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Comparative Testing Using Analog Model Power Systems, Digital Model Power Systems and Portable Test Sets

COMPARATIVE TESTING USING ANALOG MODEL POWER SYSTEMS, DIGITAL MODEL POWER SYSTEMS AND PORTABLE TEST SETS

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Background

Before the advent of Model Power System testing of protective relay systems, relays had to be judged on the basis of performance on actual power system applications. The initial relays designed to protect power systems were electromechanical. These relays were designed on the basis of the steady state conditions of the power systems. Because the relays were generally slow to respond to fault conditions, this method of design was adequate. Utilities could evaluate the performance of a specific relay design based on years of performance on their own, or another utilities power system. This was possible due, in part, to the long life of the design of an electromechanical relay.

Model Power System evaluation of protective relay designs became common in the early 1960's with the introduction of high speed solid state protective relay systems. The faster operating times of the relays caused them to respond to transient signals that did not affect the performance of the slower electromechanical design. It became apparent that high speed solid state relays designed to meet steady state criteria only were insecure when applied to actual power systems. Specific examples are the response to the transients on series compensated systems and the response to transients associate with capacitive coupled voltage transformers (CVT's). As with the electromechanical designs, the solid state relay product life is generally long enough for the utilities to evaluate performance on actual systems.

Many recent relay systems are digital in design. These digital systems often represent a dramatic departure from the previous electromechanical and solid state systems that they are intended to replace. Therefore the experience gained on previous designs may be meaningless in the evaluation of a new digital system. Some digital relays use digital techniques to simulate the measuring functions of previous relay designs, while others use new approaches that were not available in earlier technologies. However, even if the digital relay is based on analog relay designs, the system must be proven.

Model Power System Simulation

Early Model Power Systems were generally based on an AC system using inductors, resistors, and capacitors to simulate the secondary currents and voltages that the relays would see in actual use. These simulators supplied sufficient power levels to directly drive the relays without-interposing amplifiers. Other simulations are based on low power level models in which more of the power system can be represented due to the lower cost of the individual elements. Since the primary voltage and current on these simulators is less than the actual secondary values, amplifiers are required to step the levels up before the signals are supplied to the relays. Today, many new simulators are based on digital simulations of the power system such as the Electro - Magnetic Transients Program (EMTP). These simulations also require amplifiers to interface with the relays, but provide the greatest simulation accuracy of a given power system.

Relay Performance Evaluation

Model Power System testing of new relays designs must be an integral part of the development cycle of a protective relay system to insure that the final design will perform as expected on the power system. This is much more critical with digital relay designs than it was with electromechanical or solid state designs. In a discrete hardware relay such as a solid state relay, the effects of a design modification can be easily verified. In a software based relay, the effects of a coding change are much harder to evaluate. A change in one module of the program may cause problems in a totally unrelated section of the program. For this reason, Model Power System evaluation of the relay performance is extremely critical, and must be performed for every software revision.

Customer Evaluation

Since the design life of digital components is short relative to electromechanical and solid state designs, utilities will not have as much field experience data on which to evaluate various relay designs. They will be forced to use manufacturers data from testing on simulators or to perform their own evaluation testing. Analog Model Power Systems were generally too expensive for the average utility to justify the cost. At the present time, portable test equipment that will supply “pseudo-transient” waveforms is available to provide relay users with a means to test beyond the normal steady state testing. These test sets do not simulate power system transients, but rather produce sets of steady state 60 Hz waveforms without the proper transition between steady state conditions. In the future, amplifier based simulators using digitally developed currents and voltages can provide a cost effective means for a utility to test a relay for a specific application. Recent developments in portable test equipment indicate that true power system transient waveforms can be reproduced in the field. The source of the waveforms may be from digital simulation (EMTP) or even from actual fault data captured on a Digital Fault recorder.

Waveform Comparison

Appendices I and II incorporate two papers showing current and voltage waveforms captured from an analog simulator, an EMTP simulation, and a portable test set.

The first paper, “Analog vs Digital Modeling of Power Systems”, compares waveforms produced on the GE Analog Model Power System with waveforms produced using the Electro-Magnetic Transients Program (EMTP) for several system configurations. In general, the study shows that either type of power system simulation can produce good results. There are advantages and disadvantages to both approaches which are dependent upon the purpose of the testing. An EMTP model of a power system can include much more detail than the typical analog model, however the relay can not interact with the EMTP model. For example, when the relay tips, the EMTP breaker cannot respond by producing a trip. Thus, while the EMTP produces an accurate model of the initial currents and voltages, it can not exactly duplicate the complete fault cycle of fault, trip, and reclose. A second area of concern is the transients introduced by the current and voltage transducers. The EMTP program should include a capacitive coupled voltage transformer (CVT) model and a current transformer which includes the effect of saturation in order to properly evaluate the performance of a relay system.

The second paper, “Comparative Testing Using Digital Simulation and an Analog Model Power System” compares the results of various testing on a distance relaying scheme using both an analog model power system and portable test equipment capable of “pseudo-transient” testing. Pseudo-transient testing is a term introduced by Henville and Jodice (Ref. 1) to describe the use of several sets of steady state fundamental frequency current and voltage waveforms to simulate fault conditions with portable test equipment. However, typical portable test equipment is not designed to produce dc offset in the current waveforms. Thus the current waveforms supplied to the relay do not correspond to the actual waveshapes that the relay will see in use on a power system. The lack of the dc component introduces a questionable error into the performance of the relay system. The effect may be minor on a distance unit, but substantial on an overcurrent unit. In addition the effect on the performance may vary between relay designs and/or relay manufacturers. In addition, the test sets cannot duplicate high frequency components of the currents and voltages to evaluate the response of the relay to those transients. Newer test sets are now available that can duplicate a random waveform on a point by point basis. Future testing with these portable sets may provide a means to supply the relay with current and voltage waveforms similar to those now available using the Digital Model Power System approach.

Conclusions

An Analog Model Power System, a Digital Model Power System, or a Portable Test Set may supply the relay engineer with useful data concerning a particular relay system. The purpose of the testing will determine which method should be used by the engineer. Routine maintenance testing is best performed with a minimum of test equipment such as portable test equipment rather than model power systems. Pseudo-transient testing provides additional test information as to the performance of the relay system and may show changes in the performance with time before the normal steady state testing reveals a problem. The pseudo-transient tests, however, do not provide an adequate means of evaluating the expected performance of a relay on the power system. A relay design evaluation must include waveforms that the relay will see in actual use. CVT transients, dc offsets, CT saturation, heavy load flow, high frequency transients, breaker operations, etc. are all a part of a protective relays environment and must be included in a comprehensive evaluation of a relays performance. Efforts are under way to incorporate new models in the EMTP to enhance its ability to simulate the actual relay environment (Ref. 2&3). A meaningful evaluation of the performance of a protective relay system must include more than the mere collecting of trip times. The relay response for known problem areas must be included in the study.

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2. M. Kezunovic, et al, "DYNA-TEST Simulator for Relay Testing Part I: Design Characteristics", a paper presented at the IEEE Winter Power Meeting, 1991.

3. M. Kezunovic, et al, "DYNA-TEST Simulator for Relay Testing Part II: Performance Evaluation", a paper presented at the IEEE Winter Power Meeting, 1991.

ANALOG VS DIGITAL MODELING OF POWER SYSTEMS

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INTRODUCTION

This paper will discuss the differences between modeling a power system using a high power analog model and a digital model. The analog model will based on the GE Model Power System (MPS), located at the Malvern, PA, GE Protection and Control headquarters. The digital implementation discussed will be based on the Electro-Magnetic Transient Program (EMTP) using the facilities in the GE Schenectady, NY plant. The current and voltage waveforms produced by the two simulations will be compared, and the models and test methods will be discussed.

MODELING TECHNIQUES

GE Model Power System

The GE Model Power System (MPS) is a three phase transmission line simulator operating at 460 volts. The MPS has been used to simulate lines of up to 445 miles in length, and was originally designed to model a 500 KV, 2 conductor transmission line. The MPS consists of various modules that can be interconnected in different configurations depending upon the system being modeled. The basic line impedance module consists of three 12 ohm (60 Hz) reactors with adjustable shunt capacitance, in series with a 4 winding transformer which is used to adjust the zero sequence impedance (*Figure I*). The shunt capacitance is set to match the line characteristics. Adjustable ratio current transformers are used to set the secondary impedance of the MPS to match the secondary impedance seen by the relays on the power system. Faults may be applied at the connection points between any modules. Any of the 10 fault types can be selected from the MPS control panel, and faults may be applied at an incidence angle that is continuously adjustable from 0 to 360 degrees.

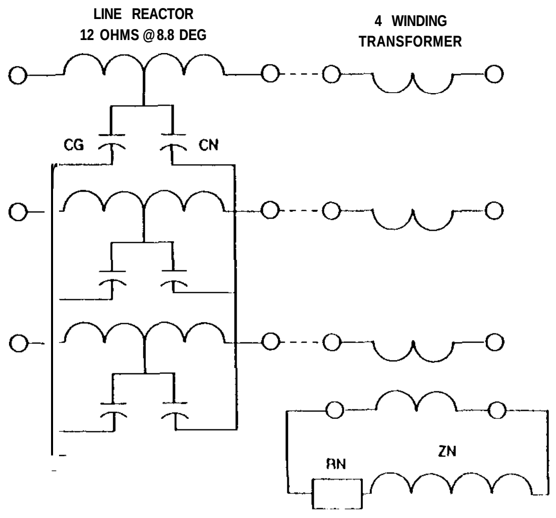

Figure 1: **Typical MPS Line Section**

The MPS uses ac contactors to simulate the circuit breakers. The contactors may be operated by the tripping outputs of the protective relay system under test. The reclosing of the breakers can be accomplished by a reclosing relay, if one is included in the scheme or by an external recloser in the MPS control system. The load current on the MPS is simulated by using an angle between the source voltages of either 30 and 60 degrees.

Electra-Magnetic Transient Program (EMTP)

The Electra-Magnetic Transient Program is a digital simulation of a transmission system originally developed by the Bonneville Power Administration. It is used by many utilities for simulation of power systems, both transient and steady state. The EMTP has the capability to model large portions of a power system. The EMTP is used to generate current and voltage waveforms which will be seen by the protective relays on the power system. In recent years, it has been proposed that these waveforms can be applied to protective relays using digital to analog converters and linear amplifiers. In this paper, the primary discussion will be in the comparison of the waveforms, rather than the technique of applying the waveforms to the relays.

POWER SYSTEMS

Two systems will be considered. The first system will be based on one of the "standard" MPS systems used in development testing of new relays. This system is the "standard" 112 mile parallel lines without zero sequence mutual impedance with 28 mile sources *(Figure 2)*. The other system will represent a more complex system with series compensation. This system will be based on PG&E's Table Mountain-Tesla line using the data supplied by PG&E for the MPS testing of the PLS relays which are used on this system *(Figure 3)*. This system includes series capacitors which are protected by zinc oxide.

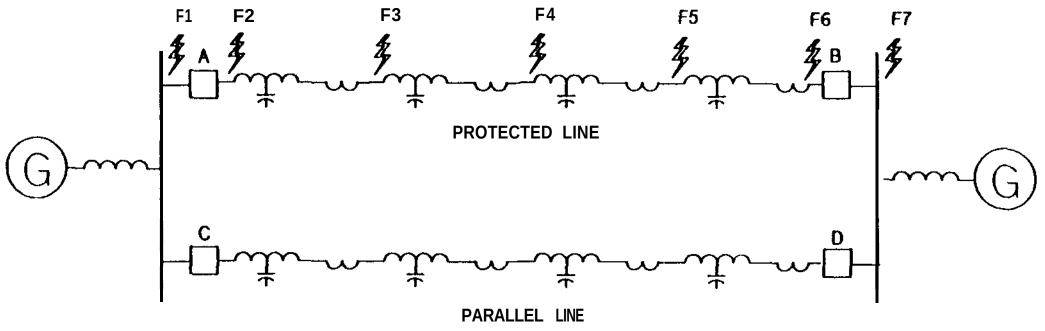

Figure 2: **Typical MPS Section**

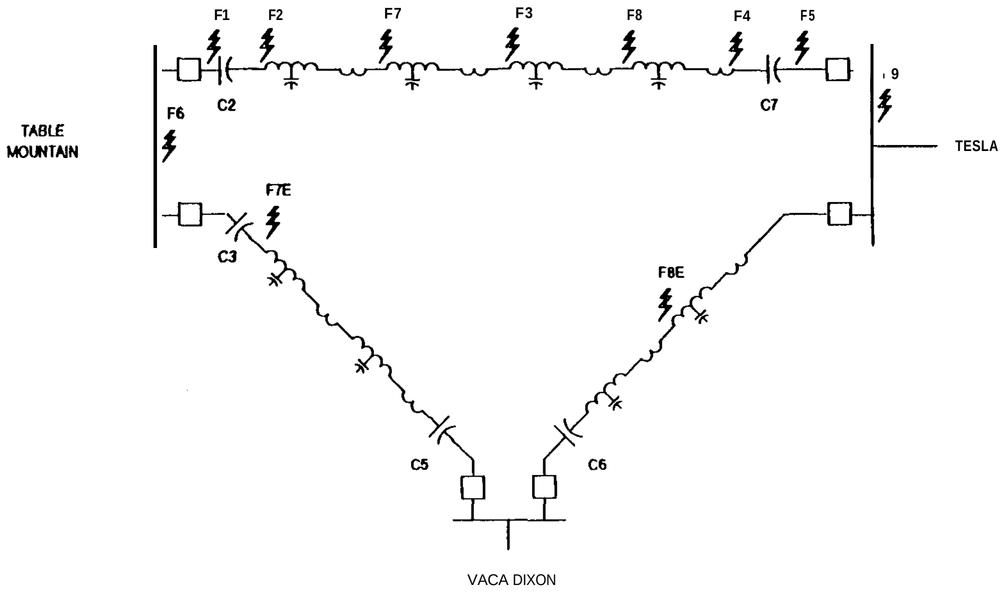

Figure 3: **Series Compensated MPS System**

Several different transmission line models, with varying degrees of detail, are available in the EMTP. For the system of Figure 2, four different EMTP models were studied. The first was a model of the MPS. This model used four cascaded “T” - sections for each line. This representation was cumbersome and inefficient in the EMTP, but allowed a direct comparison of the various modeling concepts. The next simplest model is a traveling - wave model with fixed resistance and balanced self and mutual impedance and capacitance values; i.e. a fully transposed representation. This model represents the positive and zero sequence line parameters but not the coupling between the sequence components. A more detailed traveling - wave model uses a modal algorithm allowing representation of an untransposed line’s unbalanced parameters. This model requires physical, rather than electrical, parameters. These physical parameters were calculated assuming a typical horizontal conductor configuration, adjusted to match the MPS parameters. The most detailed EMTP line model represents both the imbalance of untransposed lines and the frequency dependence of the positive and zero sequence resistance. This is referred to as the “JMARTI” line model. The “JMARTI” model was used for the series compensated system of Figure 3.

TEST CASES

Various fault types and fault locations have been used in this study. The fault locations are shown on the system diagrams. The fault incidence angle will be varied; typical initiation angles used will be: 0^o, 45^o, 90^o, and 135^o on the faulted phase voltage. Both potential transformer (PT) and GE Type CD31 coupling capacitor voltage transformer (CVT) potential sources were modeled. Faults were applied with and without load. The currents and voltages produced by the analog MPS and the EMTP program will be compared.

WAVEFORM ANALYSIS

112 Mile Line System

As noted previously, four different models of the 112 mile line system were implemented in the EMTP study. The potential transformer voltages produced by the various models for a phase A to ground fault at fault location F3 for a 90 degree incidence angle are shown in *Figure 4.* It can be seen from these traces that as the complexity of the model increases, the response of the model to the high frequency components is enhanced. It can also be seen that all four models produce similar waveforms after the first quarter cycle of fault duration. *Figure 5* shows the same four voltage traces, but the time scale is expanded to show the differences in the first quarter cycle of the fault. *Figure 6* shows the CVT waveforms for the same conditions as Figure 5. The CVT acts as a filter and substantially reduces the high frequency content of the voltage applied to the relay. The phase A current waveforms for the four models are shown in *Figure 7* with a composite graph showing all four waveforms on the same axis in *Figure 8.* Again the differences are essentially limited to the first quarter cycle of the fault. The current and voltage waveforms from the MPS are shown superimposed on the EMTP waveforms in *Figure 9.* The EMTP and MPS waveforms for a fully offset current are shown in *Figure 10.* As was expected, the time constant of the EMTP simulation is longer than that of the MPS. This is true even though the angle of the MPS line reactors is 88 degrees. The connections necessary to create the line model on the MPS and the voltage drop across the SCR’s in the fault breaker add resistance to the model line effectively lowering the line angle and shortening the time constant.

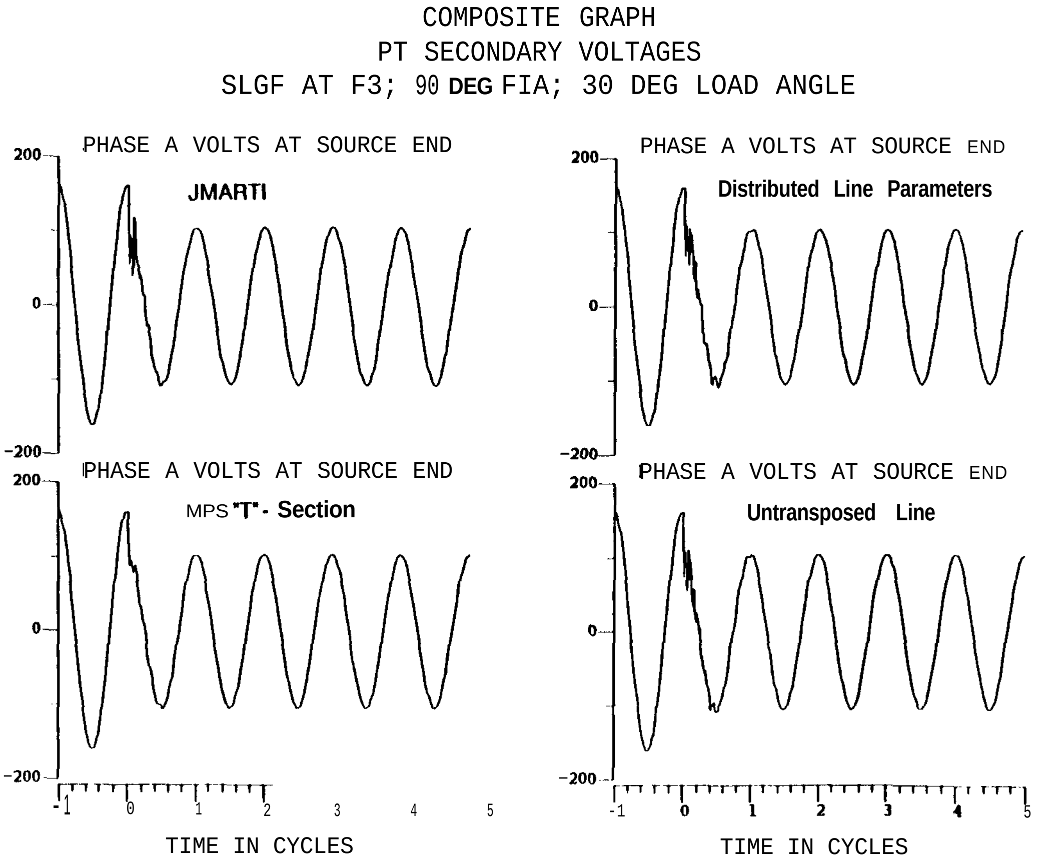

Figure 4: **EMTP PT Voltage Waveforms for Four Line Models**

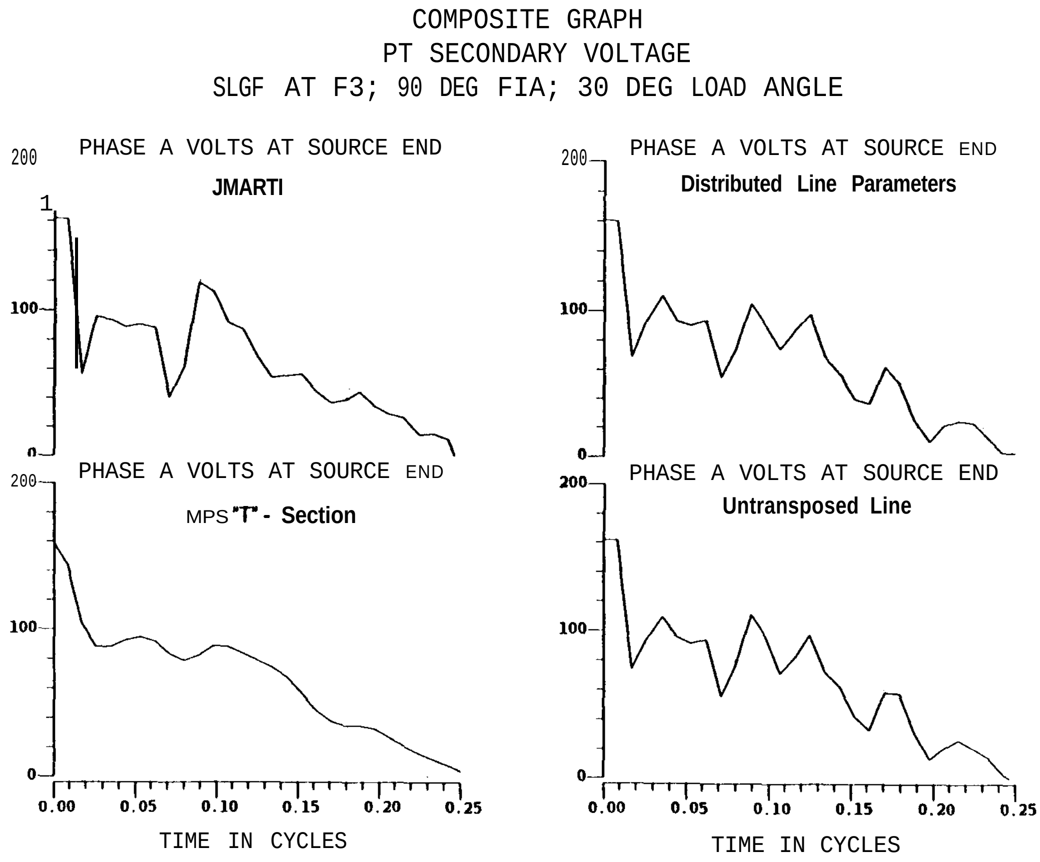

Figure 5: **EMTP PT Voltage Waveforms – Expanded**

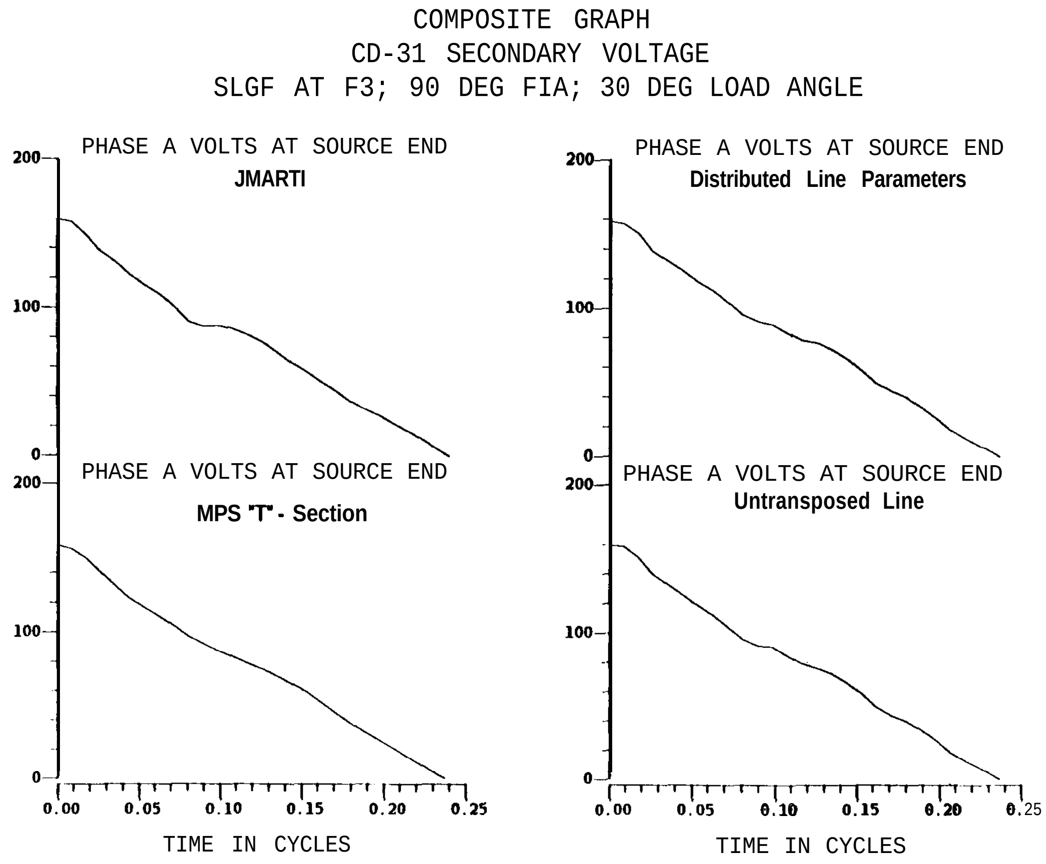

Figure 6: **EMTP CVT Voltage Waveforms – Expanded**

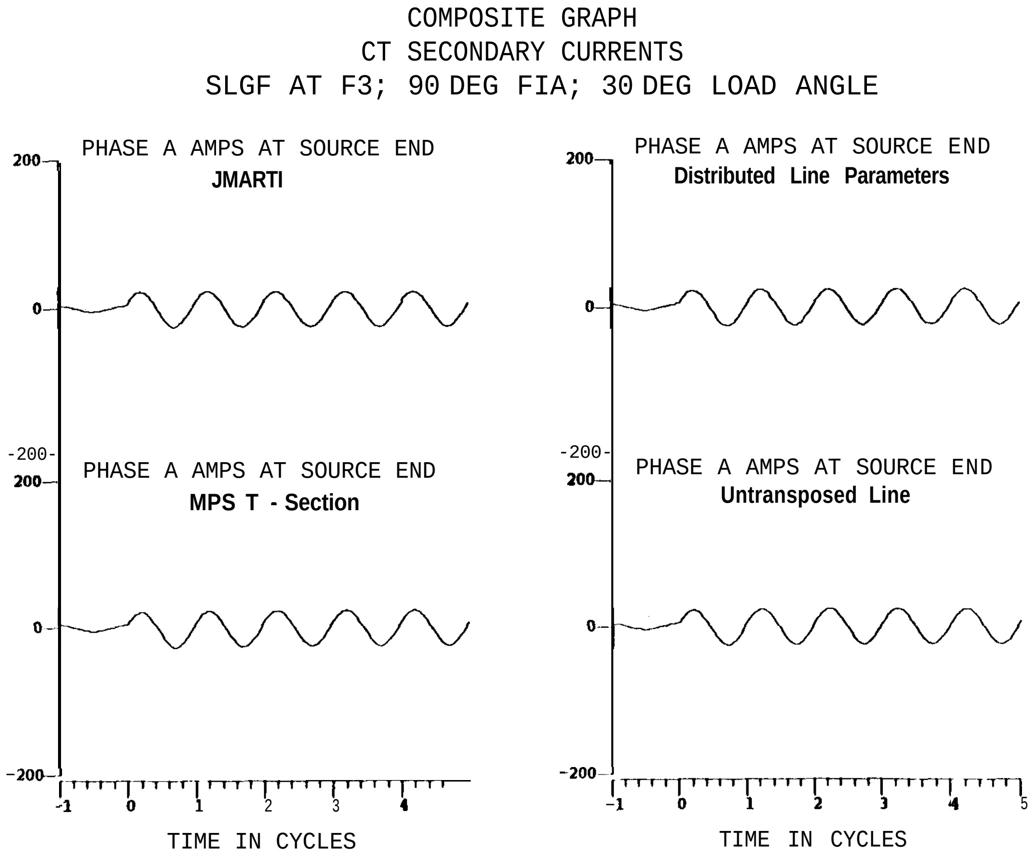

Figure 7: **EMTP Current Waveforms for Four Line Models**

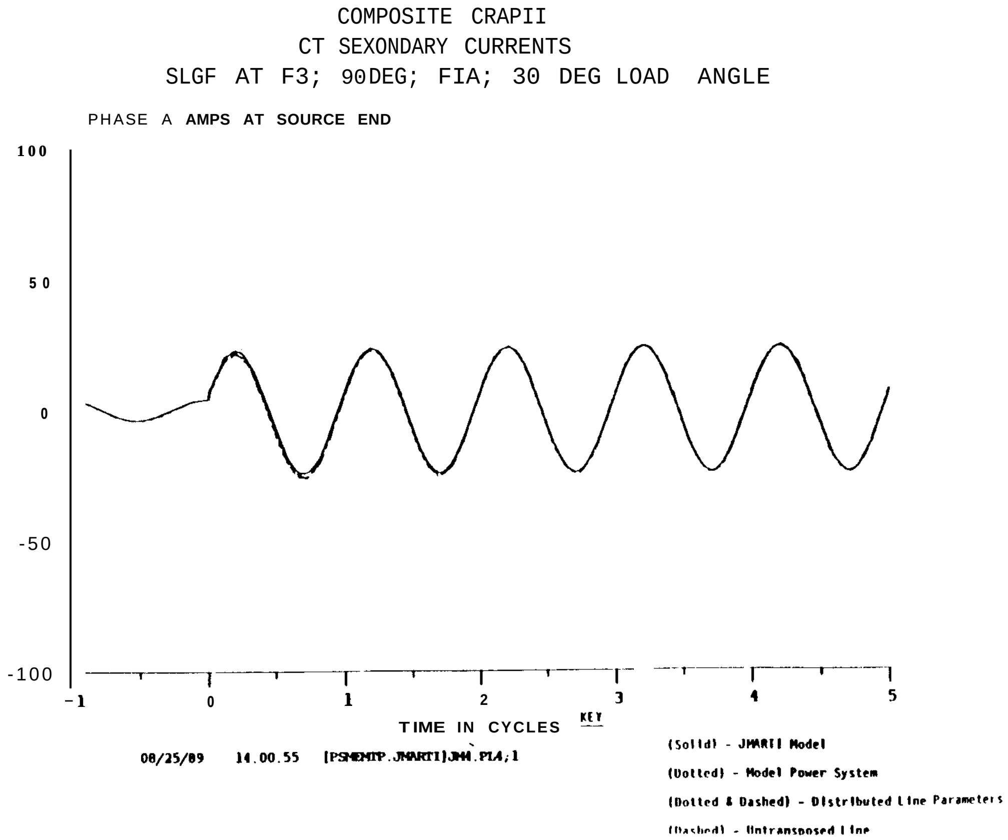

Figure 8: **Composite EMTP Current Waveforms**

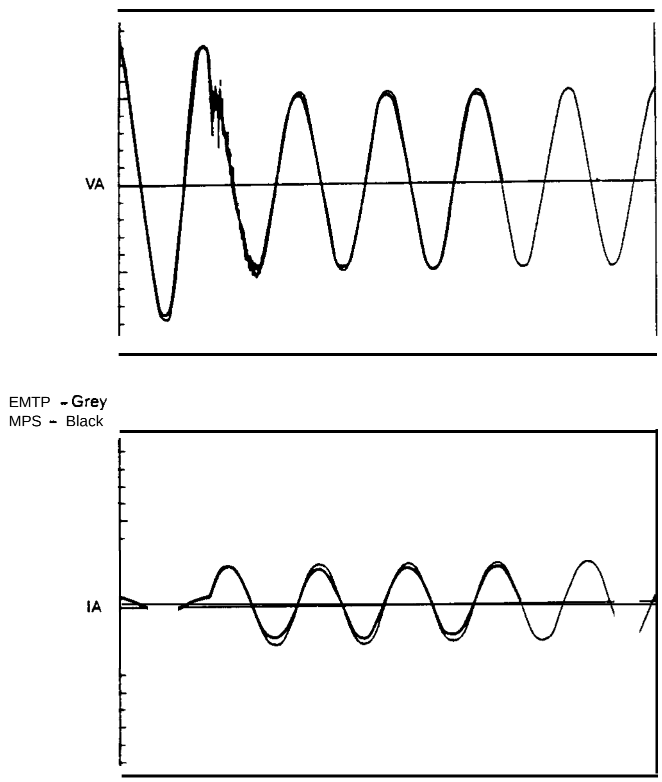

Figure 9: **EMTP and MPS Current and Voltage Waveforms**

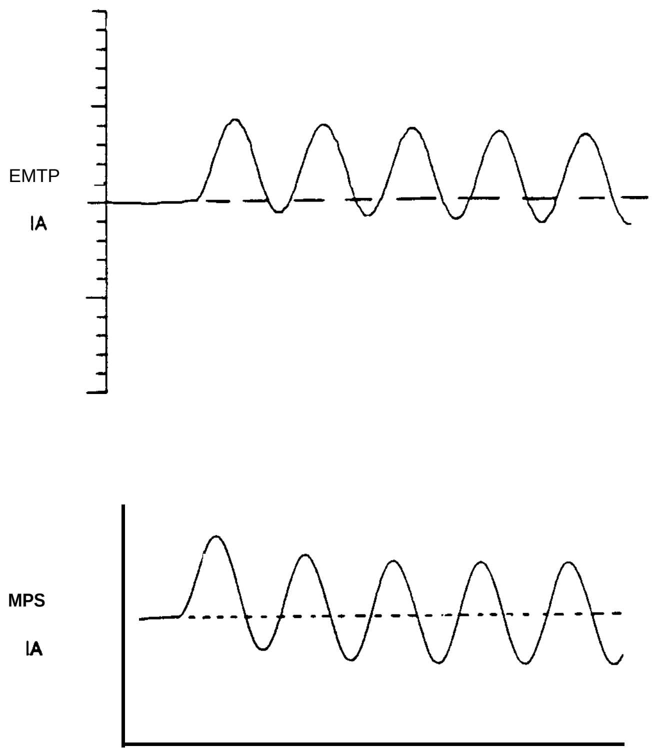

Figure 10: **Fully Offset Current Waveforms**

CVT and CT Transients

Because modern solid state relays generally operate in the first cycle after the fault inception, and because this is the time when all system transients are at their maximum, the transient behavior of the current and potential transducers is an important factor in the performance of the relay. During the analysis of the fault waveforms some differences were noted between the coupling capacitor voltage transformer (CVT) voltages on the MPS and those calculated by the EMTP model. The transient output of a CVT depends upon several factors beside the basic CVT design. One of these factors is the burden connected to the CVT secondary, another is the fault initiation angle. The secondary voltage waveforms for a GE Type CD31 CVT under test conditions are shown in *Figure 11 A and B.* The burden for Figure 11 A was a test burden "ZT"; the burden for Figure 11 B was zero (open circuit). The burden used in the EMTP model was a standard burden, "W", which is equal to 12.5 VA at 0.1 power factor. The model used on the MPS uses a complex burden based on typical relays that may be connected to the CVT in a substation. The transient waveforms for the EMTP and MPS CVT's are shown in *Figure 11 C and D.*

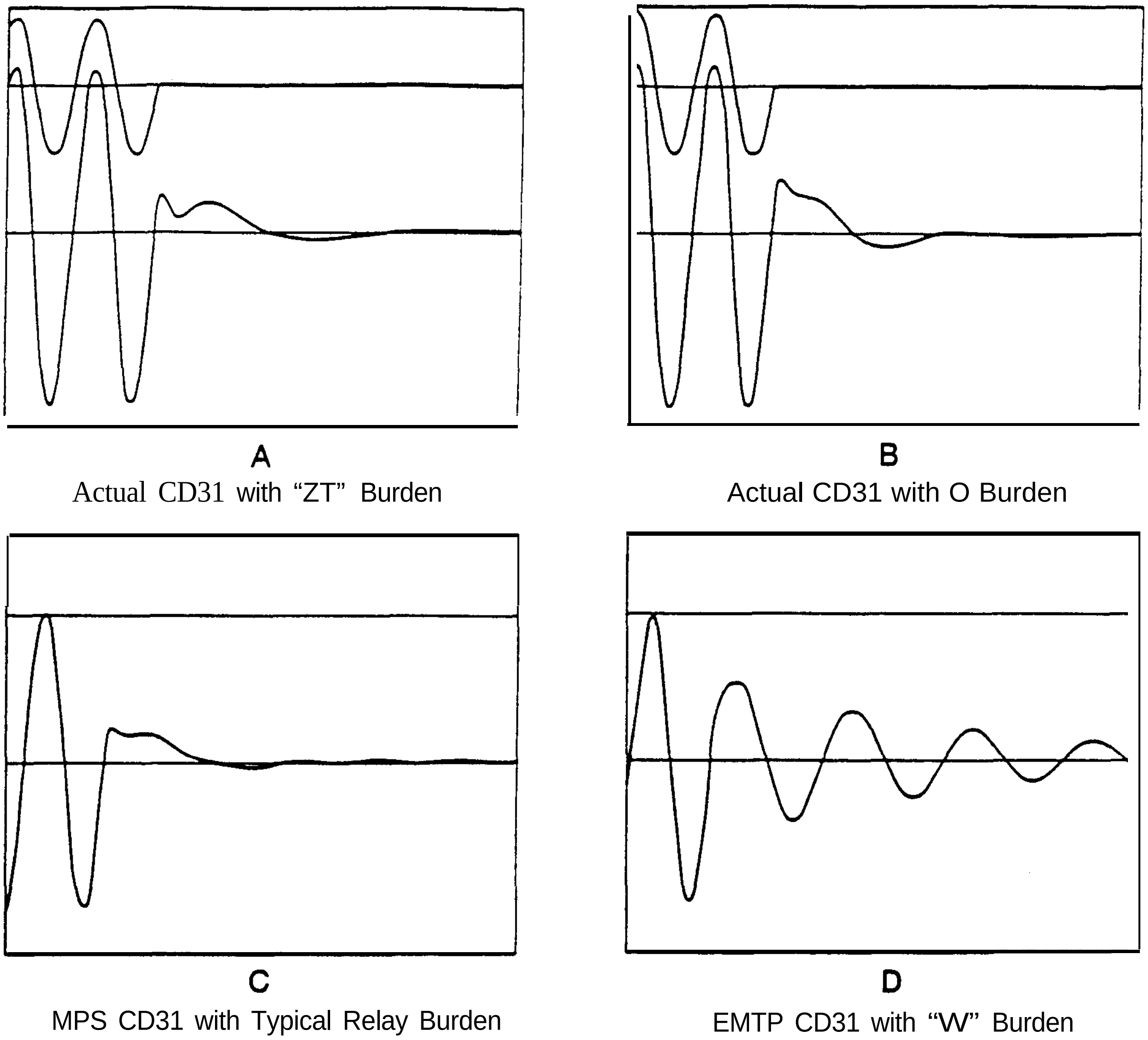

Figure 11: **Comparison of CVT Transients**

The EMTP model assumes that the secondary current is an exact replica of the line currents and does not include the effects of CT saturation. The MPS, on the other hand, uses actual CT's and the secondary current waveform can be affected by CT saturation. The effects of this CT saturation can be seen in *Figure 12.*

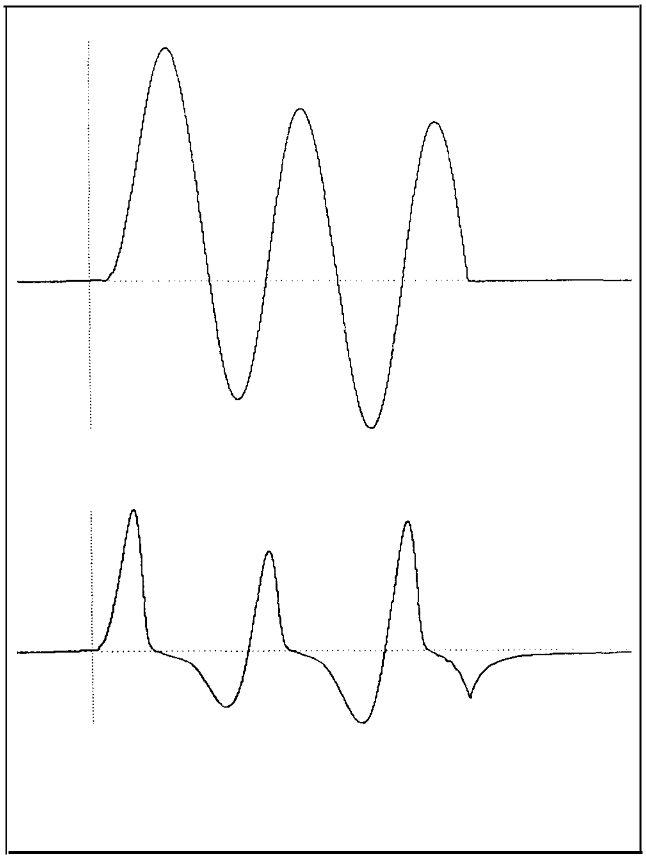

Figure 12: Example of CT Saturation on the MPS

Compensated System

A phase A to ground fault was applied to this system on the line side of the series capacitor in the upper line (Fault location F2, in Figure 3), and the current and voltage at the right end of the line were recorded. The system was unloaded, the fault incidence angle was zero degrees on the phase A voltage, and there was no fault resistance. *Figure 13* shows the phase A potential transformer voltage waveforms for both the EMTP and the MPS. The shorter time constant of the MPS results in greater attenuation of the low frequency transients in the voltage.

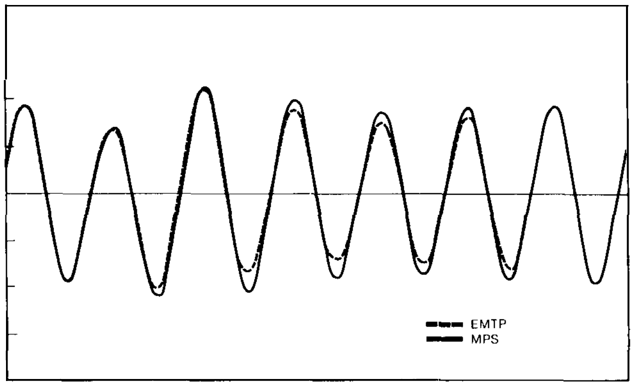

Figure 13: **EMTP and MPS PT Voltages for Series Compensated System**

Figure 14 is a comparison of the PT voltage and the CVT voltage produced by the EMTP study. It can be clearly seen that errors introduced by the CVT model are substantial in both magnitude and phase.

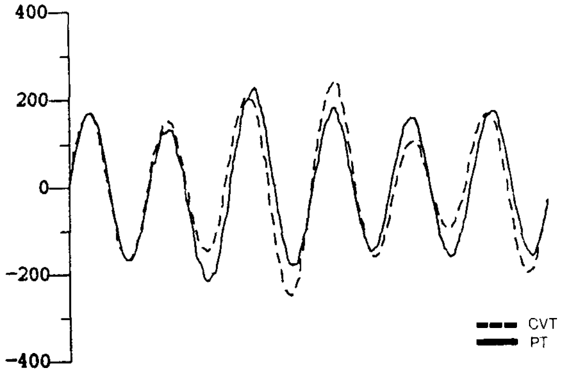

Figure 14: **EMTP PT and CVT Voltages for Series Compensated System**

Figure 1.5 is similar to Figure 14 except that the comparison is between the PT and CVT waveforms produced by the MPS.

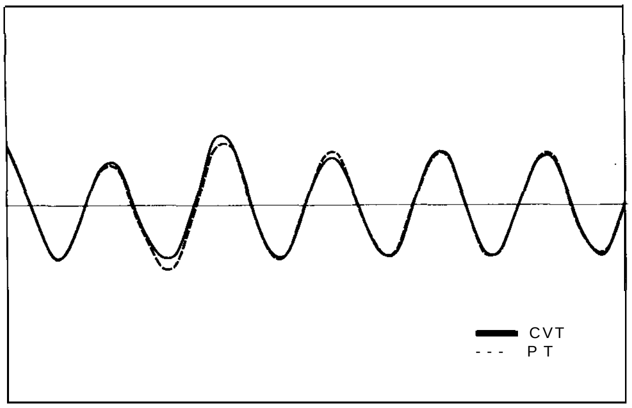

Figure 15: **MPS PT and CVT Voltages for Series Compensated System**

A similar discrepancy between the waveforms is evident, but the distortion is not as severe as in the case of the EMTP waveforms. Note that the burdens used in the two simulations are not the same. It appears that to provide the best modeling of the CVT, the burden should be similar to that which exists in service to produce the proper voltages to be applied to the relay.

A comparison of the phase A fault currents in *Figure 16* illustrates the variation in current between the EMTP study and the MPS study. Again the lower time constant of the MPS results in a reduction of the low frequency current by the end of the fault duration.

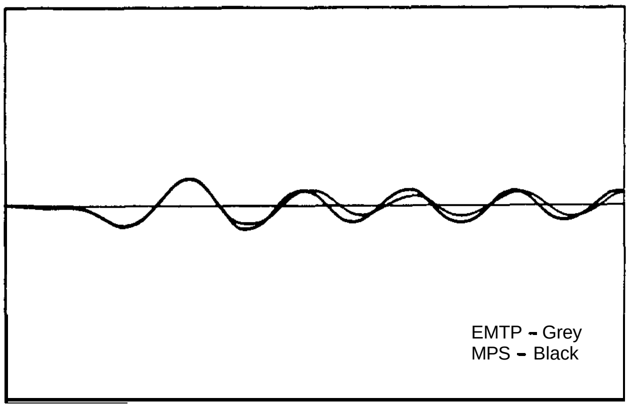

Figure 16: EMTP and MPS Fault Currents for Series Compensated System

COMPARISON OF METHODS

Modeling Accuracy

The details of an analog and a digital model are of course different. Because of size and cost considerations, a high power analog model power system is limited in the number and size of the various power system components that are modeled. Therefore, a high power analog model, such as the GE MPS, is a type of lumped parameter model and generally can only represent a small portion of the total power system. A second analog approach to power system modeling, which was not considered in this paper, is the use of a low power analog simulation coupled with high power amplifiers. With this type of model it is possible to model much more of a power system than with the high power analog simulation. A digital approach, on the other hand, can easily represent a large portion of a power system and can make use of a distributed model of the system. Because of the nature of the analog model, several differences can be noted between the results of a study on the analog system and a similar study on the EMTP. For instance, the time constant of the analog MPS is shorter than the EMTP results and will also be shorter than the actual system time constant. Of course fault or arc resistance in an actual fault will also reduce the time constant of the dc offset current on the power system. In general this does not affect the performance of the relays, especially relays designed with a transactor on the current input, since the transactor acts as a differentiator and removes the dc component of the current. The MPS is not as flexible as the EMTP for representing larger systems accurately due to the limited number of components available. Thus the EMTP can produce wave forms that are closer to those observed on the system than can the analog MPS. In general this does not negate the usefulness of the analog system. Load on the MPS is simulated in discrete steps: 0,30, or 60 degrees between the source voltages. Therefore the MPS load may not exactly match the actual load flow on the system but often represents slightly more loading, generally a more severe condition for the protective relay.

This study has indicated that the errors introduced by the CVT's and CT's may well be much greater than the differences between modeling techniques. These errors are dependent upon so many factors that accurate models are not practical. The CVT transient, for example, is dependent upon the burden connected to the device. It is very likely that every CVT on a system will have a different complement of relays, and therefore require a different model for exact modeling. Similarly the performance of the CT is dependent upon the level of residual flux in the device and this can not be predicted. Both the EMTP and the MPS can provide some level of simulation of these factors, but neither will be an exact model of the actual CT. Because the residual flux in a CT is a function of its history, an analog system is more flexible in this area than the EMTP model. For example, on the analog system the same fault with dc offset can be applied repeatedly to evaluate any change in the performance of the relay as the level of residual flux, and therefore the degree of saturation, increases.

Test Method Differences

In the testing of protective relays, the use of either an analog Model Power System or a digital simulation such as the EMTP approach, necessitates a different testing program. The analog MPS operates in "real time"; that is, the fault is applied to the system, and the relay responds and trips the circuit breaker to remove the fault just as it would in actual fault conditions. An MPS simulation of a single line to ground fault, followed by single pole tripping of the circuit breakers is shown in *Figure 17*. This test could not be run using an EMTP program since the relay operating times will not

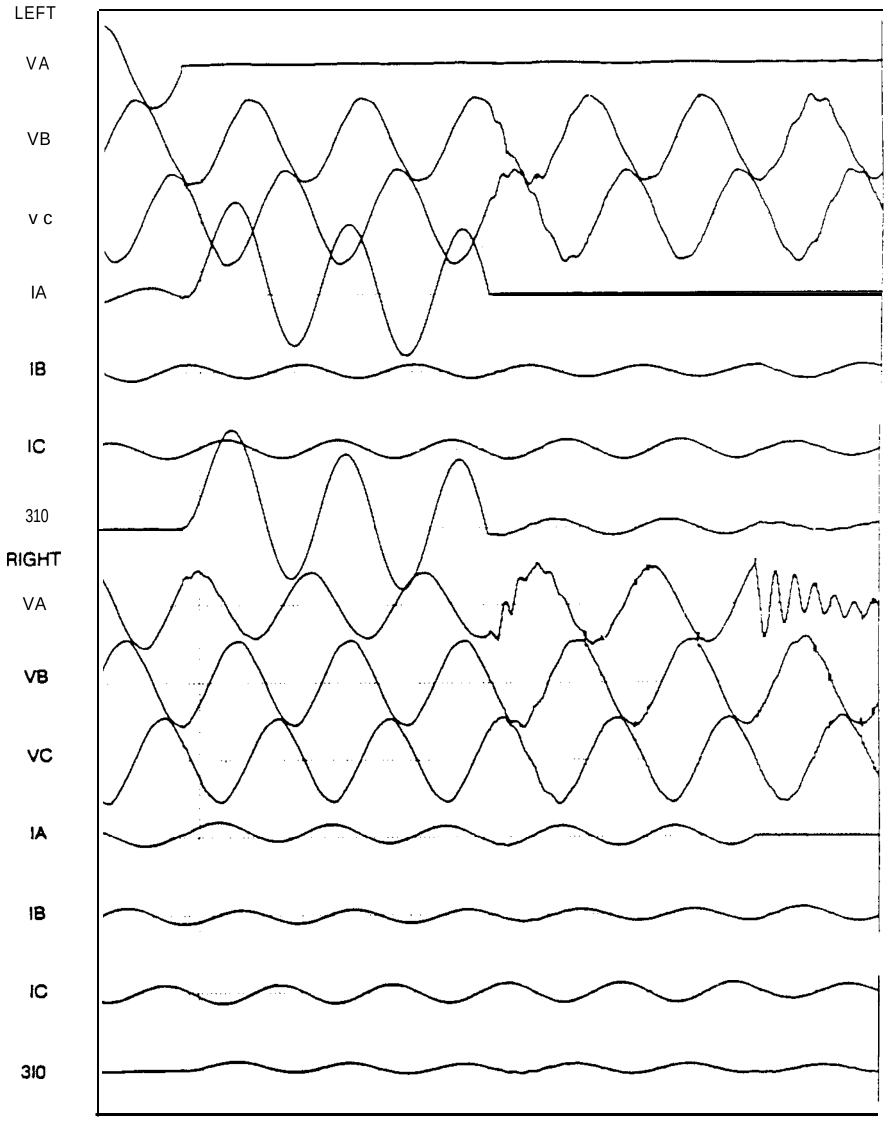

Figure 17: **Currents and Voltages for MPS Single Pole Trip**

be known in advance of the test sequence. The MPS testing program can be very flexible in that the type of fault, the location of the fault, or the system conditions can be changed quickly and the relay response determined. On the other hand, the digital approach requires that the test cases be run separately before testing the relays. Thus the relays are not allowed to interact with the power system directly, such as tripping the breaker to remove the fault. In addition, since all fault conditions must be established in advance; the testing is not as flexible as on the analog simulation where interactive testing is used to find the worst case conditions. The use of the EMTP therefore lends itself to the simulation of specific cases while the analog simulation is more general and lends itself to a more varied analysis of the relay performance.

Effects of the Amplifiers

This study has concentrated on the modeling of the power system, and not the hardware needed to complete the tests. However, if the results of a digital study such as the EMTP are to be used to test protective relays, the output of the digital study must be converted to analog signals usable by the relay. The design of this interface can have a significant effect on the signals that are eventually applied to the relay. It can not be assumed that the amplifiers will apply an exact replica of the EMTP waveforms to the relay under test; the amplifiers, under some conditions may introduce substantial distortion into the signals applied to the relay, particularly the current signal. For example, the amplifiers must be capable of reproducing the dc components of the fully offset currents without saturating. GE has ordered high power current amplifiers to be used in a digital simulation as well as to play back actual fault quantities that have been captured by digital fault recorders.

CONCLUSIONS

This paper has attempted to present information on two dissimilar methods of modeling power systems for the purpose of evaluating the performance of protective relays. The voltage and current waveforms produced by the EMTP and analog Model Power System for several different systems and faults have been examined. Based on this analysis several conclusions may be drawn.

The EMTP and the MPS produce similar waveforms when the models of the systems have similar complexity. Both methods will provide current and voltage signals that can be used to evaluate relay performance. Which method is used may depend more on what hardware is available than on the desired degree of accuracy of the model. A high power analog model power system is large and costly, and a utility may choose not to make such an investment. On the other hand, many utilities already have an EMTP program. The additional hardware needed to test relays using the EMTP output is less costly than an analog model power system. However, the current amplifiers must be suitable for the high instantaneous power required by the high current faults. While the initial cost of an EMTP based simulator is much less than the initial cost of an analog simulator, it should be noted that the EMTP based simulator requires many hours of computer programing to create the case files for the various test conditions. For this paper a total of less than 50 cases where run on the EMTP. By contrast, a normal week of testing on the MPS consists of up to 5000 faults for approximately the same cost.

The one area where the models were most dissimilar was the CVT transient response. This difference can be partially attributed to the different secondary burdens chosen for the EMTP and MPS, but may also be caused by differences in the models. This will be an area of future study. The effect of the CVT on the potential wave shape appears to be much more significant than the differences in modeling techniques. Any evaluation of a relays performance must include the effects of the CVT on the potential signal, but the CVT model must be representative of the actual device. Similarly, the performance of the relay in the face of CT saturation should be a part of an evaluation program. This can be accomplished on the analog model with much more ease than using the EMTP.

The analog MPS is very flexible, permitting rapid testing over a wide range of parameters, such as load flow, source to line impedance ratio, fault incidence angle, etc. Many cases can be run in a short time period thus allowing the number of faults applied to the relays to be orders of magnitude higher than with a digital system. This permits the user of an analog MPS to find the worst case fault conditions by monitoring the relay response as the parameters are varied. The digital approach has the advantage of being capable of modeling the power system with greater accuracy than the analog MPS and is also can model a much larger portion of the power system than the analog MPS. The EMTP provides an ideal means of duplicating the effects of an isolated instance that may have resulted in questionable performance of a relaying scheme.

The choice of a digital model or an analog model may also be influenced by the reason that the testing is being performed. A manufacturer performing development tests on a new relay may prefer the flexibility and speed of the analog MPS in order to subject the relay to as many different operating conditions as possible. A utility, on the other hand may wish to use a set of standard tests to audit the performance of the relays as they are purchased, or as a means to compare the performance of several relays under the same fault conditions. This testing would most likely encompass fewer tests, and would therefore be suitable to the use of a digital model.

ACKNOWLEDGMENT

The authors would like to thank R. A. Walling and E. A. Norton of General Electric's System Development & Engineering Department for their help in providing the EMTP models used in this paper.

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APPENDIX I

MPS Transmission Line

The MPS line modules are based on a 500 KV line having the following constants:

PT Ratio 5000,000:115
CT Ratio 2000:5

Zl = 0.58 ohms/mile
Z0 = 1.79 ohms/mile

XC1 = 0.1340 Meg ohms/mile
XC0 = 0.2021 Meg ohms/mile

System #1

"Standard" 112 Mile Line

Secondary Impedances: (Each MPS module is 1.5 Ω secondary)

	Z1	Z0	XC1	XC0
Left Source	1.5 $\angle 88°$	1.5 $\angle 88°$		
Protected Line	6.0 $\angle 88°$	18.5 $\angle 76°$	110	166
Parallel Line	6.0 $\angle 88°$	18.5 $\angle 76°$	110	166
Right Source	1.5 $\angle 88°$	1.5 $\angle 88°$		

COMPARATIVE TESTING USING DIGITAL SIMULATION AND AN ANALOG MODEL POWER SYSTEM

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In recent years, there has been increasing interest in testing the dynamic and variable characteristics of mho distance relays in addition to the standard steady state mho plot *(References 1-4).* This type of testing is more complex than the normal plot of a mho characteristic, and requires a greater knowledge of the relay design, the test set design, and the response of the actual power system to load and fault conditions.

This paper will discuss the differences between testing the dynamic response of a protective relay using Doble amplifiers versus the GE Model Power System (MPS), located at the Malvern, PA, GE Protection and Control headquarters. A set of three Doble F2200 amplifiers were used to provide the active test sources. The current and voltage waveforms produced by the two simulations will be compared, and the results and test methods will be discussed.

The dynamic testing available with the Doble amplifiers consists of three steady state 60HZ conditions: pre-fault, fault, and postfault. The amplifiers cannot model the transition between the various steady state conditions. The most obvious transition being the DC offset that is present on a power system whenever the current changes at other than a zero crossing. Of course, other transients also exist on the actual power system such as high frequency components, CVT transients, CT saturation, etc. All of which may have an effect on the performance of the protective relays. The testing done with this hardware and software should not be confused with testing with EMTP generated waveforms. Testing with EMTP generated waveforms and using suitable amplifiers can successfully reproduce all the transients of an actual power system. A comparison of EMTP and Model Power System waveforms is presented in *reference 9.*

DYNAMIC AND VARIABLE MHO CHARACTERISTICS

The terms "dynamic" and "variable" mho characteristics both refer to the expanded characteristic which includes a larger area on the R-X diagram than the typical circular plot that passes through the origin on the R-X diagram. The dynamic characteristic is caused by the "memory" action of the polarizing circuit and is a transient condition that changes as the memory voltage "decays". The duration of the dynamic characteristic is determined by the design constants of the relay and the polarizing voltage in the relay. The variable characteristic, on the other hand, is a steady state condition in which the expanded characteristic is due to some form of "healthy phase" or "cross" polarization of the mho unit (i.e. a polarizing voltage that includes some unfaulted phase voltage; for example, a quadrature polarized ground relay).

Depending on the design of a particular relay, it may have a dynamic characteristic, a variable characteristic, both a dynamic and variable characteristic, or neither a dynamic nor a variable characteristic. The dynamic and variable mho characteristics are discussed in more detail in *references 5-8.* A typical dynamic/variable mho characteristic is shown in *Figure 1.*

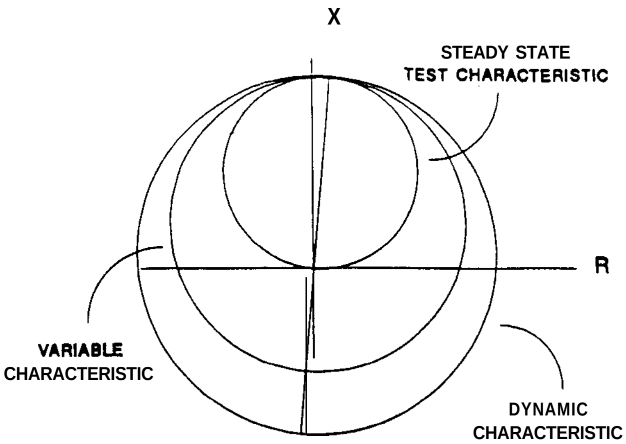

Figure 1: **Typical Dynamic, Variable, and Steady State Mho Characteristics**

It should be noted that the relay operation for faults below the R axis is restricted to faults in the tripping direction (i.e. in front of the relay) that are capacitive in nature.

Both the dynamic and the variable mho characteristics are functions of the conditions existing on the power system at the time of the fault as well as the design of the relay. One relay with a given set of settings can have an infinite number of dynamic and variable characteristics depending upon the prefault system conditions. Prefault load will have an effect on the characteristics because the load flow will produce a phase shift in the prefault (memory) voltage at the relay relative to the source voltage; that is the remembered voltage is a function of the load flow and the location of the relay in the power system. As the location of the relay changes, the variable mho characteristic also changes since it is a function of the source impedance behind the relay. Thus it is apparent that a test of the dynamic and variable mho characteristics must be based on a given set of system conditions to produce meaningful results.

TEST EQUIPMENT

GE Model Power System

The GE Model Power System (MPS) is a three phase transmission line simulator operating at 460 volts. The MPS has been used to simulate lines of up to 445 miles in length, and was originally designed to model a 500 KV, 2 conductor transmission line. The MPS consists of various. modules that can be interconnected in different configurations depending upon the system being modeled. The basic line impedance module consists of three 12 ohm (60 Hz) reactors with adjustable shunt capacitance, in series with a 4 winding transformer which is used to adjust the zero sequence impedance. The shunt capacitance is set to match the line characteristics. Adjustable ratio current transformers are used to set the secondary impedance of the MPS to match the secondary impedance seen by the relays on the power system. Faults may be applied at the connection points between any modules. Any of the 10 fault types can be selected from the MPS control panel, and faults may be applied at an incidence angle that is continuously adjustable from 0 to 360 degrees.

The MPS uses ac contactors to simulate the circuit breakers. The contactors may be operated by the tripping outputs of the protective relay system under test. The reclosing of the breakers can be accomplished by a reclosing relay, if one is included in the scheme or by an external recloser in the MPS control system. The load current on the MPS is simulated by using an angle between the source voltages of either 30 and 60 degrees.

Doble Amplifiers

Three Doble F2200 test sets were used to provide the active current and voltage sources for these tests. The instruments were equipped with the following options:

F2010 Minicontroller
F2810 Fault Rotate
F2820 Value/Time
F2825 Multiple Sources
F2910 ProTest II Starter Kit

A Toshiba T1600 lap top PC was used to control the amplifiers. Several software programs were used during the testing, including: Doble's ProTest II and FLTSIM, Power Program's Tru-Test, and GE's PC based Short Circuit Analysis Program (FAULT.EXE).

Protective Relay

The response of a GE MOD10 TYS protective relay system was evaluated during the tests; The relay, model number TYS3B56B12E2FA, was used in a blocking scheme with phase and ground distance units and ground directional overcurrent. The TYS mho distance functions are of the phase angle comparator design and use more than two inputs to the coincidence circuits. Data was collected using the F2200 timer, a digital oscilloscope, an analog oscilloscope, and an RIS 1630 Digital Fault Recorder.

Power System

For these tests the simple power system shown in *Figure 2* was used. This is typical of a 112 mile 5OOKV transmission system with out a parallel line. Fault locations on the Model Power System are indicated on the diagram. The Zone 1 distance functions of the TYS system were set to 6 ohms secondary which is 100 percent of the line length

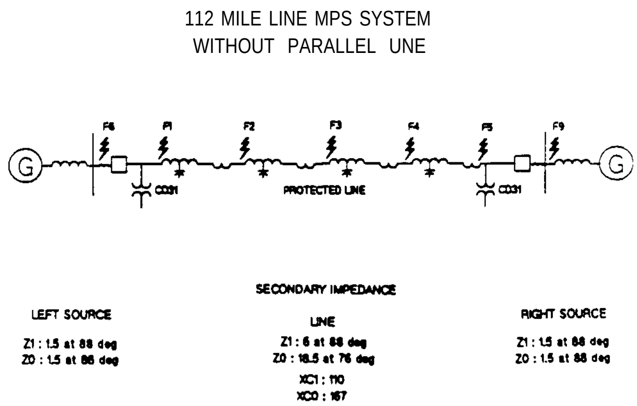

Figure 2: **Typical Transmission Line**

SYSTEM vs SOURCE ZERO CROSSING

One option on the Doble F2000 series is the selection of SYSTEM or SOURCE zero crossing. Since this setting has an effect on the dynamic testing of a relay, the effects of the setting will be reviewed. This setting determines how the current and voltage sources in the amplifiers are turned on at the start of a test sequence. In the SYSTEM setting, all sources are turned on at the same time. The point at which they are turned on is at a "system" zero crossing. This system sine wave is the reference for the phase angle settings of all the sources. Thus, if a source is set to a phase angle of zero, it will turn on at a zero crossing, if it is set for a phase angle other than zero, it will not turn on at a zero crossing, but will change instantaneously to its value. With the zero crossing set for SOURCE, each source channel will switch at its own zero crossing. In this mode, each current and voltage source may change value at a different time. *Figure 3* shows the oscillograph traces for a zero voltage three phase fault at the relay location, using the SYSTEM zero crossing setting, with a prefault VA angle of zero degrees.

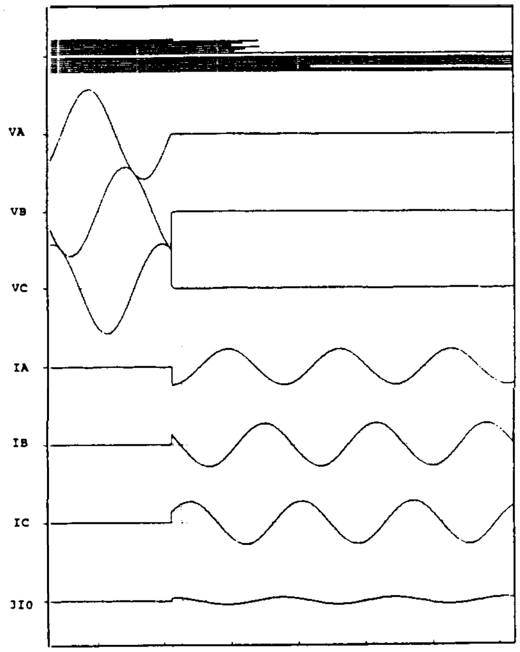

Figure 3: **Amplifier Output**
3 Phase Fault With SYSTEM Zero Crossing
Pre-fault VA Angle = 0

Figure 4 shows the same conditions except that the prefault VA angle is -90 degrees. Note that the fault incidence angle (point of wave on VA) has changed by -90 degrees. This allows the tester to change the fault incidence angle when using the Doble FLTSIM program.

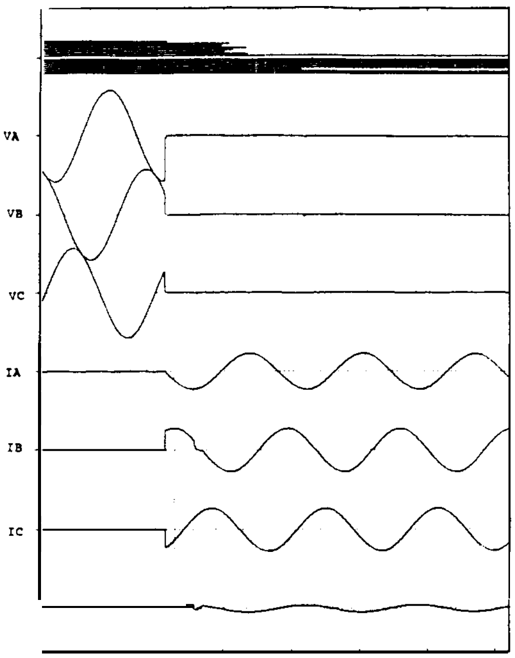

Figure 4: **Amplifier Output**
3 Phase Fault With SYSTEM Zero Crossing
Pre-fault VA Angle = – 90

Figure 5 shows the same conditions as Figure 3 except that the "SOURCE" zero crossing was used. Note that each of the six sources starts at its zero crossing. This means that no two sources start the fault conditions at the same time.

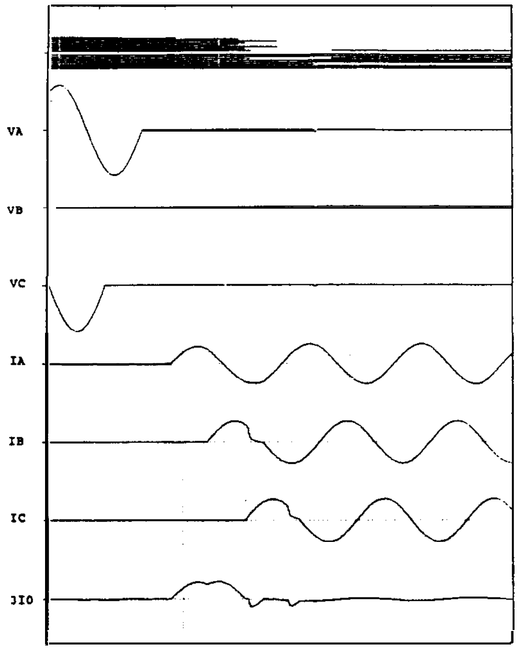

Figure 5: **Amplifier Output**
3 Phase Fault With SOURCE Zero Crossing
Pre-fault VA Angle = 0

This of course is not a realistic method of applying a fault. Also there is no one point to use as a reference to start timing the response of the relay under test since each channel starts its fault value at a different time.

Fault Current Initiation

The differences between fault current initiation using electronic amplifiers and the actual fault current initiation on a power system have been well documented in the past *(See references 1 and 2).* An inspection of the phase B and phase C currents in Figure 3 shows that the current produced by the current amplifiers instantaneously changes from prefault to fault value. The amplifiers cannot produce the decaying DC offset that the actual power system currents will exhibit.

Figure 6 shows the current and voltage waveforms produced by the GE Model Power System for a zero voltage fault similar to the conditions of Figure 3. Many relays employ a replica impedance circuit on the current inputs, such as transactor. These replica impedance circuits act as a differentiator. The instantaneous change of current produced by the amplifiers causes a large error signal to be generated on the output of the replica impedance circuit. *Figure 7* shows the input current to the relay and the output voltage from the transactor for both the amplifier and the Model Power System for a fault current initiation near the current peak (voltage zero). The large voltage spike caused by the step increase in the current signal can easily be seen in this picture. The MPS current, with the realistic dc offset current component, does not produce this spike. Because of this unrealistic current transient, Karl Englehardt of BC Hydro concluded that tests run with this magnitude of dI/dT "should be considered as doubtful if not invalid" *(Ref. 3).*

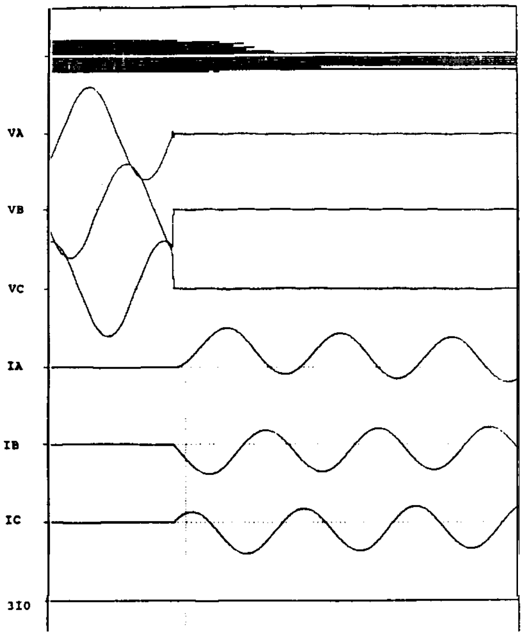

Figure 6: **Model Power System Output 3 Phase Fault**

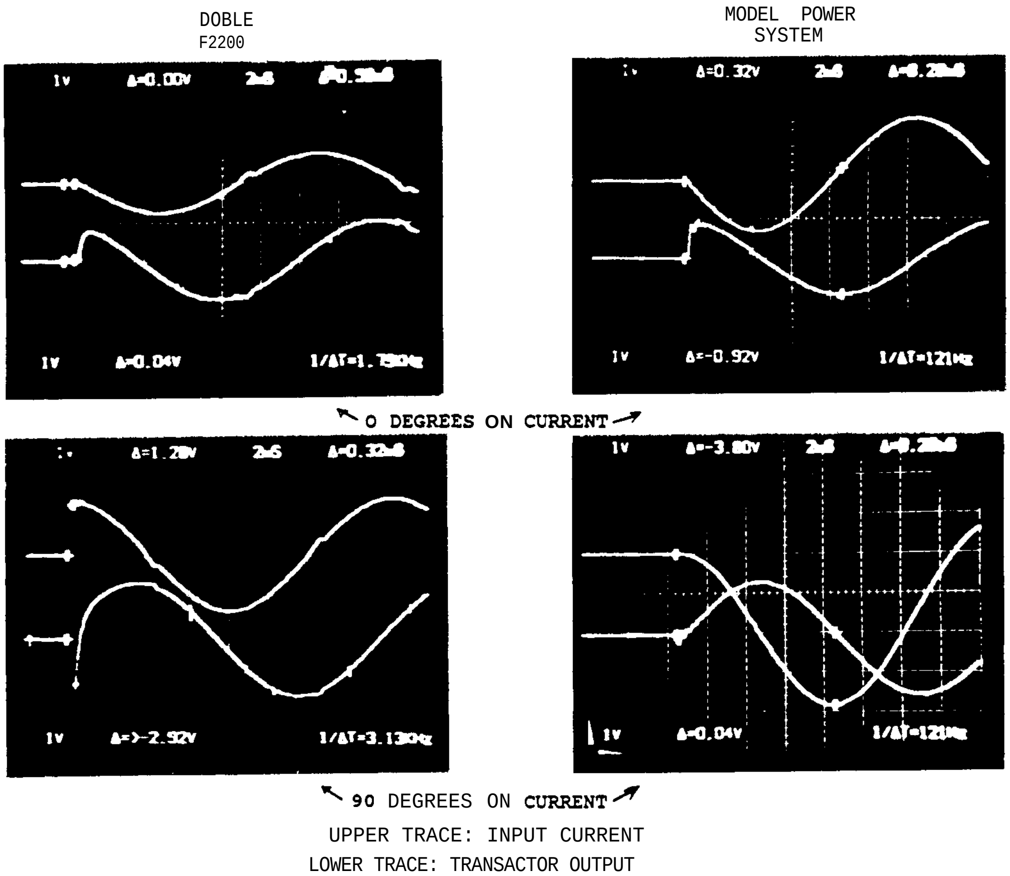

Figure 7: **TYS Transactor Output Voltage**

The testing of the TYS relay involved several distinct types of tests as outlined below.

1. Steady State Testing
2. Reach Tests
3. Fault Resistance Capability
4. Trip Times

Steady State Testing

This portion of the test program was intended to investigate any effects that the dynamic and variable mho characteristics might have on the normal steady state testing that can be accomplished using ProTest. One concern was the time required to fully energize the memory circuit between successive fault applications to insure that the polarizing voltage magnitude was large enough for proper operation of the mho unit. This was accomplished by using the F2200's to apply balance three phase voltage to the relay while observing the response of the polarizing voltage memory circuit. If the tests are applied so close together that the memory circuit does not have time to stabilize, the results of the testing may be invalid. *Figure 8* shows the charging /of the memory filter in the TYS when the voltage is applied. Based on these tests, the prefault conditions should be applied to the relay for at least 6 cycles before the fault conditions are applied.

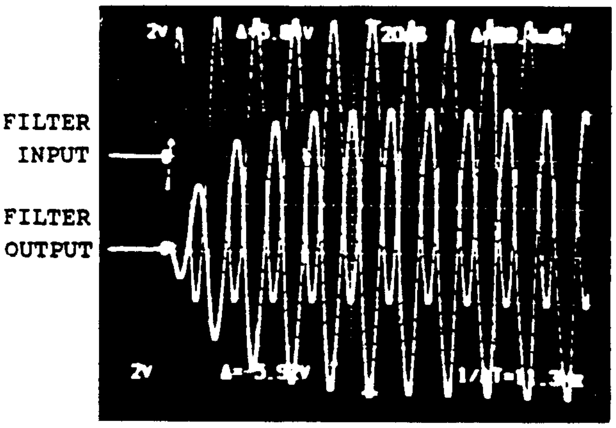

Figure 8: **TYS Polarizing Voltage Memory Filter Energization**

Note that this time will vary depending upon the specific relay type being tested and may be much longer than 6 cycles for some relay designs.

Reach Tests

The reach of the TYS relay was checked using both the F2200 test sets and the Model Power System; both the steady state reach and the dynamic reach were tested. To test the reach using the F2200's, the GE Short Circuit Analysis program was used to calculate the prefault and fault currents and voltages for a single line to ground fault and a phase to phase fault at the remote end of the line with the remote breaker open (radial feed). First, the fault quantities were applied to the TYS on a steady state basis and the relay reach was adjusted to find the point at which the relay just operated (balance point). Next, the FLTSIM program was used to apply the faults dynamically and again the reach was adjusted to find the balance point. The tests were then repeated using the Model Power System to supply the relay inputs. The results of these tests are shown in Table I.

Table I

	MPS		F2200	
Test	Ph-Ph	SLG	Ph-Ph	SLG
Steady state	6.3	6.4	6.2	6.2
Dynamic	6.3	6.4	6.1	6.1

Trip Times

The trip times of the TYS relay for various fault types at different points on the protected line were measured using both the FLTSIM program and the Model Power System. The currents and voltages for the FLTSIM program were calculated using the GE Short Circuit Analysis Program. The results of these tests are shown in Table II. Note the incidence angle of the fault was varied at all fault locations on the MPS testing to find the minimum and maximum operating times. In the FLTSIM testing the incidence angle was only varied at fault location F3 (mid-line). There are no operating times given for the FLTSIM at fault location Fl (relay location) because the fault current magnitude was higher than the capability of the amplifiers. The Zone 1 units were set for 100 percent of the line (6 ohms) for these tests.

Table II

Fault Location	Fault Type	Doble FLTSIM	MPS
Fl	AG	---	5-10 ms
F1	BC	---	5-10 ms
Fl	3PH	---	5-5.2 ms
F2	AG	8.8 ms	10.0-13.9 ms
F2	BC	11.0 ms	10.0-13.9 ms
F2	3PH	---	9.6-10.2 ms
F3	AG	10.3-15.1 ms	11.0-16.4 ms
F3	BC	10.4-15.2 ms	11.2-16.0 ms
F3	3PH	10.2- 11.2 ms	11.0-11.6 ms
F4	AG	16.6 ms	12.0- 19.0 ms
F4	BC	19.1 ms	12.0-18.5 ms
F4	3PH	16.2 ms	12.0-13.5 ms
F5	AG	No op	No op
F5	BC	No op	No op
F5	3PH	32 ms-No op	No op

Fault Resistance Capability

An attempt was also made to use the Doble FLTSIM program to show the fault resistance capability of the mho ground distance units. For these tests a different system was used, as shown in *Figure 9*. The relay setting were changed so that the Zone 1 reach was 4 ohms and the zero sequence current compensation (KO) was 4. This was to match previous testing performed by Doble on other relays. Using FLTSIM, the TYS would operate consistently for a fault resistance of 4 ohms, and occasionally for a fault resistance of 5 ohms. Similar testing was performed on the Model Power System and showed consistent operation at 5 ohms and no operation at 6.2 ohms.

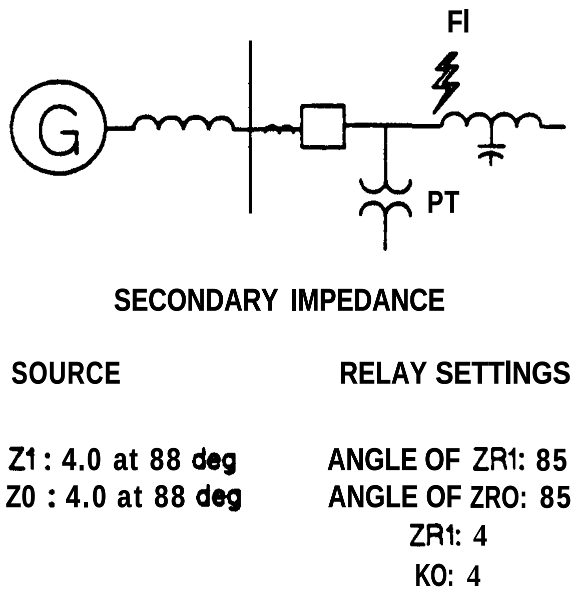

Figure 9: **Power System For Fault Resistance Test**

This series of tests has again demonstrated that the present electronic amplifier based test sources can not duplicate the currents and voltages as they actually appear to a protective relay that is in service on a power system. *Figure 10* shows that the spike on the transactor output due to the suddenly switched amplifier current is approximately 10 times the steady state peak current value. It is easy to imagine that an error of this magnitude could cause errors in relay operation as reported in earlier papers *(References 1 & 3).*

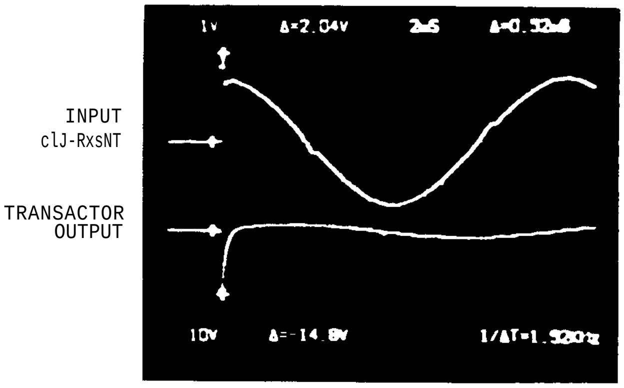

Figure 10: **TYS Transactor Response for Step Change in Current**

In the case of the particular TYS relay system used in these tests, no misoperations were observed. The operating times of the relay were similar using either the F2200 equipment or the MPS. The transient over reach of the relay was not increased by the use of the amplifiers. This consistency is probably due in part to the nature of the filtering used in the TYS relay system since this system is based on a relay designed to be applied on lines with series capacitors.

These results, however, can not be generalized even for the TYS relay system. A different set of relay settings or a different power system configuration could result in a greater difference in performance between the test methods. The design of the the various measuring functions in a relay will also have an effect on the performance differences. For instance, a direct trip over current unit that responds to peak current level is very likely to overreach for the current transients shown in Figure 10. Distance relays of different designs and/or different manufacturers will also respond differently to the amplifier waveshape.

In general, we conclude that since the amplifiers can not duplicate the wave shapes of the power system the response of the relay using the amplifiers may not reflect the response of the relay on the actual power system. In order to properly evaluate a protective relay, it should be subjected to realistic inputs. These inputs should also include transient conditions that are likely to cause performance problems (CVT transients, high frequency components etc.). The validity of any test results must be in doubt unless it can also be confirmed by other means. This is not to say that dynamic testing using amplifiers is not useful. The dynamic test procedure exercises the relay in a manner similar to an actual fault and gives the tester more information than is available through steady state testing. This data can be used to diagnose problems and to track changes in relay performance over time.

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