AN ASSESSMENT OF RESEARCH DIRECTIONS
FOR HIGH-VOLTAGE DIRECT-CURRENT
POWER SYSTEMS

MASTER

FINAL REPORT

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September, 1982

Prepared For

The U.S. Department of Energy
Under Contract No. DE-AC02-78ET29185

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ABSTRACT

High voltage direct current (HVDC) power transmission continues to be an emerging technology nearly thirty years after its introduction into modern power systems. To date its use has been restricted to either specialized applications having identifiable economic advantages (e.g., breakeven distance) or, rarely, applications where "decoupling" is needed. Only recently have the operational advantages (e.g., power modulation) of HVDC been realized on operating systems.

This report documents a research project whose objective was to identify hardware developments and, where appropriate, system applications which can exemplify cost and operational advantages of integrated ac/dc power systems. Three principal tasks were undertaken, and are reported herein:

1. Assessment of equipment developments,
2. Quantification of operational advantages,
3. Interaction with system planners.

Interest in HVDC power transmission has increased markedly over the past several years, and many new systems are now being investigated. The dissemination of information about HVDC, including specifically the symposium undertaken for Task 3, is a critical factor in fostering an understanding of this important adjunct to ac power transmission.

TASK 1 -- ASSESSMENT OF EQUIPMENT DEVELOPMENTS

This task encompassed two principal activities. The first was an assessment of hardware developments and applications deemed necessary to the future evolution and acceptance of HVDC power transmission. Those areas receiving special attention included HVDC current breakers and system studies, and harmonic filtering techniques. The second activity was the provision of ongoing advisory services to DOE/EES. This comprised detailed involvement in DOE/EES sponsored research projects, participation in professional activities for information-gathering purposes, and the review of various proposals and reports. Each of the activities mentioned is summarized in the following pages.

High Voltage Direct Current Circuit Breakers

The problem is straightforwardly stated. Is a high voltage direct current circuit breaker needed; if so, what ratings must it have regarding speed of operation, energy absorption, continuous and interrupting current, and voltage?

Several mechanisms have been put forward as being feasible, and some have been field tested. Several manufacturers have at various times claimed to be able to provide a dc circuit breaker "on demand." The system studies done to date are, in this investigator's opinion, inadequate in addressing the above stated problem.

Several conclusions can be stated at this time:

1. There is considerable doubt, in this investigator's opinion, that a satisfactory interruption technique has been demonstrated.

2. No system studies have as yet demonstrated the need for a fast dc circuit breaker.

3. HVDC system controls must be designed to both ease breaker duty and minimize system disturbances.

4. Both in-line (across the breaker) and line-to-ground surge arresters will be needed for energy absorption and overvoltage limiting.

If research and development activity in HVDC circuit interruption is to be undertaken, the above four conclusions must be addressed as part of the statement of work. Thus, it is recommended that two new activities be initiated.

1. A broadly based study or, preferably, several independent but coordinated studies, into basic phenomena of high voltage direct current interruption. Operating speed would be investigated, but no specific constraint (e.g., an opening time of 5 ms) would be stated. The result of this study would be a better understanding of the feasible state-of-the-art of direct current interruption. It is further hoped that new techniques may be developed as a result of this activity.

2. A system-specific investigation of how the design parameters of a direct current circuit breaker and the associated dc system control philosophy affect the operation and stability of the interconnected ac system. The most appropriate system now seems to be the West Coast interconnection, including the WSCC "donut." It is likely that multiple 500 kV dc lines will be in service by 1990, and interconnections are desirable providing an appropriate dc circuit breaker is available. The result of this study would be specifications for the dc circuit breaker and also a system control philosophy to complement the breaker.

A brief summary of existing dc circuit breaker technology follows:

1. General Electric Company - USA

Precharged capacitor bank

Vacuum interrupters, series connected, High Speed (5-10 ms)

Laboratory tested, 80 kV/5kA/?kJ

Fusion test facility - 10 kV/30 kA

2. Hughes Research Laboratories - USA

Crossed field switch tube

High speed (3-10 ms)

Field tested on "multiterminal system," 93 kV/840 A/805 kJ

Additional developments (MRTB,CLD) failed field tests at full ratings

3. HGU -German/ASEA Consortium

Minimum oil conventional ac breaker

Gap, capacitor to commutate

50 ms to begin interruption

Laboratory tested, 28.3 kV, 2.5 kA, 7.1 MJ

MRTB installed on CU system

4. ETNA/EDF - France

Extremely high pressure SF₆ interrupter (300 atm)

Short arcing time (3 ms)

Unknown operating time

Field tested (back to back system) 120 kV, 1kA, 1.2 mJ;

possibly also at 195 kV, 800 A, 180 kJ.

No further development is anticipated

5. Nagoya University - Japan

Liquid SF₆ puffer

Laboratory tested at 3 kV/700 A (interrupter only)

Unable to generate high arc voltage

Recommendation for Interrupter Research

The objective of this study is to conduct an exploratory and (primarily) theoretical study of the direct current interruption process. Preference will be given to ideas that are innovative and novel, and have not previously been given detailed attention. Multiple awards are anticipated; those bearing exceptional promise can expect to receive continued support toward prototype development and testing.

Tasks to be investigated include:

1. Interrupter-- i , v , arcing, di/dt , dv/dt , failure modes
2. Current transfer process
3. Speed limitations
4. Projection toward development and testing of a prototype dc circuit breaker: 600 kV, 5 kA continuous, 20 kA fault current interruption, 7.5 kA load current breaking.

It is expected that this exploratory research, if successful, can lead to field testing of a prototype interrupter. This would be in conjunction with an (at that future time) existing test bed on the Pacific Intertie. Since energy absorbers and surge capacitors will be part of that test bed, it will be straightforward to modify it to accommodate the prototype. This is true even if a reduced voltage unit is to be tested, assuming it could be either connected in series with other (existing) modules or tested at a reduced system voltage level.

Recommendation for System Study

The objective of this study is to examine the dynamic relationships of integrated ac/dc systems wherein the existence of direct current circuit breakers is postulated. Realistic systems are to be studied, the principal goal being to ascertain the relationships between dc circuit breaker design and operating parameters (including especially speed), dc system control philosophy, and ac system parameters (including especially stability).

There are two principal areas of interest which should result from this study:

1. Specific systems are to be investigated; system-specific results are to be obtained, generalize at your own risk.
2. A methodology is to be developed; i.e., it should be possible to apply the procedures developed in this study to any potential integrated ac/dc system wherein the use of dc breakers is postulated.

Let us be clear as to what is meant by the term "direct current circuit breaker." There are three classifications of said device:

1. Fast - interrupter - a device which catches the fault current on the rise,
2. Slow - load break - a device which waits for system controls to depress the dc voltage and limit current to approximately the prefault level,
3. Very slow - isolator - a device which waits for system controls to depress the dc voltage and reduce current to near-zero.

It is believed that there are two "near-term" (no date appended) applications for dc breakers, and that these applications should form the basis for the systems to be investigated:

1. Parallel line switching, as per the Nelson River System. Duties are not severe in this application, and a dc breaker would need to develop only a modest counter-voltage. This could be a fairly near-term application; presently slower air-break isolation switches are used for current transfer between bipoles.

2. Multiterminal HVDC systems in an interconnected ac system. The western portion of the U.S. has the potential of as many as seven dc terminals. Some manner of dc breaker would clearly be required for interconnection of these terminals.

The following topics could form the basis for a statement of work:

1. System Definition

The specific systems to be investigated (ac and dc) are to be identified. All data on both the ac and the dc systems are to be collected. It is suggested that the West Coast system would best serve as the study example, especially in anticipation of the testing of a prototype dc breaker at Celilo. Further, both of the "application modes" just referred to can be achieved by appropriate reconnection of the Pacific Intertie accompanied by control modifications.

2. Transient Performance Criteria

The transient response of the existing ac system is to be evaluated, and criteria for stability are to be established. These studies would be conducted both with and without the existing Pacific HVDC Intertie.

3. Breaker-related Electrical Transients

Develop the digital model for the study of electrical transients in a dc system including dc breakers. This will be applicable in two areas:

- a. DC breaker design and operation for use with the Western System,
- b. Transients associated with the design and field testing of the prototype dc breaker.

High Voltage Direct Current Interruption Research at the University of Wisconsin

A graduate student, Parvez Rashid, has recently completed his M.S. thesis "High Voltage Direct Current Interruption." The next section of this report is excerpted from the introduction to his thesis. The last chapter of this thesis, "Outlook, Conclusions and Possible Extensions of Work" is appended to this report.

INTRODUCTION

Until now there is no HVDC circuit breaker serving in an HVDC transmission line. There are two reasons for this:

- 1) Firstly, no HVDC circuit breaker has been proved commercially.
- 2) Secondly, HVDC transmission so far is employed only from point-to-point, thereby allowing station controls to shut the system down in case of a fault.

High-voltage dc transmission has proved a promising competitor to conventional extra-high voltage ac transmission under several conditions: few of them are as mentioned below:

- a) Where long transmission distances from generation to load centers exist.
- b) Where asynchronous ties are required.
- c) And where underground or underwater cables of considerable length are necessary.

Further, in the future, it is to be expected that dc systems will be tapped or interconnected. With the growth of urban centers it appears desirable to have a primary dc transmission and distribution system which would provide a nonsynchronous link between parts of the urban ac subsystem. Such a dc system is unlikely to operate without dc circuit breakers which can deal with faults and the switching of load current.

Experience with ac systems has shown that they tend to grow into complex networks. Under present conditions there is little expectation that dc systems of comparable extent will develop. Dc lines are merely adjuncts to ac systems. A good HVDC circuit breaker could change this picture.

What is needed is not so much a circuit breaker for interrupting short-circuit currents for such currents can be limited by grid control to the magnitude of rated currents, but rather a switch capable of interrupting load currents in circuits at high potential with respect to ground. With such switches, lines could be switched into or out of an unfaulted network without running the voltage down.

The aim of the present thesis is to study the high voltage direct current interruption. This thesis consists of five chapters.

Chapter I describes the theoretical concepts of high-voltage direct current (HVDC) interruption. In this chapter three approaches have been presented, which are proposed for practical HVDC interrupters. Unpractical proposals and methods have been omitted. Chapter I also covers the three fundamental problems which relate to HVDC interruption and are:

- 1) How to produce current zero
- 2) How to dissipate and absorb energy
- 3) How to prevent restriking

Chapter II deals with the high voltage direct current arc physics. The fundamental of arc has been covered in this chapter. The thermal phenomena and steady state conditions; also the transient behavior of the

arc have been considered at length. Vacuum arc which is also of importance in HVDC interruptors has been dealt with separately in this chapter.

Chapter III gives details of interrupting media. The four types of HVDC interrupting media i.e., solids, liquids, gases and vacuum are given in this chapter. The breakdown phenomena of these four types of media are also discussed.

Chapter IV covers the testing of high voltage direct current circuit breakers. The two types of testing methods i.e., Direct and Indirect have been considered in this chapter in a detailed manner.

Chapter V, the last chapter of the thesis, is about outlook, conclusions and possible extensions of work on the HVDC interruption.

AC Harmonic Filtering Using Controlled Current Injection.

A graduate student, Gary Dreifuerst, has developed a laboratory prototype of a new technique for the cancellation of harmonic currents as produced by HVDC converters. It employs a microprocessor controlled current injection technique, with phase locked loops serving as the harmonic current detection means. Magnitude and phase information are used to control an ac-dc-ac converter which acts as the harmonic current source.

The circuitry operates with low losses and fast response times, and could be applicable for 11th and 13th harmonic filtering applications. It appears to be somewhat vulnerable to transient overvoltages accompanying current change orders. This may diminish some of the advantage of low losses by requiring a higher transient overvoltage rating than originally envisioned.

The rectifier is to supply direct current of a magnitude equal to that of the current to be cancelled (the 11th harmonic, in this study). The inverter provides for the proper phase and frequency of the injected current. Together they enable cancellation of the harmonic current in question. Commutation is accomplished by series capacitors. Since the harmonic current and amplitude is $1/h$ times the amplitude of the fundamental, the currents are modest. Concern must be taken for capacitor overvoltage conditions, however, and thus the microcomputer-based control and protection system must work efficiently.

Time constraints are imposed by working at the 11th harmonic (660 Hz), and indeed the inverter controller microcomputer used in this study is pushed to its limit. One must realize, however, that the design is now several generations old, and so this limitation is not a cause for concern for future applications.

Start-up imposes another constraint, as the controller must utilize a special firing sequence to precharge the commutation capacitors prior to full operation. Again, the microcomputer enables this to be implemented effectively because of its flexibility of interrupt structure.

The next section of this report is excerpted from the abstract, circuit description and summary of Dr. Dreifuerst's thesis. Chapter 5, Experimental Results, is appended to this report.

AC HARMONIC FILTERING
USING CONTROLLED CURRENT INJECTION

GARY R. DREIFUERST

Under the Supervision of Professor Willis F. Long

ABSTRACT

The purpose of this thesis is to build a test model that will show the feasibility of an active tracking filter for power system harmonics.

To do this, an extensive review of the sources of power system harmonics is done. This includes the effects harmonics have on communication and control systems.

Second, the standard harmonic filtering technique is discussed along with converter control schemes which minimize harmonic production. Four new approaches for harmonic filtering are reported and discussed.

Third, the active tracking filter theory is presented with steady-state simulation results comparing it to a standard passive filter.

Fourth, a state-of-the-art multi-processor controlled model is designed and constructed. The model incorporates an extensive data acquisition unit which allows great flexibility for experimental work.

Finally, the model's test results are presented illustrating

protection functions, steady-state operation and dynamic responses which show that the active tracking filter approach is feasible.

APPROVED:

May 18, 1981
Date

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Chapter 3

THE ACTIVE TRACKING FILTER

3.1 Introduction

The passive, series-tuned RLC harmonic filters which are currently being used on the AC side of HVDC converters suffer from several design limitations which are circumvented by a new active tracking filter^{3.1, 3.2, 3.3}. These limitations are:

- 1) The resonant frequency of the passive filter changes as a function of the environmental status and age of the filter components. Variations in system fundamental frequency also act to detune the filter. Since the HVDC converters act as harmonic current sources, the filter must maintain a near-zero harmonic impedance. This will generate a negligible harmonic voltage. When the filter detunes, the harmonic impedance increases, often drastically. The amount of detuning, and hence the level of the harmonic impedance, determines the magnitude of the harmonic overvoltage.
- 2) The system impedance at the harmonic frequency in question is first, not known accurately, and second, varies with respect to time, due to changes in system configuration. This time-varying nature of system harmonic impedance affects the harmonic filter's performance, since the filter is located in parallel with the system harmonic impedance. The filter

must be designed to have an impedance which shunts most of the harmonic current away from the parallel system harmonic impedance. If the minimum system impedance is nearly the same magnitude as the largest filter impedance, especially when the filter is detuned as in (1) above, then substantial harmonic current will be shunted, not by the filter, but by the system.

3) The filters act as a sink for the ambient harmonic currents in the system. In the discussion of Reference 2.12, D.J. Melvold states that the Sylmar Converter Terminal experienced an increase on one of its AC feeder lines of 12.5 amperes of 5th harmonic current, when only one filter bank was energized. The HVDC converter was not energized. The 5th harmonic current was 2.9 amperes before energization. This harmonic flow creates harmonic voltage components which appear throughout the system. It also interferes with the carrier current ripple control systems used by power companies to switch water heaters and similar peak-shaving loads on and off.

4) A passive filter can parallel-resonate with other passive filters and the AC system impedance to cause harmonic overvoltages. When the filters and system are parallel resonating, the HVDC converter will see an arbitrarily large harmonic impedance. Since the harmonic current being generated by the converter acts as a constant current, the harmonic voltage produced as it is injected into the system can exceed system designs. Then an instability would occur, forcing the

converter to change its operating mode and defeating the purpose of having a filter.

The active tracking filter performs its filtering function by injecting the harmonic current which is required by the AC/DC converter into the AC supply bus. The frequency, magnitude, and phase of the injected current is made, through a closed-loop control system, to follow the converter's required harmonic. System harmonic impedance variations have no effect on the filter, since the filter acts as a dependent current source. Similarly, the active filter cannot participate in a parallel resonance, since its controller will not allow the current source to change in frequency, magnitude, or phase.

3.2 Generation

The generation of a current with an arbitrary frequency, magnitude, and phase has been shown in References 3.4 and 3.5. The concept hinges on the performance of the AC/DC/AC link in Figure 3.1. The harmonic rectifier is fed by the AC bus and is required to supply the losses in the inductor L_{dh} and the harmonic inverter. The harmonic rectifier's gate firing-angle, α_r , has complete control over the magnitude of I_{dh} . By choosing L_{dh} sufficiently large so as to make I_{dh} nearly constant, the following equivalent circuit may be used to explain the operation of the harmonic inverter. Each of the thyristors in Figure 3.2 conducts for 120° of the operating frequency. In this diagram the R-C snubber networks have been omitted; also the

Figure 3.1. An AC/DC/AC link.

Figure 3.2. The simplified harmonic inverter.

series inductors necessary to limit di/dt have not been included in the capacitor circuit. Figure 3.3 shows the line currents and phase voltages during steady-state operation. During start-up, the capacitor voltages must have the correct initial values. This can be accomplished either by an auxiliary starting circuit or by a control sequence which will require I_{dh} to be zero at start-up and will

Figure 3.3. Capacitor voltages and current waveforms for circuit of Figure 3.2.

increase I_{dh} at a preset rate to ensure even capacitor voltage build-up.

From Figure 3.3, the peak to peak voltage can be written as

$$2V_{pk} = I_{dh} / (3f_h C) \quad (3.1)$$

since the capacitor charges from $-V_{pk}$ to V_{pk} in $1/3f_h$ seconds.

f_h is the harmonic frequency expressed in Hertz.

Hence the magnitude of the harmonic current is dependent on I_h (and therefore on α_r) and the frequency is dependent on the firing frequency of the thyristors in the inverter. α_1 will be defined as the harmonic inverter gate firing-angle.

3.3 Injection

The generated three-phase harmonic currents must be injected into the AC bus without imposing the full fundamental frequency bus voltage on the harmonic current source. An arrangement of series and parallel passive filters will be used to accomplish this requirement. Figure 3.4 is a one-line diagram of the active tracking filter where the AC/DC converter has been modeled as a constant current source. I_c is defined below:

$$I_c = I_c^1 + \sum_{n=1}^{\infty} I_c^{12n \pm 1} \quad (3.2)$$

in terms of the characteristic harmonics.

Figure 3.4. One-line diagram of the active tracking filter.

Z_{sh} is the series-tuned harmonic filter

Z_{ph} is the parallel-tuned harmonic filter

Z_{qh} is the harmonic power system Thévenin impedance

I_c is the converter current

I_{jh} is the generated harmonic current

I_{fh} is the injected harmonic current

I_{qh} is the harmonic current supplied by the AC power system

E_{qh} is the power system Thévenin voltage source (assumed to be of fundamental frequency only)

From Figure 3.4 it can be seen that when $I_{qh} = 0$ total filtering for the h harmonic is effected. Figure 3.5 is the result of an application of the superposition theorem on Figure 3.4.

Figure 3.5. One-line diagram of the active tracking filter at the h harmonic frequency.

From Figure 3.5

$$V_{qh}^h = -I_{fh}^h Z_{sh}^h + (I_{qh}^h - I_{fh}^h) Z_{ph}^h = -I_{qh}^h Z_{qh}^h \quad (3.3)$$

and

$$I_c^h = I_{qh}^h + I_{fh}^h \quad (3.4)$$

however for perfect filtering of the harmonic h , $V_{qh}^h = 0$, therefore $I_{qh}^h = 0$, and $I_c^h = I_{fh}^h$. Then from Equation (3.3)

$$I_c^h (Z_{sh}^h + Z_{ph}^h) = I_{qh}^h Z_{ph}^h \quad (3.5)$$

$$I_{qh}^h = I_c^h (Z_{sh}^h + Z_{ph}^h) / Z_{ph}^h \quad (3.6)$$

Equation (3.6) gives an open loop control algorithm for the active filter. However, due to the design philosophy which requires that the active filter not be affected by filter component drift, a

closed loop control will be used where Equation (3.4) will be implemented. Magnitude and phase sensors will be placed so as to measure I_c^h and I_{fh}^h . I_{qh}^h will be altered based on the magnitude and phase information in such a manner as to reduce I_{qh}^h to an arbitrarily small value.

In Section 2.8, the control system for the active filter that was discussed operated by trying to minimize the terminal harmonic voltage. That control is inferior to the tracking filter's control in two ways. First, by sensing the voltage, the control system is observing the result, not the cause of harmonic current flow. If the system harmonic impedance were very low, a substantial fraction of the converter harmonic current would bypass the filter and enter the system. Second, by sensing the voltage, directionality of current flow is lost. This permits system harmonic sources to feed the filter and can contribute to system impedance resonances.

3.4 Steady State Analysis

Magnitude and phase errors for the generated harmonic current are defined in Equations (3.7) and (3.8) respectively.

$$\epsilon_{\theta h} = \angle I_{jh}^h - \angle I_{jh0}^h \quad (3.7)$$

$$\epsilon_{mh} = (I_{jh}^h - I_{jh0}^h) / I_{jh0}^h \quad (3.8)$$

where I_{jh}^h is the actual generated harmonic current and I_{jh0}^h is the ideal generated harmonic current as given in Equation (3.6). $\epsilon_{\theta h}$ represents the phase error and ϵ_{mh} represents the magnitude error

with respect to the ideal generated harmonic current.

The Celilo AC/DC terminal of the Pacific HVDC Intertie was chosen as a representative system to evaluate $\epsilon_{\theta h}$ and ϵ_{mh} .

The following graphs of the steady state filter performance were taken from Reference 3.3.

Figure 3.6. Active filter performance as a function of $\epsilon_{\theta h}$ and ϵ_{mh} with $h = 11$.

In Figure 3.6, I_{qh}^h is plotted as a function of $\epsilon_{\theta h}$ and ϵ_{mh} . When both errors are zero, the system current goes to zero, indicating perfect filtering. For $\epsilon_{\theta h} = \pm 5^\circ$ and $\epsilon_{mh} = \pm 0.05$ pu, approximately 0.1 pu harmonic current will not be shunted by the active filter. A system frequency deviation of ± 1 Hz. does not affect these results. It should be noted that I_{qh}^h is the harmonic current which enters the mode shared by the filters for the 5th, 7th, and 13th harmonics; the power factor correction capacitors; and the

equivalent AC system impedance.

Figure 3.7 gives an excellent indication of the effects of detuning through the medium of frequency deviation. The system frequency was varied from 59 to 61 Hertz in order to produce a comparison between the passive and active filters. The value of I_{qh}^h for the passive filter never is less than it is for the active filter, with the active filter's errors set at $\epsilon_{\theta h} = 5^\circ$ and $\epsilon_{mh} = 0.05\text{pu}$.

Figure 3.7. Frequency response of the passive and active filters.

In redesign or replacement applications of the active tracking filter, an already existing passive filter will be on-site. Therefore in an effort to limit capital expenditure, the series tuned filter Z_{sh} (see Figure 3.4) will make use of the expensive capacitor C_{sh} from the now-retired, on-site passive filter. Based on this premise, Figure 3.8 illustrates the effects of a 1% variation in the

Figure 3.8. Performance of the active and passive filters with a parameter variation in the filter capacitor C_{sh} .

value of C_{sh} . This illustrates the effects that aging and temperature variations have on the passive filter. The capacitor's temperature is a strong function of its current level, so the temperature will vary whenever the HVDC converter changes its current level, or whenever area harmonic current generators vary their output. The feedback nature of the active filter's controller compensates for the capacitive variation so no change in I_{qh}^h occurs.

When producing Figures 3.6, 3.7, and 3.8, the value of the power factor correction capacitor was made to vary throughout its range. The particular value of capacitance which made I_{qh}^h highest was then used for the respective figure calculation. This is a

worst-case calculation.

3.5 Conclusions

The active tracking filter presented in this chapter does not exhibit the deficiencies of the passive RLC filter that were listed in 3.1. It is capable of following its design harmonic current over a frequency range without detuning. It is not sensitive to ambient harmonics since it exhibits an asymmetrical impedance: it appears as an open circuit to the system while it acts as a harmonic short to the main converter.

Chapter 4 describes the experimental apparatus that was constructed to test the active tracking filter.

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Chapter 6

SUMMARY

6.1 Principle Conclusions

An active tracking 11th harmonic filter model was built and successfully tested. The test set-up was controlled by several microprocessors acting in parallel. An automatic data acquisition system collected information from an experiment and could terminate the experiment if variable setpoints were exceeded. The great versatility of the data acquisition system proved invaluable for the real-time testing of the rectifier and inverter controllers' algorithms. The rectifier's design provided α -rate limits and maximum α and output current limits. Both the rectifier and the inverter interacted properly during start-up and shutdown. Both converters used bypass and blocking techniques to cope with non-run-mode situations. Dynamic response of both converters proved satisfactory. Current sensor design using a phase-locked loop for both frequency and amplitude sensing was successful. Locking on the eleventh harmonic component, of a synthesized 12-pulse current waveform which was subjected to simultaneous amplitude and frequency modulation, provided the necessary system error signals.

Difficulties encountered included the effect of inverter noise on the data acquisition system, gain and offset drift in the analog opto-isolators and in the PLL current sensor.

This work confirms that the active tracking filter outlined in Chapter 3 can be constructed using present technology and will function properly. Simulation studies done by Professor Narendra Mohan of the University of Minnesota indicate that 60 Hz. system transients will couple large voltages to the harmonic inverter. This would cause the active filter approach to be economically unattractive. By applying recent work^{6.1} using zinc oxide varistors to limit series capacitor voltage build-up, the inverter can maintain a low voltage rating and should be economical.

6.2 Directions for Future Research

Mohan^{6.2} has proposed combining the 11th, 13th and high-pass filters into one device which uses two inverters to complement the normal passive filter currents, so as to provide nearly ideal filtration. This approach does not allow appreciable 60 Hz. transient voltages to affect the inverters. Figure 6.1 depicts the modified high-pass filter. This filter also provides substantial space savings in the power switchyard of an HVDC converter station.

The laboratory equipment constructed for this project can be used to investigate static VAR control problems by utilizing the rectifier and an external AC capacitor bank. The data acquisition system has six pairs of external, uncommitted voltage and current sensors which may be utilized for either machine laboratory or power distribution experiments.

Figure 6.1. Modified high-pass filter incorporating 11th and 13th harmonic current sources.

References-Chapter 6

- 6.1 Hamann, J.R., Miske, S.A. Jr., Johnson, I.B., Courts, A.L. "A New Zinc Oxide Varistor Protective System for Series Capacitors," IEEE-PAS, Vol. PAS-100, March 1981, pp. 929-937.
- 6.2 Mohan, N. "Modified High Pass Filters for HVDC Converter Terminals," paper presented at the IEEE PES Summer Meeting, British Columbia, Canada, 1979.

Advisory Services to DOE/EES

A substantial amount of activity has been devoted to the provisions of advisory services to DOE/EES. This has been both in a formal manner, as participant/representative of DOE/EES in specific research projects, and on an informal basis, as in reviewing reports and proposals upon request. Further activity has included active participation in IEEE and CIGRE professional meetings and working groups. The latter in particular are documented in this report.

DOE/EES Research Projects

The Philadelphia Electric Company Long Underground DC Transmission Study has examined the integration of a dc system into a large urban ac system in a normal transmission application. Dr. Long's involvement has been in providing a detailed understanding of HVDC technology to the Philadelphia Electric personnel. This has been particularly important in reviewing the dc converter station design prepared by GEC Switchgear of England. In addition, Dr. Long has provided progress reports of this study to CIGRE Study Committee 14, HVDC Links, and to the IEEE Transmission and Distribution Committee.

Commonwealth Associates has developed a model to define and compare alternative ac and dc transmission systems. This model allows an engineer with experience in transmission systems planning to make a "rule of thumb" analysis of alternative ac and dc systems (including life cycle costs). Dr. Long's involvement has been in reviewing the work and providing commentary and analysis of the dc portions thereof.

Westinghouse Electric Corporation and IREQ were contractor/subcontractor on a compressed gas insulated HVDC

transmission line project. Dr. Long monitored the systems studies conducted on the IREQ HVDC Simulator. Particular emphasis was placed on identifying overvoltages occurring from control and protection action of the converters. Additional work was done by Westinghouse in investigating lightning overvoltages. The overall objective was to ascertain what minimum BIL could be achieved.

Alcoa/General Electric Company have conducted an alternative study of HVDC CGIT systems. Again, Dr. Long's involvement was principally in monitoring the systems studies with the intention of achieving a minimum BIL.

The additional ongoing advisory services, as in reviewing reports and proposals, will not be documented here. Detailed reports containing Dr. Long's comments are on file with DOE/EES.

Professional Activities/Technical Visits

Most of the research and development activity in HVDC is international. In fact, only one domestic company, General Electric, supplies HVDC equipment. While there is a considerable body of IEEE information published on HVDC, it is CIGRE Study Committee 14, HVDC Links, that is the historical focus for dc activity. Dr. Long is an Expert Advisor to the U.S. Representative to Study Committee 14, and has been able to attend several meetings. The following comprises excerpts from his report of the August 1979 meeting in Scandinavia and subsequent visits to European manufacturers.

The following items of special interest were discussed by Study Committee 14 during the meetings:

- A massive thyristor failure occurred on the Skagerrak System three days prior to the arrival of the Study Committee. A gate firing circuit component failure led to the cessation of firing pulses to one inverter quadrivalve. This caused ac voltages to appear on the remaining two quadrivalves, resulting in overvoltages which destroyed 185 of a series string of 600 thyristors. The time to replace the thyristors was 49 hours.

- Vacuum switch bypass switches on the Vancouver Island System are having flashover problems, accounting for 80 percent of the forced outage rate on pole 2. Eight series connected bottles are used for these switches.

- Technical studies of a 2000 MW cross-channel system connecting England and France are nearing completion, but the commitment to build the system is still forthcoming. Two independent bipoles will be rated at ± 270 kV (cable limitation), 1850 A. Commissioning is anticipated in 1984-85.

- A tapped multiterminal system is under investigation wherein a converter on the island of Corsica would be added to the existing Italy-Sardinia System.

- Possible new HVDC systems were mentioned for installation in Brazil, South Africa, Austria and Canada (four possible systems).

Major attention was given to the topic of dc converter stations located in weak ac systems; three position papers were delivered by Messrs. Gavrilovic, Calverley and Martensson. It was felt that the

term "weak ac systems" was less descriptive than "high impedance ac systems." It was further agreed that steady state performance may be satisfactory down to very low short circuit ratios, but transient performance will not be acceptable for power order changes or recovery from commutation failures. The committee chairman will convene a task force to collect information on this topic and to recommend what further studies might be undertaken.

As part of the committee activity, visits were made to the two converter terminals of the Skagerrak HVDC link between Norway and Denmark. These visits were most enlightening, especially as it was possible to view the converter valve modules and discuss system control and protection philosophy with the manufacturer, ASEA.

Imperial College - London, England

Professor Brian Cory was the principal host, Professor Jerry Meisel from Wayne State University, Detroit, was also on hand. Professor Cory is participating in a study of Control of Multiterminal HVDC Networks Embedded in AC Transmission Systems; Professor Meisel is the Principal Investigator.

Discussion centered around stability augmentation using an embedded HVDC network. Professor Cory is to evaluate optimal converter station placement and control strategies, culminating in proof-of-concept tests of a three terminal dc network embedded in a ten machine test system. Conceptual ideas were explored but as this study is in the first of three years, no results are as yet available.

The HVDC System Simulator at Imperial College was examined. Particular attention was given to a microprocessor-based control system being developed by a graduate student under Professor Cory's direction.

G.E.C. Switchgear Division, Stafford, England

Aleksa Gavrilovic, Manager, Power Transmission Division was host: During technical discussions, the following points were covered.

- It is difficult to make a fair comparison between ac and dc alternatives for an embedded dc application. It is not possible to ascertain the true ac network losses in a system such as where the Kingsnorth dc system is installed. No simple comparison is valid.

- Further, the entire issue of "application credits" is difficult. One should take a specific system, and run digital computer load flow and stability studies (utilizing utility people). Look to simulator studies to resolve unexpected or unexplained results. AC and dc people must work together on these studies. From specific answers, see if one can generalize toward "application credits."

- The ability of dc to limit cascading failures needs attention. Multiple contingency studies can be done, but it is not clear just what should be examined. Can one find a cost for stiffening and compare it against a cost for deleterious performance?

- The availability or unavailability of a dc circuit breaker will have a marginal effect on the acceptance of multiterminal dc systems. It is questionable whether extensive multiterminal dc networks will ever develop. It is felt that a need for diode rectifiers and/or forced commutation converters will precede the need for a dc circuit breaker. Tapping a dc line may not be economical in the first place.

ASEA - Vasteras, Sweden

The principal host was Ture Adielsson, Section Head, Computer Applications:

Attention was primarily devoted to the topic of computer analysis of HVDC links enmeshed in ac systems. Various modeling methods were discussed, especially as relating to dynamic system performance. Algorithms were described for various components in the systems, and sample computer runs were presented. Load flow, stability and fault studies were discussed. Comparisons against standard computational methods were made.

ASEA - Ludvika, Sweden

A number of persons were visited at this facility, as follows:

Lennart Carlsson, Manager, HVDC Project Planning Office. Time was spent discussing the large Itaipu HVDC project in Brazil and how it will influence the design of future dc systems. Regarding the cost of future systems, it was felt that costs will rise but at a slower rate than inflation causes ac equipment costs to rise.

(Editorial comment - dc terminal costs have held nearly constant for ten years. It appears unlikely that converter valve cost improvements can counterbalance other inflationary equipment costs in the future. If ac equipment inflates at eight percent annually, dc terminal costs will inflate at four-six percent.)

Göte Liss, Manager, HVDC System Simulator. The component parts of the simulator were discussed in detail, especially the electronic model of ac machines. The simulator is a low power model, and incorporates feedback circuitry to correctly scale the valve conduction voltages. Transformer modeling is done in detail to include losses, hysteresis, and nonlinearities. Microprocessor controls are being incorporated for selected functions. The necessity of using the simulator in conjunction with digital computer studies of ac-dc systems was agreed upon.

Lars Eklund, Head, Valve Test Section. In addition to visiting the

test facility (including the control and instrumentation center), the importance of water cooling was discussed. While air cooled valves are considered acceptable for Skagerrak (500 MW) and CU (1000 MW), the increased overall efficiency of water cooling is clearly preferred for Itaipu (6000 MW).

Lars-Eric Juhlin, Engineer, Main Converter Design. Much of this discussion centered upon dc circuit breaker developments. He feels that the dc breaker must have high reliability (therefore must be simple) and must complement the converter controls (therefore can be relatively slow - two to three cycles). The MRTB (metallic return transfer breaker) at CU has had a number of successful operations. It uses a minimum oil ac breaker, two interrupters in series, and requires 50-100 ms arcing to build the voltage up to where it will flash over the parallel gap and transfer current. The Germans, using an air-blast interrupter, require one-two cycles to generate the arc voltage. The most apparent near-term application is for line paralleling - deparalleling, as for Nelson River (at present, this action requires 750 ms including one restart attempt.) Fast breaker operation is not required in a meshed system application, because communication and decision times of the order of 30 ms will be required to determine exactly which branch is faulted. Other topics discussed included diode rectifiers (do not appear to present significant cost advantages), forced commutation (should be studied as an alternative to strengthening via capacitor banks, which can lead to resonance problems), and the often reiterated plea for more knowledge of the associated ac system.

Brown, Boveri, and Cie, Mannheim, Germany.

Peter Lips, HVDC Development Engineer, was the host. Regarding dc circuit breaker development, he stated that the minimum oil

interrupter is unsatisfactory because of the low arc voltage. An air blast breaker is preferable in this regard, but will the air blast breaker be available in ten years? A dc breaker needs to be made from commonly available components, both for reliability and because no appreciable market can be foreseen. Someone other than a manufacturer must take the initial risk of introducing the device.

For a system study, one should investigate ac faults and how the ac and dc systems are affected:

1. What disturbances occur on the dc system,
2. How disturbances are propagated around the ac system by the dc system.

Different results will be found for a tee and for a meshed dc network--a fast breaker may be needed for the tee, but will not be for the meshed.

The following question was posed by Dr. Long: As an ac system planner, what would convince you of the viability of a dc circuit breaker?

The answer:

1. A prototype must be tested over a period of time,
2. I must have a means to learn whether it is needed on my system (control strategy, operational requirements),
3. Can I design my system to use the device?

FGH, Rheinau, Germany

Eckhardt Rumpf, Director-HVDC, was the host. FGH is a research center and test laboratory on the outskirts of Mannheim; it is supported by subscriber contributions from German utilities and industries. Interest was expressed in studies on pollution coordination. Work to date has indicated a relationship between leakage current and flashover voltage, and results appear to be

repeatable. The work is not going to be continued by FGH.

The high voltage laboratory and HVDC system simulator were visited. Again, great emphasis was placed on the value of the simulator for system studies, especially for testing control and protection concepts. High impedance ac systems should be examined on a simulator with an expanded ac system representation, not on a hybrid or a digital computer. The next generation of simulator should be very low power (perhaps 10 mA rated current) for increased flexibility.

Brown, Boveri, and Cie, Baden, Switzerland

Joe Kauferle, Head-HVDC Development, was the principal host. Clear interest was expressed in further dc circuit breaker development. As previously mentioned, line paralleling can be speeded up. Communication is a problem to be addressed--can the breaker operate with minimum information? For instance, on the Nelson River System magnetic storms often cause the microwave link to fail temporarily. It is possible for information to be transmitted when communications fail; i.e., the inverter can request a current order change by changing its voltage. Again, the near-term circuit breaker applications are for parallel line switching and tapping a point-to-point system. A small tap cannot be permitted to hold the system voltage down, as in a sustained nearby ac fault. The breaker must quickly isolate this station; still, it cannot trip for single commutation failures (for either inverter).

In discussing potential "application credits" with utilities, they are generally unable to put a cost value on them. Policies (such as redundancy criteria) vary from utility to utility, so it is difficult to identify a "standard case." AC vs dc decisions are

sometimes subject to "human" factors that can shift the cost $\pm$ 20 percent.

A number of asynchronous connections between the Western Europe system and Eastern Europe are being considered. Direct connections are not feasible because of differing control methods. A connection between Russia and West Germany with a tap at Berlin is a possibility. They do not envision a dc overlay in the United States, but rather than dc will be located where there are load flow problems.

They sense a change in attitude among ac system planners regarding dc. Formerly, they questioned whether dc would work at all. Now, they question the effects of the dc terminal on their ac system (harmonics, VARS). It would be useful to have benchmark cases for these problem areas, to establish standards of performance. This is not unlike what is needed for ac systems with subsynchronous resonance problems, or having static VAR controllers.

Appraisal and Observations

In appraising the scientific value of the above discussions and laboratory visits, several points stand out. The early work in HVDC was European, so their expertise is well established. If one is to make recommendations to Department of Energy regarding research priorities, one ought to search out those experts who have a record of achievement in the area of study. The openness of all of these persons/organizations was far in excess of what had been expected. Intimate details of computer programs were discussed; plans for major laboratory changes were revealed; expected increased device ratings were postulated; criticisms of techniques or philosophies within the hosts' companies were shared with this visitor.

A further item of interest is that this investigator's previously held opinions of HVDC research priorities have been reinforced. This implies that the research activities initiated are being given the correct priorities, and that no other research activity has been improperly slighted.

TASK 2 - QUANTIFICATION OF OPERATIONAL ADVANTAGES OF HVDC SYSTEMS

High voltage direct current power systems, in certain applications, may have operational advantages which are not shared in common with conventional ac systems. Examples of these include rapid dynamic control of real and reactive power, controlled routing of power, and asynchronous interconnections between ac systems. Under this task, computer modelling of HVDC and static var control (SVC) systems was implemented, principally using the Electromagnetic Transients Program (EMTP). Also, studies were made of the interactions between ac and dc systems. No detailed economic evaluations were attempted.

Computer Studies

Power system simulation has been an important tool for power systems planning and analysis since the early 1920s. With the advent of modern high power AC/DC converters and DC transmission there developed a need for AC/DC simulators. These simulators required the addition of AC/DC converters and controls systems to the basic ac power system simulators. Rather than model the control system, AC/DC simulators use an actual hard-wired unit. The resulting simulators have been effective tools, but are limited because of the inflexible controls.

Of the major AC/DC simulators in North America, the Wisconsin simulator has ASEA's control built in the 1960's; General Electric's simulator has similar ASEA controls plus their own design; IREQ has a more current ASEA control and an older GEC (England) control built in the early 1970s. There are no North American facilities where AC/DC systems can be studied with the most current controls.

Basically, this is due to the cost of controls and the fact the designs are being refined yearly.

With the availability of high speed digital computers digital simulation of electrical power systems became a practical alternative to model type simulators. One of the most sophisticated and widely used programs is the Electromagnetic Transients Program (EMTP), which has been developed by Bonneville Power Administration (BPA), over the last 15 years. A major breakthrough in 1976 was the addition of control models to the EMTP. This allowed power system transients, control systems, and AC/DC converters to be modelled simultaneously resulting in an all-digital modeling capability to simulate AC/DC systems. To date there have been numerous AC/DC system studies of special problems using the EMTP. These runs have used main-frame computers to simulate dynamics of 10-1000 milliseconds.

It is certain that manufacturers will always need large AC/DC simulators, especially for real-time laboratory testing of control and protection circuitry. It is also certain that utilities cannot afford to own and maintain a simulator. Digital simulation, however, is quite another matter. Many utilities now employ young engineers with an understanding of the EMTP. A modest-sized minicomputer (e.g., the DEC VAX/780) can serve as a digital simulator, providing the appropriate software (library programs) is available. A significant amount of work has been devoted to this development by Dr. Lasseter since joining the University of Wisconsin in 1980. The next section documents specific developments in static var control modeling.

Digital Transient Simulation of Static Var Control Systems

At DOE/EES's request, a technical paper was prepared for presentation at the IEE Conference "Thyristor and Variable Static Equipment for AC and DC Transmission". The paper, entitled "Digital Transient Simulation of Static Var Control Systems", was authored by Professor R.H. Lasseter and Dr. K.G. Fehrle (DOE/EES). The paper is appended to this report.

Digital models to study power systems including thyristor controlled reactors usually apply a greatly simplified representation of the thyristors and their controls. A model of static var systems was recently incorporated into the Philadelphia Electric Company Transient Stability Program by R.L. Hauth et. al. (5). A transfer function type representation of the SVC was sufficient for that purpose. A greatly simplified digital approach was used by B. Kulicka (7), who represented the controls by their behavior at the basic frequency. Byerly et. al. (8) introduces two representations for static var compensators, one a non-linear load formula, the other a dynamic auxiliary control regulating the SVC susceptance. The latter uses transfer type blocks, and it was incorporated into a major stability program. Simulations using these above mentioned and similar models suffer from one or more disadvantages, such as inaccuracy, inflexibility, lack of details, or poor simulation of transient response.

This paper describes a method for simultaneous detailed digital simulation of the thyristors, their gate pulse generating circuit, the regulating circuit, and the power system. This is achieved by using the Electromagnetic Transients Program (EMTP) including Transient Analysis of Control Systems (TACS) developed by the Bonneville Power Administration (BPA). The model of the regulator

consists of the digital simulation of the individual components found in such circuits; i.e., integrators, summers, band pass filters, non-linear interfaces, etc. The gate pulse generator makes use of logic elements, which can also be simulated by EMTF with TACS. There are practically no restrictions to the number of components in these control circuits, or to their interconnections. The control circuits can therefore be represented realistically, and their internal performance can be studied in detail. Components can easily be modified, or complete components can be added, deleted, or reconnected. This facilitates greatly the design and optimization of the control circuits.

The power system simulation can be quite extensive and can include the typical components such as sources, lines, transformers, breakers, etc. Signals from the power system, such as voltages, currents, or switch status, can be picked up as inputs to the control system. Outputs from the control system are forwarded to the power system as voltage sources, current sources, breaker open or close commands, or as thyristor gate pulses. This simultaneous simulation of the power system and the control system including the interaction between the two systems makes this method very powerful. It is particularly well suited for simulation of transients in systems with thyristors. The method is accurate, flexible, allows detail modelling, and simulates transients responses especially well.

AC/DC System Interactions

At DOE's request, a technical paper was prepared for presentation at the IEEE T&D Conference in September 1981. The title of the paper is "Considerations of AC System Impacts when

Planning HVDC Systems." Its objective is the identification of the effects of a planned dc system on interconnected ac systems located in the general vicinity. Topics include an introduction to the characteristics and equipment of HVDC systems, considerations at the interface between the ac and dc systems, and some ordinary and extraordinary planning considerations. A copy of the paper is appended to this report

The paper is intended to provide utility transmission and distribution engineers and system planners with an insight into some of the system-related effects of dc systems. As such it is expository in scope; it is aimed at the general technical level of those in attendance at the conference, rather than at dc "experts".

The paper concludes that high voltage direct current power transmission is an important adjunct to alternating current power transmission. It can, when properly applied, provide both cost and performance benefits. The fast controllability of power can be used to improve the capabilities for power transfer of the associated ac system. At the same time, there are significant effects that occur at the interface between the two systems that require detailed investigation.

HVDC is still an emerging technology, as there are only four operating systems in this country and twenty-one world wide. Judging from the number of systems now receiving serious planning attention, HVDC may be maturing very soon.

Application Credits

A number of discussions were held with a major electric utility regarding investigating the application of dc transmission in a non-traditional setting. This utility has historically expressed a

lack of interest in dc, principally because transmission line lengths do not approach the traditional "break-even distance." There are, however, other attributes of dc to be considered. These include the controlled routing of power, control of short circuit levels and fast control of energy exchanges via interconnections.

A study was proposed whose objective was to evaluate the benefits and concerns of applying HVDC technology as a highly interconnected power system. This would be as a replacement for or in conjunction with ac transmission facility additions. The analysis would be carried out utilizing comprehensive planning procedures, concentrating on evaluating system performance and economic considerations. It would be, in essence, a comparison of dc transmission vs. ac transmission in a non-traditional application, where dc (using conventional thinking) would not normally receive consideration.

As the utility did not have access to load flow and stability programs which included dc transmission, several manufacturers with such programs were invited to participate in discussions. They expressed a very high interest in the study, both because of the opportunity to interest another utility in HVDC and also because of the likelihood of valuable results to be forthcoming.

A detailed study plan was prepared by the utility, which estimated that nine man-years of work plus computer time would be required. Both manufacturers submitted proposals for computer programs and technical assistance. DOE/EES was prepared to fund the study. However, the utility at this time relocated its entire system planning department to another city. A significant loss of personnel occurred, and plans for the study were held in abeyance. No further activity is expected.

Consideration was given under this task to subcontracting a study on economic considerations of HVDC. It was recommended (and agreed to by DOE/EES) that this not be undertaken, as economic information would be included in the symposium for system planners of task 3. This is covered in the next section of this report.

TASK 3 -- INTERACTION WITH SYSTEM PLANNERS

It was originally envisioned that a small workshop would be organized (through University of Wisconsin--Extension) to familiarize system planners with HVDC systems. The intended purpose was to facilitate the interchange of information gathered in this reported study with those persons who could most benefit from it. Attendance, by invitation only, would have been limited to 40.

In discussions with DOE/EES, it was realized that a symposium having broader appeal would be more beneficial to both utility system planners and to others more familiar with HVDC. The resulting symposium was entitled "Incorporating HVDC Power Transmission into System Planning." It was held March 24-27, 1980. Attendance exceeded 200 persons, including over 100 system planners from utilities. It was the first such event ever held and, judging by the ongoing references to papers in the proceedings and a continuing demand for proceedings, was a widely recognized conference.

The description of the symposium, as contained in the brochure advertising it, is as follows: "High voltage direct current power transmission has to date been utilized for special applications. These include long distance overhead bulk power transmission (the Pacific Intertie), intermediate distance undersea cables (Vancouver Island) and asynchronous ties (David A. Hamil-Stegall, Nebraska).

Terminal costs and interconnection inflexibility have combined to limit the potential applications of HVDC.

"There are, however, other attributes of HVDC that merit consideration in the planning of utility systems over the next decade. These include dynamic power control (including real and reactive power modulation and SSR control), the controllable routing of power, corridor uprating, fault current limiting, and minimized environmental effects.

"The objective of this symposium is to examine the potential role of high voltage direct current transmission as introduced into power systems of the 1980's. Twenty-nine papers will be presented on system interconnections, energy exchanges, corridor upratings, urban applications, AC/DC economic comparisons, planned new HVDC systems, dynamic performance capabilities, HVDC circuit breakers and field effects of HVDC lines. Progress reports will be given on a number of EPRI and Department of Energy sponsored research activities.

"The keynote address will be given by E.C. Starr, Consulting Engineer, Bonneville Power Administration, Portland, Oregon. An introductory tutorial lecture "Fundamentals of HVDC Power Transmission" will be presented on Monday evening. The symposium will conclude with a panel session "What is HVDC's Role in Meeting Future Power System Needs?" Panelists will represent utility system planners and equipment manufacturers

"This symposium is sponsored by the Division of Electric Energy Systems, U.S. Department of Energy. The paper selection committee is J.J. Vithayathil, Bonneville Power Administration; A.G. Phadke, American Electric Power Service Corporation; F.J. Ellert, General Electric Company; and W.F. Long, University of Wisconsin."

The session moderators were T.F. Garrity, DOE/EES; N.G. Hingorani, EPRI; J.J. Vithayathil, BPA; A.G. Phadke, AEP; and F.J. Ellert, G.E.

The panelists were R.M. Maliszewski, American Electric Power Service Corporation; C.V. Thio, Manitoba Hydro; G.D. Breuer, General Electric; J. Kauferle, Brown, Boveri & Cie; K.J. Rooney, Commonwealth Edison Company, and H. Martensson, ASEA. The panel moderator was R.G. Flugum of Chas. T. Main, Inc.

A listing of papers and authors is included in the appendix to this report, together with a brief abstract of each paper.

Attendance was well in excess of what was anticipated (100 was considered to be an acceptable response). Half of the audience were system planners. This is a significant point--the symposium was planned and advertised to appeal to system planners from the utility industry. The remainder of the audience comprised equipment manufacturers, scientists and engineers from various laboratories, consultants, and university professors. Nine countries were represented.

The papers were well received. Audience participation was restrained until midway through the symposium, and was very animated after that point. Particular interest was expressed in the torsional oscillation problem at Square Butte. The concluding panel session also elicited substantial audience participation, particularly on the issue of equipment standardization and turnkey projects.

Overall the symposium can be considered successful. One would wish that the proceedings had included more contributions from the electric utility industry, but the development of HVDC systems in this country is not yet at a state where that kind of response is possible.

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APPENDIX A

CHAPTER V

OUTLOOK, CONCLUSIONS AND POSSIBLE EXTENSIONS OF WORK

5.1 Introduction

High-voltage d.c. transmission (h.v.d.c.) is gaining significance in today's electric power industry. The technical and economic advantages of high voltage direct current transmission have attracted the interest of power engineers from the beginning and several low power schemes were constructed during the early years of this century. The inherent lack of operational flexibility of the available conversion equipments in these early years imposed severe limitations and effectively prevented d.c. competing with a.c. for bulk power transmission. The exploitation of d.c. as a transmission medium had to await the development of the higher power mercury arc valve.

The putting to work of the Moscow-Kashira transmission in 1950 and the Gotland-Swedish Mainland link in 1954 inaugurated an era where HVDC transmission was able to compete with conventional a.c. transmission in certain circumstances. Presently, twenty high-voltage direct current (HVDC) transmission systems are operational in the world. But all of them are point-to-point systems. Their uses range from long distance bulk transmission i.e., Pacific Intertie; Nelson River; to back-to-back asynchronous coupling, i.e., Sakuma, Eel River. The Kingsnorth Project has three terminals, but is in fact not a multiterminal system in the generally accepted sense of the word.