RECEIVED

APR 04 1995

OSTI

FINAL PROJECT REPORT

"ANALYTICAL TOOLS TO PREDICT DISTRIBUTION OUTAGE RESTORATION LOAD"

**SERVICE CONTRACT
BPA AGREEMENT No. DE-B179-92BP27938**

**by the University of Idaho
for
Bonneville Power Administration**

November 14, 1994

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

University of Idaho

Electrical Engineering
Moscow, Idaho 83844-1023

208-885-6554
FAX 208-885-7579

November 14, 1994

Subject: FINAL PROJECT REPORT, SERVICE CONTRACT
(BPA Agreement No. DE-B179-92BP27938)
"ANALYTICAL TOOLS to PREDICT DISTRIBUTION
FEEDER OUTAGE RESTORATION LOAD"

Dear Mike:

At long last here is the Final Report on the CLPU project. I apologize for the lateness and hope that you were not caused any embarrassment.

Thanks for bearing with me! I am nearly up to speed again, thankful that my tests at the Spokane Heart Institute all proved negative.

The project has been an excellent learning vehicle for UI EE. A number of students have and will continue to benefit from this BPA sponsored work. As stated within the report, Larry Elliott is continuing the work in his MS(EE) thesis and recently obtained an Idaho Power Company field recorded CLPU with the "wiggles" (cyclic feeder restoration current) predicted by the harmonic model that was developed in this BPA project. We will keep you posted on future progress.

Thank you for your personal effort and contributions in the project work. Our joint paper with Don Minford of Kootenai Electric Cooperative was well received at the IEEE PES 1994 Summer Meeting.

This has been an exciting activity, in particular the interplay among energy supplier, customer and academia.

Please give me your comments and any questions/suggestions regarding the content/form of the report. If you deem any corrections/additions/deletions, please let me know. Yours is the only copy mailed out. Once you are satisfied, please let me know to whom additional copies should be sent or if you want to forward copies within BPA. Thanks.

Sincerely yours,

John Law

FINAL PROJECT REPORT

SERVICE CONTRACT
(BPA Agreement No. DE-B179-92BP27938)

ANALYTICAL TOOLS to PREDICT
DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

(Development of a Method and Software for Estimating Feeder Parameters for
Prediction of Cold Load Pickup from Field Test Step Voltage Data)

Submitted 17 Nov 1994 to

The Bonneville Power Administration
707 W. Main
Suite 500
Spokane, Washington 99201

Michael V. Storms, P.E., Electrical Engineer
Contracting Officer's Technical Representative
Telephone (509) 353-2588
Fax (509) 353-2909

by

The Electrical Engineering Department
University of Idaho
Moscow, Idaho 83844??

John Law, P.E., PhD, Professor
Contact Person
Telephone (208) 885-7692
Fax (208) 885-7579

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *ds*

MASTER

ACKNOWLEDGEMENT

This has been an exciting and rewarding project. The project grant by the Bonneville Power Administration that made this work possible is greatly appreciated as is the interest and assistance of several BPA personnel, in particular that of Michael Storms, the contracting officer's representative. Thanks also to Carson Taylor and James Ray of BPA.

Mohammed Ahlamad and Larry Elliott, grad students at the University of Idaho, worked long and hard throughout the project. Jonathan Meyer, University of Idaho senior in Computer Science spent many hours putting the CLPU and STEPV algorithms into C++ Windows version software. Greg Klemesrud, UIEE technician, contributed strongly by fabricating the data acquisition unit and putting together the arrangement for calibrating the Rochester Instrument Load Loggers prior to field installation.

My greatest thanks goes to Don Minford, Kootenai Electric Cooperative systems engineer, for his enthusiastic and professional participation throughout the project. Don supervised the installation of the loggers, did the interfacing with the loggers and KEC PCs to get the field data plus other tasks that made the project go. He also suffered through a few cold winter mornings to get the STEPV data. Coffee and donuts together at 3:00am has engendered a lasting friendship!

John Law
University of Idaho
November 1994

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

SUMMARY

PROJECT OBJECTIVE

The purpose of this work is to provide analytical tools with which to predict distribution feeder current versus time upon feeder circuit breaker closure to restore power following an outage during cold weather, Cold Load Pickup. As stated in the proposal/contract, analytical tools will be in the form of computer programs. Deliverables will include reports, technical information and procedures. A further outcome would be the development of a simplified load "time constant" model of the total feeders of all feeders of a utility district for application in voltage stability analysis.

PROJECT RESULTS

A computer algorithm based on a simplified "harmonic model" has been developed with which to predict Cold Load Pickup. A technique with which to readily obtain field test data and subsequently derive the parameters required to model the feeder in the Cold Load Pickup program has been developed and tested. The technique is called the Step Voltage Test. The deliverables with this final report include computer programs on diskettes for PC application of the Cold Load Pickup algorithm and Step Voltage Test technique. Superposition of individual feeder harmonic model Cold Load Pickup response to obtain aggregate utility district response for Voltage Stability analysis is herein proposed, but has not been implemented.

CONCLUSIONS

Correlation of predicted Cold Load Pickup response of a Coeur d'Alene, Idaho feeder (KEC Appleway 51) from Step Voltage Test obtained parameters with an actual Cold Load Pickup acquired with Load Loggers has proven the concept. However, further verification with other feeders and recorded load restorations and refinement of the methodology is desired before practical utility application. A "swing" in restoration currents actually does exist as predicted and can be observed in the filtered data of the only Cold Load Pickup obtained in the project. Recently data supplied to us by a Northwest utility shows cyclic restoration current in unfiltered data as predicted by the model and demonstrated by Niagara Mohawk in 1949.

RECOMMENDATIONS

Before further funds expenditure in this area, evaluation of the worth and likelihood of application of Cold Load Pickup current vs time prediction is recommended. "Catching a pickup" is improbable. A planned outage(s) is most desirable for further verification and refinement. In as much as Cold Load Pickup is mainly now a NW phenomena, an industry/academia conference on CLPU should be organized before future support is invested in this area; a main thrust of the conference would be the hows and whys of application of CLPU techniques and obtaining feeder parameters.

Kootenai Electric Cooperative, Inc.

A Consumer Owned Electric Utility

November 15, 1994

Mr. Michael V. Storms
Bonneville Power Administration
707 W. Main
Suite 500
Spokane, Washington 99201

Re: BPA Feeder Outage Restoration Load Project

Dear Mike:

Following are some comments relative to this project.

I feel the step voltage (STEPV) tests worked well and could easily be done on other feeders on the system. I don't recall us having any major problems in conducting those tests. The Appleway Feeder was monitored with "load loggers" to determine load profiles, and hopefully to catch an actual outage and resulting cold load pick up. Only one cold load pick up (CLPU) was captured which resulted in limited data. However, there were a few planned outages on this feeder. Better planning on my part would have allowed information to be gathered following load restoration from those outages.

We have the draft software loaded and I have "played" with it a little. I have not varied parameters, but assume it could be used for new STEPV tests or actual CLPU events which might be captured.

At this point, I am having some difficulty in visualizing the transition between experimental results and practical applications. We have had problems with CLPU and have restored feeders in stages as a result, but have not had problems with stressing equipment. However, I can see that if we had predictions of inrush current magnitudes and duration by feeder, it would be information that could allow us to manage our system with more confidence.

Early on, an effort was made to organize a utility advisory group to help guide the project. Although some utilities expressed interest, actual participation by those utilities was never achieved. This type of group would be very helpful in determining how the project results could be structured for practical applications, since a variety of operating experiences would be available.

Future work could involve STEPV tests on a variety of different type feeders. I feel more work needs to be done on analyzing type and location of various loads on the feeders in conjunction with the STEPV tests. Most of the new subdivisions in our service area have gas heat. Feeders with those subdivisions would be expected to have different CLPU characteristics than those with all electric loads. More effort should also be made to obtain actual CLPU data from real outages.

Sincerely,

A handwritten signature in cursive script, reading "Don Minford". The signature is written in dark ink and is positioned above the printed name.

Don Minford, P.E.
System Engineer

FINAL PROJECT REPORT
ANALYTICAL TOOLS to PREDICT
DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

CONTENTS

	page
Project Summary	i
Project Objective	
Project Results	
Conclusions	
Recommendations	
Comments by Kootenai Electric Cooperative	ii
Project Overview	1
Instrumentation	3
Field Measurements	3
Modeling Methods	
Harmonic Model	5
Cold Load Pickup Algorithm	10
Step Voltage Test Algorithm	10
Feeder Parameters	15
Correlation of Field and Model Results	16

APPENDIX

List of Diskette Deliverables	Appendix A	17
MathCAD Software	Appendix B	18
Procedure for Estimating Feeder Parameters from STEPV Field Test Data	Appendix C	21
IEEE Paper	Appendix D	72

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

PROJECT OVERVIEW

Time Schedule

The Bonneville Power Administration (hereafter BPA), in response to a proposal from the University of Idaho Electrical Engineering Department (hereafter UIEE), granted this Service Contract No. DE-B179-92BP27938 to UIEE for the budget period from 21Jan92 to 1Sept93. Because of good(!) weather in winter 92/93 and no Cold Load Pickup (hereafter CLPU) on the feeder selected for instrumentation, the contract was extended twice to 15Sept94. Most of the analysis and writing of computer software deliverables was done in summer 1994. UIEE project leader illness in early Fall 1994 delayed completion of this final report.

Activity

The main activity of this project has been twofold: (1) development of a computer model to predict CLPU and (2) development of a field measurement and analysis method to obtain the input parameters of the CLPU model. The field measurement and analysis method is called the Step-Voltage-Test (hereafter STEPV).

The Kootenai Electric Cooperative (hereafter KEC) Appleway 51 feeder in Coeur d'Alene was selected for analysis in this project and STEPV tests were performed in winters of 92 and 93. The STEPV data was analyzed (method and results presented within this report) to obtain the Appleway 51 feeder parameters for prediction by the CLPU model. One only CLPU record was obtained in winter 1994. Unfortunately (for the project) the actual CLPU was not dramatic (short outage and moderate temperature) and did not display cyclic restoration current. (Appleway 51 feeder has since been modified with Coeur d'Alene load growth).

A predicted Appleway 51 feeder CLPU was generated using the parameters obtained via the STEPV measurement/analysis/algorithm method at the same ambient temperature and outage duration as the measured actual CLPU. The predicted CLPU corresponds reasonably well with the single actual CLPU data obtained in winter 1994 on the Appleway 51 feeder. Theory and results were published at the IEEE Power Engineering Society 1994 Summer Meeting. A copy of the paper is given in the Appendix of this report.

Budget

The two project extensions were no-cost. The project was completed within the original budget of \$51,543.00. No purchased items exceeded \$5,000.00. By agreement with BPA, hardware will be retained by UIEE. One of two major items, the "Load Loggers", presently reside at KEC in anticipation of possible future cooperative work. The other major item, the SEL251 Relay (assembly including modem, cellular phone, power supplies and wiring for substation CT and VT connection) measurement unit fabricated by UIEE, is presently located at the University for EE senior and graduate student project use.

PROJECT OVERVIEW, continued

Deliverables

Deliverables, in addition to this final report, are four diskettes of field data, programs and results. The labeled diskettes are briefly described and listed in Appendix A.

FUTURE WORK

Larry Elliott, UIEE grad student and participant in this project, has proposed as his MSEE thesis a continuation of this work. Larry recently received CLPU data from the Idaho Power Company that clearly shows the "wiggles" (cyclic feeder restoration current) predicted by the harmonic model that was developed in this BPA project. Larry hopes to apply the STEPV concept to the IPCO feeder and improve and further verify the method. Outcome of this work will be made available to BPA. Work continues in the UIEE Senior Design course to expand the memory capability and flexibility of the SEL251 based data acquisition assembly.

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

INSTRUMENTATION

Load Loggers

The "workhorse" instrument in this project is the set of Rochester Instrument Systems, Inc., RIS, "Load Loggers" (RIS Model LL-230) purchased as part of the service contract funds. The "loggers" are three (one per each phase) electronic battery operated line-mounted digital current recorders. The loggers are "hot-stick" installed by a lineman on the live distribution lines. Each logger has a large LCD digital display of measured current that can be observed from the ground when mounted on a feeder.

Loggers sample sensed current every 16 seconds by a crystal controlled clock. these samples are averaged and stored in a non-volatile memory at selectable 1 minute or 15 minute intervals. In the BPA project, loggers were set to 1 minute recording interval during the winter months in anticipation of a CLPU event. At the 1 minute setting, four days of data may be collected, after which old data "spills" out of the memory making room for new data. During the other months, the loggers were set to the 15 minute interval in order to obtain load profile data to help in the estimation of NWS and WS load ratios.

An RIS "Computer Interface Adapter", CIA, unit is supplied with the loggers. The CIA interfaces with a PC and enables setting the record interval and the logger clock to match PC time. The CIA enables downloading of logger recorded data to the PC and also provides a logger battery test feature.

A logger calibration apparatus was designed and built by UIEE and used to test and calibrate the loggers before field installation. KEC provided line crew installation and retrieval of the loggers. KEC also downloaded the logger and made and shipped floppy disk copies of the data to UIEE. UIEE, using "Loadsoft", reviewed the data and transported data for spread sheet "massaging" as discussed in the Appendix C procedure for STEPV data. RIS "Loadsoft", LS, software is also included with the loggers package. "LS" reads and interprets logger collected current data. LS enables PC viewing of each phase of feeder current and changes the data format for transport to spreadsheet (LOTUS123 at UIEE). Example "LS" plots of logger current data obtained by PC "screenprint" command are given in Appendix C pages C41 and C42.

SEL251 Data Acquisition Unit

A portable data acquisition unit enclosing an SEL251 distribution relay, cellular phone, modem, power supplies and wiring arrangement for ready connection to substation CTs and VTs was designed and fabricated by UIEE. The unit enabled remote monitoring of the KEC Appleway feeder for voltage, current, P and Q. The unit also indicated relay feeder events.

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

FIELD MEASUREMENTS

Field measurement of the KEC Appleway 51 feeder was conducted near continuously as soon after the award of the BPA contract as the RIS Logger units could be purchased and calibrated. The first installation of the loggers on the Appleway feeder was March 1992 at one minute record interval for the initial STEPV tests discussed in this report. The loggers remained on the feeder for two days and were then retrieved, interrogated and rehung on the feeder by KEC in hopes of catching a CLPU. The loggers were removed and set to 15 minute record interval after the winter season in order to obtain load profile information.

STEPV tests were performed on Appleway 51 feeder again the following winter. Consideration of the earlier STEPV test results and the model indicated that the ideal ambient temperature was that temperature at which the ON and OFF times of the feeder mean parameters heating unit were approximately equal. At that temperature, about 10 degrees above zero fahrenheit, the model predicted the maximum "swing" of post STEPV current and best accuracy of parameter determination. At high ambient temperature, the OFF time predominates and there is little response. At low ambient temperature, the ON time is long and OFF time short with little differential in heating unit response.

Only one CLPU as reported herein was captured on Appleway during the project. (Unfortunately one other CLPU took place during the course of the project, but the loggers were at the KEC office for downloading at the time of the event!).

As stated in the summary relative to future work, an UIEE MSEE student is continuing the CLPU work and has been able to obtain SCADA field information from the IDAHO power Company that holds promise. One event shows the cyclic restoration current predicted by the HARMONIC MODEL.

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

MODELING METHODS

Harmonic Model

This section describes the theory and mathematical model of the Cold Load Harmonic Model, CLHARM, algorithm for simulation of electric power distribution feeder Cold Load Pickup, CLPU. With modifications, the algorithm may also be used to calculate feeder response to a step voltage change, STEPV. Field application of the STEPV procedure produces data similar to CLPU, the analysis of which provides the CLHARM parameters required for CLPU simulation.

A copy of the IEEE Transactions paper "MEASURED AND PREDICTED COLD LOAD PICK UP AND FEEDER PARAMETER DETERMINATION USING THE HARMONIC MODEL ALGORITHM" is attached and provides an introduction to the CLHARM, including presentation of field measured results of the application of CLHARM and STEPV to a feeder of the Kootenai Electric Cooperative, Hayden, Idaho. This document provides additional detailed description of CLHARM, assuming the reader has obtained the introductory understanding contained in the IEEE paper.

MODEL CONCEPT

All feeder current is assumed to be composed of two parts:

NWS - Non-Weather Sensitive load that is assumed to be constant. NWS magnitude is based on ambient temperature information available through the National Weather Service for the geographic area and obtained from historical load data for the time of day and day of week at interest.

WS - Weather Sensitive load that is assumed to have the following three components:

1. WSAVG - Weather Sensitive Average current that is a function of ambient temperature.
2. "Cy" - Exponentially Decaying Sinusoidal current that is a function of the outage duration and time (time incremented in minutes, y).
3. "XDCAYy - Transient exponentially increasing current that models build up of weather sensitive current akin to central electric heating unit time delays that energize heating elements successively in time.

Thus all feeder weather sensitive, WS, load is lumped in CLHARM as thermostatically controlled electric space heating. All electric thermostatically

Harmonic Model, continued

controlled heating units are assumed to have the identical parameters (N, Q, R, C, TU AND TLOW defined below) as those of the "mean" unit.

The crux of the CLHARM model concept is the pair of equations (18) and (19). COSAy, equation (18), models one-half of the electric heating units by means of an on/off wave of the periodicity of the mean heating unit. COSBy, equation (19), models the other one-half of the electric heating units, but is in-time phase shifted from COSAy as a function of the outage duration and ambient temperature (please note Fig. 5 and discussion of the IEEE paper). The sum of the average values of COSAy and COSBy equals WS, the WS average value. In time, as load diversity is regained after reclosure, the phase angle between COSAy and COSBy approaches 180 degrees.

INPUTS

There are four input categories for the CLHARM model:

A. Ambient temperature (TAMB) and outage duration (OUTDUR)

B. Mean House Parameters -

1. Number of heating units (houses), N
2. Per unit heating capacity (based on 20 KW), Q
3. Per unit thermal resistance (based on xxxxxxxxx), R
4. Per unit thermal capacitance (based on xxxxxxxxx), C
5. Thermostat set point (upper, deg F), TU
6. Thermostat lower break point (deg F), TLOW
7. Base Temperature, TBASE = 70 deg F

C. Feeder Parameters -

1. Per Unit voltage (based on 13.8 KV line), V
2. Feeder base current, IBASE = 2.51 (CALCULATE LATER!)
3. Non-Weather Sensitive current (from company data), INWS

d. Harmonic Model Parameters -

1. Cosine diversity recovery outage magnitude factor, KE
2. Cosine diversity recovery temperature magnitude factor, KT
3. Cosine diversity recovery time decay factor, KCOS
4. XDCAy time decay factor, KOFF
5. WS transient component saturation factor, STF
6. WS transient component saturation coefficient, beta
7. Long outage transition smoothing factor. SMF

EQUATIONS

Please refer to pages 11 to 14 of this document for the "MathCAD" form of the CLHARM model equations by equation number in the following discussion.

Harmonic Model, continued

Equation 1 Z defines the number of data points (time and current) of in a field obtained CLPU record to be read by the program. The file to be read is named ACLP and is read by equation (5), defined below.

Equation 2 "y" is the number of one minute interval steps in the solution of the CLHARM equations.

Equation 3 converts the solution time "y" into hours, ty. The CLHARM equations are in time units of hours.

Equation 4 converts the outage duration time OUTDUR, an input in minutes, into units of hours, OUT.

Equation 5 dMIWSy reads the file named ACLP of measured current variation vs time of a field obtained actual CLPU for comparison with the CLHARM model predicted current vs time.

Equation 6 "t" is the thermal time constant, R times C, in hours of the mean house thermal model.

Equation 7 ON is the on time in hours of the on/off cycle of the mean house at the input ambient temperature.

Equation 8 OFF is the off time in hours of the on/off cycle of the mean house at the input ambient temperature.

Equation 9 PER is the time period in hours (sum of ON plus OFF) of the on/off cycle of the mean house at the input ambient temperature.

Equation 10 WSAVG is the WS average per unit feeder current in which N*Q is the maximum WS current with all units on.

Equation 11 w is the radian frequency of PER, the time period in hours of the on/off cycle of the mean house at the input ambient temperature.

Equation 12 MWSy is the sum of the measured variation in WS current plus the WSAVG current, in per unit.

Equation 13 E establishes the magnitude of the time varying components of the COSAy and COSBy portions of the calculated per unit WS current variation. E is a function of five parameters - OUTDUR, TU, TAMB and Harmonic Model constants KE and KT.

Equation 14 LTP in degF is the lowest temperature reached by a house during the outage and just prior to reclosure. LTP is used by equation (15) to obtain the time duration during which all units are on following an outage that is longer than the OFF time of the mean house.

Harmonic Model, continued

Equation 15 ALLON is the time duration in hours during which all units are on following an outage that is longer than the mean house OFF time.

Equation 16 CC determines the magnitude of the time varying components of the COSAy and COSBy portions of the calculated per unit WS current variation. CC is a sinusoidal function of ON and PER. For high ambient temperature (low WSAVG), the WS variation will be small. For low ambient temperature (high WSAVG approaching $N*Q$), the WS variation will also be small. For some ambient temperature between those extremes ($WSAVG = 1/2 * N*Q$), the WS variation will have its maximum value - thus approaching a sinusoidal variation in the peak magnitudes of the COSAy and COSBy.

Equation 17 If the ALLON calculated by equation (17) is negative, (the OUTAGE is less than the OFF time), ALLON is set to zero. This prevents a problem with the difference in long and short outage calculations.

Equation 18 COSAy models 50% of the WS units (the "A" group) is a function of TIME, the Harmonic Model constant KCOS, and of E, CC, N, Q and the factor $4/\pi$, which is the magnitude of the fundamental (first harmonic) Fourier component of the square waves that mode the WS variation of house groups A and B. Likewise, COSBy models 50% of the WS units (the "B" group). COSAy is time phase shifted ahead and COSBy is time phase shifted behind by the exponentially time varying factor involving factors E and KCOS.

Equation 19 (See Equation (18)).

Equation 20 For convenience in programming, Cy is defined as the sum of COSAy and COSBy.

Equation 21 WSy is the sum of the time varying and WSAVG components of the WS per unit current.

Equation 22 "a" is a coefficient used to "clip" the WSy variation and is utilized in Equations (23) and (24). This procedure recognizes that with all units on following a long outage, the WSy variation plus the WSAVG currents cannot exceed $N*Q$. "a" is a function of WSy, $N*Q$ and the Harmonic Model constant STF. STF, the "saturation factor" is set at 0.9.

Equation 23 In conjunction with Equation (24), CLPDWSy limits the magnitude of the time variation in WSy to less than $N*Q$ in the region in which WSy calculated by Equation (21) exceeds STF of $N*Q$.

Equation 24 If WSy as calculated by Equation (21) is less than STF of $N*Q$, then this equation sets WSy equal to the value calculated by Equation (21). If WSy calculated by Equation (21) exceeds STF of $N*Q$, then WSy is limited to less than $N*Q$ as set by CLPDWSy.

Equation 25 This equation sets ALLON to an integer value in order that the parameter SM, as determined by Equation (26), be an integer for

Harmonic Model, continued

calculation of factor LDF by equation (28).

Equation 26 SM defines the range in integral values of steps in minutes by which the recovery of diversity (decay of CLPU current) is "smoothed". SM is a function of SMF, the factor which sets the per cent of the ALLON range in which the long outage current response is "smoothed".

Equation 27 LDF is the difference between per unit current $ALLON = N*Q$ and the value of WSy at $y = SM$. Ldf sets the peak magnitude of the cosinusoidal transition from $N*Q$ to $WSAVG$ with a long outage CLPU response in the time region $SRGNy$ as determined by equation (32).

Equation 28 If LDF is less than zero as calculated by equation (27), LDF is set to zero by this equation. If positive, LDF retains the value calculated by equation (27)

Equation 29 If $ALLON$ is less than zero (short outage), then SM is set to zero. Else SM is set to an integer value as determined by the "smoothing factor" SMF as a function of $ALLON$ for the long outage.

Equation 30 $COSP$ is a constant and a function of both $ALLON$ and SM which establishes the period of the "smoothing cosine" transition per unit current for the CLPU response of a long outage. $COSP$ must not be zero to avoid division by zero in calculation of smooth region $SRGNy$. Thus the added very small value to $COSP$.

Equation 31 Ry is the time region of per unit current $SRGNy$.

Equation 32 $SRGNy$ is the per unit current transition from $N*Q$ to $WSAVG$ as the WS current for a long outage.

Equation 33 $XDCAY0$ is the initial magnitude of the transient component of per unit WS CLPU current that requires current to start at zero at reclosure. For a long outage ($ALLON$ greater than zero), $XDCAY0$ is the negative of $N*Q$. Else $XDCAY0$ is the negative of the WS current at time zero.

Equation 34 $NQYy$ sets the WS current for a long outage equal to $N*Q$ for the time region set by $ALLON$ and the smoothing factor region SM .

Equation 35 $XDCAYy$ is the WS per unit current during the initial transient and applies to both long and short outages.

Equation 36 $IIWSy$ is the total CLPU current in amperes. For a short outage, $IIWSy$ is the sum of $XDCAYy$ and WSy in their time regions. For a long outage, $IIWSy$ is the sum of $XDCAYy$, $NQYy$, $SRGNy$ and WSy in their time regions.

Equation 37 If $IIWSy$ as calculated by equation (36) is less than $N*Q*IBASE$, then $IWSy$ is set equal to the current in amperes calculated by

Harmonic Model, continued

equation (37). It is possible in some situation using the CLHARM algorithm, that total WS calculated current may exceed the maximum value of $N*Q$ during the recovery of diversity. Total WS current is limited to a maximum of $N*Q$ by this equation.

Equation 38 ITOTy is the CLPU current, the sum of the total WS current and NWS current in amperes.

Cold Load Pickup, CLPU, Algorithm

The CLPU algorithm was initially developed in MathCAD. A listing of the present MathCAD version of CLPU is given in Appendix B. The MathCAD corresponding file is part of the deliverables and is contained on Diskette D. MathCAD software is of course necessary to read and run the MathCAD CLPU file.

The C++ Windows software of Diskette A (part of the deliverables) utilizes the MathCAD file algorithm with some minor changes for C++ implementation. This would hopefully be available for customer utilities application in the future.

Step Voltage, STEPV, Algorithm

The STEPV algorithm was also, like CLPU, initially developed in MathCAD. A listing of the present MathCAD version of STEPV is given in Appendix B. The MathCAD corresponding file is part of the deliverables and is also contained on Diskette D. MathCAD software is of course necessary to read and run the MathCAD STEPV file.

The C++ Windows software of Diskette B (part of the deliverables) utilizes the MathCAD file algorithm with some minor changes for C++ implementation. This would hopefully be available for customer utilities application in the future.

The STEPV utilizes the same basic Harmonic Model algorithm on which CLPU is built. The primary difference is that CLPU requires the outage duration, whereas STEPV requires the change in voltage. STEPV calculates the new average current per heating unit, Q_{new} , and uses that value to determine the initial phase angle (ALPHA) relationship between the COSA and COSB "harmonic components" of the weather sensitive, WS, load.

Inputs

Ambient Temperature & Outage Duration in Minutes

TAMB := 28 OUTDUR := 25

Mean House Parameters & Feeder Characteristics:

N := 65 Q := 1 R := 2.3 C := 9.006 TU := 70 TLOW := 68
 IBASE := 2.51 TBASE := 70 V := 1 INWS := 152

Harmonic Model Parameters:

KE := 10 KT := 6 KCOS := 6 KOFF := 50 STF := 0.9 β := 0.9 SMF := 0.4

Feeder Measured CLPU Input, Model Index & Minute/Hour Conversion

(1) Z := 147

(2) Y := 0 .. (Z - 1)

(3) $t := \frac{Y}{60}$ (4) OUT := $\frac{\text{OUTDUR}}{60}$ (5) $\delta \text{MIWS} := \frac{\text{READ(ACLP)}}{Y}$

Harmonic Model Equations

(6) $\tau := R \cdot C$

$$(7) \quad \text{ON} := -R \cdot C \cdot \ln \left[\frac{\frac{\text{TU} - \text{TAMB}}{\text{TBASE}} - Q \cdot R}{\frac{\text{TLOW} - \text{TAMB}}{\text{TBASE}} - Q \cdot R} \right]$$

$$(8) \quad \text{OFF} := -R \cdot C \cdot \ln \left[\frac{\text{TLOW} - \text{TAMB}}{\text{TU} - \text{TAMB}} \right]$$

(9) PER := ON + OFF

$$(10) \quad \text{WSAVG} := N \cdot Q \cdot \left[\frac{\text{ON}}{\text{PER}} \right]$$

$$(11) \quad \omega := 2 \cdot \frac{\pi}{\text{PER}}$$

$$(12) \quad \text{MWS}_Y := \frac{\delta \text{MIWS}_Y}{\text{IBASE}} + \text{WSAVG}$$

$$(13) \quad E := \left[1 - e^{-(\text{OUT} \cdot \text{KE})} \right] \cdot \left[1 - e^{-\left[\frac{\text{TU} - \text{TAMB}}{\text{TU}} \cdot \text{KT} \right]} \right]$$

$$(14) \quad \text{LTP} := \text{TAMB} + (\text{TU} - \text{TAMB}) \cdot e^{-\left[\frac{\text{OUT}}{\tau} \right]}$$

$$(15) \quad \text{ALLON} := -\tau \cdot \ln \left[\frac{\frac{\text{TLOW} - \text{TAMB}}{\text{TBASE}} - Q \cdot R}{\frac{\text{LTP} - \text{TAMB}}{\text{TBASE}} - Q \cdot R} \right] \cdot 60$$

$$(16) \quad \text{CC} := \sin \left[\frac{\text{ON} \cdot \pi}{\text{PER}} \right] \cdot \frac{1}{2}$$

$$(17) \quad \text{ALLON} := \text{if}(\text{ALLON} > 0, \text{ALLON}, 0)$$

$$(18) \quad \text{COSA}_Y := \frac{\text{CC} \cdot \text{N} \cdot Q}{1 \cdot V} \cdot \cos \left[\omega \cdot t_Y + \frac{\pi}{2} - \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right] \cdot \frac{4}{\pi}$$

$$(19) \quad \text{COSB}_Y := \frac{\text{CC} \cdot \text{N} \cdot Q}{1 \cdot V} \cdot \cos \left[\omega \cdot t_Y - \frac{\pi}{2} + \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right] \cdot \frac{4}{\pi}$$

$$(20) \quad \text{C}_Y := \text{COSA}_Y + \text{COSB}_Y$$

$$(21) \quad \text{WS}_Y := \text{C}_Y + \text{WSAVG}$$

$$(22) \quad \alpha_Y := \text{STF} - \frac{\text{WS}_Y}{\text{N} \cdot Q}$$

$$(23) \quad \text{CLPDWS}_Y := \text{STF} \cdot \text{N} \cdot Q + (1 - \text{STF}) \cdot \text{N} \cdot Q \cdot \left[\left[\left[1 - e^{\alpha_Y} \right] \right] \right]^\beta$$

- (24) $WS_Y := \text{if} \left[WS_Y < STF \cdot N \cdot Q, WS_Y, CLPDWS_Y \right]$
- (25) $ALLON := \text{ceil}(ALLON)$
- (26) $SM := \text{ceil}((1 - SMF) \cdot ALLON)$
- (27) $LDF := N \cdot Q - \frac{WS}{SM}$
- (28) $LDF := \text{if}(LDF < 0, 0, LDF)$
- (29) $SM := \text{if}(ALLON < 0, 0, \text{ceil}((1 - SMF) \cdot ALLON))$
- (30) $COSP := \frac{ALLON - SM}{15}^{-5} + 10$
- (31) $R_Y := \Phi(Y - SM) \cdot (1 - \Phi(Y - (2 \cdot ALLON - SM)))$
- (32) $SRGN_Y := \frac{LDF}{2} \cdot \left[1 + \cos \left[\frac{2 \cdot \pi}{COSP} \left[t_Y - \frac{SM}{60} \right] \right] \right] \cdot R_Y$
- (33) $XDCAY0 := \text{if} \left[ALLON > 0, -N \cdot Q, -WS_0 \right]$
- (34) $NQQ_Y := N \cdot Q \cdot (1 - \Phi(Y - SM)) \cdot e^{-t_Y \cdot KOFF}$
- (35) $XDCAY_Y := XDCAY0 \cdot e^{-t_Y \cdot KOFF}$
- (36) $IIWS_Y := \left[XDCAY_Y + NQQ_Y + SRGN_Y + WS_Y \cdot \Phi(Y - SM) \right] \cdot IBASE$
- (37) $IWS_Y := \text{if} \left[IIWS_Y < N \cdot Q \cdot IBASE, IIWS_Y, N \cdot Q \cdot IBASE \right]$
- (38) $ITOT_Y := IWS_Y + INWS_Y$

Plotting Definitions:

$$\text{ITOT} := \text{INWS} + \text{IWS} \quad \text{M} := \text{MWS} \cdot \text{IBASE} \quad \text{NN} := \text{N} \cdot \text{Q} \cdot \text{IBASE} \quad \text{T} := \text{M} + \text{INWS}$$

Output Plots & Calculated Values:

ON = 0.345	OFF = 1.011	PER = 1.356	OFF · 60 = 60.64	OUTDUR = 25
$\tau = 20.714$	WSAVG = 16.551	$\omega = 4.634$	E = 0.958	ALLON = 0
LTP = 69.164	CC = 0.359	SM = 0	LDF = 4.745	COSP = 0
				XDCAY0 = -60.26

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

FEEDER PARAMETERS

The "Harmonic Model" algorithm, as discussed in the previous section of this report, Modeling Methods, is based on the following parameters:

Feeder

N	number of heating units or houses on the feeder
Q	average current at feeder voltage of average unit
R	mean thermal resistance of a heating unit
C	mean thermal capacitance of a heating unit
Tupper	mean value of thermostat set point
Tlower	lower thermostat point (assumed to be two degrees fahrenheit, but changeable as a program constant)

Ambient

NWS	Non weather sensitive load at time of CLPU from utility historical load data and weather bureau temperature statistics
TEMP	ambient temperature at time of outage
OUTDUR(CLPU)	outage duration
delV(STEPV)	step voltage change in feeder voltage

Constants

Several constants are also included in the model that are functions of the individual feeder characteristics, "feeder signature". These constants are defined in the IEEE paper, Appendix D.

Units and typical values with example are given in the Appendix C presentation, "Procedure for Estimating Feeder Parameters from STEPV Field Test Data."

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

CORRELATION OF FIELD AND MODEL RESULTS

The IEEE paper of Appendix D, "MEASURED AND PREDICTED COLD LOAD PICKUP AND FEEDER PARAMETER DETERMINATION USING THE HARMONIC MODEL ALGORITHM, presents the correlation of field and model predicted results for the single CLPU obtained in the duration of this project.

The CLPU obtained in this project and described in the paper, occurred late on a weekday afternoon at an ambient temperature of about 28 degrees fahrenheit. The outage duration was about 25 minutes. Thus a "non-dramatic" CLPU was recorded that did not exhibit the cyclic restoration current that would have been discernable had the outage been longer and/or the ambient temperature been lower.

Nevertheless, the shape and current and time magnitudes agree fairly well with the model predicted restoration current.

As stated in the project summary, additional CLPU data from other feeders and under various outage/duration values are desirable in order to further verify and refine the harmonic model and software evolved in this project.

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT
DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

APPENDIX A

List of Diskette Deliverables

DISKETTE

DISKETTE LABEL

Software to simulate both CLPU and STEPV: object code in C++ and windows version executable code	A
RIS Loadsoft "LS" software for setting RIS "Load Loggers through RIS interface unit, downloading Load Logger field data, and viewing/graphing/ outputting field data	B
MathCAD and LOTUS123 files: MathCAD harmonic models for CLPU and STEPV; LOTUS 123 spreadsheet files of actual the STEPV and CLPU data obtained in this project and discussed in this report	C
Raw field data of actual the STEPV and CLPU data obtained in this project and discussed in this report	D

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

APPENDIX B

Listing of MathCAD files and other files referred to in the report and/or contained in the diskette deliverables as appropriate.

<u>FILE</u>	<u>Page</u>
MathCAD version of CLPU (See description, page 10)	B1
MathCAD version of STEPV (See description, page 10)	B2

CLPU MathCAD model Z := 147 y := 0 .. (Z - 1) $\delta\text{MIWS}_Y := \text{READ}(\text{ACLP})$

N := 65 Q := 1 R := 2.3 C := 9.006 TU := 70 TLOW := 68 t := $\frac{y}{60}$

KE := 10 KT := 6 KCOS := 6 KOFF := 50

IBASE := 2.51 TBASE := 70 V := 1 INWS := 152 $\tau := R \cdot C$ y

STF := 0.9 $\beta := 0.9$ SMF := 0.4

$$\text{ON} := -R \cdot C \cdot \ln \left[\frac{\frac{TU - TAMB}{TBASE} - Q \cdot R}{\frac{TLOW - TAMB}{TBASE} - Q \cdot R} \right] \quad \text{OFF} := -R \cdot C \cdot \ln \left[\frac{TLOW - TAMB}{TU - TAMB} \right] \quad \text{OUT} := \frac{\text{OUTDUR}}{60}$$

$$\text{PER} := \text{ON} + \text{OFF} \quad \text{WSAVG} := N \cdot Q \cdot \left[\frac{\text{ON}}{\text{PER}} \right]$$

$$\omega := 2 \cdot \frac{\pi}{\text{PER}}$$

$$E := \left[1 - e^{-(\text{OUT} \cdot \text{KE})} \right] \cdot \left[1 - e^{-\left[\frac{TU - TAMB}{TU} \cdot \text{KT} \right]} \right] \quad \text{MWS}_Y := \frac{\delta\text{MIWS}_Y}{\text{IBASE}} + \text{WSAVG}$$

$$\text{LTP} := TAMB + (TU - TAMB) \cdot e^{-\left[\frac{\text{OUT}}{\tau} \right]} \quad \text{ALLON} := -\tau \cdot \ln \left[\frac{\frac{TLOW - TAMB}{TBASE} - Q \cdot R}{\frac{\text{LTP} - TAMB}{TBASE} - Q \cdot R} \right] \cdot 60$$

$$\text{CC} := \sin \left[\frac{\text{ON} \cdot \pi}{\text{PER}} \right] \cdot \frac{1}{2} \quad \text{ALLON} := \text{if}(\text{ALLON} > 0, \text{ALLON}, 0)$$

$$\text{COSA}_Y := \frac{\text{CC} \cdot N \cdot Q}{1 \cdot V} \cdot \cos \left[\omega \cdot t_Y + \frac{\pi}{2} - \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right] \cdot \frac{4}{\pi}$$

$$\text{COSB}_Y := \frac{\text{CC} \cdot N \cdot Q}{1 \cdot V} \cdot \cos \left[\omega \cdot t_Y - \frac{\pi}{2} + \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right] \cdot \frac{4}{\pi}$$

$$C_Y := \text{COSA}_Y + \text{COSB}_Y \quad \text{WS}_Y := C_Y + \text{WSAVG}$$

$$\alpha_Y := \text{STF} - \frac{\text{WS}_Y}{N \cdot Q} \quad \text{CLPDWS}_Y := \text{STF} \cdot N \cdot Q + (1 - \text{STF}) \cdot N \cdot Q \cdot \left[\left[1 - e^{\alpha_Y} \right] \right]^\beta$$

$$\text{WS}_Y := \text{if} \left[\text{WS}_Y < \text{STF} \cdot N \cdot Q, \text{WS}_Y, \text{CLPDWS}_Y \right]$$

10X03 ALLON := ceil(ALLON)

SM := ceil((1 - SMF) · ALLON)

LDF := N · Q - WS
SM

LDF := if(LDF < 0, 0, LDF)

SM := if(ALLON < 0, 0, ceil((1 - SMF) · ALLON))

COSP := $\frac{ALLON - SM}{15} + 10^{-5}$

R := $\phi(y - SM) \cdot (1 - \phi(y - (2 \cdot ALLON - SM)))$

SRGN_y := $\frac{LDF}{2} \cdot \left[1 + \cos \left[\frac{2 \cdot \pi}{COSP} \cdot \left[t - \frac{SM}{60} \right] \right] \right] \cdot R$

XDCAY0 := if[ALLON > 0, -N · Q, -WS
0]

NQQ_y := N · Q · (1 - $\phi(y - SM)$)

XDCAY := XDCAY0 · e^{-t · KOFF_y}

IIWS_y := $\left[XDCAY_{y} + NQQ_{y} + SRGN_{y} + WS_{y} \cdot \phi(y - SM) \right] \cdot IBASE$

IWS_y := if[IIWS_y < N · Q · IBASE, IIWS_y, N · Q · IBASE]

ITOT_y := IWS_y + INWS_y

ITOT_y := INWS_y + IWS_y

M_y := MWS · IBASE

NN := N · Q · IBASE

T_y := M_y + INWS_y

IWS_y, N · Q, WS_y, $\frac{y}{IBASE}$, MWS_y, SRGN_y

ALLON = 0
OFF · 60 = 60.64

NN_y, IWS_y, M_y, ITOT_y, T_y

TAMB = 28
OUTDUR = 25

MathCAD model for STEPV, Step Voltage Test

$$y := 0 \dots 20$$

$$t_y := \frac{y}{10}$$

$$N := 100 \quad Q := 1 \quad R := 2.2 \quad C := 7.5 \quad \text{TAU} := R \cdot C \quad \text{KCOS} := 3$$

$$\text{TU} := 67.2 \quad \text{TLOW} := 65.2 \quad \text{TBASE} := 70 \quad \text{KOFF} := 8 \quad \text{KPK} := 0.2$$

$$\text{ONTIMOLD} := -R \cdot C \cdot \ln \left[\frac{\frac{\text{TU} - \text{TAMB}}{\text{TBASE}} - Q \cdot R}{\frac{\text{TLOW} - \text{TAMB}}{\text{TBASE}} - Q \cdot R} \right] \quad \text{OFFTIM} := -R \cdot C \cdot \ln \left[\frac{\text{TLOW} - \text{TAMB}}{\text{TU} - \text{TAMB}} \right]$$

$$\text{PERIODOLD} := \text{ONTIMOLD} + \text{OFFTIM}$$

$$\text{OMEGAOLD} := 2 \cdot \frac{\pi}{\text{PERIODOLD}}$$

$$\text{WSAVG} := N \cdot Q \cdot \left[\frac{\text{ONTIMOLD}}{\text{PERIODOLD}} \right] \quad \text{IOLDAVG} := \frac{\text{WSAVG}}{V}$$

$$\text{IINIT} := \frac{V + \delta V}{V} \cdot \text{IOLDAVG}$$

$$Q_{\text{NEW}} := Q \cdot \left[\frac{(V + \delta V)^2}{V} \right]$$

$$\text{ONTIMNEW} := -R \cdot C \cdot \ln \left[\frac{\frac{\text{TU} - \text{TAMB}}{\text{TBASE}} - Q_{\text{NEW}} \cdot R}{\frac{\text{TLOW} - \text{TAMB}}{\text{TBASE}} - Q_{\text{NEW}} \cdot R} \right]$$

$$\text{PERIODNEW} := \text{ONTIMNEW} + \text{OFFTIM}$$

$$\text{INEWAVG} := \frac{\text{WSAVG}}{V + \delta V} \quad \text{OMEGANEW} := 2 \cdot \frac{\pi}{\text{PERIODNEW}}$$

$$\text{CC} := \sin \left[\frac{\text{ONTIMNEW}}{\text{PERIODNEW}} \cdot \pi \right] \quad \text{E} := \frac{\text{PERIODOLD} - \text{PERIODNEW}}{\text{PERIODNEW}}$$

$$\text{ICOSA}_y := \left[\frac{\text{KPK} \cdot \text{CC} \cdot N \cdot Q}{V + \delta V} \right] \cdot \cos \left[\text{OMEGANEW} \cdot t_y + \frac{\pi}{2} - \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_y} \right]$$

$$\text{ICOSB}_y := \left[\frac{\text{KPK} \cdot \text{CC} \cdot N \cdot Q}{V + \delta V} \right] \cdot \cos \left[\text{OMEGANEW} \cdot t_y - \frac{\pi}{2} + \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_y} \right]$$

$$\text{COSINIT} := \left[\frac{\text{KPK} \cdot \text{CC} \cdot N \cdot Q}{V + \delta V} \right] \cdot \cos \left[\frac{\pi}{2} - \frac{\pi}{2} \cdot E \right]$$

$$\text{OFFSETINIT} := \text{IINIT} - \text{INEWAVG} - 2 \cdot \text{COSINIT} \quad -t_y \cdot \text{KOFF}_y$$

$$\text{IOFFSET}_y := \text{OFFSETINIT} \cdot e^{-t_y \cdot \text{KOFF}_y}$$

$$\text{IWS}_y := \text{INEWAVG}_y + \text{ICOSA}_y + \text{ICOSB}_y + \text{IOFFSET}_y$$

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

APPENDIX C

Procedure for Estimating Feeder Parameters for Prediction of CLPU from Data Obtained Using STEPV Field Test Data

This part of the final report and deliverables is a description of the procedure for estimating feeder parameters for prediction of CLPU (Cold Load Pickup) from data obtained using STEPV (Step Voltage) field test data. The procedure is demonstrated using actual STEPV data obtained on 7 March 1992 on the KEC (Kootenai Electric Cooperative) Appleway feeder in Hayden, Idaho. The parameters thus derived are utilized in the CLPU Harmonic Model and results compared with an outage restoration which occurred on that feeder on 20 January 1993. The description of the procedure utilizes the figures of the accompanying pages C1 through C42. A summary of the technique and comparison of results is given in the Jan 1994 IEEE Transactions paper, Appendix D of this report.

The procedure evolved in this project (service contract) by which the STEPV data is analyzed involves nine steps, each of which is detailed below.

Step 1 STEPV Field Measurement

Obtain STEPV current vs time (1 minute data points) on the three phases of subject feeder (KEC Appleway) with Rochester load loggers.

Step 2 Enter Field Data into Computer for Processing

Download logger data to UIEE/KEC computer via Rochester interface software ("LS" or "LOADLOG").

Step 3 Edit Raw Data

Edit raw data ("EDLIN" at UIEE) for transfer to spreadsheet for manipulation. Estimate period of fundamental WS (Weather Sensitive) current variation of a) pre-STEPV un-diversity caused by changing ambient temperature and b) STEPV caused un-diversity.

Step 4 Analyze Data to Obtain WS (Weather Sensitive) Components

Import edited data to spreadsheet ("LOTUS" at UIEE) for averaging and differencing to estimate WSAVG (WS average) and WS time varying components. Create output data file for time region of interest.

Step 5 Obtain Harmonic Components of WS Data

Read WS time varying data file prepared by spreadsheet to ""MathCAD" Harmonic Model" program. FFT (fast Fourier transform) analyze the WS data file to obtain the fundamental and harmonic component ratios.

Step 6 Determine Mean ON and OFF Times

Determine the ON time to PERIOD ratio of the mean thermostatically controlled electric heating unit on/off waveform that results in the same harmonic ratios as the actual data. This yields the ON time of the mean parameters values heating unit for Harmonic Model analysis.

Step 7 Pre-STEPV and STEP Diversity

Use the ""MathCAD" Fourier Analysis" model to estimate diversity and time/phase relationships of pre-STEPV and STEPV Harmonic Model currents. Compare with actual data.

Step 8 Estimate Mean Thermal Resistance and Capacitance

Estimate the mean heating unit parameter R (thermal resistance) and C (thermal capacitance) values from basic heat transfer calculations.

STEP 9 Compare Predicted with Measured CLPU

Use ""MathCAD" CLSIM" program based on the Harmonic Model using the feeder parameters obtained in step 8 above to predict CLPU (outage restoration load) for several values of ambient temperature and outage duration.

Discussion of Appleway 7 March 1992 STEPV Data Analysis

I. Phase "a", Appendix Pages C1-C12

- A. Pages C1 through C5 are plots respectively of measured current, pre-STEPV current, STEPV current, the time varying component of current, and the estimated fundamental harmonic component current superimposed on time varying component of current. The plots are obtained in procedure step 4 for the selected interval of load data.

The period of the fundamental wave (assumed to be weather sensitive load variation) of page C2 pre-STEPV current is about 94 minutes. Surprisingly long! This periodicity is evident prior to the time (not shown) of the plot of page C2. The sloping straight line is the estimate of the running average value of the current

The current waveform of page C3 following the STEPV increase in feeder voltage at 00:33 7March is postulated to be the superposition of the pre-STEPV and STEPV caused current variations as shown later in the reconstruction currents of the plot of page C12.

The estimated pre-STEPV fundamental component sine wave of page C5 corresponds well to the time varying actual current. However the estimated fundamental component sine wave of the STEPV caused waveform at 00:33 does not overlay (describe) the actual current. The reconstruction currents of the plot of page C12 indicate that the superposition of both the pre-STEPV and STEPV fundamental and their higher harmonics model the actual current, which is predominantly the second harmonic at a period of about 45 minutes.

- B. Page C6 is a MathCAD program to do FFT of the data file APAPRE of actual measured current achieved in steps 1 - 4 of the procedure. The "dc" level of 0.731 indicates that the averaging done in the step 4 could be better. The ratio of the fundamental to second harmonic is $2.822/1.295$ which establishes the ratio of the ON to PERIOD times of the mean heating unit waveform. The PERIOD estimate is 94 minute (! seems large, but is real data). Columns t_i and I_i are time (new reference required for FFT) and current in the pre-STEPV interval. U_k and k are the harmonic component magnitudes and harmonic number respectively.
- C. Page C7 is a MathCAD program to estimate the ON time. ON time "to" is guessed until the ratio of ON time to period is $2.822/1.295$. The ON time obtained for APAPRE data is 32.364 minutes. Again, as mentioned above, this appears to be long. Future confirming data and study of actual feeder loads are needed to confirm this result.
- D. Pages C8 through C12 are a MathCAD program utilizing the Harmonic Model concept to reconstruct (predict) the pre- and during STEPV current. The pre-STEPV current is modeled with two sinusoids, A and B and their second, third and fourth harmonics. The harmonic magnitudes correspond to the ON/PERIOD ratio determined in step 6.

I. Phase "a", Appendix Pages C1-C12, part (D), continued

With $ON = 32.364$ from step 6 and $PERIOD = 93$ minutes, the Fourier coefficients are calculated. The time/phase of the fundamental component and relative time/phase of each harmonic are then determined. Page C9 shows the A and B harmonics and their time/phase relationships graphically.

Likewise, page C10 is the calculation of C and D, the fundamentals and harmonics of the STEPV waveform beginning at 00:33 7 March. "OFST" is offset current superimposed to account for the step change in voltage at 00:33.

Page C11 shows the relative time/phase relationship of the A and B and the C and D fundamental components, I_{ii} and I_{iSi} , respectively. Page C11 also shows the superposition of the fundamental components, superposition of the fundamental and second harmonics, and the superposition of both sets of fundamental, 2nd, 3rd and 4th harmonics for pre- and STEPV time intervals.

Page C12 shows a plot of the time varying only component of the measured feeder current. Page C12 then shows the superposition of the latter with the model reconstructed current. Note that the fundamental components of A and B superimposed with C and D nearly cancel. This is because the STEPV was (without knowledge of we who induced it!) applied at the time the fundamental of the pre-STEPV current was near zero and decreasing. However the second harmonic components of the pre-STEPV and STEPV waveforms are nearly in phase and account for the their predominance and the great difference between pre- and post STEPV waveforms.

The overall conclusion is that the superposition of the Harmonic Model components is an appropriate model for the reconstruction of the actual feeder current.

II. Phase "b", Appendix Pages C13-C22

- A. Pages C13 through C16 are plots respectively of measured feeder current, pre-STEPV current, STEPV current, and the time varying component of current. The plots are obtained in procedure step 4 for the 1 minute interval load data of phase "b".

The period of the fundamental wave (assumed to be weather sensitive load variation) of Page C14 pre-STEPV current is about 54 minutes. This magnitude is in the range of what was anticipated for residential electric heating systems at this ambient temperature. This periodicity is also observed prior to the time (not shown) of the plot of page C14. The sloping straight line is the estimate of the running average value of the current

The current waveform of page C15 following the STEPV increase in feeder voltage at 00:33 7 March is postulated to be the superposition of the pre-STEPV and STEPV caused current variations as shown later in the reconstruction currents of the plot of page C22.

As in phase "a", the reconstruction currents of the plot of page C22 indicate that the superposition of both the pre-STEPV and STEPV fundamental and their higher harmonics approximately model the actual current, which is predominantly the second harmonic at a period of about 27 minutes.

- B. Page C17 is a MathCAD program to do FFT of the data file APBPREF of actual measured current achieved in steps 1 - 4 of the procedure. The "dc" level of 5.583 indicates that the averaging done in the step 4 is poor. The ratio of the fundamental to second harmonic is less than unity, not possible for the ON/OFF heating unit waveform. The likely explanation is that two or more "waves" of changing ambient temperature induced non-diversity variation of electric heating unit current are present and superimposed, similar to the "a" phase STEPV time region. This would account for the larger-than-fundamental second harmonic magnitude. This requires further investigation. Consequently, an ON time of one third of the PERIOD (similar to phase "a") was estimated. The MathCAD program to estimate ON time was not utilized for phase "b".

- C. Similar to "a" phase, pages C18 through C22 are a MathCAD program utilizing the Harmonic Model concept to reconstruct (predict) the pre- and during STEPV current.

With ON = 18 and PERIOD = 54 minutes, the Fourier coefficients are calculated. After STEPV the ON and PERIOD times were estimated to be 17 and 52 minutes respectively. The time/phase of the fundamental component and relative time/phase of each harmonic are then determined. Page C19 shows the A and B harmonics and their time/phase relationships graphically.

II. Phase "b", Appendix Pages C13-C22, part (D), continued

Page C22 shows a plot of the time varying only component of the measured feeder current. Page C22 then shows the superposition of the latter with the model reconstructed current. Similar to "a" phase, note that the fundamental components of A and B superimposed with C and D nearly cancel. Again, the second harmonic components of the pre-STEPV and STEPV waveforms are nearly in phase accounting for the their predominance and the great difference between pre and post STEPV waveforms.

As with "a" phase, the overall conclusion is that the superposition of the Harmonic Model components is an appropriate model for the reconstruction of the actual feeder current.

III. Phase "c", Appendix Pages C23-C31

- A. Page C23 is a plot of measured feeder current with superimposed estimated running average current and the difference of total and running average currents. The latter is assumed to predominantly be the WS time varying current. The "blip" in total current at 23:00 on 3/6 may perhaps be human response to TV programming! The "blip" in current at 00:33 on 3/7 is at least in part caused by the STEPV.

The plot of page C24 is STEPV time varying current of phase "c".

Not much "action" is apparent in "c" phase prior to the STEPV. A discernable PERIOD of assumed electric heating response of about 42 minutes appears after the STEPV.

- B. Page C25 is a MathCAD program to do FFT of the data file APCPRE of actual measured current achieved in steps 1 - 4 of the procedure. The "dc" level of 8.344 indicates that the averaging done in the step 4 is fair. The ratio of the fundamental to second harmonic is 2.964, which is reasonable and about the value anticipated.
- C. Again, page C26 is the MathCAD program to estimate the ON time. ON time "to" is guessed until the ratio of ON time to period is 2.964. The ON time thus calculated for APCPRE data is 16.4 minutes.
- D. Similar to "a" and "b" phases, pages C27 through C31 are the MathCAD program utilizing the Harmonic Model concept to reconstruct (predict) the STEPV current. The pre-STEPV time varying current is assumed to be zero for phase "c", perfect diversity!

An assumed ON = 14 minutes and estimated from measured data PERIOD = 42 minutes were used in the calculation of the Fourier coefficients of page C29. The time/phase of the fundamental component and relative time/phase of each harmonic are then determined. Page C30 shows the C and D harmonics and their time/phase relationships graphically. As stated, with pre-STEPV current variation of zero, the A and B components are zero.

Page C31 shows a plot of the measured time varying only component of the feeder current. Page C31 then shows the superposition of the latter with the model reconstructed fundamental only current. This is a much simpler situation than with phases "a" and "b".

Relative to phase "c", the overall conclusion is that the Harmonic Model components appear to reconstruct the actual feeder current.

Estimates of Phase "a" Feeder Parameters

Pages C32/33 present calculations of the phase "a" feeder parameters. Purpose is a "first pass" at the procedure and to obtain numbers with which to estimate CLPU response. The calculations are self explanatory.

Page C32 estimates the thermal resistance, R, and thermal capacitance, C, of the mean electrically heated house of "a" phase of the feeder. Critique and comment of the readers of this report are requested on the method and number results.

Page C33 estimates the magnitude of the current "swing" of the STEPV initiated current. The numbers show a rough correlation of theory and measurement. The objective here is to show the method. Refinement is necessary and could be done with additional STEPV and actual CLPU data.

Preliminary Prediction of CLPU Corresponding to Phase "a" Parameters

Pages C34 - C40 present a Harmonic Model "first pass" estimate of a CLPU response of phase "a" of the Appleway feeder. The resulting numbers are obtained using the parameter estimates of the foregoing procedure and should not be construed as a true prediction of phase "a" CLPU. Our purpose here is to demonstrate the method. Page C34 is similar to the model which Mr. McCannon programmed in C++ language during the week he spent with KEC in Spring 1992. The model utilizes only the fundamental components.

Page C35 Shows pre-STEPV estimates of "a" phase for 40F ambient:

- (1) total current, ITOT
- (2) WS average current, IWS
- (3) NWS average current, INWS

The NWS average current, INWS, value of 38 amperes at the time of the STEPV was taken from the plot of page C41, the lowest current observed during the Spring at temperatures at which neither heating nor air conditioning load are assumed present.

Page C36 shows calculated estimates of CLPU at 40F ambient for outages of 10 and 20 minutes. Page C37 shows calculated estimates of CLPU at -10F ambient for outages of 10 and 20 minutes.

Page C39 shows calculated estimates of CLPU at 40F ambient for outages of 75 and 90 minutes. Page C40 shows calculated estimates of CLPU at -10F ambient for outages of 25 and 35 minutes.

Appleway "a" Currents Recordings

Pages C41 and C42 show measured "a" phase Appleway feeder current as obtained in procedure step 2 via the Rochester Load Loggers and Rochester interface software.

The plots of page C41 are a small portion of the two months of data taken with the loggers set to record at 15 minute intervals during Spring 1992. The objective here was to obtain load profiles that would assist in determining the NWS load at various times during the day. The upper of the two plots of page C41 shows a lowest load of 38 amperes at 03:00 on 4/27/92. This was the value used in estimating CLPU in the previous pages. The lower of the two plots of page C41 shows typical load profiles of weekday and weekend load.

The plot of page C42 is a small portion of the four days of data taken with the loggers set to record at 1 minute intervals during June 1992. The objective here was to obtain ambient temperature driven variation in diversity (hopefully) that might provide information in determining the air conditioning load parameters needed to predict HLPV. Similar records were obtained during the July 1992 hot weather.

The loggers were set to record at 15 minute intervals on the Appleway feeder during Fall 1992 to continue to obtain load profile data.

As soon as cool/cold 1992 weather began, the loggers were reset to 1 minute interval recording in anticipation of possible actual CLPU and for ongoing information gathering. Both UIEE and KEC loggers were available in the event of an outage on another feeder. None occurred!

KEC STEPV APAPH

22:40 3/6 - 02:06 3/7

KEC STEPV APAPH

22:40 3/6 - 00:20 3/7

TOTAL and AVERAGE CURRENT - Amperes

KEC STEPV APAPH

00:30 3/6 - 02:06 3/7

KEC STEPV APAPH

22:40 3/6 - 02:06 3/7

TIME - Minutes, 0 = Midnight

TOTAL minus AVERAGE CURRENT - Amperes

KEC STEPV APAPH

22:40 3/6 - 02:06 3/7

APAF0UR01 FFT of APAPH pre stepv data 23June92 rad := 1
 N := 94 i := 0 .. (N - 1) I := READ (APAPRE) t := i
 i i

j := 0 .. 63 II := linterp(t, I, j) U := $\frac{\text{fft}(\text{II})}{4}$ tt := $\frac{64}{i} \cdot i$
 i P

P = 93 k := 0 .. 32

$\arg[U_k] + 113.767 \cdot \text{deg}$

t i	I i	tt i	II j
0	-1.94	0	-1.94
1	-3.78	0.688	-3.78
2	-3.62	1.376	-3.62
3	-4.46	2.065	-4.46
4	-7.3	2.753	-7.3
5	-4.14	3.441	-4.14
6	-4.98	4.129	-4.98
7	-0.82	4.817	-0.82
8	-1.66	5.505	-1.66
9	-4.5	6.194	-4.5
10	-3.34	6.882	-3.34
11	-0.18	7.57	-0.18
12	1.98	8.258	1.98
13	3.14	8.946	3.14
14	-0.7	9.634	-0.7
15	-1.54	10.323	-1.54
16	-1.38	11.011	-1.38
17	0.78	11.699	0.78
18	1.94	12.387	1.94
19	1.1	13.075	1.1
20	0.26	13.763	0.26
21	-3.58	14.452	-3.58
22	-4.42	15.14	-4.42
23	-3.26	15.828	-3.26
24	-4.1	16.516	-4.1
25	0.06	17.204	0.06
26	2.22	17.892	2.22
27	2.38	18.581	2.38
28	0.54	19.269	0.54
29	-1.3	19.957	-1.3
30	-4.14	20.645	-4.14
31	-1.98	21.333	-1.98
32	-0.82	22.022	-0.82
33	3.34	22.71	3.34
34	1.5	23.398	1.5
35	-0.34	24.086	-0.34
36	2.82	24.774	2.82
37	1.98	25.462	1.98
38	2.14	26.151	2.14
39	7.3	26.839	7.3
40	6.46	27.527	6.46
41	1.62	28.215	1.62
42	1.78	28.903	1.78
43	2.94	29.591	2.94
44	3.1	30.28	3.1
45	5.26	30.968	5.26
46	5.42	31.656	5.42
47	7.58	32.344	7.58
48	3.74	33.032	3.74
49	1.9	33.72	1.9

U k
0.731
2.822
1.295
1.678
1.536
0.696
1.562
0.994
0.776
0.824
1.449
0.255
0.636
0.542
0.3
0.291
0.401
0.196
0.652
0.638
0.136
0.173
0.282
0.382
0.42
0.275
0.252
0.215
0.102
0.501
0.298
0.304
0.129

deg	k
113.77	0
-0	1
-62.27	2
17.27	3
4.86	4
-46.01	5
275.04	6
169.5	7
192.83	8
-0.17	9
146.91	10
135.7	11
229.28	12
-61.01	13
-63.9	14
209.89	15
136.1	16
173.02	17
151.2	18
50.81	19
241.34	20
13	21
-35.96	22
125.75	23
19.72	24
112.86	25
171.54	26
184.12	27
224.29	28
182.43	29
169.22	30
141.82	31
293.77	32

CLPU FOURIER ANALYSIS n := 1 ..20 A := 1 T := 20
22June92

t0 = 6.96

$$A_n := \frac{A}{\pi} \left[\frac{\sin\left[\frac{n \cdot t_0 \cdot \pi}{T}\right]}{n} - \frac{\sin\left[\frac{-n \cdot t_0 \cdot \pi}{T}\right]}{n} \right]$$

A _n	n	A _n · X
0.565	1	2.824
0.26	2	1.298
-0.029	3	-0.146
-0.15	4	-0.75
-0.093	5	-0.464
0.029	6	0.145
0.089	7	0.445
0.05	8	0.249
-0.028	9	-0.142
-0.064	10	-0.317
-0.03	11	-0.149
0.028	12	0.139
0.049	13	0.244
0.018	14	0.089
-0.027	15	-0.135
-0.039	16	-0.194
-0.01	17	-0.049
0.026	18	0.13
0.031	19	0.157
0.004	20	0.02

$$X := \frac{2.822}{0.565}$$

$$R := \frac{2.822}{1.295}$$

$$R = 2.179$$

$$\frac{A_n}{1} = 2.176$$

$$\frac{A_n}{2}$$

$$\frac{t_0}{T} = 0.348$$

Pre STEPV PERIOD $\tau_{PRE} := 93$

Estimated ON time

$$ON := \tau_{PRE} \cdot \frac{t_0}{T}$$

$$ON = 32.364$$

APAA 7.100

APALL3 FOURIER ANALYSIS
11Aug92 APH

TP := 93

TTP := -77

ONP = 32.364

n := 1 .. 4

i := 0 .. 203

t_i := i + TTP

$$A_n := 2 \cdot \frac{A}{\pi} \left[\frac{\sin \left[\frac{n \cdot ONP \cdot \pi}{TP} \right]}{n} \right]$$

$$PAVG := A \cdot \left[\frac{ONP}{TP} \right] \quad \text{rad} := 1 \quad A_n$$

n
7.35
3.378
-0.38
-1.951

$$\text{deg} := \frac{\pi}{180} \cdot \text{rad}$$

$$APH1_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right]$$

$$APH2_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH3_i := \frac{A_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH4_i := \frac{A_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH_i := APH1_i + APH2_i + APH3_i + APH4_i$$

$$\theta_{BP1} := \frac{-DIV}{2} + \frac{\pi}{2} + \beta$$

$$BPH1_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right]$$

$$BPH2_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH3_i := \frac{A_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH4_i := \frac{A_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH_i := BPH1_i + BPH2_i + BPH3_i + BPH4_i$$

APAALL3 FOURIER ANALYSIS
11Aug92 APH

$$III_i := APH1_i + BPH1_i + APH2_i + BPH2_i$$

$$I_i := APH_i + BPH_i$$

$$II_i := APH1_i + BPH1_i$$

APH1_i, APH2_i, APH3_i, APH4_i

BPH1_i, BPH2_i, BPH3_i, BPH4_i

$$B \equiv \frac{\pi}{180} \cdot 30$$

$$\alpha \equiv 120$$

$$DIV \equiv \frac{\pi}{180} \cdot \alpha$$

$$A \equiv 13$$

$$0 < DIV < 1$$

$$0 < \alpha < 180$$

$$\Theta AP1 \equiv \frac{DIV}{2} + \frac{\pi}{2} + B$$

ONS := 30.4

TS := 91

$$S_n := 2 \cdot \frac{A}{\pi} \left[\frac{\sin \left[\frac{n \cdot \text{ONS} \cdot \pi}{\text{TS}} \right]}{n} \right]$$

S_n

7.177
3.574
-0.019
-1.801

$$\text{CPH1}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right]$$

$$\text{CPH2}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH3}_i := \frac{S_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH4}_i := \frac{S_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH}_i := \text{CPH1}_i + \text{CPH2}_i + \text{CPH3}_i + \text{CPH4}_i$$

$$\theta_{\text{DP1}} := \frac{-\text{DIVS}}{2} + \frac{\pi}{2} + \rho$$

$$\text{DPH1}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right]$$

$$\text{DPH2}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH3}_i := \frac{S_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH4}_i := \frac{S_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH}_i := \text{DPH1}_i + \text{DPH2}_i + \text{DPH3}_i + \text{DPH4}_i$$

$$x_i := t_i - 33 \quad y_i := t_i - 42$$

$$\text{STP} := 4 \quad \text{OFC}_i := 4 \cdot \phi[y_i]$$

$$\text{OFA}_i := [-1 \cdot [t_i - 33] + 4] \cdot \phi[x_i]$$

$$\text{OFB}_i := [1 \cdot [t_i - 41] - 0] \cdot \phi[y_i]$$

$$\text{OFST}_i := \text{OFA}_i + \text{OFB}_i + \text{OFC}_i$$

$$\text{IS}_i := [\text{CPH}_i + \text{DPH}_i] \cdot \phi[x_i]$$

$$\text{IIS}_i := [\text{CPH1}_i + \text{DPH1}_i] \cdot \phi[x_i]$$

$$\text{IIIS}_i := [\text{CPH1}_i + \text{DPH1}_i + \text{CPH2}_i + \text{DPH2}_i] \cdot \phi[x_i]$$

APAALL3 FOURIER ANALYSIS

11Aug92 APH

PK = -2 TC = 10

N := 204

i := 0 .. (N - 1)

IA_i := READ(APAALL)

APAALL3 FOURIER ANALYSIS

11Aug92 APH

$$ALL_i := IS_i + I_i + OFST_i$$

$$\rho \equiv \frac{\pi}{180} \cdot 170$$

$$\epsilon \equiv 110$$

$$DIVS \equiv \frac{\pi}{180} \cdot \epsilon$$

$$\theta CP1 \equiv \frac{DIVS}{2} + \frac{\pi}{2} + \rho$$

KEC STEPV APBPH

22:40 3/6 - 02:06 3/7

KEC STEPV APBPH

22:40 3/6 - 00:32 3/7

KEC STEPV APBPH

00:33 3/7 - 02:06 3/7

TOTAL and AVERAGE CURRENT - Amperes

KEC STEPV APBPH

22:40 3/6 - 02:06 3/7

APBFOUR01 FFT of APBPH pre stepv data 14Aug92 rad := 1
 N := 55 i := 0 .. (N - 1) I := READ(APBPRES) t := i
 deg := $\frac{\pi}{180}$ rad

j := 0 .. 63 II := linterp(t, I, j) U := $\frac{\text{fft}(\text{II})}{4}$ tt := $\frac{64}{P} \cdot i$

t i	I i	tt i	II j
0	6.1	0	6.1
1	3.16	1.185	3.16
2	2.22	2.37	2.22
3	7.28	3.556	7.28
4	8.34	4.741	8.34
5	3.4	5.926	3.4
6	5.46	7.111	5.46
7	6.52	8.296	6.52
8	2.58	9.481	2.58
9	-1.36	10.667	-1.36
10	-4.3	11.852	-4.3
11	0.76	13.037	0.76
12	1.82	14.222	1.82
13	-2.12	15.407	-2.12
14	-7.06	16.593	-7.06
15	-8	17.778	-8
16	-5.94	18.963	-5.94
17	-4.88	20.148	-4.88
18	-2.82	21.333	-2.82
19	-3.76	22.519	-3.76
20	-7.7	23.704	-7.7
21	-6.64	24.889	-6.64
22	-6.58	26.074	-6.58
23	-6.52	27.259	-6.52
24	-5.46	28.444	-5.46
25	-5.4	29.63	-5.4
26	-4.34	30.815	-4.34
27	-3.28	32	-3.28
28	-4.22	33.185	-4.22
29	-6.16	34.37	-6.16
30	-3.1	35.556	-3.1
31	-0.04	36.741	-0.04
32	-1.98	37.926	-1.98
33	-3.92	39.111	-3.92
34	-1.86	40.296	-1.86
35	-5.8	41.481	-5.8
36	-6.74	42.667	-6.74
37	-4.68	43.852	-4.68
38	-6.62	45.037	-6.62
39	-4.56	46.222	-4.56
40	-5.5	47.407	-5.5
41	-1.44	48.593	-1.44
42	0.62	49.778	0.62
43	-2.32	50.963	-2.32
44	-6.26	52.148	-6.26
45	-8.2	53.333	-8.2
46	-4.14	54.519	-4.14
47	-3.08	55.704	-3.08
48	-2.02	56.889	-2.02
49	4.04	58.074	4.04

P = 54 k := 0 .. 32

arg[U]
k + 113.767 deg

U k
5.583
1.519
2.503
5.47
4.194
2.954
0.931
1.305
2.059
0.512
0.983
1.392
1.003
0.882
0.59
0.882
0.419
1.41
0.909
0.78
0.342
1.19
0.671
0.692
0.346
0.675
0.452
0.408
0.739
0.401
0.491
0.558
0.565

deg
293.77
82.68
245.56
239.56
210.84
190.35
130.29
254.31
205.75
166.23
121.62
169.6
181.74
242.51
130.47
105.98
101.18
152.45
134.71
147.21
146.55
152.55
153.1
140.31
133.18
183.17
117.25
118.88
116.22
92.71
140.77
132.94
113.77

k
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

$$\frac{1.519}{2.503} = 0.607$$

APBALL4 FOURIER ANALYSIS
12Aug92 BPH

TP := 54

TTP := -80

ONP = 18

n := 1 .. 4

i := 0 .. 206

t_i := i + TTP rad := 1

$$A_n := 2 \cdot \frac{A}{\pi} \left[\frac{\sin \left[\frac{n \cdot ONP \cdot \pi}{TP} \right]}{n} \right]$$

$$PAVG := A \cdot \left[\frac{ONP}{TP} \right]$$

A_n

n
9.924
4.962
0
-2.481

$$\text{deg} := \frac{\pi}{180} \cdot \text{rad}$$

$$APH1_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right]$$

$$APH2_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH3_i := \frac{A_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH4_i := \frac{A_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH_i := APH1_i + APH2_i + APH3_i + APH4_i$$

$$\theta_{BP1} := \frac{-DIV}{2} + \frac{\pi}{2} + B$$

$$BPH1_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right]$$

$$BPH2_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH3_i := \frac{A_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH4_i := \frac{A_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH_i := BPH1_i + BPH2_i + BPH3_i + BPH4_i$$

APBALL4 FOURIER ANALYSIS
12Aug92 BPH

$$III := APH1 + BPH1 + APH2 + BPH2$$

$$I := APH + BPH$$

$$II := APH1 + BPH1$$

APH1, APH2, APH3, APH4

BPH1, BPH2, BPH3, BPH4

$$B \equiv \frac{\pi}{180} \cdot (-40)$$

$$\alpha \equiv 120$$

$$DIV \equiv \frac{\pi}{180} \cdot \alpha$$

$$A \equiv 18$$

$$0 < DIV < 1$$

$$0 < \alpha < 180$$

$$\Theta AP1 \equiv \frac{DIV}{2} + \frac{\pi}{2} + B$$

ONS := 17 TS := 52

$$S_n := 2 \cdot \frac{A}{\pi} \left[\frac{\sin \left[\frac{n \cdot \text{ONS} \cdot \pi}{\text{TS}} \right]}{n} \right]$$

S_n
9.807
5.073
0.231
-2.358

$$\text{CPH1}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right]$$

$$\text{CPH2}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH3}_i := \frac{S_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH4}_i := \frac{S_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH}_i := \text{CPH1}_i + \text{CPH2}_i + \text{CPH3}_i + \text{CPH4}_i$$

$$\theta_{\text{DP1}} := \frac{-\text{DIVS}}{2} + \frac{\pi}{2} + \sigma$$

$$\text{DPH1}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right]$$

$$\text{DPH2}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH3}_i := \frac{S_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH4}_i := \frac{S_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH}_i := \text{DPH1}_i + \text{DPH2}_i + \text{DPH3}_i + \text{DPH4}_i$$

$$x_i := t_i - 33 \quad y_i := t_i - 42$$

$$\text{STP} := 4 \quad \text{OFC}_i := 4 \cdot \Phi[y_i]$$

$$\text{OFA}_i := [-1 \cdot [t_i - 33] + 4] \cdot \Phi[x_i]$$

$$\text{OFB}_i := [1 \cdot [t_i - 41] - 0] \cdot \Phi[y_i]$$

$$\text{OFST}_i := \text{OFA}_i + \text{OFB}_i + \text{OFC}_i$$

$$\text{IS}_i := [\text{CPH}_i + \text{DPH}_i] \cdot \Phi[x_i]$$

$$\text{IIS}_i := [\text{CPH1}_i + \text{DPH1}_i] \cdot \Phi[x_i]$$

$$\text{IIIS}_i := [\text{CPH1}_i + \text{DPH1}_i + \text{CPH2}_i + \text{DPH2}_i] \cdot \Phi[x_i]$$

N := 207

i := 0 .. (N - 1)

IA_i := READ(APBALL)

APBALL4 FOURIER ANALYSIS

12Aug92 APH

ALL := IS + I + OFST

i i i i

$$\sigma \equiv \frac{\pi}{180} \cdot (-155) \quad \lambda \equiv 130$$

$$\text{DIVS} \equiv \frac{\pi}{180} \cdot \lambda$$

$$\theta_{CP1} \equiv \frac{\text{DIVS}}{2} + \frac{\pi}{2} + \sigma$$

KEC STEPV APCPH

22:00 3/6 - 02:00 3/7

KEC STEPV APCPH
00:00 3/7 - 02:00 3/7

$$\text{deg} := \frac{\pi}{180} \cdot \text{rad}$$
$$tt_i := \frac{64}{p} \cdot i$$

4

$$k := 0 \dots 32$$
$$y \begin{bmatrix} U \\ k \end{bmatrix}$$

3.6
4.7
5.8
6.9
8
9.1
10.2

U
Kdeg

k

3.494

CLPU FOURIER ANALYSIS n := 1 ..20 A := 1 T := 20
22June92

t0 := 7.81

$$A_n := \frac{A}{\pi} \left[\frac{\sin\left[\frac{n \cdot t_0 \cdot \pi}{T}\right]}{n} - \frac{\sin\left[\frac{-n \cdot t_0 \cdot \pi}{T}\right]}{n} \right]$$

An	n	An · X
0.599	1	10.363
0.202	2	3.495
-0.109	3	-1.883
-0.156	4	-2.7
-0.019	5	-0.327
0.093	6	1.616
0.068	7	1.168
-0.03	8	-0.523
-0.071	9	-1.222
-0.019	10	-0.324
0.046	11	0.801
0.044	12	0.765
-0.012	13	-0.202
-0.045	14	-0.782
-0.018	15	-0.318
0.028	16	0.483
0.034	17	0.587
-0.003	18	-0.056
-0.032	19	-0.561
-0.018	20	-0.309

X := $\frac{10.357}{0.599}$

R := $\frac{10.357}{3.494}$

R = 2.964

An
1
— = 2.965
An
2

t0
— = 0.391
T

Pre STEPV PERIOD τPRE := 42

Estimated ON time

ON := τPRE · $\frac{t_0}{T}$ ON = 16.401

APCALL FOURIER ANALYSIS
12Aug92 CPH

TP := 0

TTP := 0

ONP ≡ 0

n := 1 .. 4

i := 0 .. 120

t_i := i + TTP rad := 1

$$A_n := 2 \cdot \frac{A}{\pi} \left[\frac{\sin \left[\frac{n \cdot ONP \cdot \pi}{TP} \right]}{n} \right]$$

$$PAVG := A \cdot \left[\frac{ONP}{TP} \right]$$

A _n	n
0	0
0	1
0	2
0	3

$$\text{deg} := \frac{\pi}{180} \cdot \text{rad}$$

$$APH1_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right]$$

$$APH2_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH3_i := \frac{A_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH4_i := \frac{A_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{AP1} \right] \right]$$

$$APH_i := APH1_i + APH2_i + APH3_i + APH4_i$$

$$\theta_{BP1} := \frac{-DIV}{2} + \frac{\pi}{2} + \beta$$

$$BPH1_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right]$$

$$BPH2_i := \frac{A_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH3_i := \frac{A_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH4_i := \frac{A_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{TP} \cdot t_i + \theta_{BP1} \right] \right]$$

$$BPH_i := BPH1_i + BPH2_i + BPH3_i + BPH4_i$$

APCALL FOURIER ANALYSIS
12Aug92 CPH

$$III_i := APH1_i + BPH1_i + APH2_i + BPH2_i$$

$$I_i := APH_i + BPH_i$$

$$II_i := APH1_i + BPH1_i$$

APH1_i, APH2_i, APH3_i, APH4_i

BPH1_i, BPH2_i, BPH3_i, BPH4_i

III_i

II_i

$$B \equiv \frac{\pi}{180} \cdot (-40)$$

$$\alpha \equiv 120$$

$$DIV \equiv \frac{\pi}{180} \cdot \alpha$$

$$A \equiv 18$$

$$0 < DIV < 1$$

$$0 < \alpha < 180$$

$$\theta AP1 \equiv \frac{DIV}{2} + \frac{\pi}{2} + B$$

ONS := 14

TS := 42

$$S_n := 2 \cdot \frac{A}{\pi} \left[\frac{\sin \left[\frac{n \cdot \text{ONS} \cdot \pi}{\text{TS}} \right]}{n} \right]$$

S_n
9.924
4.962
0
-2.481

$$\text{CPH1}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right]$$

$$\text{CPH2}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH3}_i := \frac{S_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH4}_i := \frac{S_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{CP1}} \right] \right]$$

$$\text{CPH}_i := \text{CPH1}_i + \text{CPH2}_i + \text{CPH3}_i + \text{CPH4}_i$$

$$\theta_{\text{DP1}} := \frac{-\text{DIVS}}{2} + \frac{\pi}{2} + \sigma$$

$$\text{DPH1}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right]$$

$$\text{DPH2}_i := \frac{S_n}{2} \cdot \cos \left[2 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH3}_i := \frac{S_n}{2} \cdot \cos \left[3 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH4}_i := \frac{S_n}{2} \cdot \cos \left[4 \cdot \left[2 \cdot \frac{\pi}{\text{TS}} \cdot t_i + \theta_{\text{DP1}} \right] \right]$$

$$\text{DPH}_i := \text{DPH1}_i + \text{DPH2}_i + \text{DPH3}_i + \text{DPH4}_i$$

$$x_i := t_i - 33 \quad y_i := t_i - 42$$

$$\text{STP} := 4 \quad \text{OFC}_i := 4 \cdot \Phi[y_i]$$

$$\text{OFA}_i := [-1 \cdot [t_i - 33] + 4] \cdot \Phi[x_i]$$

$$\text{OFB}_i := [1 \cdot [t_i - 41] - 0] \cdot \Phi[y_i]$$

$$\text{OFST}_i := \text{OFA}_i + \text{OFB}_i + \text{OFC}_i$$

$$\text{IS}_i := [\text{CPH}_i + \text{DPH}_i] \cdot \Phi[x_i]$$

$$\text{IIS}_i := [\text{CPH1}_i + \text{DPH1}_i] \cdot \Phi[x_i]$$

$$\text{IIIS}_i := [\text{CPH1}_i + \text{DPH1}_i + \text{CPH2}_i + \text{DPH2}_i] \cdot \Phi[x_i]$$

APCALL FOURIER ANALYSIS

12Aug92 CPH

PK $\equiv$ -2 TC $\equiv$ 10

N := 121

i := 0 .. (N - 1)

IA_i := READ(APCALL)

APCALL FOURIER ANALYSIS

12Aug92 APH

ALL := IS + I + OFST
i i i i

$$\sigma \equiv \frac{\pi}{180} \cdot (15)$$

$$\lambda \equiv 130$$

$$\text{DIVS} \equiv \frac{\pi}{180} \cdot \lambda$$

$$\theta_{CP1} \equiv \frac{\text{DIVS}}{2} + \frac{\pi}{2} + \sigma$$

CLPU PARAMETERS pg1 TU := 70 TLOW := 68 TBASE := 70 TAMB := 40

KW := 20 Rpu := 1.2 QBASE := 68288

ONTIM := $\frac{32.4}{60}$ PERIOD := $\frac{93}{60}$ OFFTIM := PERIOD - ONTIM OFFTIM = 1.01
 $Q := 3412.1 \cdot KW$
 $Q = 6.824 \cdot 10^4$

$$RC := - \left[\frac{OFFTIM}{\ln \left[\frac{TLOW - TAMB}{TU - TAMB} \right]} \right]$$

RBASE := $\frac{1}{QBASE}$

RC = 14.639 HOUR

Cpu := $\frac{RC}{Rpu}$

Qpu := $\frac{Q}{QBASE}$

Qpu = 0.999 Cpu = 12.199

guess

$$GONTIM := -RC \cdot \ln \left[\frac{\frac{TU - TAMB}{TBASE} - Qpu \cdot Rpu}{\frac{TLOW - TAMB}{TBASE} - Qpu \cdot Rpu} \right]$$

ONTIM · 60 = 32.4

GONTIM · 60 = 31.976

R := Rpu · RBASE · TBASE

R = 0.001

C := $\frac{RC}{R}$
 $C = 1.19 \cdot 10^4$ R · C = 14.639

$$NGONTIM := -RC \cdot \ln \left[\frac{(TU - TAMB) - Q \cdot R}{(TLOW - TAMB) - Q \cdot R} \right]$$

NGONTIM · 60 = 31.976

$Q = 6.824 \cdot 10^4$

R = 0.001

Estimate thermal capacity, CC, and total thermal resisivity, RR, of a 50 ton mass house with a specific heat of 0.6 BTU per lbm·degF to be:

CC := $0.6 \cdot \left[100 \cdot \left[\frac{2000}{32.2} \right] \right]$
 $CC = 3.727 \cdot 10^3$ BTU/degF

ASHRAE handbook, Chapt 26, gives the surface thermal coefficient of a typical frame wall house to be 0.07 BTU per hr·sqft·degF.

Assuming a total surface area of walls and overhead of the house to be
 AREA := 25000 sqft:

GG := 0.07 · 2500 GG = 175 BTU per hr·degF and RR := $\frac{1}{GG}$
 RR = 0.006 hr·degF per BTU

RR · CC = 21.295 hour, which compares roughly with RC = 14.639 estimated.

CLPU PARAMETERS pg2

Estimate WSAVG current at time of 7 March 1992 StepV test as 20 amperes. PERIOD of WS cycle is 93 minutes. ON time is about 32.4 minutes. Assume line voltage is 13.8 KV. Therefor:

$$\text{All houses full on Power} = \text{PWSFULL} := \left[\frac{93}{32.4} \right] \cdot (20) \cdot \left[\frac{13800}{\sqrt{3}} \right]$$

$$\text{PWSFULL} = 4.574 \cdot 10^5 \text{ watt}$$

$$\text{Assume electric heating power per house} = \text{PHS} := 20000 \text{ watt}$$

Estimated number of electrically heated houses of "a" phase of Appleway feeder is = integer of NN

$$\text{NN} := \frac{\text{PWSFULL}}{\text{PHS}} \quad \text{NN} = 22.869 \quad \text{N} := 23 \quad \text{houses @ 20 KW each}$$

$$\text{Average "a" phase WS current is thus} \quad \text{IAVG} := 20 \cdot \left[\frac{\text{N}}{\text{NN}} \right] \quad \text{IAVG} = 20.114$$

FFT analysis of the "a" phase data with ON = 32.4 and PERIOD of 93 yields a fundamental component of An1 := 0.565 of the ON current.

WSAVG current at time of 7 March 1992 StepV test is composed of the two Harmonic Model" parts:

$$\text{IAWSAVG} := \left[\frac{\text{IAVG}}{2} \right] \cdot (\text{An1}) \quad \text{IAWSAVG} = 5.682 \quad \text{IBWSAVG} := \text{IAWSAVG} \quad \text{amp}$$

$$\text{Diversity was estimated to be} \quad \alpha := 120 \text{ degrees}$$

The peak of the fundamental component of the "swing" as found with "Harmonic Model" theory is thus:

$$\text{pKsW} := \text{IAWSAVG} \cdot \cos \left[\frac{\pi}{180} \cdot \frac{\alpha}{2} \right] + \text{IBWSAVG} \cdot \cos \left[\frac{\pi}{180} \cdot \left[\frac{-\alpha}{2} \right] \right] \quad \text{pKsW} = 5.682$$

The peak of the swing of the actual recorded data is about 4 amperes.

CONCLUSION: Although the above calculations are a "first cut" based on rather rough estimates of WS data, the results are in the "ballpark" and are encouraging relative to the proposed method. Further data under colder weather conditions and an evaluation of actual makeup of the feeder load is needed for improved accuracy.

CLSIM131 ontim/offtim/period matrix 27Aug91 y := 0 ..20
Short Outage Case := 0

$$t := \frac{y}{10}$$

N := 23 Q := 0.999 R := 1.2 C := 12.199 TAU := R · C KCOS := 3

TU := 70 TLOW := 68 TBASE := 70 KOFF := 20 KPK := 0.2

IBASE := 20000 · $\frac{\sqrt{3}}{13800}$ INWS := 38
IBASE = 2.51 ampere per house OUT := $\frac{\text{OUTDUR}}{60}$

$$\text{ONTIM} := -R \cdot C \cdot \ln \left[\frac{\frac{TU - TAMB}{TBASE} - Q \cdot R}{\frac{TLOW - TAMB}{TBASE} - Q \cdot R} \right]$$

$$\text{OFFTIM} := -R \cdot C \cdot \ln \left[\frac{TLOW - TAMB}{TU - TAMB} \right]$$

PERIOD := ONTIM + OFFTIM

$$\text{WSAVG} := N \cdot Q \cdot \left[\frac{\text{ONTIM}}{\text{PERIOD}} \right] \quad \text{IWSAVG} := \frac{\text{WSAVG}}{V} \quad \text{OMEGA} := 2 \cdot \frac{\pi}{\text{PERIOD}}$$

$$\text{CC} := \sin \left[\frac{\text{ONTIM}}{\text{PERIOD}} \cdot \pi \right] \quad E := 1 - e^{-\text{OUT} \cdot \text{KCOS}}$$

$$\text{COSA}_Y := \frac{\text{KPK} \cdot \text{CC} \cdot N \cdot Q}{V} \cdot \cos \left[\text{OMEGA} \cdot t_Y + \frac{\pi}{2} - \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right]$$

$$\text{COSB}_Y := \frac{\text{KPK} \cdot \text{CC} \cdot N \cdot Q}{V} \cdot \cos \left[\text{OMEGA} \cdot t_Y - \frac{\pi}{2} + \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right]$$

$$\text{OFFSET0} := \left[\frac{N \cdot Q \cdot \text{OFFTIM}}{V \cdot \text{PERIOD}} - \text{COSA}_0 - \text{COSB}_0 \right] \cdot \left[\frac{\text{OUT}}{\text{OFFTIM}} \right]$$

$$\text{OFFSET}_Y := \text{OFFSET0} \cdot e^{-t_Y \cdot \text{KOFF}}$$

$$\text{WS}_Y := \text{WSAVG} + \text{COSA}_Y + \text{COSB}_Y + \text{OFFSET}_Y$$

$$\text{IWS}_Y := \text{WS}_Y \cdot \text{IBASE} \quad \text{IWSAVG} := \text{WSAVG} \cdot \text{IBASE} \quad \text{ITOT}_Y := \text{IWS}_Y + \text{INWS}_Y$$

CLSIM131

Short Outage Cold Load Pickup via "Harmonic Model"

Case = 0

minutes
 ONTIM 60 = 31.992
 OFFTIM 60 = 60.598
 PERIOD 60 = 92.59

IWSAVG = 19.929
 TAMB = 40
 OUTDUR = 0

INWS = 38
 V = 1

minutes, must be < OFFTIM

CLSIM131 Short Outage Cold Load Pickup via "Harmonic Model" Case = 1

minutes
 ONTIM 60 = 31.992
 OFFTIM 60 = 60.598
 PERIOD 60 = 92.59

IWSAVG = 19.929
 TAMB = 40
 OUTDUR = 10 minutes, must be < OFFTIM

INWS = 38
 V = 1

CLSIM131 Short Outage Cold Load Pickup via "Harmonic Model" Case = 2

minutes
 ONTIM 60 = 31.992
 OFFTIM 60 = 60.598
 PERIOD 60 = 92.59

IWSAVG = 19.929
 TAMB = 40
 OUTDUR = 20 minutes, must be < OFFTIM

INWS = 38
 V = 1

CLSIM131 Short Outage Cold Load Pickup via "Harmonic Model" Case = 3

minutes
 ONTIM· 60 = 362.389
 OFFTIM· 60 = 22.237
 PERIOD· 60 = 384.627

IWSAVG = 54.343
 TAMB = -10
 OUTDUR = 10 minutes, must be < OFFTIM

INWS = 38
 V = 1

CLSIM131 Short Outage Cold Load Pickup via "Harmonic Model" Case = 4

minutes
 ONTIM· 60 = 362.389
 OFFTIM· 60 = 22.237
 PERIOD· 60 = 384.627

IWSAVG = 54.343
 TAMB = -10
 OUTDUR = 20 minutes, must be < OFFTIM

INWS = 38
 V = 1

CLSIM132 ontim/offtim/period matrix 17Aug92 y := 0 ..20 t := $\frac{y}{10}$
Long Outage Case := 6 y 10
N := 23 Q := 0.999 R := 1.2 C := 12.199 TAU := R · C KCOS := 3
TU := 70 TLOW := 68 TBASE := 70 KOFF := 8 KPK := 0.2
IBASE := 20000 · $\left[\frac{\sqrt{3}}{13800} \right]$ INWS := 38 ampere per house OUT := $\frac{\text{OUTDUR}}{60}$
ONTIM := $-R \cdot C \cdot \ln \left[\frac{\frac{TU - TAMB}{TBASE} - Q \cdot R}{\frac{TLOW - TAMB}{TBASE} - Q \cdot R} \right]$ OFFTIM := $-R \cdot C \cdot \ln \left[\frac{TLOW - TAMB}{TU - TAMB} \right]$
PERIOD := ONTIM + OFFTIM
WSAVG := $N \cdot Q \cdot \left[\frac{\text{ONTIM}}{\text{PERIOD}} \right]$ IWSAVG := $\frac{\text{WSAVG}}{V}$
OMEGA := $2 \cdot \frac{\pi}{\text{PERIOD}}$ LOWTEMP := TAMB + (TU - TAMB) · $e^{\frac{-\text{OUT}}{\text{TAU}}}$
ALLON := $-R \cdot C \cdot \ln \left[\frac{\frac{TLOW - TAMB}{TBASE} - Q \cdot R}{\frac{\text{LOWTEMP} - TAMB}{TBASE} - Q \cdot R} \right]$ CC := $\sin \left[\frac{\text{ONTIM}}{\text{PERIOD}} \cdot \pi \right]$
E := $1 - e^{\frac{-\text{OUT} \cdot \text{KCOS}}{\text{TAU}}}$
 $\text{COSA}_Y := \frac{\text{KPK} \cdot \text{CC} \cdot \text{N} \cdot \text{Q}}{V} \cdot \cos \left[\text{OMEGA} \cdot t_Y + \frac{\pi}{2} - \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right]$
 $\text{COSB}_Y := \frac{\text{KPK} \cdot \text{CC} \cdot \text{N} \cdot \text{Q}}{V} \cdot \cos \left[\text{OMEGA} \cdot t_Y - \frac{\pi}{2} + \frac{\pi}{2} \cdot E \cdot e^{-\text{KCOS} \cdot t_Y} \right]$
 $\text{OFFSET0} := \left[\frac{\text{N} \cdot \text{Q} \cdot \text{OFFTIM}}{V \cdot \text{PERIOD}} - \text{COSA}_0 - \text{COSB}_0 \right]$
 $\text{OFFSET}_Y := \text{OFFSET0} \cdot e^{-t_Y \cdot \text{KOFF}}$
 $\text{WS}_Y := \text{WSAVG} + \text{COSA}_Y + \text{COSB}_Y + \text{OFFSET}_Y$ TIME := ALLON + t
 $\text{IWS}_Y := \text{WS}_Y \cdot \text{IBASE}$ IWSAVG := WSAVG · IBASE ITOT := IWS_Y + INWS_Y

CLSIM:32

Long Outage Cold Load Pickup via "Harmonic Model"

Case = 6

amperes

ALLON = 0.119 hours

TIME - hours

minutes
 ONTIM: 60 = 31.992
 OFFTIM: 60 = 60.598
 PERIOD: 60 = 92.59

LOWTEMP = 67.545

IWSAVG = 19.929

TAMB = 40

OUTDUR = 75

INWS = 38

V = 1

minutes, must be > OFFTIM

CLSIM:32

Long Outage Cold Load Pickup via "Harmonic Model"

Case = 7

amperes

ALLON = 0.239 hours

TIME - hours

minutes
 ONTIM: 60 = 31.992
 OFFTIM: 60 = 60.598
 PERIOD: 60 = 92.59

LOWTEMP = 67.078

IWSAVG = 19.929

TAMB = 40

OUTDUR = 90

INWS = 38

V = 1

minutes, must be > OFFTIM

CLSIM132

Long Outage Cold Load Pickup via "Harmonic Model"

Case = 8

CLSIM132

Long Outage Cold Load Pickup via "Harmonic Model"

Case = 9

val

38A

Time: 03:00 04-27-92

val

63A

Time: 00:00 04-04-92

Time: 23:00 06-26-92

FINAL PROJECT REPORT

ANALYTICAL TOOLS to PREDICT
DISTRIBUTION FEEDER OUTAGE RESTORATION LOAD

APPENDIX D

**"MEASURED AND PREDICTED COLD LOAD PICKUP AND FEEDER
PARAMETER DETERMINATION USING THE HARMONIC MODEL ALGORITHM**

a paper presented to the

IEEE POWER ENGINEERING SOCIETY
Summer 1994 Meeting
San Francisco, California

and published in the IEEE Transactions

MEASURED AND PREDICTED COLD LOAD PICK UP AND FEEDER PARAMETER DETERMINATION USING THE HARMONIC MODEL ALGORITHM

John Law, Senior Member, IEEE
University of Idaho
Moscow, Idaho

Donald Minford, Senior Member, IEEE
Kootenai Electric Cooperative
Hayden, Idaho

Larry Elliott, Nonmember, IEEE
Elliott Electrical Engineering
Moscow, Idaho

Michael Storms, Member, IEEE
Bonneville Power Administration
Spokane, Washington

Abstract - This paper presents theory of the "Cold Load Harmonic", CLHARM, model algorithm for simulation of power feeder currents resulting from both Cold Load Pickup, CLPU, and the "Step Voltage Test", STEPV. The STEPV method is also presented. Feeder parameters obtained from field STEPV measurement are used to predict CLPU on that feeder using the CLHARM algorithm. STEPV test measurements and actual measured CLPU currents on the same feeder are compared with computer predictions. The CLHARM aggregates feeder thermostatically controlled load to simulate regain of diversity during outage restoration. All feeder weather sensitive load is lumped in CLHARM, using mean parameter values of a simple thermodynamic model. The ultimate objective of this work is experimentally obtained feeder "signatures" for CLPU prediction as a feeder design tool.

Key Words: Feeder, outage, restoration, diversity, Cold Load Pickup, Step Voltage Test.

I. INTRODUCTION

Cold Load Pickup, CLPU, is the load on an electric power feeder after service has been restored following an outage during cold weather. As a result of loss of diversity among thermostatically controlled electric heating units during the outage, feeder load may exceed twice normal load and endure for some time. CLPU can be severe on feeders with a large percentage of electric heating load. Transformer and conductor overheating may result. Service restoration may be difficult. Sectionalizing may be required. Feeder design and cost, relay settings, fuse sizing and coordination are influenced by CLPU.

Throughout restoration, feeder load stochastic properties result in regain of diversity and load returns to normal. CLPU magnitude and duration depend on ambient temperature, outage duration, feeder parameters and restoration procedures. During normal days, diversity varies with changes in ambient temperature, voltage and other factors.

II. BACKGROUND AND MODEL BASIS

A. CLPU Prediction

Prediction of CLPU is essential to transformer rating, feeder configuration, wire size, sectionalizing, protection requirements, and maintenance and restoration procedures. From a transmission viewpoint, modeling of the aggregate CLPU response is a factor in voltage stability analysis [1]. Present CLPU prediction methods include "guestimation" factors based on experience and specific practical knowledge of a feeder, manual application of REA Demand Tables [2], and commercially available PC software which includes the REA Demand Tables diversity factors.

94 SM 546-2 PWRS. A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1994 Summer Meeting, San Francisco, CA, July 24-28, 1994. Manuscript submitted December 30, 1993; made available for printing June 1, 1994.

The "Cold Load Harmonic", CLHARM, model algorithm of this paper was developed to enable simplified simulation of CLPU. CLHARM also enables simulation of the proposed "Step Voltage Test", STEPV, method used to measure feeder parameters required to predict CLPU with the CLHARM. The CLHARM concept evolved from MS Thesis work by Athow [3]. Work presently underway in load restoration relative to CLPU is reported by Price and Ihara [4]. A "Least Cost" method and a large scale computer program to obtain feeder parameters from STEPV data was developed by Hunt [5]. Hunt's algorithm is elegant and accurate, but is computer intensive.

B. Diversity

Diversity of feeder thermostatically controlled electric heating load, as observed in feeder restoration current, is assumed regained in an exponential manner. The result is a "swing" or periodicity in the WS component of CLPU, as noted in the 1949 testing by Niagara Mohawk [6] and predicted by Price and Ihara [4] and Athow [3]. The wave form may resemble an underdamped servo response, depending on outage duration and other factors. If ideally all heating units and their environments were identical, all units would turn off at the same time and WS load would be zero until all of the thermostat low set points were reached; a "step" wave of WS current would result without diversity.

The Athow [7] random variable CLPU model utilizes statistically assigned parameters to a large number of units and achieves regain of diversity by causing random variations in all unit on/off times. The Athow model is computer intensive, but provides an excellent research tool. CLHARM models the regain of diversity as an exponential decay for rapid, simple solution, but is less flexible as a research tool. With both short and long outages, periodicity of the WS load may not be noticeable, in particular if WS load is a small percentage of the total feeder load. Following a long outage, the enduring WS component of CLPU load persists until all thermostats are operating within their deadband. WS load then decays exponentially to normal load.

C. Assumptions

Total feeder load is assumed to be the sum of weather sensitive, WS, and nonweather sensitive, NWS, current. The CLHARM assumes that all WS load may be lumped as thermostatically controlled on/off and with parameters corresponding to a mean parameters thermodynamic model of the feeder. NWS load is assumed constant at a value predicted for the feeder temperature for the day and time of day of the outage. WS and NWS loads are estimated from customer billing and Fast Fourier Transform, FFT, analysis of feeder STEPV test data.

CLPU current is calculated at one minute intervals and does not include the several milliseconds of inrush current. Thus the time zero current at reclosure corresponds to the RMS phase current data as recorded by load logger type instruments. WS current is assumed to take several seconds to change from zero at reclosure. This corresponds to typical thermostatically controlled central electric space heating units which utilize timed stage start of several heating elements.

MODEL

The basic thermodynamic building block utilized in the CLHARM model is shown in Fig. 1. Acronyms used in this paper are defined as they are introduced and are summarized in the Appendix for easy reference.

Fig. 1. CLHARM circuit analog of electrically heated house thermodynamic model

A. Thermostat Model

The thermostat model of CLHARM is given in Fig. 2, showing the hysteresis. Thermostat anticipation is not included. When heated space temperature reaches the upper set point temperature T_U , the thermostat contacts open and injected heat $Q = 0$. Thermostat contacts close when heated space temperature reaches T_{LOW} , the lower switch point. The thermostat differential is $T_U - T_{LOW}$ and is about 2 degF for most units.

Fig. 2. Thermostat Hysteresis Characteristic

B. Electric Heating Cycle

Solution of the differential equations for the thermodynamic model are given by Athow (3). Solution yields the thermostat cycle of heated space temperature versus time of Fig. 3. During the off time, temperature decreases exponentially to the thermostat lower set point.

Fig. 3. Thermostat and Heating Cycle

The heating cycle results in the dotted line "step wave" of current of Fig. 4. The sinusoid is the fundamental component of the step wave. The magnitude and time phase of this fundamental component may be obtained by FFT analysis of experimental feeder measurements, as discussed below.

"Step" Wave and Fundamental

Fig. 4. "Step" Wave of Heating Unit Current

C. CLHARM Concept

The CLHARM algorithm concept is analogous to the air gap field model of a two-phase servomotor in which superimposed synchronous-speed contra-rotating constant-magnitude sinusoidal air gap fields model unbalanced conditions. Balanced two-phase operation results in a constant magnitude synchronously rotating field. This corresponds to perfect diversity of feeder thermostatically controlled electric heating load with resulting lowest and steady RMS aggregate current. Unbalanced two-phase servomotor operation results in a time varying air gap field. This corresponds to feeder non-diverse thermostatically controlled electric heating load and resulting RMS aggregate current that is time varying.

The period of the fundamental Fourier component of the current step wave is a sinusoid of period that is the sum of the unit off-time, OFFTIM, and on-time, ONTIM. The crux of the CLHARM concept is the division of the total WS load into two step waves, A and B, whose phase relationship relates to diversity, as shown in Fig. 5. The average value of each of A and B step wave is one half of the WS total average value. Sinusoids COSA and COSB are the fundamental components of step waves A and B respectively. ALPHA is the phase difference between sinusoids COSA and COSB.

Fig. 5. COSA and COSB WS Component Currents

Perfect diversity occurs with ALPHA equal to 180 degrees phase angle. For complete "undiversity", ALPHA is zero. Under normal operating conditions, ALPHA is near 180 degrees and some small time variation is normally present in the WS load. ALPHA at reclosure is determined by the outage duration and ambient temperature. Both are user inputs to the CLHARM algorithm, as well as the feeder parameters.

The ratio of ONTIM to PERIOD determines the magnitude and phase of the higher Fourier components. Thus a FFT analysis of the feeder current waveform can be used to obtain the mean period and ONTIM/OFFTIM ratio for the WS load. The ratio enables calculation of the mean values of the feeder thermostatically controlled electric heating model of Fig. 1 from STEPV measurement.

Observation of normal feeder current shows that periodic variations in current occur with rapid change in ambient temperature. The variations are similar to those observed with CLPU and STEPV response. These variations are probably also due to change in diversity, driven by temperature change. This phenomena may, if properly interpreted, provide a basis to obtain feeder "signature" parameters with simple load logger measurements or SCADA.

EQUATIONS

The equations of CLHARM, given in the Appendix in the form and order in which they appear in the authors' PC math software solution, are discussed below by equation number. These equations are utilized in both CLPU and STEPV solutions for various parameters, step voltage change, ambient conditions and outage duration. The STEPV algorithm is slightly different from CLPU and is discussed below under ALGORITHM FOR STEP VOLTAGE CHANGE. The reader may use the equations, after defining parameters, to readily obtain CLPU solution.

A. Thermodynamic Model Equations

Equations (1) through (18) describe the behavior of the circuit and are derived from the Fig. 1 thermodynamic model differential equations; see Athow [3]. The ambient temperature, TAMB, is a user input to CLHARM. Circuit model analogy current source, Q , capacitance C and resistance R represent respectively the heating unit capacity and net house thermal capacity and insulation. All parameters are defined in the Appendix.

With normal operation, the unit OFFTIM and ONTIM intervals and PERIOD are obtained by equations (1), (2) and (3) respectively. Temperature of the heated space is inherent in the equations and not explicitly obtained.

The thermodynamic time constant, τ , of equation (4) is the product of thermal resistance, R , and thermal capacitance, C . τ is in the order of seven hours for a typical feeder residence. With the feeder off, the heated space temperature would coast down exponentially from the thermostat set point value to ambient temperature with time constant τ . ω of equation (5) is the radian fundamental frequency of the PERIOD.

The WS average, WSAVG, a per unit quantity, is obtained by equation (6). WS average current is the product of WSAVG and IBASE, the feeder base current at primary voltage and is given by equation (16).

B. Diversity Equations

Of frequency ω , sinusoids $\cos \alpha$ and $\cos \beta$ respectively are generated by equations (10) and (11). N is the number of electric space heated units (houses, if all residential) and Q the mean value in per unit of the heating unit capacity of the feeder phase of interest. Q is estimated by the feeder engineer based on knowledge of the feeder area and building construction and KWH billing records. α , the phase angle difference between $\cos \alpha$ and $\cos \beta$, is an exponential time function as given by equation (9). Under ideal steady state perfect diversity conditions, α is zero. Subscript y is the time index for computer solution of equations (8), (9) and (10).

The factor E is an exponential function of outage duration, OUT , and ambient temperature. The factors K_E , K_T and K_{COS} are empirical "signatures" of the feeder of interest and are obtained experimentally from CLPU and STEPV measurement.

Equations (12) and (13) define the per unit OFFSET current required to make the net WS current zero at time zero of reclosure. OFFSET current decays exponentially at the inverse time constant K_{OFF} , also a feeder "signature" factor.

Time varying weather sensitive current, IWS , is obtained by equation (14) by multiplication of the sum of the WS components by IBASE. Equation (15) provides total feeder current, the sum of IWS and the non-weather sensitive current $INWS$ in amperes at primary voltage.

For an outage that exceeds the mean OFFTIM of the mean thermodynamic cycle, all units will be on at reclosure. All units remain on for a time $ALLON$, equation (18), in minutes until the first unit recovers. Equation (18) requires determination of $LOWTEMP$, the

lowest temperature; obtained by equation (17), for the given ambient temperature and outage duration reached by any unit prior to reclosure.

ALGORITHMS

A. CLPU Algorithm

The CLPU equations described above were solved using PC math software and subsequently programmed in C++ for DOS and Windows utilization. Fig. 6 shows a short outage example that is easily obtained by PC math software for the feeder parameters, outage duration and ambient temperature values given with the definition of parameters in the Appendix.

The curves of Fig. 6 are the restoration total phase current in amperes at primary voltage. The steady state total current is approximately 200 amperes, of which the weather sensitive portion, $IWSAVG$, is about 50 amperes. The solid line is the CLHARM predicted restoration current. The "ragged" curve is actual restoration current of the Appleway 51 feeder of the Kootenai Electric Cooperative, Coeur d'Alene, Idaho for a 25 minute outage at TAMB = 28 degrees Fahrenheit. The outage occurred at 15:54 hours on 20 January 1993.

Fig. 6. Predicted and Measured Short Outage CLPU

Fig. 7 shows CLHARM predicted response for an outage greater than the OFFTIM of the mean heating cycle. In this case, all WS load is on, $ALLON$, for about 20.4 minutes, during which feeder current is over 300 amperes. The outage was about 100 minutes at TAMB of 20 degF. Calculated steady state IWS and $INWS$ component currents are 49.5 and 152 amperes respectively, for a total of 201.5 amperes. Normal Appleway load on this day of the year and time of day is about 200 amperes. This demonstrates the algorithm function at long outage. No confirming experimental evidence is yet available to the authors for a long outage on the feeder under study.

Fig. 7. Predicted long outage CLPU response

B. STEPV Algorithm

Because no outage is involved, use of the CLHARM algorithm for solution of STEPV involves simply defining the feeder ambient temperature, initial voltage, the step change in voltage, and calculating both the old and new ONTIM values. OFFTIM will of course be the same because TAMB is the same. The STEPV test is conducted in a

substation by placing the feeder voltage regulators in manual and then raising or lowering the feeder phases regulators to a new fixed positions while staying within safe operating limits.

The STEPV equations based on CLHARM were also solved using PC math software and subsequently programmed in C++ for DOS and Windows utilization. Fig. 8 shows an example STEPV calculation for a step increase of voltage of 0.03 per unit and the feeder parameters and ambient temperature values given with the definition of parameters in the Appendix.

Only the change in the weather sensitive component current, IWS, in amperes at primary voltage is given in the plot of Fig. 8. After the STEPV, the change in WS current would be superimposed on the pre-STEPV feeder current. Note that with a step increase in feeder voltage to accomplish the STEPV test, the final steady state current, 40.2 amperes, will be less than the original steady state current, 41.4 amperes. The single phase RMS voltage times the RMS current product is, for a given time, the energy. Energy is a constant in the steady state for the thermodynamic system with STEPV.

Fig. 8. Predicted STEPV response, $KCOS=4$
IWSOLDAVG = 41.4 IWSNEWAVG = 40.2 amp

One observation in this work is that actual feeder data for STEPV show that the change in weather sensitive current decays much more slowly than anticipated. Possibly the decay coefficient, $KCOS$, employed in the CLPU algorithm is not appropriate for STEPV. Perhaps the describing phenomena (before and after outage for CLPU) and time required to bring all units within the thermostat deadband differ from the STEPV situation in which all units remain within the deadband. This requires further research. Thus a different STEPV $KCOS$ value of 0.1 was employed with the CLHARM algorithm to reproduce results akin to experimental observations. Fig. 9 shows the STEPV response for a step increase of voltage of 0.03 per unit and the feeder parameters and ambient temperature values given with the definition of parameters in the Appendix, except for the $KCOS$ value. As discussed below and illustrated in Figures 11 and 12, Fig. 9 more nearly models observed STEPV induced WS components of feeder currents.

Fig. 9. Predicted STEPV response, $KCOS=0.1$

Both the CLPU and STEPV algorithms use only the fundamental sinusoidal components, $COSA$ and $COSE$. The authors believe this gives a sufficiently accurate representation of both the STEPV and CLPU responses of an actual feeder for practical engineering design purposes. However, in the analysis and results reported below, higher order harmonics were included in the overall detailed analysis in order to more closely correlate with actual recorded feeder data and to illustrate the superposition of pre-STEPV diversity with STEPV caused change in feeder diversity in the current waveforms.

INSTRUMENTATION AND DATA PROCESSING

A. Load Loggers

The currents of the three phases of the feeder of interest were obtained using line mounted current recorders, load loggers, that are self contained battery operated units placed on each phase with a "hot stick". The loggers were set to take a data point every minute during the STEPV tests and during the winter and summer high load seasons to, hopefully, capture a CLPU (or HLP, hot load pickup). At the one minute sampling rate, four days of data may be collected. During the Spring and Fall low load seasons, the loggers were set to sample at a 15 minute rate to collect three months of load curve data. At present, Kootenai Electric Cooperative, KEC, records of KWh billing and spot load KW values are being evaluated relative to temperature data from the National Weather Service to correlate feeder load throughout the year in order to separate WS and MWS load for employing the CLHARM model. The CLHARM model neglects wind, rain and solar insolation, which can be significant factors in WS load. Predicted WSAVG load should be modified to account for the latter.

Commercial software and associated interfacing units are used to initialize the loggers and to download the logger recorded data to PCs. The commercial software is then used to analyze the data and transport data to spreadsheet file for manipulation. The resulting file is utilized with PC math software to conduct FFT analysis to obtain feeder parameters and subsequently to compare field data with CLHARM prediction of CLPU and STEPV.

B. Remote Sampling Unit

A "Remote Sampling Unit", RSL, consisting of a cellular telephone, modem, SEL251 Distribution Relay, power supplies and connections to feeder and bus current and voltage transformers, respectively, was assembled in a portable case for additional data collection capability. At present the RSL enables telephone access to feeder RMS and several cycles of instantaneous voltage and current status. The digital relay can be remotely triggered to record an event (several cycles, as do digital relays during fault situations), from which real and reactive power and power factor are determined. Work is underway to add a controller to the RSL to recognize and record two hours of restoration data for detailed remote acquisition of CLPU data.

KOOTENAI ELECTRIC COOP APPLEWAY 51 FEEDER

Work discussed in this paper is a cooperative effort of the Bonneville Power Administration, KEC and the University of Idaho. The KEC Appleway 51 feeder, Coeur d'Alene, Idaho, was selected for the measurements and studies done during the past two years. Although Appleway 51 feeder is lightly loaded, it contains a mix of residential and commercial load that is fairly typical in the Pacific Northwest. The feeder has approximately 301, 244 and 229 customers on phases A, B and C, respectively. In January 1993 each phase also had about 700 KW spot load and approximately 560 MWh energy per phase.

STEPV tests can be obtained at will by watching for the appropriate weather window. Obviously, obtaining CLPU data is uncertain. The load loggers, set at the one minute sampling interval, and maintained on the phases to, hopefully, captured a CLPU. Only one CLPU was captured in this project and is reported herein. (Good for customers, but not for the project!)

STEP VOLTAGE TEST PROCEDURE

A. Field Procedure

The instrumentation and procedure discussed above was used to obtain STEPV data. With the load loggers set for one minute interval sampling rate, the Appleway 51 feeder voltage regulators were placed in manual. The regulator taps were moved manually to achieve the largest reasonable, about 3 per cent, increase (or decrease) in voltage. The loggers were retrieved the following day and data downloaded to PC. Early morning hours were chosen to perform STEPV because load is relatively flat and the ratio of WS to NWS load is highest at night.

B. Data Processing Procedure

Raw data was scanned and converted with the commercial software and a file of STEPV current created. The file was then edited and spread sheet manipulated to select, graph and file the STEPV data segment of interest. Total WS and change, dWS, files were then created. Appleway feeder STEPV total phase C current, is given in Fig. 10. The "ragged" curve of Fig. 11 is the change in C phase WS current. Several appropriate other days of data were averaged and scaled to match the load just prior to the STEPV test. The average was subtracted from the total phase C current to obtain the change in WS current. It is assumed that the change in voltage mainly affects resistive, thus WS load current, and that the long term WS energy is nearly constant for the same TAMB. This also assumes that some weather sensitive loads types increase in current while others decrease. Total NWS load is thus considered essentially insensitive to STEPV.

Fig. 10 Appleway 51 Phase C STEPV 00:33-7 Mar 92

The solid line sine curve of Fig. 11 is the FFT estimated magnitude and phase of the fundamental component of change in WS load that was STEPV initiated at 00:33 hours. Note the relatively small variation or noise of C phase load just prior to the STEPV. This is the most nearly perfect feeder diversity observed in these tests.

Fig. 11 Phase C STEPV Currents, dWS meas & predicted

Change in WS current is then FFT analyzed. Table 1 gives the spectrum of magnitude and phase of the "dc" (average), fundamental frequency and higher harmonic components of the WS current. STWV and MEAS are, respectively, the harmonic magnitudes of the ideal step wave and measured data waves as functions of the harmonic numbers k and n . $k = 0$ is the "dc" or average level. The FFT fundamental component gives the period, PERIOD, of the feeder mean thermostatically controlled cycle, which can be roughly estimated from the Figures 10 and 11 actual feeder data.

STWV		MEAS	
n	n	k	k
1	10.363	8.344	0
2	3.495	10.357	1
3	1.883	3.494	2
4	2.7	2.295	3
5	0.327	1.405	4
6	1.616	3.137	5
7	1.168	2.092	6
8	0.523	1.229	7
9	1.222	0.819	8
10	0.324	0.67	9
11	0.801	1.115	10
12	0.765	0.497	11
13	0.202	1.151	12
		0.342	13

Table 1 - C Phase FFT dWS Spectrum

C. On/Off Cycle & Feeder Phase C STEPV Results

The best match, Table 1, of the actual spectrum in comparison to the harmonic spectrum of a "pure" theoretical step wave is then made in order to obtain the on/off ratio of the feeder mean thermostat cycle. For C Phase post STEPV, the ratio of 1st to 2nd harmonics is $10.357/3.494 = 2.964$. The PERIOD of the C phase STEPV cycle is established as 42 minutes. The on/off ratio from FFT spectrum matching is calculated to be 0.391 minutes. This yields ONTIM and OFFTIM values respectively of 16.4 and 25.6 minutes. The ONTIM, OFFTIM and WSAVG are calculated respectively by equations (1), (2) and (3).

With STEPV increased feeder voltage, feeder thermostatically controlled electric heating load will have a new higher heat output, Q , and thus a shorter ONTIM. The result is rearrangement of the actual individual unit step electrical loads, producing the change in diversity evident in the data after the STEPV imposition.

Assuming a thermostat upper setpoint, TU , of 70 degrees Fahrenheit and a 2 degF thermostat differential, the low set point temperature, $TLOW$, is 68 degrees. Note that the thermostat differential value is critical to the on/off cycle period. The product of thermal resistance, R , and thermal capacitance, C , can now be obtained from equation (1). N , the equivalent number of electric heating units on that phase is calculated using equation (2) by assuming a mean electric heating unit capacity, Q , of 20 KW = 68,230 BTU/hour. The Q value estimate requires KWh billing and/or familiarity with the construction of the area generally served by the feeder. The $N \cdot Q$ product is of main concern. The feeder mean parameters Q , N , R , C , TU and $TLOW$ are then input to the STEPV program along with ambient temperature, $TAMB$, and outage duration, $OUTDUR$, to produce the example theoretical curves like those of Figs. 8 and 9. Note again that KCOS determines the rate of recovery of diversity.

D. Feeder Phase A STEPV Results

The "ragged" curve of Fig. 12 is the phase A change in WS load. Nondiversity is now observed in the pre 00:33 hours STEPV current. FFT analysis of the data prior to STEPV yields the pre-STEPV PERIOD, ONTIM and OFFTIM. The continuing (after STEPV imposition) pre STEPV fundamental is now subtracted from the total post STEPV change in WS current. This difference is the change in WS current due only to the STEPV and is now FFT analyzed to obtain the post STEPV PERIOD, ONTIM and OFFTIM.

Fig. 12 Phase A Actual and Predicted STEP V

The pre and post STEP V fundamental sinusoids of slightly different periods due to different pre and post STEP V values of Q are then superimposed to provide a measure of the change in WS pre and post STEP V currents.

At first only the fundamental components of pre and post STEP V sinusoids were utilized with disappointing results. The shorter period (higher frequency) current peaks of the actual data were not predicted. It was discovered that the pre and post STEP V fundamental components of A phase (by coincidence and a result of the phase at which the STEP V test was humanly initiated) just happened to be nearly 180 degrees out of phase and nearly cancel. It was further discovered that the second and some higher order harmonics of the pre and post STEP V waves obtained by FFT were of phase relationship that they reinforced one another. This explains the observed predominance of the double and other higher frequency peaks in the actual currents.

E. Inclusion of Higher Order Harmonics

The theoretical post STEP V portion of the curve of Fig. 12 contains fundamental, 2nd, 3rd and 4th harmonics in proper phase relationship of both the pre and post STEP V currents. The net result is a predicted curve that approaches the measured curve in magnitude and form. Unfortunately, the higher order harmonics (in particular for small or large on/off ratios) obtained from FFT analysis contain significant energy. With $ONTIM = OFFTIM$, unity on/off ratio, all FFT even order harmonics are zero. The step response is "cleaner", with the conclusion that the STEP V test should ideally be done at the corresponding TAMB, instead of the coldest ambient, for best results. Inclusion of additional higher order harmonics may provide better match of predicted and theoretical STEP V results verification than with only the fundamental. However, only the fundamental wave appears warranted for CLPU prediction.

CLPU FIELD TEST AND DATA PROCESSING PROCEDURE

The same instrumentation and data processing procedures are used for CLPU as with STEP V. However, instead of imposing a step voltage, the load loggers are left on the feeder until an outage has occurred. The loggers retain four days of data at the one minute sampling rate and thus must be removed from the feeder and data downloaded to PC within less than four days after feeder restoration.

A. Results

Using the feeder parameters obtained via STEP V for the phase of interest, the CLHARM CLPU PC math software algorithm was used to predict the CLPU recorded on the Appleyway 51 feeder A phase. The outage occurred at 15:54 hours on 20 January 1993. Service was restored and the feeder breaker closed at 16:18 hours, a 25 minute outage at TAMB of 28 degrees Fahrenheit.

Fig. 13 shows four CLPU curves: a) actual total feeder current, b) feeder change in WS current obtained by subtracting the normal load pattern taken by averaging and scaling two previous days of data prior to the outage, c) the predicted change in WS load and d) the predicted total feeder load. Slight adjustments in the "feeder factor" KCOs and others were necessary to model the feeder. Future restoration recordings (if obtained!) and analysis are desired to confirm the parameters and factors.

Fig. 13 A Phase CLPU Currents, Appleyway 20Jan92

CONCLUSIONS AND RECOMMENDATIONS

The CLHARM algorithm for both STEP V and CLPU gives predicted results that appear to confirm the harmonic modeling technique and compare favorably with the detailed Athow [2] model results for both CLPU and STEP V response.

CLHARM readily enables step voltage, STEP V, prediction and analysis of test results to provide a basis to obtain feeder parameters for CLPU prediction.

The CLHARM empirical method to predict CLPU and STEP V response is relatively simple and provides fast solution algorithms.

Further field testing and refinement are necessary to verify the technique, in particular by obtaining additional KEC Appleyway feeder CLPU events (as available) as well as other feeder parameters by STEP V and CLPU data. The EPRI voltage stability recording program with some 300 data acquisition units in place nationally may provide the needed data and assistance.

Instrumentation and data processing methods need refining and systemizing. Techniques and software to evaluate utility billing information for use with CLHARM techniques are needed.

Although preliminary C++ language DOS and Windows software based on CLHARM have been developed at the University of Idaho, the software must be refined and included in commercially available software.

A CLHARM technique which utilizes the TAMB driven change in feeder thermostatically controlled electric heating load appears to hold promise and would obviate the need for STEP V testing. Such technique would enable ready gathering of feeder "signatures" via SCADA. This identifies a promising research area that would benefit from analogous existing digital signal processing and control technology.

Finally, a technique to utilize CLHARM for aggregate feeder modeling for Voltage Stability studies awaits further research effort.

ACKNOWLEDGEMENT

This research is funded by the Bonneville Power Administration, Portland, Oregon. Prior work by Athow and Law [3,7] was funded by the Washington Water Power Company, Spokane, Washington.

REFERENCES

- 1) C.W. Taylor and G. L. Comegys, "Bonneville Uses LOADSYN for Voltage Stability Analysis," Power System Dynamics, March 1991.
- 2) Demand Tables, REA Bulletin 45-2, Rural Electrification Administration, U.S. Department of Agriculture, June 1963.
- 3) D. Athow, "Development and Applications of a Model for Cold Load Pickup", M. S. Thesis, Department of Electrical Engineering, University of Idaho, January 1987.

4) W. W. Price and S. Ihara, "Special Consideration in Power System Restoration, The Second Working Group Report: Col Load Pickup - Modeling", 93 WM 202-2 PWRD.

5) M. Hunt, "Development of a General Purpose Nonlinear Optimization Algorithm with Applications to the Harmonic Model Analysis of the Cold Load Pickup Problem", M. S. Thesis, Department of Electrical Engineering, University of Idaho, December 1987.

6) L. J. Audlin, M. H. Pratt and A. J. McConnell, "New Relay Assures Feeder Resumption After Outage", parts 1 & 2, Electrical World, September 10, 1949, pp. 99-103 & September 24, 1949, pp. 95-98.

7) D. Athow and J. Law, "Development and Applications of a Random, Variable Model for Cold Load Pickup, paper presented at IEEE PES Meeting Winter 1994, 94 WM 073-7 PWRD.

APPENDIX

The equations of the CLHARM model for CLPU and STEPV are given below taken directly from the authors' PC math software solutions.

$$ONTIM := -R \cdot C \cdot \ln \left[\frac{\frac{TU - TAMB}{TBASE} - Q \cdot R}{\frac{TLOW - TAMB}{TBASE} - Q \cdot R} \right] \quad (1)$$

$$OFFTIM := -R \cdot C \cdot \ln \left[\frac{TLOW - TAMB}{TU - TAMB} \right] \quad (2)$$

$$PERIOD := ONTIM + OFFTIM \quad (3)$$

$$TAU := R \cdot C \quad (4)$$

$$OMEGA := \frac{2 \cdot \pi}{PERIOD} \quad (5)$$

$$WSAVG := N \cdot Q \cdot \left[\frac{ONTIM}{PERIOD} \right] \quad (6)$$

$$CC := \sin \left[\frac{ONTIM}{PERIOD} \cdot \pi \right] \quad (7)$$

$$E := \left[1 - e^{-(OUT \cdot KE)} \right] \cdot \left[1 - e^{-\left[\frac{TU - TAMB}{TU} \cdot KT \right]} \right] \quad (8)$$

$$\alpha_y := \frac{\pi}{2} \cdot E \cdot e^{-KCOS \cdot t_y} \quad (9)$$

$$COSA_y := \frac{KPK \cdot CC \cdot N \cdot Q}{1 \cdot V} \cos \left[OMEGA \cdot t_y + \frac{\pi}{2} - \alpha_y \right] \quad (10)$$

$$COSB_y := \frac{KPK \cdot CC \cdot N \cdot Q}{1 \cdot V} \cos \left[OMEGA \cdot t_y - \frac{\pi}{2} + \alpha_y \right] \quad (11)$$

$$OFFSET0_y := COSA_y + COSB_y + WSAVG \quad (12)$$

$$OFFSET_y := OFFSET0_y \cdot e^{-t_y \cdot KOFF} \quad (13)$$

$$IWS_y := \left[WSAVG + COSA_y + COSB_y - OFFSET_y \right] \cdot IBASE \quad (14)$$

$$ITOT_y := IWS_y + INWS_y \quad (15)$$

$$IWSAVG := WSAVG \cdot IBASE \quad (16)$$

$$LOWTEMP := TAMB + (TU - TAMB) \cdot \frac{-OUTDUR}{TAU} \quad (17)$$

$$ALLON := -R \cdot C \cdot \ln \left[\frac{\frac{TLOW - TAMB}{TBASE} - Q \cdot R}{\frac{LOWTEMP - TAMB}{TBASE} - Q \cdot R} \right] \quad (18)$$

Acronym	Units/Definition
Feeder Parameters	
Q = 1	pu, KW, BTU/h
	heat capability
TU = 70	degF, pu
	thermist upper switch temp
TLOW = 68	degF, pu
	thermist lower switch temp
R = 2.3	pu,
	thermal resistance
C = 9	pu,
	thermal capacitance
N = 65	equivalent number units

Feeder Factors	
KPK = 1	cos magnitude
KE = 2	1/min
	ALPHA magnitude
KT = 4	1/degF
	ALPHA magnitude
KCOS = 4	1/min
	ALPHA decay
KOFF = 40	1/min
	OFFSET decay

Inputs	
TAMB = 28	degF
	ambient temperature
OUTDUR = 25	min
	outage duration
dv = 0.03	pu, KV for STEPV
	step chng in voltage

Outputs	
ONTIM = 20.7	min
	cycle on time
OFFTIM = 60.6	min
	cycle off time
PERIOD = 81.3	min
	cycle period
TBASE = 70	degF
	pu base temperature
TAU = 20.7	1/min
	R=C time constant
OMEGA = 4.637	1/min
	radian frequency
IWSAVG = 41.5	amp
	weather sensitive avg
CC = 0.717	cos magnitude
E = 0.514	cos magnitude
	ALPHA magnitude
	radian
	diversity regain angle
OFFSET0 = 84	amp
	starts WS current zero
LOWTEMP = 52	degF, for long outage
	outage lowest unit temp
ALLON = 36	min, for long outage
	outage all units on time

* = unitless pu = or in per unit

Lawrence Elliott (Nonmember) was born in Addis Ababa, Ethiopia on 29 September 1954. He received the B.S. degree with power emphasis from the University of Idaho in 1976. He also holds the MDiv degree from Western Conservative Baptist Seminary and is currently completing an M.S. degree at the University of Idaho in Electrical Engineering.

In 1976 Mr. Elliott was employed by the Idaho Power Company and has since worked for Boeing Commercial Airplane Company. Currently he is proprietor of Elliott Electrical Engineering, E', a small consulting firm serving industrial, institutional, public and private clients in Idaho, Oregon and Washington. He is a Registered Professional Engineer in those states.

Michael Storms (M'68) was born in Spokane, WA on 6 February 1944. He received the B.S.E.E. degree from the Gonzaga University in 1979. In 1970 he joined the Bonneville Power Administration in Walla Walla WA. From 1970 to 1980 he held various positions in the BPA service area (i.e. northwest CONUS) in customer service, control and protection, heavy electrical equipment procurement, transformer and capacitor specifications and field computer applications. Since 1980 he has been a staff electrical engineer in BPA's Upper Columbia Area Office in Spokane WA. Mr. Storms is a member of the IEEE Power Engineering Society. He is a Registered Professional Engineer in the states of Oregon and Washington.

Donald Minford (S'58-M'74-SM'76) was born in North Platte, Nebraska on 27 July 1937. He received the B.S.E.E. degree from the University of Nebraska in 1959, and the Master of Engineering Administration degree from Washington University in St. Louis in 1967. Since 1987, he has been the System Engineer at Kootenai Electric Cooperative, Hayden, Idaho. Prior to joining Kootenai Electric, he was employed for ten years in a similar capacity with Big Bend Electric Cooperative in Ritzville, Washington. Additional experience includes four years with Stanley Consultants, Muscatine, Iowa, and fourteen years with Union Electric, St. Louis, Missouri. Mr. Minford is a member of the IEEE Power Engineering Society and the Industrial Applications Society. He is a Registered Professional Engineer in five states.

John Law (S'57-M'62-SM'65) was born in Cleveland, Ohio on 8 Dec 1930. He received the B.S.E.E. degree from Case Western Reserve University in 1957 and the M.S.E.E. and Ph.D.E.E. degrees respectively from the University of Wisconsin Madison in 1960 and 1962. He is Professor of Electrical Engineering at the University of Idaho where he has taught and conducted research since 1975. From 1963 to 1974 he was with the Research Division of Carrier Corporation as Senior and then Chief Electrical Engineer. Dr. Law is a member of the IEEE Power Engineering Society and is a Registered Professional Engineer in Idaho, New York and Ohio. He holds five U.S. Patents related to air conditioning and control.