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Comparison of Iowa State University harmonics program outputs to actual system data

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Comparison of Iowa State University harmonics program outputs to actual observed system data

by

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LIST OF SYMBOLS AND DEFINITIONS

C	Capacitance
d	Diameter of Conductor
E	Voltage
E_H	Ideal Transformer High Side Voltage
E_{L-L}	Voltage (Line to Line)
E_{L-N}	Voltage (Line to Neutral)
E_X	Ideal Transformer Low Side Voltage
f	Frequency
GMD	Geometric Mean Distance
GMR	Geometric Mean Radius
H	Primary Winding
H_1	H Winding Lead
H_2	H Winding Lead
HVDC	High Voltage Direct Current
I_C	Core Resistance Current
I_E	Exciting Current
I_H	H Winding Current
I_M	Magnetizing Reactance Current
I_{MAG}	Magnetizing Current
I_X	X Winding Current
KW	Kilowatts
KVAR	Kilo-voltamperes

L	Inductance
MW	Megawatts
MVAR	Mega-voltamperes Reactive
n	Turns Ratio
n_h	Number of Turns on the H Winding
n_x	Number of Turns on the X Winding
r_c	a-c Resistance of Conductor
R_C	Core Resistance
R_H	Resistance of H Winding
r_s	a-c Resistance of Conductor Sheath
R_X	Resistance of X Winding
R_0	Zero Sequence Resistance
R_1	Positive Sequence Resistance
R_2	Negative Sequence Resistance
S_B	Base Voltamperes
S_{BO}	Voltampere Base (Old)
S_{BN}	Voltampere Base (New)
S	Spacing between Conductor Centers
V_B	Base Voltage
V_{BN}	Voltage Base (New)
V_{BO}	Voltage Base (Old)
V_H	H Winding Terminal Voltage
V_X	X Winding Terminal Voltage

x_a	Reactance of Conductor
x_c	Capacitive Reactance
x_d	Reactance Spacing Factor
x_h	Reactance of H Winding
X_L	Inductive Reactance
x_m	Mutual Reactance
X_M	Magnetizing Reactance
X_S	Reactance of Sheath
X_X	Reactance of X Winding
Z_{Base}	Base Impedance
Z_H	Impedance of H Winding
Z_{HL}	Impedance H Side to Low Side
Z_X	Impedance of X Winding
Z_0	Zero Sequence Impedance
Z_1	Positive Sequence Impedance
Z_2	Negative Sequence Impedance

Miscellaneous

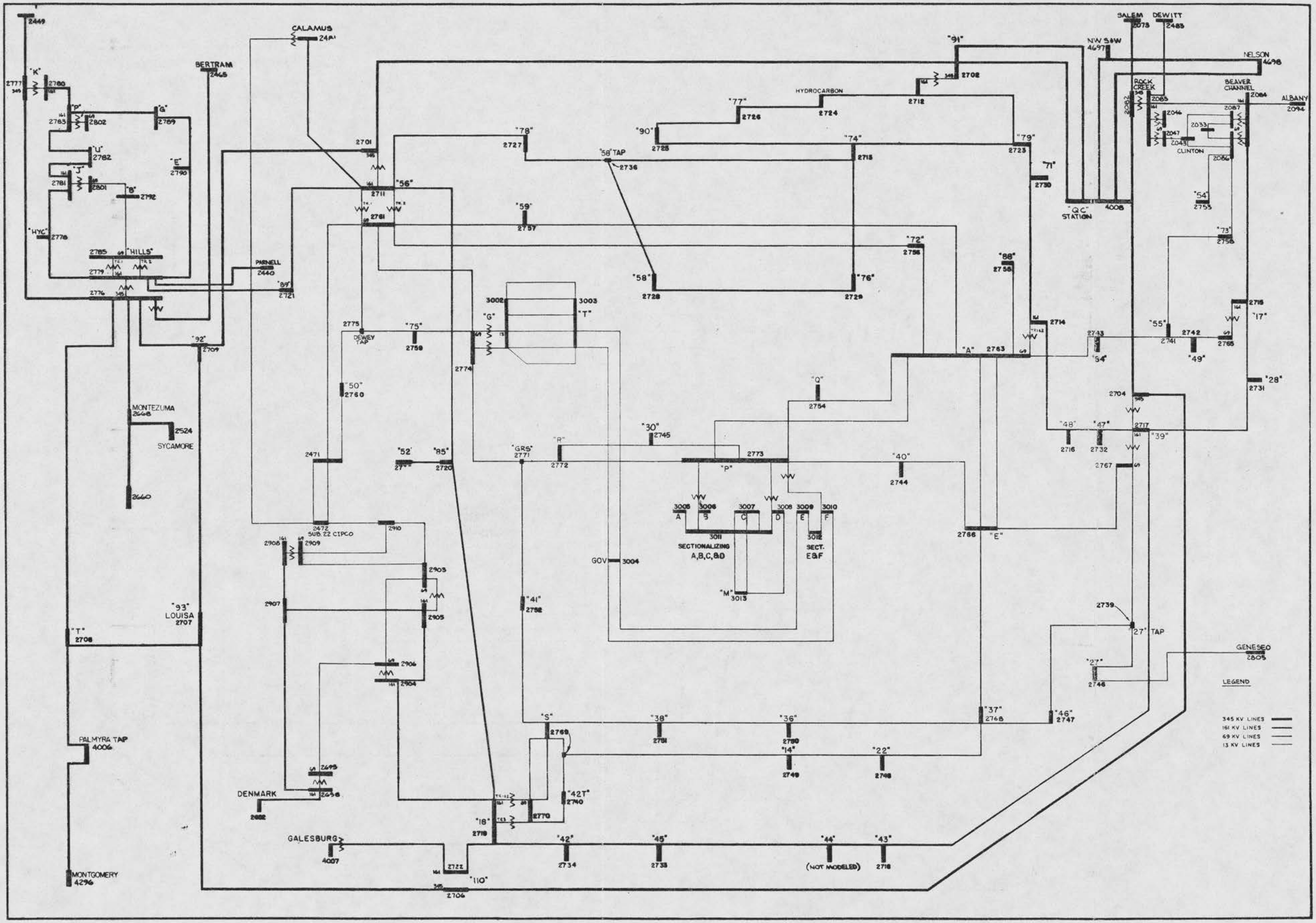
$\triangle$	Delta
Y	Wye

ABSTRACT

The objective was to evaluate the Iowa State University Harmonic Loadflow Program to determine if it fulfilled the present need as an analysis tool for evaluating harmonic effects.

The material is arranged in the sequence of actual steps which occurred to accomplish the research objective. Most of the system as shown on the next page was modeled. Actual field measurements from this system were used to evaluate the program.

Results show the present program is useful for predicting harmonic effects to an existing system as a result of a single new source. Here, the program predictions match very close to measured values. The research also shows the present program is of very limited value for analyzing multiple harmonic sources on an existing system. Hence, it is recommended the program be enhanced to perform this function.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I. INTRODUCTION

A. Preamble

There is a general need both from the utility and industrial sectors for an analysis tool to evaluate the effects of harmonics. From the utility point of view an analysis tool is desired which can handle a multitude of harmonic sources all applied simultaneously. The tool needs to accept harmonic source inputs in a variety of forms. This variety should include various converter types, current and voltage waveforms in the form of oscillographs, and spectrum analyzer results in the form of photographs or computer recordings. The tool should be able to analyze existing as well as new sources.

Thus, this research focused on evaluating the Iowa State University Harmonic Loadflow Program to determine how many of these needs it fulfilled. It also examined the program's advantages and disadvantages. One of the goals of the research was to answer the management question concerning the allocation of manpower to use this particular program.

The program was known to have a lot of flexibility at accepting inputs. It appeared that the number of buses it could handle could be easily expanded. It appeared to permit more detailed modeling of a system compared to other harmonic programs.

It was originally thought that the loadflow approach used by this program could be expanded to permit multiple sources on a system. This would permit determining harmonics at various buses throughout a system. No major documentation existed at the time this research commenced noting the actual limitations of the program and its use.

B. Review of Previous Work

The harmonics program under study is the Iowa State University Harmonic Loadflow Program. The program is a continuing refinement of R. D. Schultz's, "Harmonic Current Propagation on AC Systems Due to HVDC Links", Ph.D. dissertation from Iowa State University, dated 1979; K. H. Kuyper's, "Effects of Wind and Solar Converters on Utility Distribution Networks", Master's thesis from Iowa State University, dated 1980, and modifications to the aforementioned by Dr. A. L. Day, beginning June, 1982 to the present.

The program uses the bus impedance loadflow technique and the superposition principle for analyzing each harmonic frequency separately. The types of sources that can be entered into the program include sampled harmonic voltage or current waveforms, AC-DC converters, and voltage or current harmonic magnitudes. The program was originally set up to accept up to 130 nodes, 475 elements, and a three digit bus number. When this research began, the program had only been used for the analysis of small systems (less than 20 buses).

C. Research Objective

The research objective was to evaluate the Iowa State University Harmonic Loadflow Program to determine if it fulfilled the present need as an analysis tool for evaluating the effects of harmonics.

This was to be accomplished by comparing program output from measured voltage harmonic source values to the program output from measured current harmonic source values for the same harmonic source location. This would indicate if the program functioned correctly.

Following the initial verification, various other measured harmonic magnitudes, which were obtained throughout the system, would be entered into the program. This would then be used to determine if the program predicted what was actually observed on the system. At this point, comparisons and conclusions concerning its use as as analysis tool should be possible and the appropriate recommendations could be made.

D. Summary of Chapters

The material is arranged in the sequence of actual steps which occurred to accomplish the research objective.

The test data that were used for input to the program were taken from actual field testing prior to this research. The data did have some deficiencies associated with them, but the majority of the data were quite usable.

The program was modified to accept up to 500 buses, 4000 elements, and use up to a four digit bus number. The research studies were run on an IBM 3083 Mainframe Computer. Several errors that existed in the original program were corrected.

Approximately 350 buses and their associated devices were modeled in the electrical system for this research. Examples and techniques to handle each device are included.

II. HARMONIC MEASUREMENTS AND PROGRAM MODIFICATIONS

A. Discussion of Measurements

The test data that were used for input to the program were taken from actual field tests (1). These test data are included in Appendix A and, a sequence of slides at the end of this thesis. A slide listing is also included in Appendix B. The slides show harmonics which were measured by a Hewlett Packard 3580A Spectrum Analyzer at various substations throughout the electrical system.

Appendix A includes a listing of all the test equipment. It also shows the current and voltage probes which were used. This same test equipment and probe set-up were used for every harmonic measurement taken and recorded via the slides.

The data included in Appendix B differ from those shown on the slides because of a scaling factor. The scaling factor resulted from the current probes that convert current to voltage. The Appendix B data are scaled correctly.

The current harmonic values which were measured and recorded in the sequence of slides, have no measurements of the line current in amps. Therefore, there is no way to scale the line current magnitude to its appropriate per unit value. This lack of information limits the value of these measurements. The voltage harmonic values which are shown in the slides, can be scaled to correct per unit values and are quite usable.

B. Program Modifications

The harmonic loadflow program was modified to accept up to 500 buses, 4000 elements, and four digit bus numbers. Two unexpected logic errors in the original program were discovered and corrected during this research. These errors did not invalidate results obtained in previous research.

The listing shown in Appendix C is the present operating program. The first page of Appendix D shows a coded letter designator, followed by a corresponding program modification type. These letter codes are included in the program listing in Appendix D to indicate which lines must be changed to complete each type of modification.

For example, a voltage base modification is assigned the code letter "A" on the first page of Appendix D. Every line where the letter "A" occurs in the Appendix D listing should be examined to determine if it should be changed.

III. ASSEMBLING THE SYSTEM MODEL

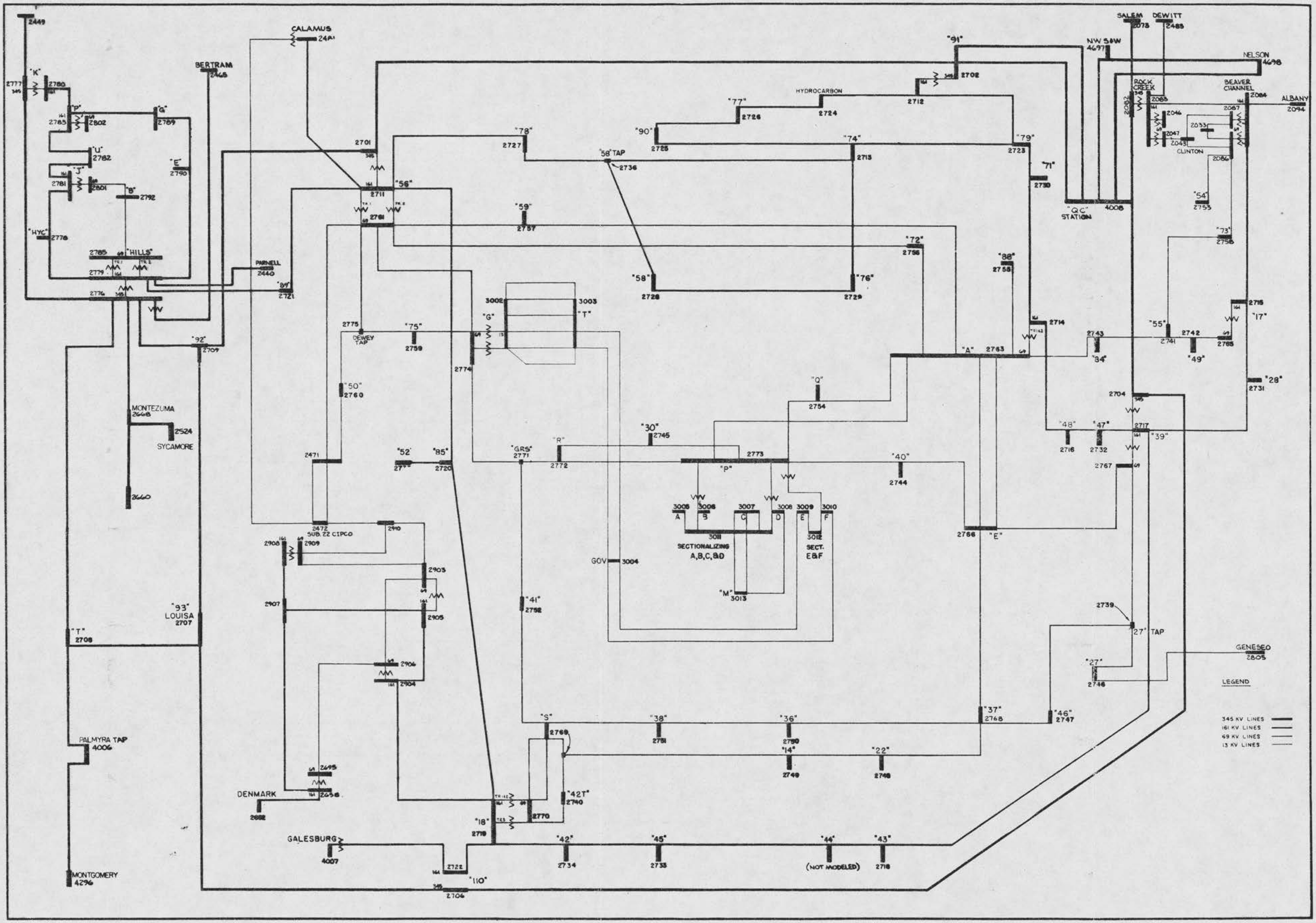
A. The Electrical System

The electrical network under study is shown on the next page. This encompasses the major generation, transmission, and distribution systems and their components in a significant area in the eastern part of Iowa. A few of the buses in both the upper left and right hand corners of the network were not included in the harmonic analyses because of their remoteness to the harmonic sources.

Fossil, nuclear, and hydro generation, all at different voltage classes, are present on the system as well as combustion turbines. In addition, the system still has some two phase which had to be addressed and incorporated. The system also includes three-winding transformers, two-winding transformers (both regular and auto), grounding transformers, reactors (both series and shunt), capacitors, overhead lines, underground cables, major interconnections, urban areas, and rural areas.

B. System Bases

The harmonics program uses a 100 MVA voltampere base. Thus, all impedances, voltages, and currents were trans-



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ferred to this base. To aid in base changes, some programmable calculator programs were written. Their listings appear in Appendix E. These programs were used to save time, to eliminate calculation errors, and to double check calculations.

C. Line Data

1. Normal

The line data for the model were taken from system data books covering 13.8 KV, 69 KV, 161 KV, and 345 KV lines. These books furnished any available data concerning circuit description, the length in miles, and the resistance, reactance, and susceptance values in actual quantities and in percent on 100 MVA base for positive, negative, and zero sequences. Some of the data were missing for the older lines because it was not required in an earlier era. In these cases, Anderson (2), the Westinghouse Electric Corporation reference books (3), (4), and the Electric Power Research Institute reference book (5) were utilized to estimate any missing data.

2. Circuits 13-A-12, 13, & 15

There are three circuits labeled 13-A-12, 13, and 15 that are cabled in such a way that they can be treated as an extension to the buses at Substation A. These circuits directly feed buses which power solid-state drives which, in turn, feed aluminum rolling mills. One of these aluminum mills is the largest of its kind in the world.

Because of the proximity of these circuits to a very large harmonic source, a more detailed model for them was developed. The only information available for these circuits were lengths and cable descriptions. One reason for this is that the present computer program used by the utility to calculate line data parameters cannot handle these cabling configurations and routings. The geometries become too elaborate with four conductors per phase. A second reason was that this modeling information was not required for any of the previous system studies performed by the utility. Hand calculations were made for detailed models of these circuits using references (2), (3), (4), and (5).

D. Two-Winding Transformers

1. Regular Transformers

Assembling and incorporating transformer data into the program had to be one of the more interesting, but laborious facets of the modeling process. Each transformer test report had to be accessed and reviewed so the necessary parameters could be extracted. These consisted of:

1. type of construction, shell or core form
2. the number of windings
3. the voltamperes capability
4. the voltage transformation
5. the type of connections (i.e., delta, wye, etc.)
6. the impedances and their MVA base
7. the magnetizing current at 100% voltage and its MVA base
8. the no load loss at 100% voltage and its MVA base

Figures 1 through 6 show the two-winding transformer equivalents. In each succeeding figure, the model is further simplified. For these equivalents, all of the series resistance has been neglected. The magnetizing impedance has been assigned to the H or Primary Winding. The equivalent circuit shown in Figure 6 is derived by making the assumptions that RR1/2 is much, much less that RRO and

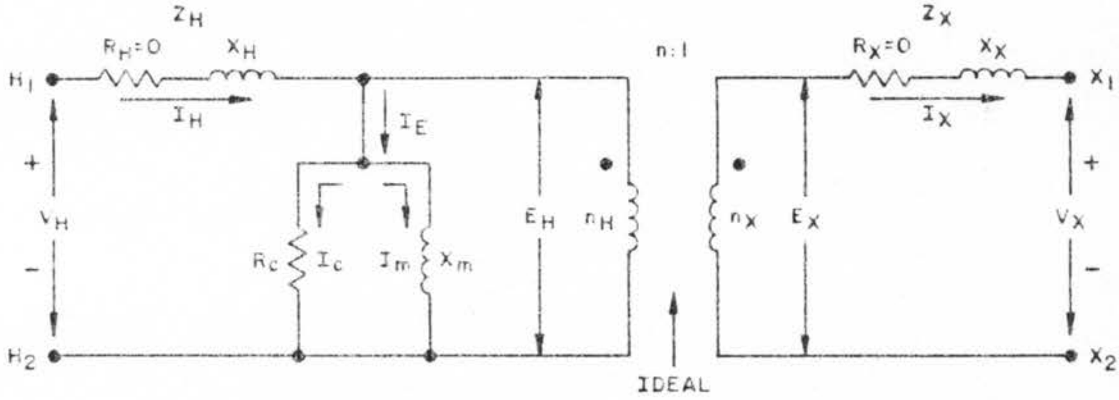
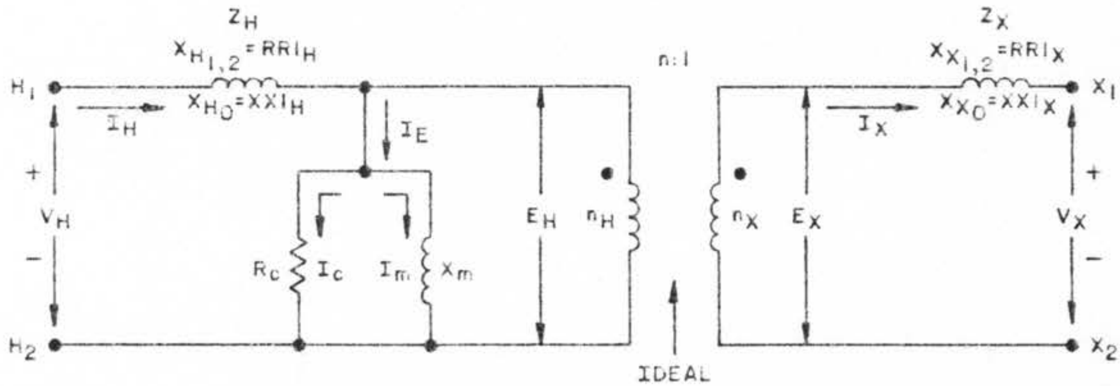


FIG. 1. EQUIVALENT IN SYSTEM QUANTITIES



WHERE: $X_{m_{1,2}}$ = XCI X_{m_0} = XCO $R_{c_{1,2,0}}$ = RRO

FIG. 2. EQUIVALENT IN SYSTEM QUANTITIES SHOWING PROGRAM DESIGNATIONS

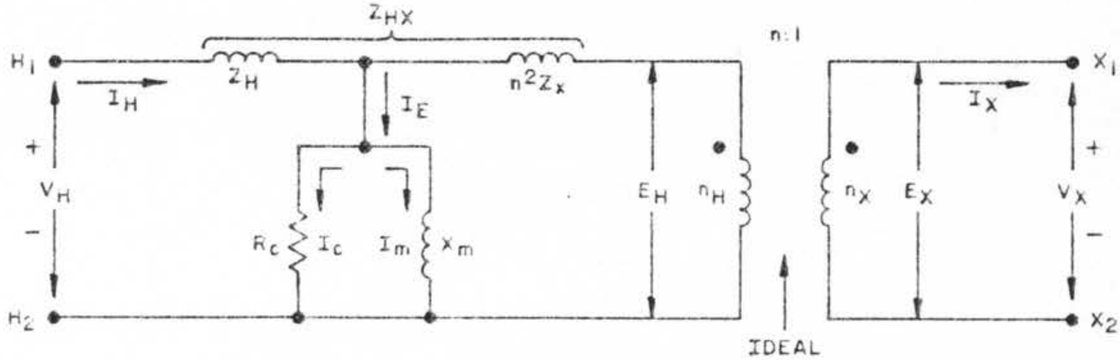


FIG. 3. EQUIVALENT WITH ALL SERIES IMPEDANCE REFERRED TO THE H WINDING

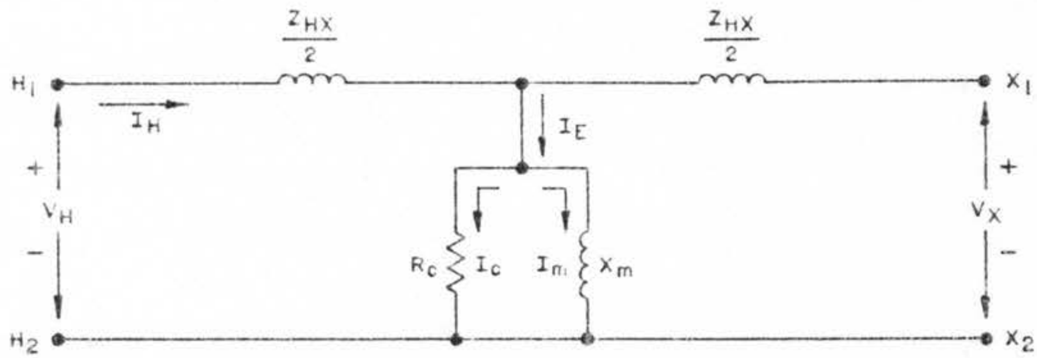


FIG. 4. P.U. EQUIVALENT

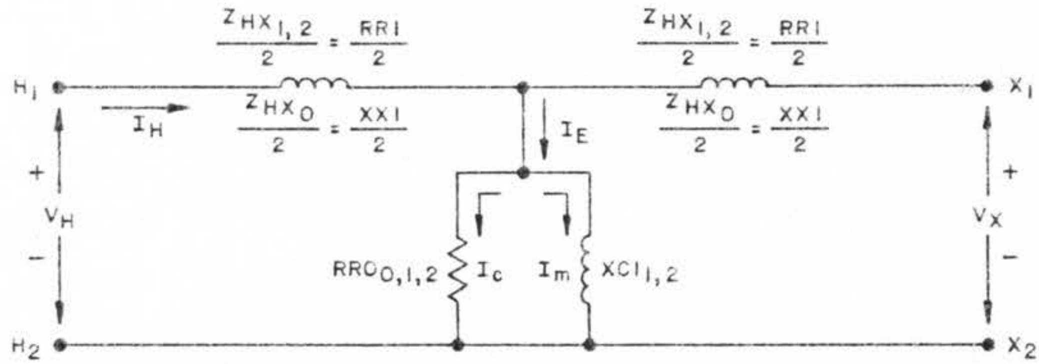


FIG. 5. P.U. EQUIVALENT SHOWING PROGRAM DESIGNATIONS

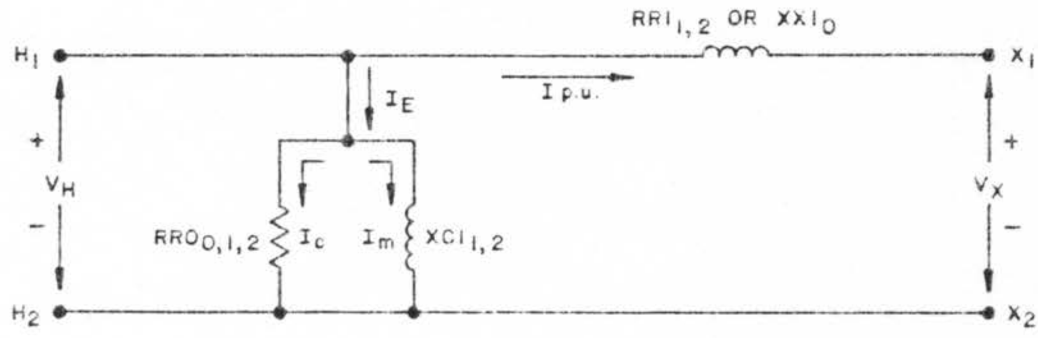


FIG. 6. MODIFIED P.U. EQUIVALENT SHOWING PROGRAM DESIGNATIONS

XX1/2 is much, much less than XC1. This is the model used in the Harmonic Loadflow Program.

The exciting current at 100% voltage obtained from the transformer test report is substituted into the following equation to determine the positive/negative sequence shunt reactance XC1.

$$XC1 = \frac{\text{Voltage}}{\text{Magnetizing Current in \% @ 100\% Voltage}}$$

$$= \frac{100\%}{I_{MAG}\%}\ \text{pu}$$

Similarly, the no load loss at 100% voltage obtained from the transformer test report is substituted into the following equation to obtain the positive/negative/zero sequence core loss resistance RR0.

$$RR0 = \frac{(\text{Voltage})^2}{\text{No Load Losses At 100\% Voltage}}\ \text{ohms}$$

Next, divide RR0 by the base impedance and express it in percent. The positive, negative, and zero sequence series reactance values for RR1 and XX1 are all directly obtained from modern day transformer test reports.

However, there were many cases (due to the age of some of the transformers) where some of the parameters were not available. If the type of construction was unknown, a shell design was assumed because a majority of large power transformers are shell type. If zero sequence information was unavailable, then the zero sequence impedance was assumed to be equal to the positive sequence impedance and the zero sequence equivalent was assumed to be the same as that developed for three single-phase units.

Appendix E includes a TI-59 Program Listing that was used to calculate the final transformer data values for direct entry into the system data.

2. Autotransformers

Two-winding autotransformers do not require any special treatment and are handled the same as a regular two-winding transformer. Thus, the same parameters are extracted from the transformer test report and the same process is utilized to determine the sequence shunt reactance XC1 and the sequence core loss resistance RR0.

E. Three-Winding Transformers

1. Regular

The program is not set up to accept three-winding transformers. To overcome this limitation, the appropriate three-winding transformer model is selected and then transformed into an equivalent set of three separate two-winding transformers via a STAR to DELTA conversion.

The positive sequence impedances and voltampere ratings associated with each set of corresponding voltage levels are obtained from the transformer test report. These impedances are then transferred to the same voltampere base, normally that of the H, or Primary Winding. Next, the impedances are transferred to the equivalent per unit values. In this form, the model resembles the equivalent T model shown in Figure 10. A STAR to DELTA conversion is then made to transform the model to three two-winding transformers connected in a triangle configuration as shown in Figure 11. The equivalent circuits illustrating this modeling process are shown in Figures 7 through 11. The same technique is applicable for the negative and zero sequences. The zero sequence connection codes must be carefully selected to correctly model the zero sequence circuits. An example three-winding transformer model is developed in Appendix F.

For the X and Y windings, the no-load losses and magnetizing currents at 100% voltage are set to values approaching zero because the H winding already includes these quantities for all three windings. Thus, the values

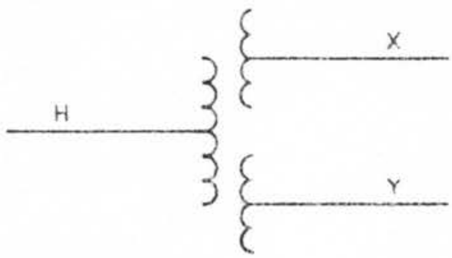


FIG. 7. SCHEMATIC OF A THREE-WINDING TRANSFORMER

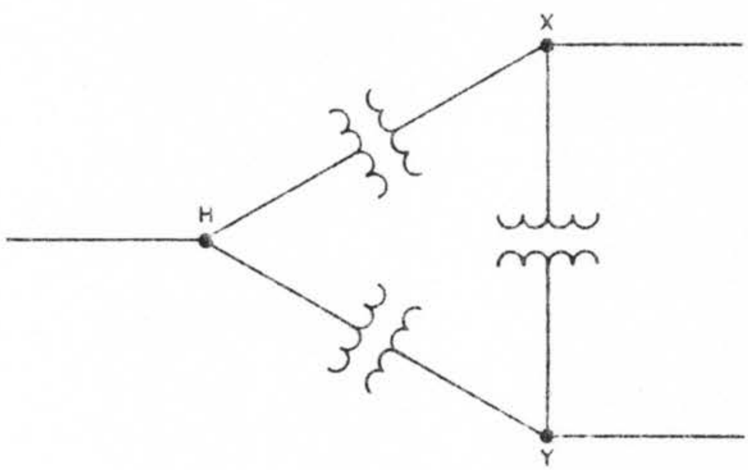


FIG. 8. SCHEMATIC OF THREE TWO-WINDING TRANSFORMERS CONNECTED IN A TRIANGLE

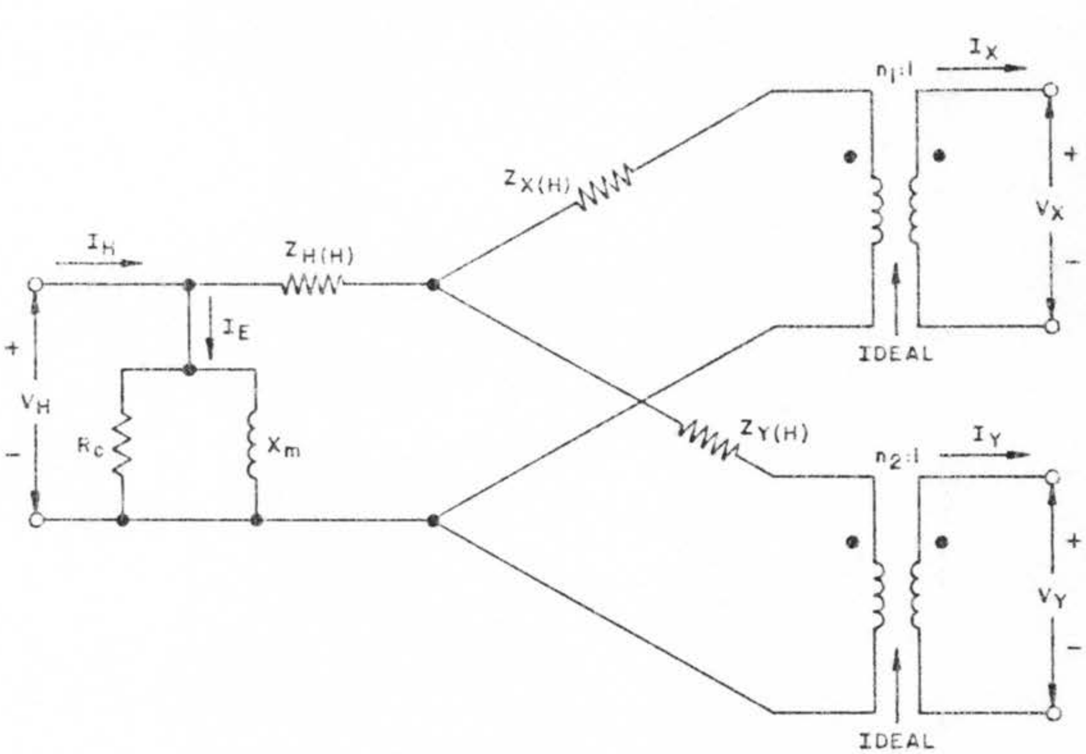


FIG. 9. EQUIVALENT FOR THREE-WINDING TRANSFORMER IN SYSTEM QUANTITIES WITH IMPEDANCES REFERRED TO THE H WINDING

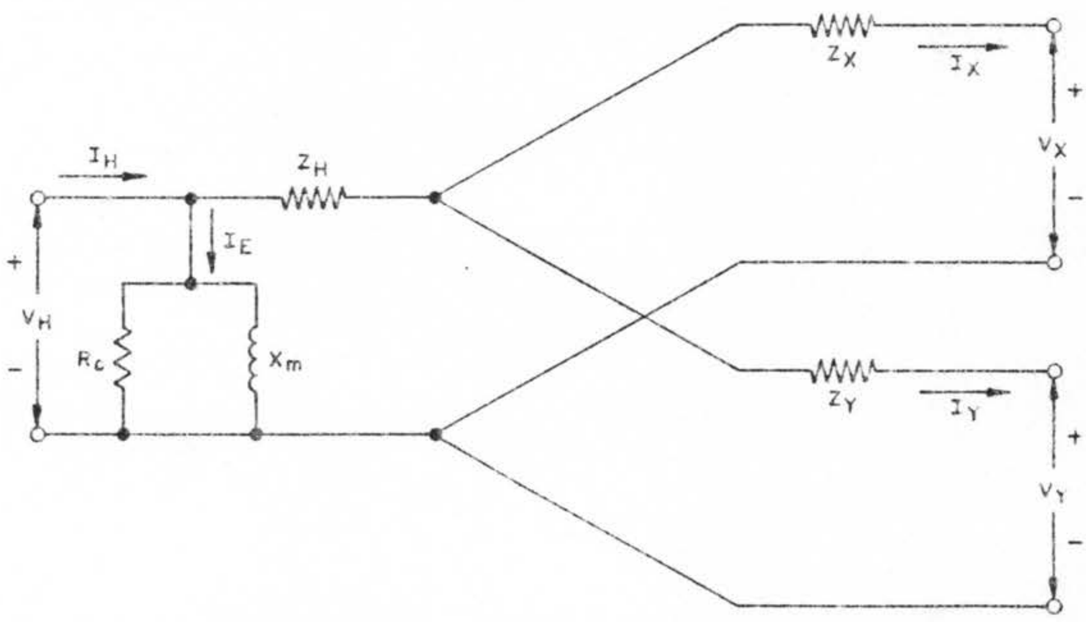


FIG. 10. EQUIVALENT FOR THREE-WINDING TRANSFORMER PER UNIT

WHERE: $V_Y < V_X < V_H$

AND $R_{c_{XY}}$, $X_{m_{XY}}$, $R_{c_{HY}}$ AND $X_{m_{HY}}$ ALL APPROACH INFINITY

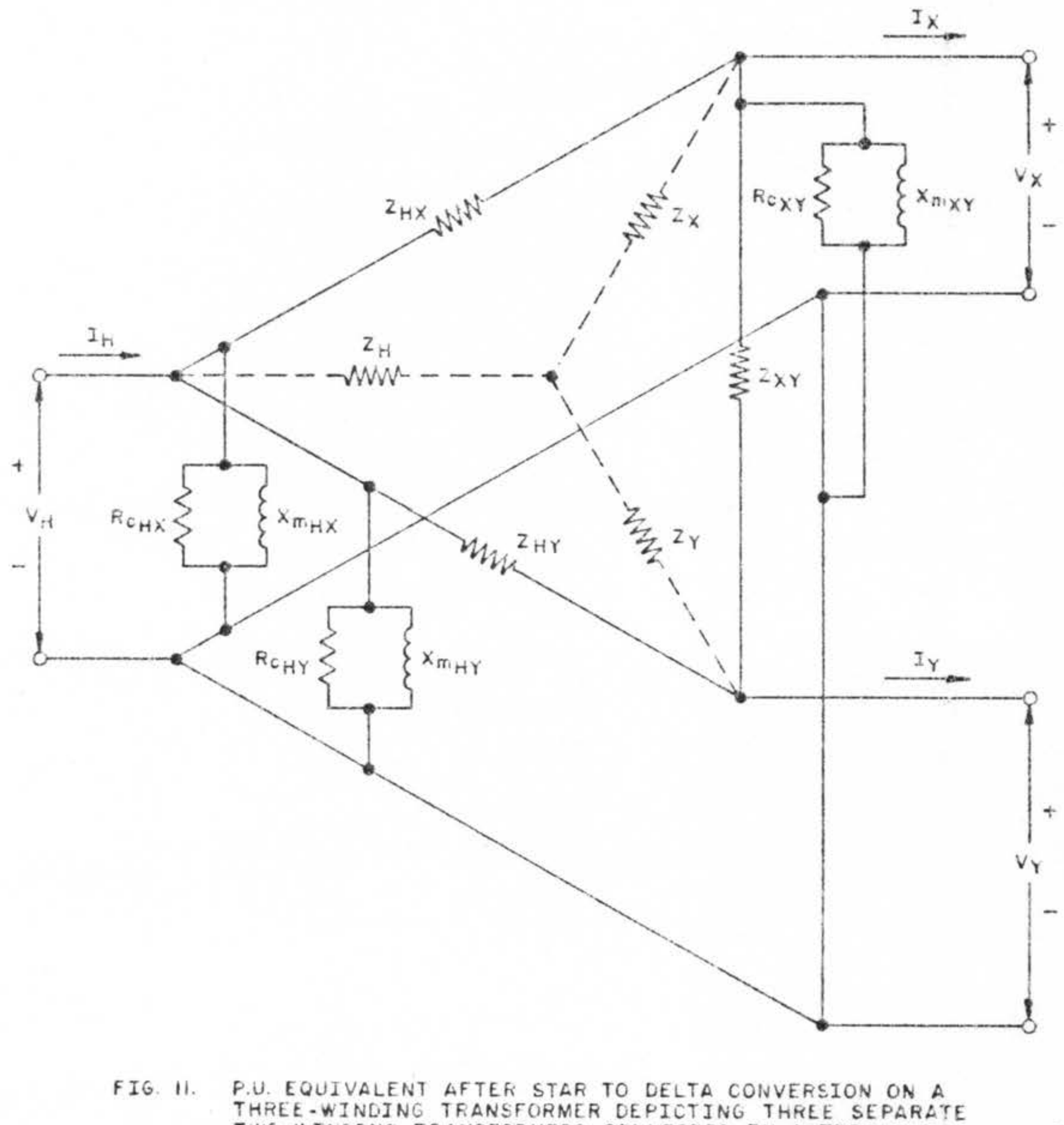


FIG. 11. P.U. EQUIVALENT AFTER STAR TO DELTA CONVERSION ON A THREE-WINDING TRANSFORMER DEPICTING THREE SEPARATE TWO-WINDING TRANSFORMERS CONNECTED IN A TRIANGLE

for the sequence shunt reactance XC1 and the sequence core loss resistance RR0 for the X and Y windings approach open circuit conditions.

A TI-59 Program Listing for making the change to the per unit equivalent circuit values is shown in Appendix E. A TI-59 Program Listing to perform the STAR to DELTA conversion is also included in Appendix E.

2. Autotransformers

Three-winding autotransformers do not require any special treatment and are handled the same as the regular three-winding transformer. That is, the appropriate three-winding autotransformer model is chosen and then it is modeled as three separate two-winding transformers connected in a "triangle" configuration after a STAR to DELTA conversion is made.

F. Scott Connected Transformers (Three to Two-Phase Transformers)

In reviewing Anderson (2, Chapter 1), we know for single-phase systems

$$Z_{pu} = \frac{S_{B-1\,phase}}{V^2_{B-LN}} (Z\ ohm)$$

and

$$Y = \frac{V^2_{B - LN}}{S_{B - 1\ phase}} \quad (Y\ mho)\ pu$$

But using LL to indicate "line to line" and 2 phase for "two-phase", we write for a balanced system

$$V_{B - LN} = \frac{V_{B-LL}}{\sqrt{2}} \qquad V$$

and

$$S_{B - 1\ phase} = \frac{S_{B - 2\ phase}}{2} \qquad VA$$

Making the appropriate substitutions we compute

$$Z = \frac{\dfrac{S_{B} - 2\ phase}{2}}{\dfrac{V^2_{B-LL}}{\left(\sqrt{2}\right)^2}} (Z\ ohm)\ pu$$

$$= \frac{S_{B - 2\ phase}}{V^2_{B-LL}} \qquad (Z\ ohm)\ pu$$

and

$$Y = \frac{V^2_{B-LL}}{S_{B-2\ phase}} \qquad (Y\ mho)\ pu$$

Writing voltages in kV and voltamperes in MVA

$$Z = \frac{\text{Base MVA}_{2\ -\ phase}}{(\text{Base kV}_{LL})^2} \qquad (Z\ ohm)\ pu$$

These equations are almost identical to those derived in Anderson for three-phase systems. In fact, if the arbitrary two-phase voltage and voltampere bases are equal to the arbitrary three-phase voltage and voltampere bases, then the results will be identical. Therefore, if the impedances are transferred to these bases, the program will handle both the two-phase and three-phase systems the same way.

An example of a three-winding, three-two phase transformer is included in Appendix G. The impedance values listed closely resemble those of the three-winding transformer values shown in Appendix F. The three-winding, three-two phase transformer parameters are determined in the same manner as for a regular three-winding transformer.

G. Grounding Transformers

Grounding transformers are modeled as linear elements connected from the bus to ground. The program will require three parameters to be entered consisting of RR1, XX1, and XC1. RR1 is the series resistance of the grounding transformer. If the resistance is to be neglected as it was for the other transformer models, then RR1 can be entered as a zero value. XX1 is the shunt reactance of the grounding transformer. The same technique used to calculate the shunt reactance for the other transformer models can be used to calculate XX1. XC1 is the zero sequence reactance of the grounding transformer. This reactance is equivalent to the series reactance of a conventional transformer. The same technique for calculating the series reactance of a conventional transformer will be used to determine values for XC1 in this model.

Appendix H shows an example of a grounding transformer modeling procedure.

H. Power Capacitors

Power capacitors are normally rated in three-phase kilovars. From elementary circuit theory we know:

$$X_C(\text{ohms})_{1\ \text{phase}} = \frac{E_{L-L}^{2}}{Q_{3\ \text{phase}}}$$

The program requires the capacitive reactance values to be entered on a per phase basis. Thus, knowing the three-phase line to line voltage and the three-phase kilovar rating (as furnished by the manufacturer), the capacitive reactance per phase can be easily determined. This value is entered into the Harmonic Loadflow Program as a linear element.

The kilovar manufacturing tolerance on power capacitors is minus zero and plus 15 percent. A normal distribution curve covering this variation is available from the various manufacturers. By taking this into account, more representative values of the actual KVAR capability can be entered into the program.

In the studies associated with this research, there was no allowance made for the manufacturing tolerances. In addition, the capacitors were all assumed to be located at the respective buses. This is in contrast to actual system conditions where the capacitors are usually located somewhere out on the line itself. To include the actual location of the capacitors in the model, the line lengths would have to be taken into account and appropriate corrections would have to be made.

If the program results identify a specific problem area resulting from capacitor resonance, then the additional modeling may be appropriate for the capacitors in that area.

Capacitor banks are often a major contributing factor to harmonic problems. Resonance at harmonic frequencies can cause overvoltage at the capacitor. In addition, since impedance of capacitors decreases with frequency, high harmonic voltages will result in high current causing blown capacitor fuses, overheating, and possible failure. See references (4), (6), (7), (8), (9), (10), (11), (12), (13), and (14).

Appendix E includes a TI-59 Program Listing that was used to calculate the capacitive element reactances.

I. Power Reactors

Power reactors are normally rated in three-phase kilovars. From elementary circuit theory:

$$X_{L_{1\ \text{phase}}}\ (\text{ohms}) = \frac{(E_{L-L})^2}{Q_{3\ \text{phase}}}$$

The program requires the inductive reactance values to be entered on a per phase basis. Thus, knowing the three-phase line to line voltage and the three-phase kilovar rating (as furnished by the manufacturers) the inductive reactance per phase can be easily determined. This value is entered into the Harmonic Loadflow Program as a linear element.

1. Shunt Reactors

There were only five shunt reactors associated with the system studies. These were of 13.8 KV and 345 KV classes. Their inductive reactance values in ohms were all determined in the manner just described. Then, these impedances were transferred into percent reactance on a 100 MVA base by utilizing the appropriate Z base.

2. Series Reactors

There were only six series reactors associated with the system studies. These were all located in the 13.8 KV network. Their inductive reactance values in ohms were determined by utilizing their respective test reports where the voltage drop across the reactor is given at rated current. Then using

$$E_L = I_L X_L$$

which is the voltage drop equation across the inductor yields

$$X_L = \frac{E_L}{I_L} \text{ (ohms)}$$

The impedance in percent is

$$Z(\%) = \frac{\frac{E_L}{I_L}(100)}{\frac{(V_B)^2}{S_B}}$$

where

E_L = voltage drop across the inductor at rated current

I_L = rated current of the inductor

V_B = voltage base

S_B = voltampere base

Appendix E includes a TI-59 Program Listing which can be used to calculate the inductive element reactance for shunt reactors.

J. Generators

Obtaining the necessary data for the generator model was fairly easy. Usually, good records are kept on these machines. There were twenty-four generators included in the system model ranging from generator voltages of 2400 Volts to 24 KV. A problem was encountered associated with four very old two-phase hydro units. These generators had been rewound, but no testing was performed. For these particular units, both references (2) and (9) were utilized to arrive at acceptable representative values.

K. Loads

Representative loads were obtained for the various substations for input into the model. These were obtained from utility company system studies. Depending upon the particular substation configuration, the loads were then apportioned to the various buses.

IV. RESULTS

A. Entering Data Into Program

Entering the harmonic magnitude values into the program from the slides is straightforward and is per the instruction sheet (see Appendix I). The particular harmonic magnitude value (in decibels) was read from the slide. The decibel equation is:

$$20 \log \left(\frac{V_1}{V_2}\right) = \text{db}$$

To transfer directly to per unit or percent values requires that V_2 be chosen as 1 pu or 100% voltage. For voltage harmonics,

$$V_2 = \text{base voltage (volts)} = 100\% \text{ voltage} = 1 \text{ pu}$$

For the current harmonics measured as voltage equivalents,

$$V_2 = \text{base current (amps)} = 100\% \text{ current} = 1 \text{ pu}$$

Thus:

$$\frac{V_1}{1 \text{ pu}} = \frac{V_1}{100\%} = \text{antilog} \left(\frac{\text{db}}{20}\right)$$

which yields V_1 directly in percent or per unit for that particular harmonic. This process is repeated for each successive harmonic until they have all been transcribed. See references (1), (10), (11), (12), (13), and (14).

Appendix E includes a TI-59 Program Listing which was quite useful to obtain the per unit voltage or current values from the harmonic measurements given in decibles. Appendix E also includes a TI-59 Program Listing which is useful for calculating harmonic distortion factors from the data obtained from the spectrum analyzer.

B. Actual Results

There were specific measured test data available only for Substations A, 36, 76, 78, 88, and 91. Of major interest to this research is Substation A. This particular substation supplies both arc furnace loads and solid-state converters for rolling mill drives. These loads combine into the dominant harmonic source in the area. The measurements at this substation and Substation 88 were used to verify that the Iowa State University Harmonic Loadflow Program functioned correctly.

The voltage harmonic distortion factor values for each bus in the system are printed at the end of the program output for each case. These values were used for the comparisons to actual measured data. A sample of the program output is shown in Appendix J. This sample output corresponds to the case where the harmonic source values are entered as the measured voltage harmonic values at Substation A.

The harmonic distortion factors at Substation 88 matched within .01 percent of the fundamental, with no unanticipated results. The program output showed that the effects of the harmonics produced by this source at Substation A could easily be observed as far away as Missouri. Voltage harmonic distortion factor contributions in the range of .3 percent are shown to exist on the 345 KV system in Missouri.

The measured system data at Substation 36, 76, 78, and 91 do not correlate to the Iowa State University Harmonic Loadflow Program output. This is because the test data which were taken reflects the actual system with a multitude of harmonic sources applied. There is no way the system harmonic measurements can be obtained with only one harmonic source present, which is the way the Harmonic Loadflow Program treats each case.

Measured test data from Substation A were entered to compare the program output from "measured voltage harmonic source values" to the program output from "measured current harmonic source values" for the same harmonic source location. Eighty-seven percent of the harmonic distortion factors showed less than one-half percent variation between the voltage and current cases. Ninety-eight percent of the harmonic distortion factors showed less than one percent variation. Some of the differences were the result of the system being sensitive to resonance at different locations for different input harmonic frequencies. The measured current harmonic source data peaked at different harmonic frequencies than they did for the measured voltage harmonic source data. This is also covered in Appendix A.

A case was analyzed using the detailed line model for circuits 13-A-12, 13, and 15. The results from this case were compared to cases which did not include the detailed line model for these circuits. These comparisons showed essentially the same results, with or without the detailed line model.

The computation times for the actual system data consisting of approximately 350 buses were in a range of approximately five to fifteen minutes. For this system, harmonic source location appeared to play the major role in determining CPU time.

It should be noted that the printout will vary depending upon harmonic source location. The variations will be in the bus numbers included in the printout. The reason for this difference is directly attributed to the transformer connection codes. The program takes these into account and incorporates them directly into the printout.

In addition, if a converter input is used, the computer printout will only show certain harmonics. These will be determined by the formula $h = pq \pm 1$, where p equals the nubmer of pulses and q is an integer. This is quite apparent in the printouts.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The program is operating smoothly with an excess of 345 buses, a large number of linear elements, and four digit bus numbers. It can accept up to 500 buses, 4000 elements, and use four digit bus numbers up to 9,998. Expanding the dimensions of the program is fairly easy provided that the computer system is large enough to handle the increased array sizes. Using the techniques outlined in Chapter III, the unique system devices are easily incorporated.

The program, as it currently exists, appears to be useful only in analyzing new harmonic sources which are being added to the system. A program, as such, would give an indication of the percent harmonic distortion factor increase for the various buses on the system. The test data available support the fact that the program is functioning correctly and as designed.

There were differences in the harmonic distortion factor results between the cases that used measured voltage and measured current harmonic source values for the same circuit. These differences were attributed to amplitude variations associated with select harmonic orders which were different for the voltage harmonic measurements than they were for the current harmonic measurements. Each study indicated that certain areas of the system were sensitive to resonance at different harmonic frequencies and at different locations. The suspected cause of the differences is that the phase angle differences between the voltages and currents were not included. Since the phase angle data were unavailable, then the procedure is to run analyses of both the current and voltage harmonics for the same circuit. This will indicate any specific resonance for each case.

Based on the closely matching comparisons of the cases with and without detailed line modeling for circuits 13-A-12, 13, and 15, the extra work involved in calculating the detailed models for bus extensions is not recommended.

The algorithms used in the program are not highly efficient in terms of CPU time and memory requirements. However, it was observed in this research that even when the program was used for a large system, it arrived at solutions in reasonable times. Modifications to reduce computational times is not recommended and are not seen as a major benefit. This recommendation is based upon the fact that most programs of this type are run during off-hours and weekends. During these low use periods the computer time is discounted because, frequently, the computer is idle.

The harmonic source location affects the CPU time required for a program solution. However, it appears that reasonable solution times are obtained no matter where the harmonic source is located. There was no obvious advantage of using a voltage over a current input in the studies performed as they had essentially the same execution times for the same circuit.

One of the print options in the Iowa State University Harmonic Loadflow Program is "to print harmonic analyses of elements adjacent to the harmonic source bus only". Based on the results obtained during this research it is concluded that this is not a recommended option. It will overlook significant harmonic distortions located further out in the electrical system.

Based on the experience gained during this research, it would require about ninety man-days to model a 350 bus electrical system. This estimate includes the time required to gather the necessary system data, to make calculations for the device models, to enter the data into a computer file, and to verify the data.

This thesis provides the necessary assistance and guidance to others who will use the Iowa State University Harmonic Loadflow Program. It reduces the confusion associated with the modeling of the unique system elements and devices. Finally, it provides good insight to the limitations of the program and its advantages.

B. Measurement Recommendations

An additional effort should have been made to obtain measurements associated with phase angles. In addition, the daily and seasonal variation of harmonic levels should be considered when interpreting measured data.

For any measurements obtained, there is engineering judgement required to understand what they show and how they are associated with the Iowa State University Harmonic Loadflow Program. For many locations the measurements show the composite of all harmonics at a particular bus resulting from a multitude of harmonic sources. It is not feasible to have only one harmonic source connected to the system.

In summary, it is recommended that the measurement data obtained include at least as much data as that shown in Appendix A. Current and voltage waveforms should be recorded in addition to photographs or computer recordings of the actual spectrum analyzer settings and traces. This will help answer questions involving the measurement data and provide for a cross-reference. Good communications between the parties obtaining the measurements and those requesting the measurements are also needed. This is to assure that pertinent details associated with the measurements are not overlooked.

C. Program Enhancement Recommendations

The program as designed, can only handle one source at a time. Its major intended use would be for analyzing new sources.

However, what is truly needed is a program which handles multiple harmonic sources derived from measured data. The program should resemble a true loadflow program in which multiple generators can arbitrary be connected to various buses. This would limit the number of locations where test data would need to be obtained. It would also permit analyses in areas where test data can not be obtained. It would overcome the obstacle of single source analysis that requires the removal of customers or systems from service to obtain harmonic source data.

The use of a multiple source program appears to be the logical solution. Entering harmonic measurements from key locations in the system would permit a complete harmonic picture of the overall system. The contribution from each customer's harmonic source could be determined.

In addition, the following modifications are recommended:

1. Modify the program to output a summary of the ten, twenty, or any assignable number of the largest bus harmonic magnitudes listed in decending order. This would greatly simplify review.
2. Modify the program to accept both alpha and numeric bus designations.
3. Modify the program to facilitate entering values directly from data sheets, test reports, etc.
4. Include an arc furnace harmonic source model (7).

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VIII. APPENDIX

A. CIRCUIT 13-A-12 TEST DATA AND REPORT

Circuit 13-A-12 Test
August 27, 1985

1. Personnel Present

   Davis, Coppens, Hender, Mathias

2. Equipment Used

   A. Recording Voltmeters EM100, EM101, EM102

   B. Bell and Howell Portable Oscillograph

   C. Hewlett Packard 3580A Spectrum Analyzer

3. Equipment Calibration

   A. Potential Transformers 7976/66.4 or 120/1

   B. Current Transformers 2000/5

   C. Potential Probe on Spectrum Analyzer x10.
      Voltages derived from an uncalibrated voltage divider.
      Voltage information is relative to 60 HZ fundamental.

   D. Current Probes Bell clamp-on Hall effect - 1 volt equals 10 amperes

   E. Scale Settings indicated on oscillographs and photographs

4. Quantities Measured

   A. 13 kV bus 1A volts phases 1, 2, 3

   B. 13-A-12 currents phases 1, 2, 3

5. System Conditions

   A. 161-69 kV transformers #1 & #2 OFF

   B. 69-13 kV transformer #4 OFF

   C. 69-13 kV transformer #5 ON

   D. 69-13 kV transformer #6 ON

   E. 25.2 MVAR 69 kV capacitor ON

F. 13 kV capacitors

Test	C-156 5400 kVAR	C-326 4200 kVAR
1	OFF	ON
2	OFF	OFF
3	ON	OFF
4	ON	ON

Note: OCC would not permit tests to be done with only one 69-13 kV transformer in-service.

6. Test Results

A. Recording Meters

Exhibits 1 and 2 show recording voltmeter charts on 8/27/85 and 8/28/85. Both of these charts are typical of the voltage variations recorded from 8/27/85 to 8/30/85 and from 9/3/85 to 9/6/85. The voltages were fairly flat during the Labor Day holiday weekend.

Some of the more severe voltage excursions are indicated on the exhibits. The worst is point "B" on Exhibit 1 which showed a dip from 14.0 to 13.3 kV. This represents a 5.3% change on a 13.2 kV base. Point "D" on Exhibit 2 shows an incident where the voltage dropped to 13.1 kV.

The frequency of the voltage dips ranged from about 35 to 60 occurrences per hour.

B. Oscillograph

The portable oscillograph was used to record all three voltages and currents on circuit 13-A-12. When the paper feed was set at a low speed, the variations of voltage and current magnitudes can be seen. A fast paper feed rate was used to monitor the individual waveforms to detect harmonic distortion.

Exhibit 3 graphically illustrates the varying current demands of the rolling mill at 12:05. The current varies rapidly from 353 to 990 amperes (rms). The voltages are also varying but the percentage change is too small to measure with this device.

Exhibit 4 is another slow speed run taken at 13:00. The maximum current spike was 1272 amperes. The voltage trace is very uneven.

A fast speed run done during test #1 is shown on Exhibit 5. The phase #1 current shows a definite harmonic content. The peaks of the current waveform have been "chopped" by operation of the solid state devices. The sides of the waves show when different pulses of the convertor are fired. The voltage waveform is more uniform but it definitely has a harmonic signal riding on top of the 60 HZ fundamental.

Exhibit 6 shows the waveforms during test #2 when there were no capacitors on. The harmonics in the current waveform are a little more pronounced.

Exhibit 7 was produced during test #3 when the 5400 kVAR capacitor bank C-156 was on-line. High frequency harmonics are very evident.

The presence of both capacitor banks in test #4 really emphasized the harmonic problem as shown on Exhibit 8. By looking at the entire oscillograph which includes several seconds of time, the following observation was made. The worst harmonics appear to be generated when the mill is coasting down from a high current level to a lower one.

C. Spectrum Analyzer

The spectrum analyzer was used to resolve the voltage and current waveforms into their harmonic components. This device plotted the signal magnitude at a specific frequency on the verticle axis while it swept through the frequencies on the horizontal axis. The vertical axis was a logarithmic scale measured in dB. {A voltage ratio in decibels is equal to 20 log (V_1/V_2)} This allowed the small harmonic components to be shown on the same screen as the 60 HZ fundamental. The results were a percentage of the fundamental. The frequency sweep took about 20 seconds to complete. This introduced some error because the magnitude of the waveform was changing during the sweep.

Exhibits 9 and 10 show photographs taken of the spectrum analyzer screen. The locations of the 1st, 3rd, 5th, 7th, 9th, 11th and 13th harmonics are shown. These correspond to the signals at 60, 180, 300, 420, 540, 660 and 780 Hertz, respectively.

These pictures show that the predominant harmonics are the odd multiples of 60 HZ. Since these graphs are on a logarithmetic scale, they are difficult to read. Therefore, the results will be summarized in Figure 1.

FIGURE 1

SPECTRUM ANALYZER RESULTS

System Conditions				Harmonics						
	C156	C326		3rd	5th	7th	9th	11th	13th	DF
Test#	5400 kVAR	4200 kVAR	Quantity	%	%	%	%	%	%	%
1	OFF	ON	V	.8	5.0	1.0	.4	.6	1.8	5.5
1	OFF	ON	I	.6	1.6	.5	.1	.3	.5	1.9
2	OFF	OFF	V	.8	4.0	2.5	.6	.6	.5	4.9
2	OFF	OFF	I	.2	2.5	1.0	.2	7.9	.4	8.4
3	ON	OFF	V	.3	5.0	.8	.2	1.0	1.6	5.4
3	ON	OFF	I	.2	.9	.3	.0	.4	2.5	2.7
4	ON	ON	V	.4	4.0	.8	.2	2.5	.4	4.8
4	ON	ON	I	.5	1.3	.4	.0	.2	6.3	6.5

V = Voltage I = Current DF = Distortion Factor

$$\text{Distortion Factor} = \sqrt{\frac{V_2^2}{V_1^2} + \frac{V_3^2}{V_1^2} + \frac{V_4^2}{V_1^2} + \ldots \frac{V_N^2}{V_1^2}}$$

where 1, 2, 3, and 4 refer to first, second, third and fourth harmonic

This analysis only included the odd harmonics from 3 to 11 for example.

$$DF = \left(\frac{0.8^2}{1.0^2} + \frac{5.0^2}{1.0^2} + \frac{1.0^2}{1.0^2} + \frac{0.4^2}{1.0^2} + \frac{0.6^2}{1.0^2} + \frac{1.8^2}{1.0^2} \right)^{\frac{1}{2}} = 5.5$$

The predominant harmonic in the voltage waveforms was the 5th. This 300 Hertz signal was 4 to 5 % in all four test cases. The switching of capacitors did not seem to affect it. The next worst at 2.5% was the 7th in case 2, the 11th in case 3 and the 13th in case 4. Increasing shunt capacitance tended to shift the second highest harmonic to a higher frequency.

The current waveforms exhibited different characteristics. The largest harmonic was the 11th at 7.9% in case 2 with no capacitors. The second largest was the 13th at 6.3% in case 4 with both capacitors on. The other two cases showed small harmonics.

7. Other Observations

A. Recording Voltmeter

There is a recording voltmeter permanently attached to the 13 kV bus. This meter has an unknown calibration and it appears to be overly damped. However, it does allow a comparison between the voltage before and after the installation of the solid state drive.

Exhibit 11 shows the voltage record on June 12, 1985, which was the roughest observed on the June chart. This was before the mill drive was installed. The maximum voltage dip was about 250 volts or 2%.

Exhibit 12 shows the record made on August 13, 1985, by the same meter. This trace is much rougher. The maximum voltage dip approaches 500 volts or 4%. The frequency is approximately 10 to 20 times per hour.

B. Operator's Digital Voltmeter

The 13 kV bus voltage at is controlled by changing taps on 69-13 kV transformers #5 and #6. The tap changer control is located in the 800# boiler control room. The bus voltage is shown on a digital voltmeter that changes state about every second. The operator attempts to keep the voltage at 13.8 kV.

On August 27th, the operation of this digital voltmeter was observed. During a five-minute time span the meter varied from 14.1 kV to 13.3 kV. The right most two digits which represent the decimal parts of the kilovolt reading were very rarely the same each time the display was refreshed.

It is almost impossible for the operator to keep the voltage within tolerance. It moves so much he does not know whether to raise or lower at any given time. The best he can do is to limit the high voltage excursions and ignore the voltage dips.

8. Conclusions

The voltage flicker on the Sub A 13 kV bus exceeds the limits set forth in Planning Standard P820-200. In addition, the voltage dips may also put us in violation of voltage minimums at our other customers served at the end of Sub A 13 kV circuits. Comparison of the voltage conditions before and after the installation of the new mill drive indicates that it is the source of the problem.

The harmonic content of the voltages and currents measured at also violates criteria. IEEE Standard 519-1981 lists the limits for voltage distortion factor as 5.0% for voltages from 2.4 to 69 kV and 1.5% for 115 kV and above. Figure 1 lists voltage distortion factors as high as 5.5%.

In addition, the presence of harmonic currents may be detrimental to the generating unit R-4 which is directly connected to the Sub A 13 kV bus. Harmonics can cause overheating of the rotor. Further research would be necessary to determine the extent of the problem.

In order to properly identify the new solid state drive as the source of the harmonic problem, it will be necessary to perform the harmonic tests with the mill not in service. Harmonic problems can show up at buses remote from their service. The harmonics measured at could be coming from a number of sources inside and outside of .

9. Possible Solutions

There are three possible solutions to the voltage flicker problem:

A. Make adjustments to the solid state drive system controls

B. Put on its own separate transformer

C. Install a static var generator

Possible solutions to the harmonic problem are:

A. Put on a separate transformer

B. Install tuned filters

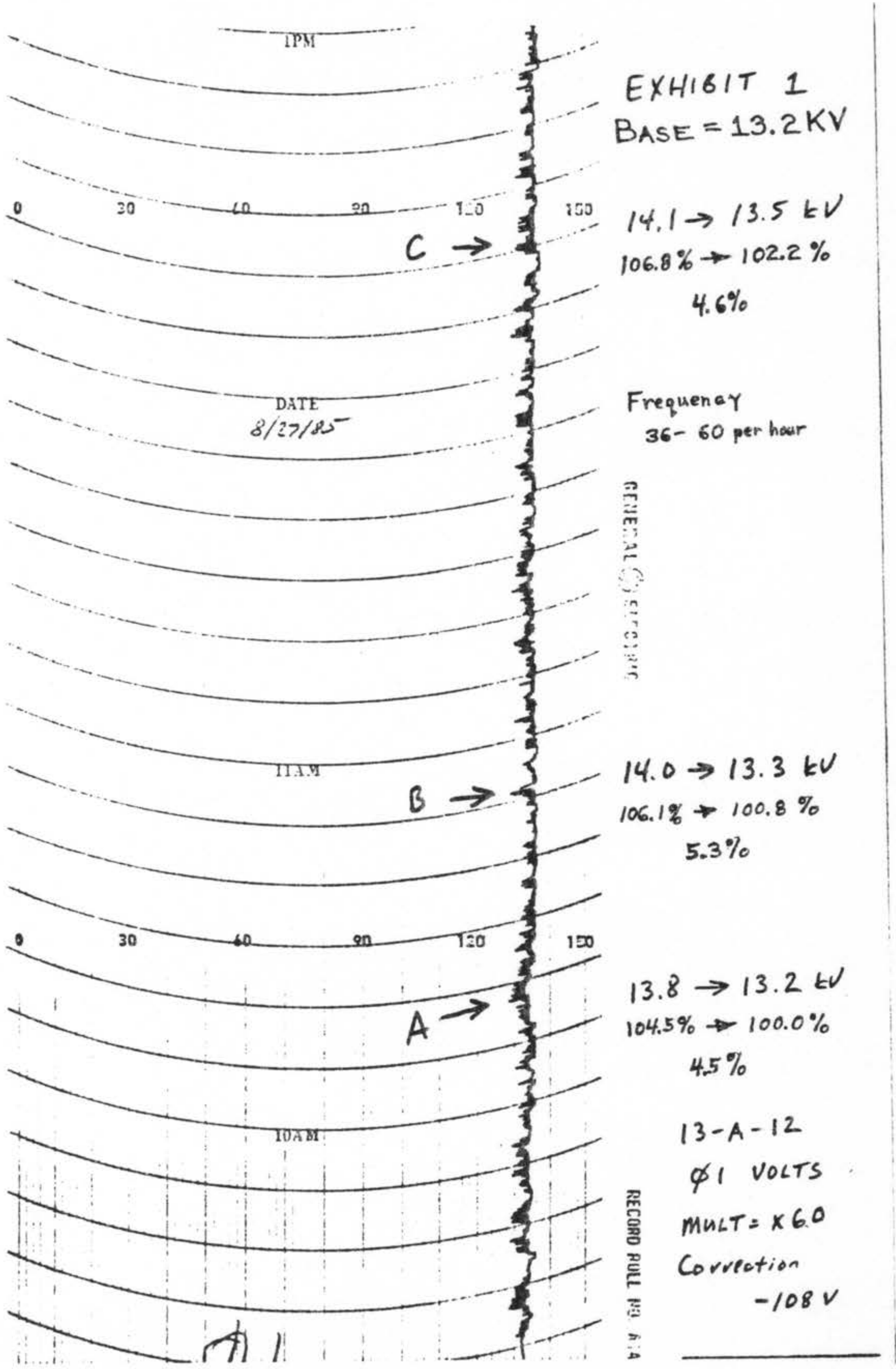
Isolating on its own transformer would allow the application of the IEEE suggested limit of 8% for the voltage distortion factor. It would also place the customer on the lower impedance 161 kV system further away from other customers and generator R-4.

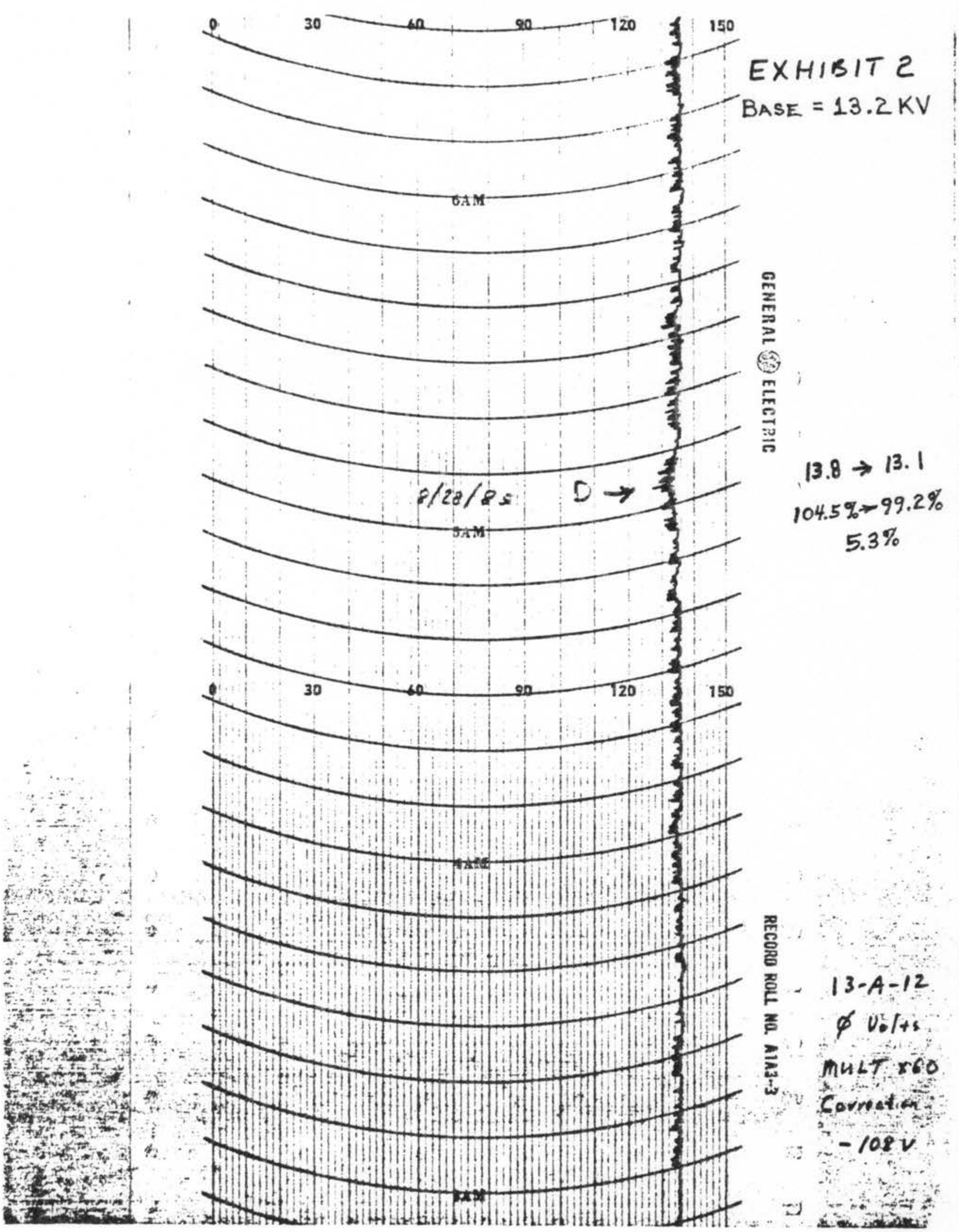
10. Recommendations

A. A test should be coordinated with which would allow us to measure harmonics with the new mill drive on and off. This would positively determine if the new drive is the source of the harmonics.

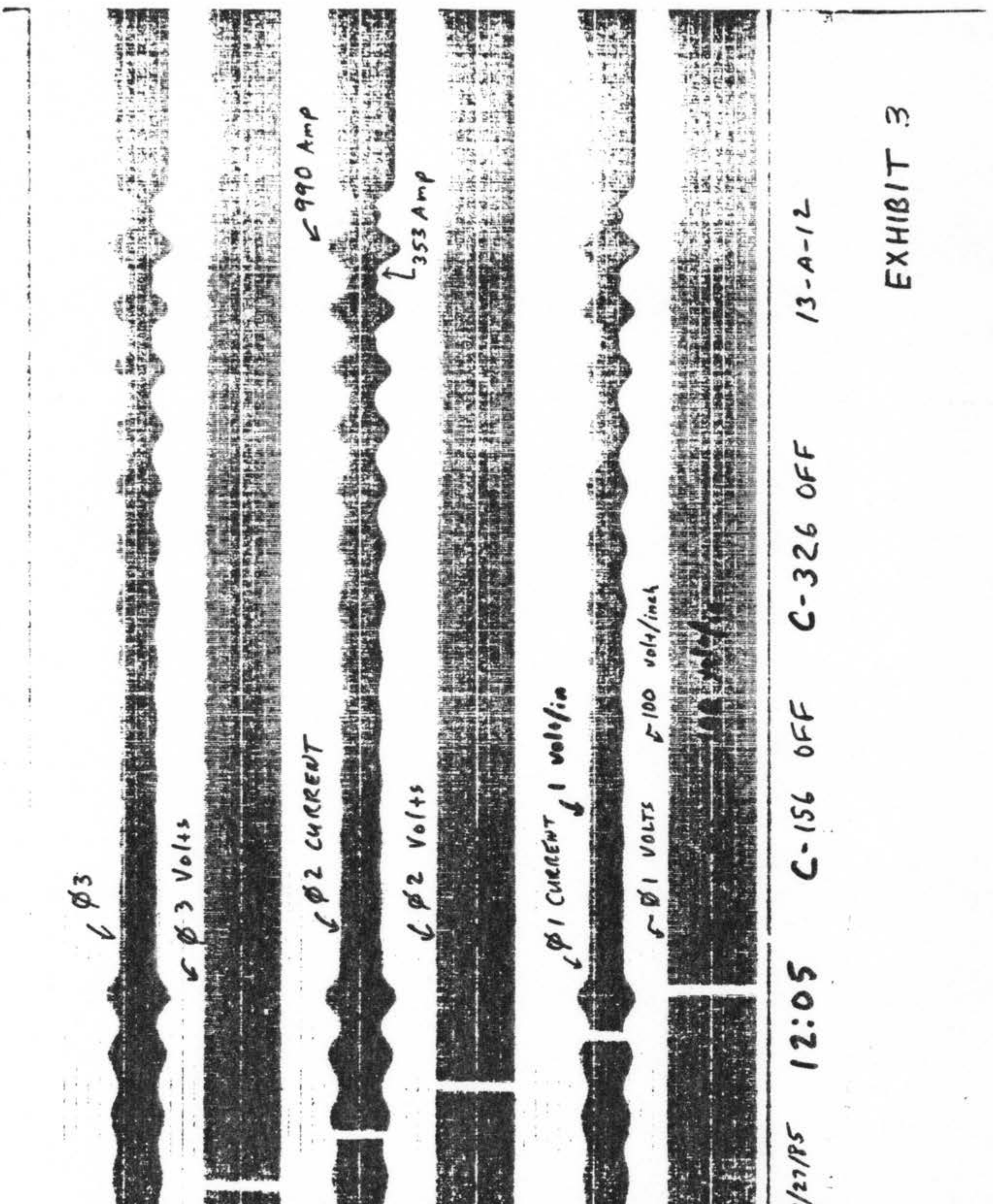
B. A meeting should be arranged with representatives of and (manufacturer of the solid state drive) to resolve the problem.

LTD:sjb
09-09-85

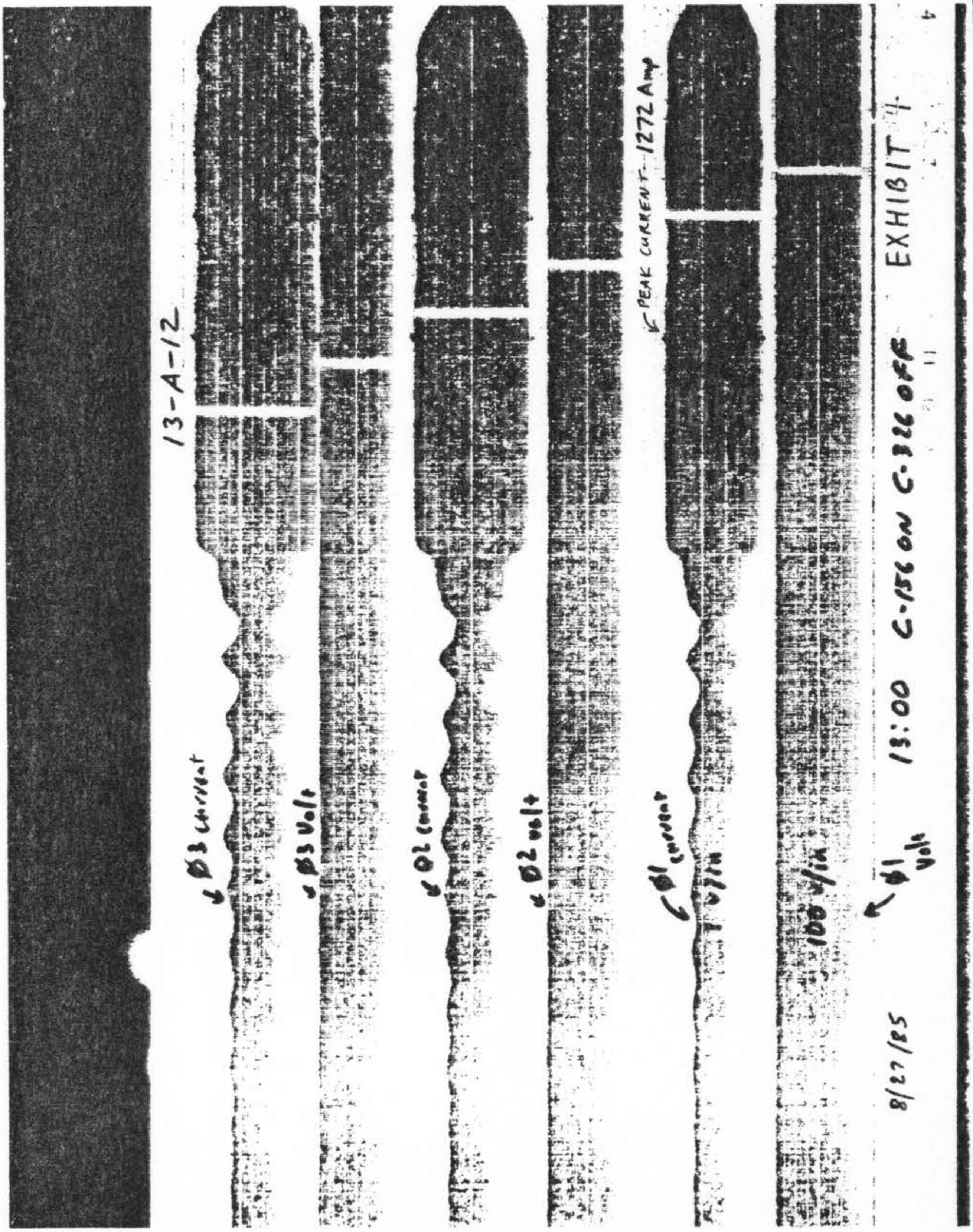

1PM
0 30 60 90 120 150
C →
DATE
8/27/85
11AM
B →
0 30 60 90 120 150
A →
10AM
EXHIBIT 1
BASE = 13.2KV
14.1 → 13.5 kV
106.8% → 102.2%
4.6%
Frequenay
36- 60 per hour
14.0 → 13.3 kV
106.1% → 100.8%
5.3%
13.8 → 13.2 kV
104.5% → 100.0%
4.5%
13-A-12
φ1 VOLTS
MULT = x 6.0
Correction
-108 V
RECORD ROLL NO.

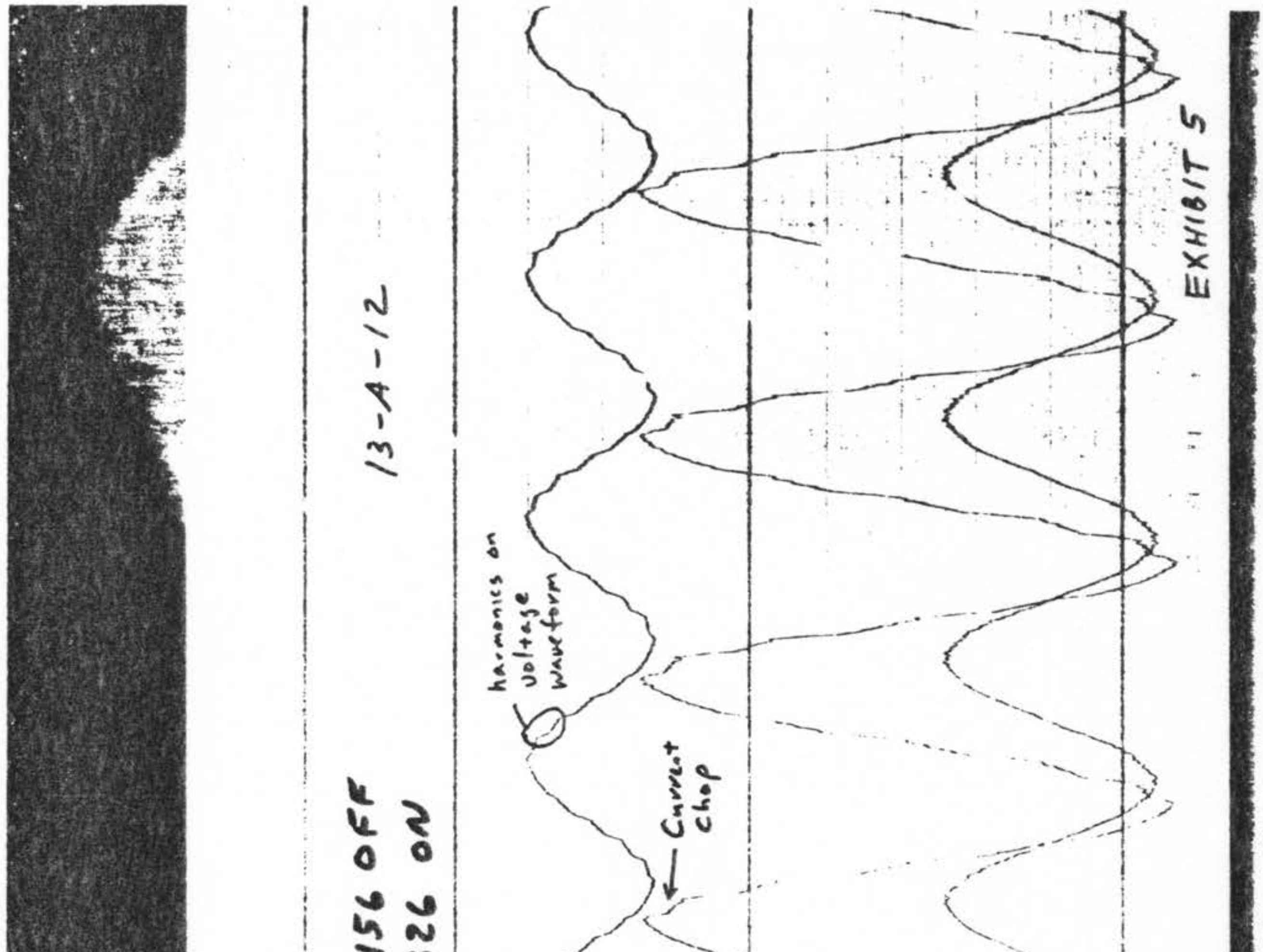


0 30 60 90 120 150
EXHIBIT 2
BASE = 13.2 KV
6AM
GENERAL ELECTRIC
8/28/85
D →
5AM
13.8 → 13.1
104.5% → 99.2%
5.3%
RECORD ROLL NO. A1A3-3
13-A-12
φ Volts
MULT x60
Correction
-108 V



Ø3
Ø 3 Volts
Ø2 CURRENT
990 Amp
353 Amp
Ø2 Volts
Ø1 CURRENT
1 volt/in
Ø1 VOLTS
100 volt/inch
9/27/85
12:05
C-156 OFF
C-326 OFF
13-A-12
EXHIBIT 3


13-A-12
Ø3 current
Ø3 Volts
Ø2 current
Ø2 volt
PEAK CURRENT - 1272 Amp
Ø1 current
100 v/in
Ø1 Volts
8/27/85 13:00 C-156 ON C-326 OFF
EXHIBIT 4


8/27/85
1020
C-156 OFF
C-326 ON
13-A-12
harmonics on voltage waveform
Current chop
Possible pulses
ϕ2 Current 1 V/in
ϕ1 Current 1 V/in
50 V/in
ϕ1 Volts
EXHIBIT 5

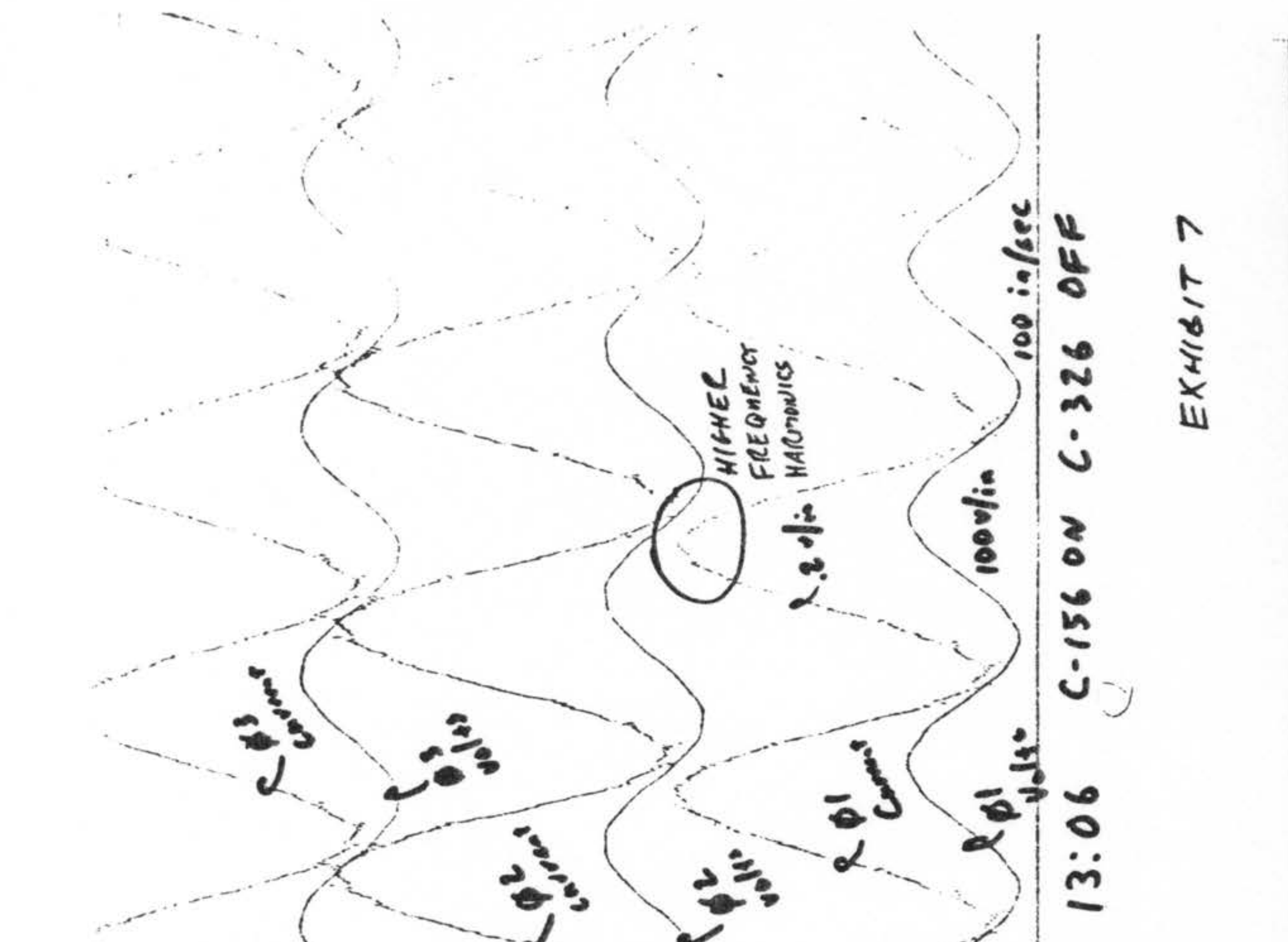
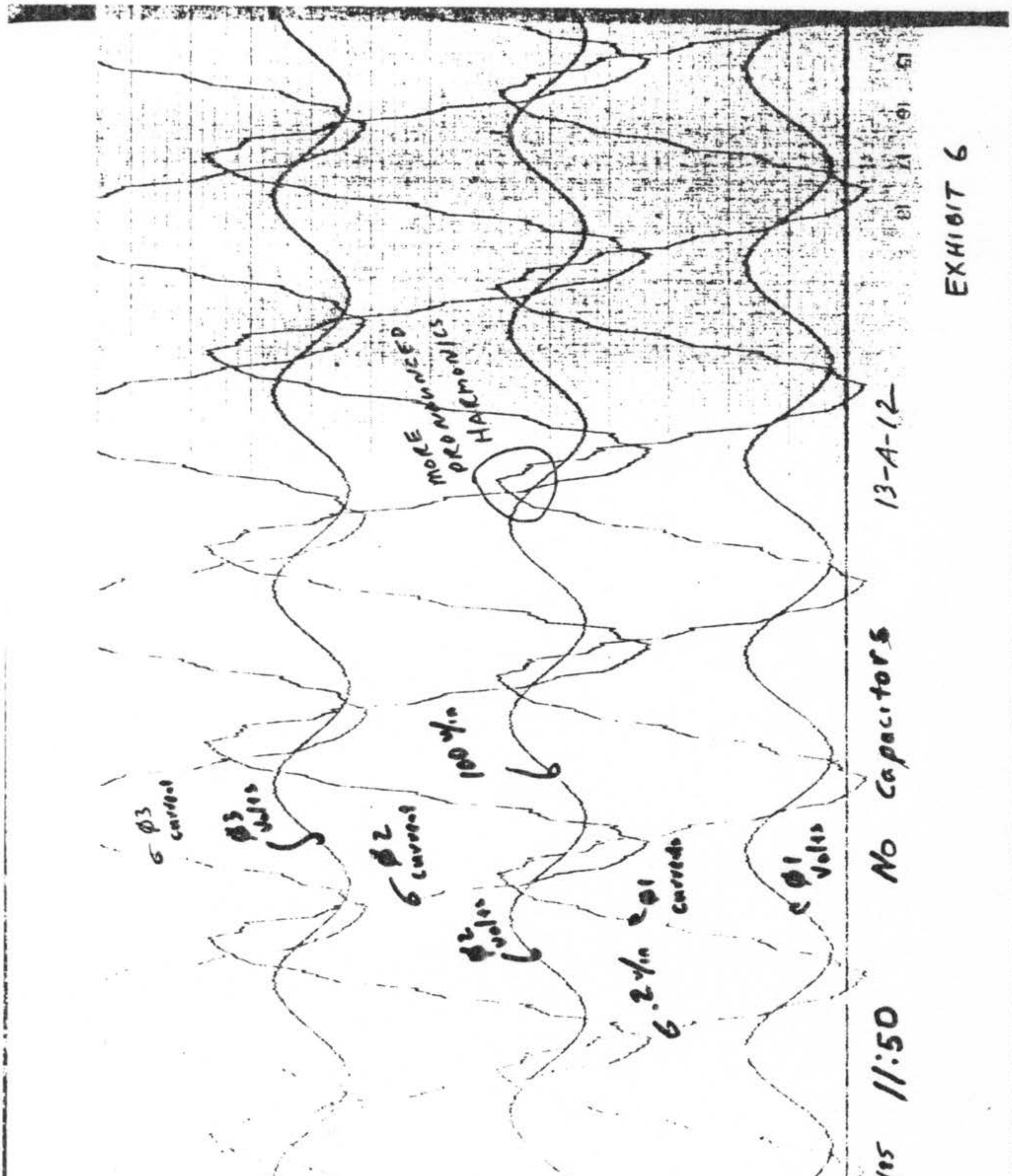
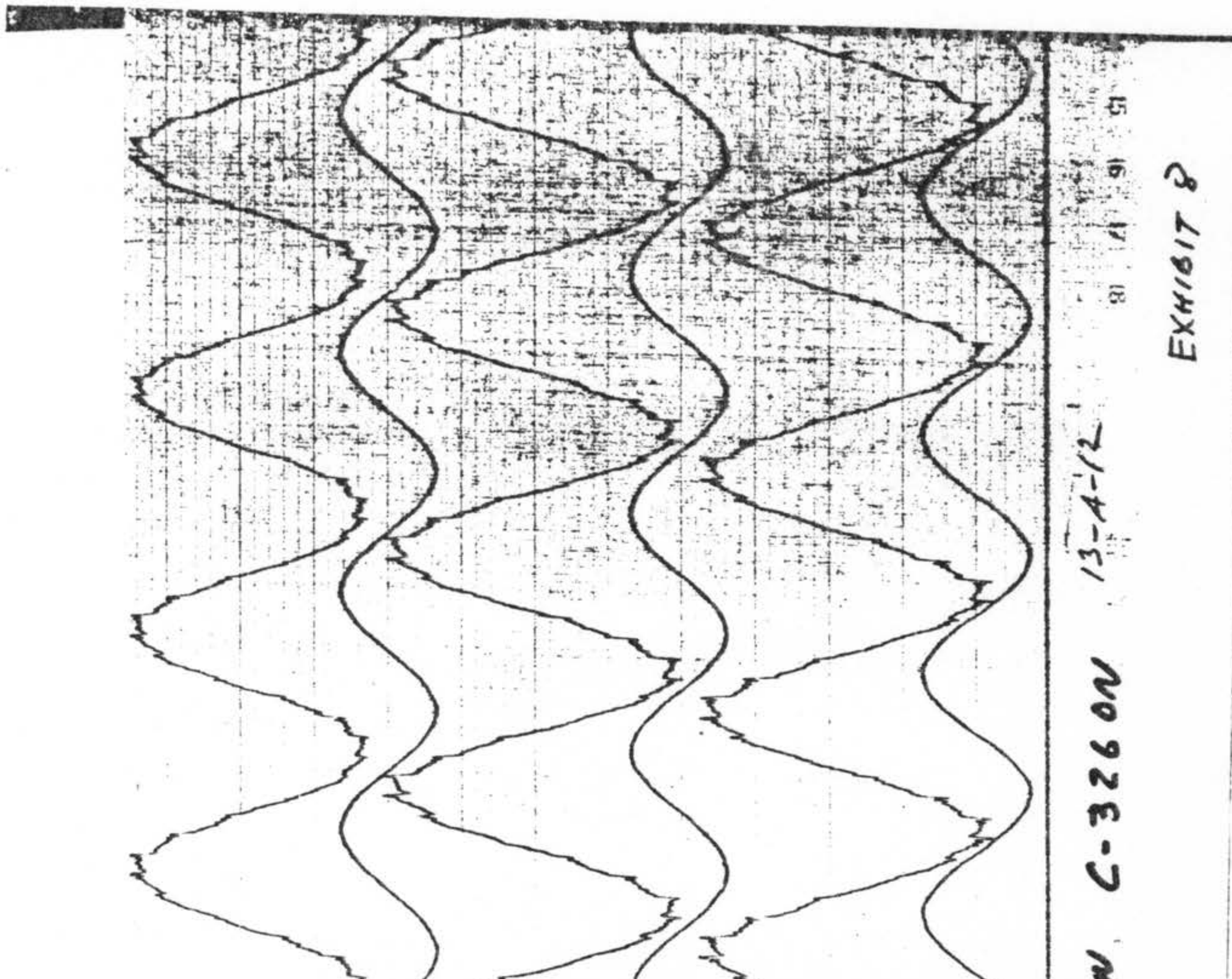

13-A-12
8/27/95
13:06
C-156 ON C-326 OFF
100 in/sec
100 V/in
HIGHER FREQUENCY HARMONICS

EXHIBIT 7


8/22/85 11:50 No Capacitors 13-A-12
EXHIBIT 6
MORE PRONOUNCED HARMONICS
100 V/in
.2 V/in
Ø3 current
Ø3 volts
Ø2 current
Ø2 volts
Ø1 current
Ø1 volts


8/27/95 13:20 C-156 ON C-326 ON 13-A-12
EXHIBIT 8
Φ3 Current
Φ3 Volts
Φ2 Current
Φ2 Volts
Φ1 Current
Φ1 Volts

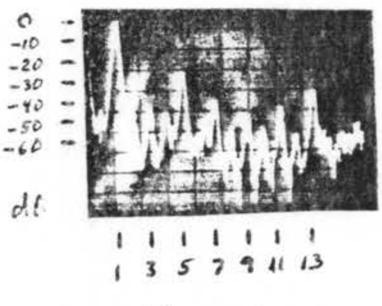
SPECTRUM ANALYZER SHEET NO ______ OF ______

TEST DATE 8/27/85 BY LTD

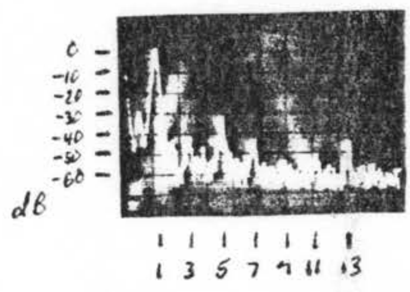
NOTE: POTENTIAL PROBE = 10 X
CURRENT PROBE = 1V = 10 AMPS

TEST #1

Sub A 13-A-12
Voltage Ø1
VERT -30 db/div ~~11:20~~
HORZ 100 Hz/div 11:25

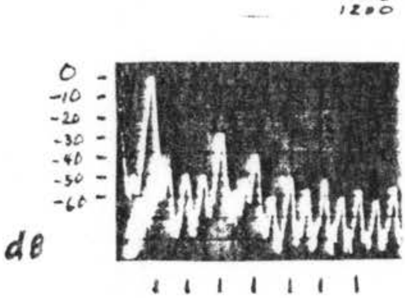


Sub A 13-A-12 Ø1
Current ~~11:20~~
Vertical .0 db/div 0 db input ~~11:25~~
Horz 100 Hz/div 11:33



TEST #2

Sub A 13-A-12 C366D
Voltage C326 ON
Vert 10 db/div Ø1
Horz 100 Hz/div ~~11:55~~ 12:00



Sub A 13-A-12 C36 OFF
Current C326 OFF
Vertical .0 db/div 0 db input Ø1
Horz 100 Hz/div

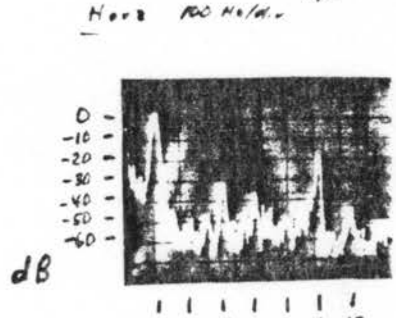


EXHIBIT 9

FORM CO-9L

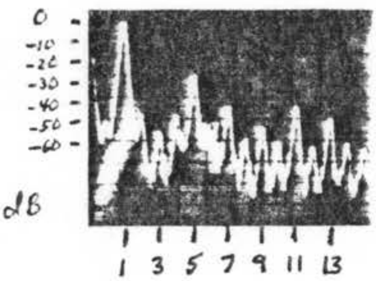
SPECTRUM ANALYZER — SHEET NO. ____ OF ____

TEST — DATE 8/27/85 BY LTD

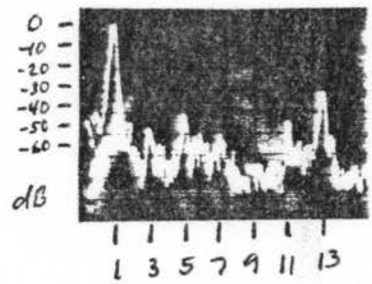
NOTE: POTENTIAL PROBE = 10X
CURRENT PROBE = 1V = 10 AMPS

TEST #3

Sub A 13-A-12 C156 ON
Voltage C326 OFF
Vert 10 db/div Ø1
Horz 100 cyls/div 1256

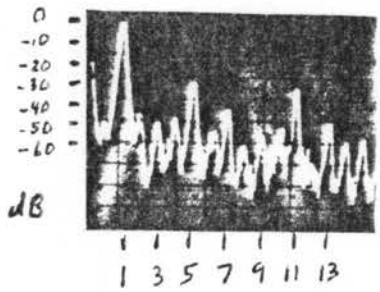


Sub A 13-A-12 C156 ON
C326 OFF
Current Ø1
Vertical 10 db/div 1256
Horz 100 Hz/div 300



TEST #4

Sub A 13-A-12 C156 ON
Voltage C326 ON
Vert 10 db/div Ø1
Horz 100 cyls/div 1315



Sub A 13-A-12 C156 ON
Current C326 ON
Vertical 10 db/div Ø1
Horz 100 Hz/div 1310

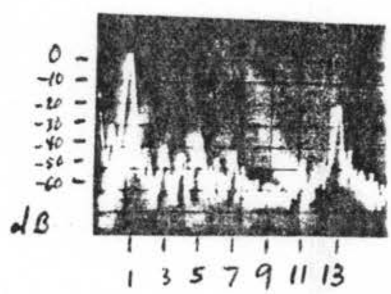


EXHIBIT 10

13kV Bus Voltage

6/12/85

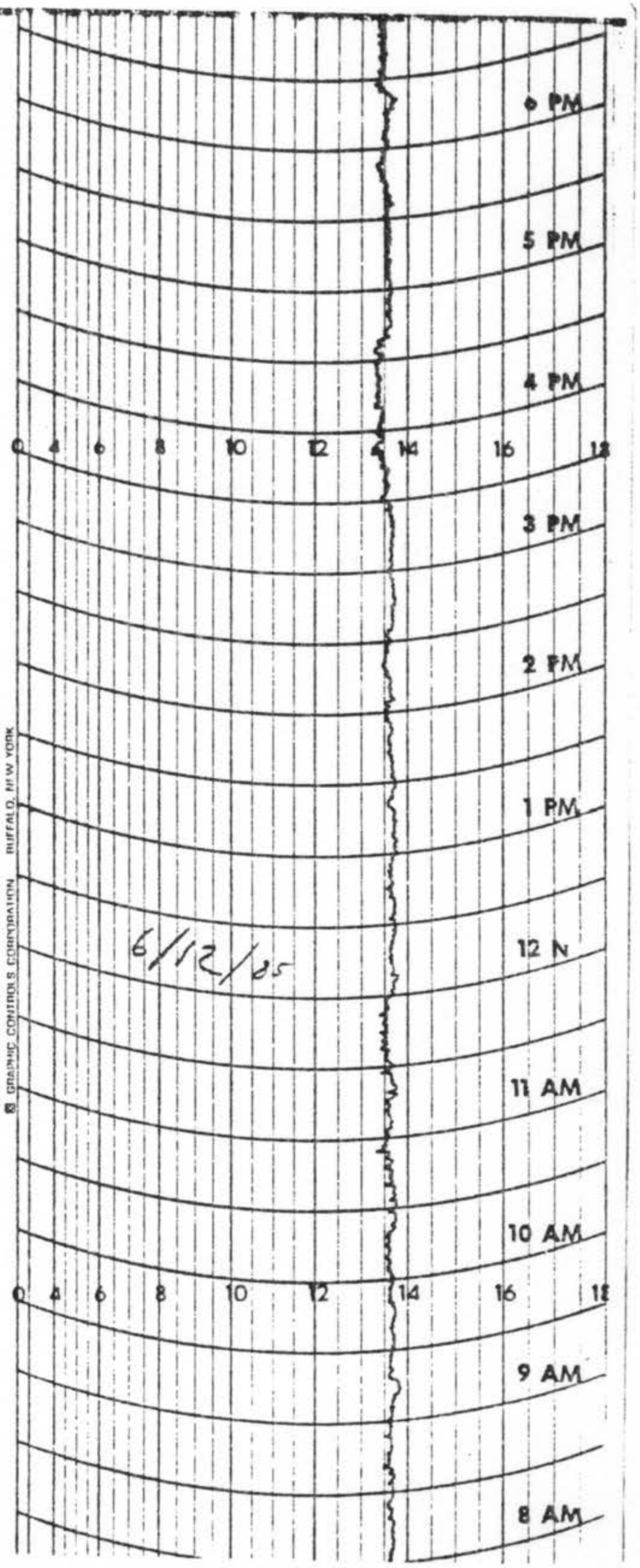


EXHIBIT 11

13 kV Bus Voltage

8/13/85

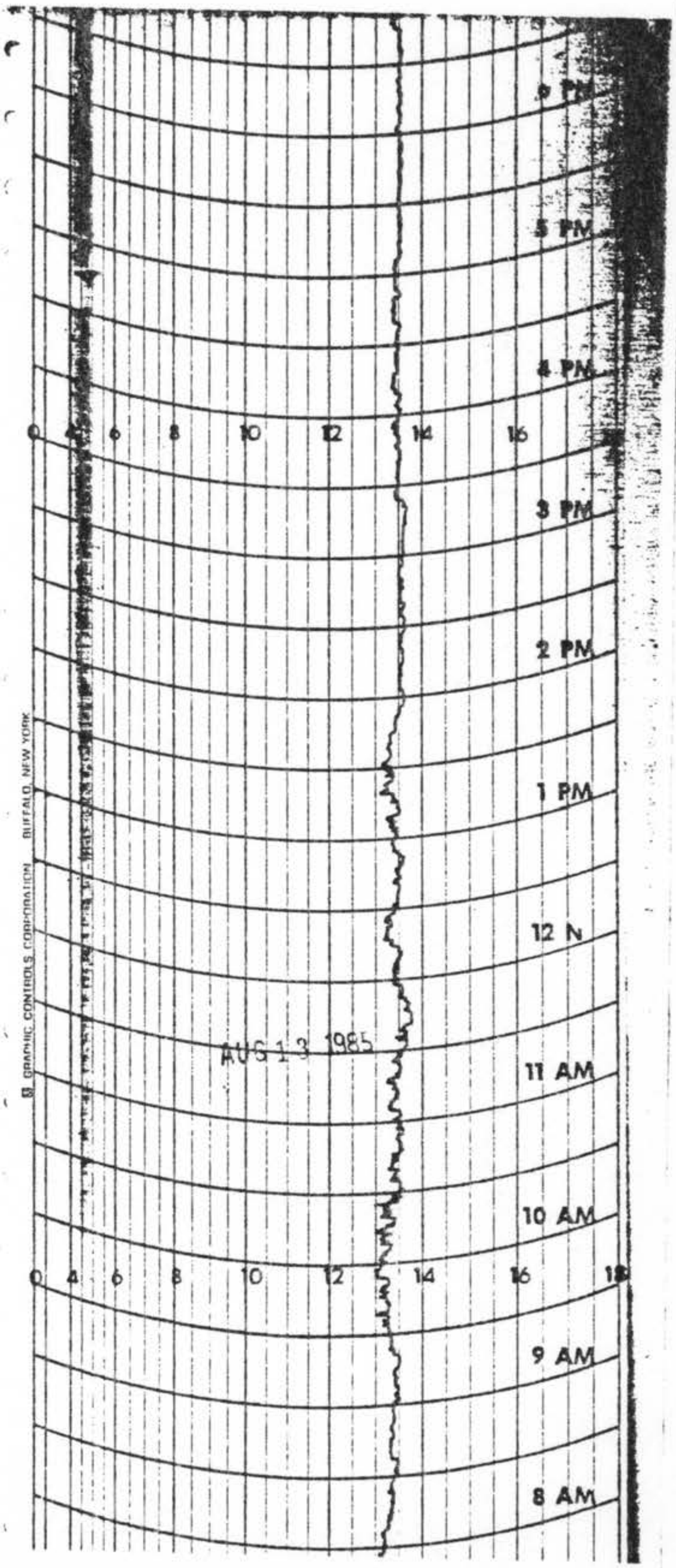


EXHIBIT 12

IX. APPENDIX

B. SLIDE LISTINGS

SLIDE LISTINGS

1. SUB S TR #1
CURRENT - HIGH SIDE
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

2. SUB S TR #1
CURRENT - HIGH SIDE
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

3. SUB S TR #1
CURRENT - HIGH SIDE
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

4. SUB S TR #1
CURRENT
Vert = 10dB/div
Horiz = 100 cycles
Phase 1

5. SUB S TR #1
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

6. SUB S TR #1
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

7. SUB S TR #1
CURRENT - LOW SIDE (13 KV)
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

8. SUB S TR #1
CURRENT - LOW SIDE (13 KV)
Vert = 10dB/div
Horiz = 100 cycles
Phase 2

9. SUB S TR #1
CURRENT - LOW SIDE (13 KV)
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

10. SUB S
13 KV BUS 1 VOLTS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

11. SUB S
13 KV BUS 1 VOLTS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

12. SUB S
13 KV BUS 1 VOLTS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

13. SUB S TR #1
CURRENT - HIGH SIDE
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

14. SUB S TR #1
CURRENT - HIGH SIDE
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

15. SUB S TR #1
CURRENT - HIGH SIDE
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

16. SUB S TR #1
CURRENT - LOW SIDE (13 KV)
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

SLIDE LISTINGS

(Continued)

17. SUB S TR #1
CURRENT - LOW SIDE (13 KV)
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

18. SUB S TR #1
CURRENT - LOW SIDE (13 KV)
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

19. SUB S
69 KV BUS 2 VOLTS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

20. SUB S
69 KV BUS 2 VOLTS
Vert = 10dB/div
Horiz = 100 cycles/div
Phasel

21. SUB S
69 KV BUS 2 VOLTS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

22. SUB S
69 KV BUS 2 VOLTS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

23. SUB 36 VOLTS - 13 KV
13 KV BUS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

24 SUB 36 VOLTS - 13 KV
13 KV BUS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

25. SUB 36 VOLTS - 13 KV
13 KV BUS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

26. SUB 36 VOLTS - 69 KV
66-36-38-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

27. SUB 36 VOLTS - 69 KV
66-36-38-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

28. SUB 36 VOLTS 69 KV
66-36-38-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

29. SUB 36
CURRENT - 13 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

30. SUB 36
CURRENT - 13 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

31. SUB 36
CURRENT - 13 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

32. SUB 36
CURRENT - 69 KV
69 Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

SLIDE LISTINGS

(Continued)

33. SUB 36
CURRENT - 69 KV
69 Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

34. SUB 36
CURRENT - 69 KV
69 Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

35. SUB 36
CURRENT - 13 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

36. SUB 36
CURRENT - 13 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

37. SUB 36
CURRENT - 13 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

38. SUB 76 VOLTS 161 KV
161-76-58-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

39. SUB 76 VOLTS 161 KV
161-76-58-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

40. SUB 76 VOLTS 161 KV
161-76-58-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

41. SUB 76
CURRENT - 161 KV
161 KV Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

42. SUB 76
CURRENT - 161 KV
161 KV Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

43. SUB 76
CURRENT - 161 KV
161 KV Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

44. SUB 76 VOLTS 13 KV
13 KV BUS 2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

45. SUB 76 VOLTS 13 KV
13 KV BUS 2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

46. SUB 76 VOLTS 13 KV
13 KV BUS 2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

SLIDE LISTINGS

(Continued)

47. SUB 76
CURRENT - 13 KV
161 KV Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

48. SUB 76
CURRENT - 13 KV
161 KV Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

49. SUB 76
CURRENT - 13 KV
161 KV Trans #1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

50. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

51. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

52. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

53. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

54. SUB 78 Thu 6-21-84
161-58-74-78-1 line
current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

55. SUB 78 Thu 6-21-84
161-58-74-78-1 line
current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

56. SUB 78 Thu 6-21-84
161-58-74-78-1 line
current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

57. SUB 78 Thu 6-21-84
161-58-74-78-1 line
current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

58. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles
Phase 1

59. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

60. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

SLIDE LISTINGS

(Continued)

61. SUB 78 Thu 6-21-84
Tr #1 13 KV Current
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

62. SUB 78 Thu 6-21-84
Tr #1 13 KV Volts
Phase 1

63. SUB 78 Thu 6-21-84
Tr #1 13 KV Volts
Phase 2

64. SUB 78 Thu 6-21-84
Tr #1 13 KV Volts
Phase 3

65. SUB 78 Thu 6-21-84
161-58-74-78-1 line
voltage
Phase 1

66. SUB 78 Thu 6-21-84
161-58-74-78-1 line
voltage
Phase 2

67. SUB 78 Thu 6-21-84
161-58-74-78-1 line
voltage
Phase 3

68. SUB 78
161 BUS Volts
Phase 1

69. SUB 78
161 BUS Volts
Phase 2

70. SUB 78
161 BUS Volts
Phase 3

71. SUB 78
13 BUS 2 Volts
Phase 1

72. SUB 78
13 BUS 2 Volts
Phase 2

73. SUB 78
13 BUS 2 Volts
Phase 3

74. SUB 78
Trans #2 13 Currents
Phase 1

75. SUB 78
Trans #2 13 Currents
Phase 1

76. SUB 78
Trans #2 13 Currents
Phase 2

77. SUB 78
Trans #2 13 Currents
Phase 3

78. SUB 78
161-58-74-78-1
Phase 1

79. SUB 78
161-58-74-78-1
Phase 2

80. SUB 78
161-58-74-78-1
Phase 3

81. SUB 78 - Volts - 13 KV
13 KV BUS
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

SLIDE LISTINGS

(Continued)

82. SUB 78 - Volts - 13 KV
13 KV BUS 1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

83. SUB 78 - Volts - 13 KV
13 KV BUS 1
Vert = 10 dB/div
Horiz = 100 cycles/div
Phase 3

84. SUB 78 - Volts - 13 KV
13 KV BUS 2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

85. SUB 78 - Volts - 13 KV
13 KV BUS 2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

86. SUB 78 - Volts - 13 KV
13 KV BUS 2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

87. SUB 78 - Volts - 161 KV
161-74-78-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

88. SUB 78 - Volts - 161 KV
161-74-78-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

89. SUB 78 - Volts - 161 KV
161-74-78-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

90. SUB 88
CURRENT - 13 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

91. No Title - Assumed to be
SUB 88
current - 13 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

92. SUB 88
CURRENT - 13 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

93. SUB 88 - Volts - 13 KV
13 KV BUS 2 (Alcoa Pots)
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

94. SUB 88 - Volts - 13 KV
13 KV BUS 2 (Alcoa Pots)
Vert = 10 dB/div
Horiz = 100 cycles/div
Phase 2

95. SUB 88 - Volts - 13 KV
13 KV BUS 2 (Alcoa Pots)
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

96. SUB 88
CURRENT - 69 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

SLIDE LISTINGS

(Continued)

97. SUB 88
CURRENT - 69 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

98. SUB 88
CURRENT - 69 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

99. SUB 88
CURRENT - 69 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

100. SUB 88
CURRENT - 69 KV
69/13 Trans #2
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

101. SUB 91 - Volts - 345
345-QC-91-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

102. SUB 91 - Volts - 345
345-QC-91-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

103. SUB 91 - Volts - 345
345-QC-91-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

104. SUB 91 - Volts 161 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

105. SUB 91 - Volts - 161 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

106. SUB 91 - Volts - 161 KV
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

107. SUB 91
CURRENT - 345 KV
345-91-QC-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

108. SUB 91
CURRENT - 345 KV
345-91-QC-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

109. SUB 91
CURRENT - 345 KV
345-91-QC-1
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

110. SUB 91
CURRENT - 161 KV
345/161 Trans
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

SLIDE LISTINGS

(Continued)

111. SUB 91
CURRENT - 161 KV
345/161 Trans
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

112. SUB 91
CURRENT - 161 KV
345/161 Trans
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

113. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
C156 On
C326 On
Phase 1

114. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
C156 On
C326 On
Phase 1

115. SUB A 13-A-12
CURRENT
Vert = 20 volt/div
Horiz = 100 cycles/div
C156 On
C326 On
Phase 1

116. SUB A 13-A-1
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
C156 On
C326 On
Phase 1

117. SUB A 13-A-12
CURRENT
Vert = .2 v/div
Horiz = 100 cycles/div
C156 On
C326 On
Phase 1

118. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
C156 On
C326 Off
Phase 1

119. SUB A 13-A-12
CURRENT
Vert = 20 v/div
Horiz = 100 cycles/div
C156 On
C326 Off
Phase

120. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
C156 On
C326 Off
Phase 1

121. SUB A 13-A-12
CURRENT
Vert = .2 v/div
Horiz = 100 cycles/div
C156 On
C326 Off
Phase 1

122. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
C156 Off
C326 Off
Phase 1

SLIDE LISTINGS

(Continued)

123. SUB A 13-A-12
CURRENT
Vert = 20 v/div
Horiz = 100 cycles/div
C156 Off
C326 Off
Phase 1

124. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
C156 Off
C326 Off
Phase 1

125. SUB A 13-A-12
CURRENT
Vert = .2 v/div
Horiz = 100 cycles/div
C156 Off
C326 Off
Phase 1

126. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

127. SUB A 13-A-12
CURRENT
Vert = .2 v/div
Horiz = 100 cycles/div
Phase 3

128. SUB A 13-A-12
CURRENT
Vert = .2 v/div
Horiz = 100 cycles/div
Phase 1

129. SUB A 13-A-12
CURRENT
Vert = .2 v/div
Horiz = 100 cycles/div
Phase 1

130. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
0 db Input
Phase 1

131. SUB A 13-A-12
CURRENT
Vert = 20 v/div
Horiz = 100 cycles/div
Phase 1

132. SUB A 13-A-12
CURRENT
Vert = +30dB/div
Horiz = 100 cycles/div
Phase 1

133. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 1

134. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 2

135. SUB A 13-A-12
CURRENT
Vert = 10dB/div
Horiz = 100 cycles/div
Phase 3

136. Picture of Test Equipment

137. Picture of Test Equipment

138. Picture of Test Equipment

139. Picture of Test Equipment

X. APPENDIX

C. MODIFIED HARMONIC LOADFLOW PROGRAM LISTING

```
C---   IOWA STATE UNIVERSITY HARMONICS PROGRAM
C---   ENERGY SUPPLY DEPARTMENT
C---   QUAD CITIES PRODUCTION DIVISON
C---
C---      HARMONIC LOADFLOW USING FFT OF SAMPLED HARMONIC SOURCE
C---      VOLTAGE OR CURRENT WAVEFORM OR AC-DC CONVERTER CURRENT
C---      WAVEFORM
C---         REF: KUYPER,K.H. 'EFFECTS OF WIND AND SOLAR CONVERTERS
C---         ON UTILITY DISTRIBUTION NETWORKS', MASTER'S THESIS,
C---         IOWA STATE UNIVERSITY, 1980.
C---         REF: SCHULTZ,R.D. 'HARMONIC CURRENT PROPAGATION ON AC
C---         SYSTEMS DUE TO HVDC LINKS', PHD DISSERTATION, IOWA
C---         STATE UNIVERSITY, 1979.
C---      MODIFIED BY A.L.DAY BEGINNING JUNE, 1982.
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,MBUS,IDSN,IW,N,IWK
      COMPLEX*8 D1,D2,DD1,DD,DZ1,DZ,DE,DSH,DCH,DYS,DZS,CMPLX,CSQRT,CEXP
      COMPLEX*8 DT1,DT2,DT3,DYZ,CWK,SOURCE,CONJG,ZO,GAML,VC,VCK
      COMMON /K1/IRD,IWT,IW,IDSN,H2
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      COMMON /BASE/LLL,JJJJ,IOPT
      COMMON /CDC/SOURCE,VCK,LHARM,JJJ,IVC
      DIMENSION IP(4000),IQ(4000),ICT(4000),R(4000),X(4000),ILIN(4000)
      DIMENSION KP1(4000),KP2(4000),ILO(4000),SOURCE(128,4)
      DIMENSION NB(9998),NLB(500),NBE(500),DATLAB(5,4)
      DIMENSION JP1(500),JP2(500),IBO(500),ISC(500)
      DIMENSION RBUS(125250),XBUS(125250),RL(500),XL(500)
      DIMENSION IWK(918),A(128),WK(918),VC(128)
      DIMENSION ZO(4000),GAML(4000),YLAB(5,2),GLAB(5,2)
      DIMENSION VMSQ(9998),HDF(9998),VVM1(9998)
      DATA DATLAB/'SOUR','CE #',' 1  ','    ','    ','SOUR','CE #',
     1 ' 2  ','    ','    ','SOUR','CE #',' 3  ','    ','    ',
     2 'SOUR','CE #',' 4  ','    ','    '/
      DATA YLAB/'VOLT','AGE ','(PU)',':   ','    ','CURR','ENT ',
     1 '(PU)',':   ','    '/
      DATA GLAB/'HARM',' SOU','RCE ','VOLT','AGE:','HARM',' SOU',
     1 'RCE ','CURR','ENT:'/
C---      IRD=LOGICAL UNIT # FOR READ STATEMENTS
      IRD=5
C---      IWT=LOGICAL UNIT  IUNIT # FOR WRITE STATEMENTS
      IWT=6
C---      NBX=MAXIMUM NUMBER OF BUSES
      NBX=500
C---      NEX=MAXIMUM NUMBER OF ELEMENTS
      NEX=4000
C---      NBH=LARGEST BUS NUMBER ALLOWED
      NBH=9998
C---      MBUS=LENGTH OF ARRAY FOR BUS IMPEDANCE MATRIX
      MBUS=NBX*(NBX+1)/2
C---      JJJJ=COMBINED CONVERTER ACTION FLAG
C---         0=SINGLE CONVERTER
C---         1=COMBINED CONVERTERS
      JJJJ=0
C---      RTD=RADIAN TO DEGREE CONVERSION
      RTD=57.29577951
C---      H2=BESSEL FUNCTION FLAG FOR LINEIN
C---         0.=NEED TO CALCULATE BESSEL FUNCTION PARAMETERS
      H2=0.
C---      READ HARMONIC SOURCE INPUT DATA
C---         N=NUMBER OF SAMPLED DATA POINTS (EVEN,.LE.128)
C---         (OR) N=NUMBER OF PULSES FOR CONVERTER
C---         VCBASE=BASE VALUE OF VOLTAGE OR CURRENT FOR HARM SOURCE
C---         LHARM=HIGHEST ORDER HARMONIC TO BE ANALYZED
C---         IPLOT=PLOT CODE
```

```
C---              0=NO PLOTS
C---            IVC=VOLTAGE OR CURRENT OR CONVERTER CODE
C---              LESS THAN -1 = CURRENT HARMONIC MAGNITUDES GIVEN
C---              -1=VOLTAGE HARMONIC MAGNITUDES GIVEN
C---              0=VOLTAGE WAVEFORM
C---              1=CONVERTER
C---              ANYTHING ELSE=CURRENT WAVEFORM
C---            IUNIT=OUTPUT UNITS
C---              0=VOLTS
C---              ANYTHING ELSE=PER UNIT
      READ(IRD,1000)N,VCBASE,LHARM,IPLOT,IVC,IUNIT
 1000 FORMAT(I3,F10.2,4I3)
      WRITE(IWT,109)N,VCBASE,LHARM,IPLOT,IVC,IUNIT
  109 FORMAT(1X,'N = ',I3,5X,'VCBASE = ',F7.2,5X,'LHARM = ',I3,
     1 5X,'IPLOT = ',I3,5X,'IVC = ',I3,5X,'IUNIT = ',I3)
      IF(IVC.GE.0)GO TO 40
C---    READ MEASURED HARMONIC VOLTAGES OR CURRENTS
C---      IY=HARMONIC ORDER
C---      VCM=HARMONIC VOLTAGE (CURRENT) MAGNITUDE
C---      VCA=HARMONIC VOLTAGE (CURRENT) ANGLE
      IF (IVC.NE.-1) GO TO 28
      IVC=0
      GO TO 29
   28 IVC=2
   29 CONTINUE
      WRITE(IWT,1051)
      DO 31 IM=1,65
   31 VC(IM)=(0.,0.)
   30 READ(IRD,600)IY,VCM,VCA
      IF(IY.EQ.999)GO TO 34
      WRITE(IWT,600)IY,VCM,VCA
  600 FORMAT(3X,I3,2X,F12.8,2X,F12.8)
      IF(VCA.EQ.0.0)GO TO 32
      IM=IY+1
      VC(IM)=CMPLX(-VCM,0.)
      GO TO 33
   32 IM=IY-1
      VC(IM+2)=CMPLX(VCM,0.)
   33 GO TO 30
   34 IF=65
      GO TO 308
   40 IF(IVC.NE.1)GO TO 301
C---      READ CONVERTER DATA
C---          POW=MW RATING OF CONVERTER
C---          ALFA=DELAY ANGLE IN DEGREES (0-60)
C---          OVLP=OVERLAP ANGLE IN DEGREES
      READ(IRD,302) POW,ALFA,OVLP
  302 FORMAT(3F10.2)
      WRITE(IWT,303) POW,ALFA,OVLP
  303 FORMAT('0POW = ',F10.2,5X,'ALFA = ',F10.2,5X,'OVLP = ',F10.2)
      ALFA=ALFA/RTD
      OVLP=OVLP/RTD
      GAM=ALFA+OVLP
      DO 304 IM=3,65
  304 VC(IM)=(0.,0.)
      WRITE(IWT,1051)
      DH=COS(ALFA)-COS(GAM)
      DO 305 IM=N,65,N
      IF(OVLP.NE.0.)GO TO 306
C---      0.779697=SQRT(6)/PI
      SHAR1=0.779697/(IM-1.)
      SHAR2=0.779697/(IM+1.)
      GO TO 307
  306 SHM=SIN((IM-2.)*OVLP/2.)
      SHP=SIN(IM*OVLP/2.)
      F2=SQRT((SHM/(IM-2.))**2+(SHP/IM)**2-2.*SHM*SHP*
```

```
     1 COS(2.*ALFA+OVLP)/((IM-2.)*IM))
       SHAR1=0.779697*F2/((IM-1.)*DH)
       SHM=SIN(IM*OVLP/2.)
       SHP=SIN((IM+2.)*OVLP/2.)
       F2=SQRT((SHM/IM)**2+(SHP/(IM+2.))**2-2.*SHM*SHP*
     1 COS(2.*ALFA+OVLP)/(IM*(IM+2.)))
       SHAR2=0.779697*F2/((IM+1.)*DH)
C---      2.5651=2*PI/SQRT(6)
   307 CR=2.5651*POW/((COS(ALFA)+COS(GAM))*100.)
       VCA=180.
       VCM=CR*SHAR1
       IY=IM-1
       VC(IM)=CMPLX(-VCM,0.)
       WRITE(IWT,106) IY,VCM,VCA
       VCA=0.
       VCM=CR*SHAR2
       IY=IM+1
       VC(IM+2)=CMPLX(VCM,0.)
       WRITE(IWT,106) IY,VCM,VCA
   305 CONTINUE
       IF=65
       GO TO 308
C---      READ IN SAMPLED DATA WAVEFORM
   301 J=(N-1)/8+1
       DO 9 IB=1,J
       KI=8*(IB-1)+1
       KJ=KI+7
C---      A=ARRAY OF N VALUES OF THE SAMPLED DATA WAVEFORM IN COSINE
C---      FORM IN KV
       READ(IRD,1050) (A(K),K=KI,KJ)
  1050 FORMAT(8F10.2)
     9 CONTINUE
       WRITE(IWT,200)
   200 FORMAT(1H0,5X,'SAMPLED DATA POINTS'/1H0,'NUMBER',35X,'VALUES')
       DO 110 IB=1,J
       KI=8*(IB-1)+1
       KJ=KI+7
       WRITE(IWT,111) KI,(A(K),K=KI,KJ)
   111 FORMAT(1H0,I4,8F10.2)
   110 CONTINUE
       DO 300 IB=1,N
   300 VC(IB)=CMPLX(A(IB),0.)
C---      FFTCC IS A SPECIAL PROGRAM FROM A LIBRARY NOT INCLUDED
C---      THERE IS A DUMMY PROGRAM INCLUDED TO SATISFY EXTERNAL
C---      REFERENCES
C---      PERFORM FAST FOURIER TRANSFORM
C---      IWK=INTEGER WORK ARRAY OF LENGTH 6N+150
C---      WK=REAL WORK ARRAY OF LENGTH 6N+150
       CALL FFTCC(VC,N,IWK,WK)
C---      RN=NUMBER OF SAMPLED DATA POINTS/2
       RN=N/2
       WRITE(IWT,1051)
  1051 FORMAT(1H-,'HARMONIC VALUES'/'0ORDER',8X,'MAG',8X,'ANG')
       IZ=N/2
C---      RESCALE TRANSFORM COEFFICIENTS
       DO 26 IM=1,IZ
       VC(IM)=CONJG(VC(IM))/(RN*VCBASE)
       VCM=CABS(VC(IM))
       VCA=ANGLE(VC(IM))*RTD
C---      IY=HARMONIC ORDER
       IY=IM-1
C---      PRINT HARMONIC VALUES
       WRITE(IWT,106) IY,VCM,VCA
   106 FORMAT(3X,I2,2X,F12.4,F12.2)
    26 CONTINUE
C---      LLL=FIRST TIME THROUGH LOOP FLAG
```

```
C---          1=FIRST TIME
          IF=N/2+1
    308 LLL=1
          IF(IPLOT.EQ.0) IF=LHARM+1
C---        INITIALIZE DC HARMONIC TO ZERO
          DO 167 IE=1,4
    167 SOURCE(1,IE)=(0.,0.)
C---        BEGIN LOOP FOR HARMONIC ANALYSIS
C---        JJ=HARMONIC ORDER + 1
          DO 27 JJ=3,IF
C---        IW=HARMONIC ORDER
          IW=JJ-1
C---        VCK=HARMONIC SOURCE VALUE IN PU
          VCK=VC(JJ)
C---        IDSN=SEQUENCE CODE FOR HARMONIC (SEE LINEIN)
          IDSN=0
C---        IF HARMONIC INJEC NEGLBLE, DO NOT PERFORM HARMONIC ANAL
          IF(CABS(VCK).GT.0.00000001)GO TO 17
          DO 984 IE=1,4
    984 SOURCE(JJ,IE)=(0.,0.)
          GO TO 27
     17 IF(IW.GT.LHARM) GO TO 18
          GO TO 19
     18 WRITE(IWT,108) IW
    108 FORMAT('0XXX HARMONICS OF ORDER',3X,I3/)
     19 CONTINUE
C---        LINEIN=SUBROUTINE FOR READING AND STORING LINE, TRANSFORMER,
C---            GENERATOR, SHUNT CAPACITOR, AND LOAD DATA
C---        IP=ARRAY CONTAINING EXTERNAL 'FROM' BUS #'S
C---        IQ=ARRAY CONTAINING EXTERNAL 'TO' BUS #'S
C---        ICT=ARRAY CONTAINING ELEMENT CIRCUIT #'S
C---        R,X=ARRAYS CONTAINING ELEMENT RESISTANCE AND REACTANCE
C---        NB=ARRAY CONTAINING CONVERSION OF EXTERNAL TO INTERNAL
C---            BUS #'S
C---        NLB=ARRAY CONTAINING THE # OF ELEMENTS TO A BUS
C---        NBE=ARRAY CONTAINING CONVERSION OF INTERNAL TO EXTERNAL
C---            BUS #'S
          CALL LINEIN(IP,IQ,ICT,R,X,NB,NLB,NBE,ILIN,ZO,GAML,&2,&500)
C---        ORDER=SUBROUTINE FOR ORDERING AND INDEXING SYSTEM TOPOLOGY
C---        JP1=POINTER ARRAY FOR 'FROM' BUS TO ELEMENT #
C---        JP2=POINTER ARRAY FOR 'TO' BUS TO ELEMENT #
C---        KP1=POINTER ARRAY FOR 'FROM' BUS (ONE ELEMENT # TO NEXT)
C---        KP2=POINTER ARRAY FOR 'TO' BUS (ONE ELEMENT # TO NEXT)
C---        ISC=ARRAY CONTAINING THE ORDERING SCORE OF THE BUS
C---        ILO=ARRAY CONTAINING THE ELEMENT ORDER
C---        IBO=ARRAY CONTAINING THE BUS ORDER
      2 CALL ORDER(IP,IQ,NLB,JP1,JP2,KP1,KP2,ISC,ILO,IBO,&4,&500)
C---        ZBUS=SUBROUTINE FOR CALCULATION OF IMPEDANCE MATRIX
C---        RBUS=ARRAY CONTAINING REAL PART OF BUS IMPEDANCE MATRIX
C---        XBUS= ARRAY CONTAINING IMAGINARY PART OF BUS IMPEDANCE MATRI
C---        RL=ARRAY CONTAINING ELEMENT RESISTANCE
C---        XL=ARRAY CONTAINING ELEMENT REACTANCE
      4 CALL ZBUS(IP,IQ,R,X,ILO,IBO,ISC,RBUS,XBUS,RL,XL,NBE,&6,&500)
C---        HARMI=SUBROUTINE FOR HARMONIC ANALYSIS
      6 WRITE(IWT,107)IW
    107 FORMAT('1XXX HARMONICS OF ORDER',3X,I3,/)
          CALL HARMI(IP,IQ,ICT,R,X,KP1,KP2,NB,NBE,JP1,JP2,ISC,RBUS,XBUS,RL,
         1XL,ILIN,ZO,VMSQ,VVM1,GAML,&7,&500)
      7 CONTINUE
          LLL=2
     27 CONTINUE
C---         COMPUTE HARMONIC (VOLTAGE) DISTORTION FACTOR
C         IF(IOPT.EQ.0) GO TO 470
          WRITE (IWT,450)
          DO 400 J=1,NBH
C            J=EXTERNAL BUS#
```

```
C         KP=INTERNAL BUS #
          KP=NB(J)
C         BUS EXISTS?
          IF(KP.EQ.0)GO TO 400
          IF(IUNIT.EQ.0)GO TO 430
          IF(VVM1(J).EQ.0.)VVM1(J)=1.0
          HDF(J)=(VMSQ(J)**0.5)*100./VVM1(J)
          GO TO 440
      430 IF(VVM1(J).EQ.0.)VVM1(J)=VCBASE*1000./SQRT(3.)
          HDF(J)=(VMSQ(J)**0.5)*100./VVM1(J)
      440 WRITE(IWT,460)J,HDF(J)
      400 CONTINUE
      450 FORMAT('1HARMONIC DISTORTION FACTOR'//6X,'BUS',12X,'HDF (%)'/)
      460 FORMAT(6X,I4,8X,F10.4)
          IF(IPLOT.EQ.0) GO TO 500
          IVCO=1
          IF(IVC.EQ.0) IVCO=2
          IF(IVC.EQ.1) N=128
          J=(N-1)/4-1
          IC=N/2-1
          DO 37 IE=1,JJJ
          WRITE(6,220) IE
      220 FORMAT(1H1,5X,'WAVEFORM FOR HARMONIC SOURCE NUMBER',I5)
          DO 47 IG=1,IC
          IA=IG+N/2+1
          IB=N/2+1-IG
       47 SOURCE(IA,IE)=CONJG(SOURCE(IB,IE))
C---         FFTCC IS A SPECIAL PROGRAM FROM A LIBRARY NOT INCLUDED
C---         THERE IS A DUMMY PROGRAM INCLUDED TO SATISFY EXTERNAL
C---         REFERENCES
          CALL FFTCC(SOURCE(1,IE),N,IWK,WK)
          DO 57 IA=1,N
          SOURCE(IA,IE)=SOURCE(IA,IE)/2.
          A(IA)=REAL(SOURCE(IA,IE))
       57 X(IA)=(IA-1.)*1000./(60.*N)
          DO 67 IB=1,J
          KI=4*(IB-1)+1
          KJ=KI+3
       67 WRITE(6,210) KI,(SOURCE(I,IE),I=KI,KJ)
      210 FORMAT(1H0,I4,8F10.5)
C---           THIS CALLS IOWA STATE UNIVERSITY'S VERSION OF CALCOM
C---           THIS MAY NOT WORK WITH STANDARD CALCOM
          CALL GRAPH(N,X,A,4,103,12.,9.,1.5,0.,0.,0.,'TIME (MS);',
         1 YLAB(1,IVCO),GLAB(1,IVCO),DATLAB(1,IE))
       37 CONTINUE
      500 STOP
          END
          SUBROUTINE LINEIN(IP,IQ,ICT,R,X,NB,NLB,NBE,ILIN,ZO,GAML,*,*)
C---        READ AND STORE LINE, TRANSFORMER, GENERATOR, SHUNT CAPACITOR
C---          AND LOAD DATA
C---        CALLED FROM HARMONIC LOADFLOW MAIN PROGRAM ONCE FOR EACH
C---           HARMONIC ORDER TO BE ANALYZED
          IMPLICIT INTEGER*4(I-N)
          INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,IDSN,IW
          COMPLEX*8 D1,D2,DD1,DD,DZ1,DZ,DE,DSH,DCH,DYS,DZS,CMPLX,CSQRT,CEXP
          COMPLEX*8 DT1,DT2,DT3,DVZ,ZO,GAML
          COMMON /K1/IRD,IWT,IW,IDSN,H2
          COMMON /KL/NEX,NEL
          COMMON /KB/NBH,NBS,NBX,MS,NLR
          COMMON /BASE/LLL,JJJJ
          DIMENSION IP(NEX),IQ(NEX),ICT(NEX),R(NEX),X(NEX),ILIN(NEX)
          DIMENSION NB(NBH),NLB(NBX),NBE(NBX),ZO(NEX),GAML(NEX)
          DIMENSION RDN(4000,7),IRDN(4000,5)
          DIMENSION RDC(4000),A6(4000),BER(2),BEI(2),BERD(2),BEID(2)
C---        NEX=MAXIMUM NUMBER OF ELEMENTS
C---        NEL=NUMBER OF ELEMENTS
```

```
C---      NBH=LARGEST BUS NUMBER ALLOWED
C---      NBS=NUMBER OF BUSES
C---      NBX=MAXIMUM NUMBER OF BUSES
C---      IP=ARRAY CONTAINING INTERNAL 'FROM' BUS #'S
C---      IQ=ARRAY CONTAINING INTERNAL 'TO' BUS #'S
C---      ICT=ARRAY CONTAINING ELEMENT CIRCUIT #'S
C---      R, X=ARRAYS CONTAINING IMPEDANCE
C---      NB=ARRAY CONTAINING CONVERSION OF EXTERNAL TO INTERNAL BUS #
C---      NBE=ARRAY CONTAINING CONVERSION OF INTERNAL TO EXTERNAL BUS #
C---      NLB=ARRAY CONTAINING THE NUMBER OF LINES TO A BUS
      NBS=0
      NE1=0
      NEL=0
C---      IERROR=NUMBER OF BUS # ERRORS
      IERROR=0
C---      NLR=NUMBER OF ELEMENTS CONNECTED TO REFERENCE
      NLR=0
      DO 1 I=1,NBH
    1 NB(I)=0
      DO 2 I=1,NBX
    2 NLB(I)=0
      IF (LLL.GT.1)GO TO 11
      WRITE(IWT,1100)
C---      NE1=NUMBER OF ELEMENTS + 1
   11 NE1=NE1+1
C---      LLL=FIRST TIME THROUGH LOOP FLAG
C---         1=FIRST TIME
      IF(LLL.GT.1)GO TO 300
C---      INITIALIZE RDC ARRAY TO ZERO
      DO 3 I=1,NEX
    3 RDC(I)=0.
C---      READ ELEMENT DATA
C---      KJ=ELEMENT CODE
C---         1=LINE
C---         2=TRANSFORMER
C---         3=GENERATOR OR SHUNT CAPACITOR
C---         4=LOAD
C---      KJP='FROM' BUS (9999 FOR END OF ELEMENTS)
C---      KJQ='TO' BUS
C---      KCT=ELEMENT CIRCUIT # (OR) TRANSFORMER AUXILIARY BUS #
C---      RP1=LINE POS/NEG SEQ RESISTANCE (OR) TRANSFORMER POS/NEG
C---         SEQ SERIES REACTANCE BOTH IN % (OR) LOAD REAL POWER IN MW
C---      XX1=LINE POS/NEG SEQ REACTANCE (OR) TRANSFORMER ZERO SEQ
C---         SERIES REACTANCE (OR) GEN/CAP REACTANCE ALL IN % (OR)
C---         LOAD REACTIVE POWER IN MVAR
C---      XC1=LINE POS/NEG SEQ SUSCEPTANCE (OR) TRANSFORMER POS/NEG
C---         SEQ SHUNT REACTANCE (OR) GEN ZERO SEQ REACTANCE ALL IN %
C---      RR0=LINE ZERO SEQ RESISTANCE (OR) TRANSFORMER POS/NEG/ZERO
C---         SEQ CORE LOSS RESISTANCE BOTH IN %
C---      XX0=LINE ZERO SEQ REACTANCE IN % (OR) TRANSFORMER CONNECTION
C---         CODE
C---      XC0=LINE ZERO SEQ SUSCEPTANCE (OR) TRANSFORMER ZERO SEQ
C---         SHUNT REACTANCE BOTH IN %
C---      KK=LINE VOLTAGE AND BUNDLE CODE
C---         VOLTAGE(KV)  CODE(FIRST DIDIT)   (SECOND DIGIT)
C---           13.80              9            NUMBER OF BUNDLES
C---           69                 1              PER CONDUCTOR
C---           115                2
C---           132                3
C---           138                4
C---           161                5
C---           230                6
C---           345                7
C---           500                8
C---      (OR) KK=TRANSFORMER CONNECTION CODE
C---               0,XX0.GT.1.:NO ZERO SEQ IMPEDANCE
```

```
C---                    0.0.9.LT.XXO.LT.1.;ONE IMPEDANCE (XX1) 'TO' BUS TO
C---                    REFERENCE
C---                    0.0.7.LT.XXO.LT.0.9;ONEIMPEDANCE (XX1) 'FROM' BUS
C---                    TO REFERENCE
C---                    0.XXO.LT.0.7;T-TYPE CKT WITH POS/NEG SEQ MAG BRANCH
C---                    1;SHORTED T-TYPE (XX1,XCO) 'FROM' BUS TO REFERENCE
C---                    2;SHORTED T-TYPE (XX1,XCO) 'TO' BUS TO REFERENCE
C---                    3;OPEN T-TYPE (XX1,XCO) 'TO' BUS TO REFERENCE
C---                    4;OPEN T-TYPE (XX1,XCO) 'FROM' BUS TO REFERENCE
C---                    .GT.4;T-TYPE (XX1,XCO) CORE LOSS NEGLECTED
C---        (OR) KK=GEN/CAP CODE
C---                    1=CAPACITOR
C---        (OR) KK=LOAD CODE
C---                    1=RESIDENTIAL
C---                    2=COMMERCIAL
C---                    3=INDUSTRIAL
C---        XLM=LINE LENGTH IN MILES
      READ(IPD,1000,END=50)KJ,KJP,KJQ,KCT,RR1,XX1,XC1,RRO,XXO,XCO,KK,XLM
      IF(KJP.EQ.9999) GO TO 200
      WRITE (IWT,1200)KJ,KJP,KJQ,KCT,RR1,XX1,XC1,RRO,XXO,XCO,KK,XLM
  200 CONTINUE
C---        CONVERT FROM PER CENT TO PER UNIT
      RR1=RR1/100.0
      XX1=XX1/100.0
      XC1=XC1/100.0
      RRO=RRO/100.0
C---        XXO IS CONVERTED LATER
      XCO=XCO/100.0
C---        STORE INPUT DATA
C---        IRDN=INTEGER ARRAY STORING INPUT DATA
      IRDN(NE1,1)=KJ
      IRDN(NE1,2)=KJP
      IRDN(NE1,3)=KJQ
      IRDN(NE1,4)=KCT
      IRDN(NE1,5)=KK
C---        RDN=REAL ARRAY STORING INPUT DATA
      RDN(NE1,1)=RR1
      RDN(NE1,2)=XX1
      RDN(NE1,3)=XC1
      RDN(NE1,4)=RRO
      RDN(NE1,5)=XXO
      RDN(NE1,6)=XCO
      RDN(NE1,7)=XLM
      GO TO 301
C---        RECOVER INPUT DATA
  300 KJ=IRDN(NE1,1)
      KJP=IRDN(NE1,2)
      KJQ=IRDN(NE1,3)
      KCT=IRDN(NE1,4)
      KK=IRDN(NE1,5)
      RR1=RDN(NE1,1)
      XX1=RDN(NE1,2)
      XC1=RDN(NE1,3)
      RRO=RDN(NE1,4)
      XXO=RDN(NE1,5)
      XCO=RDN(NE1,6)
      XLM=RDN(NE1,7)
  301 IF(KJP.EQ.9999) GO TO 45
C---        IDSN=SEQUENCE CODE FOR HARMONIC
C---            0=UNDETERMINED
C---            1=ZERO SEQUENCE
C---            2=NEG SEQUENCE
C---            3=POS SEQUENCE
  150 IF(IDSN-1)101,106,141
  141 IF(IDSN-2)110,110,112
  101 B=1.0
```

```
C---      WT=HARMONIC ORDER
          WT=FLOAT(IW)
          IF(WT.EQ.1) GO TO 112
C---      IS HARMONIC ZERO SEQ.
      107 A=3.0*B
          IF(WT.A-1.0)105,106,105
      105 B=B+1.0
          IF(B-22.0)107,108,108
C---      IS HARMONIC NEG. SEQ.
      108 B=1.0
      111 A=(3.0*B)-1.0
          IF(WT/A-1.0)109,110,109
      109 B=B+1.0
          IF(B-22.0)111,112,112
      112 IDSN=3
C---      HARMONIC IS POS.SEQ.
C---      WHAT IS ELEMENT
          IF(KJ-2)113,114,115
C---      POS. + NEG. SEQ. TRANSMISSION LINE
C---      DETERMINE BASE IMPEDANCE
      113 IF(KK.GT.20)GO TO 210
C---      BI=BASE IMPEDANCE
          BI=47.61
          GO TO 218
      210 IF(KK.GT.30)GO TO 211
          BI=132.25
          KK=KK-10
          GO TO 218
      211 IF(KK.GT.40)GO TO 212
          BI=174.24
          KK=KK-20
          GO TO 218
      212 IF(KK.GT.50)GO TO 213
          BI=190.44
          KK=KK-30
          GO TO 218
      213 IF(KK.GT.60)GO TO 214
          BI=259.21
          KK=KK-40
          GO TO 218
      214 IF(KK.GT.70)GO TO 215
          BI=529.00
          KK=KK-50
          GO TO 218
      215 IF(KK.GT.80)GO TO 216
          BI=1190.25
          KK=KK-60
          GO TO 218
      216 IF(KK.GT.90)GO TO 217
          BI=2500.00
          KK=KK-70
          GO TO 218
      217 BI=1.9044
          KK=KK-80
C---      R60=60 HZ LINE RESISTANCE IN OHMS/MILE
      218 R60=RR1*BI*(KK-10)/XLM
          IF(WT.EQ.1) GO TO 160
          I=1
          IF(RDC(NE1).NE.0.) GO TO 206
C---      RDC=DC LINE RESISTANCE IN OHMS/MILE
          RDC(NE1)=R60
C---      F=FREQUENCY IN HZ
          F=60.0
C---      SKIN EFFECT
      203 B=F/RDC(NE1)
C---      A=MR
```

```
C---      BER(I)=REAL BESSEL FUNCTION OF MR
C---            1=60 HZ
C---            2=HARMONIC FREQ
      A=0.0636*SQRT(B)
      IF(H2.NE.0.) GO TO 400
      H2=4.
      H4=64.
      H6=2304
      H8=147456.
      H10=1.47456E7
      H12=H10*144
      H14=H12*196.
      H16=H14*256.
      H18=H16*324.
      H20=H18*400.
      H22=H20*484.
      H24=H22*576.
      H26=H24*676.
      H28=H26*784.
      H30=H28*900.
      H32=H30*1024.
      H34=H32*1156.
      H36=H34*1296.
C---      BER(I)=REAL BESSEL FUNCTION OF MR
C---            1=60 HZ
C---            2=HARMONIC FREQ
  400 BER(I)=1.0-A**4/H4+A**8/H8-A**12/H12+A**16/H16-A**20/H20
     1 +A**24/H24-A**28/H28+A**32/H32-A**36/H36
C---      BEI(I)=IMAGINARY BESSEL FUNCTION OF MR
      BEI(I)=A**2/H2-A**6/H6+A**10/H10-A**14/H14+A**18/H18
     1 -A**22/H22+A**26/H26-A**30/H30+A**34/H34
C---      BERD(I)=DERIVATIVE OF BER(I)
      BERD(I)=-4.0*A**3/H4+8.0*A**7/H8-12.0*A**11/H12+16.0*A**15/H16
     1 -20.0*A**19/H20+24.0*A**23/H24-28.0*A**27/H28+32.0*A**31/H32
     2 -36.0*A**35/H36
C---      BEID(I)=DERIVATIVE OF BEI(I)
      BEID(I)=2.0*A/H2-6.0*A**5/H6+10.0*A**9/H10-14.0*A**13/H14
     1 +18.0*A**17/H18-22.0*A**21/H22+26.0*A**25/H26-30.0*A**29/H30
     2 +34.0*A**33/H34
C---      RR7=AC TO DC RESISTANCE RATIO
      RR7=A*(BER(I)*BEID(I)-BEI(I)*BERD(I))/
     1 (2.0*(BEID(I)**2+BERD(I)**2))
      IF(F.NE.60.0)GO TO 204
C---      TR60=ESTIMATE OF 60 HZ RESISTANCE
      TR60=RR7*RDC(NE1)
      ER=TR60-R60
C---      ERA=ERROR DIFFERENCE OF ACTUAL AND ESTIMATE OF 60 HZ RESIS
      ERA=ABS(ER)
C---      CHECK ACCURACY OF TR60
      IF(ERA.GT.0.00005)GO TO 205
C---      A6=ALPHAL AT 60 HZ
      A6(NE1)=4.0*(BER(I)*BERD(I)+BEI(I)*BEID(I))/
     1 (A*(BERD(I)**2+BEID(I)**2))
      GO TO 206
C---      OBTAIN NEW ESTIMATE OF RDC
  205 RDC(NE1)=RDC(NE1)-ER
      GO TO 203
C---      F=HARMONIC FREQUENCY
  206 F=60.0*IW
      I=2
      GO TO 203
C---      R1=LINE RESISTANCE AT HARMONIC FREQ IN PU
C-------R1=RR1 IS USED FOR FUNDAMENTAL FREQ ONLY
  160 R1=RR1
      GO TO 170
  204 R1=RR7*RDC(NE1)*XLM/(BI*(KK-10))
C---      AL=ALPHAL AT HARMONIC FREQUENCY
  208 AL=4.0*(BER(I)*BERD(I)+BEI(I)*BEID(I))/
     1 (A*(BERD(I)**2+BEID(I)**2))
```

```
C---      X60=TOTAL 60 HZ REACTANCE IN OHMS/MILE
      X60=XX1*BI/XLM
C---      D=60 HZ EXTERNAL REACTANCE IN OHMS/MILE
      D=X60-A6(NE1)*0.030335/(KK-10)
C---      XF=TOTAL REACTANCE AT HARMONIC FREQUENCY IN OHMS/MILE
      XF=(D+AL*0.030335/(KK-10))*WT
C---      XL=LINE REACTANCE IN PU
      GO TO 175
C------ XL=XX1 IS USED FOR FUNDAMENTAL FREQ ONLY
  170 XL=XX1
      GO TO 180
  175 XL=XF*XLM/BI
C---      YC=LINE SHUNT SUSCEPTANCE AT HARMONIC FREQ IN PU
  180 YC=WT*XC1
C---      GO=LINE SHUNT CONDUCTANCE
  116 GO=0.0
C---      D1=LINE SERIES IMPEDANCE IN PU
      D1=CMPLX(R1,XL)
C---      D2=LINE SHUNT ADMITTANCE IN PU
      D2=CMPLX(GO,YC)
      DD1=D1*D2
C---      DD=GAMMA*L (GAMMA=PROPAGATION CONSTANT, L=LINE LENGTH)
      DD=CSQRT(DD1)
      DZ1=D1/D2
C---      DZ=CHARACTERISTIC IMPEDANCE IN PU
      DZ=CSQRT(DZ1)
      DE=CEXP(DD)
C---      DSH=SINH(GAMMA*L)
      DSH=0.5D0*(DE-1.0D0/DE)
C---      DCH=COSH(GAMMA*L)
      DCH=0.5D0*(DE+1.0D0/DE)
C---      DYS=PI LINE SHUNT ADMITTANCE IN PU
      DYS=(1.0D0/DZ)*((DCH-1.0D0)/DSH)
C---      DZS=PI LINE SERIES IMPEDANCE IN PU
      DZS=DZ*DSH
C---      DYZ=PI LINE SHUNT IMPEDANCE IN PU
      DYZ=1.0/DYS
C---      RS1=REAL PART OF SERIES IMPEDANCE IN PU
      RS1=REAL(DZS)
C---      RS2=REAL PART OF SHUNT IMPEDANCE IN PU
      RS2=REAL(DYZ)
C---      XS1=IMAGINARY PART OF SERIES IMPEDANCE IN PU
      XS1=AIMAG(DZS)
C---      XS2=IMAGINARY PART OF SHUNT IMPEDANCE IN PU
      XS2=AIMAG(DYZ)
      GO TO 117
  110 IDSN=2
C---      HARMONIC IS NEGATIVE SEQUENCE
C---      WHAT IS ELEMENT
      IF(KJ-2)113,114,120
  106 IDSN=1
C---      HARMONIC IS ZERO SEQUENCE
C---      WHAT IS ELEMENT
      IF(KJ-2)118,121,122
C---      ZERO SEQ. TRANSMISSION LINE
C---      RROE=EARTH RESISTANCE COMPONENT AT 60 HZ IN PU
  118 RROE=RR0-RR1
C---      RRWE=EARTH RESISTANCE COMPONENT AT 60 HZ IN PU
      RRWE=RROE*WT
C---      R1=LINE RESISTANCE AT HARMONIC FREQ IN PU
      R1=RR1+RRWE
C---      XL=LINE SERIES REACTANCE AT HARMONIC FREQ IN PU
      XL=XX0*WT/100.0
C---      YC=LINE SHUNT SUSCEPTANCE AT HARMONIC FREQ IN PU
      YC=WT*XC0
      GO TO 116
```

```
C---      POS. + NEG. SEQ. TRANSFORMER
C---      XS3=HALF OF TX SERIES REACTANCE AT HARMONIC FREQ IN PU
    114 XS3=RR1*WT/2.0
C---      XS4=TX SHUNT REACTANCE AT HARMONIC FREQ IN PU
    127 XS4=XC1*WT
C---      ASSUME SILICON STEEL W/ 3/1 HYS/EDDY LOSSES
C---      RR4=TX SHUNT RESISTANCE AT HARMONIC FREQ IN PU
        RR4=(3.0*RRO/(WT*4.0))+(RRO/(4.0*WT**2))
        XS5=0.0
        RR3=0.0
        DT1=CMPLX(RR4,XS5)
        DT2=CMPLX(RR3,XS4)
C---      DT3=TX SHUNT IMPEDANCE AT HARMONIC FREQ IN PU
        DT3=(DT1*DT2)/(DT1+DT2)
C---      RT1=REAL PART OF TX SHUNT IMPEDANCE
        RT1=REAL(DT3)
C---      XT1=IMAGINARY PART OF TX SHUNT IMPEDANCE
        XT1=AIMAG(DT3)
        GO TO 119
C---      ZERO SEQ. TRANSFORMER
    121 IF(KK)143,142,143
    142 IF(XXO-1.0)123,124,124
    124 GO TO 1[illegible]
    123 IF(XXO-.70)125,125,126
    125 XS3=XX1*WT/2.0
        GO TO 127
    126 XT2=XX1*WT
        IF(XXO-.90)128,129,129
    143 XZ=XX1*WT/2.0
        XT2=XZ+(XZ*XCO*WT)/(XZ+XCO*WT)
        IF(KK-2)144,145,146
    146 IF(KK-4)147,148,149
    144 GO TO 128
    145 GO TO 129
    147 XT2=XZ+XCO*WT
        GO TO 129
    148 XT2=XZ+XCO*WT
        GO TO 128
    149 XS3=XZ
        RT1=0.0
        XT1=XCO*WT
        GO TO 119
C---      POS SEQUENCE GENERATORS
C---      GENERATOR OR LOAD?
    115 IF(KJ.GE.4)GO TO 444
C---      GENERATOR OR CAPACITOR?
        IF(KK.EQ.1)GO TO 500
C---      XG1=GEN REACTANCE AT HARMONIC FREQ IN PU
        XG1=XX1*WT
        GO TO 130
C---      ZERO SEQUENCE GENERATORS
    122 IF(KJ.EQ.4)GO TO 444
        IF(KK.EQ.1)GO TO 500
        XG1=XC1*WT
        GO TO 130
C---      NEG SEQUENCE GENERATORS
    120 IF(KJ.EQ.4)GO TO 444
        IF(KK.EQ.1)GO TO 500
        XG1=XX1*WT
        GO TO 130
C---      SHUNT CAPACITORS
C---      XG1=CAP REACTANCE AT HARMONIC FREQ IN PU
    500 XG1=XX1/WT
        GO TO 130
C---      LOADS
C---      RESIDENTIAL, COMMERCIAL, OR INDUSTRIAL?
```

```
  444 IF (IW.EQ.1) GO TO 510
      IF(KK-2)445,446,447
C---     RESIDENTIAL LOADS
C---     PMOT=MOTOR COMPONENT OF REAL POWER
  445 PMOT=0.5*RR1
C---     PRES=RESISTIVE COMPONENT OF REAL POWER
      PRES=0.5*RR1
      GO TO 448
C---     COMMERCIAL LOADS
  446 PMOT=0.6*RR1
      PRES=0.4*RR1
      GO TO 448
C---     INDUSTRIAL LOADS
  447 PMOT=0.7*RR1
      PRES=0.3*RR1
C---     XONE=MOTOR STATOR REACTANCE AT HARMONIC FREQ IN PU
  448 XONE=XX1/(4.64*(PMOT**2+XX1**2))
      XONE=XONE*WT
      RHE=1.03/(0.03*PMOT)
C---     ASSUME SILICON STEEL W/ 3/1 HYS/EDDY LOSSES
C---     RHE=MOTOR CORE LOSS RESISTANCE AT HARMONIC FREQ IN PU
      RHE=(3.0*RHE/(WT*4.0))+(RHE/(4.0*WT**2))
C---     REQM=MOTOR EQUIV SERIES RESISTANCE IN PU
  520 REQM=(XONE**2)*RHE/(RHE**2+XONE**2)
C---     XEQM=MOTOR EQUIV SERIES REACTANCE IN PU
      XEQM=((RHE**2)*XONE/(RHE**2+XONE**2))+XONE
C---     RES=CONSTANT LOAD RESISTANCE
      RES=1.0/PRES
      DEQ=(REQM+RES)**2+XEQM**2
      REQN=(RES**2*REQM)+(REQM**2*RES)+(XEQM**2*RES)
      XEQN=XEQM*RES**2
C---     REQ=LOAD RESISTANCE AT HARMONIC FREQ IN PU
      REQ=REQN/DEQ
C---     XEQ=LOAD REACTANCE AT HARMONIC FREQ IN PU
      XEQ=XEQN/DEQ
      GO TO 449
C--------- LOAD SERIES RESISTANCE AND REACTANCE FOR FUNDAMENTAL FREQ
  510 REQ=RR1/(RR1**2+XX1**2)
      XEQ=XX1/(RR1**2+XX1**2)
      GO TO 449
C---     ASSIGN TRANSMISSION LINE ELEMENTS
C---     M=ELEMENT FLAG
C---        0=SERIES ELEMENT
C---        1='FROM' BUS SHUNT ELEMENT
C---        2='TO' BUS SHUNT ELEMENT
  117 M=0
  139 IF(M-1)131,132,133
C---     JP='FROM' BUS EXTERNAL NUMBER
  131 JP=KJP
C---     JQ='TO' BUS EXTERNAL NUMBER
      JQ=KJQ
C---     JCT=CIRCUIT NUMBER
      JCT=KCT
C---     RR=ELEMENT RESISTANCE IN PU
      RR=RS1
C---     XX=ELEMENT REACTANCE IN PU
      XX=XS1
C---     ILINE=LINE FLAG
      ILINE=1
      GO TO 134
  132 JP=KJP
      JQ=0
      JCT=KCT
      RR=RS2
      XX=XS2
      ILINE=0
```

```
      GO TO 134
  133 JP=0
      JQ=KJQ
      JCT=KCT
      RR=RS2
      XX=XS2
      ILINE=0
      GO TO 134
C---      ASSIGN GENERATOR ELEMENTS
  130 M=2
      JP=KJP
      JQ=KJQ
      JCT=KCT
      RR=RR1
      XX=XG1
      ILINE=0
      GO TO 134
C---      ASSIGN LOAD ELEMENTS
  449 M=2
      JP=KJP
      JQ=0
      JCT=KCT
      RR=REO
      XX=XEO
      ILINE=0
      GO TO 134
C---      ASSIGN TRANSFORMER ELEMENTS
  119 M=0
  140 IF(M-1)135,136,137
  135 JP=KJP
C---      ASSIGN ADDITIONAL NODE = KCT
      JQ=KCT
      RR=0.0
      JCT=1
      XX=XS3
      ILINE=0
      GO TO 134
  136 JP=KCT
      JQ=KJQ
      RR=0.0
      JCT=1
      XX=XS3
      ILINE=0
      GO TO 134
  137 JP=KCT
      JQ=0
      RR=RT1
      XX=XT1
      JCT=1
      ILINE=0
      GO TO 134
  128 M=2
      JP=KJP
      JQ=0
      RR=0.0
      JCT=1
      XX=XT2
      ILINE=0
      GO TO 134
  129 M=2
      JP=0
      JQ=KJQ
      RR=0.0
      JCT=1
      XX=XT2
      ILINE=0
```

```
          GO TO 134
C---         CHANGE TO INTERNAL BUS NUMBERS
C---         BUS NUMBER ERROR?
      134 IF(JP.EQ.JQ)GO TO 40
C---         IS 'FROM' BUS REF NODE?
          IF(JP.GT.0)GO TO 12
C---         KP=INTERNAL BUS NUMBER INDEX
          KP=0
C---         INCREMENT NUMBER OF ELEMENTS CONNECTED TO REF
          NLR=NLR+1
          GO TO 14
C---         IS 'FROM' BUS NUMBER TOO LARGE?
       12 IF(JP.GT.NBH)GO TO 40
          KP=NB(JP)
C---         FIRST ELEMENT CONNECTED TO BUS?
          IF(KP.NE.0)GO TO 13
C---         TOO MANY BUSES?
          IF(NBS.GE.NBX)GO TO 55
C---         INCREMENT NUMBER OF BUSES
          NBS=NBS+1
C---         STORE INTERNAL BUS NUMBER
          NB(JP)=NBS
          KP=NBS
C---         STORE EXTERNAL 'FROM' BUS NUMBER
          NBE(KP)=JP
C---         INCREMENT NUMBER OF SERIES ELEMENTS CONNECTED TO BUS
       13 NLB(KP)=NLB(KP)+1
C---         IS 'TO' BUS REFERENCE NODE?
       14 IF(JQ.GT.0)GO TO 15
C---         KQ=INTERNAL BUS NUMBER INDEX
          KQ=0
C---         INCREMENT NUMBER OF ELEMENTS CONNECTED TO REF
          NLR=NLR+1
          GO TO 17
C---         IS 'TO' BUS NUMBER TOO LARGE?
       15 IF(JQ.GT.NBH)GO TO 40
          KQ=NB(JQ)
C---         FIRST ELEMENT CONNECTED TO BUS?
          IF(KQ.NE.0)GO TO 16
C---         TOO MANY BUSES?
          IF(NBS.GE.NBX)GO TO 55
C---         INCREMENT NUMBER OF BUSES
          NBS=NBS+1
C---         STORE INTERNAL BUS NUMBER
          NB(JQ)=NBS
          KQ=NBS
C---         STORE EXTERNAL 'TO' BUS NUMBER
          NBE(KQ)=JQ
C---         INCREMENT NUMBER OF SERIES ELEMENTS CONNECTED TO BUS
       16 NLB(KQ)=NLB(KQ)+1
C---         KP, KQ CONTAIN THE INTERNAL BUS NUMBER - NOW STORE THE DATA
C---         TOO MANY ELEMENTS?
       17 IF(NEL.GE.NEX)GO TO 60
C---         INCREMENT NUMBER OF ELEMENTS
          NEL=NEL+1
C---         STORE INTERNAL 'FROM' BUS NUMBER
          IP(NEL)=KP
C---         STORE INTERNAL 'TO' BUS NUMBER
          IQ(NEL)=KQ
C---         STORE CIRCUIT NUMBER
          ICT(NEL)=JCT
C---         STORE ELEMENT RESISTANCE
          R(NEL)=RR
C---         STORE ELEMENT REACTANCE
          X(NEL)=XX
C---         STORE LINE FLAG
```

```
      ILIN(NEL)=ILINE
C---     STORE CHARACTERISTIC IMPEDANCE FOR LINES
      ZO(NEL)=DZ
C---      STORE PROPAGATION CONSTANT FOR LINES
      GAML(NEL)=DD
C---     ALL ELEMENTS OF COMPONENT?
      IF(M-2)138,11,11
C---     BUS NUMBER ERROR
   40 WRITE(IWT,1001)JP,JQ,JCT,RR,XX
C---     COUNT BUS NUMBER ERRORS
      IERROR=IERROR+1
      IF(M-2)138,11,11
C---     INCREMENT ELEMENT FLAG
  138 M=M+1
C---     LINE OR TRANSFORMER?
      IF(KJ-2)139,140,140
C---     NORMAL RETURN
   45 IF(IERROR.EQ.0)RETURN 1
C---     PRINT NUMBER OF BUS NUMBER ERRORS
      WRITE(IWT,1002)IERROR
C---     ABNORMAL RETURN
      RETURN 2
C---     LAST CARD (9999) NOT READ
   50 WRITE(IWT,1003)
      RETURN 2
C---     TOO MANY BUSES
   55 WRITE(IWT,1004)NBX
      RETURN 2
C---     TOO MANY ELEMENTS
   60 WRITE(IWT,1005)NEX
      RETURN 2
 1000 FORMAT(I1,2I4,I3,F10.4,F12.4,F10.8,2F9.4,F10.8,I2,F6.2)
 1001 FORMAT('0*** BUS NUMBER ERROR - ',2(I4,2X),I2,2(4X,F6.2))
 1002 FORMAT('0*** TOTAL NUMBER OF ERRORS = ',I5)
 1003 FORMAT('0*** UNEXPECTED END OF LINE DATA')
 1004 FORMAT('0*** TOO MANY BUSES - MORE THAN ',I4)
 1005 FORMAT('0*** TOO MANY ELEMENTS - MORE THAN ',I5)
 1100 FORMAT('1',2X,'KJ',2X,'KJP',2X,'KJQ',2X,'KCT',6X,'RR1',11X,'XX1'
     1,12X,'XC1',12X,'RRO',11X,'XXO',9X,'XCO',10X,'KK',4X,'XLM'/)
 1200 FORMAT(4X,I1,1X,I4,1X,I4,2X,I3,1X,F10.4,2X,F12.4,
     12X,F15.8,2(2X,F12.4),2X,F15.8,2X,I2,2X,F6.2)
      END
      SUBROUTINE ORDER(IP,IQ,NLB,JP1,JP2,KP1,KP2,ISC,ILO,IBO,*,*)
C---     CREATE ORDERED LISTS FOR BUSES AND ELEMENTS
C---     CALLED FROM HARMONIC LOADFLOW MAIN PROGRAM ONCE FOR EACH
C---         HARMONIC ORDER TO BE ANALYZED
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,IW,IDSN
      COMMON /K1/IRD,IWT,IW,IDSN
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      DIMENSION IP(NEL),IQ(NEL),KP1(NEL),KP2(NEL),ILO(NEL)
      DIMENSION NLB(NBS),JP1(NBS),JP2(NBS),ISC(NBS),IBO(NBS)
C---     JP1=POINTER FROM BUS TO THE LINE 'FROM' BUS
C---     JP2=POINTER FROM BUS TO THE LINE 'TO' BUS
C---     KP1=POINTER FROM LINE TO THE NEXT LINE 'FROM' BUS
C---     KP2=POINTER FROM LINE TO THE NEXT LINE 'TO' BUS
C---     JP1R, JP2R= POINTERS FROM THE REFERENCE BUS
C---     ISC=THE ORDERING SCORE OF THE BUS
C---     IBO=THE BUS ORDER
C---     ILO=THE LINE ORDER
      DO 1 I=1,NBS
      JP1(I)=0
      JP2(I)=0
    1 ISC(I)=0
      JP1R=0
```

```
      JP2R=0
C---      CHAIN LINES BY BUS NUMBER
      DO 29 I=1,NEL
C---      KP=INTERNAL 'FROM' BUS NUMBER
      KP=IP(I)
C---      KQ=INTERNAL 'TO' BUS NUMBER
      KQ=IQ(I)
      KP1(I)=0
      KP2(I)=0
C---      IS 'FROM' BUS REF NODE?
      IF(KP.NE.0)GO TO 13
C---      INCREMENT ORDERING SCORE OF 'TO' BUS
      ISC(KQ)=ISC(KQ)+1
      IF(JP1R.NE.0)GO TO 10
      JP1R=I
      GO TO 19
   10 JP=JP1R
   11 JQ=KP1(JP)
      IF(JQ.EQ.0)GO TO 12
      JP=JQ
      GO TO 11
   12 KP1(JP)=I
      GO TO 19
   13 JP=JP1(KP)
      IF(JP.NE.0)GO TO 11
      JP1(KP)=I
   19 IF(KQ.NE.0)GO TO 23
      ISC(KP)=ISC(KP)+1
      IF(JP2R.NE.0)GO TO 20
      JP2R=I
      GO TO 29
   20 JP=JP2R
   21 JQ=KP2(JP)
      IF(JQ.EQ.0)GO TO 22
      JP=JQ
      GO TO 21
   22 KP2(JP)=I
      GO TO 29
   23 JP=JP2(KQ)
      IF(JP.NE.0)GO TO 21
      JP2(KQ)=I
   29 CONTINUE
C---      CREATE THE ORDERED LISTS
      ML=0
      MB=0
      MS=0
   30 ISCH=0
      DO 33 I=1,NBS
      IF(ISC(I)-ISCH)33,31,32
   31 IF(ISCH.EQ.0)GO TO 33
      IF(NLB(N).GE.NLB(I))GO TO 33
   32 N=I
      ISCH=ISC(I)
   33 CONTINUE
C---      ADD BUS N TO ORDERED BUS LIST
      IF(ISCH.EQ.0)GO TO 70
      ISCH=ISCH-1
      MB=MB+1
      MS=MS+ISCH*((MB*(MB+3))/2)
      IBO(MB)=N
      ISC(N)=-9999
C---      CHECK FOR LINES CONNECTED TO BUS N
      JP=JP1(N)
   51 IF(JP.EQ.0)GO TO 55
      KQ=IQ(JP)
      IF(KQ.EQ.0)GO TO 52
```

```
      IF(ISC(KQ).LT.0)GO TO 52
      ISC(KQ)=ISC(KQ)+1
      GO TO 53
   52 ML=ML+1
      ILO(ML)=JP
   53 JP=KP1(JP)
      GO TO 51
   55 JP=JP2(N)
   56 IF(JP.EQ.0)GO TO 60
      KP=IP(JP)
      IF(KP.EQ.0)GO TO 57
      IF(ISC(KP).LT.0)GO TO 57
      ISC(KP)=ISC(KP)+1
      GO TO 58
   57 ML=ML+1
      ILO(ML)=JP
   58 JP=KP2(JP)
      GO TO 56
   60 IF(ML.LT.NEL)GO TO 30
      RETURN 1
C---     ORDERED LISTS ARE COMPLETE IOB, IOL
   70 WRITE(IWT,1000)
      RETURN 2
 1000 FORMAT('0*** SYSTEM IS NOT CONNECTED TOGETHER')
      END
      SUBROUTINE ZBUS(IP,IQ,R,X,ILO,IBO,IBOR,RBUS,XBUS,RL,XL,NBE,*,*)
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,MBUS,IW,IDSN
      COMMON /K1/IRD,IWT,IW,IDSN
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      DIMENSION IP(NEL),IQ(NEL),R(NEL),X(NEL),ILO(NEL)
      DIMENSION IBO(NBS),IBOR(NBS),NBE(NBS),RL(NBS),XL(NBS)
      DIMENSION RBUS(MBUS),XBUS(MBUS)
C---     RBUS=REAL PART OF ZBUS
C---     XBUS=IMAGINARY PART OF ZBUS
C---     IBOR=BUS ORDER LIST WITH INDEX AS INTERNAL BUS NUMBER
C---     RL, XL=LINK IMPEDANCES
      MB=0
      DO 1 I=1,NBS
      J=IBO(I)
    1 IBOR(J)=I
C---     READY TO START THE ALGORITHM
      DO 40 I=1,NEL
      II=ILO(I)
      IPP=IP(II)
      IF(IPP.EQ.0)GO TO 2
      IPP=IBOR(IPP)
    2 IQQ=IQ(II)
      IF(IQQ.EQ.0)GO TO 3
      IQQ=IBOR(IQQ)
    3 IF(IPP.LT.IQQ)GO TO 6
      IT=IQQ
      IQQ=IPP
      IPP=IT
C---     TEST FOR BRANCH OR A LINK
    6 IF(IQQ.LE.MB)GO TO 15
      JJ=(MB*(MB+1))/2
C---     FOUND A BRANCH, TEST FOR REFERENCE
      IF(IPP.NE.0)GO TO 9
C---     BRANCH TO REFERENCE
      IF(MB.GT.0)GO TO 7
      RBUS(1)=R(II)
      XBUS(1)=X(II)
      MB=1
```

```
      GO TO 40
    7 DO 8 J=1,MB
      JJJ=JJ+J
      RBUS(JJJ)=0.0
    8 XBUS(JJJ)=0.0
      JJJ=JJJ+1
      RBUS(JJJ)=R(II)
      XBUS(JJJ)=X(II)
      MB=MB+1
      GO TO 40
C---       BRANCH TO AN OLD BUS
    9 DO 12 J=1,MB
      JJJ=JJ+J
      IF(IPP.LT.J)GO TO 10
      KK=J+(IPP*(IPP-1))/2
      GO TO 11
   10 KK=IPP+(J*(J-1))/2
   11 RBUS(JJJ)=RBUS(KK)
   12 XBUS(JJJ)=XBUS(KK)
      JJJ=JJJ+1
      KK=JJ+IPP
      RBUS(JJJ)=RBUS(KK)+R(II)
      XBUS(JJJ)=XBUS(KK)+X(II)
      MB=MB+1
      GO TO 40
C---       FOUND A LINK,TEST FOR REFERENCE
   15 IF(IPP.NE.0)GO TO 20
C---       LINK TO REFERENCE
      DO 18 J=1,MB
      IF(IQQ.LT.J)GO TO 16
      KK=J+(IQQ*(IQQ-1))/2
      GO TO 17
   16 KK=IQQ+(J*(J-1))/2
   17 RL(J)=-RBUS(KK)
   18 XL(J)=-XBUS(KK)
      RLL=-RL(IQQ)+R(II)
      XLL=-XL(IQQ)+X(II)
      GO TO 30
C---       LINK BETWEEN OLD BUSES
   20 DO 25 J=1,MB
      IF(IPP.LT.J)GO TO 21
      JJ=J+(IPP*(IPP-1))/2
      GO TO 22
   21 JJ=IPP+(J*(J-1))/2
   22 IF(IQQ.LT.J)GO TO 23
      KK=J+(IQQ*(IQQ-1))/2
      GO TO 24
   23 KK=IQQ+(J*(J-1))/2
   24 RL(J)=RBUS(JJ)-RBUS(KK)
   25 XL(J)=XBUS(JJ)-XBUS(KK)
      RLL=RL(IPP)-RL(IQQ)+R(II)
      XLL=XL(IPP)-XL(IQQ)+X(II)
C---       KRON REDUCTION
   30 ZLL=RLL*RLL+XLL*XLL
      IF(ZLL.LT.1.E-50)GO TO 50
      DO 32 J=1,MB
      JJ=(J*(J-1))/2
      RLJ=(RLL*RL(J)+XLL*XL(J))/ZLL
      XLJ=(RLL*XL(J)-XLL*RL(J))/ZLL
      DO 31 K=1,J
      KJ=JJ+K
      RBUS(KJ)=RBUS(KJ)-RLJ*RL(K)+XLJ*XL(K)
   31 XBUS(KJ)=XBUS(KJ)-RLJ*XL(K)-XLJ*RL(K)
   32 CONTINUE
   40 CONTINUE
      RETURN 1
```

```
   50 IPP=IP(II)
      I=NBE(IPP)
      IQQ=IQ(II)
      J=NBE(IQQ)
      WRITE(IWT,1000)II,I,J
      RETURN 2
 1000 FORMAT('0*** LINE NUMBER ',I4,' BETWEEN BUSES ',I4,' AND ',I4,' CA
     1USED A ZLL**2 DIVISOR IN THE KRON REDUCTION OF ',E12.5)
      END
      SUBROUTINE HARMI(IP,IQ,ICT,R,X,KP1,KP2,NB,NBE,JP1,JP2,IBOR,RBUS,
     1XBUS,VR,VI,ILIN,ZO,VMSQ,VVM1,GAML,*,*)
C---     READ HARMONIC SOURCE LOCATION AND OPTIONS, PERFORM HARMONIC
C---         LOADFLOW, PRINT RESULTS
C---     CALLED FROM HARMONIC LOADFLOW MAIN PROGRAM ONCE FOR EACH
C---         HARMONIC ORDER TO BE ANALYZED
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,MBUS,IW,IDSN,FLAG
      REAL*8 NAME,EE2,EE5,EE8,EE11,EE15,EE18,RSH,XSH,RSE,XSE
      COMPLEX*8 CMPLX,SOURCE,FUND,ZO,GAML,DZ,DD,ZR,KR,IR
      COMPLEX*8 IRPLUS,IRMIN,IMAX,VCK,VCL
      COMMON /K1/IRD,IWT,IW,IDSN
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      COMMON /CDC/SOURCE,VCK,LHARM,JJJ,IVC
      COMMON /BASE/LLL,JJJJ,IOPT
      DIMENSION IP(NEL),IQ(NEL),ICT(NEL),R(NEL),X(NEL),KP1(NEL),KP2(NEL)
      DIMENSION RBUS(MBUS),XBUS(MBUS),SOURCE(128,4),ILIN(NEL)
      DIMENSION IBOR(NBS),NBE(NBS),NB(NBH),JP1(NBS),JP2(NBS)
      DIMENSION VR(NBS),VI(NBS),ZO(NEL),GAML(NEL)
      DIMENSION SVR(9998),SVI(9998),VMSQ(9998),VVM1(9998)
C---     JJJ=COUNTER FOR NUMBER OF OPTIONS
      JJJ=0
C---     FIRST TIME CALLED?
    1 IF(LLL.GT.1)GO TO 700
      IF(JJJ.GT.0)GO TO 3
      DO 2 I=1,NBH
      VMSQ(I)=0.
      VVM1(I)=0.
    2 CONTINUE
    3 READ(IRD,1000,END=99)JF,NAME,IOPT,PHA,FUND
C---     JF=HARMONIC SOURCE BUS # LOCATION (SET TO 9999 FOR END)
C---     NAME=BUS NAME
C---     IOPT=OPTION
C---         0=ADJACENT BUSES ONLY
C---         1=ALL BUSES
C---         2=FIRST ENTRY FOR COMBINED ANALYSIS OF TWO HARMONIC SOURCES
C---         3=SEC ENTRY FOR COMBINED ANALYSIS OF TWO HARMONIC SOURCES
C---     PHA=PHASE ANGLE BETWEEN VOLTAGES FOR HARM SOURCES 2 & 3
C---     FUND=FUNDAMENTAL COMPONENT OF HARMONIC SOURCE CURRENT (COMPLEX)
C---     OPTION 2 OR 3?
      IF(IOPT.GT.1)GO TO 800
      IF(JJJ.NE.0)GO TO 701
C---     EE1-EE13=TEMPORARY STORAGE LOCATIONS FOR INPUT DATA
      EE1=JF
      EE2=NAME
      EE3=IOPT
      SOURCE(2,1)=FUND
      GO TO 705
  701 IF(JJJ.NE.1)GO TO 702
      EE4=JF
      EE5=NAME
      EE6=IOPT
      SOURCE(2,2)=FUND
      GO TO 705
  702 IF(JJJ.NE.2)GO TO 703
```

```
      EE7=JF
      EE8=NAME
      EE9=IOPT
      SOURCE(2,3)=FUND
      GO TO 705
  703 IF(JJJ.NE.3)GO TO 704
      EE10=JF
      EE11=NAME
      EE12=IOPT
      SOURCE(2,4)=FUND
      GO TO 705
  704 EE13=JF
      GO TO 705
C---     JJJJ=COMBINED ANALYSIS CODE
C---         1=COMBINED ANALYSIS (OPTION 2,3)
  700 IF(JJJJ.EQ.1)GO TO 802
      IF(JJJ.NE.0)GO TO 708
C---     RECOVER INPUT DATA
      JF=EE1
      NAME=EE2
      IOPT=EE3
      GO TO 705
  708 IF(JJJ.NE.1)GO TO 709
      JF=EE4
      NAME=EE5
      IOPT=EE6
      GO TO 705
  709 IF(JJJ.NE.2)GO TO 710
      JF=EE7
      NAME=EE8
      IOPT=EE9
      GO TO 705
  710 IF(JJJ.NE.3)GO TO 711
      JF=EE10
      NAME=EE11
      IOPT=EE12
      GO TO 705
  711 JF=EE13
C---     END OF ANALYSIS?
  705 IF(JF.EQ.9999)RETURN 1
      JJJ=JJJ+1
C---     TOO MANY OPTIONS?
      IF(JJJ.GT.4)GO TO 706
      GO TO 707
  706 WRITE(IWT,1009)
      EE13=9999
      RETURN 1
C---     HARMONIC SOURCE BUS EXISTS?
  707 IF(JF.LE.0.OR.JF.GT.NBH)GO TO 90
C---     KF=INTERNAL BUS # LOCATION OF HARMONIC SOURCE
      KF=NB(JF)
C---     HARMONIC SOURCE BUS EXISTS?
      IF(KF.EQ.0)GO TO 90
C---     LF=BUS ORDER NUMBER FOR HARMONIC SOURCE
      LF=IBOR(KF)
C---     LL=INDEX TO HARMONIC SOURCE BUS IMPEDANCE (DIAGONAL ELEMENT
C---         OF A LOWER TRIAGULARIZED MATRIX)
      LL=(LF*(LF+1))/2
C---      RX,XX=HARMONIC SOURCE BUS RESISTANCE AND REACTANCE
      RX=RBUS(LL)
      XX=XBUS(LL)
C---     ZX=SQUARE OF HARMONIC SOURCE BUS IMPEDANCE MAGNITUDE
      ZX=RX*RX+XX*XX
C---     CONVERT PHASE FROM DEGREES TO RADIANS
      PHA=PHA/57.29577951
      VCL=VCK*CMPLX(COS(PHA),SIN(PHA))
```

```
      IF(IVC.EQ.0) GO TO 620
      CR=REAL(VCL)
      CI=AIMAG(VCL)
      VRK=CR*RX-CI*XX
      VIK=CR*XX+CI*RX
      SOURCE(IW+1,JJJ)=CMPLX(VRK,VIK)
      GO TO 621
C---     VRK=REAL COMPONENT OF HARMONIC SOURCE VOLTAGE
  620 VRK=REAL(VCL)
C---     VIK=IMAGINARY COMPONENT OF HARMONIC SOURCE VOLTAGE
      VIK=AIMAG(VCL)
C---     CR=REAL COMPONENT OF HARMONIC SOURCE CURRENT
      CR=(VRK*RX+VIK*XX)/ZX
C---     CI=IMAGINARY COMPONENT OF HARMONIC SOURCE CURRENT
      CI=(VIK*RX-VRK*XX)/ZX
      SOURCE(IW+1,JJJ)=CMPLX(CR,CI)
  621 CALL MAGANG(CR,CI,CM,CA)
C---     CM=HARMONIC SOURCE CURRENT MAGNITUDE
C---     CA=HARMONIC SOURCE CURRENT ANGLE
      CALL MAGANG(VRK,VIK,VKM,VKA)
C---     VKM=HARMONIC SOURCE VOLTAGE MAGNITUDE
C---     VKA=HARMONIC SOURCE VOLTAGE ANGLE
C---     PRINT HARMONIC SOURCE SUMMARY
      WRITE(IWT,1001)JF,NAME,IOPT,PHA,FUND,CM,CA,VKM,VKA
      IF(IW.GT.LHARM) GO TO 1
      IF(IOPT.EQ.2)GO TO 804
      IF(IOPT.EQ.3)GO TO 805
      IF(IOPT.GT.0)GO TO 30
C---     CALCULATIONS FOR ADJACENT BUSES ONLY
C---     PRINT HEADING FOR ADJACENT BUS LOADFLOW SUMMARY
      WRITE(IWT,1002)
C---     J='FROM' BUS OR 'TO' BUS FLAG
      J=1
C---     JP=# OF FIRST ELEMENT CONNECTED 'FROM' HARMONIC SOURCE BUS
      JP=JP1(KF)
C---     ELEMENT EXISTS?
      IF(JP.EQ.0)GO TO 16
C---     KP=ADJACENT INTERNAL BUS #
    9 KP=IQ(JP)
C---     SHUNT ELEMENT?
   10 IF(KP.NE.0)GO TO 11
      VRR=-VRK
      VII=-VIK
      N=0
      GO TO 15
   11 CALL VBUS(KP,KP,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
C---     VR(KP)=REAL COMPONENT OF 'TO' BUS VOLTAGE
C---     VI(KP)=IMAGINARY COMPONENT OF 'TO' BUS VOLTAGE
      CALL MAGANG(VR(KP),VI(KP),VMM,VAA)
C---     VMM='TO' BUS VOLTAGE MAGNITUDE
C---     VAA='TO' BUS VOLTAGE ANGLE
C---     VRR=REAL COMPONENT OF VOLTAGE DROP
      VRR=VR(KP)-VRK
C---     VII=IMAGINARY COMPONENT OF VOLTAGE DROP
      VII=VI(KP)-VIK
C---     N=ADJACENT EXTERNAL BUS #
      N=NBE(KP)
C---     RX,XX=ELEMENT RESISTANCE AND REACTANCE
   15 RX=R(JP)
      XX=X(JP)
C---     ZX=SQUARE OF ELEMENT IMPEDANCE MAGNITUDE
      ZX=RX*RX+XX*XX
C---     CRL=REAL COMPONENT OF ELEMENT CURRENT
      CRL=(VII*XX+VRR*RX)/ZX
C---     CIL=IMAGINARY COMPONENT OF ELEMENT CURRENT
      CIL=(VII*RX-VRR*XX)/ZX
```

```
      IF(ILIN(JP).EQ.0) GO TO 14
      DZ=ZO(JP)
      DD=GAML(JP)
      IF(J.EQ.2) GO TO 12
      JP=KP1(JP)
      GO TO 13
   12 JP=KP2(JP)
   13 RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      CRL=CRL-(VIK*XX+VRK*RX)/ZX
      CIL=CIL-(VIK*RX-VRK*XX)/ZX
      CM1=CRL*CRL+CIL*CIL
      IF(CM1.LT.1.E-8) GO TO 631
      RX=(VRK*CRL+VIK*CIL)/CM1
      XX=(VIK*CRL-VRK*CIL)/CM1
      ZR=CMPLX(RX,XX)
  631 RX=REAL(DZ)
      XX=AIMAG(DZ)
      CALL MAGANG(CRL,CIL,CMM,CAA)
      WRITE(IWT,1003) N,VMM,VAA,ICT(JP),CMM,CAA,RX,XX
      IF(CM1.LT.1.E-8) GO TO 604
      KR=(ZR-DZ)/(ZR+DZ)
      IR=-CMPLX(CRL,CIL)
      IRPLUS=IR/(1.-KR)
      IRMIN=KR*IR/(KR-1.)
      BL=ABS(AIMAG(DD))
      WAVE=6.2831853/BL
      IF (BL .EQ. 0.) CALL SDUMP
      NLAM=0
  603 XOL=(ANGLE(IRMIN)-ANGLE(IRPLUS))/(2.*BL)+NLAM*WAVE/2.
      IF(XOL.GE.1.) GO TO 604
      IF(XOL.LE.0.) GO TO 605
C     IMAX=(IR/(2.*DZ))*((ZR+DZ)*CEXP(DD*XOL)+(DZ-ZR)*CEXP(-DD*XOL))
C     CMAXM=CABS(IMAX)
C     CMAXA=ANGLE(IMAX)*57.29577951
C     WRITE(IWT,1011) CMAXM,CMAXA,XOL,WAVE
  605 NLAM=NLAM+1
      GO TO 603
   14 CALL MAGANG(CRL,CIL,CMM,CAA)
C---        CMM=ELEMENT CURRENT MAGNITUDE
C---        CAA=ELEMENT CURRENT ANGLE
C---        SERIES OR SHUNT ELEMENT?
      IF(N.NE.0)GO TO 900
      VMM=0.0
      VAA=0.0
C---        PRINT SUMMARY FOR ELEMENT
  900 WRITE(IWT,1003)N,VMM,VAA,ICT(JP),CMM,CAA,RX,XX
C---        'FROM' BUS OR 'TO' BUS?
  604 IF(J.EQ.2)GO TO 18
C---        JP=# OF NEXT ELEMENT CONNECTED 'FROM' HARMONIC SOURCE BUS
      JP=KP1(JP)
C---        ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 9
C---        COMPLETED SUMMARY OF ALL ELEMENTS CONNECTED 'FROM' HARMONIC
C---            SOURCE BUS
   16 J=2
C---        JP=# OF FIRST ELEMENT CONNECTED 'TO' HARMONIC SOURCE BUS
      JP=JP2(KF)
C---        ELEMENT EXISTS?
      IF(JP.EQ.0)GO TO 1
C---        KP=ADJACENT INTERNAL BUS #
   17 KP=IP(JP)
      GO TO 10
C---        JP=# OF NEXT ELEMENT CONNECTED 'TO' HARMONIC SOURCE BUS
   18 JP=KP2(JP)
```

```
C---      ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 17
      GO TO 1
C---      CALCULATIONS FOR ALL BUSES
C---      CALCULATIONS FOR BUS VOLTAGES
   30 NBDUM=NBS
      JDUM=1
      CALL VBUS(JDUM,NBDUM,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
C---      VR=REAL COMPONENT OF BUS VOLTAGE
C---      VI=IMAGINARY COMPONENT OF BUS VOLTAGE
C---      PRINT HEADING FOR ALL BUS LOADFLOW SUMMARY
      WRITE(IWT,1004)
      DO 50 J=1,NBH
C---      J=EXTERNAL BUS #
C---      KP=INTERNAL BUS #
      KP=NB(J)
C---      BUS EXISTS?
      IF(KP.EQ.0)GO TO 50
      CALL MAGANG(VR(KP),VI(KP),VVM,VVA)
C---      VVM=BUS VOLTAGE MAGNITUDE
C---      VVA=BUS VOLTAGE ANGLE
C---      PRINT BUS VOLTAGE SUMMARY
      WRITE(IWT,1005)J,VVM,VVA
      IF(IW.EQ.1) GO TO 20
      VMSQ(J)=VMSQ(J)+VVM*VVM
      GO TO 25
   20 VVM1(J)=VVM1(J)+VVM
   25 CONTINUE
C     WRITE(IWT,1012)J,VMSQ(J),VVM1(J)
C---      K='FROM' BUS OR 'TO' BUS FLAG
      K=1
C---      JP=# OF FIRST ELEMENT CONNECTED 'FROM' THE BUS
      JP=JP1(KP)
C---      ELEMENT EXISTS?
      IF(JP.EQ.0)GO TO 39
C---      KQ=INTERNAL 'TO' BUS #
   35 KQ=IQ(JP)
   36 RSH=0.0
      XSH=0.0
      RSE=0.0
      XSE=0.0
C---      SHUNT ELEMENT?
      IF(KQ.NE.0)GO TO 37
      VRR=0.0
      VII=0.0
      N=0
      FLAG=0
      GO TO 38
C---      VRR=REAL COMPONENT OF ADJACENT BUS VOLTAGE
   37 FLAG=1
      VRR=VR(KQ)
C---      VII=IMAGINARY COMPONENT OF ADJACENT BUS VOLTAGE
      VII=VI(KQ)
C---      N=ADJACENT EXTERNAL BUS #
      N=NBE(KQ)
C---      VRR=REAL COMPONENT OF VOLTAGE DROP
   38 VRR=VR(KP)-VRR
C---      VII=IMAGINARY COMPONENT OF VOLTAGE DROP
      VII=VI(KP)-VII
C----------------------------------------------------------------------------
      IF (FLAG.GT.0) GO TO 26
C--------RSH,XSH ARE SHUNT ELEMENT RESISTANCE AND REACTANCE
      RSH=R(JP)
      XSH=X(JP)
      GO TO 27
C--------RSE,XSE ARE SERIES ELEMENT RESISTANCE AND REACTANCE
```

```
   26 RSE=R(JP)
      XSE=X(JP)
C---------------------------------------------------------------------
C---     RX,XX=ELEMENT RESISTANCE AND REACTANCE
   27 RX=R(JP)
      XX=X(JP)
C---     ZX=SQUARE OF ELEMENT IMPEDANCE MAGNITUDE
      ZX=RX*RX+XX*XX
C---     CRL=REAL COMPONENT OF ELEMENT CURRENT
      CRL=(VII*XX+VRR*RX)/ZX
C---     CIL=IMAGINARY COMPONENT OF ELEMENT CURRENT
      CIL=(VII*RX-VRR*XX)/ZX
      IF(ILIN(JP).EQ.0) GO TO 42
      DZ=Z0(JP)
      DD=GAML(JP)
      IF(K.EQ.2) GO TO 31
      JP=KP1(JP)
      GO TO 32
   31 JP=KP2(JP)
   32 RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      RSH=R(JP)
      XSH=X(JP)
      CRL=CRL+(VI(KP)*XX+VR(KP)*RX)/ZX
      CIL=CIL+(VI(KP)*RX-VR(KP)*XX)/ZX
      CM2=CRL*CRL+CIL*CIL
      IF(CM2.LT.1.E-8)GO TO 630
      RX=(VR(KP)*CRL+VI(KP)*CIL)/CM2
      XX=(VI(KP)*CRL-VR(KP)*CIL)/CM2
      ZR=-CMPLX(RX,XX)
  630 RX=REAL(DZ)
      XX=AIMAG(DZ)
      CALL MAGANG(CRL,CIL,CCM,CCA)
      WRITE(IWT,1006) N,ICT(JP),CCM,CCA,RSH,XSH,RSE,XSE
      IF(CM2.LT.1.E-8)GO TO 601
      KR=(ZR-DZ)/(ZR+DZ)
      IR=-CMPLX(CRL,CIL)
      IRPLUS=IR/(1.-KR)
      IRMIN=KR*IR/(KR-1.)
      BL=ABS(AIMAG(DD))
      WAVE=6.2831853/BL
      NLAM=0
  600 XOL=(ANGLE(IRMIN)-ANGLE(IRPLUS))/(2.*BL)+NLAM*WAVE/2.
      IF(XOL.GE.1.) GO TO 601
      IF(XOL.LE.0.) GO TO 602
C     IMAX=(IR/(2.*DZ))*((ZR+DZ)*CEXP(DD*XOL)+(DZ-ZR)*CEXP(-DD*XOL))
C     CMAXM=CABS(IMAX)
C     CMAXA=ANGLE(IMAX)*57.29577951
C     WRITE(IWT,1010) CMAXM,CMAXA,XOL,WAVE
  602 NLAM=NLAM+1
      GO TO 600
   42 CALL MAGANG(CRL,CIL,CCM,CCA)
C---     CCM=ELEMENT CURRENT MAGNITUDE
C---     CCA=ELEMENT CURRENT ANGLE
C---     PRINT SUMMARY FOR ELEMENT
      WRITE(IWT,1006)N,ICT(JP),CCM,CCA,RSH,XSH,RSE,XSE
C---     'FROM' BUS OR 'TO' BUS?
  601 IF(K.EQ.2)GO TO 41
C---     JP=# OF NEXT ELEMENT CONNECTED 'FROM' THE BUS
      JP=KP1(JP)
C---     ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 35
C---     COMPLETED SUMMARY OF ALL ELEMENTS CONNECTED 'FROM' THE BUS
   39 K=2
C---     JP=# OF FIRST ELEMENT CONNECTED 'TO' THE BUS
```

```
      JP=JP2(KP)
C---     ELEMENT EXISTS?
      IF(JP.EQ.0)GO TO 50
C---     KQ=ADJACENT INTERNAL 'FROM' BUS #
   40 KQ=IP(JP)
      GO TO 36
C---     JP=# OF NEXT ELEMENT CONNECTED 'TO' THE BUS
   41 JP=KP2(JP)
C---     ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 40
   50 CONTINUE
      GO TO 1
C---     CALCULATIONS FOR COMBINED CONVERTER ACTION
C---     CONVERTER VOLTAGES AND CURRENTS
  800 JJJJ=1
C---     FIRST OPTION?
      IF(JJJ.NE.0)GO TO 801
C---     EE14-EE20=TEMPORARY STORAGE LOCATIONS FOR INPUT DATA
      EE14=JF
      EE15=NAME
      EE16=IOPT
      SOURCE(2,1)=FUND
      JJJ=JJJ+1
      GO TO 1
  801 EE17=JF
      EE18=NAME
      EE19=IOPT
      EE20=PHA
      SOURCE(2,2)=FUND
      JJJ=0
  802 JF=EE14
      NAME=EE15
      IOPT=EE16
      PHA=0.0
      GO TO 705
  804 LF1=LF
      CR1=CR
      CI1=CI
      JF=EE17
      NAME=EE18
      IOPT=EE19
      PHA=EE20
      GO TO 705
C---     BUS VOLTAGES AND CURRENTS
  805 NBDUM=NBS
      JDUM=1
      CALL VBUS(JDUM,NBDUM,IBOR,LF1,SVR,SVI,CR1,CI1,RBUS,XBUS)
      CALL VBUS(JDUM,NBDUM,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
  821 WRITE(IWT,1004)
C---     COMBINED HARMONIC SOURCE ANALYSIS USES SIMILAR PROCEDURE
C---        TO SINGLE HARMONIC SOURCE
      DO 850 J=1,NBH
      KP=NB(J)
      IF(KP.EQ.0)GO TO 850
      TVR=VR(KP)+SVR(KP)
      TVI=VI(KP)+SVI(KP)
      CALL MAGANG(TVR,TVI,VVM,VVA)
      WRITE(IWT,1005)J,VVM,VVA
      K=1
      JP=JP1(KP)
      IF(JP.EQ.0)GO TO 839
  835 KQ=IQ(JP)
  836 IF(KQ.NE.0)GO TO 837
      VRR=0.0
      VII=0.0
      N=0
```

```
      GO TO 838
  837 VRR=VR(KQ)+SVR(KQ)
      VII=VI(KQ)+SVI(KQ)
      N=NBE(KQ)
  838 VRR=TVR-VRR
      VII=TVI-VII
      RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      CRL=(VII*XX+VRR*RX)/ZX
      CIL=(VII*RX-VRR*XX)/ZX
      IF(ILIN(JP).EQ.0) GO TO 831
      DZ=Z0(JP)
      DD=GAML(JP)
      IF(K.EQ.2) GO TO 832
      JP=KP1(JP)
      GO TO 833
  832 JP=KP2(JP)
  833 RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      CRL=CRL+(TVI*XX+TVR*RX)/ZX
      CIL=CIL+(TVI*RX-TVR*XX)/ZX
      CM2=CRL*CRL+CIL*CIL
      IF(CM2.LT.1.E-8) GO TO 632
      RX=(TVR*CRL+TVI*CIL)/CM2
      XX=(TVI*CRL-TVR*CIL)/CM2
      ZR=-CMPLX(RX,XX)
  632 RX=REAL(DZ)
      XX=AIMAG(DZ)
      CALL MAGANG(CRL,CIL,CCM,CCA)
      WRITE(IWT,1006) N,ICT(JP),CCM,CCA,RX,XX
      IF(CM2.LT.1.E-8) GO TO 607
      KR=(ZR-DZ)/(ZR+DZ)
      IR=-CMPLX(CRL,CIL)
      IRPLUS=IR/(1.-KR)
      IRMIN=KR*IR/(KR-1.)
      BL=ABS(AIMAG(DD))
      WAVE=6.2831853/BL
      NLAM=0
  606 XOL=(ANGLE(IRMIN)-ANGLE(IRPLUS))/(2.*BL)+NLAM*WAVE/2.
      IF(XOL.GE.1.) GO TO 607
      IF(XOL.LE.0.) GO TO 608
C     IMAX=(IR/(2.*DZ))*((ZR+DZ)*CEXP(DD*XOL)+(DZ-ZR)*CEXP(-DD*XOL))
C     CMAXM=CABS(IMAX)
C     CMAXA=ANGLE(IMAX)*57.29577951
C     WRITE(IWT,1010) CMAXM,CMAXA,XOL,WAVE
  608 NLAM=NLAM+1
      GO TO 606
  831 CALL MAGANG(CRL,CIL,CCM,CCA)
      WRITE(IWT,1006)N,ICT(JP),CCM,CCA,RX,XX
  607 IF(K.EQ.2)GO TO 841
      JP=KP1(JP)
      IF(JP.NE.0)GO TO 835
  839 K=2
      JP=JP2(KP)
      IF(JP.EQ.0)GO TO 850
  840 KQ=IP(JP)
      GO TO 836
  841 JP=KP2(JP)
      IF(JP.NE.0)GO TO 840
  850 CONTINUE
      RETURN 1
   90 WRITE(IWT,1007)JF
      GO TO 1
   99 WRITE(IWT,1008)
```

```
      RETURN 2
 1000 FORMAT(I4,A7,I1,3F10.2)
 1001 FORMAT('0*** CONVERTER AT BUS ',I4,3X,A7,3X,'***',5X,'IOPT = ',
     1 I2,5X,'PHA = ',F10.2,'FUND = ',2F10.2/'0HARMONIC CURRENT = ',
     2 F10.4,' MAG    ',F10.2,' ANG ',10X,'    HARMONIC VOLTAGE = ',
     3 F10.4,' MAG    ',F10.2,' ANG ')
 1002 FORMAT('0',11X,'ADJACENT    ADJACENT BUS VOLTAGE      CIRCUIT   CUR
     1RENT TOWARD CONVERTER',6X,'LINE IMPEDANCE'/14X,'BUS',9X,'MAG ',8X,
     2'ANG ',7X,'NUMBER',7X,'MAG ',8X,'ANG ',12X,'R',12X,'X')
C    3'------------------------  ---------------------'/63X,
C    4'MAX CURRENT FLOW',6X,'LOCATION     WAVELENGTH')
 1003 FORMAT(12X,I4,5X,F10.4,1X,F10.2,7X,I2,6X,F10.4,1X,F10.2,5X,F10.4,3
     1X,F10.4)
 1004 FORMAT('0',8X,'FROM',9X,'BUS VOLTAGE',11X,'TO',5X,'CIRCUIT',5X,
     1'TERM CURRENT FLOW',12X,'SHUNT ELEMENT',3X,'SERIES ELEMENT'/8X,
     2'BUS',7X,'MAG',8X,'ANG ',9X,'BUS     NUMBER',7X,'MAG ',8X,
     3'ANG ',12X,'R',12X,'X',12X,'R',12X,'X')
C    365X,'------------------',8X,'---------------------'/66X,
C    4'MAX CURRENT FLOW',8X,'LOCATION     WAVELENGTH')
 1005 FORMAT('0',9X,I4,3X,F10.4,1X,F10.2)
 1006 FORMAT(42X,I4,5X,I2,6X,F10.4,1X,F10.2,2(2X,F11.2),2(2X,F11.6))
 1007 FORMAT('0*** CONVERTER BUS ',I5,' IS NOT IN THE SYSTEM'/)
 1008 FORMAT('0*** UNEXPECTED END OF CONVERTER BUS DATA')
 1009 FORMAT('0***ONLY FOUR CONVERTER OPTIONS CAN BE USED FOR ONE ZBUS')
C1010 FORMAT(62X,F10.4,1X,F10.2,5X,F10.4,3X,F10.2)
C1011 FORMAT(57X,F10.4,1X,F10.2,5X,F10.4,3X,F10.2)
C1012 FORMAT(1X,'VBUS J,VMSQ(J),VVM1(J)',I4,5X,E17.4,5X,E17.4)
      END
      SUBROUTINE VBUS(J1,J2,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
C---     CALCULATE HARMONIC BUS VOLTAGES
C---     CALLED FROM HARMI
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 NBH,NBS,NBX,MS,MBUS
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      DIMENSION IBOR(NBS),VR(NBS),VI(NBS),RBUS(MBUS),XBUS(MBUS)
      DO 30 J=J1,J2
C---     J=INTERNAL BUS #'S
C---     I=BUS ORDER NUMBER
      I=IBOR(J)
      IF(I.LT.LF) GO TO 10
C---     LL=INDEX TO IMPEDANCE BETWEEN BUSES
      LL=LF+(I*(I-1))/2
      GO TO 20
   10 LL=I+(LF*(LF-1))/2
C---     VR=REAL COMPONENT OF BUS VOLTAGE
   20 VR(J)=CR*RBUS(LL)-CI*XBUS(LL)
C---     VI=IMAGINARY COMPONENT OF BUS VOLTAGE
      VI(J)=CR*XBUS(LL)+CI*RBUS(LL)
   30 CONTINUE
      RETURN
      END
      SUBROUTINE MAGANG(REAL,AIMAG,AMAG,ANG)
C---     CALCULATE MAGNITUDE & ANGLE FROM REAL & IMAG COMPONENTS
C---     CALLED FROM HARMI
      AMAG2=REAL*REAL+AIMAG*AIMAG
      AMAG=SQRT(AMAG2)
      ANG=0.
      IF(REAL.EQ.0..AND.AIMAG.EQ.0.) GO TO 10
      ANG=ATAN2(AIMAG,REAL)
   10 ANG=ANG*57.29577951
      RETURN
      END
      FUNCTION ANGLE(COMPLX)
      COMPLEX*8 COMPLX
      A=REAL(COMPLX)
```

```
      B=AIMAG(COMPLX)
      ANGLE=0.
      IF(A.EQ.0..AND.B.EQ.0.) GO TO 10
      ANGLE=ATAN2(B,A)
   10 RETURN
      END
      SUBROUTINE FFTCC
      WRITE(6,1000)
 1000 FORMAT(1H-,132(1H*)/62HOTHIS IS A DUMMY FFTCC ROUTINE TO SATISFY E
     1XTERNAL REFERENCES./1H0,132(1H*)/1H0)
      RETURN
      END
      SUBROUTINE GRAPH
      WRITE(6,1000)
 1000 FORMAT(1H-,132(1H*)/62HOTHIS IS A DUMMY GRAPH ROUTINE TO SATISFY E
     1XTERNAL REFERENCES./1H0,132(1H*)/1H0)
      RETURN
      END
```

XI. APPENDIX

D. MODIFICATION MATRIX FOR PROGRAM

HARMONIC LOADFLOW ANALYSIS PROGRAM MODIFICATIONS

LETTER CODE		DESIRED CHANGE TO THE PROGRAM
A	--	VOLTAGE BASE
B	--	VOLTAMPERE BASE
C	--	ARRAY FOR THE NUMBER OF ELEMENTS
D	--	ARRAY FOR THE NUMBER BUSES OR NODES
E	--	ARRAY FOR THE LARGEST BUS NUMBER
F	--	FOUR DIGIT BUS NUMBERS

NOTE - * REPRESENTS ARRAY DIMENSION IS DETERMINED BY THE FORMULA $\left[\frac{(\#\ \text{OF BUSES})^2}{2} + \frac{\#\ \text{OF BUSES}}{2}\right]$

```
C---  IOWA STATE UNIVERSITY HARMONICS PROGRAM
C---  ENERGY SUPPLY DEPARTMENT
C---  QUAD CITIES PRODUCTION DIVISON
C---
C---     HARMONIC LOADFLOW USING FFT OF SAMPLED HARMONIC SOURCE
C---     VOLTAGE OR CURRENT WAVEFORM OR AC-DC CONVERTER CURRENT
C---     WAVEFORM
C---        REF: KUYPER,K.H. 'EFFECTS OF WIND AND SOLAR CONVERTERS
C---        ON UTILITY DISTRIBUTION NETWORKS', MASTER'S THESIS,
C---        IOWA STATE UNIVERSITY, 1980.
C---        REF: SCHULTZ,R.D. 'HARMONIC CURRENT PROPAGATION ON AC
C---        SYSTEMS DUE TO HVDC LINKS', PHD DISSERTATION, IOWA
C---        STATE UNIVERSITY, 1979.
C---     MODIFIED BY A.L.DAY BEGINNING JUNE, 1982.
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,MBUS,IDSN,IW,N,IWK
      COMPLEX*8 D1,D2,DD1,DD,DZ1,DZ,DE,DSH,DCH,DYS,DZS,CMPLX,CSQRT,CEXP
      COMPLEX*8 DT1,DT2,DT3,DYZ,CWK,SOURCE,CONJG,ZO,GAML,VC,VCK
      COMMON /K1/IRD,IWT,IW,IDSN,H2
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      COMMON /BASE/LLL,JJJJ,IOPT
      COMMON /CDC/SOURCE,VCK,LHARM,JJJ,IVC
      DIMENSION IP(4000),IQ(4000),ICT(4000),R(4000),X(4000),ILIN(4000)
      DIMENSION KP1(4000),KP2(4000),ILO(4000),SOURCE(128,4)
      DIMENSION NB(9998),NLB(500),NBE(500),DATLAB(5,4)
      DIMENSION JP1(500),JP2(500),IBO(500),ISC(500)
      DIMENSION RBUS(125250),XBUS(125250),RL(500),XL(500)
      DIMENSION IWK(918),A(128),WK(918),VC(128)
      DIMENSION ZO(4000),GAML(4000),YLAB(5,2),GLAB(5,2)
      DIMENSION VMSO(9998),HDF(9998),VVM1(9998)
      DATA DATLAB/'SOUR','CE #',' 1  ','    ','    ','SOUR','CE #',
     1 ' 2  ','    ','    ','SOUR','CE #',' 3  ','    ','    ',
     2 'SOUR','CE #',' 4  ','    ','    '/
      DATA YLAB/'VOLT','AGE ','(PU)',':   ','    ','CURR','ENT ',
     1 '(PU)',':   ','    '/
      DATA GLAB/'HARM',' SOU','RCE ','VOLT','AGE:','HARM',' SOU',
     1 'RCE ','CURR','ENT:'/
C---     IRD=LOGICAL UNIT # FOR READ STATEMENTS
      IRD=5
C---     IWT=LOGICAL UNIT  IUNIT # FOR WRITE STATEMENTS
      IWT=6
C---     NBX=MAXIMUM NUMBER OF BUSES
      NBX=500
C---     NEX=MAXIMUM NUMBER OF ELEMENTS
      NEX=4000
C---     NBH=LARGEST BUS NUMBER ALLOWED
      NBH=9998
C---     MBUS=LENGTH OF ARRAY FOR BUS IMPEDANCE MATRIX
      MBUS=NBX*(NBX+1)/2
C---     JJJJ=COMBINED CONVERTER ACTION FLAG
C---        0=SINGLE CONVERTER
C---        1=COMBINED CONVERTERS
      JJJJ=0
C---     RTD=RADIAN TO DEGREE CONVERSION
      RTD=57.29577951
C---     H2=BESSEL FUNCTION FLAG FOR LINEIN
C---        0.=NEED TO CALCULATE BESSEL FUNCTION PARAMETERS
      H2=0.
C---     READ HARMONIC SOURCE INPUT DATA
C---        N=NUMBER OF SAMPLED DATA POINTS (EVEN,.LE.128)
C---        (OP) N=NUMBER OF PULSES FOR CONVERTER
C---        VCBASE=BASE VALUE OF VOLTAGE OR CURRENT FOR HARM SOURCE
C---        LHARM=HIGHEST ORDER HARMONIC TO BE ANALYZED
C---        IPLOT=PLOT CODE
```

```
C---          0=NO PLOTS
C---        IVC=VOLTAGE OR CURRENT OR CONVERTER CODE
C---          LESS THAN -1 = CURRENT HARMONIC MAGNITUDES GIVEN
C---          -1=VOLTAGE HARMONIC MAGNITUDES GIVEN
C---          0=VOLTAGE WAVEFORM
C---          1=CONVERTER
C---          ANYTHING ELSE=CURRENT WAVEFORM
C---        IUNIT=OUTPUT UNITS
C---          0=VOLTS
C---          ANYTHING ELSE=PER UNIT
      READ(IRD,1000)N,VCBASE,LHARM,IPLOT,IVC,IUNIT
 1000 FORMAT(I3,F10.2,4I3)
      WRITE(IWT,109)N,VCBASE,LHARM,IPLOT,IVC,IUNIT
  109 FORMAT(1X,'N = ',I3,5X,'VCBASE = ',F7.2,5X,'LHARM = ',I3,
     1 5X,'IPLOT = ',I3,5X,'IVC = ',I3,5X,'IUNIT = ',I3)
      IF(IVC.GE.0)GO TO 40
C---    READ MEASURED HARMONIC VOLTAGES OR CURRENTS
C---      IY=HARMONIC ORDER
C---      VCM=HARMONIC VOLTAGE (CURRENT) MAGNITUDE
C---      VCA=HARMONIC VOLTAGE (CURRENT) ANGLE
      IF (IVC.NE.-1) GO TO 28
      IVC=0
      GO TO 29
   28 IVC=2
   29 CONTINUE
      WRITE(IWT,1051)
      DO 31 IM=1,65
   31 VC(IM)=(0.,0.)
   30 READ(IRD,600)IY,VCM,VCA
      IF(IY.EQ.999)GO TO 34
      WRITE(IWT,600)IY,VCM,VCA
  600 FORMAT(3X,I3,2X,F12.8,2X,F12.8)
      IF(VCA.EQ.0.0)GO TO 32
      IM=IY+1
      VC(IM)=CMPLX(-VCM,0.)
      GO TO 33
   32 IM=IY-1
      VC(IM+2)=CMPLX(VCM,0.)
   33 GO TO 30
   34 IF=65
      GO TO 308
   40 IF(IVC.NE.1)GO TO 301
C---     READ CONVERTER DATA
C---        POW=MW RATING OF CONVERTER
C---        ALFA=DELAY ANGLE IN DEGREES (0-60)
C---        OVLP=OVERLAP ANGLE IN DEGREES
      READ(IRD,302) POW,ALFA,OVLP
  302 FORMAT(3F10.2)
      WRITE(IWT,303) POW,ALFA,OVLP
  303 FORMAT('0POW = ',F10.2,5X,'ALFA = ',F10.2,5X,'OVLP = ',F10.2)
      ALFA=ALFA/RTD
      OVLP=OVLP/RTD
      GAM=ALFA+OVLP
      DO 304 IM=3,65
  304 VC(IM)=(0.,0.)
      WRITE(IWT,1051)
      DH=COS(ALFA)-COS(GAM)
      DO 305 IM=N,65,N
      IF(OVLP.NE.0.)GO TO 306
C---      0.779697=SQRT(6)/PI
      SHAR1=0.779697/(IM-1.)
      SHAR2=0.779697/(IM+1.)
      GO TO 307
  306 SHM=SIN((IM-2.)*OVLP/2.)
      SHP=SIN(IM*OVLP/2.)
      F2=SQRT((SHM/(IM-2.))**2+(SHP/IM)**2-2.*SHM*SHP*
```

```
     1 COS(2.*ALFA+OVLP)/((IM-2.)*IM))
       SHAR1=0.779697*F2/((IM-1.)*DH)
       SHM=SIN(IM*OVLP/2.)
       SHP=SIN((IM+2.)*OVLP/2.)
       F2=SQRT((SHM/IM)**2+(SHP/(IM+2.))**2-2.*SHM*SHP*
     1 COS(2.*ALFA+OVLP)/(IM*(IM-2.)))
       SHAR2=0.779697*F2/((IM+1.)*DH)
C---      2.5651=2*PI/SQRT(6)
   307 CR=2.5651*POW/((COS(ALFA)+COS(GAM))*100.)
       VCA=180.
       VCM=CR*SHAR1
       IV=IM-1
       VC(IM)=CMPLX(-VCM,0.)
       WRITE(IWT,106) IV,VCM,VCA
       VCA=0.
       VCM=CR*SHAR2
       IV=IM+1
       VC(IM+2)=CMPLX(VCM,0.)
       WRITE(IWT,106) IV,VCM,VCA
   305 CONTINUE
       IF=65
       GO TO 308
C---      READ IN SAMPLED DATA WAVEFORM
   301 J=(N-1)/8+1
       DO 9 IB=1,J
       KI=8*(IB-1)+1
       KJ=KI+7
C---      A=ARRAY OF N VALUES OF THE SAMPLED DATA WAVEFORM IN COSINE
C---      FORM IN KV
       READ(IRD,1050) (A(K),K=KI,KJ)
  1050 FORMAT(8F10.2)
     9 CONTINUE
       WRITE(IWT,200)
   200 FORMAT(1H0,5X,'SAMPLED DATA POINTS'/1H0,'NUMBER',35X,'VALUES')
       DO 110 IB=1,J
       KI=8*(IB-1)+1
       KJ=KI+7
       WRITE(IWT,111) KI,(A(K),K=KI,KJ)
   111 FORMAT(1H0,I4,8F10.2)
   110 CONTINUE
       DO 300 IB=1,N
   300 VC(IB)=CMPLX(A(IB),0.)
C---      FFTCC IS A SPECIAL PROGRAM FROM A LIBRARY NOT INCLUDED
C---      THERE IS A DUMMY PROGRAM INCLUDED TO SATISFY EXTERNAL
C---      REFERENCES
C---      PERFORM FAST FOURIER TRANSFORM
C---      IWK=INTEGER WORK ARRAY OF LENGTH 6N+150
C---      WK=REAL WORK ARRAY OF LENGTH 6N+150
       CALL FFTCC(VC,N,IWK,WK)
C---      RN=NUMBER OF SAMPLED DATA POINTS/2
       RN=N/2
       WRITE(IWT,1051)
  1051 FORMAT(1H-,'HARMONIC VALUES'/'0ORDER',8X,'MAG',8X,'ANG')
       IZ=N/2
C---      RESCALE TRANSFORM COEFFICIENTS
       DO 26 IM=1,IZ
       VC(IM)=CONJG(VC(IM))/(RN*VCBASE)
       VCM=CABS(VC(IM))
       VCA=ANGLE(VC(IM))*RTD
C---      IV=HARMONIC ORDER
       IV=IM-1
C---      PRINT HARMONIC VALUES
       WRITE(IWT,106) IV,VCM,VCA
   106 FORMAT(3X,I2,2X,F12.4,F12.2)
    26 CONTINUE
C---      LLL=FIRST TIME THROUGH LOOP FLAG
```

```
C---         1=FIRST TIME
      IF=N/2+1
  308 LLL=1
      IF(IPLOT.EQ.0) IF=LHARM+1
C---     INITIALIZE DC HARMONIC TO ZERO
      DO 167 IE=1,4
  167 SOURCE(1,IE)=(0.,0.)
C---     BEGIN LOOP FOR HARMONIC ANALYSIS
C---     JJ=HARMONIC ORDER + 1
      DO 27 JJ=3,IF
C---     IW=HARMONIC ORDER
      IW=JJ-1
C---     VCK=HARMONIC SOURCE VALUE IN PU
      VCK=VC(JJ)
C---     IDSN=SEQUENCE CODE FOR HARMONIC (SEE LINEIN)
      IDSN=0
C---     IF HARMONIC INJEC NEGLBLE, DO NOT PERFORM HARMONIC ANAL
      IF(CABS(VCK).GT.0.0001)GO TO 17
      DO 984 IE=1,4
  984 SOURCE(JJ,IE)=(0.,0.)
      GO TO 27
   17 IF(IW.GT.LHARM) GO TO 18
      GO TO 19
   18 WRITE(IWT,108) IW
  108 FORMAT('0XXX HARMONICS OF ORDER',3X,I3/)
   19 CONTINUE
C---     LINEIN=SUBROUTINE FOR READING AND STORING LINE, TRANSFORMER,
C---          GENERATOR, SHUNT CAPACITOR, AND LOAD DATA
C---     IP=ARRAY CONTAINING EXTERNAL 'FROM' BUS #'S
C---     IQ=ARRAY CONTAINING EXTERNAL 'TO' BUS #'S
C---     ICT=ARRAY CONTAINING ELEMENT CIRCUIT #'S
C---     R,X=ARRAYS CONTAINING ELEMENT RESISTANCE AND REACTANCE
C---     NB=ARRAY CONTAINING CONVERSION OF EXTERNAL TO INTERNAL
C---          BUS #'S
C---     NLB=ARRAY CONTAINING THE # OF ELEMENTS TO A BUS
C---     NBE=ARRAY CONTAINING CONVERSION OF INTERNAL TO EXTERNAL
C---          BUS #'S
      CALL LINEIN(IP,IQ,ICT,R,X,NB,NLB,NBE,ILIN,ZO,GAML,&2,&500)
C---     ORDER=SUBROUTINE FOR ORDERING AND INDEXING SYSTEM TOPOLOGY
C---     JP1=POINTER ARRAY FOR 'FROM' BUS TO ELEMENT #
C---     JP2=POINTER ARRAY FOR 'TO' BUS TO ELEMENT #
C---     KP1=POINTER ARRAY FOR 'FROM' BUS (ONE ELEMENT # TO NEXT)
C---     KP2=POINTER ARRAY FOR 'TO' BUS (ONE ELEMENT # TO NEXT)
C---     ISC=ARRAY CONTAINING THE ORDERING SCORE OF THE BUS
C---     ILO=ARRAY CONTAINING THE ELEMENT ORDER
C---     IBO=ARRAY CONTAINING THE BUS ORDER
    2 CALL ORDER(IP,IQ,NLB,JP1,JP2,KP1,KP2,ISC,ILO,IBO,&4,&500)
C---     ZBUS=SUBROUTINE FOR CALCULATION OF IMPEDANCE MATRIX
C---     RBUS=ARRAY CONTAINING REAL PART OF BUS IMPEDANCE MATRIX
C---     XBUS= ARRAY CONTAINING IMAGINARY PART OF BUS IMPEDANCE MATRI
C---     RL=ARRAY CONTAINING ELEMENT RESISTANCE
C---     XL=ARRAY CONTAINING ELEMENT REACTANCE
    4 CALL ZBUS(IP,IQ,R,X,ILO,IBO,ISC,RBUS,XBUS,RL,XL,NBE,&6,&500)
C---     HARMI=SUBROUTINE FOR HARMONIC ANALYSIS
    6 WRITE(IWT,107)IW
  107 FORMAT('1XXX HARMONICS OF ORDER',3X,I3,/)
      CALL HARMI(IP,IQ,ICT,R,X,KP1,KP2,NB,NBE,JP1,JP2,ISC,RBUS,XBUS,RL,
     1XL,ILIN,ZO,VMSQ,VVM1,GAML,&7,&500)
    7 CONTINUE
      LLL=2
   27 CONTINUE
C---    COMPUTE HARMONIC (VOLTAGE) DISTORTION FACTOR
C     IF(IOPT.EQ.0) GO TO 470
      WRITE (IWT,450)
      DO 400 J=1,NBH
C       J=EXTERNAL BUS#
```

```
C        KP=INTERNAL BUS #
         KP=NB(J)
C        BUS EXISTS?
         IF(KP.EQ.0)GO TO 400
         IF(IUNIT.EQ.0)GO TO 430
         IF(VVM1(J).EQ.0.)VVM1(J)=1.0
         HDF(J)=(VMSQ(J)**0.5)*100./VVM1(J)
         GO TO 440
  430    IF(VVM1(J).EQ.0.)VVM1(J)=VCBASE*1000./SQRT(3.)
         HDF(J)=(VMSQ(J)**0.5)*100./VVM1(J)
  440    WRITE(IWT,460)J,HDF(J)
  400    CONTINUE
  450    FORMAT('1HARMONIC DISTORTION FACTOR'//6X,'BUS',12X,'HDF (%)'/)
  460    FORMAT(6X,I4,8X,F10.4)
         IF(IPLOT.EQ.0) GO TO 500
         IVCO=1
         IF(IVC.EQ.0) IVCO=2
         IF(IVC.EQ.1) N=128
         J=(N-1)/4+1
         IC=N/2-1
         DO 37 IE=1,JJJ
         WRITE(6,220) IE
  220    FORMAT(1H1,5X,'WAVEFORM FOR HARMONIC SOURCE NUMBER',I5)
         DO 47 IG=1,IC
         IA=IG+N/2+1
         IB=N/2+1-IG
   47    SOURCE(IA,IE)=CONJG(SOURCE(IB,IE))
C---       FFTCC IS A SPECIAL PROGRAM FROM A LIBRARY NOT INCLUDED
C---       THERE IS A DUMMY PROGRAM INCLUDED TO SATISFY EXTERNAL
C---       REFERENCES
         CALL FFTCC(SOURCE(1,IE),N,IWK,WK)
         DO 57 IA=1,N
         SOURCE(IA,IE)=SOURCE(IA,IE)/2.
         A(IA)=REAL(SOURCE(IA,IE))
   57    X(IA)=(IA-1.)*1000./(60.*N)
         DO 67 IB=1,J
         KI=4*(IB-1)+1
         KJ=KI+3
   67    WRITE(6,210) KI,(SOURCE(I,IE),I=KI,KJ)
  210    FORMAT(1H0,I4,8F10.5)
C---         THIS CALLS IOWA STATE UNIVERSITY'S VERSION OF CALCOM
C---         THIS MAY NOT WORK WITH STANDARD CALCOM
         CALL GRAPH(N,X,A,4,103,12.,9.,1.5,0.,0.,0.,'TIME (MS);',
     1   YLAB(1,IVCO),GLAB(1,IVCO),DATLAB(1,IE))
   37    CONTINUE
  500    STOP
         END
         SUBROUTINE LINEIN(IP,IQ,ICT,R,X,NB,NLB,NBE,ILIN,ZO,GAML,*,*)
C---       READ AND STORE LINE, TRANSFORMER, GENERATOR, SHUNT CAPACITOR
C---           AND LOAD DATA
C---       CALLED FROM HARMONIC LOADFLOW MAIN PROGRAM ONCE FOR EACH
C---           HARMONIC ORDER TO BE ANALYZED
         IMPLICIT INTEGER*4(I-N)
         INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,IDSN,IW
         COMPLEX*8 D1,D2,DD1,DD,DZ1,DZ,DE,DSH,DCH,DYS,DZS,CMPLX,CSQRT,CEXP
         COMPLEX*8 DT1,DT2,DT3,DYZ,ZO,GAML
         COMMON /K1/IRD,IWT,IW,IDSN,H2
         COMMON /KL/NEX,NEL
         COMMON /KB/NBH,NBS,NBX,MS,NLR
         COMMON /BASE/LLL,JJJJ
         DIMENSION IP(NEX),IQ(NEX),ICT(NEX),R(NEX),X(NEX),ILIN(NEX)
         DIMENSION NB(NBH),NLB(NBX),NBE(NBX),ZO(NEX),GAML(NEX)
         DIMENSION RDN(4000,7),IRDN(4000,5)
         DIMENSION RDC(4000),A6(4000),BER(2),BEI(2),BERD(2),BEID(2)
C---       NEX=MAXIMUM NUMBER OF ELEMENTS
C---       NEL=NUMBER OF ELEMENTS
```

```
C---      NBH=LARGEST BUS NUMBER ALLOWED                                   . . . D E F . . .
C---      NBS=NUMBER OF BUSES                                              . . . D E F . . .
C---      NBX=MAXIMUM NUMBER OF BUSES                                      . . . D E F . . .
C---      IP=ARRAY CONTAINING INTERNAL 'FROM' BUS #'S                      . . . D . . . . .
C---      IO=ARRAY CONTAINING INTERNAL 'TO' BUS #'S                        . . . D . . . . .
C---      ICT=ARRAY CONTAINING ELEMENT CIRCUIT #'S                         . . C . . . . . .
C---      R, X=ARRAYS CONTAINING IMPEDANCE                                 . . . . . . . . .
C---      NB=ARRAY CONTAINING CONVERSION OF EXTERNAL TO INTERNAL BUS #     . . . D . . . . .
C---      NBE=ARRAY CONTAINING CONVERSION OF INTERNAL TO EXTERNAL BUS #    . . . D . . . . .
C---      NLB=ARRAY CONTAINING THE NUMBER OF LINES TO A BUS                . . . D . . . . .
      NBS=0                                                                . . . . . . . . .
      NE1=0                                                                . . . . . . . . .
      NEL=0                                                                . . . . . . . . .
C---      IERROR=NUMBER OF BUS # ERRORS                                    . . . D . . . . .
      IERROR=0                                                             . . . . . . . . .
C---      NLR=NUMBER OF ELEMENTS CONNECTED TO REFERENCE                    . . C . . . . . .
      NLR=0                                                                . . . . . . . . .
      DO 1 I=1,NBH                                                         . . . . . . . . .
    1 NB(I)=0                                                              . . . . . . . . .
      DO 2 I=1,NBX                                                         . . . . . . . . .
    2 NLB(I)=0                                                             . . . . . . . . .
      IF (LLL.GT.1)GO TO 11                                                . . . . . . . . .
      WRITE(IWT,1100)                                                      . . . . . . . . .
C---      NE1=NUMBER OF ELEMENTS + 1                                       . . C . . . . . .
   11 NE1=NE1+1                                                            . . . . . . . . .
C---      LLL=FIRST TIME THROUGH LOOP FLAG                                 . . . . . . . . .
C---         1=FIRST TIME                                                  . . . . . . . . .
      IF(LLL.GT.1)GO TO 300                                                . . . . . . . . .
C---      INITIALIZE RDC ARRAY TO ZERO                                     . . . . . . . . .
      DO 3 I=1,NEX                                                         . . . . . . . . .
    3 RDC(I)=0.                                                            . . . . . . . . .
C---      READ ELEMENT DATA                                                . . C . . . . . .
C---      KJ=ELEMENT CODE                                                  . . C . . . . . .
C---         1=LINE                                                        . . C . . . . . .
C---         2=TRANSFORMER                                                 . . C . . . . . .
C---         3=GENERATOR OR SHUNT CAPACITOR                                . . C . . . . . .
C---         4=LOAD                                                        . . C . . . . . .
C---      KJP='FROM' BUS (9999 FOR END OF ELEMENTS)                        . . C D E F . . .
C---      KJQ='TO' BUS                                                     . . . D E F . . .
C---      KCT=ELEMENT CIRCUIT # (OR) TRANSFORMER AUXILIARY BUS #           . . C D E F . . .
C---      RR1=LINE POS/NEG SEQ RESISTANCE (OR) TRANSFORMER POS/NEG         . . . . . . . . .
C---         SEQ SERIES REACTANCE BOTH IN % (OR) LOAD REAL POWER IN MW     . . . . . . . . .
C---      XX1=LINE POS/NEG SEQ REACTANCE (OR) TRANSFORMER ZERO SEQ         . . . . . . . . .
C---         SERIES REACTANCE (OR) GEN/CAP REACTANCE ALL IN % (OR)         . . . . . . . . .
C---         LOAD REACTIVE POWER IN MVAR                                   . . . . . . . . .
C---      XC1=LINE POS/NEG SEQ SUSCEPTANCE (OR) TRANSFORMER POS/NEG        . . . . . . . . .
C---         SEQ SHUNT REACTANCE (OR) GEN ZERO SEQ REACTANCE ALL IN %      . . . . . . . . .
C---      RR0=LINE ZERO SEQ RESISTANCE (OR) TRANSFORMER POS/NEG/ZERO       . . . . . . . . .
C---         SEQ CORE LOSS RESISTANCE BOTH IN %                            . . . . . . . . .
C---      XX0=LINE ZERO SEQ REACTANCE IN % (OR) TRANSFORMER CONNECTION     . . . . . . . . .
C---         CODE                                                          . . . . . . . . .
C---      XC0=LINE ZERO SEQ SUSCEPTANCE (OR) TRANSFORMER ZERO SEQ          . . . . . . . . .
C---         SHUNT REACTANCE BOTH IN %                                     . . . . . . . . .
C---      KK=LINE VOLTAGE AND BUNDLE CODE                                  . . . . . . . . .
C---         VOLTAGE(KV)   CODE(FIRST DIDIT)   (SECOND DIGIT)              . . . . . . . . .
C---           13.80             9             NUMBER OF BUNDLES           A . . . . . . . .
C---           69                1               PER CONDUCTOR             A . . . . . . . .
C---           115               2                                         A . . . . . . . .
C---           132               3                                         A . . . . . . . .
C---           138               4                                         A . . . . . . . .
C---           161               5                                         A . . . . . . . .
C---           230               6                                         A . . . . . . . .
C---           345               7                                         A . . . . . . . .
C---           500               8                                         A . . . . . . . .
C---      (OR) KK=TRANSFORMER CONNECTION CODE                              . . . . . . . . .
C---              0,XX0.GT.1.;NO ZERO SEQ IMPEDANCE                        . . . . . . . . .
```

```
C---             0.0.9.LT.XXO.LT.1.:ONE IMPEDANCE (XX1) 'TO' BUS TO
C---             REFERENCE
C---             0.0.7.LT.XXO.LT.0.9:ONEIMPEDANCE (XX1) 'FROM' BUS
C---             TO REFERENCE
C---             0.XXO.LT.0.7:T-TYPE CKT WITH POS/NEG SEQ MAG BRANCH
C---             1:SHORTED T-TYPE (XX1,XCO) 'FROM' BUS TO REFERENCE
C---             2:SHORTED T-TYPE (XX1,XCO) 'TO' BUS TO REFERENCE
C---             3:OPEN T-TYPE (XX1,XCO) 'TO' BUS TO REFERENCE
C---             4:OPEN T-TYPE (XX1,XCO) 'FROM' BUS TO REFERENCE
C---             .GT.4:T-TYPE (XX1,XCO) CORE LOSS NEGLECTED
C---       (OR) KK=GEN/CAP CODE
C---             1=CAPACITOR
C---       (OR) KK=LOAD CODE
C---             1=RESIDENTIAL
C---             2=COMMERCIAL
C---             3=INDUSTRIAL
C---       XLM=LINE LENGTH IN MILES
      READ(IRD,1000,END=50)KJ,KJP,KJQ,KCT,RR1,XX1,XC1,RRO,XXO,XCO,KK,XLM
      IF(KJP.EQ.9999) GO TO 200
      WRITE (IWT,1200)KJ,KJP,KJQ,KCT,RR1,XX1,XC1,RRO,XXO,XCO,KK,XLM
  200 CONTINUE
C---       CONVERT FROM PER CENT TO PER UNIT
      RR1=RR1/100.0
      XX1=XX1/100.0
      XC1=XC1/100.0
      RRO=RRO/100.0
C---       XXO IS CONVERTED LATER
      XCO=XCO/100.0
C---       STORE INPUT DATA
C---       IRDN=INTEGER ARRAY STORING INPUT DATA
      IRDN(NE1,1)=KJ
      IRDN(NE1,2)=KJP
      IRDN(NE1,3)=KJQ
      IRDN(NE1,4)=KCT
      IRDN(NE1,5)=KK
C---       RDN=REAL ARRAY STORING INPUT DATA
      RDN(NE1,1)=RR1
      RDN(NE1,2)=XX1
      RDN(NE1,3)=XC1
      RDN(NE1,4)=RRO
      RDN(NE1,5)=XXO
      RDN(NE1,6)=XCO
      RDN(NE1,7)=XLM
      GO TO 301
C---       RECOVER INPUT DATA
  300 KJ=IRDN(NE1,1)
      KJP=IRDN(NE1,2)
      KJQ=IRDN(NE1,3)
      KCT=IRDN(NE1,4)
      KK=IRDN(NE1,5)
      RR1=RDN(NE1,1)
      XX1=RDN(NE1,2)
      XC1=RDN(NE1,3)
      RRO=RDN(NE1,4)
      XXO=RDN(NE1,5)
      XCO=RDN(NE1,6)
      XLM=RDN(NE1,7)
  301 IF(KJP.EQ.9999) GO TO 45
C---       IDSN=SEQUENCE CODE FOR HARMONIC
C---          0=UNDETERMINED
C---          1=ZERO SEQUENCE
C---          2=NEG SEQUENCE
C---          3=POS SEQUENCE
  150 IF(IDSN-1)101,106,141
  141 IF(IDSN-2)110,110,112
  101 B=1.0
```

```
C---      WT=HARMONIC ORDER
      WT=FLOAT(IW)
      IF(WT.EQ.1) GO TO 112
C---      IS HARMONIC ZERO SEQ.
  107 A=3.0*B
      IF(WT/A-1.0)105,106,105
  105 B=B+1.0
      IF(B-22.0)107,108,108
C---      IS HARMONIC NEG. SEQ.
  108 B=1.0
  111 A=(3.0*B)-1.0
      IF(WT/A-1.0)109,110,109
  109 B=B+1.0
      IF(B-22.0)111,112,112
  112 IDSN=3
C---      HARMONIC IS POS.SEQ.
C---      WHAT IS ELEMENT
      IF(KJ-2)113,114,115
C---      POS. + NEG. SEQ. TRANSMISSION LINE
C---      DETERMINE BASE IMPEDANCE
  113 IF(KK.GT.20)GO TO 210
C---      BI=BASE IMPEDANCE
      BI=47.61
      GO TO 218
  210 IF(KK.GT.30)GO TO 211
      BI=132.25
      KK=KK-10
      GO TO 218
  211 IF(KK.GT.40)GO TO 212
      BI=174.24
      KK=KK-20
      GO TO 218
  212 IF(KK.GT.50)GO TO 213
      BI=190.44
      KK=KK-30
      GO TO 218
  213 IF(KK.GT.60)GO TO 214
      BI=259.21
      KK=KK-40
      GO TO 218
  214 IF(KK.GT.70)GO TO 215
      BI=529.00
      KK=KK-50
      GO TO 218
  215 IF(KK.GT.80)GO TO 216
      BI=1190.25
      KK=KK-60
      GO TO 218
  216 IF(KK.GT.90)GO TO 217
      BI=2500.00
      KK=KK-70
      GO TO 218
  217 BI=1.9044
      KK=KK-80
C---      R60=60 HZ LINE RESISTANCE IN OHMS/MILE
  218 R60=RR1*BI*(KK-10)/XLM
      IF(WT.EQ.1) GO TO 160
      I=1
      IF(RDC(NE1).NE.0.) GO TO 206
C---      RDC=DC LINE RESISTANCE IN OHMS/MILE
      RDC(NE1)=R60
C---      F=FREQUENCY IN HZ
      F=60.0
C---      SKIN EFFECT
  203 B=F/RDC(NE1)
C---      A=MR
```

```
      A=0.0636*SQRT(B)
      IF(H2.NE.0.) GO TO 400
      H2=4.
      H4=64.
      H6=2304.
      H8=147456.
      H10=1.47456E7
      H12=H10*144
      H14=H12*196.
      H16=H14*256.
      H18=H16*324.
      H20=H18*400.
      H22=H20*484.
      H24=H22*576.
      H26=H24*676.
      H28=H26*784.
      H30=H28*900.
      H32=H30*1024.
      H34=H32*1156.
      H36=H34*1296.
C---      BER(I)=REAL BESSEL FUNCTION OF MR
C---            1=60 HZ
C---            2=HARMONIC FREQ
  400 BER(I)=1.0-A**4/H4+A**8/H8-A**12/H12+A**16/H16-A**20/H20
     1 +A**24/H24-A**28/H28+A**32/H32-A**36/H36
C---      BEI(I)=IMAGINARY BESSEL FUNCTION OF MR
      BEI(I)=A**2/H2-A**6/H6+A**10/H10-A**14/H14+A**18/H18
     1 -A**22/H22+A**26/H26-A**30/H30+A**34/H34
C---      BERD(I)=DERIVATIVE OF BER(I)
      BERD(I)=-4.0*A**3/H4+8.0*A**7/H8-12.0*A**11/H12+16.0*A**15/H16
     1 -20.0*A**19/H20+24.0*A**23/H24-28.0*A**27/H28+32.0*A**31/H32
     2 -36.0*A**35/H36
C---      BEID(I)=DERIVATIVE OF BEI(I)
      BEID(I)=2.0*A/H2-6.0*A**5/H6+10.0*A**9/H10-14.0*A**13/H14
     1 +18.0*A**17/H18-22.0*A**21/H22+26.0*A**25/H26-30.0*A**29/H30
     2 +34.0*A**33/H34
C---      RR7=AC TO DC RESISTANCE RATIO
      RR7=A*(BER(I)*BEID(I)-BEI(I)*BERD(I))/
     1 (2.0*(BEID(I)**2+BERD(I)**2))
      IF(F.NE.60.0)GO TO 204
C---      TR60=ESTIMATE OF 60 HZ RESISTANCE
      TR60=RR7*RDC(NE1)
      ER=TR60-R60
C---      ERA=ERROR DIFFERENCE OF ACTUAL AND ESTIMATE OF 60 HZ RESIS
      ERA=ABS(ER)
C---      CHECK ACCURACY OF TR60
      IF(ERA.GT.0.00005)GO TO 205
C---      A6=ALPHAL AT 60 HZ
      A6(NE1)=4.0*(BER(I)*BERD(I)+BEI(I)*BEID(I))/
     1 (A*(BERD(I)**2+BEID(I)**2))
      GO TO 206
C---      OBTAIN NEW ESTIMATE OF RDC
  205 RDC(NE1)=RDC(NE1)-ER
      GO TO 203
C---      F=HARMONIC FREQUENCY
  206 F=60.0*IW
      I=2
      GO TO 203
C---      R1=LINE RESISTANCE AT HARMONIC FREQ IN PU
C-------R1=RR1 IS USED FOR FUNDAMENTAL FREQ ONLY
  160 R1=RR1
      GO TO 170
  204 R1=RR7*RDC(NE1)*XLM/(BI*(KK-10))
C---      AL=ALPHAL AT HARMONIC FREQUENCY
  208 AL=4.0*(BER(I)*BERD(I)+BEI(I)*BEID(I))/
     1 (A*(BERD(I)**2+BEID(I)**2))
```

```
C---     X60=TOTAL 60 HZ REACTANCE IN OHMS/MILE
      X60=XX1*BI/XLM
C---     D=60 HZ EXTERNAL REACTANCE IN OHMS/MILE
      D=X60-A6(NE1)*0.030335/(KK-10)
C---     XF=TOTAL REACTANCE AT HARMONIC FREQUENCY IN OHMS/MILE
      XF=(D+AL*0.030335/(KK-10))*WT
C---     XL=LINE REACTANCE IN PU
      GO TO 175
C------ XL=XX1 IS USED FOR FUNDAMENTAL FREQ ONLY
  170 XL=XX1
      GO TO 180
  175 XL=XF*XLM/BI
C---     VC=LINE SHUNT SUSCEPTANCE AT HARMONIC FREQ IN PU
  180 VC=WT*XC1
C---     GO=LINE SHUNT CONDUCTANCE
  116 GO=0.0
C---     D1=LINE SERIES IMPEDANCE IN PU
      D1=CMPLX(R1,XL)
C---     D2=LINE SHUNT ADMITTANCE IN PU
      D2=CMPLX(GO,VC)
      DD1=D1*D2
C---     DD=GAMMA*L (GAMMA=PROPAGATION CONSTANT, L=LINE LENGTH)
      DD=CSQRT(DD1)
      DZ1=D1/D2
C---     DZ=CHARACTERISTIC IMPEDANCE IN PU
      DZ=CSQRT(DZ1)
      DE=CEXP(DD)
C---     DSH=SINH(GAMMA*L)
      DSH=0.5D0*(DE-1.0D0/DE)
C---     DCH=COSH(GAMMA*L)
      DCH=0.5D0*(DE+1.0D0/DE)
C---     DYS=PI LINE SHUNT ADMITTANCE IN PU
      DYS=(1.0D0/DZ)*((DCH-1.0D0)/DSH)
C---     DZS=PI LINE SERIES IMPEDANCE IN PU
      DZS=DZ*DSH
C---     DYZ=PI LINE SHUNT IMPEDANCE IN PU
      DYZ=1.0/DYS
C---     RS1=REAL PART OF SERIES IMPEDANCE IN PU
      RS1=REAL(DZS)
C---     RS2=REAL PART OF SHUNT IMPEDANCE IN PU
      RS2=REAL(DYZ)
C---     XS1=IMAGINARY PART OF SERIES IMPEDANCE IN PU
      XS1=AIMAG(DZS)
C---     XS2=IMAGINARY PART OF SHUNT IMPEDANCE IN PU
      XS2=AIMAG(DYZ)
      GO TO 117
  110 IDSN=2
C---     HARMONIC IS NEGATIVE SEQUENCE
C---     WHAT IS ELEMENT
      IF(KJ-2)113,114,120
  106 IDSN=1
C---     HARMONIC IS ZERO SEQUENCE
C---     WHAT IS ELEMENT
      IF(KJ-2)118,121,122
C---     ZERO SEQ. TRANSMISSION LINE
C---     RROE=EARTH RESISTANCE COMPONENT AT 60 HZ IN PU
  118 RROE=RRO-RR1
C---     RRWE=EARTH RESISTANCE COMPONENT AT 60 HZ IN PU
      RRWE=RROE*WT
C---     R1=LINE RESISTANCE AT HARMONIC FREQ IN PU
      R1=RR1+RRWE
C---     XL=LINE SERIES REACTANCE AT HARMONIC FREQ IN PU
      XL=XXO*WT/100.0
C---     VC=LINE SHUNT SUSCEPTANCE AT HARMONIC FREQ IN PU
      VC=WT*XCO
      GO TO 116
```

```
C---      POS. + NEG. SEQ. TRANSFORMER
C---      XS3=HALF OF TX SERIES REACTANCE AT HARMONIC FREQ IN PU
  114 XS3=RR1*WT/2.D
C---      XS4=TX SHUNT REACTANCE AT HARMONIC FREQ IN PU
  127 XS4=XC1*WT
C---      ASSUME SILICON STEEL W/ 3/1 HYS/EDDY LOSSES
C---      RR4=TX SHUNT RESISTANCE AT HARMONIC FREQ IN PU
      RR4=(3.D*RRO/(WT*4.D))+(RRO/(4.D*WT**2))
      XS5=0.D
      RR3=0.D
      DT1=CMPLX(RR4,XS5)
      DT2=CMPLX(RR3,XS4)
C---      DT3=TX SHUNT IMPEDANCE AT HARMONIC FREQ IN PU
      DT3=(DT1*DT2)/(DT1+DT2)
C---      RT1=REAL PART OF TX SHUNT IMPEDANCE
      RT1=REAL(DT3)
C---      XT1=IMAGINARY PART OF TX SHUNT IMPEDANCE
      XT1=AIMAG(DT3)
      GO TO 119
C---      ZERO SEQ. TRANSFORMER
  121 IF(KK)143,142,143
  142 IF(XXO-1.D)123,124,124
  124 GO TO 11
  123 IF(XXO-.70)125,125,126
  125 XS3=XX1*WT/2.D
      GO TO 127
  126 XT2=XX1*WT
      IF(XXO-.90)128,129,129
  143 XZ=XX1*WT/2.D
      XT2=XZ+(XZ*XCO*WT)/(XZ+XCO*WT)
      IF(KK-2)144,145,146
  146 IF(KK-4)147,148,149
  144 GO TO 128
  145 GO TO 129
  147 XT2=XZ+XCO*WT
      GO TO 129
  148 XT2=XZ+XCO*WT
      GO TO 128
  149 XS3=XZ
      RT1=0.D
      XT1=XCO*WT
      GO TO 119
C---      POS SEQUENCE GENERATORS
C---      GENERATOR OR LOAD?
  115 IF(KJ.GE.4)GO TO 444
C---      GENERATOR OR CAPACITOR?
      IF(KK.EQ.1)GO TO 500
C---      XG1=GEN REACTANCE AT HARMONIC FREQ IN PU
      XG1=XX1*WT
      GO TO 130
C---      ZERO SEQUENCE GENERATORS
  122 IF(KJ.EQ.4)GO TO 444
      IF(KK.EQ.1)GO TO 500
      XG1=XC1*WT
      GO TO 130
C---      NEG SEQUENCE GENERATORS
  120 IF(KJ.EQ.4)GO TO 444
      IF(KK.EQ.1)GO TO 500
      XG1=XX1*WT
      GO TO 130
C---      SHUNT CAPACITORS
C---      XG1=CAP REACTANCE AT HARMONIC FREQ IN PU
  500 XG1=XX1/WT
      GO TO 130
C---      LOADS
C---      RESIDENTIAL, COMMERCIAL, OR INDUSTRIAL?
```

```
  444 IF (IW.EQ.1) GO TO 510
      IF(KK-2)445,446,447
C---      RESIDENTIAL LOADS
C---      PMOT=MOTOR COMPONENT OF REAL POWER
  445 PMOT=0.5*RR1
C---      PRES=RESISTIVE COMPONENT OF REAL POWER
      PRES=0.5*RR1
      GO TO 448
C---      COMMERCIAL LOADS
  446 PMOT=0.6*RR1
      PRES=0.4*RR1
      GO TO 448
C---      INDUSTRIAL LOADS
  447 PMOT=0.7*RR1
      PRES=0.3*RR1
C---      XONE=MOTOR STATOR REACTANCE AT HARMONIC FREQ IN PU
  448 XONE=XX1/(4.64*(PMOT**2+XX1**2))
      XONE=XONE*WT
      RHE=1.03/(0.03*PMOT)
C---      ASSUME SILICON STEEL W/ 3/1 HYS/EDDY LOSSES
C---      RHE=MOTOR CORE LOSS RESISTANCE AT HARMONIC FREQ IN PU
      RHE=(3.0*RHE/(WT*4.0))+(RHE/(4.0*WT**2))
C---      REQM=MOTOR EQUIV SERIES RESISTANCE IN PU
  520 REQM=(XONE**2)*RHE/(RHE**2+XONE**2)
C---      XEQM=MOTOR EQUIV SERIES REACTANCE IN PU
      XEQM=((RHE**2)*XONE/(RHE**2+XONE**2))+XONE
C---      RES=CONSTANT LOAD RESISTANCE
      RES=1.0/PRES
      DEQ=(REQM+RES)**2+XEQM**2
      REQN=(RES**2*REQM)+(REQM**2*RES)+(XEQM**2*RES)
      XEQN=XEQM*RES**2
C---      REQ=LOAD RESISTANCE AT HARMONIC FREQ IN PU
      REQ=REQN/DEQ
C---      XEQ=LOAD REACTANCE AT HARMONIC FREQ IN PU
      XEQ=XEQN/DEQ
      GO TO 449
C---------- LOAD SERIES RESISTANCE AND REACTANCE FOR FUNDAMENTAL FREQ
  510 REQ=RR1/(RR1**2+XX1**2)
      XEQ=XX1/(RR1**2+XX1**2)
      GO TO 449
C---      ASSIGN TRANSMISSION LINE ELEMENTS
C---      M=ELEMENT FLAG
C---         0=SERIES ELEMENT
C---         1='FROM' BUS SHUNT ELEMENT
C---         2='TO' BUS SHUNT ELEMENT
  117 M=0
  139 IF(M-1)131,132,133
C---      JP='FROM' BUS EXTERNAL NUMBER
  131 JP=KJP
C---      JQ='TO' BUS EXTERNAL NUMBER
      JQ=KJQ
C---      JCT=CIRCUIT NUMBER
      JCT=KCT
C---      RR=ELEMENT RESISTANCE IN PU
      RR=RS1
C---      XX=ELEMENT REACTANCE IN PU
      XX=XS1
C---      ILINE=LINE FLAG
      ILINE=1
      GO TO 134
  132 JP=KJP
      JQ=0
      JCT=KCT
      RR=RS2
      XX=XS2
      ILINE=0
```

```
      GO TO 134
  133 JP=0
      JQ=KJQ
      JCT=KCT
      RR=RS2
      XX=XS2
      ILINE=0
      GO TO 134
C---      ASSIGN GENERATOR ELEMENTS
  130 M=2
      JP=KJP
      JQ=KJQ
      JCT=KCT
      RR=RR1
      XX=XG1
      ILINE=0
      GO TO 134
C---      ASSIGN LOAD ELEMENTS
  449 M=2
      JP=KJP
      JQ=0
      JCT=KCT
      RR=REQ
      XX=XEQ
      ILINE=0
      GO TO 134
C---      ASSIGN TRANSFORMER ELEMENTS
  119 M=0
  140 IF(M-1)135,136,137
  135 JP=KJP
C---      ASSIGN ADDITIONAL NODE = KCT
      JQ=KCT
      RR=0.0
      JCT=1
      XX=XS3
      ILINE=0
      GO TO 134
  136 JP=KCT
      JQ=KJQ
      RR=0.0
      JCT=1
      XX=XS3
      ILINE=0
      GO TO 134
  137 JP=KCT
      JQ=0
      RR=RT1
      XX=XT1
      JCT=1
      ILINE=0
      GO TO 134
  128 M=2
      JP=KJP
      JQ=0
      RR=0.0
      JCT=1
      XX=XT2
      ILINE=0
      GO TO 134
  129 M=2
      JP=0
      JQ=KJQ
      RR=0.0
      JCT=1
      XX=XT2
      ILINE=0
```

```
      GO TO 134                                                          . . C D E F . . .
C---     CHANGE TO INTERNAL BUS NUMBERS                                  . . C D E F . . .
C---     BUS NUMBER ERROR?                                               . . C D E F . . .
  134 IF(JP.EQ.JQ)GO TO 40                                               . . C D E F . . .
C---     IS 'FROM' BUS REF NODE?                                         . . C D E F . . .
      IF(JP.GT.0)GO TO 12                                                . . C D E F . . .
C---     KP=INTERNAL BUS NUMBER INDEX                                    . . C D E F . . .
      KP=0                                                               . . C D E F . . .
C---     INCREMENT NUMBER OF ELEMENTS CONNECTED TO REF                   . . C D E F . . .
      NLR=NLR+1                                                          . . C D E F . . .
      GO TO 14                                                           . . C D E F . . .
C---     IS 'FROM' BUS NUMBER TOO LARGE?                                 . . C D E F . . .
   12 IF(JP.GT.NBH)GO TO 40                                              . . C D E F . . .
      KP=NB(JP)                                                          . . C D E F . . .
C---     FIRST ELEMENT CONNECTED TO BUS?                                 . . C D E F . . .
      IF(KP.NE.0)GO TO 13                                                . . C D E F . . .
C---     TOO MANY BUSES?                                                 . . C D E F . . .
      IF(NBS.GE.NBX)GO TO 55                                             . . C D E F . . .
C---     INCREMENT NUMBER OF BUSES                                       . . C D E F . . .
      NBS=NBS+1                                                          . . C D E F . . .
C---     STORE INTERNAL BUS NUMBER                                       . . C D E F . . .
      NB(JP)=NBS                                                         . . C D E F . . .
      KP=NBS                                                             . . C D E F . . .
C---     STORE EXTERNAL 'FROM' BUS NUMBER                                . . C D E F . . .
      NBE(KP)=JP                                                         . . C D E F . . .
C---     INCREMENT NUMBER OF SERIES ELEMENTS CONNECTED TO BUS            . . C D E F . . .
   13 NLB(KP)=NLB(KP)+1                                                  . . C D E F . . .
C---     IS 'TO' BUS REFERENCE NODE?                                     . . C D E F . . .
   14 IF(JQ.GT.0)GO TO 15                                                . . C D E F . . .
C---     KQ=INTERNAL BUS NUMBER INDEX                                    . . C D E F . . .
      KQ=0                                                               . . C D E F . . .
C---     INCREMENT, NUMBER OF ELEMENTS CONNECTED TO REF                  . . C D E F . . .
      NLR=NLR+1                                                          . . C D E F . . .
      GO TO 17                                                           . . C D E F . . .
C---     IS 'TO' BUS NUMBER TOO LARGE?                                   . . C D E F . . .
   15 IF(JQ.GT.NBH)GO TO 40                                              . . C D E F . . .
      KQ=NB(JQ)                                                          . . C D E F . . .
C---     FIRST ELEMENT CONNECTED TO BUS?                                 . . C D E F . . .
      IF(KQ.NE.0)GO TO 16                                                . . C D E F . . .
C---     TOO MANY BUSES?                                                 . . C D E F . . .
      IF(NBS.GE.NBX)GO TO 55                                             . . C D E F . . .
C---     INCREMENT NUMBER OF BUSES                                       . . C D E F . . .
      NBS=NBS+1                                                          . . C D E F . . .
C---     STORE INTERNAL BUS NUMBER                                       . . C D E F . . .
      NB(JQ)=NBS                                                         . . C D E F . . .
      KQ=NBS                                                             . . C D E F . . .
C---     STORE EXTERNAL 'TO' BUS NUMBER                                  . . C D E F . . .
      NBE(KQ)=JQ                                                         . . C D E F . . .
C---     INCREMENT NUMBER OF SERIES ELEMENTS CONNECTED TO BUS            . . C D E F . . .
   16 NLB(KQ)=NLB(KQ)+1                                                  . . C D E F . . .
C---     KP, KQ CONTAIN THE INTERNAL BUS NUMBER - NOW STORE THE DATA     . . C D E F . . .
C---     TOO MANY ELEMENTS?                                              . . C D E F . . .
   17 IF(NEL.GE.NEX)GO TO 60                                             . . C D E F . . .
C---     INCREMENT NUMBER OF ELEMENTS                                    . . C D E F . . .
      NEL=NEL+1                                                          . . C D E F . . .
C---     STORE INTERNAL 'FROM' BUS NUMBER                                . . C D E F . . .
      IP(NEL)=KP                                                         . . C D E F . . .
C---     STORE INTERNAL 'TO' BUS NUMBER                                  . . C D E F . . .
      IQ(NEL)=KQ                                                         . . C D E F . . .
C---     STORE CIRCUIT NUMBER                                            . . C D E F . . .
      ICT(NEL)=JCT                                                       . . C D E F . . .
C---     STORE ELEMENT RESISTANCE                                        . . C D E F . . .
      R(NEL)=RR                                                          . . C D E F . . .
C---     STORE ELEMENT REACTANCE                                         . . C D E F . . .
      X(NEL)=XX                                                          . . C D E F . . .
C---     STORE LINE FLAG                                                 . . C D E F . . .
```

```
      ILIN(NEL)=ILINE
C---      STORE CHARACTERISTIC IMPEDANCE FOR LINES
      ZO(NEL)=DZ
C---       STORE PROPAGATION CONSTANT FOR LINES
      GAML(NEL)=DD
C---      ALL ELEMENTS OF COMPONENT?
      IF(M-2)138,11,11
C---      BUS NUMBER ERROR
   40 WRITE(IWT,1001)JP,JQ,JCT,RR,XX
C---      COUNT BUS NUMBER ERRORS
      IERROR=IERROR+1
      IF(M-2)138,11,11
C---      INCREMENT ELEMENT FLAG
  138 M=M+1
C---      LINE OR TRANSFORMER?
      IF(KJ-2)139,140,140
C---      NORMAL RETURN
   45 IF(IERROR.EQ.0)RETURN 1
C---      PRINT NUMBER OF BUS NUMBER ERRORS
      WRITE(IWT,1002)IERROR
C---      ABNORMAL RETURN
      RETURN 2
C---      LAST CARD (9999) NOT READ
   50 WRITE(IWT,1003)
      RETURN 2
C---      TOO MANY BUSES
   55 WRITE(IWT,1004)NBX
      RETURN 2
C---      TOO MANY ELEMENTS
   60 WRITE(IWT,1005)NEX
      RETURN 2
 1000 FORMAT(I1,2I4,I3,F10.4,F12.4,F10.8,2F9.4,F10.8,I2,F6.2)
 1001 FORMAT('0*** BUS NUMBER ERROR - ',2(I4,2X),I2,2(4X,F6.2))
 1002 FORMAT('0*** TOTAL NUMBER OF ERRORS = ',I5)
 1003 FORMAT('0*** UNEXPECTED END OF LINE DATA')
 1004 FORMAT('0*** TOO MANY BUSES - MORE THAN ',I4)
 1005 FORMAT('0*** TOO MANY ELEMENTS - MORE THAN ',I5)
 1100 FORMAT('1',2X,'KJ',2X,'KJP',2X,'KJO',2X,'KCT',6X,'RR1',11X,'XX1'
     1,12X,'XC1',12X,'RRO',11X,'XXO',9X,'XCO',10X,'KK',4X,'XLM'/)
 1200 FORMAT(4X,I1,1X,I4,1X,I4,2X,I3,1X,F10.4,2X,F12.4,
     12X,F15.8,2(2X,F12.4),2X,F15.8,2X,I2,2X,F6.2)
      END
      SUBROUTINE ORDER(IP,IQ,NLB,JP1,JP2,KP1,KP2,ISC,ILO,IBO,*,*)
C---      CREATE ORDERED LISTS FOR BUSES AND ELEMENTS
C---      CALLED FROM HARMONIC LOADFLOW MAIN PROGRAM ONCE FOR EACH
C---           HARMONIC ORDER TO BE ANALYZED
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,IW,IDSN
      COMMON /K1/IRD,IWT,IW,IDSN
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      DIMENSION IP(NEL),IQ(NEL),KP1(NEL),KP2(NEL),ILO(NEL)
      DIMENSION NLB(NBS),JP1(NBS),JP2(NBS),ISC(NBS),IBO(NBS)
C---      JP1=POINTER FROM BUS TO THE LINE 'FROM' BUS
C---      JP2=POINTER FROM BUS TO THE LINE 'TO' BUS
C---      KP1=POINTER FROM LINE TO THE NEXT LINE 'FROM' BUS
C---      KP2=POINTER FROM LINE TO THE NEXT LINE 'TO' BUS
C---      JP1R, JP2R= POINTERS FROM THE REFERENCE BUS
C---      ISC=THE ORDERING SCORE OF THE BUS
C---      IBO=THE BUS ORDER
C---      ILO=THE LINE ORDER
      DO 1 I=1,NBS
      JP1(I)=0
      JP2(I)=0
    1 ISC(I)=0
      JP1R=0
```

```
      JP2R=0
C---     CHAIN LINES BY BUS NUMBER
      DO 29 I=1,NEL
C---     KP=INTERNAL 'FROM' BUS NUMBER
      KP=IP(I)
C---     KQ=INTERNAL 'TO' BUS NUMBER
      KQ=IQ(I)
      KP1(I)=0
      KP2(I)=0
C---     IS 'FROM' BUS REF NODE?
      IF(KP.NE.0)GO TO 13
C---     INCREMENT ORDERING SCORE OF 'TO' BUS
      ISC(KQ)=ISC(KQ)+1
      IF(JP1R.NE.0)GO TO 10
      JP1R=I
      GO TO 19
   10 JP=JP1R
   11 JQ=KP1(JP)
      IF(JQ.EQ.0)GO TO 12
      JP=JQ
      GO TO 11
   12 KP1(JP)=I
      GO TO 19
   13 JP=JP1(KP)
      IF(JP.NE.0)GO TO 11
      JP1(KP)=I
   19 IF(KQ.NE.0)GO TO 23
      ISC(KP)=ISC(KP)+1
      IF(JP2R.NE.0)GO TO 20
      JP2R=I
      GO TO 29
   20 JP=JP2R
   21 JQ=KP2(JP)
      IF(JQ.EQ.0)GO TO 22
      JP=JQ
      GO TO 21
   22 KP2(JP)=I
      GO TO 29
   23 JP=JP2(KQ)
      IF(JP.NE.0)GO TO 21
      JP2(KQ)=I
   29 CONTINUE
C---     CREATE THE ORDERED LISTS
      ML=0
      MB=0
      MS=0
   30 ISCH=0
      DO 33 I=1,NBS
      IF(ISC(I)-ISCH)33,31,32
   31 IF(ISCH.EQ.0)GO TO 33
      IF(NLB(N).GE.NLB(I))GO TO 33
   32 N=I
      ISCH=ISC(I)
   33 CONTINUE
C---     ADD BUS N TO ORDERED BUS LIST
      IF(ISCH.EQ.0)GO TO 70
      ISCH=ISCH-1
      MB=MB+1
      MS=MS+ISCH*((MB*(MB+3))/2)
      IBO(MB)=N
      ISC(N)=-9999
C---     CHECK FOR LINES CONNECTED TO BUS N
      JP=JP1(N)
   51 IF(JP.EQ.0)GO TO 55
      KQ=IQ(JP)
      IF(KQ.EQ.0)GO TO 52
```

```
      IF(ISC(KQ).LT.0)GO TO 52
      ISC(KQ)=ISC(KQ)+1
      GO TO 53
   52 ML=ML+1
      ILO(ML)=JP
   53 JP=KP1(JP)
      GO TO 51
   55 JP=JP2(N)
   56 IF(JP.EQ.0)GO TO 60
      KP=IP(JP)
      IF(KP.EQ.0)GO TO 57
      IF(ISC(KP).LT.0)GO TO 57
      ISC(KP)=ISC(KP)+1
      GO TO 58
   57 ML=ML+1
      ILO(ML)=JP
   58 JP=KP2(JP)
      GO TO 56
   60 IF(ML.LT.NEL)GO TO 30
      RETURN 1
C---     ORDERED LISTS ARE COMPLETE IOB, IOL
   70 WRITE(IWT,1000)
      RETURN 2
 1000 FORMAT('0*** SYSTEM IS NOT CONNECTED TOGETHER')
      END
      SUBROUTINE ZBUS(IP,IQ,R,X,ILO,IBO,IBOR,RBUS,XBUS,RL,XL,NBE,*,*)
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,MBUS,IW,IDSN
      COMMON /K1/IRD,IWT,IW,IDSN
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      DIMENSION IP(NEL),IQ(NEL),R(NEL),X(NEL),ILO(NEL)
      DIMENSION IBO(NBS),IBOR(NBS),NBE(NBS),RL(NBS),XL(NBS)
      DIMENSION RBUS(MBUS),XBUS(MBUS)
C---     RBUS=REAL PART OF ZBUS
C---     XBUS=IMAGINARY PART OF ZBUS
C---     IBOR=BUS ORDER LIST WITH INDEX AS INTERNAL BUS NUMBER
C---     RL, XL=LINK IMPEDANCES
      MB=0
      DO 1 I=1,NBS
      J=IBO(I)
    1 IBOR(J)=I
C---     READY TO START THE ALGORITHM
      DO 40 I=1,NEL
      II=ILO(I)
      IPP=IP(II)
      IF(IPP.EQ.0)GO TO 2
      IPP=IBOR(IPP)
    2 IQQ=IQ(II)
      IF(IQQ.EQ.0)GO TO 3
      IQQ=IBOR(IQQ)
    3 IF(IPP.LT.IQQ)GO TO 6
      IT=IQQ
      IQQ=IPP
      IPP=IT
C---     TEST FOR BRANCH OR A LINK
    6 IF(IQQ.LE.MB)GO TO 15
      JJ=(MB*(MB+1))/2
C---     FOUND A BRANCH, TEST FOR REFERENCE
      IF(IPP.NE.0)GO TO 9
C---     BRANCH TO REFERENCE
      IF(MB.GT.0)GO TO 7
      RBUS(1)=R(II)
      XBUS(1)=X(II)
      MB=1
```

```
      GO TO 40
    7 DO 8 J=1,MB
      JJJ=JJ+J
      RBUS(JJJ)=0.0
    8 XBUS(JJJ)=0.0
      JJJ=JJJ+1
      RBUS(JJJ)=R(II)
      XBUS(JJJ)=X(II)
      MB=MB+1
      GO TO 40
C---      BRANCH TO AN OLD BUS
    9 DO 12 J=1,MB
      JJJ=JJ+J
      IF(IPP.LT.J)GO TO 10
      KK=J+(IPP*(IPP-1))/2
      GO TO 11
   10 KK=IPP+(J*(J-1))/2
   11 RBUS(JJJ)=RBUS(KK)
   12 XBUS(JJJ)=XBUS(KK)
      JJJ=JJJ+1
      KK=JJ+IPP
      RBUS(JJJ)=RBUS(KK)+R(II)
      XBUS(JJJ)=XBUS(KK)+X(II)
      MB=MB+1
      GO TO 40
C---      FOUND A LINK,TEST FOR REFERENCE
   15 IF(IPP.NE.0)GO TO 20
C---      LINK TO REFERENCE
      DO 18 J=1,MB
      IF(IQQ.LT.J)GO TO 16
      KK=J+(IQQ*(IQQ-1))/2
      GO TO 17
   16 KK=IQQ+(J*(J-1))/2
   17 RL(J)=-RBUS(KK)
   18 XL(J)=-XBUS(KK)
      RLL=-RL(IQQ)+R(II)
      XLL=-XL(IQQ)+X(II)
      GO TO 30
C---      LINK BETWEEN OLD BUSES
   20 DO 25 J=1,MB
      IF(IPP.LT.J)GO TO 21
      JJ=J+(IPP*(IPP-1))/2
      GO TO 22
   21 JJ=IPP+(J*(J-1))/2
   22 IF(IQQ.LT.J)GO TO 23
      KK=J+(IQQ*(IQQ-1))/2
      GO TO 24
   23 KK=IQQ+(J*(J-1))/2
   24 RL(J)=RBUS(JJ)-RBUS(KK)
   25 XL(J)=XBUS(JJ)-XBUS(KK)
      RLL=RL(IPP)-RL(IQQ)+R(II)
      XLL=XL(IPP)-XL(IQQ)+X(II)
C---      KRON REDUCTION
   30 ZLL=RLL*RLL+XLL*XLL
      IF(ZLL.LT.1.E-50)GO TO 50
      DO 32 J=1,MB
      JJ=(J*(J-1))/2
      RLJ=(RLL*RL(J)+XLL*XL(J))/ZLL
      XLJ=(RLL*XL(J)-XLL*RL(J))/ZLL
      DO 31 K=1,J
      KJ=JJ+K
      RBUS(KJ)=RBUS(KJ)-RLJ*RL(K)+XLJ*XL(K)
   31 XBUS(KJ)=XBUS(KJ)-RLJ*XL(K)-XLJ*RL(K)
   32 CONTINUE
   40 CONTINUE
      RETURN 1
```

```
   50 IPP=IP(II)
      I=NBE(IPP)
      IQQ=IQ(II)
      J=NBE(IQQ)
      WRITE(IWT,1000)II,I,J
      RETURN 2
 1000 FORMAT('0*** LINE NUMBER ',I4,' BETWEEN BUSES ',I4,' AND ',I4,' CA
     1USED A ZLL**2 DIVISOR IN THE KRON REDUCTION OF ',E12.5)
      END
      SUBROUTINE HARMI(IP,IQ,ICT,R,X,KP1,KP2,NB,NBE,JP1,JP2,IBOR,RBUS,
     1XBUS,VR,VI,ILIN,ZO,VMSQ,VVM1,GAML,*,*)
C---     READ HARMONIC SOURCE LOCATION AND OPTIONS, PERFORM HARMONIC
C---          LOADFLOW, PRINT RESULTS
C---     CALLED FROM HARMONIC LOADFLOW MAIN PROGRAM ONCE FOR EACH
C---          HARMONIC ORDER TO BE ANALYZED
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 IRD,IWT,NEX,NEL,NBH,NBS,NBX,MS,MBUS,IW,IDSN,FLAG
      REAL*8 NAME,EE2,EE5,EE8,EE11,EE15,EE18,RSH,XSH,RSE,XSE
      COMPLEX*8 CMPLX,SOURCE,FUND,ZO,GAML,DZ,DD,ZR,KR,IR
      COMPLEX*8 IRPLUS,IRMIN,IMAX,VCK,VCL
      COMMON /K1/IRD,IWT,IW,IDSN
      COMMON /KL/NEX,NEL
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      COMMON /CDC/SOURCE,VCK,LHARM,JJJ,IVC
      COMMON /BASE/LLL,JJJJ,IOPT
      DIMENSION IP(NEL),IQ(NEL),ICT(NEL),R(NEL),X(NEL),KP1(NEL),KP2(NEL)
      DIMENSION RBUS(MBUS),XBUS(MBUS),SOURCE(128,4),ILIN(NEL)
      DIMENSION IBOR(NBS),NBE(NBS),NB(NBH),JP1(NBS),JP2(NBS)
      DIMENSION VR(NBS),VI(NBS),ZO(NEL),GAML(NEL)
      DIMENSION SVR(9998),SVI(9998),VMSQ(9998),VVM1(9998)
C---     JJJ=COUNTER FOR NUMBER OF OPTIONS
      JJJ=0
C---     FIRST TIME CALLED?
    1 IF(LLL.GT.1)GO TO 700
      IF(JJJ.GT.0)GO TO 3
      DO 2 I=1,NBH
      VMSQ(I)=0.
      VVM1(I)=0.
    2 CONTINUE
    3 READ(IRD,1000,END=99)JF,NAME,IOPT,PHA,FUND
C---     JF=HARMONIC SOURCE BUS # LOCATION (SET TO 9999 FOR END)
C---     NAME=BUS NAME
C---     IOPT=OPTION
C---        0=ADJACENT BUSES ONLY
C---        1=ALL BUSES
C---        2=FIRST ENTRY FOR COMBINED ANALYSIS OF TWO HARMONIC SOURCES
C---        3=SEC ENTRY FOR COMBINED ANALYSIS OF TWO HARMONIC SOURCES
C---     PHA=PHASE ANGLE BETWEEN VOLTAGES FOR HARM SOURCES 2 & 3
C---     FUND=FUNDAMENTAL COMPONENT OF HARMONIC SOURCE CURRENT (COMPLEX)
C---     OPTION 2 OR 3?
      IF(IOPT.GT.1)GO TO 800
      IF(JJJ.NE.0)GO TO 701
C---     EE1-EE13=TEMPORARY STORAGE LOCATIONS FOR INPUT DATA
      EE1=JF
      EE2=NAME
      EE3=IOPT
      SOURCE(2,1)=FUND
      GO TO 705
  701 IF(JJJ.NE.1)GO TO 702
      EE4=JF
      EE5=NAME
      EE6=IOPT
      SOURCE(2,2)=FUND
      GO TO 705
  702 IF(JJJ.NE.2)GO TO 703
```

```
      EE7=JF
      EE8=NAME
      EE9=IOPT
      SOURCE(2,3)=FUND
      GO TO 705
  703 IF(JJJ.NE.3)GO TO 704
      EE10=JF
      EE11=NAME
      EE12=IOPT
      SOURCE(2,4)=FUND
      GO TO 705
  704 EE13=JF
      GO TO 705
C---      JJJJ=COMBINED ANALYSIS CODE
C---          1=COMBINED ANALYSIS (OPTION 2,3)
  700 IF(JJJJ.EQ.1)GO TO 802
      IF(JJJ.NE.0)GO TO 708
C---      RECOVER INPUT DATA
      JF=EE1
      NAME=EE2
      IOPT=EE3
      GO TO 705
  708 IF(JJJ.NE.1)GO TO 709
      JF=EE4
      NAME=EE5
      IOPT=EE6
      GO TO 705
  709 IF(JJJ.NE.2)GO TO 710
      JF=EE7
      NAME=EE8
      IOPT=EE9
      GO TO 705
  710 IF(JJJ.NE.3)GO TO 711
      JF=EE10
      NAME=EE11
      IOPT=EE12
      GO TO 705
  711 JF=EE13
C---      END OF ANALYSIS?
  705 IF(JF.EQ.9999)RETURN 1                                          C D E F
      JJJ=JJJ+1
C---      TOO MANY OPTIONS?
      IF(JJJ.GT.4)GO TO 706
      GO TO 707
  706 WRITE(IWT,1009)
      EE13=9999                                                       C D E F
      RETURN 1
C---      HARMONIC SOURCE BUS EXISTS?
  707 IF(JF.LE.0.OR.JF.GT.NBH)GO TO 90
C---      KF=INTERNAL BUS # LOCATION OF HARMONIC SOURCE
      KF=NB(JF)
C---      HARMONIC SOURCE BUS EXISTS?
      IF(KF.EQ.0)GO TO 90
C---      LF=BUS ORDER NUMBER FOR HARMONIC SOURCE
      LF=IBOR(KF)
C---      LL=INDEX TO HARMONIC SOURCE BUS IMPEDANCE (DIAGONAL ELEMENT
C---          OF A LOWER TRIAGULARIZED MATRIX)
      LL=(LF*(LF+1))/2
C---      RX,XX=HARMONIC SOURCE BUS RESISTANCE AND REACTANCE
      RX=RBUS(LL)
      XX=XBUS(LL)
C---      ZX=SQUARE OF HARMONIC SOURCE BUS IMPEDANCE MAGNITUDE
      ZX=RX*RX+XX*XX
C---      CONVERT PHASE FROM DEGREES TO RADIANS
      PHA=PHA/57.29577951
      VCL=VCK*CMPLX(COS(PHA),SIN(PHA))
```

```
      IF(IVC.EQ.0) GO TO 620
      CR=REAL(VCL)
      CI=AIMAG(VCL)
      VRK=CR*RX-CI*XX
      VIK=CR*XX+CI*RX
      SOURCE(IW+1,JJJ)=CMPLX(VRK,VIK)
      GO TO 621
C---     VRK=REAL COMPONENT OF HARMONIC SOURCE VOLTAGE
  620 VRK=REAL(VCL)
C---     VIK=IMAGINARY COMPONENT OF HARMONIC SOURCE VOLTAGE
      VIK=AIMAG(VCL)
C---     CR=REAL COMPONENT OF HARMONIC SOURCE CURRENT
      CR=(VRK*RX+VIK*XX)/ZX
C---     CI=IMAGINARY COMPONENT OF HARMONIC SOURCE CURRENT
      CI=(VIK*RX-VRK*XX)/ZX
      SOURCE(IW+1,JJJ)=CMPLX(CR,CI)
  621 CALL MAGANG(CR,CI,CM,CA)
C---     CM=HARMONIC SOURCE CURRENT MAGNITUDE
C---     CA=HARMONIC SOURCE CURRENT ANGLE
      CALL MAGANG(VRK,VIK,VKM,VKA)
C---     VKM=HARMONIC SOURCE VOLTAGE MAGNITUDE
C---     VKA=HARMONIC SOURCE VOLTAGE ANGLE
C---     PRINT HARMONIC SOURCE SUMMARY
      WRITE(IWT,1001)JF,NAME,IOPT,PHA,FUND,CM,CA,VKM,VKA
      IF(IW.GT.LHARM) GO TO 1
      IF(IOPT.EQ.2)GO TO 804
      IF(IOPT.EQ.3)GO TO 805
      IF(IOPT.GT.0)GO TO 30
C---     CALCULATIONS FOR ADJACENT BUSES ONLY
C---     PRINT HEADING FOR ADJACENT BUS LOADFLOW SUMMARY
      WRITE(IWT,1002)
C---     J='FROM' BUS OR 'TO' BUS FLAG
      J=1
C---     JP=# OF FIRST ELEMENT CONNECTED 'FROM' HARMONIC SOURCE BUS       C
      JP=JP1(KF)                                                         C
C---     ELEMENT EXISTS?                                                 C
      IF(JP.EQ.0)GO TO 16
C---     KP=ADJACENT INTERNAL BUS #
    9 KP=IQ(JP)
C---     SHUNT ELEMENT?                                                  C
   10 IF(KP.NE.0)GO TO 11
      VRR=-VRK
      VII=-VIK
      N=0
      GO TO 15
   11 CALL VBUS(KP,KP,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
C---     VR(KP)=REAL COMPONENT OF 'TO' BUS VOLTAGE
C---     VI(KP)=IMAGINARY COMPONENT OF 'TO' BUS VOLTAGE
      CALL MAGANG(VR(KP),VI(KP),VMM,VAA)
C---     VMM='TO' BUS VOLTAGE MAGNITUDE
C---     VAA='TO' BUS VOLTAGE ANGLE
C---     VRR=REAL COMPONENT OF VOLTAGE DROP
      VRR=VR(KP)-VRK
C---     VII=IMAGINARY COMPONENT OF VOLTAGE DROP
      VII=VI(KP)-VIK
C---     N=ADJACENT EXTERNAL BUS #
      N=NBE(KP)
C---     RX,XX=ELEMENT RESISTANCE AND REACTANCE                          C
   15 RX=R(JP)
      XX=X(JP)
C---     ZX=SQUARE OF ELEMENT IMPEDANCE MAGNITUDE                        C
      ZX=RX*RX+XX*XX
C---     CRL=REAL COMPONENT OF ELEMENT CURRENT                           C
      CRL=(VII*XX+VRR*RX)/ZX
C---     CIL=IMAGINARY COMPONENT OF ELEMENT CURRENT                      C
      CIL=(VII*RX-VRR*XX)/ZX
```

```
      IF(ILIN(JP).EQ.0) GO TO 14
      DZ=ZO(JP)
      DD=GAML(JP)
      IF(J.EQ.2) GO TO 12
      JP=KP1(JP)
      GO TO 13
   12 JP=KP2(JP)
   13 RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      CRL=CRL-(VIK*XX+VRK*RX)/ZX
      CIL=CIL-(VIK*RX-VRK*XX)/ZX
      CM1=CRL*CRL+CIL*CIL
      IF(CM1.LT.1.E-8) GO TO 631
      RX=(VRK*CRL+VIK*CIL)/CM1
      XX=(VIK*CRL-VRK*CIL)/CM1
      ZR=CMPLX(RX,XX)
  631 RX=REAL(DZ)
      XX=AIMAG(DZ)
      CALL MAGANG(CRL,CIL,CMM,CAA)
      WRITE(IWT,1003) N,VMM,VAA,ICT(JP),CMM,CAA,RX,XX
      IF(CM1.LT.1.E-8) GO TO 604
      KR=(ZR-DZ)/(ZR+DZ)
      IR=-CMPLX(CRL,CIL)
      IRPLUS=IR/(1.-KR)
      IRMIN=KR*IR/(KR-1.)
      BL=AIMAG(DD)
      WAVE=6.2831853/BL
      IF (BL .EQ. 0.) CALL SDUMP
      NLAM=0
  603 XOL=(ANGLE(IRMIN)-ANGLE(IRPLUS))/(2.*BL)+NLAM*WAVE/2.
      IF(XOL.GE.1.) GO TO 604
      IF(XOL.LE.0.) GO TO 605
C     IMAX=(IR/(2.*DZ))*((ZR+DZ)*CEXP(DD*XOL)+(DZ-ZR)*CEXP(-DD*XOL))
C     CMAXM=CABS(IMAX)
C     CMAXA=ANGLE(IMAX)*57.29577951
C     WRITE(IWT,1011) CMAXM,CMAXA,XOL,WAVE
  605 NLAM=NLAM+1
      GO TO 603
   14 CALL MAGANG(CRL,CIL,CMM,CAA)
C---     CMM=ELEMENT CURRENT MAGNITUDE
C---     CAA=ELEMENT CURRENT ANGLE
C---     SERIES OR SHUNT ELEMENT?
      IF(N.NE.0)GO TO 900
      VMM=0.0
      VAA=0.0
C---     PRINT SUMMARY FOR ELEMENT
  900 WRITE(IWT,1003)N,VMM,VAA,ICT(JP),CMM,CAA,RX,XX
C---     'FROM' BUS OR 'TO' BUS?
  604 IF(J.EQ.2)GO TO 18
C---     JP=# OF NEXT ELEMENT CONNECTED 'FROM' HARMONIC SOURCE BUS
      JP=KP1(JP)
C---     ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 9
C---     COMPLETED SUMMARY OF ALL ELEMENTS CONNECTED 'FROM' HARMONIC
C---        SOURCE BUS
   16 J=2
C---     JP=# OF FIRST ELEMENT CONNECTED 'TO' HARMONIC SOURCE BUS
      JP=JP2(KF)
C---     ELEMENT EXISTS?
      IF(JP.EQ.0)GO TO 1
C---     KP=ADJACENT INTERNAL BUS #
   17 KP=IP(JP)
      GO TO 10
C---     JP=# OF NEXT ELEMENT CONNECTED 'TO' HARMONIC SOURCE BUS
   18 JP=KP2(JP)
```

```
C---      ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 17
      GO TO 1
C---      CALCULATIONS FOR ALL BUSES
C---      CALCULATIONS FOR BUS VOLTAGES
   30 NBDUM=NBS
      JDUM=1
      CALL VBUS(JDUM,NBDUM,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
C---      VR=REAL COMPONENT OF BUS VOLTAGE
C---      VI=IMAGINARY COMPONENT OF BUS VOLTAGE
C---      PRINT HEADING FOR ALL BUS LOADFLOW SUMMARY
      WRITE(IWT,1004)
      DO 50 J=1,NBH
C---      J=EXTERNAL BUS #
C---      KP=INTERNAL BUS #
      KP=NB(J)
C---      BUS EXISTS?
      IF(KP.EQ.0)GO TO 50
      CALL MAGANG(VR(KP),VI(KP),VVM,VVA)
C---      VVM=BUS VOLTAGE MAGNITUDE
C---      VVA=BUS VOLTAGE ANGLE
C---      PRINT BUS VOLTAGE SUMMARY
      WRITE(IWT,1005)J,VVM,VVA
      IF(IW.EQ.1) GO TO 20
      VMSQ(J)=VMSQ(J)+VVM*VVM
      GO TO 25
   20 VVM1(J)=VVM1(J)+VVM
   25 CONTINUE
C     WRITE(IWT,1012)J,VMSQ(J),VVM1(J)
C---      K='FROM' BUS OR 'TO' BUS FLAG
      K=1
C---      JP=# OF FIRST ELEMENT CONNECTED 'FROM' THE BUS
      JP=JP1(KP)
C---      ELEMENT EXISTS?
      IF(JP.EQ.0)GO TO 39
C---      KQ=INTERNAL 'TO' BUS #
   35 KQ=IQ(JP)
   36 RSH=0.0
      XSH=0.0
      RSE=0.0
      XSE=0.0
C---      SHUNT ELEMENT?
      IF(KQ.NE.0)GO TO 37
      VRR=0.0
      VII=0.0
      N=0
      FLAG=0
      GO TO 38
C---      VRR=REAL COMPONENT OF ADJACENT BUS VOLTAGE
   37 FLAG=1
      VRR=VR(KQ)
C---      VII=IMAGINARY COMPONENT OF ADJACENT BUS VOLTAGE
      VII=VI(KQ)
C---      N=ADJACENT EXTERNAL BUS #
      N=NBE(KQ)
C---      VRR=REAL COMPONENT OF VOLTAGE DROP
   38 VRR=VR(KP)-VRR
C---      VII=IMAGINARY COMPONENT OF VOLTAGE DROP
      VII=VI(KP)-VII
C-----------------------------------------------------------------
      IF (FLAG.GT.0) GO TO 26
C-------RSH,XSH ARE SHUNT ELEMENT RESISTANCE AND REACTANCE
      RSH=R(JP)
      XSH=X(JP)
      GO TO 27
C-------RSE,XSE ARE SERIES ELEMENT RESISTANCE AND REACTANCE
```

```
   26 RSE=R(JP)
      XSE=X(JP)
C----------------------------------------------------------------------
C---     RX,XX=ELEMENT RESISTANCE AND REACTANCE
   27 RX=R(JP)
      XX=X(JP)
C---     ZX=SQUARE OF ELEMENT IMPEDANCE MAGNITUDE
      ZX=RX*RX+XX*XX
C---     CRL=REAL COMPONENT OF ELEMENT CURRENT
      CRL=(VII*XX+VRR*RX)/ZX
C---     CIL=IMAGINARY COMPONENT OF ELEMENT CURRENT
      CIL=(VII*RX-VRR*XX)/ZX
      IF(ILIN(JP).EQ.0) GO TO 42
      DZ=ZO(JP)
      DD=GAML(JP)
      IF(K.EQ.2) GO TO 31
      JP=KP1(JP)
      GO TO 32
   31 JP=KP2(JP)
   32 RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      RSH=R(JP)
      XSH=X(JP)
      CRL=CRL+(VI(KP)*XX+VR(KP)*RX)/ZX
      CIL=CIL+(VI(KP)*RX-VR(KP)*XX)/ZX
      CM2=CRL*CRL+CIL*CIL
      IF(CM2.LT.1.E-8)GO TO 630
      RX=(VR(KP)*CRL+VI(KP)*CIL)/CM2
      XX=(VI(KP)*CRL-VR(KP)*CIL)/CM2
      ZR=-CMPLX(RX,XX)
  630 RX=REAL(DZ)
      XX=AIMAG(DZ)
      CALL MAGANG(CRL,CIL,CCM,CCA)
      WRITE(IWT,1006) N,ICT(JP),CCM,CCA,RSH,XSH,RSE,XSE
      IF(CM2.LT.1.E-8)GO TO 601
      KR=(ZR-DZ)/(ZR+DZ)
      IR=-CMPLX(CRL,CIL)
      IRPLUS=IR/(1.-KR)
      IRMIN=KR*IR/(KR-1.)
      BL=AIMAG(DD)
      WAVE=6.2831853/BL
      NLAM=0
  600 XOL=(ANGLE(IRMIN)-ANGLE(IRPLUS))/(2.*BL)+NLAM*WAVE/2.
      IF(XOL.GE.1.) GO TO 601
      IF(XOL.LE.0.) GO TO 602
C     IMAX=(IR/(2.*DZ))*((ZR+DZ)*CEXP(DD*XOL)+(DZ-ZR)*CEXP(-DD*XOL))
C     CMAXM=CABS(IMAX)
C     CMAXA=ANGLE(IMAX)*57.29577951
C     WRITE(IWT,1010) CMAXM,CMAXA,XOL,WAVE
  602 NLAM=NLAM+1
      GO TO 600
   42 CALL MAGANG(CRL,CIL,CCM,CCA)
C---     CCM=ELEMENT CURRENT MAGNITUDE
C---     CCA=ELEMENT CURRENT ANGLE
C---     PRINT SUMMARY FOR ELEMENT
      WRITE(IWT,1006)N,ICT(JP),CCM,CCA,RSH,XSH,RSE,XSE
C---     'FROM' BUS OR 'TO' BUS?
  601 IF(K.EQ.2)GO TO 41
C---     JP=# OF NEXT ELEMENT CONNECTED 'FROM' THE BUS
      JP=KP1(JP)
C---     ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 35
C---     COMPLETED SUMMARY OF ALL ELEMENTS CONNECTED 'FROM' THE BUS
   39 K=2
C---     JP=# OF FIRST ELEMENT CONNECTED 'TO' THE BUS
```

```
      JP=JP2(KP)
C---      ELEMENT EXISTS?
      IF(JP.EQ.0)GO TO 50
C---      KQ=ADJACENT INTERNAL 'FROM' BUS #
   40 KQ=IP(JP)
      GO TO 36
C---      JP=# OF NEXT ELEMENT CONNECTED 'TO' THE BUS
   41 JP=KP2(JP)
C---      ELEMENT EXISTS?
      IF(JP.NE.0)GO TO 40
   50 CONTINUE
      GO TO 1
C---      CALCULATIONS FOR COMBINED CONVERTER ACTION
C---      CONVERTER VOLTAGES AND CURRENTS
  800 JJJJ=1
C---      FIRST OPTION?
      IF(JJJ.NE.0)GO TO 801
C---      EE14-EE20=TEMPORARY STORAGE LOCATIONS FOR INPUT DATA
      EE14=JF
      EE15=NAME
      EE16=IOPT
      SOURCE(2,1)=FUND
      JJJ=JJJ+1
      GO TO 1
  801 EE17=JF
      EE18=NAME
      EE19=IOPT
      EE20=PHA
      SOURCE(2,2)=FUND
      JJJ=0
  802 JF=EE14
      NAME=EE15
      IOPT=EE16
      PHA=0.0
      GO TO 705
  804 LF1=LF
      CR1=CR
      CI1=CI
      JF=EE17
      NAME=EE18
      IOPT=EE19
      PHA=EE20
      GO TO 705
C---      BUS VOLTAGES AND CURRENTS
  805 NBDUM=NBS
      JDUM=1
      CALL VBUS(JDUM,NBDUM,IBOR,LF1,SVR,SVI,CR1,CI1,RBUS,XBUS)
      CALL VBUS(JDUM,NBDUM,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
  821 WRITE(IWT,1004)
C---      COMBINED HARMONIC SOURCE ANALYSIS USES SIMILAR PROCEDURE
C---           TO SINGLE HARMONIC SOURCE
      DO 850 J=1,NBH
      KP=NB(J)
      IF(KP.EQ.0)GO TO 850
      TVR=VR(KP)+SVR(KP)
      TVI=VI(KP)+SVI(KP)
      CALL MAGANG(TVR,TVI,VVM,VVA)
      WRITE(IWT,1005)J,VVM,VVA
      K=1
      JP=JP1(KP)
      IF(JP.EQ.0)GO TO 839
  835 KQ=IQ(JP)
  836 IF(KQ.NE.0)GO TO 837
      VRR=0.0
      VII=0.0
      N=0
```

```
      GO TO 838
  837 VRR=VR(KQ)+SVR(KQ)
      VII=VI(KQ)+SVI(KQ)
      N=NBE(KQ)
  838 VRR=TVR-VRR
      VII=TVI-VII
      RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      CRL=(VII*XX+VRR*RX)/ZX
      CIL=(VII*RX-VRR*XX)/ZX
      IF(ILIN(JP).EQ.0) GO TO 831
      DZ=ZO(JP)
      DD=GAML(JP)
      IF(K.EQ.2) GO TO 832
      JP=KP1(JP)
      GO TO 833
  832 JP=KP2(JP)
  833 RX=R(JP)
      XX=X(JP)
      ZX=RX*RX+XX*XX
      CRL=CRL+(TVI*XX+TVR*RX)/ZX
      CIL=CIL+(TVI*RX-TVR*XX)/ZX
      CM2=CRL*CRL+CIL*CIL
      IF(CM2.LT.1.E-8) GO TO 632
      RX=(TVR*CRL+TVI*CIL)/CM2
      XX=(TVI*CRL-TVR*CIL)/CM2
      ZR=-CMPLX(RX,XX)
  632 RX=REAL(DZ)
      XX=AIMAG(DZ)
      CALL MAGANG(CRL,CIL,CCM,CCA)
      WRITE(IWT,1006) N,ICT(JP),CCM,CCA,RX,XX
      IF(CM2.LT.1.E-8) GO TO 607
      KR=(ZR-DZ)/(ZR+DZ)
      IR=-CMPLX(CRL,CIL)
      IRPLUS=IR/(1.-KR)
      IRMIN=KR*IR/(KR-1.)
      BL=AIMAG(DD)
      WAVE=6.2831853/BL
      NLAM=0
  606 XOL=(ANGLE(IRMIN)-ANGLE(IRPLUS))/(2.*BL)+NLAM*WAVE/2.
      IF(XOL.GE.1.) GO TO 607
      IF(XOL.LE.0.) GO TO 608
C     IMAX=(IR/(2.*DZ))*((ZR+DZ)*CEXP(DD*XOL)+(DZ-ZR)*CEXP(-DD*XOL))
C     CMAXM=CABS(IMAX)
C     CMAXA=ANGLE(IMAX)*57.29577951
C     WRITE(IWT,1010) CMAXM,CMAXA,XOL,WAVE
  608 NLAM=NLAM+1
      GO TO 606
  831 CALL MAGANG(CRL,CIL,CCM,CCA)
      WRITE(IWT,1006)N,ICT(JP),CCM,CCA,RX,XX
  607 IF(K.EQ.2)GO TO 841
      JP=KP1(JP)
      IF(JP.NE.0)GO TO 835
  839 K=2
      JP=JP2(KP)
      IF(JP.EQ.0)GO TO 850
  840 KQ=IP(JP)
      GO TO 836
  841 JP=KP2(JP)
      IF(JP.NE.0)GO TO 840
  850 CONTINUE
      RETURN 1
   90 WRITE(IWT,1007)JF
      GO TO 1
   99 WRITE(IWT,1008)
```

```
      RETURN 2
 1000 FORMAT(I4,A7,I1,3F10.2)
 1001 FORMAT('0*** CONVERTER AT BUS ',I4,3X,A7,3X,'***',5X,'IOPT = ',
     1 I2,5X,'PHA = ',F10.2,'FUND = ',2F10.2/'0HARMONIC CURRENT = ',
     2 F10.4,' MAG   ',F10.2,' ANG ',10X,'   HARMONIC VOLTAGE = ',
     3 F10.4,' MAG   ',F10.2,' ANG ')
 1002 FORMAT('0',11X,'ADJACENT    ADJACENT BUS VOLTAGE      CIRCUIT   CUR
     1RENT TOWARD CONVERTER',6X,'LINE IMPEDANCE'/14X,'BUS',9X,'MAG ',8X,
     2'ANG ',7X,'NUMBER',7X,'MAG ',8X,'ANG ',12X,'R',12X,'X')
C    3'------------------------  ---------------------'/63X,
C    4'MAX CURRENT FLOW',6X,'LOCATION    WAVELENGTH')
 1003 FORMAT(12X,I4,5X,F10.4,1X,F10.2,7X,I2,6X,F10.4,1X,F10.2,5X,F10.4,3
     1X,F10.4)
 1004 FORMAT('0',8X,'FROM',9X,'BUS VOLTAGE',11X,'TO',5X,'CIRCUIT',5X,
     1'TERM CURRENT FLOW',12X,'SHUNT ELEMENT',3X,'SERIES ELEMENT'/8X,
     2'BUS',7X,'MAG',8X,'ANG ',9X,'BUS    NUMBER',7X,'MAG ',8X,
     3'ANG ',12X,'R',12X,'X',12X,'R',12X,'X')
C    365X,'-----------------',8X,'---------------------'/66X,
C    4'MAX CURRENT FLOW',8X,'LOCATION    WAVELENGTH')
 1005 FORMAT('0',9X,I4,3X,F10.4,1X,F10.2)
 1006 FORMAT(42X,I4,5X,I2,6X,F10.4,1X,F10.2,2(2X,F11.2),2(2X,F11.6))
 1007 FORMAT('0*** CONVERTER BUS ',I5,' IS NOT IN THE SYSTEM'/)
 1008 FORMAT('0*** UNEXPECTED END OF CONVERTER BUS DATA')
 1009 FORMAT('0***ONLY FOUR CONVERTER OPTIONS CAN BE USED FOR ONE ZBUS')
C1010 FORMAT(62X,F10.4,1X,F10.2,5X,F10.4,3X,F10.2)
C1011 FORMAT(57X,F10.4,1X,F10.2,5X,F10.4,3X,F10.2)
C1012 FORMAT(1X,'VBUS J,VMSQ(J),VVM1(J)',I4,5X,E17.4,5X,E17.4)
      END
      SUBROUTINE VBUS(J1,J2,IBOR,LF,VR,VI,CR,CI,RBUS,XBUS)
C---     CALCULATE HARMONIC BUS VOLTAGES
C---     CALLED FROM HARMI
      IMPLICIT INTEGER*4(I-N)
      INTEGER*4 NBH,NBS,NBX,MS,MBUS
      COMMON /KB/NBH,NBS,NBX,MS,NLR
      COMMON /KZ/MBUS
      DIMENSION IBOR(NBS),VR(NBS),VI(NBS),RBUS(MBUS),XBUS(MBUS)
      DO 30 J=J1,J2
C---     J=INTERNAL BUS #'S
C---     I=BUS ORDER NUMBER
      I=IBOR(J)
      IF(I.LT.LF) GO TO 10
C---     LL=INDEX TO IMPEDANCE BETWEEN BUSES
      LL=LF+(I*(I-1))/2
      GO TO 20
   10 LL=I+(LF*(LF-1))/2
C---     VR=REAL COMPONENT OF BUS VOLTAGE
   20 VR(J)=CR*RBUS(LL)-CI*XBUS(LL)
C---     VI=IMAGINARY COMPONENT OF BUS VOLTAGE
      VI(J)=CR*XBUS(LL)+CI*RBUS(LL)
   30 CONTINUE
      RETURN
      END
      SUBROUTINE MAGANG(REAL,AIMAG,AMAG,ANG)
C---     CALCULATE MAGNITUDE & ANGLE FROM REAL & IMAG COMPONENTS
C---     CALLED FROM HARMI
      AMAG2=REAL*REAL+AIMAG*AIMAG
      AMAG=SQRT(AMAG2)
      ANG=0.
      IF(REAL.EQ.0..AND.AIMAG.EQ.0.) GO TO 10
      ANG=ATAN2(AIMAG,REAL)
   10 ANG=ANG*57.29577951
      RETURN
      END
      FUNCTION ANGLE(COMPLX)
      COMPLEX*8 COMPLX
      A=REAL(COMPLX)
```

```
      B=AIMAG(COMPLX)
      ANGLE=0.
      IF(A.EQ.0..AND.B.EQ.0.) GO TO 10
      ANGLE=ATAN2(B,A)
   10 RETURN
      END
      SUBROUTINE FFTCC
      WRITE(6,1000)
 1000 FORMAT(1H-,132(1H*)/62H0THIS IS A DUMMY FFTCC ROUTINE TO SATISFY E
     1XTERNAL REFERENCES./1H0,132(1H*)/1H0)
      RETURN
      END
      SUBROUTINE GRAPH
      WRITE(6,1000)
 1000 FORMAT(1H-,132(1H*)/62H0THIS IS A DUMMY GRAPH ROUTINE TO SATISFY E
     1XTERNAL REFERENCES./1H0,132(1H*)/1H0)
      RETURN
      END
```

XII. APPENDIX

E. TI-59 PROGRAM LISTINGS

TI-59 PROGRAM LISTING
CALCULATES NEW IMPEDANCE VALUE

Where:

Button A is pressed to enter the old impedance value

Button B is pressed to enter the old voltage base

Button C is pressed to enter the old voltampere base

Button B' is pressed to enter the new voltage base

Button C' is pressed to enter the new voltampere base

and then:

Button E is pressed to calculate the new impedance

```
000  76 LBL
001  11  A
002  42 STO
003  00  00
004  91 R/S
005  76 LBL
006  12  B
007  42 STO
008  01  01
009  91 R/S
010  76 LBL
011  17 B'
012  42 STO
013  02  02
014  91 R/S
015  76 LBL
016  13  C
017  42 STO
018  04  04
019  91 R/S
020  76 LBL
021  18 C'
022  42 STO
023  03  03
024  91 R/S
025  76 LBL
026  15  E
027  43 RCL
028  00  00
029  65  ×
030  53  (
031  43 RCL
032  01  01
033  55  ÷
034  43 RCL
035  02  02
036  54  )
037  33 X²
038  65  ×
039  43 RCL
040  03  03
041  55  ÷
042  43 RCL
043  04  04
044  95  =
045  22 INV
046  57 ENG
047  91 R/S
```

TI-59 PROGRAM LISTING
CALCULATES TRANSFORMER DATA VALUES

Where:

Button A' is pressed to enter the old voltampere base

Button B' is pressed to enter RR1 in % in the old base

Button C' is pressed to enter XX1 in % in the old base

Button D' is pressed to enter the magnetizing current in % at 100% voltage

Button E' is pressed to enter the no load losses in watts at 100% voltage

Button A is pressed to enter new voltampere base

and then:

Button B is pressed to calculate RR1 in % in the new base

Button C is pressed to calculate XX1 in % in the new base

Button D is pressed to calculate XC1 in % in the new base

Button E is pressed to calculate RR0 in % in the new base

```
76 LBL
16 A'
42 STO
00  00
91 R/S
76 LBL
17 B'
42 STO
01  01
91 R/S
76 LBL
18 C'
42 STO
02  02
91 R/S
76 LBL
19 D'
42 STO
03  03
91 R/S
76 LBL
10 E'
42 STO
04  04
91 R/S
76 LBL
11  A
42 STO
05  05
91 R/S
```

TI-59 PROGRAM LISTING
CALCULATES TRANSFORMER DATA VALUES

(Continued)

030	76	LBL
031	12	B
032	43	RCL
033	05	05
034	55	÷
035	43	RCL
036	00	00
037	95	=
038	65	×
039	43	RCL
040	01	01
041	95	=
042	22	INV
043	57	ENG
044	91	R/S
045	76	LBL
046	13	C
047	43	RCL
048	05	05
049	55	÷
050	43	RCL
051	00	00
052	95	=
053	65	×
054	43	RCL
055	02	02
056	95	=
057	22	INV
058	57	ENG
059	91	R/S
060	76	LBL
061	14	D
062	01	1
063	00	0
064	00	0
065	55	÷
066	43	RCL
067	03	03
068	95	=
069	65	×
070	53	(
071	43	RCL
072	05	05
073	55	÷
074	43	RCL
075	00	00
076	54	)
077	95	=
078	65	×
079	01	1
080	00	0
081	00	0
082	95	=
083	22	INV
084	57	ENG
085	91	R/S
086	76	LBL
087	15	E
088	43	RCL
089	04	04
090	55	÷
091	43	RCL
092	00	00
093	95	=
094	35	1/X
095	65	×
096	53	(
097	43	RCL
098	05	05
099	55	÷
100	43	RCL
101	00	00
102	54	)
103	95	=
104	65	×
105	01	1
106	00	0
107	00	0
108	95	=
109	22	INV
110	57	ENG
111	91	R/S

TI-59 PROGRAM LISTING
MATRIX PROGRAM

Multiplies two 3 X 3 complex matrices [A] and [B] together

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$$

and stores the new complex matrix [C] where complex matrix [A] was located. Complex matrix [B] is left undisturbed.

For computation, this program uses:

Storage Locations 00 through 37

Storage Locations 40 through 51

Also the following labels are used:

A, B, C, A', B', C', D', ln X,

Sin, Cos, tan, and log X.

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

Where:

Complex Matrix [A] is stored in storage locations 00 through 17 by entering them directly to the storage locations.

Enter real part of	a_{11}	in storage location	00.
Enter imaginary part of	a_{11}	in storage location	01.
Enter real part of	a_{12}	in storage location	02.
Enter imaginary part of	a_{12}	in storage location	03.
Enter real part of	a_{13}	in storage location	04.
Enter imaginary part of	a_{13}	in storage location	05.
Enter real part of	a_{21}	in storage location	06.
Enter imaginary part of	a_{21}	in storage location	07.
Enter real part of	a_{22}	in storage location	08.
Enter imaginary part of	a_{22}	in storage location	09.
Enter real part of	a_{23}	in storage location	10.
Enter imaginary part of	a_{23}	in storage location	11.
Enter real part of	a_{31}	in storage location	12.
Enter imaginary part of	a_{31}	in storage location	13.
Enter real part of	a_{32}	in storage location	14.
Enter imaginary part of	a_{32}	in storage location	15.

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

Enter real part of	a_{33}	in storage location	16.
Enter imaginary part of	a_{33}	in storage location	17.

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

Where:

Complex Matrix [B] is stored in storage locations 20 through 37 by entering them directly to the storage locations.

Enter real part of b_{11} in storage location 20.

Enter imaginary part of b_{11} in storage location 21.

Enter real part of b_{12} in storage location 22.

Enter imaginary part of b_{12} in storage location 23.

Enter real part of b_{13} in storage location 24.

Enter imaginary part of b_{13} in storage location 25.

Enter real part of b_{21} in storage location 26.

Enter imaginary part of b_{21} in storage location 27.

Enter real part of b_{22} in storage location 28.

Enter imaginary part of b_{22} in storage location 29.

Enter real part of b_{23} in storage location 30.

Enter imaginary part of b_{23} in storage location 31.

Enter real part of b_{31} in storage location 32.

Enter imaginary part of b_{31} in storage location 33.

Enter real part of b_{32} in storage location 34.

Enter imaginary part of b_{32} in storage location 35.

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

Enter real part of b_{33} in storage location 36.

Enter imaginary part of b_{33} in storage location 37.

and then:

Button E is pressed to calculate [A] X [B] = [C], which takes approximately 3 minutes.

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

Where:

Complex Matrix [C] is found stored in storage locations 00 through 17, where the previous Complex Matrix [A] was located. Then:

Pressing RCL 00 displays the real part of C_{11}.

Pressing RCL 01 displays the imaginary part of C_{11}.

Pressing RCL 02 displays the real part of C_{12}.

Pressing RCL 03 displays the imaginary part of C_{12}.

Pressing RCL 04 displays the real part of C_{13}.

Pressing RCL 05 displays the imaginary part of C_{13}.

Pressing RCL 06 displays the real part of C_{21}.

Pressing RCL 07 displays the imaginary part of C_{21}.

Pressing RCL 08 displays the real part of C_{22}.

Pressing RCL 09 displays the imaginary part of C_{22}.

Pressing RCL 10 displays the real part of C_{23}.

Pressing RCL 11 displays the imaginary part of C_{23}.

Pressing RCL 12 displays the real part of C_{31}.

Pressing RCL 13 displays the imaginary part of C_{31}.

Pressing RCL 14 displays the real part of C_{32}.

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

Pressing RCL 15 displays the imaginary part of C_{32}

Pressing RCL 16 displays the real part of C_{33}

Pressing RCL 17 displays the imaginary part of C_{33}

```
000  76 LBL
001  15  E
002  43 RCL
003  00  00
004  32 X⇌T
005  43 RCL
006  01  01
007  71 SBR
008  11  A
009  43 RCL
010  02  02
011  32 X⇌T
012  43 RCL
013  03  03
014  71 SBR
015  12  B
016  43 RCL
017  04  04
018  32 X⇌T
019  43 RCL
020  05  05
021  71 SBR
022  13  C
023  71 SBR
024  23 LNX
025  71 SBR
026  38 SIN
027  43 RCL
028  18  18
029  42 STO
030  00  00
031  43 RCL
032  19  19
033  42 STO
034  01  01
035  71 SBR
036  23 LNX
037  71 SBR
038  28 LOG
039  71 SBR
040  39 COS
041  43 RCL
042  18  18
043  42 STO
044  02  02
045  43 RCL
046  19  19
047  42 STO
048  03  03
049  71 SBR
050  23 LNX
051  71 SBR
052  28 LOG
053  71 SBR
054  30 TAN
055  43 RCL
056  18  18
057  42 STO
058  04  04
059  43 RCL
060  19  19
061  42 STO
062  05  05
063  43 RCL
064  06  06
065  32 X⇌T
066  43 RCL
067  07  07
068  71 SBR
069  11  A
```

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

```
070  43 RCL
071  08  08
072  32 X⇌T
073  43 RCL
074  09  09
075  71 SBR
076  12  B
077  43 RCL
078  10  10
079  32 X⇌T
080  43 RCL
081  11  11
082  71 SBR
083  13  C
084  71 SBR
085  23 LNX
086  71 SBR
087  38 SIN
088  43 RCL
089  18  18
090  42 STO
091  06  06
092  43 RCL
093  19  19
094  42 STO
095  07  07
096  71 SBR
097  23 LNX
098  71 SBR
099  28 LOG
100  71 SBR
101  39 COS
102  43 RCL
103  18  18
104  42 STO
105  08  08
106  43 RCL
107  19  19
108  42 STO
109  09  09
110  71 SBR
111  23 LNX
112  71 SBR
113  28 LOG
114  71 SBR
115  30 TAN
116  43 RCL
117  18  18
118  42 STO
119  10  10
120  43 RCL
121  19  19
122  42 STO
123  11  11
124  43 RCL
125  12  12
126  32 X⇌T
127  43 RCL
128  13  13
129  71 SBR
130  11  A
131  43 RCL
132  14  14
133  32 X⇌T
134  43 RCL
135  15  15
136  71 SBR
137  12  B
138  43 RCL
139  16  16
140  32 X⇌T
141  43 RCL
142  17  17
143  71 SBR
144  13  C
145  71 SBR
146  23 LNX
147  71 SBR
148  38 SIN
149  43 RCL
150  18  18
151  42 STO
```

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

152	12	12
153	43	RCL
154	19	19
155	42	STO
156	13	13
157	71	SBR
158	23	LNX
159	71	SBR
160	28	LOG
161	71	SBR
162	39	COS
163	43	RCL
164	18	18
165	42	STO
166	14	14
167	43	RCL
168	19	19
169	42	STO
170	15	15
171	71	SBR
172	23	LNX
173	71	SBR
174	28	LOG
175	71	SBR
176	30	TAN
177	43	RCL
178	18	18
179	42	STO
180	16	16
181	43	RCL
182	19	19
183	42	STO
184	17	17
185	91	R/S
186	76	LBL
187	11	A
188	22	INV
189	37	P/R
190	42	STO
191	41	41
192	42	STO
193	47	47
194	32	X:T
195	42	STO
196	40	40
197	42	STO
198	46	46
199	92	RTN
200	76	LBL
201	12	B
202	22	INV
203	37	P/R
204	42	STO
205	43	43
206	42	STO
207	49	49
208	32	X:T
209	42	STO
210	42	42
211	42	STO
212	48	48
213	92	RTN
214	76	LBL
215	13	C
216	22	INV
217	37	P/R
218	42	STO
219	45	45
220	42	STO
221	51	51
222	32	X:T
223	42	STO
224	44	44
225	42	STO
226	50	50
227	92	RTN
228	76	LBL
229	16	A'
230	22	INV
231	37	P/R
232	44	SUM
233	41	41

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

234	32	X:T
235	49	PRD
236	40	40
237	43	RCL
238	40	40
239	32	X:T
240	43	RCL
241	41	41
242	37	P/R
243	71	SBR
244	19	D'
245	92	RTN
246	76	LBL
247	17	B'
248	22	INV
249	37	P/R
250	44	SUM
251	43	43
252	32	X:T
253	49	PRD
254	42	42
255	43	RCL
256	42	42
257	32	X:T
258	43	RCL
259	43	43
260	37	P/R
261	71	SBR
262	19	D'
263	92	RTN
264	76	LBL
265	18	C'
266	22	INV
267	37	P/R
268	44	SUM
269	45	45
270	32	X:T
271	49	PRD
272	44	44
273	43	RCL
274	44	44
275	32	X:T
276	43	RCL
277	45	45
278	37	P/R
279	71	SBR
280	19	D'
281	92	RTN
282	76	LBL
283	19	D'
284	44	SUM
285	19	19
286	32	X:T
287	44	SUM
288	18	18
289	92	RTN
290	76	LBL
291	23	LNX
292	25	CLR
293	42	STO
294	18	18
295	42	STO
296	19	19
297	92	RTN
298	76	LBL
299	38	SIN
300	43	RCL
301	20	20
302	32	X:T
303	43	RCL
304	21	21
305	71	SBR
306	16	A'
307	43	RCL
308	26	26
309	32	X:T
310	43	RCL
311	27	27
312	71	SBR
313	17	B'
314	43	RCL
315	32	32
316	32	X:T
317	43	RCL

TI-59 PROGRAM LISTING
MATRIX PROGRAM

(Continued)

318	33	33
319	71	SBR
320	18	C'
321	92	RTN
322	76	LBL
323	39	COS
324	43	RCL
325	22	22
326	32	X:T
327	43	RCL
328	23	23
329	71	SBR
330	16	A'
331	43	RCL
332	28	28
333	32	X:T
334	43	RCL
335	29	29
336	71	SBR
337	17	B'
338	43	RCL
339	34	34
340	32	X:T
341	43	RCL
342	35	35
343	71	SBR
344	18	C'
345	92	RTN
346	76	LBL
347	30	TAN
348	43	RCL
349	24	24
350	32	X:T
351	43	RCL
352	25	25
353	71	SBR
354	16	A'
355	43	RCL
356	30	30
357	32	X:T
358	43	RCL
359	31	31
360	71	SBR
361	17	B'
362	43	RCL
363	36	36
364	32	X:T
365	43	RCL
366	37	37
367	71	SBR
368	18	C'
369	76	LBL
370	28	LOG
371	43	RCL
372	47	47
373	42	STO
374	41	41
375	43	RCL
376	46	46
377	42	STO
378	40	40
379	43	RCL
380	49	49
381	42	STO
382	43	43
383	43	RCL
384	48	48
385	42	STO
386	42	42
387	43	RCL
388	51	51
389	42	STO
390	45	45
391	43	RCL
392	50	50
393	42	STO
394	44	44
395	92	RTN

TI-59 PROGRAM LISTING
CALCULATES STAR TO DELTA TRANSFORMATION

Where:

Button A' is pressed to enter Z_H

Button B' is pressed to enter Z_X

Button C' is pressed to enter Z_Y

and then:

Button A is pressed to calculate Z_{HX}

Button B is pressed to calculate Z_{HY}

Button C is pressed to calculate Z_{HY}

000	76	LBL
001	16	A'
002	42	STO
003	00	00
004	91	R/S
005	76	LBL
006	17	B'
007	42	STO
008	01	01
009	91	R/S
010	76	LBL
011	18	C'
012	42	STO
013	02	02
014	91	R/S
015	76	LBL
016	11	A
017	43	RCL
018	00	00
019	65	×
020	43	RCL
021	01	01
022	55	÷
023	43	RCL
024	02	02
025	85	+
026	43	RCL
027	01	01
028	85	+
029	43	RCL
030	00	00
031	95	=
032	91	R/S
033	76	LBL
034	12	B
035	43	RCL
036	01	01
037	65	×
038	43	RCL
039	02	02
040	55	÷
041	43	RCL
042	00	00
043	85	+
044	43	RCL
045	02	02
046	85	+
047	43	RCL
048	01	01
049	95	=
050	91	R/S

TI-59 PROGRAM LISTING
CALCULATES STAR TO DELTA TRANSFORMATION

(Continued)

```
051  76 LBL
052  13  C
053  43 RCL
054  00  00
055  65  ×
056  43 RCL
057  02  02
058  55  ÷
059  43 RCL
060  01  01
061  85  +
062  43 RCL
063  02  02
064  85  +
065  43 RCL
066  00  00
067  95  =
068  91 R/S
```

TI-59 PROGRAM LISTING
CALCULATES CAPACITIVE ELEMENT REACTANCE

Where:

Button A' is pressed to enter the frequency

Button B' is pressed to enter the 3-phase VARS

Button A is pressed to enter the line to line voltage base

Button B is pressed to enter the 3-phase voltampere base

then:

Button C is pressed to calculate capacitance single phase

Button D is pressed to calculate $X_{c_{1\text{-phase}}}$ in ohms

Button E' is pressed to calculate $X_{c_{1\text{-phase}}}$ in per unit

Button D' is pressed to calculate $X_{c_{1\text{-phase}}}$ in %

Button E is pressed to calculate impedance base

```
000  76 LBL
001  11  A
002  42 STO
003  00  00
004  91 R/S
005  76 LBL
006  16 A'
007  42 STO
008  01  01
009  91 R/S
010  76 LBL
011  12  B
012  42 STO
013  02  02
014  91 R/S
015  76 LBL
016  17 B'
017  42 STO
018  03  03
019  91 R/S
020  76 LBL
021  13  C
022  43 RCL
023  03  03
024  55  ÷
025  53  (
026  43 RCL
027  00  00
028  33 X²
029  65  ×
```

TI-59 PROGRAM LISTING
CALCULATES CAPACITIVE ELEMENT REACTANCE

(Continued)

030	02	2
031	65	×
032	89	π
033	65	×
034	43	RCL
035	01	01
036	54	)
037	95	=
038	57	ENG
039	91	R/S
040	76	LBL
041	14	D
042	43	RCL
043	00	00
044	33	X²
045	55	÷
046	43	RCL
047	03	03
048	95	=
049	22	INV
050	57	ENG
051	91	R/S
052	76	LBL
053	15	E
054	43	RCL
055	00	00
056	33	X²
057	55	÷
058	43	RCL
059	02	02
060	95	=
061	22	INV
062	57	ENG
063	91	R/S
064	76	LBL
065	10	E'
066	53	(
067	43	RCL
068	00	00
069	33	X²
070	55	÷
071	43	RCL
072	03	03
073	54	)
074	55	÷
075	53	(
076	43	RCL
077	00	00
078	33	X²
079	55	÷
080	43	RCL
081	02	02
082	54	)
083	95	=
084	22	INV
085	57	ENG
086	91	R/S
087	76	LBL
088	19	D'
089	53	(
090	43	RCL
091	00	00
092	33	X²
093	55	÷
094	43	RCL
095	03	03
096	54	)
097	55	÷
098	53	(
099	43	RCL
100	00	00
101	33	X²
102	55	÷
103	43	RCL
104	02	02
105	54	)
106	95	=
107	65	×
108	01	1
109	00	0
110	00	0
111	95	=
112	22	INV
113	57	ENG
114	91	R/S

TI-59 PROGRAM LISTING
CALCULATES INDUCTIVE ELEMENT REACTANCE

Where:

Button A' is pressed to enter the frequency

Button B' is pressed to enter the 3-phase VARS

Button A is pressed to enter the line to line voltage base

Button B is pressed to enter the 3-phase voltampere base

then:

Button C is pressed to calculate inductance single phase

Button D is pressed to calculate $X_{L_{1\text{-phase}}}$ in ohms

Button E' is pressed to calculate $X_{L_{1\text{-phase}}}$ in per unit

Button D' is pressed to calculate $X_{L_{1\text{-phase}}}$ in %

Button E is pressed to calculate impedance base

```
000  76 LBL
001  11  A
002  42 STO
003  00  00
004  91 R/S
005  76 LBL
006  16 A'
007  42 STO
008  01  01
009  91 R/S
010  76 LBL
011  12  B
012  42 STO
013  02  02
014  91 R/S
015  76 LBL
016  17 B'
017  42 STO
018  03  03
019  91 R/S
020  76 LBL
021  13  C
022  43 RCL
023  00  00
024  33 X²
025  55  ÷
026  53  (
027  02  2
028  65  ×
029  89  π
```

TI-59 PROGRAM LISTING
CALCULATES INDUCTIVE ELEMENT REACTANCE

(Continued)

030	65	×
031	43	RCL
032	01	01
033	65	×
034	43	RCL
035	03	03
036	54	)
037	95	=
038	57	ENG
039	91	R/S
040	76	LBL
041	14	D
042	43	RCL
043	00	00
044	33	X²
045	55	÷
046	43	RCL
047	03	03
048	95	=
049	22	INV
050	57	ENG
051	91	R/S
052	76	LBL
053	15	E
054	43	RCL
055	00	00
056	33	X²
057	55	÷
058	43	RCL
059	02	02
060	95	=
061	22	INV
062	57	ENG
063	91	R/S
064	76	LBL
065	10	E'
066	53	(
067	43	RCL
068	00	00
069	33	X²
070	55	÷
071	43	RCL
072	03	03
073	54	)
074	55	÷
075	53	(
076	43	RCL
077	00	00
078	33	X²
079	55	÷
080	43	RCL
081	02	02
082	54	)
083	95	=
084	22	INV
085	57	ENG
086	91	R/S
087	76	LBL
088	19	D'
089	53	(
090	43	RCL
091	00	00
092	33	X²
093	55	÷
094	43	RCL
095	03	03
096	54	)
097	55	÷
098	53	(
099	43	RCL
100	00	00
101	33	X²
102	55	÷
103	43	RCL
104	02	02
105	54	)
106	95	=
107	65	×
108	01	1
109	00	0
110	00	0
111	95	=
112	22	INV
113	57	ENG
114	91	R/S

TI-59 PROGRAM LISTING
CALCULATES PER UNIT VOLTAGE OR CURRENT PROGRAM INPUT VALUES FROM HARMONIC MEASUREMENTS GIVEN IN DECIBELS

Where:

Button A is pressed to enter decibel value

Button B is pressed to enter per unit V_2

and then:

Button E is pressed to obtain per unit value

Formula used is:

$$V_1 \text{ pu} = (V_2)\text{x}[\text{antilog } (\frac{\text{db}}{20})] \text{ pu}$$

where:

$$V_2 = \frac{\text{Actual Voltage}}{\text{Base Voltage}}$$

or

$$V_2 = \frac{\text{Actual Current}}{\text{Base Current}}$$

000	76	LBL
001	11	A
002	42	STO
003	00	00
004	99	PRT
005	91	R/S
006	76	LBL
007	12	B
008	42	STO
009	01	01
010	99	PRT
011	91	R/S
012	76	LBL
013	15	E
014	43	RCL
015	00	00
016	55	÷
017	02	2
018	00	0
019	95	=
020	22	INV
021	28	LOG
022	95	=
023	65	×
024	43	RCL
025	01	01
026	95	=
027	99	PRT
028	98	ADV
029	98	ADV
030	91	R/S

TI-59 PROGRAM LISTING
CALCULATES HARMONIC DISTORTION FACTORS
UP TO THE 35th ORDER HARMONIC

Where:

Each harmonic is stored in its respective storage location.

Enter harmonic of order 1 and press STO 01.

Enter harmonic of order 2 and press STO 02.

Enter harmonic of order 3 and press STO 03.

Enter harmonic of order 4 and press STO 04.

Enter harmonic of order 5 and press STO 05.

Enter harmonic of order 6 and press STO 06.

Enter harmonic of order 7 and press STO 07.

Enter harmonic of order 8 and press STO 08.

Enter harmonic of order 9 and press STO 09.

Enter harmonic of order 10 and press STO 10.

Enter harmonic of order 11 and press STO 11.

Enter harmonic of order 12 and press STO 12.

Enter harmonic of order 13 and press STO 13.

Enter harmonic of order 14 and press STO 14.

Enter harmonic of order 15 and press STO 15.

Enter harmonic of order 16 and press STO 16.

Enter harmonic of order 17 and press STO 17.

Enter harmonic of order 18 and press STO 18.

Enter harmonic of order 19 and press STO 19.

Enter harmonic of order 20 and press STO 20.

Enter harmonic of order 21 and press STO 21.

Enter harmonic of order 22 and press STO 22.

TI-59 PROGRAM LISTING
CALCULATES HARMONIC DISTORTION FACTORS
UP TO THE 35th ORDER HARMONIC

(Continued)

Enter harmonic of order 23 and press STO 23.

Enter harmonic of order 24 and press STO 24.

Enter harmonic of order 25 and press STO 25.

Enter harmonic of order 26 and press STO 26.

Enter harmonic of order 27 and press STO 27.

Enter harmonic of order 28 and press STO 28.

Enter harmonic of order 29 and press STO 29.

Enter harmonic of order 30 and press STO 30.

Enter harmonic of order 31 and press STO 31.

Enter harmonic of order 32 and press STO 32.

Enter harmonic of order 33 and press STO 33.

Enter harmonic of order 34 and press STO 34.

Enter harmonic of order 35 and press STO 35.

```
000  76 LBL
001  15  E
002  43 RCL
003  02  02
004  33 X²
005  55  ÷
006  43 RCL
007  01  01
008  33 X²
009  85  +
010  43 RCL
011  03  03
012  33 X²
013  55  ÷
014  43 RCL
015  01  01
016  33 X²
017  85  +
018  43 RCL
019  04  04
020  33 X²
021  55  ÷
022  43 RCL
023  01  01
024  33 X²
025  85  +
```

TI-59 PROGRAM LISTING
CALCULATES HARMONIC DISTORTION FACTORS
UP TO THE 35th ORDER HARMONIC

(Continued)

```
026  43 RCL
027  05  05
028  33 X²
029  55  ÷
030  43 RCL
031  01  01
032  33 X²
033  85  +
034  43 RCL
035  06  06
036  33 X²
037  55  ÷
038  43 RCL
039  01  01
040  33 X²
041  85  +
042  43 RCL
043  07  07
044  33 X²
045  55  ÷
046  43 RCL
047  01  01
048  33 X²
049  85  +
050  43 RCL
051  08  08
052  33 X²
053  55  ÷
054  43 RCL
055  01  01
056  33 X²
057  85  +
058  43 RCL
059  09  09
060  33 X²
061  55  ÷
062  43 RCL
063  01  01
064  33 X²
065  85  +
066  43 RCL
067  10  10
068  33 X²
069  55  ÷
070  43 RCL
071  01  01
072  33 X²
073  85  +
074  43 RCL
075  11  11
076  33 X²
077  55  ÷
078  43 RCL
079  01  01
080  33 X²
081  85  +
082  43 RCL
083  12  12
084  33 X²
085  55  ÷
086  43 RCL
087  01  01
088  33 X²
089  85  +
090  43 RCL
091  13  13
092  33 X²
093  55  ÷
094  43 RCL
095  01  01
096  33 X²
097  85  +
098  43 RCL
099  14  14
100  33 X²
101  55  ÷
102  43 RCL
103  01  01
```

TI-59 PROGRAM LISTING
CALCULATES HARMONIC DISTORTION FACTORS
UP TO THE 35th ORDER HARMONIC

(Continued)

104	33	X^2
105	85	+
106	43	RCL
107	15	15
108	33	X^2
109	55	÷
110	43	RCL
111	01	01
112	33	X^2
113	85	+
114	43	RCL
115	16	16
116	33	X^2
117	55	÷
118	43	RCL
119	01	01
120	33	X^2
121	85	+
122	43	RCL
123	17	17
124	33	X^2
125	55	÷
126	43	RCL
127	01	01
128	33	X^2
129	85	+
130	43	RCL
131	18	18
132	33	X^2
133	55	÷
134	43	RCL
135	01	01
136	33	X^2
137	85	+
138	43	RCL
139	19	19
140	33	X^2
141	55	÷
142	43	RCL
143	01	01
144	33	X^2
145	85	+
146	43	RCL
147	20	20
148	33	X^2
149	55	÷
150	43	RCL
151	01	01
152	33	X^2
153	85	+
154	43	RCL
155	21	21
156	33	X^2
157	55	÷
158	43	RCL
159	01	01
160	33	X^2
161	85	+
162	43	RCL
163	22	22
164	33	X^2
165	55	÷
166	43	RCL
167	01	01
168	33	X^2
169	85	+
170	43	RCL
171	23	23
172	33	X^2
173	55	÷
174	43	RCL
175	01	01
176	33	X^2
177	85	+
178	43	RCL
179	24	24
180	33	X^2
181	55	÷

TI-59 PROGRAM LISTING
CALCULATES HARMONIC DISTORTION FACTORS
UP TO THE 35th ORDER HARMONIC

(Continued)

182	43	RCL
183	01	01
184	33	X²
185	85	+
186	43	RCL
187	25	25
188	33	X²
189	55	÷
190	43	RCL
191	01	01
192	33	X²
193	85	+
194	43	RCL
195	26	26
196	33	X²
197	55	÷
198	43	RCL
199	01	01
200	33	X²
201	85	+
202	43	RCL
203	27	27
204	33	X²
205	55	÷
206	43	RCL
207	01	01
208	33	X²
209	85	+
210	43	RCL
211	28	28
212	33	X²
213	55	÷
214	43	RCL
215	01	01
216	33	X²
217	85	+
218	43	RCL
219	29	29
220	33	X²
221	55	÷
222	43	RCL
223	01	01
224	33	X²
225	85	+
226	43	RCL
227	30	30
228	33	X²
229	55	÷
230	43	RCL
231	01	01
232	33	X²
233	85	+
234	43	RCL
235	31	31
236	33	X²
237	55	÷
238	43	RCL
239	01	01
240	33	X²
241	85	+
242	43	RCL
243	32	32
244	33	X²
245	55	÷
246	43	RCL
247	01	01
248	33	X²
249	85	+
250	43	RCL
251	33	33
252	33	X²
253	55	÷
254	43	RCL
255	01	01
256	33	X²
257	85	+
258	43	RCL
259	34	34
260	33	X²
261	55	÷

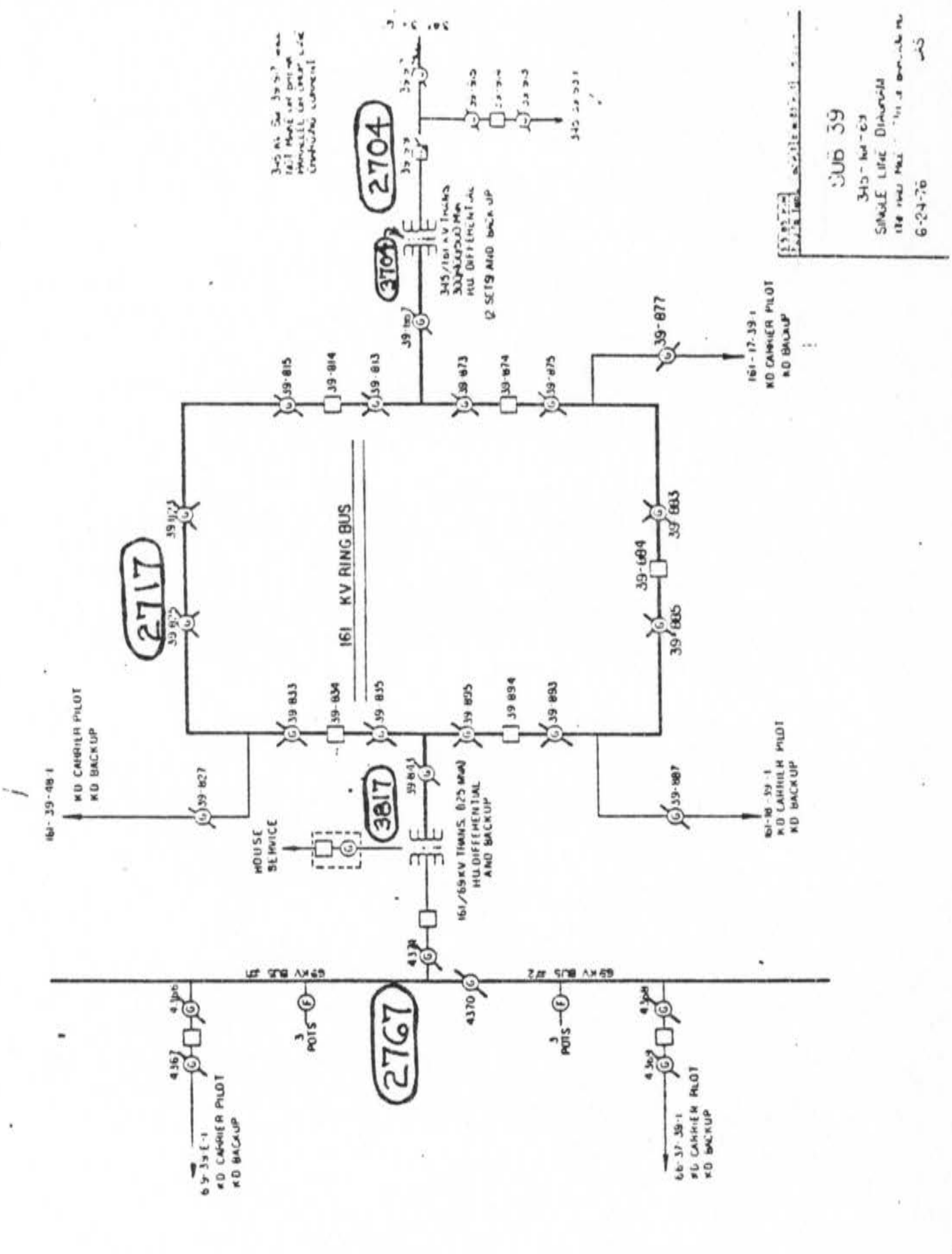
TI-59 PROGRAM LISTING
CALCULATES HARMONIC DISTORTION FACTORS
UP TO THE 35th ORDER HARMONIC

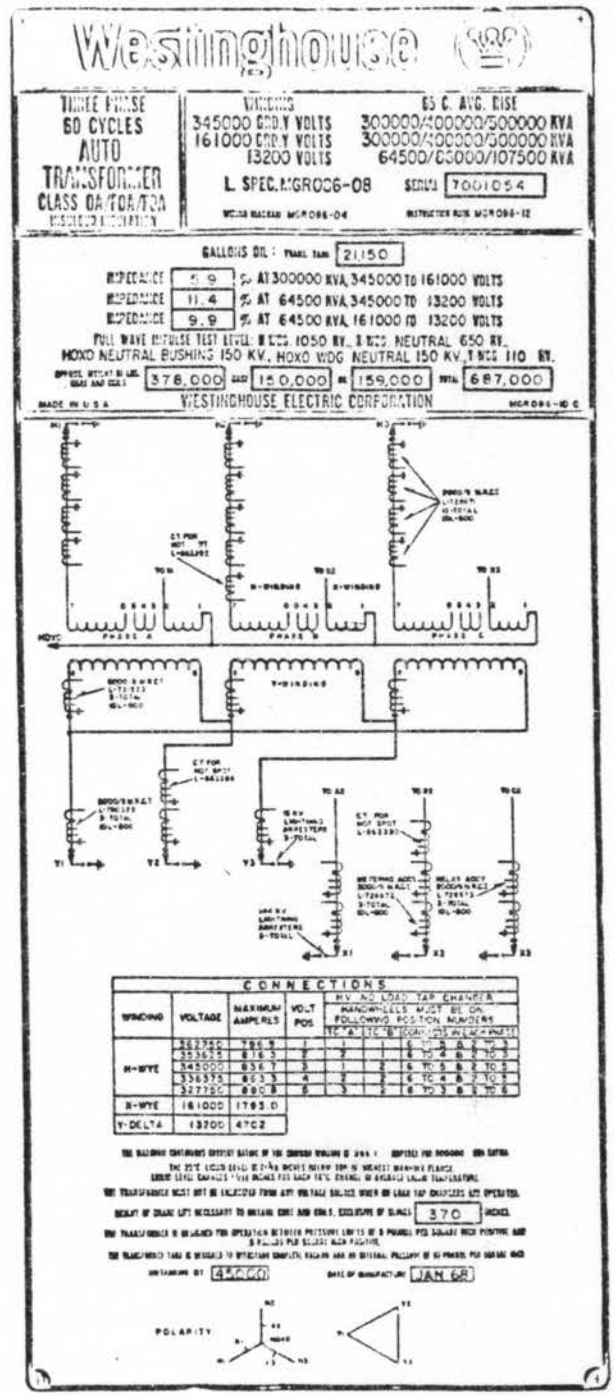
(Continued)

```
262  43 RCL
263  01  01
264  33 X²
265  85  +
266  43 RCL
267  35  35
268  33 X²
269  55  ÷
270  43 RCL
271  01  01
272  33 X²
273  95  =
274  34 √X
275  91 R/S
```

XIII. APPENDIX

F. THREE-WINDING TRANSFORMER EXAMPLE


161 KV RING BUS
2717
2704
3704
3817
2767
69 KV BUS #1
69 KV BUS #2
HOUSE SERVICE
161/69 KV TRANS. 8.25 MVA
KD CARRIER PILOT
KD BACKUP
39-877
39-833
39-834
39-835
39-895
39-894
39-893
39-813
39-814
39-815
39-873
39-874
39-875
39-827
39-887
39-884
39-883
39-885
4370
3 POTS
SUB 39
SINGLE LINE DIAGRAM
6-24-76


Westinghouse
60 CYCLES
AUTO
CLASS OA/FOA/FOA
345000 GRD.Y VOLTS
161000 GRD.Y VOLTS
13200 VOLTS
300000/400000/500000 KVA
300000/400000/500000 KVA
64500/86000/107500 KVA
L SPEC.MGR006-08
7001054
GALLONS OIL :
21,150
5.9 % AT 300000 KVA, 345000 TO 161000 VOLTS
11.4 % AT 64500 KVA, 345000 TO 13200 VOLTS
9.9 % AT 64500 KVA, 161000 TO 13200 VOLTS
HOXO NEUTRAL BUSHING 150 KV., HOXO WDG NEUTRAL 150 KV.
378,000
150,000
159,000
687,000
MADE IN U.S.A
WESTINGHOUSE ELECTRIC CORPORATION
CONNECTIONS
WINDING
VOLTAGE
MAXIMUM AMPERES
VOLT POS
H-WYE
X-WYE
Y-DELTA
161000
1793.0
13200
4702
370
JAN 68
POLARITY

REPORT OF TRANSFORMER TESTS
FORM [illegible]

Westinghouse Electric Corporation

~~SPARE TRANSF~~ "39"

Date of Test 1-20-68 Purchaser's Order No. 63759 G.O. DP-18400 S.O. No. MJR086
Type OA/FOA/FOA Auto Phase 3 Cycles 60 Insulating Fluid Oil L. Spec. MJR086-08 Polarity See I.P.

Winding	H	Winding	X	Winding	Y
Kva	300000/400000/500000	Kva	300000/400000/500000	Kva	64500/86000/107500
Voltage	345000 Grd. Y	Voltage	161000 Grd. Y	Voltage	13200

For polarity, additional tap voltages and connections, see Instruction Plate MJR086-10.

RESISTANCES, EXCITING CURRENT, LOSSES AND IMPEDANCE—Based on normal rating, unless otherwise stated. Losses and regulation are based on wattmeter measurements. For three-phase transformers the resistances are the sum of the three phases in series.

SERIAL NO.	RESISTANCE IN OHMS AT 75°C WINDINGS H	X	Y	% EXCITE CURRENT AT 100% RATED VOLTAGE	NO LOAD LOSS WATTS AT 100% RATED VOLTAGE	345 Kv TO 161 Kv 300000 Kva LOAD LOSS WATTS 75°C	% IMP 75°C	345 Kv TO 13.2 Kv 64500 Kva LOAD LOSS WATTS 75°C	% IMP 75°C	161 Kv TO 13.2 Kv 64500 Kva LOAD LOSS WATTS 75°C	% IMP 75°C
7001054	.5676	.4443	.0251	.78	257940	369423	5.94	123495	11.42	135845	9.93
						TOTAL LOSS	% IMP. 75°C	TOTAL LOSS	% IMP. 75°C	TOTAL LOSS	% IMP. 75°C
AVERAGE				.78	257940	627363	5.94	381435	11.42	393785	9.93
GUARANTEE				.77	286000	641000	6.0	--	10.75-12.9	--	8.6-10.75

345 to 161 KV
REGULATION AT 75°C
@300000 KVA

	100% PF	90% PF	80% PF	% PF
AVERAGE	.30	2.85	3.77	
GUARANTEE	.32	2.90	3.84	

TEMPERATURE RISES—Average rise in degrees C. corrected to instant of shutdown of transformer.
Serial No. 7001054 with windings connected and loaded as follows:
H Winding 362.25 Kv 478 Amp.; X Winding 161 Kv 845 Amp.;
Y Winding 13.2 Kv 282 Amp. until constant temperature rise was reached.

Load Constant	RISE OF WINDINGS BY RESISTANCE H	X	Y	GUARANTEE	TOP FLUID RISE	AMBIENT TEMP. INCOMING WATER	[illegible]	WATER RISE	GALLONS PER MIN.	POUNDS PRESSURE
100%	44.0	47.5	48.0	65	58.0		25.0			
133-1/3%	54.7	49.9	64.7	65	42.7		27.0			
166-2/3%	53.1	48.2	64.6	65	38.4		29.8			

INSULATION TESTS	WINDING	VOLT RATING	TEST VOLTAGE APPLIED IN Kv	DURATION OF TEST IN SECONDS
APPLIED POTENTIAL TESTS (Voltage applied between each winding and all other windings connected to core and ground.)	H	345000	50	60
	X	161000	50	60
	Y	13200	34	60
	Wiring, Fans & Pumps		1.5	60

INDUCED POTENTIAL TEST * — times rated voltage across full winding, 460 Kv from 327.75 Kv Line terminal to ground; at 180 cycles per second for 7200 cycles.

REMARKS

* Also induced 575 KV line to line (3 Phase Test)

See separate report for results of ASA Impulse Tests and Switching Surge Tests.

I hereby certify that this is a true report based on factory tests made in accordance with the latest Transformer Test Code C57 of the American Standards Association, and that each transformer withstood the above insulation tests.

Signed [illegible] Date February 2, 1968 Approved [illegible]

Page 1 of 3 Pages

REPORT OF TESTS

Westinghouse

DATE February 2, 1968

PURCHASER

WESTINGHOUSE GENERAL ORDER NO. DP-18400

APPARATUS Class OA/FOA/FOA Shell Form Autotransformer

SHOP ORDER NO. MCR086

RATING 300000/400000/500000 KVA - 345000 Grd. Y/161000 Grd. Y/13200 Volts, 3 Phase, 60 Cycles

Exciting Current and No Load Loss Measurements

% Rated Voltage	% Exciting Current		No Load Loss, Watts	
	Measured	Guaranteed	Measured	Guaranteed
110%	2.2	2.0	415526	426000
115%	3.5	3.2	482000	500000

Additional Impedance and Load Loss Measurements at 75°C

Voltage Connection	NLTC Pos.	KVA	% Impedance	Load Loss, Watts
362250 - 161000	1	300000	6.08	393159
353625 - 161000	2	300000	5.96	384668
336375 - 161000	4	300000	5.93	371899
327750 - 161000	5	300000	6.04	384803
362250 - 13200	1	64500	11.84	127355
353625 - 13200	2	64500	11.59	123335
336375 - 13200	4	64500	11.23	123856
327750 - 13200	5	64500	11.04	124239

Zero Sequence Impedance Measurements

Voltage Connection	NLTC Pos.	KVA	% Impedance
362250 - 161000	1	300000	6.07
353625 - 161000	2	300000	5.88
345000 - 161000	3	300000	5.90
336375 - 161000	4	300000	5.82
327750 - 161000	5	300000	5.96
362250 - 13200	1	64500	11.59
353625 - 13200	2	64500	11.24
345000 - 13200	3	64500	11.37
336375 - 13200	4	64500	11.24
327750 - 13200	5	64500	10.99
161000 - 13200	-	64500	9.56

Pump and Fan Losses

230 Volts, 3 Phase, 60 Cycles

	T.W.	A.W.
Measured	30160	43150
Guaranteed	63500	-----

Additional Losses

	345/161 KV @ 500 MVA	345/13.2 KV @ 107.5 MVA
Load Loss (Watts)	1026175	343042
No Load Loss (Watts)	257940	257940
Total	1284115	600982
Guaranteed	1273000	610000

THE ABOVE IS A TRUE AND CORRECT RECORD OF DATA OBTAINED FROM TESTS AT THE MUNCIE PLANT OF WESTINGHOUSE ELECTRIC CORPORATION.

PAGE 2 OF 3 PAGES

SIGNED [signature]

REPORT OF TESTS

Westinghouse

DATE February 2, 1968

PURCHASER

WESTINGHOUSE GENERAL ORDER NO DP-18400

APPARATUS Class OA/FOA/FOA Shell Form Autotransformer SHOP ORDER NO MGR086

RATING 300000/400000/500000 KVA - 345000 Grd. Y/161000 Grd. Y/13200 Volts, 3 Phase, 60 Cycl.

Efficiencies at 300000 KVA
(Power for cooling not included)

Load	Full	3/4	1/2	1/4
Measured	99.79	99.79	99.77	99.62
Guaranteed	99.78	99.78	99.75	99.59

Ratio Test

H.V.-NLTC Volt. Pos.	Ph. A	Ph. B	Ph. C
	100 Volts Applied On High Voltage Measured On Low Voltage		
1	44.56	44.56	44.56
2	45.54	45.54	45.54
3	46.67	46.67	46.67
4	47.86	47.86	47.86
5	49.11	49.11	49.11
	250 Volts Applied On High Voltage Measured On Tertiary Voltage		
5	17.36	17.36	17.36

Corona Tests

% Induced Test	H1 (Microvolts)	H2 (Microvolts)	H3 (Microvolts)
50	35	12.2	1.6
70	125	204	188
100	300	306	242
100	300	102	161
70	125	81.6	97
50	90	25.5	97
0	0	0	0
50	70	127	2.7
70	85	178	2.7

THE ABOVE IS A TRUE AND CORRECT RECORD OF DATA OBTAINED FROM TESTS AT THE MUNCIE PLANT OF WESTINGHOUSE ELECTRIC CORPORATION

PAGE 3 OF 3 PAGES

SIGNED [signature] ENGR.

$$[A] \times [B] = [C]$$

$$\begin{bmatrix} .5 & .5 & -.5 \\ .5 & -.5 & .5 \\ -.5 & .5 & .5 \end{bmatrix} \times \begin{bmatrix} Z_{HX(H)} \\ Z_{HY(H)} \\ Z_{XY(H)} \end{bmatrix} = \begin{bmatrix} Z_{H_{1,2}} \\ Z_{X_{1,2}} \\ Z_{Y_{1,2}} \end{bmatrix}$$

USING MATRIX PROGRAM -- which multiplies two 3 X 3 complex matrices together

PRESS 2nd CMS TO CLEAR ALL MEMORY STORAGE LOCATIONS .

ENTER MATRIX [A] (see Anderson (4), Page 246 for this example) by the following steps:

ENTER .5 and PRESS STO 00
ENTER .5 and PRESS STO 02
ENTER -.5 and PRESS STO 04
ENTER .5 and PRESS STO 06
ENTER -.5 and PRESS STO 08
ENTER .5 and PRESS STO 10
ENTER -.5 and PRESS STO 12
ENTER .5 and PRESS STO 14
ENTER .5 AND PRESS STO 16

ENTER MATRIX [B] by the following steps:

ENTER $Z_{HX(H)}$ VALUE and PRESS STO 20
ENTER $Z_{HY(H)}$ VALUE and PRESS STO 26
ENTER $Z_{XY(H)}$ VALUE and PRESS STO 32

PRESS BUTTON E TO EXECUTE.

AFTER PROGRAM EXECUTION CEASES (Approximately 3 minutes):

PRESS RCL 00 to Find $Z_{H_{1,2}}$ VALUE

PRESS RCL 06 to Find $Z_{X_{1,2}}$ VALUE

PRESS RCL 12 to Find $Z_{Y_{1,2}}$ VALUE

SUB 39
345/161/13.8 KV XFMR

FROM THE TRANSFORMER TEST REPORT

345 KV to 161 KV

$Z_{HX(H)_{1,2}}$ = 5.9400% @ 300 MVA

345 KV to 13.8 KV

$Z_{HY(X)_{1,2}}$ = 11.4200% @ 64.5 MVA

161 KV to 13.8 KV

$Z_{XY(Y)_{1,2}}$ = 9.9300% @ 64.5 MVA

TRANSFERRING EVERYTHING TO THE H-WINDING VOLTAMPERE BASE YIELDS:

$Z_{HX(H)_{1,2}}$ = 1.9800% @ 100 MVA

$Z_{HY(H)_{1,2}}$ = 17.7054% @ 100 MVA

$Z_{XY(H)_{1,2}}$ = 15.3953% @ 100 MVA

CHANGING TO PER UNIT EQUIVALENT CIRCUIT VALUES

$Z_{H_{1,2}}$ = 2.1451% @ 100 MVA

$Z_{X_{1,2}}$ = -.1651% @ 100 MVA

$Z_{Y_{1,2}}$ = 15.5604% @ 100 MVA

PERFORMING STAR TO DELTA CONVERSION

Z_{HX} = 1.9572% @ 100 MVA

Z_{XY} = 14.1977% @ 100 MVA

Z_{HY} = -184.4666% @ 100 MVA

SUB 39
345/161/13.8 KV XFMR

FROM THE TRANSFORMER TEST REPORT

345 KV to 161 KV

$Z_{HX(H)_0}$ = 5.9000% @ 300 MVA

345 KV to 13.8 KV

$Z_{HY(Y)_0}$ = 11.3700% @ 64.5 MVA

161 KV to 13.8 KV

$Z_{XY(X)_0}$ = 9.5600% @ 64.5 MVA

TRANSFERRING EVERYTHING TO THE H- WINDING VOLTAMPERE BASE YIELDS:

$Z_{HX(H)_0}$ = 1.9667% @ 100 MVA

$Z_{HY(H)_0}$ = 17.6279% @ 100 MVA

$Z_{XY(H)_0}$ = 14.8217% @ 100 MVA

CHANGING TO PER UNIT EQUIVALENT CIRCUIT VALUES

Z_{H_0} = 2.3865% @ 100 MVA

Z_{X_0} = -.4198% @ 100 MVA

Z_{Y_0} = 15.2415% @ 100 MVA

PERFORMING STAR TO DELTA CONVERSION

Z_{HX} = 1.9010% @ 100 MVA

Z_{xy} = 12.1406% @ 100 MVA

Z_{HY} = -69.0176% @ 100 MVA

SUB 39 345/161/13.8 KV XFRM
USING 3 INDIVIDUAL TRANSFORMER REPRESENTATION

Given: SHELL FORM XFMR
2 WDG XFMR
300 MVA

345 KV GRD WYE to 161 KV GRD WYE

Impedance =

Z_0 =

$I_{\text{Magnetizing Current @ 100\% Voltage}}$ = .78% @ 300 MVA

No Load Losses @ 100% Voltage = 257940 Watts @ 300 MVA

From Bus 2704

To Bus 2717

RR1 = 1.9572 % @ 100 MVA

XX1 = 1.9010 % @ 100 MVA

XC1 = 4273.5043 % @ 100 MVA

RR0 = 38768.7059 % @ 100 MVA

KK = 0

XX0 = .7

XC0 = 4273.5043 % @ 100 MVA

SUB 39 345/161/13.8 KV XFRM
USING 3 INDIVIDUAL TRANSFORMER REPRESENTATION

Given: SHELL FORM XFMR
2 WDG XFMR
64.5 MVA

345 GRD WYE to 13.8 KV DELTA

Impedance =

Z_0 =

$I_{\text{Magnetizing Current @ 100\% Voltage}} = 1 \times 10^{-95}\%$ @ 64.5 MVA

No Load Losses @ 100% Voltage = 1×10^{-89} Watts @ 64.5 MVA

From Bus 2704

To Bus 3704

RR1 = -184.4666 % @ 100 MVA

XX1 = - 69.0176 % @ 100 MVA

XC1 = $1.5504 \times 10^{99}\%$ @ 100 MVA

RR0 = $1.0000 \times 10^{99}\%$ @ 100 MVA

KK = 0

XX0 = .8

XC0 = $1.5504 \times 10^{99}\%$ @ 100 MVA

SUB 39 345/161/13.8 KV XFRM
USING 3 INDIVIDUAL TRANSFORMER REPRESENTATION

Given: SHELL FORM XFMR
2 WDG XFMR
64.5 MVA

161 KV GRD WYE to 13.8 KV DELTA

Impedance =

Z_0 =

$I_{\text{Magnetizing Current @ 100\% Voltage}} = 1 \times 10^{-95}\%$ @ 64.5 MVA

No Load Losses @ 100% Voltage = 1×10^{-89} Watts @ 64.5 MVA

From Bus 2717

To Bus 3704

RR1 = 14.1977 % @ 100 MVA

XX1 = 12.1406 % @ 100 MVA

XC1 = 1.5504×10^{99} % @ 100 MVA

RR0 = 1.0000×10^{99} % @ 100 MVA

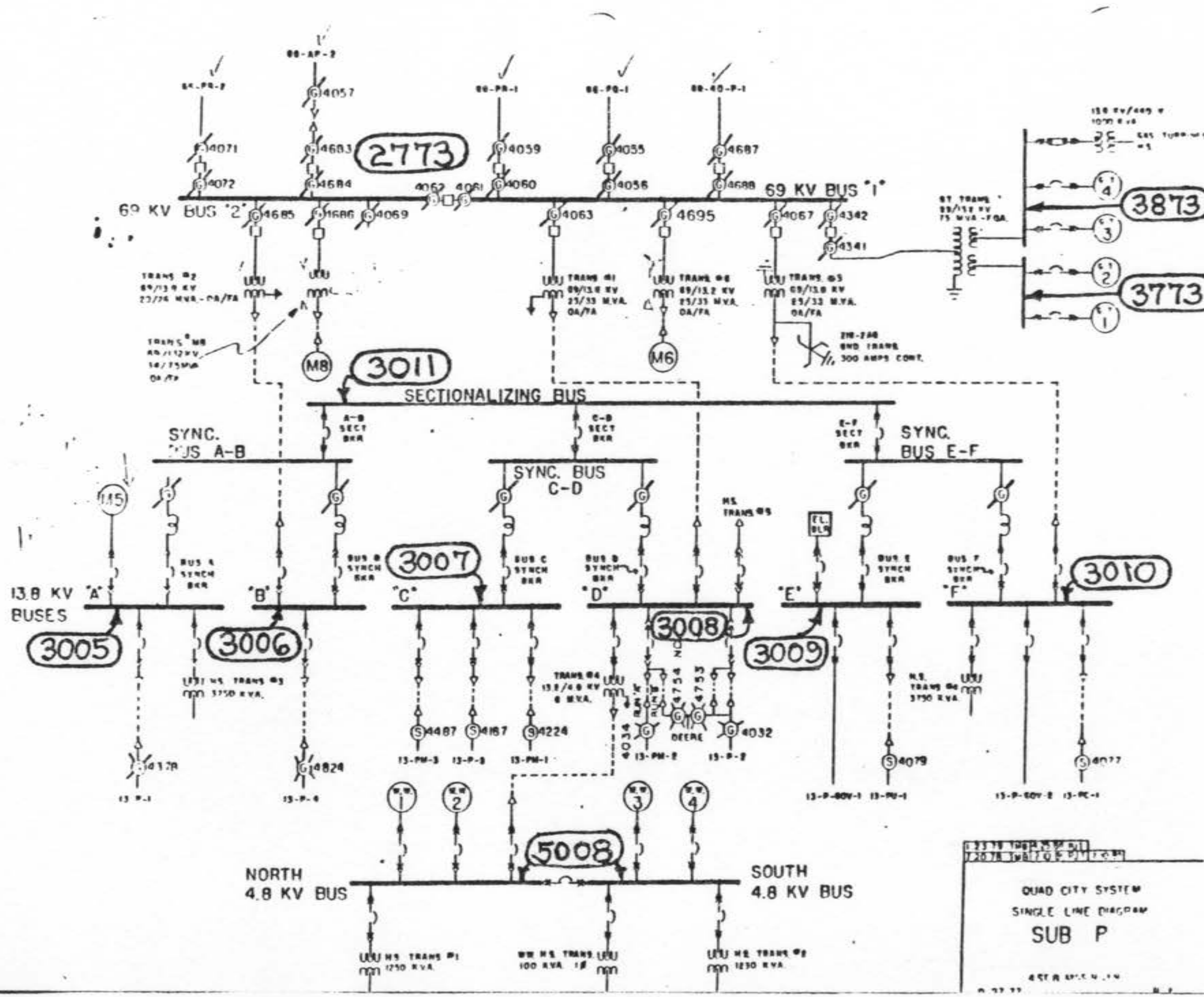
KK = 0

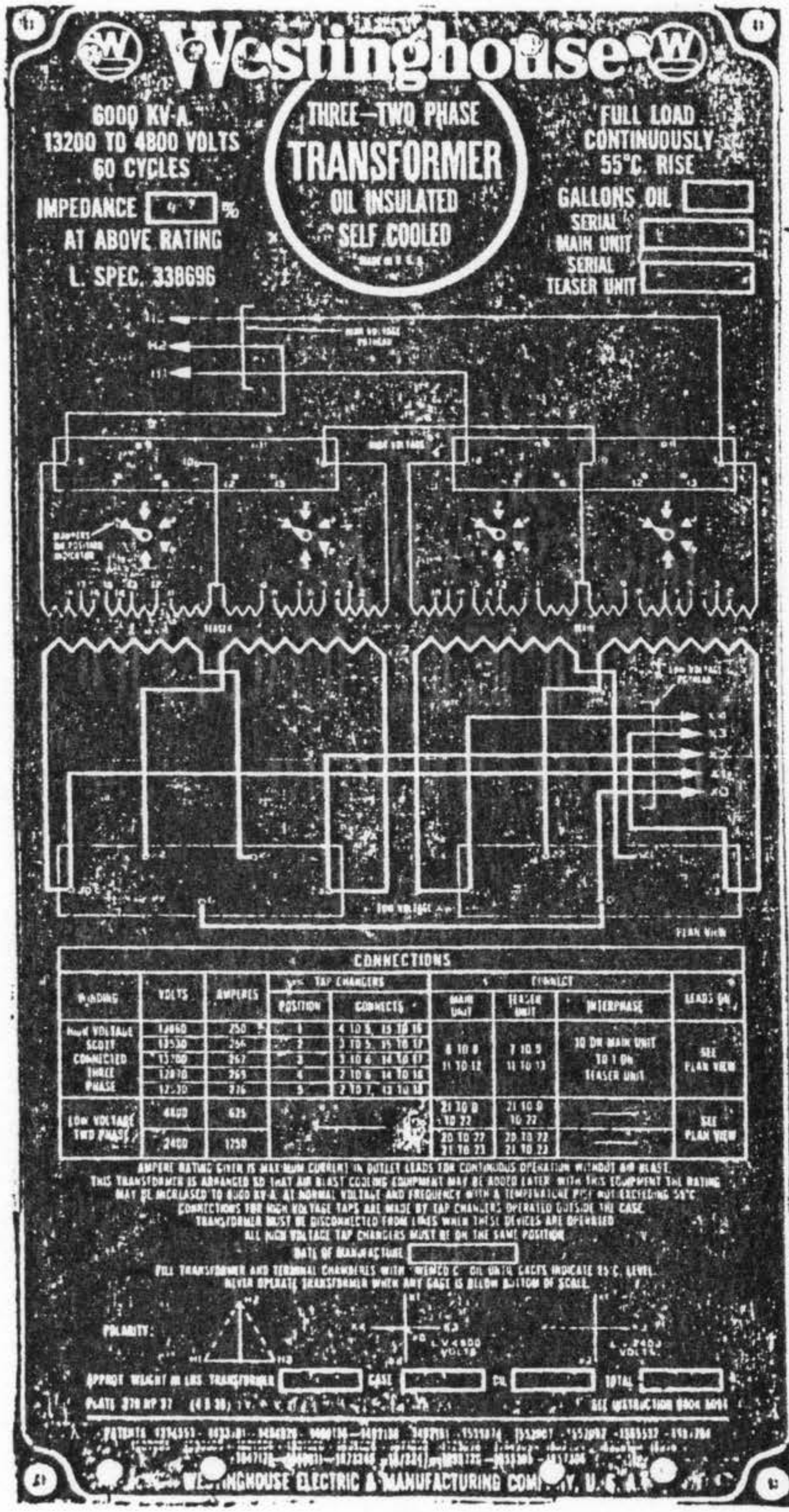
XX0 = .8

XC0 = 1.5504×10^{99} % @ 100 MVA

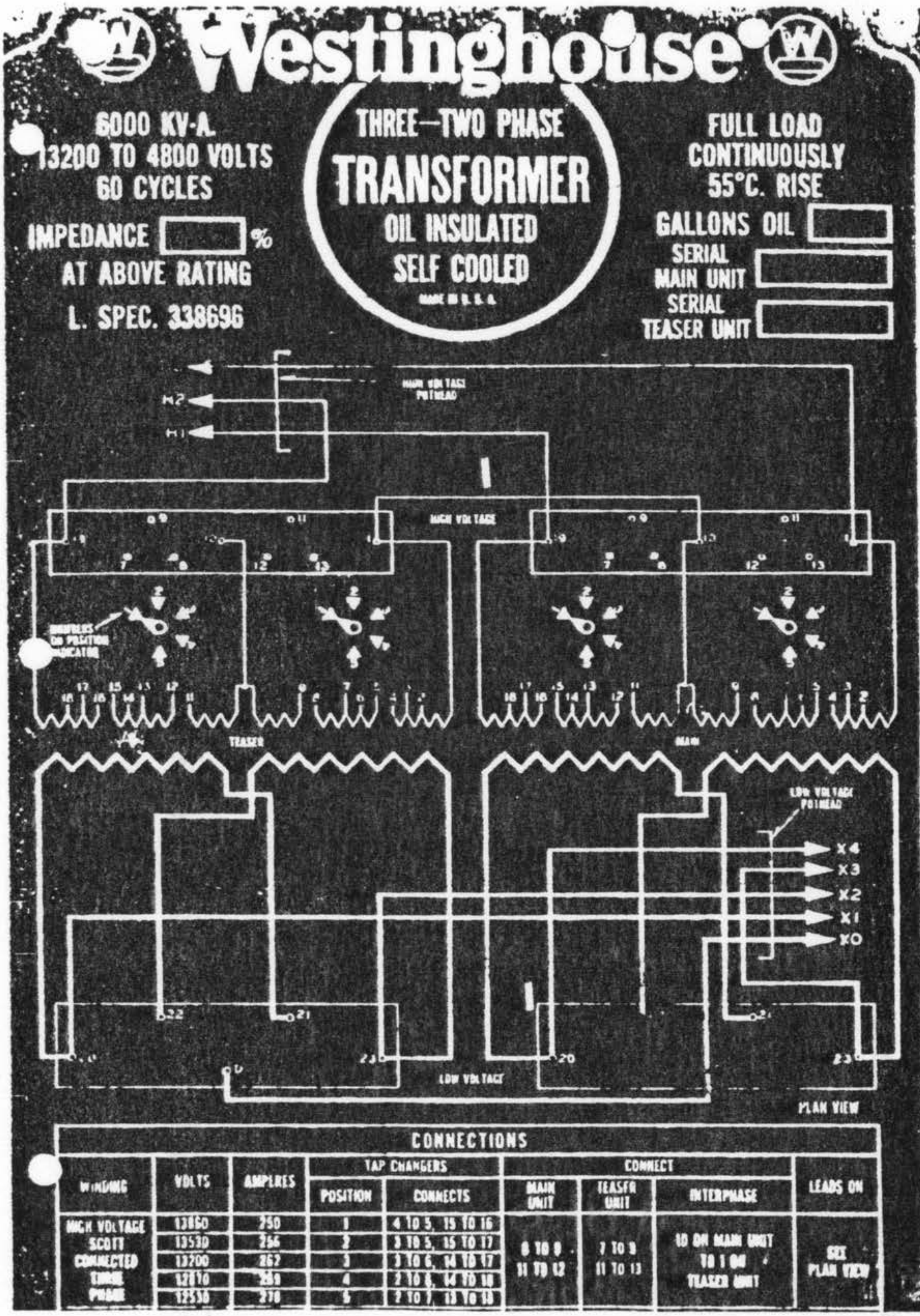
XIV. APPENDIX

G. THREE-TWO PHASE TRANSFORMER EXAMPLE


69 KV BUS "2"
69 KV BUS "1"
2773
3873
3773
3011
SECTIONALIZING BUS
SYNC. BUS A-B
SYNC. BUS C-D
SYNC. BUS E-F
13.8 KV BUSES
"A"
"B"
"C"
"D"
"E"
"F"
3005
3006
3007
3008
3009
3010
5008
NORTH 4.8 KV BUS
SOUTH 4.8 KV BUS
M8
M6
4057
4071
4072
4683
4684
4685
4686
4069
4062
4061
4059
4060
4055
4056
4687
4688
4063
4695
4067
4342
4341
4487
4167
4224
4034
4734
4733
4032
DEERE
4079
4077
4824
QUAD CITY SYSTEM
SINGLE LINE DIAGRAM
SUB P



"P"
MOL.
~~H.S.~~
POWER
TRANS.
4


Westinghouse
6000 KV-A.
13200 TO 4800 VOLTS
60 CYCLES
IMPEDANCE %
AT ABOVE RATING
L. SPEC. 338696
THREE—TWO PHASE
TRANSFORMER
OIL INSULATED
SELF COOLED
FULL LOAD
CONTINUOUSLY
55°C. RISE
GALLONS OIL
SERIAL
MAIN UNIT
SERIAL
TEASER UNIT
H2
H1
HIGH VOLTAGE
TEASER
X4
X3
X2
X1
X0
LOW VOLTAGE
PLAN VIEW
CONNECTIONS
WINDING
VOLTS
AMPERES
TAP CHANGERS
POSITION
CONNECTS
CONNECT
MAIN UNIT
TEASER UNIT
INTERPHASE
LEADS ON
SCOTT
13530
13200
262
4 TO 5, 15 TO 16
3 TO 5, 15 TO 17
11 TO 13
SEE
PLAN VIEW

Form 2362-3-2

ALLIS-CHALMERS MANUFACTURING COMPANY

MILWAUKEE, WISCONSIN

TRANSFORMER TEST REPORT Spec. 11626

Purchaser Moline Rock Island Manufacturing Company MOLINE H.S.

Date of Test 11-9-40 Purchaser's Order No. 59613 A-C Order No. 8170Y-1

Type OISC - 55° C Rise Phase 3-2 Cycles 60 Insulating Fluid ACU #3 Oil

Winding (1) 4800 Volts (2) 480 Volts (3) Volts
1250 Kva 1250 Kva Kva

Taps (1) F.C. 5040,4920,4680,4560 (2) Scott Taps *

RESISTANCES, EXCITING CURRENT, LOSSES AND IMPEDANCE—Based on Normal Rating unless otherwise stated. Losses and regulation are based on wattmeter measurements. For three-phase transformers the resistances given are the sum of the three phases in series.

Main and Teaser mounted in same tank.

Serial No.	Resistance in Ohms at 75° C (1)	(2)	(3)	Exciting Current Per Cent at 100% Voltage	No Load Loss in Watts 100% Voltage	4800 V to 480 V 625 Kva Load Loss	% Imp.	4800 V to 480 V 625 Kva Load Loss	% Imp.	4800 V to 480 V 1250 Kva Load Loss	% Imp.
	Total	Total		3Ø	3Ø	MAIN		TEASER		Total	Avg.
1722132-3	.255	.00255		1.50	3440	5374	4.01	6163	4.41	15120	4.21
1722134-5	.250	.00254		1.70	3470	5336	4.02	6094	4.33	14894	4.18
						Total Loss		Total Loss		Total Loss	
Average				1.60	3455	7104	4.02	7880	4.37	15007	4.20
Guarantee				3.00	4020	-	-	-	-	15460	-

REGULATION AT 75° C		100% PF	% PF	80% PF	% PF
	Average	1.00		3.25	
	Guarantee	1.10		4.00	

TEMPERATURE RISES are average rises in degrees C corrected to instant of shutdown.

Serial No. 1722132-3 with windings connected and loaded as follows:

(1) 4560 Volts 137 Amp. (2) 480 Volts 1500 Amp

(3) Volts Amp. until constant temperature has been reached.

	Temp. Rise of Windings by Resistance (1)	(2)	(3)	Guarantee	Top Fluid Temp. Rise	Ambient Temp. Ingoing Water	Idler or Room	Water Temp. Rise	Gallons per Min.	Pounds Pressure	Hot Spot Detector
	36.3	39.6		55	37.5		17.5				

INSULATION TESTS—If Impulse Tests are required, see separate Transformer Impulse Test Report.

APPLIED POTENTIAL TESTS — Voltage applied between each winding and all other windings connected to core and ground.	Voltage Rating of Winding Tested	Test Voltage Applied	Duration of Test in Seconds
	4800	26000	60
	480	10000	60

INDUCED POTENTIAL TESTS	200 cycles per sec. for 7200 cycles	2 times rated voltage across full winding; kv from kv line terminal to ground

REMARKS: * See Connection Diagram Dwg. G-931759

% Ex. Current 3Ø
@90% E.
Avg. 1.0
Guar. 1.9
@110% E.
Avg. 2.8
Guar. 5.3

% Efficiencies @ 75°C @100% PF.

Load	5/4	4/4	3/4	1/2	1/4
Average	98.67	98.84	98.97	99.01	98.68
Guarantee	98.63	98.79	98.91	98.92	98.51

I hereby certify this is a true report based on factory tests made in accordance with the Transformer Test Code C57.2 current edition of the American Standards Association ... transformer withstood the above insulation ...

Signed ... Date 8-24-50 Approved ...

blb

Copied from Test Report dated 11-27-40

REPORT OF TESTS
WESTINGHOUSE FORM 5401 B

DATE

PURCHASER Peoples Light Co.

WESTINGHOUSE GENERAL ORDER NO. DP-28612

RATING

SHOP ORDER NO. 22-R-48

ADDITIONAL TEST DATA

Serial	Watts Iron Loss 90 % Voltage	% Exciting Current 90% Voltage
2351494	5500 Watts	1.44%
2351495	5700 Watts	1.47%
Total 2 Units	11200 Watts	1.46%
Guar.	13270 Watts	1.5%

Serial	Watts Iron Loss 110% Voltage	% Exciting Current 110% Voltage
2351494	9600 Watts	4.92%
2351495	9900 Watts	4.75%
Total 2 Units	19500 Watts	4.83
Guar.	21460 Watts	7.3%

RATIO TESTS

Volts Applied	Applied on H.V. Term.	H.V. Tap Changer Position	Meas. On L.V. Term.	Volts Measured Serial 2351494	Volts Measured Serial 2351495
500	1, 8-9, 19 11-12	1	20, 21-22, 23	173.00	173.00
"	"	2	"	177.82	177.81
"	"	3	"	181.86	181.85
"	"	4	"	186.09	186.10
"	"	5	"	191.63	191.63
"	1, 8-9, 19 11-13	5	"	206.50	206.48
"	1, 7-9, 19 11-13	5	"	222.28	222.25
"		5	20-22, 21-23	111.13	111.12

ABOVE IS A TRUE AND CORRECT RECORD OF DATA OBTAINED FROM TESTS AT THE WORKS OF WESTINGHOUSE ELECTRIC CORPORATION

PAGE 2 OF 2 PAGES

SIGNED ________ ENGINEER

REPORT OF TRANSFORMER TESTS

COPY

WESTINGHOUSE ELECTRIC CORPORATION

P. mol. #3 #4 H.V. Trans #5

Customer Peoples Light Co.

Test — Customer's Order No. — G.O. DP-28612 S.O. No. 22-R-48 L-Spec. 338696

OISC-R Duplex Phase 3/2 Cycles 60 Insulating Fluid 011

Windings (1) 13200 Volts (2) 4800 Volts (3) Volts

6000 Kva (2) 6000 Kva (3) Kva

Taps (1) 13860 - 13530 - 12870 - 12530 F.C.

Taps (2) 2400 By series parallel

RESISTANCES, EXCITING CURRENT, LOSSES AND IMPEDANCE—Based on normal rating, unless otherwise stated. Losses and regulation are based on wattmeter measurements. For three-phase transformers the resistances are the sum of the three phases in series.

SERIAL NO.	RESISTANCE IN OHMS AT 75°C (1)	(2)	(3)	% EXCITE CURRENT AT 100% RATED VOLTAGE	NO LOAD LOSS WATTS AT 100% RATED VOLTAGE	13.2 Kv TO 4.8 Kv 3000 (D) Kva LOAD LOSS WATTS 75°C	% IMP 75°C	13.2 Kv TO 4.8 Kv 6000 (C) Kva LOAD LOSS WATTS 75°C	% IMP 75°C	Kv TO Kv Kva LOAD LOSS WATTS 75°C	% IMP 75°C
2351494 (A)	.1301	.01798		2.4	7150	14690	3.19				
2351495 (B)	.1299	.01777		2.5	7400	14680	3.22	32300	3.38		
				(E)	(E)	TOTAL LOSS WATTS 75°C		TOTAL LOSS WATTS 75°C		TOTAL LOSS WATTS 75°C	
AVERAGE				2.45	14550						
GUARANTEE				3.0	16380						

REGULATION AT 75°C		100% PF (D)	% PF	80% PF (D)	% PF
	AVERAGE	.54		2.33	
	GUARANTEE	.7		3.0	

TEMPERATURE RISES—Average rise in degrees C., corrected to instant of shutdown, of transformer.

No. 2351494 - 5 with windings connected and loaded as follows:

12.53 Kv 276 Amp. (2) 2.4 Kv 1250 Amp.

Kv Amp. until constant temperature rise was reached.

	RISE OF WINDINGS BY RESISTANCE (1)	(2)	(3)	(4)	GUARANTEE	TOP FLUID RISE	AMBIENT TEMP. INCOMING WATER	IDLER OR ROOM	WATER RISE	GALLONS PER MIN.	POUNDS PRESSURE
*	49.5	44.5	48.5	48.3	55	46.5		26			

INSULATION TESTS

APPLIED POTENTIAL TESTS	VOLTAGE RATING OF WINDING TESTED	TEST VOLTAGE APPLIED IN KV	DURATION OF TEST IN SECONDS
(Voltage applied between each winding and all other windings connected to core and ground.)	13200 4800	34 26	60 60

INDUCED POTENTIAL TEST: 2 times rated voltage across full winding; kv from kv line terminal to ground; at 120 cycles per second for 7200 cycles.

REMARKS * Winding identified as follows:
(1) H.V. Main unit (2) L.V. main unit (3) H.V. teaster unit (4) LV teaser unit
(A) Main Unit (B) Teaser Unit
(C) Main and Teaser Units connected for 3/2 phase operation
(D) As single phase units (E) Total for two units

I hereby certify that this is a true report based on factory tests made in accordance with the latest Transformer Test Code C57.2 of the American Standards Association; and that each transformer withstood the above insulation tests.

Signed ____ Date July 15, 1938 Approved ____ TRANSFORMER ENG. DEPT

Page 1 of 2 Pages

SUB P
TRANSFORMER #4

NOTE: This is a three-winding three to two-phase transformer

GIVEN: ? Form Transformer
3 WDG Transformer
6 MVA Transformer

13.2 KV DELTA to 4.8 KV STAR GROUNDED

Impedance = 3.38 % @ 13.2 KV @ 6 MVA
Impedance = 3.0925% @ 13.8 KV @ 6 MVA

Z_0 = 3.38 % @ 13.2 KV @ 6 MVA
Z_0 = 3.0925% @ 13.8 KV @ 6 MVA

$I_{\text{Magnetizing Current @ 100\% Voltage}}$ = 2.4+2.5% @ 6 MVA
= 4.9% @ 6 MVA

No Load Losses @ 100% Voltage = 7150+7400 Watts @ 6 MVA
= 14550 Watts @ 6 MVA

Assume Shell Form Transformer

FROM 3008

TO 5008

RR1 = 51.5413 % @ 100 MVA

XX1 = 51.5413 % @ 100 MVA

XC1 = 34013.6054 % @ 100 MVA

RR0 = 687285.2234 % @ 100 MVA

KK = 0

XX0 = .9

XC0 = 34013.6054 % @ 100 MVA

XV. APPENDIX

H. GROUNDING TRANSFORMER EXAMPLE

REPORT OF TRANSFORMER TESTS

WESTINGHOUSE ELECTRIC CORPORATION

Customer
Date of Test 9-27-41 Customer's Order No. — G.O. DI-34330 S.O. No. 52-A-780 L-Spec. 380338
Type SL - Grounding Phase 3 Cycles 60 Insulating Fluid 011
Windings (1) 13800 Volts / 8000 Kva (2) Volts Kva (3) Volts Kva
(1) 7970 to neutral for 1 min.

RESISTANCES, EXCITING CURRENT, LOSSES AND IMPEDANCE—Based on normal rating, unless otherwise stated. Losses and regulation are based on wattmeter measurements. For three-phase transformers the resistances are the sum of the three phases in series.

SERIAL NO.	RESISTANCE IN OHMS AT 75°C (1)	(2)	(3)	% EXCITE CURRENT AT 100% RATED VOLTAGE	NO LOAD LOSS WATTS AT 100% RATED VOLTAGE	H-2 Kv TO X-0 Kv (per phase) Kva LOAD LOSS WATTS 75°C	% IMP 75°C	Kv TO Kv Kva LOAD LOSS WATTS 75°C	% IMP 75°C	Kv TO Kv Kva LOAD LOSS WATTS 75°C	% IMP 75°C
3012677	3.32 Total			.303	1950	111150	76.2				
						TOTAL LOSS WATTS 75°C		TOTAL LOSS WATTS 75°C		TOTAL LOSS WATTS 75°C	
AVERAGE						113100					
GUARANTEE											

REGULATION AT 75°C		100% PF		% PF	80% PF		% PF
	AVERAGE						
	GUARANTEE						

TEMPERATURE RISES—Average rise in degrees C., corrected to instant of shutdown, of transformer.
Serial No. 3012677 with windings connected and loaded as follows:
(1) 13.8 Kv 335 Amp. (2) Kv Amp.
(3) Kv Amp. until constant temperature rise was reached.

	RISE OF WINDINGS BY RESISTANCE H2 (1) X0	H1 (2) X0	H3 (3) X0	GUARANTEE	TOP FLUID RISE	AMBIENT TEMP. INCOMING WATER	IDLER OR ROOM	WATER RISE	GALLONS PER MIN.	POUNDS PRESSURE
3012677	38.5	39.5	37.5				27			

INSULATION TESTS

APPLIED POTENTIAL TESTS	VOLTAGE RATING OF WINDING TESTED	TEST VOLTAGE APPLIED IN KV	DURATION OF TEST IN SECONDS
(Voltage applied between each winding and all other windings connected to core and ground.)	13800	34	60

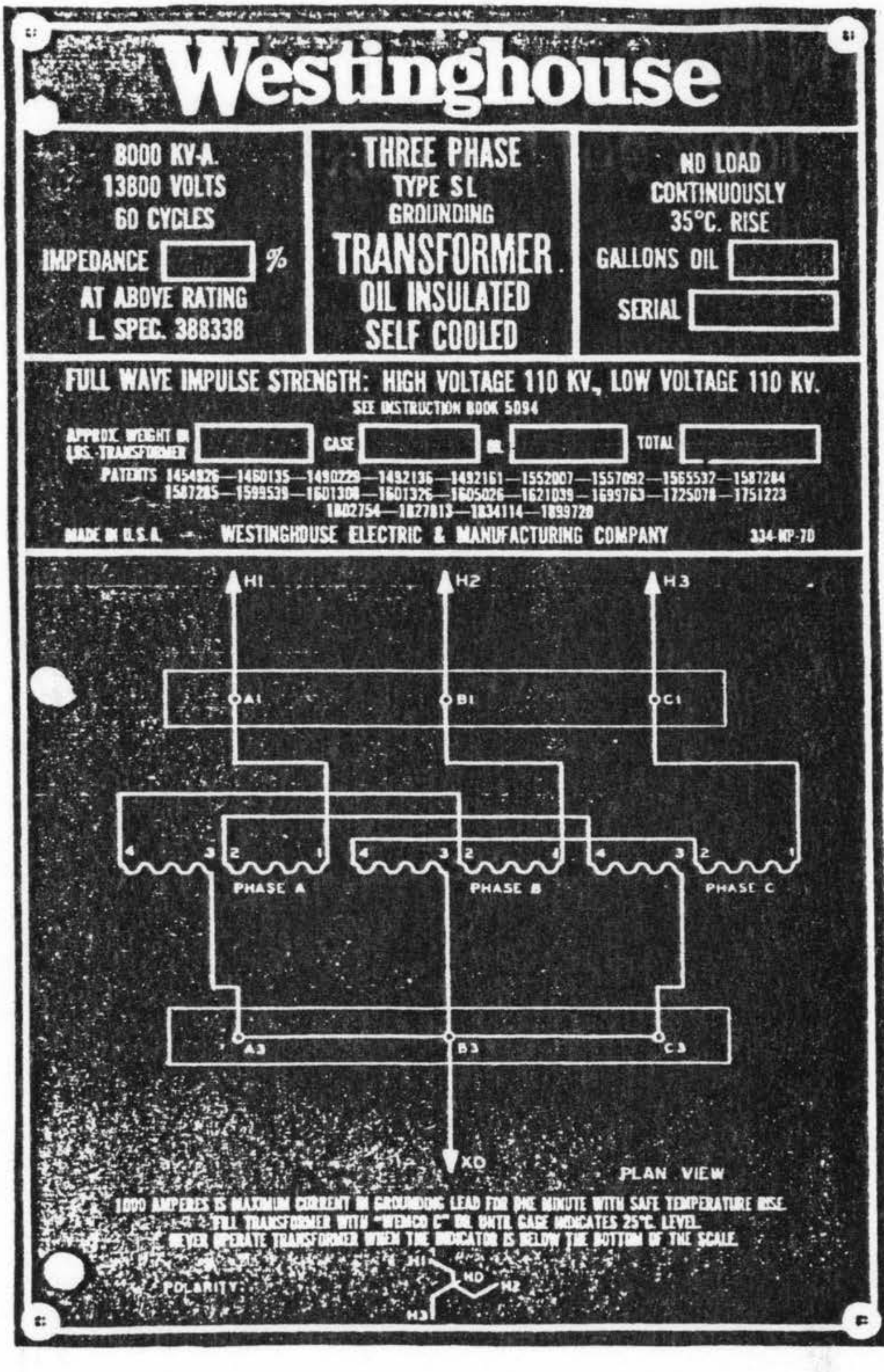
INDUCED POTENTIAL TEST
2 times rated voltage across full winding;
kv from kv line terminal to ground
at cycles per second for 1 min. cycles

REMARKS

I hereby certify that this is a true report based on factory tests made in accordance with the latest Transformer Test Code C57.2 of the American Standards Association; and that each transformer withstood the above insulation tests.

Signed Date 8/28/50 Approved TRANSFORMER ENG. DEPT.

Page 1 of 1 Pages



ZIC-3?
TR #1

13 Kv
Bus #1
(1975)

SUB A GROUNDING TRANSFORMER
(Treat Like Linear Element to Ground)

NOTE:
1. Put in "Small" values for RR1. (This doesn't exist in transformer model.)
2. Put in "Large" values for XX1. (This is equivalent to XC1 in transformer model.)
3. Put in "Small" values for XC1. (This is equivalent to RR1 in transformer model.
4. Show linear element as connected in shunt to ground; i.e., KJQ = 0.
5. Only Zero sequence values need be used.
6. RR1 and XC1 are series impedance values of grounding transformer.

R_{Series} = 3.32 ohms

$Z_{1,2,0}$ = 76.2 % @ 13.8 KV @ 8 MVA

$I_{Exciting\ @\ 100\%\ V}$ = .263 %

$Losses_{N.L.\ @\ 100\%\ V}$ = 1950 Watts

Bus # 3763

RR1 = 174.3331 % @ 100 MVA

XX1 = 475285.1711 % @ 100 MVA

XC1 = 952.5000 % @ 100 MVA

$$Z\ (pu) = \frac{Z\ ohms}{Z\ base} = \frac{3.32\ ohms}{23.805\ ohms} = .1395\ pu\ @\ 8\ MVA$$

$$= 1.7438\ pu\ @\ 100\ MVA$$

$$= 174.3331\ \%\ @\ 100\ MVA$$

XVI. APPENDIX

I. REVISED HARMONIC ANALYSIS PROGRAM INSTRUCTIONS

HARMONIC ANALYSIS PROGRAM

The harmonic analysis program developed at Iowa State University accepts data input in a formatted card image form. Several options exist in the type of harmonic analysis to be made. The selection of a particular option will influence the type, amount, and order of input data. The different options are described first, followed by the required input data for each of the possible combinations of options.

Card Image #1

The first card image read by the program has the following format:

N	VCBASE	LHARM	IPLOT	IVC	IUNIT
I3	F10.2	I3	I3	I3	I3

The first option which must be specified is whether a sampled waveform or a converter current waveform is to be used as the harmonic source. The option is specified in the IVC field of the first card image as follows:

IVC = integer < -1	current harmonic magnitudes
IVC = -1	voltage harmonic magnitudes
IVC = 0	voltage waveform
IVC = 1	converter current source
IVC = any other integer	current waveform

The choice of harmonic source type determines the interpretation of input variables N and VCBASE as follows:

For IVC = integer less than -1 (current harmonic magnitudes)

N = ignored

VCBASE = base value of current

For IVC = -1 (voltage harmonic magnitudes)

N = ignored

VCBASE = base value of voltage

For IVC = 0 (voltage waveform)

N = number of sampled data points

VCBASE = base value of voltage

For IVC = 1 (converter current source)

N = number of pulses per cycle

VCBASE = base value of voltage

For IVC = any other integer (current waveform)

N = number of sampled data points

VCBASE = base value of current

The remaining input variables on the first card image are defined as:

LHARM = highest order harmonic to be analyzed

IPLOT = 0	no plots generated
IPLOT = any other integer	plots of voltage or current waveforms at the harmonic source will be generated
IUNIT = 0	input data is assumed to be actual quantities
IUNIT = any other integer	input data is assumed to be in per unit

Card Images #2

If the converter current source option is selected (IVC = 1 on the first card), then the second card has the following format.

POW	ALFA	OVLP
F10.2	F10.2	F10.2

POW = power rating of the converter in MW

ALFA = delay angle in degrees

OVLP = overlap angle in degrees

If either the voltage waveform or current waveform option is selected (IVC = 0 or integer greater than 1 on the first card), then Card Images 2 through 1 + N/8 have the following format.

A(K)	A(K+1)	A(K+2)	A(K+3)	A(K+4)	A(K+5)	A(K+6)	A(K+7)
F10.2	F10.2	F10.2	F10.2	F10.2	F10.2	F10.2	F10.2

A(K) = K^{th} value of the sampled waveform.

If either the voltage harmonic magnitudes or current harmonic magnitudes option is selected (IVC = -1 or integer less than -1 on the first card), then the next set of card images have the following format.

	IY		VCM		VCA
3X	I3	2X	F12.8	2X	F12.8

where IY = harmonic order
VCM = magnitude of harmonic component
VCA = phase of harmonic component

The program will continue reading this type of card image until a card with IY = 999 is read.

Card Images #3

The card images following the converter or waveform specification are the power system element specification cards. All impedance values are entered in % on a 100 MVA base. The format for these cards is:

KJ	KJP	KJQ	KCT	RRI	XXI	XCI	RRO	XXO	XCO	KK	XLM
I1	I4	I4	I2	F10.4	F12.4	F10.8	F9.4	F9.4	F10.8	I2	F6.4

The type of element is defined by the KJ field as follows:

KJ ≤ 1 transmission lines

KJ = 2 transformers

KJ = 3 generators or linear elements

KJ ≥ 4 loads

The definitions of the remaining fields depends on the element type selected.

Transmission lines (KJ ≤ 1)

KJP = node number at one end of the line

KJQ = node number at the other end of the line

KCT = circuit number

RR1 = positive/negative sequence resistance in %

XX1 = positive/negative sequence reactance in %

XC1 = positive/negative sequence susceptance in %

RRO = zero sequence resistance in %

XXO = zero sequence reactance in %

XCO = zero sequence susceptance in %

KK = voltage and bundle code

first digit	voltage (KV)
1	69
2	115
3	132
4	138
5	161
6	230
7	345
8	500
9	13.80

second digit = number of bundles per conductor

XLM = length in miles

<u>Transformers</u> (KJ = 2)

KJP = node number at one end of the transformer

KJQ = node number at the other end of the transformer

KCT = internal node number at center of T model

RR1 = positive/negative sequence series reactance in %

XX1 = zero sequence series reactance in %

XC1 = positive/negative sequence shunt reactance in %

RRO = positive/negative/zero sequence core loss resistance in %

XXO = connection code for zero sequence

	If KK = 0 and
$1.0 \leq$ XX0	delta-delta, wye-wye, delta-wye, or wye-delta
$0.9 \leq$ XX0 < 1.0	delta-grounded wye
$0.7 <$ XX0 < 0.9	grounded wye-delta
XX0 ≤ 0.7	grounded wye-grounded wye-delta tertiary with zero sequence core loss

If KK $\neq$ 0, then XX0 is not used.

XC0 = zero sequence shunt reactance in %

KK = connection code for zero sequence

If KK = 0, the connection is determined by XX0.

KK = 1	grounded wye-delta-delta tertiary
KK = 2	delta-grounded wye-delta tertiary
KK = 3	wye-grounded wye-delta tertiary
KK = 4	grounded wye-wye-delta tertiary
KK $\geq$ 5	grounded wye-grounded wye-delta tertiary without zero sequence core loss

XLM = ignored

<u>Generators or linear elements</u> (KJ = 3)

KJP = node number at one end of the element

KJQ = node number at the other end of the element. For generators or if the linear element is connected in shunt to ground, use KJQ =0.

KCT = circuit number

RR1 = series resistance for generator or linear elements in %

XX1 = positive/negative sequence reactance for generator or inductive element in %
= positive/negative/zero sequence reactance for capacitive element in % (enter a negative value for capacitors)

XC1 = zero sequence reactance for generator or inductive element in %
= ignored for capacitive element

RR0 = ignored

XX0 = ignored

XC0 = ignored

KK $\neq$ 1 for generator or inductive element

= 1 for capacitive element

XLM = ignored

Loads (KJ $\geq$ 4)

KJP = node number of load

KJQ = 0 (connected to ground)

KCT = circuit number

RR1 = power in MW

XX1 = reactive volt-amperes in MVAR

XC1 = ignored

RR0 = ignored

XX0 = ignored

XC0 = ignored

KK = type code

KK $\leq$ 1 residential, 50% motor load

KK = 2 commercial, 60% motor load

KK $\geq$ 3 industrial, 70% motor load

XLM = ignored

The end of the power system element specification card images is determined by a card image with KJP = 9999. All other fields on this card image are ignored.

Card Image #4

The fourth type of card image specifies the location and other information about the harmonic source. The format for these cards is:

JF	NAME	IOPT	PHA	FUND	(complex)
14	47	11	F10.2	F10.2	F10.2

JF = harmonic source bus number location

NAME = bus name at harmonic source

IOPT = analysis option code

IOPT $\leq$ 0 print harmonic analysis for elements adjacent to the harmonic source bus only.

IOPT = 1 print harmonic analysis for all elements in the system

With either of these options, up to four different card images may be inserted to analyze the system with the harmonic source in different locations. To end the harmonic source specification card images, the last card should have JF = 9999. All other fields on this card are ignored.

IOPT = 2   combined analysis of two harmonic sources

IOPT = 3   combined analysis of two harmonic sources

Identical harmonic sources may be placed at two separate locations simultaneously with these options. IOPT = 2 card image specifies the first location, and the IOPT = 3 card image specifies the second. It is not necessary to follow these cards with an end card with JF = 9999.

PHA = phase angle of the harmonic source waveforms

This field is intended for use with the combined analysis option to specify a phase difference between the two sources.

FUND = the complex magnitude of the fundamental component of the harmonic source waveform in per unit.

This field is required to achieve a reasonable plot of the harmonic source waveform. If no plot is to be made, then this field may be left blank.

Size Limits

This program will accept up to 500 nodes. A node is any place where two or more elements connect (usually a bus). However, each transformer requires one internal node in this program. Therefore, the number of buses plus the number of transformers will be the number of nodes required.

With this program, each transmission line is represented as three elements, each transformer is represented as three elements, each generator or linear element is represented as one element; and each load is represented as one element. Therefore, the total number of elements need will be:

Total Number of Elements = 3 X (number of transmission lines + number of transformers) + number of generators + number of linear elements + number of loads.

This program will accept up to 4000 elements.

The size limits are determined by the array dimensions in the program and could be increased or decreased. The limits selected above were arbitrarily chosen as large enough to accomodate most studies of harmonic propagation in power systems.

Distribution Systems

The same techniques used for harmonic analysis of transmission systems may be used to analyze distribution systems. The program has been used to determine where harmonic resonance occurs on industrial plant distribution systems, and to verify the effectiveness of corrective actions.

NOTES:

1. On the connection code for transformers, the program assigns the first bus number entered to correspond to the first type of winding. The second bus number entered corresponds to the last type of winding (see Page 4).

   As an example: KK = 0 and $0.9 \leq XX0 < 1.0$

   The first bus number entered would go with the DELTA winding. The second bus number entered would go with the grounded wye.

2. The program as it is currently set up uses a 100 Mega-voltampere base.

XVII. APPENDIX

J. SAMPLE PROGRAM OUTPUT

The output data shown in this appendix correspond to the case where the harmonic source values are entered as the measured voltage harmonic values at Substation A.

```
N =    0     VCBASE =   13.80     LHARM =  15     IPLOT =   0     IVC =  -1     IUNIT =   1
HARMONIC VALUES
ORDER          MAG          ANG
    1          1.0000           0.00
    2          0.0063           0.00
    3          0.0040           0.00
    4          0.0050           0.00
    5          0.0355           0.00
    6          0.0025           0.00
    7          0.0089           0.00
    8          0.0016           0.00
    9          0.0025           0.00
   10          0.0040           0.00
   11          0.0282           0.00
   12          0.0011           0.00
   13          0.0045           0.00
   14          0.0018           0.00
   15          0.0020           0.00
  KJ  KJP  KJQ  KCT       RR1            XX1            XC1              RRO           XXO          XCO           KK    XLM

  1 2701 2702    1      0.0590         0.6380       10.83199980        0.6180        2.3750       6.89290047  72    12.74
*****************************************************************************************************************************
( ALL BUT THE FIRST AND LAST LINES OF SYSTEM DATA WERE DELETED HERE FOR CLARITY )
*****************************************************************************************************************************
  4 3050    0    1      1.0000         0.8500        0.00000000        0.0000        0.0000       0.00000000   3     0.00
XXX HARMONICS OF ORDER      2

*** CONVERTER AT BUS 3763   CONVERT   ***      IOPT =  1      PHA =        0.00FUND =        0.00       0.00
HARMONIC CURRENT =       0.0429 MAG      -87.50 ANG               HARMONIC VOLTAGE =        0.0063 MAG          0.00 ANG
     FROM            BUS VOLTAGE             TO      CIRCUIT       TERM CURRENT FLOW              SHUNT ELEMENT    SERIES ELEMENT
     BUS        MAG            ANG           BUS     NUMBER       MAG          ANG              R           X           R              X
        15         0.0005        -6.81
                                             4660       1         0.0033       -96.30          0.00         0.00      0.000000      0.035637
                                                0       1         0.0000       -66.14         38.08        64.22      0.000000      0.000000
                                             2660       1         0.0033        83.75          0.00         0.00      0.000000      0.035637
        50         0.0016        -6.60
                                             3766       1         0.0001       -61.12          0.00         0.00      0.000000      0.372000
                                                0       1         0.0000       -58.95        431.81       559.75      0.000000      0.000000
                                             2766       1         0.0001       118.92          0.00         0.00      0.000000      0.372000
*****************************************************************************************************************************
( ALL BUT THE FIRST TWO AND LAST TWO BUS DATA VALUES WERE DELETED HERE FOR CLARITY )
*****************************************************************************************************************************
      5763         0.0019         0.08
                                                0      12         0.0001       -33.90         14.15         9.54      0.000000      0.000000
                                                0      13         0.0001       -33.90         14.15         9.54      0.000000      0.000000
                                                0      15         0.0001       -33.90         14.15         9.54      0.000000      0.000000
                                             3763      12         0.0001       145.67         -4.13    -13330.21      0.690848      0.441552
                                             3763      13         0.0001       145.63         -4.78    -13330.32      0.689743      0.441522
                                             3763      15         0.0001       147.08         -2.62    -13332.40      0.763293      0.461555
      8776         0.0000         0.00
                                                0       1         0.0000         0.00          0.00         4.81      0.000000      0.000000
                                              804       1         0.0000         0.00          0.00         0.00      0.000000      0.267082
HARMONIC DISTORTION FACTOR

     BUS           HDF (%)

      75           0.1485
     108           0.4181
     109           0.4184
     135           0.1238
     140           0.1692
     171           0.3093
     181           0.1700
     184           0.1700
     187           0.1700
     195           0.1349
```

230	0.1275
391	0.1484
394	0.2443
561	0.1405
564	0.1587
567	0.1587
801	0.1200
804	0.1177
807	0.1227
810	0.1227
910	0.1302
2081	0.2094
2087	0.2093
2471	0.1237
2472	0.1138
2481	0.1525
2524	0.2074
2652	0.2050
2658	0.1775
2660	0.1505
2668	0.1716
2695	0.1612
2701	0.1290
2702	0.1240
2704	0.1282
2707	0.1114
2708	0.1027
2709	0.1201
2711	0.1522
2712	0.1366
2713	0.1449
2714	0.1730
2715	0.2079
2716	0.1683
2717	0.1699
2719	0.1911
2720	0.1743
2721	0.1382
2723	0.1509
2724	0.1374
2725	0.1398
2726	0.1388
2727	0.1430
2728	0.1409
2729	0.1441
2730	0.1611
2731	0.1790
2732	0.1671
2735	0.1740
2736	0.1435
2737	0.1522
2739	0.2322
2740	0.1664
2741	0.1499
2742	0.4783
2743	0.6737
2744	0.4021
2745	0.4078
2746	0.0000
2747	0.2485
2748	0.1747
2749	0.1654
2750	0.1712
2751	0.1732
2752	0.1830
2753	0.7804

2754	0.4424
2755	0.6961
2756	0.3947
2757	0.1932
2758	0.7810
2759	0.1630
2760	0.1470
2761	0.1721
2762	0.0000
2763	0.7064
2764	0.6583
2765	0.4210
2766	0.4762
2767	0.3362
2768	0.2627
2769	0.1675
2770	0.1660
2771	0.2010
2772	0.2242
2773	0.3007
2774	0.1839
2775	0.1598
2776	0.1177
277[illegible]	0.1227
278[illegible]	0.12[illegible]7
279[illegible]	0.1227
280[illegible]	0.1449
280[illegible]	0.0000
2903	0.1092
2904	0.1440
2905	0.1386
2906	0.1258
2907	0.1404
2908	0.1371
2909	0.1183
2910	0.1135
3001	0.3334
3002	0.6764
3003	0.6808
3004	0.5186
3005	0.2750
3006	0.5152
3007	0.3790
3008	0.2280
3009	0.6064
3010	0.2730
3011	0.2121
3013	0.3706
3021	0.0000
30[illegible]	0.1392
3050	0.1717
3088	0.0000
3[illegible]71	0.2632
3498	0.3193
3701	0.1358
3707	0.0734
3713	0.1364
3715	0.1379
3716	0.1494
3721	0.0955
3724	0.1420
3725	0.1392
3726	0.9083
3727	0.5683
3728	0.2202
37[illegible]9	0.2976

3730	0.6887
3731	0.3997
3732	0.3934
3740	0.1837
3742	0.4435
3743	1.1172
3744	0.8794
3746	0.0000
3747	1.6192
3748	0.3427
3749	0.5163
3750	0.3990
3751	0.2641
3752	0.2997
3753	0.7664
3754	0.66[illegible]
3755	0.6027
3756	2.0078
3757	0.6489
3758	1.4795
3759	0.3276
3760	0.1784
3763	4.7698
3764	1.2624
3765	0.1379
3766	0.87[illegible]
3768	1.0984
3769	1.2180
3770	0.4473
3771	0.3023
3773	0.1227
3776	0.1130
3813	0.2944
3821	0.1381
3825	0.0000
3827	0.3589
3828	0.2243
3829	0.2652
3844	0.8691
3848	0.6259
3851	0.2925
3854	0.5908
3855	0.6032
3856	1.2617
3857	0.3569
3859	0.4151
3863	1.9370
3866	0.9200
3868	0.5108
3869	0.6377
3872	2.7880
3873	0.1235
3925	0.1392
3963	0.4012
4007	0.2159
4008	0.1127
4018	0.0768
4028	0.0768
4471	0.0566
4660	0.0933
4763	3.6615
4802	0.0000
4903	0.0387
4905	0.0752
5008	0.0494
5763	4.6963