.23	56.07
17	1	54.62	17.47	52.10	16.40
17	2	103.12	53.32	61.60	82.70
17	3	87.75	64.19	38.20	79.00
3	1	111.70	-23.33	102.57	-44.24
3	2	73.80	2.18	73.75	2.81
4	1	71.10	16.54	68.16	20.24
4	2	69.90	13.59	67.94	16.42
18	1	88.56	7.00	87.90	10.80
18	2	87.20	11.98	85.30	18.10
18	3	89.51	11.86	87.60	18.40
5	1	80.00	16.49	76.71	22.71
5	2	81.30	12.05	79.51	16.97
6	1	74.60	16.54	71.51	21.24
7	1	75.90	16.92	72.61	22.09
7	2	74.90	14.48	72.52	18.73
8	1	80.80	18.44	76.65	25.56
8	2	80.80	3.03	80.69	4.27
9	1	64.30	32.27	54.37	34.33
9	2	118.20	-16.09	113.57	-32.76
10	1	59.10	-12.97	57.59	-13.26
10	2	83.40	19.03	78.84	27.19
10	3	73.50	-7.47	72.88	-9.56
10	4	36.20	121.16	-18.73	30.98
10	5	90.70	39.61	69.88	57.83
10	6	80.10	-10.97	78.64	-15.24
11	1	82.00	5.40	81.64	7.72
12	1	73.50	4.26	73.30	5.46
12	2	73.30	1.10	73.29	1.41
13	1	70.80	4.10	70.62	5.06
13	2	39.30	-7.54	38.96	-5.16
13	3	66.20	-3.54	66.07	-4.09
13	4	38.70	-46.35	26.71	-28.00
13	5	77.80	19.85	73.18	26.42
14	1	40.90	21.55	38.04	15.02
15	1	73.30	3.99	73.12	5.10

45TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	66.00	31.29	56.40	34.28
1	2	62.20	19.39	58.67	20.65
2	1	54.30	-28.42	47.76	-25.84
2	2	34.00	-61.15	16.41	-29.78
17	1	98.01	19.30	92.50	32.40
17	2	35.43	45.11	25.00	25.10
17	3	71.77	49.41	46.70	54.50
3	1	66.90	6.65	66.45	7.75
3	2	57.20	28.26	50.38	27.08
4	1	59.10	38.40	46.32	36.71
4	2	63.00	35.92	51.02	36.96
18	1	56.39	42.92	41.30	38.40
18	2	61.83	40.80	46.80	40.40
18	3	64.18	49.36	41.80	48.70
5	1	121.50	20.65	113.69	42.85
5	2	108.80	19.08	102.82	35.57
6	1	55.00	41.34	41.29	36.33
7	1	52.80	36.45	42.47	31.37
7	2	55.00	42.50	40.55	37.16
8	1	71.60	54.34	41.74	58.17
8	2	72.90	20.19	68.42	25.16
9	1	66.70	134.06	-46.38	47.93
9	2	128.00	27.70	113.33	59.50
10	1	70.10	38.41	54.93	43.55
10	2	32.60	-19.35	30.76	-10.80
10	3	25.80	-2.59	25.77	-1.17
10	4	46.20	60.89	22.48	40.36
10	5	55.00	87.54	2.36	54.95
10	6	58.10	-119.92	-28.98	-50.36
11	1	51.90	22.49	47.95	19.85
12	1	55.80	32.46	47.08	29.95
12	2	60.60	33.29	50.66	33.26
13	1	50.70	27.40	45.01	23.33
13	2	54.00	25.97	48.55	23.65
13	3	73.30	30.90	62.90	37.64
13	4	57.50	23.01	52.93	22.48
13	5	61.70	26.35	55.29	27.39
14	1	51.70	14.82	49.98	13.22
15	1	56.60	33.73	47.07	31.43

47TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	49.60	31.84	42.14	26.17
1	2	32.90	33.89	27.31	18.35
2	1	105.90	92.11	-3.90	105.83
2	2	82.60	-79.52	15.02	-81.22
17	1	69.42	-10.29	68.30	-12.40
17	2	22.13	-29.81	19.20	-11.00
17	3	35.65	51.49	22.20	27.90
3	1	55.20	43.17	40.26	37.77
3	2	30.20	-2.14	30.18	-1.13
4	1	40.20	36.67	32.24	24.01
4	2	41.60	38.26	32.66	25.76
18	1	38.36	37.59	30.40	23.40
18	2	38.78	37.67	30.70	23.70
18	3	39.12	38.77	30.50	24.50
5	1	34.90	42.17	25.87	23.43
5	2	37.20	46.21	25.74	26.85
6	1	41.80	38.18	32.86	25.84
7	1	43.50	40.52	33.07	28.26
7	2	42.20	39.45	32.59	26.81
8	1	36.50	45.01	25.80	25.81
8	2	29.30	61.88	13.81	25.84
9	1	131.50	177.66	-131.39	5.37
9	2	66.70	-43.69	48.23	-46.07
10	1	62.70	10.72	61.61	11.66
10	2	318.80	75.98	77.23	309.30
10	3	48.80	34.72	40.11	27.79
10	4	50.60	83.40	5.82	50.26
10	5	51.60	74.68	13.63	49.77
10	6	89.80	18.34	85.24	28.26
11	1	41.20	47.83	27.66	30.54
12	1	45.30	39.37	35.02	28.73
12	2	45.00	39.37	34.79	28.54
13	1	48.70	35.82	39.49	28.50
13	2	39.90	60.80	19.47	34.83
13	3	42.30	32.49	35.68	22.72
13	4	39.90	62.58	18.37	35.42
13	5	49.00	35.03	40.12	28.13
14	1	46.70	40.49	35.52	30.32
15	1	45.80	40.10	35.03	29.50

49TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	45.40	26.78	40.53	20.46
1	2	59.60	44.07	42.82	41.45
2	1	164.90	85.51	12.91	164.39
2	2	69.90	148.96	-59.89	36.04
17	1	52.44	6.57	52.10	6.00
17	2	17.90	-14.89	17.30	-4.60
17	3	98.94	31.23	84.60	51.30
3	1	69.90	66.28	28.12	64.00
3	2	33.90	34.78	27.84	19.34
4	1	48.00	60.69	23.50	41.86
4	2	49.00	58.04	25.94	41.57
18	1	47.88	61.56	22.80	42.10
18	2	47.82	61.93	22.50	42.20
18	3	48.24	61.52	23.00	42.40
5	1	45.60	59.39	23.22	39.25
5	2	45.40	58.73	23.57	38.80
6	1	47.90	61.33	22.98	42.03
7	1	48.60	60.60	23.86	42.34
7	2	47.40	62.30	22.03	41.97
8	1	34.00	61.24	16.36	29.81
8	2	40.00	113.50	-15.95	36.68
9	1	39.50	33.02	33.12	21.52
9	2	115.70	-109.69	-38.98	-108.93
10	1	28.40	6.98	28.19	3.45
10	2	374.50	-166.55	-364.23	-87.11
10	3	56.80	58.52	29.66	48.44
10	4	43.80	53.44	26.09	35.18
10	5	76.50	113.76	-30.82	70.02
10	6	71.70	52.36	43.79	56.78
11	1	42.40	68.66	15.43	39.49
12	1	49.60	56.47	27.40	41.35
12	2	49.30	56.63	27.12	41.17
13	1	50.90	46.03	35.34	36.63
13	2	45.20	75.60	11.24	43.78
13	3	52.10	52.56	31.67	41.37
13	4	54.60	82.70	6.94	54.16
13	5	52.00	44.53	37.07	36.47
14	1	51.00	58.13	26.93	43.31
15	1	48.50	55.80	27.26	40.11

2ND HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	55.10	92.48	-2.38	55.05
1	2	53.50	130.67	-34.87	40.58
2	1	23.10	47.21	15.69	16.95
2	2	54.10	-174.72	-53.87	-4.98
3	1	57.20	142.89	-45.62	34.51
3	2	50.20	66.10	20.34	45.90
4	1	12.00	80.72	1.94	11.84
4	2	6.90	85.07	0.59	6.87
5	1	37.20	100.52	-6.79	36.57
5	2	67.00	151.76	-59.03	31.70
6	1	9.80	75.42	2.47	9.48
7	1	12.70	66.85	4.99	11.68
7	2	10.60	73.26	3.05	10.15

4TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	14.20	70.30	4.79	13.37
1	2	45.80	79.17	8.61	44.98
2	1	27.80	119.10	-13.52	24.29
2	2	50.50	112.04	-18.95	46.81
3	1	19.20	92.90	-0.97	19.18
3	2	51.50	1.00	51.49	0.90
4	1	29.90	90.17	-0.09	29.90
4	2	21.20	100.99	-4.04	20.81
5	1	58.30	41.57	43.62	38.68
5	2	44.70	-51.34	27.92	-34.90
6	1	23.60	73.15	6.84	22.59
7	1	41.50	96.73	-4.86	41.21
7	2	26.60	89.92	0.04	26.60

6TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	3.00	20.02	2.82	1.03
1	2	83.70	102.55	-18.19	81.70
2	1	135.70	76.79	31.01	132.11
2	2	33.90	95.22	-3.08	33.76
3	1	34.40	145.48	-28.34	19.49
3	2	57.90	104.56	-14.56	56.04
4	1	23.30	92.75	-1.12	23.27
4	2	19.60	96.28	-2.14	19.48
5	1	361.00	-17.42	344.44	-108.07
5	2	159.40	10.09	156.93	27.93
6	1	42.70	86.83	2.36	42.63
7	1	34.30	84.55	3.26	34.14
7	2	26.40	86.21	1.75	26.34

8TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	42.00	75.68	10.39	40.70
1	2	56.90	74.47	15.23	54.82
2	1	39.60	86.62	2.33	39.53
2	2	43.20	76.48	10.10	42.00
3	1	43.40	75.14	11.13	41.95
3	2	46.20	82.17	6.29	45.77
4	1	40.50	83.27	4.75	40.22
4	2	40.90	76.47	9.57	39.76
5	1	37.90	0.28	37.90	0.19
5	2	20.00	35.18	16.35	11.52
6	1	40.20	76.90	9.11	39.15
7	1	42.70	81.18	6.55	42.20
7	2	42.20	81.89	5.95	41.78

10TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	63.70	57.33	34.39	53.62
1	2	82.70	53.79	48.85	66.73
2	1	70.20	57.57	37.65	59.25
2	2	69.50	52.93	41.89	55.45
3	1	62.30	51.19	39.05	48.55
3	2	90.60	62.69	41.57	80.50
4	1	70.30	58.77	36.45	60.11
4	2	67.10	56.30	37.23	55.82
5	1	97.10	59.37	49.47	83.55
5	2	95.40	39.03	74.11	60.08
6	1	70.20	56.76	38.48	58.71
7	1	67.30	55.95	37.68	55.76
7	2	65.50	52.15	40.19	51.72

12TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	66.60	39.04	51.73	41.95
1	2	64.30	66.11	26.04	58.79
2	1	64.40	23.36	59.12	25.54
2	2	58.60	45.56	41.03	41.84
3	1	58.20	41.14	43.83	38.29
3	2	67.10	49.98	43.15	51.39
4	1	62.00	54.31	36.17	50.36
4	2	63.60	50.15	40.75	48.83
5	1	97.30	-36.41	78.31	-57.75
5	2	120.70	-14.19	117.02	-29.59
6	1	57.20	50.59	36.31	44.19
7	1	59.80	45.88	41.63	42.93
7	2	54.70	54.77	31.55	44.68

14TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	22.30	58.65	11.60	19.04
1	2	20.70	43.35	15.05	14.21
2	1	20.20	-18.57	19.15	-6.43
2	2	18.10	-22.74	16.69	-7.00
3	1	16.90	45.31	11.89	12.01
3	2	16.80	34.08	13.91	9.41
4	1	18.30	36.78	14.66	10.96
4	2	20.60	19.11	19.46	6.74
5	1	28.30	-121.30	-14.70	-24.18
5	2	20.90	-125.87	-12.25	-16.94
6	1	20.10	56.86	10.99	16.83
7	1	18.70	9.51	18.44	3.09
7	2	17.80	8.13	17.62	2.52

16TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	38.70	65.08	16.31	35.10
1	2	37.00	76.03	8.93	35.91
2	1	35.40	53.94	20.84	28.62
2	2	26.60	75.73	6.56	25.78
3	1	37.20	72.45	11.22	35.47
3	2	43.30	68.65	15.76	40.33
4	1	40.70	66.71	16.09	37.38
4	2	41.80	66.34	16.77	38.29
5	1	21.10	73.16	6.11	20.20
5	2	27.70	52.16	16.99	21.88
6	1	36.60	62.72	16.78	32.53
7	1	39.60	65.89	16.18	36.15
7	2	42.90	65.40	17.86	39.01

18TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	31.40	53.73	18.58	25.32
1	2	43.80	45.94	30.46	31.48
2	1	54.10	12.94	52.73	12.11
2	2	39.50	4.52	39.38	3.11
3	1	38.00	55.40	21.58	31.28
3	2	46.00	32.11	38.96	24.45
4	1	60.90	14.09	59.07	14.83
4	2	37.30	38.66	29.13	23.30
5	1	223.10	5.92	221.91	23.01
5	2	254.30	17.95	241.92	78.37
6	1	55.30	24.70	50.24	23.11
7	1	49.80	30.37	42.97	25.18
7	2	66.90	26.59	59.82	29.94

20TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	51.00	60.30	25.27	44.30
1	2	55.70	61.60	26.49	49.00
2	1	64.60	31.62	55.01	33.87
2	2	72.00	58.05	38.10	61.09
3	1	48.90	54.75	28.22	39.93
3	2	46.30	59.09	23.78	39.72
4	1	64.90	59.73	32.71	56.05
4	2	62.50	61.71	29.62	55.04
5	1	115.00	91.68	-3.37	114.95
5	2	133.30	77.67	28.47	130.23
6	1	54.10	47.10	36.83	39.63
7	1	57.00	58.97	29.38	48.84
7	2	58.60	56.17	32.62	48.68

22RD HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	72.10	31.26	61.63	37.41
1	2	64.00	23.21	58.82	25.22
2	1	112.00	19.77	105.40	37.88
2	2	105.70	39.09	82.04	66.65
3	1	80.90	35.49	65.87	46.97
3	2	54.40	20.19	51.06	18.78
4	1	66.40	40.44	50.54	43.07
4	2	61.20	43.89	44.11	42.43
5	1	110.30	83.95	11.63	109.69
5	2	131.00	67.13	50.91	120.70
6	1	67.20	41.53	50.31	44.55
7	1	53.70	39.35	41.53	34.05
7	2	60.00	39.53	46.24	38.23

24TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	57.20	20.29	53.65	19.84
1	2	56.50	51.28	35.34	44.08
2	1	82.70	5.50	82.32	7.93
2	2	28.00	115.83	-12.20	25.20
3	1	63.80	29.39	55.59	31.31
3	2	37.50	6.18	37.28	4.04
4	1	73.80	29.19	64.43	35.99
4	2	59.50	36.87	47.60	35.70
5	1	220.80	-21.58	205.32	-81.21
5	2	333.40	4.42	332.41	25.69
6	1	52.90	2.17	52.86	2.00
7	1	60.50	5.82	60.19	6.13
7	2	57.50	15.83	55.32	15.69

26TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	97.50	67.61	37.14	90.15
1	2	98.90	71.13	31.99	93.58
2	1	124.60	26.43	111.58	55.46
2	2	146.10	55.29	83.19	120.10
3	1	105.90	54.64	61.29	86.36
3	2	91.20	55.71	51.38	75.35
4	1	101.80	53.16	61.04	81.47
4	2	100.30	58.25	52.78	85.29
5	1	140.70	-15.88	135.33	-38.50
5	2	277.30	0.55	277.29	2.66
6	1	89.60	56.09	49.99	74.36
7	1	102.10	48.78	67.28	76.80
7	2	108.50	59.94	54.35	93.91

28TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	43.80	-28.94	38.33	-21.19
1	2	77.20	-40.06	59.09	-49.69
2	1	204.60	-39.28	158.37	-129.53
2	2	114.60	-14.57	110.91	-28.83
3	1	144.50	-29.17	126.17	-70.43
3	2	100.10	-37.31	79.62	-60.61
4	1	92.70	-14.51	89.74	-23.23
4	2	103.70	-20.99	96.82	-37.15
5	1	165.60	-48.08	110.64	-123.22
5	2	169.80	-36.16	137.09	-100.19
6	1	88.90	-19.72	83.69	-30.00
7	1	85.30	-12.34	83.33	-18.23
7	2	98.90	-18.48	93.80	-31.35

30TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	38.10	22.00	35.33	14.27
1	2	51.10	29.03	44.68	24.80
2	1	136.90	28.28	120.56	64.86
2	2	77.90	-172.83	-77.29	-9.72
3	1	36.60	12.10	35.79	7.67
3	2	31.00	49.83	20.00	23.69
4	1	49.90	47.73	33.56	36.93
4	2	52.30	28.00	46.18	24.55
5	1	409.10	33.57	340.87	226.21
5	2	403.00	30.93	345.69	207.14
6	1	60.70	37.21	48.34	36.71
7	1	56.90	30.81	48.87	29.14
7	2	50.80	35.97	41.11	29.84

32ND HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	66.40	7.99	65.76	9.23
1	2	77.20	-13.36	75.11	-17.84
2	1	83.40	-12.33	81.48	-17.81
2	2	79.50	-11.38	77.94	-15.69
3	1	62.30	-7.85	61.72	-8.51
3	2	52.40	-10.14	51.58	-9.23
4	1	58.50	-5.29	58.25	-5.39
4	2	63.30	-0.86	63.29	-0.95
5	1	81.50	-58.15	43.01	-69.23
5	2	77.90	-65.32	32.53	-70.78
6	1	60.20	-0.42	60.20	-0.44
7	1	67.60	6.08	67.22	7.16
7	2	71.30	4.23	71.11	5.26

34TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	34.60	6.43	34.38	3.87
1	2	60.90	18.36	57.80	19.18
2	1	106.10	-15.87	102.06	-29.01
2	2	89.80	38.04	70.72	55.34
3	1	44.80	22.41	41.42	17.08
3	2	40.40	-5.16	40.24	-3.63
4	1	47.40	12.97	46.19	10.64
4	2	53.20	19.21	50.24	17.50
5	1	112.40	60.98	54.53	98.29
5	2	115.30	46.53	79.32	83.68
6	1	49.20	19.28	46.44	16.25
7	1	48.80	23.92	44.61	19.79
7	2	48.50	7.31	48.11	6.17

36TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	72.90	16.67	69.84	20.91
1	2	84.20	25.22	76.17	35.88
2	1	96.40	-14.15	93.48	-23.57
2	2	53.60	-79.22	10.03	-52.65
3	1	33.00	24.69	29.98	13.78
3	2	45.80	58.38	24.01	39.00
4	1	49.00	44.53	34.93	34.36
4	2	39.20	40.21	29.94	25.31
5	1	352.00	122.65	-189.91	296.38
5	2	362.50	118.02	-170.30	320.01
6	1	19.00	27.53	16.85	8.78
7	1	36.40	41.34	27.33	24.04
7	2	35.80	38.25	28.11	22.16

38TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	57.60	38.84	44.86	36.12
1	2	40.60	39.38	31.38	25.76
2	1	124.90	-50.15	80.03	-95.89
2	2	76.20	81.02	11.89	75.27
3	1	44.80	-2.65	44.75	-2.07
3	2	56.40	-5.71	56.12	-5.61
4	1	59.90	10.98	58.80	11.41
4	2	55.30	-1.10	55.29	-1.06
5	1	301.90	-62.31	140.29	-267.32
5	2	354.10	-72.20	108.25	-337.15
6	1	67.50	17.18	64.49	19.94
7	1	26.60	96.97	-3.23	26.40
7	2	34.50	53.69	20.43	27.80

40TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	26.00	42.18	19.27	17.46
1	2	44.40	17.08	42.44	13.04
2	1	166.90	34.00	138.37	93.33
2	2	69.90	-34.52	57.59	-39.61
3	1	46.40	26.25	41.61	20.52
3	2	92.40	15.37	89.10	24.49
4	1	59.10	19.39	55.75	19.62
4	2	56.20	32.49	47.40	30.19
5	1	294.30	28.66	258.24	141.15
5	2	197.20	30.35	170.17	99.64
6	1	53.70	27.64	47.57	24.91
7	1	63.50	27.43	56.36	29.25
7	2	26.40	50.07	16.94	20.24

42TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	57.10	47.07	38.89	41.81
1	2	21.70	-0.22	21.70	-0.08
2	1	232.60	-24.54	211.59	-96.61
2	2	166.00	10.49	163.23	30.22
3	1	67.20	48.44	44.58	50.28
3	2	61.30	30.66	52.73	31.26
4	1	54.40	15.50	52.42	14.54
4	2	51.60	23.02	47.49	20.18
5	1	165.20	-63.75	73.07	-148.16
5	2	230.90	-53.41	137.64	-185.39
6	1	84.20	19.27	79.48	27.79
7	1	64.60	14.01	62.68	15.64
7	2	56.00	10.73	55.02	10.43

44TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	29.00	0.22	29.00	0.11
1	2	45.30	11.38	44.41	8.94
2	1	51.20	32.65	43.11	27.62
2	2	128.80	-22.01	119.41	-48.27
3	1	43.30	-1.34	43.29	-1.01
3	2	27.50	-9.10	27.15	-4.35
4	1	33.40	23.47	30.64	13.30
4	2	32.00	38.50	25.04	19.92
5	1	124.10	-20.39	116.32	-43.24
5	2	119.80	-25.64	108.00	-51.84
6	1	30.40	24.19	27.73	12.46
7	1	30.90	27.11	27.51	14.08
7	2	30.60	33.04	25.65	16.68

46TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	31.10	35.95	25.18	18.26
1	2	32.30	5.92	32.13	3.33
2	1	255.00	41.64	190.57	169.43
2	2	29.90	-75.95	7.26	-29.01
3	1	38.40	29.80	33.32	19.08
3	2	50.80	0.35	50.80	0.31
4	1	31.40	38.33	24.63	19.47
4	2	35.60	39.32	27.54	22.56
5	1	100.40	79.88	17.64	98.84
5	2	101.60	75.75	25.01	98.47
6	1	30.10	14.19	29.18	7.38
7	1	41.30	34.46	34.05	23.37
7	2	32.50	26.54	29.08	14.52

48TH HARMONIC IMPEDANCE

DATA SET	EVENT	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS
1	1	36.40	70.94	11.89	34.40
1	2	37.30	64.56	16.02	33.68
2	1	75.00	145.87	-62.08	42.08
2	2	33.50	37.76	26.48	20.51
3	1	32.20	76.13	7.72	31.26
3	2	24.70	16.77	23.65	7.13
4	1	47.40	68.28	17.54	44.03
4	2	48.20	55.85	27.06	39.89
5	1	455.40	167.49	-444.59	98.64
5	2	457.20	-172.47	-453.26	-59.91
6	1	49.50	111.39	-18.05	46.09
7	1	57.10	78.54	11.34	55.96
7	2	34.00	105.43	-9.05	32.77

D.2 Averaged Harmonic Impedances of Data Sets 1 to 15, 17 and 18

AVERAGE OF DATA SET 1

DATA SETS PROCESSED :
(1,1) (1,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	16.35	37.22	13.02	9.89	12.38
5	16.26	77.82	3.43	15.89	3.60
7	34.58	82.00	4.81	34.25	1.84
9	57.51	66.30	23.11	52.66	6.33
11	51.05	4.82	50.87	4.29	1.84
13	51.08	-8.74	50.49	-7.77	4.18
15	34.39	46.13	23.83	24.79	1.39
17	63.00	57.46	33.88	53.11	2.33
19	56.93	59.35	29.02	48.98	1.55
21	57.97	53.30	34.65	46.48	2.91
23	58.28	47.42	39.44	42.92	1.67
25	61.00	61.92	28.71	53.83	3.45
27	137.69	30.99	118.04	70.90	10.75
29	58.27	11.25	57.16	11.37	3.78
31	76.44	43.62	55.34	52.73	7.42
33	39.00	50.62	24.75	30.15	3.22
35	69.73	64.25	30.30	62.80	5.02
37	65.57	40.48	49.88	42.57	9.24
39	43.93	43.29	31.98	30.13	3.79
41	54.54	30.78	46.86	27.91	5.11
43	66.15	17.68	63.03	20.09	3.02
45	63.75	25.52	57.53	27.47	6.91
47	41.25	32.66	34.72	22.26	8.38
49	51.91	36.60	41.67	30.95	10.56

AVERAGE OF DATA SET 2

DATA SETS PROCESSED :
(2,1) (2,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	12.36	18.38	11.73	3.89	11.08
5	24.40	91.00	-0.42	24.40	4.41
7	35.30	80.72	5.69	34.84	0.64
9	52.61	67.63	20.03	48.65	3.82
11	52.55	0.10	52.55	0.09	1.15
13	49.94	-13.20	48.62	-11.40	2.67
15	34.61	52.37	21.13	27.41	2.62
17	73.00	53.34	43.59	58.56	3.36
19	49.51	58.31	26.01	42.13	8.07
21	68.77	58.47	35.96	58.62	12.77
23	60.94	58.03	32.26	51.69	15.97
25	65.95	74.35	17.80	63.50	11.30
27	149.78	24.20	136.62	61.40	93.47
29	71.48	21.84	66.35	26.59	21.03
31	68.52	37.15	54.61	41.38	14.33
33	36.42	-20.90	34.02	-12.99	60.73
35	49.44	-122.45	-26.53	-41.72	115.18
37	36.61	65.36	15.26	33.28	54.30
39	80.35	-8.44	79.48	-11.79	49.00
41	68.66	-54.54	39.83	-55.92	34.65
43	84.09	92.94	-4.32	83.97	58.06
45	42.46	-40.92	32.08	-27.81	15.80
47	13.50	65.68	5.56	12.31	94.00
49	102.93	103.19	-23.49	100.22	73.78

AVERAGE OF DATA SET 17

DATA SETS PROCESSED :
(17.1) (17.2) (17.3)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	583.81	-126.99	-351.23	-466.33	857.46
5	22.08	65.76	9.07	20.13	3.71
7	36.08	78.33	7.30	35.33	5.21
9	45.87	73.15	13.30	43.90	13.31
11	53.92	4.82	53.73	4.53	8.14
13	50.47	15.63	48.60	13.60	14.74
15	26.82	62.38	12.43	23.77	2.72
17	63.68	57.27	34.43	53.57	17.87
19	56.61	69.92	19.43	53.17	13.41
21	55.68	50.83	35.17	43.17	6.86
23	55.35	55.35	31.47	45.53	25.00
25	61.09	70.72	20.17	57.67	19.69
27	148.24	29.72	128.73	73.50	57.87
29	62.69	8.32	62.03	9.07	10.66
31	89.87	58.59	46.83	76.70	21.60
33	60.77	5.70	60.47	6.03	164.47
35	54.53	84.03	5.67	54.23	82.78
37	21.93	56.41	12.13	18.27	60.85
39	65.54	15.12	63.27	17.10	53.65
41	35.95	39.02	27.93	22.63	42.72
43	78.03	49.54	50.63	59.37	31.90
45	66.25	34.30	54.73	37.33	30.79
47	36.60	2.35	36.57	1.50	29.22
49	54.26	18.89	51.33	17.57	36.65

AVERAGE OF DATA SET 3

DATA SETS PROCESSED :
(3,1) (3,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	16.72	136.09	-12.05	11.60	4.33
5	16.99	79.32	3.15	16.70	5.41
7	33.63	82.47	4.41	33.34	1.28
9	45.35	73.32	13.02	43.44	3.75
11	51.33	4.88	51.14	4.37	2.78
13	37.28	-3.11	37.22	-2.03	2.36
15	32.49	53.64	19.26	26.16	2.82
17	62.54	57.52	33.58	52.76	1.93
19	52.77	61.74	24.99	46.47	8.64
21	51.38	47.94	34.42	38.15	3.33
23	57.22	39.91	43.89	36.71	11.27
25	61.67	57.70	32.95	52.13	4.12
27	140.90	9.85	138.82	24.10	23.74
29	55.10	10.65	54.15	10.19	3.27
31	74.61	36.00	60.36	43.86	11.73
33	41.00	29.22	35.78	20.01	15.25
35	1.65	113.54	-0.66	1.51	19.99
37	47.14	23.41	43.26	18.73	16.04
39	38.51	34.43	31.76	21.77	11.16
41	44.54	25.61	40.17	19.25	3.32
43	90.56	-13.22	88.16	-20.72	27.59
45	60.96	16.60	58.42	17.42	12.57
47	39.70	27.48	35.22	18.32	20.09
49	50.19	56.12	27.98	41.67	22.33

AVERAGE OF DATA SET 4

DATA SETS PROCESSED :
(4,1) (4,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	32.68	63.50	14.58	29.25	7.08
5	16.38	129.79	-10.48	12.59	4.01
7	35.63	83.43	4.07	35.40	1.17
9	45.79	69.30	16.18	42.83	0.91
11	56.00	10.96	54.98	10.65	0.18
13	45.50	-6.90	45.17	-5.47	0.13
15	33.99	62.41	15.74	30.13	0.97
17	56.08	78.10	11.56	54.88	1.46
19	56.00	55.39	31.81	46.09	0.84
21	63.10	54.57	36.58	51.41	0.87
23	55.60	46.72	38.12	40.48	0.03
25	61.65	63.50	27.51	55.17	0.16
27	152.10	30.52	131.03	77.24	2.17
29	66.35	13.84	64.42	15.87	2.40
31	79.45	51.20	49.78	61.92	3.96
33	46.62	28.61	40.93	22.33	11.57
35	59.40	40.19	45.38	38.34	4.21
37	64.79	31.93	54.99	34.27	1.04
39	55.33	39.09	42.94	34.89	2.85
41	54.77	39.50	42.26	34.83	3.09
43	70.48	15.08	68.05	18.33	1.91
45	61.04	37.12	48.67	36.83	2.35
47	40.89	37.48	32.45	24.89	0.90
49	48.49	59.35	24.72	41.72	1.23

AVERAGE OF DATA SET 18

DATA SETS PROCESSED :
(18,1) (18,2) (18,3)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	110.03	136.29	-79.53	76.03	74.64
5	101.37	143.71	-81.70	60.00	8.14
7	323.70	47.90	217.03	240.17	23.80
9	41.81	49.24	27.30	31.67	19.04
11	55.16	5.17	54.93	4.97	1.51
13	45.21	-8.91	44.67	-7.00	0.09
15	28.49	69.02	10.20	26.60	0.82
17	31.24	56.89	17.07	26.17	3.20
19	52.83	51.30	33.03	41.23	0.83
21	69.46	54.10	40.73	56.27	0.81
23	56.42	46.22	39.03	40.73	0.13
25	62.73	63.35	28.13	56.07	0.11
27	154.28	33.98	127.93	86.23	3.68
29	67.63	26.49	60.53	30.17	1.38
31	88.56	57.51	47.57	74.70	1.76
33	46.10	20.89	43.07	16.43	4.55
35	58.79	37.88	46.40	36.10	2.50
37	64.88	29.92	56.23	32.37	0.64
39	54.77	43.50	39.73	37.70	0.92
41	60.18	31.94	51.07	31.83	2.19
43	88.35	10.28	86.93	15.77	3.70
45	60.67	44.47	43.30	42.50	5.10
47	38.75	38.01	30.53	23.87	0.48
49	47.98	61.67	22.77	42.23	0.24

AVERAGE OF DATA SET 5

DATA SETS PROCESSED :
(5,1) (5,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	24.67	93.88	-1.67	24.61	12.07
5	21.74	95.29	-2.01	21.65	5.78
7	35.05	83.64	3.89	34.83	0.49
9	50.78	67.06	19.79	46.76	1.67
11	56.54	9.85	55.71	9.68	1.11
13	45.55	-7.46	45.16	-5.92	0.43
15	30.69	70.32	10.34	28.90	0.55
17	70.16	76.45	16.44	68.21	4.78
19	55.81	47.54	37.67	41.18	2.13
21	61.58	62.32	28.60	54.53	2.23
23	55.70	46.11	38.62	40.14	0.59
25	61.09	64.09	26.70	54.94	1.28
27	144.25	27.15	128.35	65.82	0.86
29	68.98	23.60	63.21	27.62	2.70
31	77.73	45.08	54.89	55.04	1.81
33	44.32	4.03	44.21	3.11	8.11
35	63.72	39.29	49.32	40.36	5.64
37	61.86	33.90	51.35	34.50	5.98
39	39.34	21.99	36.48	14.73	2.81
41	32.92	56.25	18.29	27.38	2.43
43	80.59	14.25	78.11	19.84	3.19
45	115.14	19.91	108.26	39.21	6.54
47	36.03	44.25	25.81	25.14	1.71
49	45.50	59.06	23.40	39.03	0.29

AVERAGE OF DATA SET 6

DATA SETS PROCESSED :
(6,1)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	6.10	117.24	-2.79	5.42	0.00
5	16.00	85.55	1.24	15.95	0.00
7	35.90	79.10	6.79	35.25	0.00
9	47.30	67.93	17.77	43.83	0.00
11	37.90	12.60	36.99	8.27	0.00
13	45.80	-11.30	44.91	-8.97	0.00
15	31.60	68.99	11.33	29.50	0.00
17	63.60	55.51	36.01	52.42	0.00
19	55.00	54.50	31.94	44.78	0.00
21	62.70	58.78	32.50	53.62	0.00
23	56.20	48.08	37.55	41.82	0.00
25	63.70	59.38	32.44	54.82	0.00
27	148.40	29.09	129.68	72.15	0.00
29	64.10	12.37	62.61	13.73	0.00
31	81.10	51.30	50.71	63.29	0.00
33	61.69	12.12	60.32	12.95	0.00
35	56.50	34.67	46.47	32.14	0.00
37	51.80	34.13	42.88	29.06	0.00
39	54.40	31.74	46.26	28.62	0.00
41	54.00	38.01	42.55	33.25	0.00
43	74.60	16.54	71.51	21.24	0.00
45	55.00	41.34	41.29	36.33	0.00
47	41.80	38.18	32.86	25.84	0.00
49	47.90	61.33	22.98	42.03	0.00

AVERAGE OF DATA SET 7

DATA SETS PROCESSED :
(7,1) (7,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	12.01	126.35	-7.12	9.68	23.91
5	18.49	63.85	8.15	16.60	2.54
7	35.40	78.19	7.25	34.65	0.44
9	49.33	68.92	17.75	46.03	1.53
11	38.00	12.13	37.15	7.99	0.15
13	44.15	-9.92	43.49	-7.61	0.16
15	29.64	68.33	10.94	27.55	0.62
17	57.40	72.65	17.12	54.78	1.30
19	52.19	49.82	33.67	39.88	1.03
21	62.18	60.00	31.09	53.85	1.60
23	55.85	48.49	37.02	41.83	0.26
25	62.30	59.79	31.35	53.84	0.41
27	156.33	29.37	136.24	76.67	2.66
29	69.60	15.20	67.17	18.25	1.70
31	79.97	52.29	48.92	63.27	2.30
33	62.72	1.81	62.69	1.99	7.01
35	58.60	44.78	41.60	41.28	3.18
37	49.90	37.21	39.74	30.18	0.27
39	57.94	30.55	49.90	29.45	3.95
41	54.54	35.27	44.53	31.50	1.74
43	75.38	15.71	72.57	20.41	1.68
45	53.83	39.54	41.51	34.26	3.05
47	42.85	39.99	32.83	27.53	0.76
49	47.99	61.44	22.95	42.16	0.93

AVERAGE OF DATA SET 8

DATA SETS PROCESSED :
(8,1) (8,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	17.43	55.51	9.87	14.36	14.23
5	26.13	90.05	-0.03	26.13	11.85
7	39.21	77.24	8.66	38.24	2.29
9	47.72	66.84	18.77	43.87	12.33
11	49.50	-9.92	48.76	-8.53	3.13
13	32.05	-21.95	29.73	-11.98	1.98
15	26.28	62.91	11.97	23.40	8.69
17	60.87	46.62	41.81	44.24	8.66
19	55.16	47.80	37.05	40.86	6.17
21	56.14	60.86	27.34	49.03	7.11
23	65.75	60.58	32.30	57.27	10.40
25	65.27	64.86	27.73	59.09	7.99
27	135.27	33.82	112.38	75.29	21.44
29	55.74	1.97	55.71	1.92	17.20
31	73.59	40.88	55.65	48.16	1.69
33	55.76	11.43	54.65	11.05	11.42
35	16.60	17.31	15.85	4.94	80.82
37	57.79	31.62	49.22	30.30	36.33
39	50.44	41.46	37.80	33.40	9.82
41	55.62	28.60	48.84	26.63	5.27
43	80.07	10.74	78.67	14.91	10.83
45	69.06	37.11	55.08	41.67	21.22
47	32.54	52.52	19.81	25.83	6.00
49	33.25	89.65	0.21	33.24	16.52

AVERAGE OF DATA SET 9

DATA SETS PROCESSED :
(9,1) (9,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	48.36	97.10	-5.97	47.99	16.46
5	50.94	121.77	-26.82	43.31	36.97
7	43.22	74.65	11.44	41.67	2.86
9	58.41	71.59	18.44	55.42	25.64
11	55.73	-7.04	55.31	-6.84	1.55
13	34.56	-15.45	33.28	-9.32	2.64
15	15.89	146.65	-13.27	8.73	3.43
17	75.28	52.87	45.44	60.02	21.35
19	66.07	52.49	40.23	52.41	14.65
21	61.08	98.51	-9.04	60.41	19.57
23	36.69	98.54	-5.45	36.28	38.01
25	61.90	76.98	13.94	60.31	9.21
27	161.53	25.31	146.03	69.06	46.56
29	68.64	18.98	64.91	22.32	37.95
31	58.99	41.13	44.44	38.81	10.04
33	90.84	33.64	75.63	50.33	42.75
35	166.69	35.14	136.32	95.94	111.89
37	185.64	15.34	179.03	49.11	142.39
39	21.15	140.62	-16.35	13.42	18.45
41	41.32	57.50	22.20	34.85	14.54
43	83.97	0.54	83.97	0.79	44.74
45	63.29	58.07	33.48	53.72	80.06
47	46.29	-153.92	-41.58	-20.35	93.42
49	43.80	-93.84	-2.93	-43.71	74.52

AVERAGE OF DATA SET 10

DATA SETS PROCESSED :

(10,1) (10,2) (10,3) (10,4) (10,5) (10,6)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	56.94	30.82	48.90	29.17	79.40
5	15.27	86.29	0.99	15.24	18.35
7	40.78	80.08	7.03	40.17	3.93
9	64.56	65.61	26.65	58.80	21.55
11	58.11	-8.25	57.51	-8.34	14.73
13	39.46	-23.87	36.09	-15.97	14.93
15	30.78	65.55	12.74	28.02	12.95
17	56.34	75.04	14.55	54.43	26.70
19	33.44	56.73	18.34	27.96	37.13
21	76.09	59.49	38.63	65.56	33.23
23	18.08	98.61	-2.71	17.87	86.66
25	69.02	60.28	34.21	59.94	23.25
27	166.36	25.32	150.38	71.16	47.41
29	68.41	8.80	67.61	10.47	30.91
31	83.71	40.70	63.46	54.59	29.47
33	46.87	30.28	40.48	23.64	40.44
35	20.53	-71.60	6.48	-19.48	80.73
37	29.38	47.30	19.93	21.59	58.75
39	90.32	-19.58	85.10	-30.27	106.21
41	45.79	34.12	37.91	25.68	34.07
43	57.99	12.94	56.52	12.99	44.02
45	21.97	35.49	17.89	12.76	45.24
47	92.50	59.26	47.27	79.51	107.93
49	49.31	154.63	-44.55	21.13	154.17

AVERAGE OF DATA SET 11

DATA SETS PROCESSED :
(11,1)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	7.40	106.89	-2.15	7.08	0.00
5	30.80	94.28	-2.30	30.71	0.00
7	39.90	76.14	9.56	38.74	0.00
9	52.50	73.26	15.12	50.28	0.00
11	57.70	-10.26	56.78	-10.28	0.00
13	36.90	-25.75	33.24	-16.03	0.00
15	30.10	71.42	9.59	28.53	0.00
17	58.70	56.40	32.48	48.89	0.00
19	56.10	49.71	36.28	42.79	0.00
21	65.70	60.25	32.60	57.04	0.00
23	49.20	66.12	19.92	44.99	0.00
25	71.80	65.55	29.72	65.36	0.00
27	150.01	32.41	126.64	80.40	0.00
29	66.10	0.03	66.10	0.03	0.00
31	69.90	37.31	55.60	42.37	0.00
33	51.70	24.39	47.09	21.35	0.00
35	44.20	10.49	43.46	8.05	0.00
37	34.50	14.83	33.35	8.83	0.00
39	48.60	36.89	38.87	29.17	0.00
41	61.00	36.73	48.89	36.48	0.00
43	82.00	5.40	81.64	7.72	0.00
45	51.90	22.49	47.95	19.85	0.00
47	41.20	47.83	27.66	30.54	0.00
49	42.40	68.66	15.43	39.49	0.00

AVERAGE OF DATA SET 12

DATA SETS PROCESSED :
(12,1) (12,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	15.79	64.71	6.74	14.28	10.01
5	27.64	42.78	20.28	18.77	13.19
7	35.30	79.74	6.29	34.74	0.21
9	53.29	66.68	21.09	48.94	1.48
11	14.22	-45.67	9.93	-10.17	7.74
13	34.57	-15.15	33.37	-9.03	3.74
15	33.69	59.05	17.33	28.90	1.20
17	55.75	65.01	23.55	50.53	0.08
19	57.90	57.55	31.07	48.86	0.54
21	69.85	56.26	38.79	58.08	0.97
23	56.40	47.49	38.12	41.58	0.10
25	62.75	64.96	26.56	56.85	0.06
27	153.55	28.05	135.51	72.21	0.39
29	62.30	9.60	61.43	10.39	0.63
31	78.50	45.95	54.58	56.43	0.91
33	42.53	18.74	40.28	13.67	21.67
35	52.85	35.08	43.25	30.38	3.95
37	58.86	38.01	46.38	36.24	2.31
39	53.35	34.29	44.08	30.06	0.74
41	53.55	35.70	43.49	31.25	0.45
43	73.38	2.68	73.30	3.43	2.03
45	58.20	32.89	48.87	31.60	2.44
47	45.15	39.36	34.91	28.64	0.15
49	49.45	56.55	27.26	41.26	0.17

AVERAGE OF DATA SET 13

DATA SETS PROCESSED :

(13,1) (13,2) (13,3) (13,4) (13,5)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	27.91	111.80	-10.36	25.91	3.55
5	63.41	106.39	-17.90	60.83	55.52
7	35.54	80.72	5.73	35.08	2.70
9	54.11	70.69	17.90	51.07	4.06
11	25.87	40.94	19.54	16.95	49.36
13	56.97	-17.90	54.22	-17.51	36.38
15	32.41	53.21	19.41	25.95	5.02
17	56.11	62.45	25.95	49.74	11.22
19	55.95	52.20	34.29	44.21	3.86
21	68.04	58.57	35.48	58.06	8.01
23	56.57	48.43	37.54	42.32	7.24
25	63.13	64.95	26.73	57.19	10.05
27	160.24	32.23	135.54	85.47	46.78
29	65.74	7.88	65.12	9.01	8.47
31	76.06	49.05	49.85	57.44	13.65
33	42.08	25.48	37.98	18.10	23.22
35	58.71	33.28	49.08	32.22	9.09
37	55.30	38.90	43.04	34.73	10.26
39	103.90	52.93	62.63	82.90	68.38
41	54.64	46.36	37.71	39.54	22.65
43	55.12	-1.20	55.11	-1.15	25.69
45	59.38	26.94	52.94	26.90	8.31
47	42.82	44.33	30.63	29.92	10.77
49	49.02	60.08	24.45	42.48	14.29

AVERAGE OF DATA SET 14

DATA SETS PROCESSED :
(14,1)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	4.70	-19.40	4.43	-1.56	0.00
5	30.10	44.03	21.64	20.92	0.00
7	36.80	80.38	6.15	36.28	0.00
9	54.80	64.98	23.18	49.66	0.00
11	78.40	104.15	-19.17	76.02	0.00
13	32.00	30.60	27.54	16.29	0.00
15	42.00	34.77	34.50	23.95	0.00
17	56.20	67.81	21.23	52.04	0.00
19	54.30	59.92	27.22	46.99	0.00
21	70.90	49.52	46.03	53.93	0.00
23	55.71	47.73	37.47	41.22	0.00
25	63.40	64.77	27.02	57.35	0.00
27	158.80	32.68	133.66	85.74	0.00
29	66.50	6.19	66.11	7.17	0.00
31	69.20	49.16	45.25	52.35	0.00
33	73.80	-23.79	67.53	-29.77	0.00
35	51.80	32.05	43.90	27.49	0.00
37	59.49	42.09	44.15	39.88	0.00
39	68.10	40.72	51.61	44.43	0.00
41	53.60	44.88	37.98	37.82	0.00
43	40.90	21.55	38.04	15.02	0.00
45	51.70	14.82	49.98	13.22	0.00
47	46.70	40.48	35.52	30.32	0.00
49	51.00	58.13	26.93	43.31	0.00

AVERAGE OF DATA SET 15

DATA SETS PROCESSED :
(15,1)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	17.70	-178.90	-17.70	-0.34	0.00
5	31.60	131.74	-21.04	23.58	0.00
7	37.00	80.40	6.17	36.48	0.00
9	54.20	64.11	23.67	48.76	0.00
11	13.90	-47.10	9.46	-10.18	0.00
13	38.00	-24.57	34.56	-15.80	0.00
15	36.51	63.50	16.29	32.67	0.00
17	53.89	63.09	24.39	48.06	0.00
19	58.29	56.48	32.19	48.60	0.00
21	68.31	57.55	36.65	57.64	0.00
23	56.30	47.27	38.20	41.36	0.00
25	62.90	64.95	26.63	56.98	0.00
27	157.00	27.22	139.61	71.81	0.00
29	61.70	8.64	61.00	9.27	0.00
31	82.40	46.13	57.11	59.40	0.00
33	45.60	-0.15	45.60	-0.12	0.00
35	69.40	29.64	60.32	34.32	0.00
37	57.50	28.78	50.40	27.68	0.00
39	50.50	32.59	42.55	27.20	0.00
41	54.90	35.90	44.47	32.19	0.00
43	73.30	3.99	73.12	5.10	0.00
45	56.60	33.73	47.07	31.43	0.00
47	45.80	40.10	35.03	29.50	0.00
49	48.50	55.80	27.26	40.11	0.00

AVERAGE OF DATA SET 1 EVEN HARMONICS

DATA SETS PROCESSED :
(1,1) (1,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	51.31	111.28	-18.63	47.82	17.78
4	29.93	77.07	6.70	29.17	15.92
6	42.07	100.52	-7.69	41.36	41.68
8	49.45	74.99	12.81	47.76	7.46
10	73.17	55.33	41.62	60.18	9.76
12	63.63	52.33	38.89	50.37	15.36
14	21.31	51.29	13.33	16.63	2.97
16	37.68	70.43	12.62	35.51	3.71
18	37.52	49.19	24.52	28.40	6.69
20	53.35	60.98	25.00	46.65	2.43
22	67.88	27.47	60.23	31.32	6.25
24	54.78	35.69	44.50	31.96	15.19
26	98.15	69.38	34.56	91.87	3.09
28	60.24	-36.04	48.71	-35.44	17.63
30	44.52	26.03	40.01	19.53	7.04
32	70.57	-3.50	70.44	-4.31	14.32
34	47.51	14.04	46.09	11.53	13.99
36	78.33	21.25	73.00	28.40	8.13
38	49.10	39.06	38.12	30.94	8.50
40	34.42	26.30	30.85	15.25	11.79
42	36.78	34.56	30.30	20.86	22.64
44	36.98	7.03	36.71	4.52	8.88
46	30.62	20.64	28.66	10.80	8.23
48	36.79	67.71	13.96	34.04	2.10

AVERAGE OF DATA SET 2 EVEN HARMONICS

DATA SETS PROCESSED :
(2,1) (2,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	20.01	162.59	-19.09	5.99	36.47
4	39.08	114.55	-16.24	35.55	11.58
6	84.10	80.44	13.97	82.93	52.05
8	41.24	81.33	6.22	40.76	4.08
10	69.79	55.26	39.77	57.35	2.85
12	60.35	33.93	50.08	33.69	12.18
14	19.14	-20.54	17.92	-6.72	1.26
16	30.46	63.27	13.70	27.20	7.28
18	46.68	9.38	46.06	7.61	8.05
20	66.50	45.56	46.56	47.48	16.02
22	107.31	29.15	93.72	52.27	18.53
24	38.78	25.29	35.06	16.57	48.04
26	131.11	42.03	97.39	87.78	35.30
28	156.20	-30.46	134.64	-79.18	55.66
30	35.05	51.88	21.63	27.57	105.72
32	81.45	-11.37	79.71	-16.75	2.06
34	87.39	8.66	86.39	13.16	44.99
36	64.27	-36.37	51.76	-38.11	44.19
38	47.10	-12.64	45.96	-10.31	92.11
40	101.59	15.33	97.98	26.86	77.78
42	190.33	-10.04	187.41	-33.19	67.87
44	81.91	-7.24	81.26	-10.32	53.81
46	121.30	35.37	98.92	70.21	135.07
48	36.00	119.63	-17.80	31.30	45.57

AVERAGE OF DATA SET 3 EVEN HARMONICS

DATA SETS PROCESSED :
(3,1) (3,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	42.15	107.45	-12.64	40.21	33.47
4	27.18	21.68	25.26	10.04	27.78
6	43.43	119.60	-21.45	37.76	19.53
8	44.72	78.77	8.71	43.86	3.08
10	76.08	58.01	40.31	64.53	16.02
12	62.47	45.88	43.49	44.84	6.56
14	16.77	39.70	12.90	10.71	1.65
16	40.23	70.41	13.49	37.90	3.33
18	41.14	42.63	30.27	27.87	9.34
20	47.56	56.86	26.00	39.83	2.22
22	67.07	29.35	58.47	32.88	15.92
24	49.69	20.84	46.44	17.67	16.42
26	98.55	55.13	56.34	80.86	7.41
28	122.00	-32.50	102.90	-65.55	23.78
30	32.00	29.34	27.90	15.68	11.25
32	57.34	-8.90	56.65	-8.87	5.08
34	41.38	9.35	40.83	6.72	10.37
36	37.75	44.35	27.00	26.39	12.96
38	50.58	-4.35	50.44	-3.84	5.95
40	69.12	19.00	65.36	22.51	23.83
42	63.48	39.96	48.66	40.77	10.35
44	35.32	-4.35	35.22	-2.68	8.24
46	43.16	12.98	42.06	9.69	12.82
48	24.79	50.75	15.68	19.19	14.46

AVERAGE OF DATA SET 4 EVEN HARMONICS

DATA SETS PROCESSED :
(4,1) (4,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	9.44	82.30	1.26	9.36	2.58
4	25.44	94.66	-2.07	25.35	4.96
6	21.44	94.36	-1.63	21.38	1.96
8	40.63	79.85	7.16	39.99	2.42
10	68.68	57.56	36.84	57.97	2.18
12	62.76	52.21	38.46	49.60	2.41
14	19.22	27.42	17.06	8.85	3.20
16	41.25	66.53	16.43	37.84	0.57
18	48.04	23.38	44.10	19.07	15.56
20	63.69	60.70	31.17	55.55	1.63
22	63.77	42.09	47.33	42.75	3.23
24	66.50	32.62	56.01	35.85	8.42
26	100.95	55.68	56.91	83.38	4.55
28	98.04	-17.93	93.28	-30.19	7.81
30	50.34	37.63	39.87	30.74	8.84
32	60.85	-2.99	60.77	-3.17	3.36
34	50.23	16.27	48.22	14.07	3.98
36	44.07	42.61	32.44	29.84	5.17
38	57.28	5.18	57.05	5.18	6.48
40	57.27	25.78	51.58	24.91	6.74
42	52.89	19.16	49.96	17.36	3.75
44	32.42	30.82	27.84	16.61	4.34
46	33.50	38.86	26.09	21.01	2.12
48	47.52	62.01	22.30	41.96	5.19

AVERAGE OF DATA SET 5 EVEN HARMONICS

DATA SETS PROCESSED :
(5,1) (5,2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	47.42	133.95	-32.91	34.14	26.23
4	35.82	3.02	35.77	1.89	37.62
6	253.87	-9.08	250.68	-40.07	115.82
8	27.75	12.18	27.13	5.86	12.17
10	94.74	49.29	61.79	71.82	17.01
12	106.98	-24.09	97.67	-43.67	23.93
14	24.58	-123.24	-13.48	-20.56	3.82
16	24.00	61.24	11.55	21.04	5.50
18	237.39	12.33	231.92	50.69	29.43
20	123.23	84.15	12.55	122.59	17.66
22	119.36	74.81	31.27	115.19	20.40
24	270.29	-5.89	268.87	-27.76	83.04
26	207.09	-4.96	206.31	-17.92	73.90
28	166.79	-42.05	123.86	-111.71	17.54
30	405.94	32.26	343.28	216.68	9.83
32	79.54	-61.65	37.77	-70.01	5.30
34	112.95	53.66	66.93	90.99	14.39
36	356.96	120.30	-180.11	308.20	15.35
38	326.79	-67.65	124.27	-302.24	38.41
40	245.72	29.34	214.21	120.39	48.68
42	197.27	-57.72	105.36	-166.78	37.27
44	121.82	-22.97	112.16	-47.54	5.98
46	100.93	77.80	21.33	98.65	3.69
48	449.34	177.53	-448.93	19.36	79.39

AVERAGE OF DATA SET 6 EVEN HARMONICS

DATA SETS PROCESSED :
(6,1)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	9.80	75.40	2.47	9.48	0.00
4	23.60	73.15	6.84	22.59	0.00
6	42.70	86.83	2.36	42.63	0.00
8	40.20	76.90	9.11	39.15	0.00
10	70.20	56.76	38.48	58.71	0.00
12	57.19	50.59	36.31	44.19	0.00
14	20.10	56.86	10.99	16.83	0.00
16	36.60	62.71	16.78	32.53	0.00
18	55.30	24.70	50.24	23.11	0.00
20	54.10	47.10	36.83	39.63	0.00
22	67.20	41.53	50.31	44.55	0.00
24	52.90	2.17	52.86	2.00	0.00
26	89.60	56.09	49.99	74.36	0.00
28	88.90	-19.72	83.69	-30.00	0.00
30	60.70	37.21	48.34	36.71	0.00
32	60.20	-0.42	60.20	-0.44	0.00
34	49.20	19.29	46.44	16.25	0.00
36	19.00	27.52	16.85	8.78	0.00
38	67.50	17.18	64.49	19.94	0.00
40	53.70	27.64	47.57	24.91	0.00
42	84.20	19.27	79.48	27.79	0.00
44	30.40	24.20	27.73	12.46	0.00
46	30.10	14.19	29.18	7.38	0.00
48	49.50	111.39	-18.05	46.09	0.00

AVERAGE OF DATA SET 7 EVEN HARMONICS

DATA SETS PROCESSED :
(7.1) (7.2)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	11.63	69.78	4.02	10.91	1.24
4	33.99	94.07	-2.41	33.90	7.70
6	30.34	85.26	2.51	30.24	3.97
8	42.45	81.53	6.25	41.99	0.37
10	66.36	54.08	38.94	53.74	2.38
12	57.08	50.13	36.59	43.81	5.12
14	18.25	8.84	18.03	2.81	0.50
16	41.25	65.63	17.02	37.58	1.66
18	58.32	28.20	51.40	27.56	8.75
20	57.78	57.55	31.00	48.76	1.62
22	56.85	39.47	43.89	36.14	3.15
24	58.78	10.70	57.76	10.91	5.36
26	104.80	54.53	60.81	85.36	10.72
28	91.97	-15.64	88.57	-24.79	8.39
30	53.79	33.24	44.99	29.49	3.90
32	69.44	5.13	69.17	6.21	2.16
34	48.14	15.64	46.36	12.98	7.03
36	36.03	39.81	27.72	23.10	1.02
38	28.43	72.39	8.60	27.10	11.85
40	44.22	34.03	36.65	24.75	20.22
42	60.28	12.49	58.85	13.04	4.63
44	30.71	30.05	26.58	15.38	1.60
46	36.81	30.97	31.57	18.95	5.08
48	44.38	88.52	1.14	44.37	15.44

D.3 Averaged Harmonic Impedances of Data Sets 21 to 28

AVERAGE OF FIRST DAY DC ON SINGLE PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(18,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	110.03	136.29	-79.53	76.03	0.00
5	101.37	143.71	-81.70	60.00	0.00
7	323.70	47.90	217.03	240.17	0.00
9	41.81	49.24	27.30	31.67	0.00
11	55.15	5.17	54.93	4.97	0.00
13	45.22	-8.91	44.67	-7.00	0.00
15	28.49	69.02	10.20	26.60	0.00
17	31.25	56.88	17.07	26.17	0.00
19	52.83	51.30	33.03	41.23	0.00
21	69.46	54.10	40.73	56.27	0.00
23	56.41	46.22	39.03	40.73	0.00
25	62.73	63.36	28.13	56.07	0.00
27	154.28	33.98	127.93	86.23	0.00
29	67.63	26.49	60.53	30.17	0.00
31	88.56	57.51	47.57	74.70	0.00
33	46.10	20.88	43.07	16.43	0.00
35	58.79	37.88	46.40	36.10	0.00
37	64.88	29.93	56.23	32.37	0.00
39	54.77	43.50	39.73	37.70	0.00
41	60.18	31.93	51.07	31.83	0.00
43	88.35	10.28	86.93	15.77	0.00
45	60.67	44.47	43.30	42.50	0.00
47	38.75	38.02	30.53	23.87	0.00
49	47.98	61.67	22.77	42.23	0.00

AVERAGE OF FIRST DAY DC ON 3 PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(4,0) (5,0) (6,0) (7,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	17.26	87.51	0.75	17.24	12.91
5	16.72	92.66	-0.78	16.70	7.44
7	35.46	81.08	5.50	35.03	1.56
9	48.29	68.28	17.87	44.86	2.04
11	47.10	11.20	46.21	9.15	9.20
13	45.23	-8.89	44.68	-6.99	1.56
15	31.44	67.39	12.09	29.02	2.34
17	61.04	70.59	20.28	57.57	11.21
19	54.66	51.84	33.77	42.98	3.47
21	62.31	58.89	32.19	53.35	3.12
23	55.83	47.35	37.83	41.07	0.97
25	62.14	61.66	29.50	54.69	2.49
27	150.24	29.06	131.32	72.97	5.47
29	67.06	16.34	64.35	18.87	5.58
31	79.47	50.01	51.08	60.88	4.11
33	53.01	10.98	52.04	10.10	12.64
35	59.45	39.77	45.69	38.03	4.51
37	57.06	34.12	47.24	32.00	6.63
39	51.49	31.52	43.90	26.92	8.93
41	48.68	40.70	36.91	31.74	11.14
43	75.25	15.38	72.56	19.96	3.77
45	70.25	31.45	59.93	36.66	28.11
47	40.35	39.84	30.99	25.85	3.17
49	47.47	60.31	23.51	41.24	1.47

AVERAGE OF FIRST DAY DC OFF SINGLE PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(17,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	583.80	-126.99	-351.23	-466.33	0.00
5	22.08	65.75	9.07	20.13	0.00
7	36.08	78.33	7.30	35.33	0.00
9	45.87	73.15	13.30	43.90	0.00
11	53.92	4.82	53.73	4.53	0.00
13	50.47	15.63	48.60	13.60	0.00
15	26.82	62.39	12.43	23.77	0.00
17	63.68	57.27	34.43	53.57	0.00
19	56.61	69.93	19.43	53.17	0.00
21	55.68	50.83	35.17	43.17	0.00
23	55.35	55.35	31.47	45.53	0.00
25	61.10	70.72	20.17	57.67	0.00
27	148.24	29.72	128.73	73.50	0.00
29	62.69	8.32	62.03	9.07	0.00
31	89.87	58.59	46.83	76.70	0.00
33	60.77	5.69	60.47	6.03	0.00
35	54.53	84.03	5.67	54.23	0.00
37	21.93	56.42	12.13	18.27	0.00
39	65.54	15.12	63.27	17.10	0.00
41	35.95	39.02	27.93	22.63	0.00
43	78.03	49.54	50.63	59.37	0.00
45	66.25	34.30	54.73	37.33	0.00
47	36.60	2.35	36.57	1.50	0.00
49	54.25	18.90	51.33	17.57	0.00

AVERAGE OF FIRST DAY DC OFF 3 PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(1,0) (2,0) (3,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	9.46	63.42	4.23	8.46	11.99
5	19.11	83.83	2.05	19.00	4.22
7	34.50	81.72	4.97	34.14	0.82
9	51.75	68.79	18.72	48.25	5.66
11	51.60	3.24	51.52	2.92	2.13
13	45.99	-8.84	45.44	-7.07	7.02
15	33.77	50.66	21.41	26.12	2.16
17	66.14	55.97	37.02	54.81	5.35
19	53.05	59.82	26.67	45.86	3.31
21	59.21	53.75	35.01	47.75	8.43
23	58.32	48.65	38.53	43.77	7.79
25	62.39	64.88	26.49	56.49	8.11
27	141.14	21.68	131.16	52.13	22.25
29	61.36	15.16	59.22	16.05	9.09
31	73.06	39.01	56.77	45.99	5.50
33	33.86	21.46	31.52	12.39	19.04
35	7.60	82.16	1.04	7.53	48.77
37	47.95	41.10	36.13	31.53	17.93
39	49.58	15.65	47.74	13.37	28.84
41	42.39	-3.95	42.29	-2.92	37.78
43	56.29	29.57	48.96	27.78	58.14
45	49.67	6.58	49.34	5.69	26.97
47	30.73	35.01	25.17	17.63	14.46
49	59.63	75.05	15.39	57.61	41.40

AVERAGE OF SECOND DAY DC ON SINGLE PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(13,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	27.90	111.79	-10.36	25.91	0.00
5	63.41	106.40	-17.90	60.83	0.00
7	35.54	80.72	5.73	35.08	0.00
9	54.12	70.68	17.90	51.07	0.00
11	25.87	40.94	19.54	16.95	0.00
13	56.98	-17.90	54.22	-17.51	0.00
15	32.41	53.20	19.41	25.95	0.00
17	56.10	62.45	25.95	49.74	0.00
19	55.95	52.20	34.29	44.21	0.00
21	68.04	58.57	35.48	58.06	0.00
23	56.57	48.43	37.54	42.32	0.00
25	63.13	64.95	26.73	57.19	0.00
27	160.24	32.24	135.54	85.47	0.00
29	65.74	7.88	65.12	9.01	0.00
31	76.06	49.05	49.85	57.44	0.00
33	42.07	25.48	37.98	18.10	0.00
35	58.71	33.28	49.08	32.22	0.00
37	55.30	38.90	43.04	34.73	0.00
39	103.90	52.93	62.63	82.90	0.00
41	54.64	46.36	37.71	39.54	0.00
43	55.12	-1.20	55.11	-1.15	0.00
45	59.38	26.94	52.94	26.90	0.00
47	42.82	44.33	30.63	29.92	0.00
49	49.01	60.08	24.45	42.48	0.00

AVERAGE OF SECOND DAY DC ON 3 PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(12,0) (14,0) (15,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	4.67	117.81	-2.18	4.13	13.16
5	22.21	71.74	6.96	21.09	19.90
7	36.37	80.18	6.20	35.83	0.78
9	54.09	65.25	22.65	49.12	1.18
11	18.56	89.77	0.07	18.56	42.85
13	31.95	-5.11	31.82	-2.85	14.15
15	36.44	51.46	22.71	28.51	9.08
17	55.25	65.34	23.06	50.21	2.12
19	56.82	57.94	30.16	48.15	2.28
21	69.55	54.40	40.49	56.55	4.42
23	56.14	47.50	37.93	41.39	0.36
25	63.01	64.89	26.74	57.06	0.29
27	156.31	29.34	136.26	76.59	6.94
29	63.48	8.10	62.85	8.94	2.67
31	76.68	46.98	52.31	56.06	5.86
33	51.42	-6.04	51.14	-5.41	21.62
35	57.97	32.01	49.16	30.73	8.38
37	58.34	36.37	46.98	34.60	5.73
39	57.20	36.34	46.08	33.90	8.52
41	53.87	38.80	41.98	33.75	4.07
43	61.99	7.28	61.49	7.85	17.35
45	54.88	27.59	48.64	25.42	8.71
47	45.88	39.99	35.15	29.49	0.73
49	49.64	56.84	27.15	41.56	1.33

AVERAGE OF SECOND DAY DC OFF SINGLE PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(10,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	56.94	30.82	48.90	29.17	0.00
5	15.27	86.28	0.99	15.24	0.00
7	40.78	80.07	7.03	40.17	0.00
9	64.56	65.62	26.65	58.80	0.00
11	58.11	-8.25	57.51	-8.34	0.00
13	39.47	-23.87	36.09	-15.97	0.00
15	30.78	65.55	12.74	28.02	0.00
17	56.34	75.03	14.55	54.43	0.00
19	33.44	56.74	18.34	27.96	0.00
21	76.09	59.49	38.63	65.56	0.00
23	18.07	98.62	-2.71	17.87	0.00
25	69.02	60.28	34.21	59.94	0.00
27	166.37	25.32	150.38	71.16	0.00
29	68.42	8.80	67.61	10.47	0.00
31	83.71	40.70	63.46	54.59	0.00
33	46.88	30.28	40.48	23.64	0.00
35	20.53	-71.60	6.48	-19.48	0.00
37	29.38	47.29	19.93	21.59	0.00
39	90.32	-19.58	85.10	-30.27	0.00
41	45.79	34.11	37.91	25.68	0.00
43	57.99	12.94	56.52	12.99	0.00
45	21.97	35.50	17.89	12.76	0.00
47	92.50	59.27	47.27	79.51	0.00
49	49.31	154.63	-44.55	21.13	0.00

AVERAGE OF SECOND DAY DC OFF 3 PHASE SWITCHING
DATA SETS

DATA SETS PROCESSED :
(8,0) (9,0) (11,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
3	23.15	88.56	0.58	23.14	19.05
5	34.77	106.23	-9.72	33.38	14.14
7	40.77	75.96	9.89	39.55	1.91
9	52.82	70.72	17.44	49.86	5.00
11	54.29	-9.06	53.62	-0.55	3.76
13	34.41	-21.20	32.08	-12.44	3.22
15	20.41	82.22	2.76	20.22	14.14
17	64.80	51.98	39.91	51.05	8.58
19	59.07	50.15	37.85	45.35	5.33
21	58.03	73.00	16.97	55.49	19.12
23	48.74	71.35	15.59	46.18	17.92
25	66.02	68.87	23.80	61.59	7.52
27	148.61	30.27	128.35	74.92	14.55
29	62.76	7.41	62.24	8.09	11.11
31	67.47	39.72	51.90	43.11	6.53
33	65.24	25.01	59.12	27.58	20.55
35	74.64	29.11	65.21	36.31	66.59
37	92.03	18.64	87.20	29.41	67.30
39	32.34	51.56	20.11	25.33	27.18
41	51.62	39.24	39.98	32.65	13.29
43	81.80	5.48	81.43	7.81	6.16
45	59.55	40.17	45.50	38.41	16.65
47	12.17	80.71	1.96	12.01	38.54
49	10.56	66.35	4.24	9.67	38.67

ALL FIRST DAY DC OFF DATA SETS EVEN HARMONICS

DATA SETS PROCESSED :
(1,0) (2,0) (3,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	35.55	118.17	-16.79	31.34	18.43
4	25.46	78.13	5.24	24.92	20.14
6	54.25	95.35	-5.06	54.02	25.15
8	45.09	78.17	9.25	44.13	3.95
10	73.00	56.24	40.57	60.69	3.05
12	61.61	44.22	44.15	42.97	8.32
14	16.24	25.03	14.72	6.87	10.17
16	36.07	68.41	13.27	33.54	4.61
18	39.79	32.35	33.62	21.29	13.29
20	55.41	53.69	32.81	44.65	10.31
22	80.75	28.74	70.81	38.82	18.81
24	47.44	27.72	42.00	22.07	8.59
26	107.14	54.14	62.76	86.84	26.44
28	112.74	-32.19	95.42	-60.06	39.91
30	36.45	35.04	29.85	20.93	9.10
32	69.65	-8.24	68.93	-9.98	10.78
34	58.71	10.27	57.77	10.47	20.53
36	50.89	6.27	50.59	5.56	36.16
38	45.19	7.11	44.84	5.60	18.82
40	68.22	18.41	64.73	21.54	27.82
42	89.29	6.09	88.79	9.48	76.78
44	51.14	-3.17	51.06	-2.83	22.20
46	64.12	28.13	56.55	30.23	41.56
48	28.45	82.03	3.95	28.18	16.59

ALL FIRST DAY DC ON DATA SETS EVEN HARMONICS

DATA SETS PROCESSED :
(4,0) (5,0) (6,0) (7,0)

AVERAGE HARMONIC IMPEDANCE

HARMONIC NUMBER	MAGNITUDE OHMS	PHASE DEGREES	R OHMS	X OHMS	STANDARD DEVIATION
2	17.17	111.49	-6.29	15.97	18.64
4	23.00	65.52	9.53	20.93	19.53
6	64.91	12.04	63.48	13.55	112.69
8	34.09	68.65	12.41	31.75	17.25
10	74.86	53.99	44.01	60.56	12.32
12	57.29	24.20	52.26	23.48	46.87
14	8.39	13.67	8.15	1.98	18.90
16	35.76	64.41	15.45	32.25	7.17
18	99.10	17.69	94.41	30.11	80.38
20	72.23	67.29	27.89	66.63	34.05
22	73.66	54.09	43.20	59.66	33.02
24	109.00	2.76	108.88	5.25	95.15
26	109.14	31.05	93.50	56.30	78.17
28	109.06	-26.80	97.35	-49.17	39.42
30	142.51	33.35	119.12	78.40	152.12
32	59.42	-16.48	56.98	-16.85	33.00
34	61.89	32.85	51.99	33.57	34.28
36	96.00	105.57	-25.77	92.48	153.43
38	89.17	-44.50	63.60	-62.50	144.59
40	100.16	29.12	87.50	48.74	84.22
42	78.27	-20.29	73.41	-27.15	83.56
44	48.58	-0.91	48.58	-0.77	45.60
46	45.42	53.46	27.04	36.50	36.46
48	117.20	161.11	-110.88	37.94	195.99

Below are five index cards that allow for filing according to the four cross-references in addition to the title of the report. A brief abstract describing the major subject area covered in the report is included on each card.

EPRI

**EPRI EL-2583
Volume 1
RP1138-1
Final Report
September 1982**

HVDC-AC System Interaction From AC Harmonics
Volume 1: Harmonic Impedance Calculations
Contractor: General Electric Company

Volume 1 of this two-volume report presents an evaluation of present alternating-current filter design practices in high-voltage direct-current systems. Two methods for calculating system harmonic impedances are discussed, and the results of the analysis of both the measurement method and the analytic method are presented. Recommendations for further testing of the two methods are addressed. 352 pp.

EPRI Project Managers: G. Addis, N. G. Hingorani

Cross-References:

1. EPRI EL-2583, Volume 1
2. RP1138-1
3. Transmission Substations Program
4. High-Voltage Direct Current

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

EPRI EL-2583, VOLUME 1

EPRI

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TRANSMISSION SUBSTATIONS PROGRAM

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HIGH-VOLTAGE DIRECT CURRENT

EPRI

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