DYNAMIC TESTING OF LOSS OF FIELD PROTECTION

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

in

Electrical Engineering

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February, 1996

Blacksburg, Virginia
The thesis begins with a discussion of loss of field relaying principles, which is followed by a discussion of real-time playback systems. Loss of excitation protection has been implemented in General Electric's EX2000 Digital Exciter. Through the use of EMTP, several different system disturbances are simulated. The EMTP files are then played back with the help of a real-time playback system. The signals from the playback system are then fed to the EX2000 and General Electric's Digital Generator Protection (DGP) System, in order to compare the performances of both systems. The paper concludes by showing that the loss of excitation protection function in the EX2000 works identical to conventional protection systems.
ACKNOWLEDGEMENTS

I would first like to express gratitude to my advisor, Dr. Arun G. Phadke, for his professional guidance and his technical and financial support. I would also like to thank Dr. Yilu Liu and Dr. Jaime De La Ree for serving on my graduate committee. I also express gratitude to General Electric Drive Systems for their support of this project, and in particular, I would like to thank Rod Lawson and E.J. Sabir for their help in completing the research. I am thankful also to Doble Engineering Company for their generous donation, without which this project could not have been completed. I would like to thank the graduate students in the Power Systems Lab for their support, especially Virgilio Centeno for helping me with the playback system. Lastly, I would like to thank my family for their support over the last few years.
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CHAPTER 1: INTRODUCTION

Over the years, protective relays have advanced from the electromechanical type to the current digital multifunctional models being manufactured, which can implement several protection functions at the same time in the same system. These current models have always been separate from the digital control systems which controlled generator parameters. However, in this advanced technological age, there has been a call to integrate the control and protection functions into the same system, due largely to the introduction of digital excitation systems. Thus, companies like General Electric are now attempting to implement certain protection functions into their digital excitation systems, such as the EX2000 Digital Exciter. This setup will allow the protection functions to provide redundancy when the digital multifunctional systems are applied as primary protection.

Testing the EX2000 protection functions through the use of transient simulators and then comparing its performance with that of a proven digital protection system is the scope of this thesis. Simulations are first set up through EMTP (ElectroMagnetic Transients Program), and then amplified voltage and current signals are fed into both systems for performance evaluation. The principal protection function which is tested in this thesis is the loss of excitation (LOE) function. An algorithm for a negative phase sequence current protection function is also configured and tested, but not implemented.
1.1 Loss of Excitation

Generator loss of excitation can be damaging to a generator, due to the low system voltages which accompany a running generator loss of excitation condition. This possible damage is due to the heating which occurs both in the generator rotor and in the armature. During generator loss of excitation, generated lagging vars from the generator to the system are lost, and lagging vars from the system to the generator are supplied instead [1]. Thus, the generating unit continues to supply power as an induction generator, obtaining its excitation from the system as a large reactive drain on the system. Such a large reactive drain can cause problems not only with the faulted machine, but also with the system and adjacent machines.

Through the use of a transient simulator system, several different conditions are played back in order to trip loss of excitation functions. Examples of such conditions are a control malfunction, terminal fault condition, and a stable and unstable swing of the same system. With these simulations, a more accurate and realistic evaluation of relay performance can be made.

1.2 EMTP (ElectroMagnetic Transients Program)

In order to determine the exact behavior of a generator following a loss of excitation condition, the use of a sophisticated dynamic stability computer program is required. The ElectroMagnetic Transients Program allows the user to model a system and to simulate fault conditions or disturbances within the system. Thus, generators,
transmission lines, motors, switches, and other power system components can be modeled by entering their parameters into an EMTP data file.

Generator control systems can also be modeled with the use of EMTP, which becomes extremely useful in the testing of a loss of excitation function. A loss of excitation can be simulated by creating a loss of control, or control malfunction. After such a simulation, the EMTP output file can then be analyzed in order to determine the impedance trajectory of the system.

In order to simulate different system conditions, the parameters in an EMTP data file must be altered. Thus, in order to simulate different load conditions, the system impedance data would be changed in the data file. Also, the simulation of different loss of excitation tests can be carried out by changing a control parameter or simulating a switch (fault case). These changes allow the user to analyze the system behavior, including the impedance trajectory, for such cases.

1.3 The Playback System

The playback system setup in the Power Systems Lab converts the EMTP output files into a form in which the voltage and current data can be played back in real-time. The playback system consists of a VAX workstation, computer terminal, microprocessor card, digital-to-analog converter, R-C filter, and power amplifiers. The VAX workstation acts as the host computer in this setup. From the computer terminal, the user accesses the EMTP output files previously created. There is a command procedure which scales the EMTP data and converts it into assembly code for microprocessor use. After processing,
the data is sent to the digital-to-analog (D/A) converter in order to create an analog signal. This signal is then fed into the R-C filter in order to smooth out the curves. This final signal can then be viewed through the playback outputs or through the Crown amplifiers.

This setup is an effective way of testing protective functions through the use of the output signals from the amplifiers. These output signals are then fed to other components for further amplification. The voltage outputs from the Crown amplifiers are fed to a power step-up transformer, while the current outputs are fed to current transformers configured in reverse.

1.4 The Doble Test Instruments

The current transformers mentioned in the last section were abandoned in order to use a better and more accurate system, the Doble F2375 Transient Current Sources. These test instruments can easily amplify the Crown amplifier output current signals to the desired current levels (e.g., 100% load=5 Amps). This system is much more reliable than using current transformers in reverse because the current levels are more easily attained and there is no possibility of saturation. Thus, this setup is used for all the transient tests performed.

1.5 Negative-Sequence Overcurrent Algorithm

An algorithm for a negative-sequence overcurrent protective function was set up for future implementation. This algorithm consists of two MATLAB m-files—one program simulates two current input signals while the other analyzes these input signals. Only two
input current signals are needed for this algorithm because the EX2000 requires only two current inputs. The first program, the input program, simulates normal operation of a system for eight cycles, then simulates a disturbance for twelve cycles, and finally returns to normal operation again for eight cycles. This input program also plots the two input current waveforms, as well as the magnitudes of the positive- and negative-sequence currents. The second program analyzes the waveforms through the use of sampled-data techniques. Samples from the input waveforms were first obtained. Then, a recursive method is used in order to form phasors for the two input currents. From these phasors, the positive- and negative-sequence currents can be calculated. Finally, the magnitudes of these currents are computed. This algorithm also accumulates the product of the square of the negative sequence magnitude and the time difference between samples (\((I^2)\times T\)). Any sustained disturbance would cause this sum to exceed a constant (K) value, which in the real world would trigger a relay.
CHAPTER 2: BACKGROUND AND SETUP DESCRIPTION

The purpose of this chapter is to give a more detailed description of the topics mentioned in the introduction. Detailed background information is discussed in order to give a better understanding of the research that was performed. Several plots are referred to in the chapter.

2.1 Loss of Excitation

As mentioned in the introduction, when a loss of excitation occurs, the generator loses lagging vars to the system and instead absorbs lagging vars from the system, causing it to operate as an induction generator. Operation as an induction generator for the faulted machine causes induced currents to flow in the field winding as well as the rotor body, teeth wedges, retaining ring, etc. Also, severe torque oscillations occur in the rotor shaft. The rotor is not designed to sustain such currents, and the turbine-generator shaft is not designed to withstand alternating torques [2]. Rotor overheating, coupling slippage, and even rotor failure can result. Some systems cannot tolerate continued operation of a generator without excitation, due to the vars absorbed to make up for the low excitation. Thus, if the generator is not disconnected immediately after a loss of excitation, instability may develop quickly and system shutdown could result. The allowable time before damage can occur in these situations depends on the type of machine, type of excitation loss, turbine governor characteristics and system conditions [3].
In order to prevent significant damage to the generator, a loss of excitation relay must be employed. Because a loss of excitation results in a change in reactive volt-amperes, an impedance type loss of excitation relay is usually used [2]. These relays usually have two setting determinations, the circle offset setting and the circle diameter setting. Usually, two loss of excitation relays are employed for security purposes. The offset of the two relays is usually set to one-half the direct axis transient reactance (Xd'/2). The diameter of the small circle is set to 1.0 per unit reactance on the machine base, while the larger diameter is set to the direct axis synchronous reactance (Xd).

Figure 2.1 shows a typical loss of excitation relay configuration.

![Figure 2.1 Typical Loss of Excitation Relay Settings](image)

The region inside each circle on the R-X diagram represents each relay’s contact close condition. While the “inner” relay is instantaneous (i.e., has no time delay), the “outer”
relay usually employs a time delay of 0.5-0.6 seconds. This time delay is adequate to avoid relay operation for stable generator swings whose impedance trajectories enter and then leave the operating region of the outer relay. These protective relays are commonly referred to as ohmic relays because they operate in response to the three variables of voltage, current, and the phase angle between the voltage and current.

Attention is now focused back to Figure 2.1, which shows an R-X diagram with the two loss of excitation relays. The R-X diagram is an extremely useful tool because it permits the illustration of certain power system behaviors on the same diagram. Thus, the behaviors of voltage, current and the phase angle between them, which are of interest to relay operation and application, can be analyzed [1]. It is also interesting to note that the R-X diagram also represents different phases of generator operation. For example, the upper right quadrant (positive R, positive X) represents the region of operation in which the generator is supplying real and reactive (lagging vars) power to the system, while the bottom right quadrant (positive R, negative X) represents the region in which real power is supplied to the system and reactive power is absorbed from the system. Thus, the loss of excitation relays are placed in the bottom half of the diagram, where the generator is absorbing lagging vars.

Figure 2.2 [1] shows some typical impedance trajectories on the R-X diagram for a generator which has experienced loss of excitation. This generator is assumed to be tied to an infinite bus through an external system impedance. Curve A describes the impedance path for a generator at 100% load prior to loss of excitation. The travel time
for the trajectory to reach the trip region of this relay is in the order of 2-5 seconds [1]. Point A' represents the final impedance value following loss of excitation at 100% load.

![Diagram of impedance trajectories](image)

**Figure 2.2** Typical Loss of Excitation Impedance Trajectories

According to past studies, this final impedance value approaches, but is always greater than, the average of the direct and quadrature sub-transient impedances of the generator \((Xd''+Xq'')/2\). This explains why the offset is set equal to one half the transient impedance—it assures that the impedance region around the point A’ always falls inside the relay impedance circle because \(Xd''/2\) is always less than \(Xd''\) [1]. Curve B represents the impedance path for a generator operating at approximately 50% load prior to loss of excitation. Curve A’B’C’ represents the final impedance value region following loss of excitation. Point A’ represents the final value at 100% load, while point C’ represents the
final value at no load. Point C' approaches but never reaches the average of the direct and quadrature synchronous impedances of the generator \((X_d+X_q)/2\). Thus, it is recommended that the diameter for the relay impedance circle be set equal to the generator synchronous impedance.

2.2 EMTP (ElectroMagnetic Transients Program)

The ElectroMagnetic Transients Program allows for the determination of the behavior of a generator following a loss of excitation. EMTP is able to provide exact numbers, as well as plots, which can be used to play back such disturbances in real-time. Thus, EMTP becomes a useful tool in the testing and evaluation of loss of excitation protective functions.

EMTP operates just like any other program—a system first has to be configured in an input data file before being compiled. This system can be modeled with the use of several different configurations. For example, there are many different ways to model a power source. A synchronous machine can be modeled as a Type 59 3-phase dynamic synchronous machine source, while a Type 14 conventional voltage source is used for an infinite bus \([4]\). The rest of the system can also be modeled differently.

The first parameter cards to be entered into EMTP are the miscellaneous data cards. These cards consist of the time steps in which data is recorded (deltaT), the length of the simulation (Tmax), the frequency in which the system will operate (60 Hz), as well as the rate of output (Iout) and the rate of plotting (Iplot) \([4]\). DeltaT and Iout are the parameters that determine the sampling rate of EMTP. It is extremely important to
control these parameters because the playback system only operates at a certain sampling rate (125 samples per 3 cycles).

The next aspect of the power system which is modeled is the control system, which simulates the synchronous machine's excitation controls. The Transient Analysis of Control Systems (TACS) allows the user to describe the system through the use of block diagram representation. The coefficients of both the numerators and denominators of the different blocks are inputted into the data file, along with the different variables from within the system.

Figure 2.3 IEEE Type 1 Excitation Control System

Figure 2.3 [5] shows the control system employed for the testing of General Electric's EX2000 Digital Exciter. This system is known as an IEEE Type-1 control system. The constant values used for this system were inputted into the data file. TACS signals and
EMTP electrical-network variables can be interfaced to form a hybrid EMTP-TACS configuration [4], which is extremely useful in simulating a control malfunction (which in turn leads to a loss of excitation). TACS control variables can also be plotted similar to the way the electrical-network variables in EMTP are plotted.

The main components of the power system are the last ones to be inputted into the EMTP data file. First, the line impedances are modeled by placing the node names around the branch with their corresponding impedance values. Next, the switches are modeled by entering the closing and opening times of the switches with their corresponding node names. The switch data section allows the user to simulate various faults, such as three-phase or single-phase-to-ground faults, which are useful in evaluating system behavior during such disturbances. The final section which is modeled is the source data section. Because of the complexity of a synchronous generator, this section is one of the more complicated sections to model. Modeling of an infinite bus only requires entering the voltage, frequency, and phase angle data of a Type 14 conventional voltage source. For a synchronous machine source, however, several parameters such as the number of poles, MVA rating, and voltage rating, as well as the synchronous, transient, and sub-transient reactance data, have to be entered into the input file. Also, several field time constants and other reactance data are inputted. Data for this testing was obtained from one of General Electric’s generator data sheets for a conventional steam turbine.

The final step in the input process is output plotting requests, which is necessary to obtain proper playback system results. Because of the manner in which the playback system is configured, it is required to request that the terminal three-phase voltage data is
listed in the first three columns, followed by the three-phase current data listings. This translates into a total of six output requests, in order to obtain six output signals. This setup makes it easier to keep track of the outputs from the playback system. Also, the scaling factors in the playback system are different for voltage and current. Thus, in order to obtain signal magnitudes large enough to obtain nominal voltage and current signals for testing in the protective systems, the EMTP output requests must be set up in this way.

2.3 The Playback System

Laboratory real-time power system simulations are important for relay testing which must be done in real-time because it is impractical and expensive to perform fault tests on a real power system [6]. By playing back the off-line digital computer simulation record from EMTP via conditioning amplifiers, tests can be carried out on protective systems. This method of analysis is one of the more cost-effective ways in which relay response to fast electromagnetic transients can be investigated.

Figure 2.4 [6] shows the playback system setup block diagram. This setup includes all the hardware needed for the real-time playback of the EMTP output file record. A VAX workstation functions as the host computer for MVME133A Microcomputer [6]. All the necessary EMTP output and control files are stored in the VAX and are accessed from the VT220 terminal. The VAX also installs the Macro Assembler for the Motorola 68020 microprocessor, which translates the machine codes into object code for the MVME133A Microcomputer [6]. A Global Positioning System (GPS) Clock interfaces with the control computer to generate a precise frequency using
the CA code radiated by the NAVSTAR GPS satellites, which is available to the civil community [6]. The Motorola MVME133A Microcomputer functions as the playback system master controller. It outputs the EMTP data to the digital-to-analog converter, which uses six channels to produce analog phase voltage outputs. The output of each channel is rated at $\pm 10$V. Any steps in the signal waveforms are then removed by the two-stage RC filter. The voltage outputs are then increased via the three Crown PS-400 power amplifiers. Because the voltage levels outputted from the amplifiers (~7Vrms) is still not high enough for relay testing (69.3V), power transformer are then used in reverse to obtain a high enough signal. The current signals, which are actually voltage signals in the playback process, are fed to current transformers (also in reverse) in order to obtain the nominal 5A current signals needed for relay testing.
The playback system implements a command procedure which analyzes the EMTP output file and converts the data to the proper form for processing. The playback process requires control and data files which are derived from the EMTP output file. The first step in the procedure is the compilation of the EMTP data file to obtain an output file. The command procedure is then implemented at this point in the process. First, a FORTRAN file skims through the EMTP output file, collects the bus voltage and branch current data, and compiles this data into a playback data source file [6]. The rest of the command procedure involves compiling the source data file into machine codes. The source data file is compiled and linked to the assembly code file for playback during this procedure. The assembly code file, as well as a control program which is used for all cases, is then downloaded to the control computer for playback. The following procedure illustrates the necessary commands for playback:

```
EMTP input file name - STABLE.DAT

$ em stable.dat                       //creates EMTP output file STABLE.OUT
$ rename stable.out batch1.out       
$ run batch1                          //runs FORTRAN file BATCH1.FOR,
                                         //creates source file BATCH1.SRC
$ rename batch1.src stable.src       
$ a6 stable.src                       //creates object file STABLE.OBJ
$ l6 stable.obj                      //creates assembly code file STABLE.ABS
Ctrl-A                                //in order to enter operating system
```
The playback system output signals then undergo two steps of amplification. First, the signals are amplified by Crown amplifiers. In the second amplification step, the voltage and current signals undergo separate amplifications: the voltage signals are fed into a power voltage transformer, and the current signals are fed into the Doble Transient Current Sources. In the case of the voltage signals, the gain of the Crown amplifiers is set so that the output (input to the voltage transformer) is about 6.9 V. The resulting output voltage from the transformer is around 69.3V, which is the required line-to-neutral voltage for the DGP system (120V line-to-line / √3).

Although this system is an effective way of playing back signals at real time, there are a few drawbacks. The manner in which the system is set up allows for only voltages to be played back. Thus, the branch current (from synchronous generator) is actually outputted as a voltage by the playback. When these “current” signals are connected from the power amplifiers to a current transformer in reverse, the result is a voltage source driving a short circuit. This method is still effective in obtaining the desired 5A current signals for relay testing from the current transformer “secondary” side (actually primary side because of reverse configuration). The output voltage signals are also too small for relay testing, resulting in the use of power voltage transformers in reverse. Another
drawback is the fact that the transient output must have a specific “sampling rate”, meaning a time-step interval (deltaT) and output rate (Iout) equivalent to 125 samples per three cycles.

2.4 The Doble Test Instruments

As mentioned in the introduction, the Doble F2375 Transient Current Sources replaced the current transformers, resulting in a more accurate method of testing the two relays. The F2375 system is a direct coupled transconductance (voltage to current) power amplifier [7]. Driving power system protective relaying or control systems with transient waveforms is a typical application of these instruments. The F2375 can easily supply the necessary 5 A required to test the relays, and can actually supply up to 12 A continuously. The F2375 requires a low level analog input signal, which is supplied by an external source. In this case, the external source is the output of the Crown amplifiers, which are connected to the appropriate pins of a 37-pin F2375 interface cable (one per phase connected to each F2375) [7]. Thus, these sources simulate three-phase transient currents, which are fed into the two systems being tested—the DGP and the EX2000. The current inputs of these systems are connected in series, so that each system views the same current.

2.5 EX2000 Digital Exciter

General Electric’s EX2000 excitation system is a control tool used to limit generator operation. The EX2000 consists of three parts: the power potential transformer
(PPT), the three-phase full-wave inverting thyristor bridge, and the control core, which is the focus of this thesis. The PPT supplies power to the exciter through its connection directly to the terminals of the generator [8]. The output of the PPT is connected to the input of the inverting thyristor bridge, which provides both positive and negative forcing voltage for optimum performance [8]. The control core controls the ac terminal voltage and/or the reactive volt amperes of the generator by controlling the field excitation [8]. The EX2000 also contains protective functions such as the loss of excitation protection function, which is the scope of this thesis.

The control system contains both a generator terminal voltage regulator and a generator field voltage regulator, known as the automatic or ac regulator and the manual or dc regulator, respectively [8]. During dc regulator operation, a constant generator field voltage is maintained regardless of the operating conditions on the generator terminals. During ac regulator operation, a constant generator voltage is maintained under varying load conditions [8].

The Potential Transformer Current Transformer (PTCT) card is an essential part of the EX2000 excitation system. This board is used to isolate and scale the secondary voltage and current signals from the PTs and CTs (primary-to-secondary transformers on a real power system) [8]. In the playback system setup, the amplified voltage and current signals (from the PTs and CTs in reverse) are connected to the input terminals of the PTCT card. The low-voltage output signals of this card are fed into the EX2000 control core via a 50-pin connector ribbon cable.
As mentioned above, the EX2000 also contains several protection functions, such as loss of excitation and overvoltage functions. The loss of excitation protection function consists of two impedance relays, with characteristics similar to those in Figure 2.1. Each relay has a time delay setting, as well as an output parameter, which can be viewed on an oscilloscope to detect relay operation.

The pickup settings for these functions can be entered into the excitation system through the use of the EX2000 programmer keypad. The programmer keypad allows an operator to control the exciter by examining exciter parameters, inputting alphanumeric data, and running diagnostics [8]. Thus, software adjustments can easily be made through the use of this operator interface system. The programmer also provides a digital display which gives readouts of fault codes, status, RAM values, and EEPROM values.

2.6 Digital Generator Protection System (DGP)

General Electric’s Digital Generator Protection System (DGP) is a proven multi-functional generator protection scheme which employs microprocessor-based technology once waveform-sampled data related to a power system is obtained. Thus, the DGP provides a numerical relaying system with a wide range of protection, monitoring, control, and recording functions [9]. The EX2000’s loss of excitation function performance is compared to that of the DGP’s in this thesis.

The DGP, unlike the EX2000, does not require the use of an external PTCT card, thus, allowing for a direct connection from the PTs and Doble units. Instead, the DGP employs two magnetic modules, which each contain two CTs and two PTs. The DGP
also differs from the EX2000 in that it contains four trip output contacts and four alarm output contacts. Of course, the major difference between the two systems is the fact that the DGP is an extensive relaying system focused mostly on protection, while the EX2000 is more concerned with the control aspects of the generator.

The DGP, like the EX2000, provides a user-friendly keypad from which control and protection function parameters can be accessed. This keypad is called the Man-Machine Interface (MMI). The MMI allows the operator to enter settings, access data, and test outputs [9]. The DGP also has LED displays for all its relay protection functions. Thus, when a trip of a function occurs, it is indicated on the LED display for that particular relay, and a trip message is also displayed on the MMI.

2.7 Negative-Sequence Current Algorithm

Protection against prolonged faults or unbalanced loads is necessary in any power system. A negative-sequence, overcurrent relay is designed to protect generators against possible damage from unbalanced currents resulting from the above conditions. Sampled-data techniques can be used to evaluate these unbalanced currents, and thus prevent damage to the generators.

An algorithm has been formed and tested to perform such a task. This algorithm determines the magnitudes of the positive- and negative-sequence currents. If the magnitude of the negative-sequence current reaches a certain level due to an imbalance,
then the $(I_2^2*2)$ value is calculated, where $I_2$ is the magnitude of the negative-sequence current and $T$ is the duration of the unbalanced condition.

Negative-sequence components exist in stator currents when a generator is subjected to an unbalanced fault or load. This negative-sequence component sets up a counter-rotating flux field in the machine, which in turn causes double-frequency currents to flow in the rotor iron and slot wedges [10]. These currents may cause high and possibly dangerous temperatures in a very short time. The following equation, Equation 2.1, expressed in terms of negative-sequence current and time, expresses the heating of a machine operating with unbalanced stator currents:

$$HeatEnergy = \int I_2^2*dt < K$$

(2.1)

The limits of the integral are between $T$ and 0, where $T$ is the duration of the unbalanced condition. $K$ represents maximum permissible heating of a machine. The values of $K$ may vary from 5 to 40, depending on the rating, design, and type of the generator to be protected [10].

There are several unbalanced system conditions which may result in these high temperatures. Often, the failure of the protection or equipment external to the machine is to blame. Some typical conditions that result in unbalanced generator currents are: (1) accidental single-phasing of the generator due to open leads or buswork, (2) unbalanced generator step-up transformers, (3) unbalanced system fault conditions and a failure of the relays and breakers, and (4) planned single-phase tripping without rapid reclosing [11].

The negative-sequence function, thus, allows corrective action to be taken before having to remove the machine from service, due to the above conditions.
In order to prevent the damaging of generators due to unbalanced conditions, computer relaying techniques are used to evaluate the phase current waveforms. A listing of an algorithm used to perform this task is shown in Appendix B (GERecur2.m). All phase currents are assumed to be at zero before time t=0, and only the a and c phase currents are analyzed (only two current inputs are needed in the EX2000 setup). Data points are sampled from each cycle, at a sampling rate of 32 samples per cycle. Each data point is then evaluated. First, the difference between a current data point and the corresponding data point from the previous cycle is calculated, which is just the difference in each phase current once a full cycle has passed. These difference values for the a and c phases are then used in recursive equations, which use the previous values of these equations (the first values being equal to zero) and add the difference terms multiplied by a constant and a sine or cosine term. The constant term is \( \sqrt{2} \) divided by the number of samples. The other term consists of a cosine or sine of a fraction of \( 2\pi \) (depending upon the sample number of the cycle - jth sample/32). Thus, the a and c phases each have two recursive equations - a cosine equation and a sine equation [12]. Phasors of the a and c phase currents can then be formed by using cosine and sine quantities for each phase current - the real part of the phasor being equal to the cosine term and the imaginary part being equal to the negative of the sine term.

Now that the a and c current phasor quantities have been calculated, the positive- and negative-sequence currents can also be calculated. This computation is done by using the linear transformation matrix equations, in which the positive- and negative-sequence currents can be calculated from the a and c phasor quantities. Of course, these equations
are in terms of only the a and c phases due to the absence of the b phase current input.

The real and imaginary components of the positive and negative sequence phasor quantities are then determined, and thus their magnitudes can be calculated and plotted. This algorithm also contains a loop (which will be discussed in Chapter 4) which calculates the \((I^2)^2*T\) quantity.
CHAPTER 3: SETUP OF TEST CASES

This chapter describes the manner in which a loss of excitation is simulated in EMTP from the different conditions, and the impedance trajectories which result from the different parameters. This chapter also discusses the LOE function settings of both the DGP and EX2000.

3.1 Control Malfunction

One method of simulating a loss of excitation in a generator is to force a loss of control. In the case of a control malfunction, the feedback loop of a control system is ignored because of a constant terminal voltage signal being applied to the input. As mentioned in Chapter 2, an IEEE Type 1 Excitation Control System (as in Figure 2.3) is configured in the TACS section of the EMTP input data file. When a constant voltage of 2 per unit is applied to the input of this control system, the feedback loop is ignored and the system tries to compensate for the high voltage. This action results in an almost linear decrease of the peak voltage signals at the generator terminals over the length of the simulation.

A number of tests simulating such a condition were set up in EMTP and simulated using the aforementioned playback system. The behavior of a simple two bus system-a synchronous generator and an infinite bus separated by a system impedance-was simulated for the tests. These tests were run at various generator load conditions, system impedances, and inertia constants. The different load conditions simulated were 100, 50,
and 30 percent load. The tests simulated system impedances of 0.05, 0.2, and 0.4 per unit, and inertia constants of 0.125, 1.25, and 12.5 million pound-feet x radians per second squared (M lb-ft * rad/s²). Thus, twenty-seven different tests were run for the control malfunction condition.

In order to simulate a synchronous generator in EMTP, it is important to know the different generator parameters. In this case, the generator parameters used were obtained from General Electric data sheets for a conventional steam unit currently in service. The following table shows the different reactances, time constants, and other data required for the input data file:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMVA</td>
<td>Total 3-phase volt-ampere rating of machine</td>
<td>229.741 MVA</td>
</tr>
<tr>
<td>RKV</td>
<td>Rated line-to-line voltage of machine</td>
<td>34.5 kV (rms)</td>
</tr>
<tr>
<td>Ra</td>
<td>Armature resistance</td>
<td>0.004 pu</td>
</tr>
<tr>
<td>Xi</td>
<td>Armature leakage reactance</td>
<td>0.093 pu</td>
</tr>
<tr>
<td>Xd</td>
<td>Direct-axis synchronous reactance</td>
<td>2.134 pu</td>
</tr>
<tr>
<td>Xq</td>
<td>Quadrature-axis synchronous reactance</td>
<td>2.050 pu</td>
</tr>
<tr>
<td>Xd'</td>
<td>Direct-axis transient reactance</td>
<td>0.234 pu</td>
</tr>
<tr>
<td>Xq'</td>
<td>Quadrature-axis transient reactance</td>
<td>0.479 pu</td>
</tr>
<tr>
<td>Xd''</td>
<td>Direct-axis subtransient reactance</td>
<td>0.224 pu</td>
</tr>
<tr>
<td>Xq''</td>
<td>Quadrature-axis subtransient reactance</td>
<td>0.217 pu</td>
</tr>
<tr>
<td>T_{do}</td>
<td>Direct-axis open circuit transient time constant</td>
<td>3.7970 s</td>
</tr>
<tr>
<td>T_{qo}</td>
<td>Quadrature-axis open circuit transient time constant</td>
<td>0.438 s</td>
</tr>
<tr>
<td>T_{do}''</td>
<td>Direct-axis open circuit subtransient time constant</td>
<td>0.033 s</td>
</tr>
<tr>
<td>T_{qo}''</td>
<td>Quadrature-axis open circuit subtransient time constant</td>
<td>0.070 s</td>
</tr>
<tr>
<td>X_0</td>
<td>Zero-sequence reactance</td>
<td>0.103 s</td>
</tr>
</tbody>
</table>

In order to simulate the different generator load conditions, the angle of the synchronous generator had to be determined. The angle of the infinite bus (phase a) was
set at zero degrees (the definition of an infinite bus). Different values for the synchronous generator angle were entered until the steady-state solution of the corresponding output files showed that the generator was operating at the appropriate load condition. For example, at a system impedance of 0.2 per unit and an inertia constant of 1.25 at 100 percent load, the necessary angle to achieve such a load condition is 11 degrees. Thus, the steady-state solution in the output file for this case shows that the power flow in each phase is approximately 76.67 MVA (230 MVA for three phases). Determining the angle for the system impedance of 0.2 per unit makes it easier to determine the angle at other system impedances. For example, for a system impedance of 0.4 per unit at the same load, the angle needed in the input file is double the angle of the 0.2 per unit cases (i.e., 22 degrees). Thus, in order to maintain the same load condition for different system impedances, the synchronous generator angle must be changed by the same ratio as the system impedances. Also, if it is desired to change only the loading of the generator for a certain system impedance, only the angle need be changed. For example, if it is desired to change the loading from 100 percent to 50 percent at a certain system impedance, the angle needs to be cut in half in the input file. It also must be noted that varying the inertia constant has little effect on the loading conditions and only changes the path of the impedance trajectory. The following is a table of the generator angles used in the testing for the various system impedances and load conditions:
Table 3.2 Generator Angles Used in Input Files

<table>
<thead>
<tr>
<th>Load Condition (Percent)</th>
<th>System Impedance (per unit)</th>
<th>Generator Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.4</td>
<td>22</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
<td>11</td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
<td>2.75</td>
</tr>
<tr>
<td>50</td>
<td>0.4</td>
<td>11</td>
</tr>
<tr>
<td>50</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>50</td>
<td>0.05</td>
<td>1.375</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
<td>6.6</td>
</tr>
<tr>
<td>30</td>
<td>0.2</td>
<td>3.3</td>
</tr>
<tr>
<td>30</td>
<td>0.05</td>
<td>0.825</td>
</tr>
</tbody>
</table>

In order to determine the system impedance value to be entered for each case, the base impedance of this synchronous machine first had to be calculated. The following equation shows this calculation using the generator MVA and kV ratings:

\[ Z_{BASE} = \frac{(34.5 kV)^2}{229.741 MVA} = 5.18 \text{ Ohms} \quad (3.1) \]

Thus, for system impedances of 0.4, 0.2, and 0.05 per unit, impedance values of 2.0, 1.0, and 0.25 Ohms were entered into the input file, respectively. The inertia values could be entered directly into the input data file and did not have to be converted.

With all the necessary parameters having been determined, the next step was to run the tests on EMTP at the required sampling rate of 125 samples per 3 cycles, and through the playback procedures. After having obtained the necessary files via the command procedure mentioned in Chapter 2, the files could be downloaded to the microprocessor card for real-time playback in order to test the two systems. Appendix B lists one example of an EMTP input file.
Plots of the expected impedance trajectories were also made in order to verify proper operation of the two systems. These plots were constructed using MATLAB through the use of m-files. These subroutines analyzed voltage and current data (sampled at a rate of 33 samples per cycle), which had been stored in an output file as a matrix. The data was first converted to per unit by dividing each sample by the base voltage and base current. Using sampled-data techniques similar to those used for the negative-sequence function, voltage and current phasors were formed. By dividing the voltage phasor by the current phasor, an impedance phasor was calculated for each corresponding cycle. The impedance point for each cycle was then plotted by determining the real and imaginary parts of the phasor. The relay settings (in per unit) were also plotted on the same graph in order to determine if an outer and/or inner trip was expected for each case. These plots were made geometrically in the m-file ‘impcirc.m’, which is listed in Appendix B along with the other m-files dealing with these plots.

Figures 3.1-3.9 show the expected impedance trajectories for the different control malfunction cases. Figures 3.1-3.3 show trajectories for a generator operating initially at 100 percent load for the three different inertia constants, while Figures 3.4-3.6 and 3.7-3.9 correspond to initial generator operation of 50 and 30 percent load, respectively. The tests run at 100 percent load were plotted for a duration of 4 seconds. However, the other load condition tests had to be run for a longer period of time to allow the trajectories to enter the loss of excitation function trip zones. Thus, the 50 percent tests were plotted for a length of 6 seconds, while the 30 percent tests were plotted for 8 seconds. It should be noted that the playback system was initially set up to play back fault
simulations lasting only 2 seconds, and the system allows for a maximum simulation time of only up to 4 seconds. Thus, when the 50 and 30 percent tests were played back, only the last four seconds could be simulated. However, this length of time was sufficient for testing the inner and outer zones of the relays. Thus, these plots of expected system behavior not only aided in determining the lengths of the simulations, but also revealed the problem mentioned above.

![Graph showing impedance trajectories](image)

**Figure 3.1** Control Malfunction Impedance Trajectories at 100% Load, Inertia=0.125, System Impedances of a) 0.4 pu, b) 0.2 pu, and c) 0.05 pu (holds for Figures 3.1-3.9)
Figure 3.2 Control Malfunction Impedance Trajectories at 100% Load and Inertia=1.25

Figure 3.3 Control Malfunction Impedance Trajectories at 100% Load and Inertia=12.5
Figure 3.4 Control Malfunction Impedance Trajectories at 50% Load and Inertia=0.125

Figure 3.5 Control Malfunction Impedance Trajectories for 50% Load and Inertia=1.25
Figure 3.6 Control Malfunction Impedance Trajectories for 50% Load and Inertia=12.5

Figure 3.7 Control Malfunction Impedance Trajectories for 30% Load and Inertia=0.125
Figure 3.8 Control Malfunction Impedance Trajectories for 30% Load and Inertia=1.25

Figure 3.9 Control Malfunction Impedance Trajectories for 30% Load and Inertia=12.5
By examining these figures, many trends are discovered and system behavior could be predicted, if necessary, at different system parameters. For example, the impedance locus of 0.4 per unit system impedance, at all loads, always travels the fastest [13], while the 0.05 per unit locus is more gradual. The 0.4 per unit locus is also closer to the top of the relay zones, which implies that the higher the system impedance, the “higher” the impedance locus. Also, at full load, the impedance locus of 0.4 per unit always spirals into the zones, whereas the 0.05 per unit locus reacts differently in each case. Changing the load conditions causes a significant change in the trajectories. For example, the 50 percent load locii are more gradual than those at 100 percent, and the 30 percent load locii are even more gradual. Unlike the 100 percent locii, the 50 percent locii only travel to a point just inside the inner relay characteristic before reversing, and the 30 percent locii travel to a point outside the inner relay characteristic before reversing.

Changing the inertia constant greatly affects the terminating point. The figures show that by increasing the inertia constant, the impedance locii terminate at a point farther away from the origin. It should be noted that the final impedance values will always be greater than the offset setting (Xd'2) and, thus, will always fall inside the relay characteristics [13]. A higher inertia constant signifies a stiffer system, meaning less reaction to a loss of excitation. This fact is verified in the plots, which show more direct (less spiraling) locii as the inertia constants are increased.
3.2 Stable and Unstable Swings

Subjecting a system to stable and unstable generator swings by placing a balanced fault within the system is a good method of testing the loss of excitation function characteristics, even though a loss of excitation does not occur. The stability status of the system depends upon how long the fault is sustained (i.e., when a circuit breaker within the system is opened). Figure 3.10 [5] shows the circuit used to simulate the stable and unstable swings. The figure shows that this system, like the system used for the control malfunction tests, is a two-machine system. However, this system consists of transformers and an intermediate bus in between the synchronous machine and infinite bus.

![Diagram of Power System Used in Stability Studies](image)

**Figure 3.10** Power System Used in Stability Studies

Figure 3.10 also shows a circuit breaker which is used to cause the stable and unstable conditions. First, the system is run at normal operation for 100 ms (for playback purposes). Then, the three-phase fault is simulated at Bus 12. For the stable swing case,
the fault is sustained for 100 ms (i.e., the breaker is opened 100 ms after the fault is simulated). This small time duration enables the system to recover from the fault. Figures 3.11 and 3.12 show the mechanical angle and velocity of the synchronous machine, respectively.

**Figure 3.11 Mechanical Angle for Stable Case**
These figures show that the parameters converge to a certain value, meaning that the oscillations caused by the fault decay. Appendix B lists an example of an EMTP stable case input data file. A file similar to this one was also used for the unstable cases. For the unstable case, the fault is sustained for 300 ms (i.e., the breaker is opened 300 ms after the fault is simulated). Because of this sustained fault, the system is not allowed time to recover and goes unstable. Figures 3.13 and 3.14 show the machine mechanical angle and velocity, respectively. In this case, the plots show that the angle and velocity do not converge and instead keep increasing in value, which is expected in an unstable swing.
Figure 3.13 Mechanical Angle for Unstable Case

Figure 3.14 Velocity for Unstable Case
Impedance trajectory plots were also used to predict relay operation for the stable and unstable swing cases. These plots were constructed in the same manner as the control malfunction trajectory plots. Five total cases were plotted and later run, which consisted of two pairs of stable and unstable swings at two different inertia constant values and one unstable swing at 30 percent load. Figures 3.15-3.19 show the trajectories for each of these cases. These graphs show that the impedance trajectories for all the cases do not enter the tripping zones. The stable cases eventually oscillate between two points, whereas the unstable cases act differently depending on the inertia constant.

Figure 3.15 Stable Case Trajectory for 100% Load and Inertia=0.18
Figure 3.16 Unstable Case Trajectory for 100% Load and Inertia=0.18

Figure 3.17 Stable Case Trajectory for 100% Load and Inertia=1.8
Figure 3.18 Unstable Case Trajectory for 100% Load and Inertia=1.8

Figure 3.19 Unstable Case Trajectory for 30% Load and Inertia=1.8
3.3 Determination of Relay Settings

The final step of the test setup involved setting the parameters of the DGP and EX2000 LOE protection functions properly. It was important to set the inner and outer functions properly in order to ensure correct operation of the two systems. If the function characteristics were not set properly, then there would be a discrepancy in the data and the results would not be reliable.

Both systems contain a keypad programmer which allows for an easy interface between the user and each system. For the EX2000 Digital Exciter, it was necessary to change the EEPROM variables (via the keypad) corresponding to the diameter and center of each function circle characteristic, as well as the time delay for each circle. The numerical values were entered in counts, with 4096 counts being equivalent to one per unit. As listed in Table 3.1, the synchronous reactance (Xd) and transient reactance (Xd') are 2.134 and 0.234 per unit, respectively. The center (distance on the -X axis from the origin) for each circle is one-half the synchronous reactance plus one-half the transient reactance (i.e., the offset added to the circle radius). Thus, for the small circle, the following parameter values were entered into the keypad: diameter-4096 counts, center-2527 counts, time delay-10 ms. For the large circle, values of 8741 counts, 4850 counts, and 500 ms were entered corresponding to the diameter, center, and time delay, respectively.

Setting the DGP loss of excitation functions was trickier because this system requires the parameter values to be entered in secondary ohms. Thus, a new base
impedance was calculated using the nominal secondary voltage and current values of 120 V (line-to-line) and 5 A, respectively. Equation 3.2 shows this calculation:

$$Z_{BASE\_SECONDARY} = \frac{120V (I - I) \sqrt{3}}{5A} = 13.856 \text{Ohms}$$ (3.2)

Hence, by multiplying the per unit reactance values by the above base impedance, the diameters and centers of each circle can be converted to secondary ohms. However, the DGP requires the radii of the circles to be entered, not the diameters. For the small circle, values of 8.55 Ω, 6.93 Ω, and 10 ms were entered into the DGP for the center, radius, and time delay, respectively. For the large circle, values of 16.41 Ω, 14.79 Ω, and 500 ms were entered for those same parameters. These two relays also had to be set to trip one of four available contacts. With the relays having been configured, the two systems could be evaluated. It should be noted that these same settings were used for the stable/unstable swing tests (in both systems) in order to simplify things.
CHAPTER 4: RESULTS AND ANALYSIS

This final chapter displays the results from the tests described in Chapter 3 and analyzes the performance of the EX2000 compared with that of the DGP. The results from the negative-sequence protective function is also discussed.

4.1 Control Malfunction

The impedance characteristics of the simulated generators were studied to determine the reliability of the EMTP simulation and the playback system. The impedance trajectories produced by the playback system and fed into the DGP and EX2000 were found to be very close to what was expected. The characteristics behaved in a manner very similar to what studies in the past have shown.

A loss of excitation was simulated by triggering a loss of control of the generator, as discussed in Chapter 3. The performances of the loss of excitation functions were compared by reviewing the difference in trip times of the two systems for each case. Table 4.1 summarizes the test case results utilizing the simulated conditions developed with EMTP. For the rated load condition, the trajectories moved quickly from the initial load point through the outer zones and spiraled into the inner zones. The traverse time from the simulated initial condition to the function inner zone was within 3 seconds for most cases, with the swing for 0.4 per unit system impedance traveling the fastest. In all cases, the trajectories entered the inner zones, causing both inner and outer LOE functions in DGP and the EX2000 to operate, as Table 4.1 shows.
Table 4.1 Control Malfunction Spreadsheet ('X' denotes relay operation)

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>Inertia Constant (Mlb-ft*rad/s^2)</th>
<th>System Impedance (pu)</th>
<th>EX2000 Outer Relay Trip</th>
<th>EX2000 Inner Relay Trip</th>
<th>DGP Outer Relay Trip</th>
<th>DGP Inner Relay Trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.125</td>
<td>0.05</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>1.25</td>
<td>0.05</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>12.5</td>
<td>0.05</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>0.125</td>
<td>0.2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>1.25</td>
<td>0.2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>12.5</td>
<td>0.2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>0.125</td>
<td>0.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>1.25</td>
<td>0.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>100</td>
<td>12.5</td>
<td>0.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>50</td>
<td>0.125</td>
<td>0.05</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>1.25</td>
<td>0.05</td>
<td>X</td>
<td>-</td>
<td>X</td>
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<td>12.5</td>
<td>0.05</td>
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<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>0.125</td>
<td>0.2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>50</td>
<td>1.25</td>
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<td>50</td>
<td>12.5</td>
<td>0.2</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
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<td>50</td>
<td>0.125</td>
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<tr>
<td>50</td>
<td>1.25</td>
<td>0.4</td>
<td>X</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>50</td>
<td>12.5</td>
<td>0.4</td>
<td>X</td>
<td>X</td>
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</tr>
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<td>0.125</td>
<td>0.05</td>
<td>X</td>
<td>-</td>
<td>X</td>
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<td>1.25</td>
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<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>0.125</td>
<td>0.2</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>1.25</td>
<td>0.2</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>0.125</td>
<td>0.4</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>1.25</td>
<td>0.4</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>12.5</td>
<td>0.4</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>
As the simulated initial load point was reduced to 50% of rated, the trajectories took longer paths from the initial point before entering the outer function zones, which is shown in Figures 3.4-3.6. This is partly due to the initial point being at 2 per unit instead of 1 per unit. The impedance trajectories were also more gradual, which explains the lengthening of the simulation to six seconds (with the last four seconds being simulated, as explained in Chapter 3) for the 50% load tests. For most of the 0.2 and 0.4 per unit system impedance swings, the trajectories entered the inner and outer zones, forcing both inner and outer functions to pick up as shown in Table 4.1. These trajectories entered the inner characteristic and then, at a certain point, reversed and oscillated between the inner and outer zones in most cases. However, for the 0.05 per unit cases, the trajectories did not reach the inner zones. Therefore, the LOE inner zone functions did not operate for the 0.05 per unit system impedance swings, and only the outer zones operated. The traverse times for all the 50% load swings were within 5 to 7 seconds, but because the simulations lasted only six seconds some trajectories did not reach the inner zone. Had the simulations been carried out for a longer period of time, all the 50% load cases would have eventually tripped the inner protection functions.

Finally, at 30% of the rated load, the impedance swings took even longer paths from the initial load points to the function characteristic zones. Again, this is partly due to a change in the initial load point. None of the trajectories entered the inner function zone, even though the trajectories lasted eight seconds (with the last four seconds being simulated). The impedance swings traveled to a point outside the inner zone and then reversed and started oscillating between the inner and outer zones. Table 4.1 shows that
the LOE inner function did not operate for these conditions in either of the two protection systems. The impedance traverse times from initial load point to the point where they reversed for 30% load conditions were more than 7 seconds for all cases.

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>Inertia Constant (Mlb-ft*rad/s^2)</th>
<th>System Impedance (pu)</th>
<th>EX2000-DGP Outer Relay (ms)</th>
<th>EX2000-DGP Inner Relay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.125</td>
<td>0.05</td>
<td>+20</td>
<td>+10</td>
</tr>
<tr>
<td>100</td>
<td>1.25</td>
<td>0.05</td>
<td>-10</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>12.5</td>
<td>0.05</td>
<td>-10</td>
<td>+10</td>
</tr>
<tr>
<td>100</td>
<td>0.125</td>
<td>0.2</td>
<td>+40</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>1.25</td>
<td>0.2</td>
<td>-20</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>12.5</td>
<td>0.2</td>
<td>+50</td>
<td>+40</td>
</tr>
<tr>
<td>100</td>
<td>0.125</td>
<td>0.4</td>
<td>-20</td>
<td>-20</td>
</tr>
<tr>
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<td>0.4</td>
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<td>-20</td>
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<td>0.4</td>
<td>-20</td>
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<td>0.05</td>
<td>+60</td>
<td>NT</td>
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<td>0.05</td>
<td>+160</td>
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<td>0.05</td>
<td>+90</td>
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<td>0.2</td>
<td>+60</td>
<td>+20</td>
</tr>
<tr>
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<td>0.2</td>
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<tr>
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<td>+90</td>
<td>NT</td>
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<tr>
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<td>0.4</td>
<td>+30</td>
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</tr>
<tr>
<td>50</td>
<td>1.25</td>
<td>0.4</td>
<td>+60</td>
<td>+20</td>
</tr>
<tr>
<td>50</td>
<td>12.5</td>
<td>0.4</td>
<td>+40</td>
<td>0</td>
</tr>
<tr>
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<td>0.05</td>
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<tr>
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<td>+270</td>
<td>NT</td>
</tr>
<tr>
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<td>12.5</td>
<td>0.05</td>
<td>+110</td>
<td>NT</td>
</tr>
<tr>
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<td>0.125</td>
<td>0.2</td>
<td>0</td>
<td>NT</td>
</tr>
<tr>
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<td>1.25</td>
<td>0.2</td>
<td>+270</td>
<td>NT</td>
</tr>
<tr>
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<td>12.5</td>
<td>0.2</td>
<td>+180</td>
<td>NT</td>
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<tr>
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<td>+40</td>
<td>NT</td>
</tr>
<tr>
<td>30</td>
<td>1.25</td>
<td>0.4</td>
<td>+80</td>
<td>NT</td>
</tr>
<tr>
<td>30</td>
<td>12.5</td>
<td>0.4</td>
<td>+80</td>
<td>NT</td>
</tr>
</tbody>
</table>
The time differences during zone operations of the two systems was measured. Table 4.2 shows the estimated time differences for the inner and outer zones. At rated load, the maximum time difference between the two functions issuing a trip was 50 milliseconds, however, typically the two systems operated within 20 milliseconds of each other, with the inner zone time difference being smaller. At 50% load, the inner zone time differences were relatively the same, but the outer zone time differences were noticeably greater in most cases (also applies to 30% load cases). This discrepancy is due to the fact that the EX2000 outer zone is actually just inside the outer circle plotted in the previous figures. This was discovered during steady-state tests performed on the EX2000 prior to transient testing. Thus, because the 30% and 50% load trajectories are more gradual, the EX2000 picked up well after the DGP had picked up. This time discrepancy was not evident during the much quicker 100% load tests. The table also shows that the EX2000 performed better during the quicker 0.4 per unit system impedance tests. Output plots for the EX2000 and DGP inner and outer zones for the cases in which a trip occurred are included in Appendix A. For the EX2000 plots, a voltage jump from 0 V to 5 V indicates a trip, and once a zone is tripped it stays tripped until a soft reset. For the DGP plots, a voltage divider was employed, and a trip was indicated when the voltage “stepped down” to zero (short circuit across part of the voltage divider). It should be noted that these plots are 5-second “windows” and not the actual simulation lengths.
4.2 Stable and Unstable Swings

As Figures 3.15-3.19 showed, the impedance trajectories were not expected to enter the protection function zones. As expected, the inner or outer zones were not tripped during the two stable and three unstable swing cases. Thus, the EX2000 and DGP performed as expected.

4.3 Negative-Sequence Current Algorithm

In order to verify that this algorithm was worthy of being implemented into a power system protection scheme, it was first necessary to test it to verify proper calculation of the positive- and negative-sequence current quantities. Figure 4.1 shows the magnitudes of both the positive- and negative-sequence currents during a simulation of an imbalance, as well as the a and c phase input currents (the EX2000 only requires two current inputs). Normal operation occurs in the first two cycles, while an unbalanced situation occurs in the last two cycles. The imbalance was simulated by switching the a and b phase angles. Thus, because only the a phase current is needed, only its phase angle was switched from 0° to -120°.

During the first cycle, the positive-sequence current magnitude “ramps”, or increases linearly until it reaches the rms magnitude value of 0.707, where it remains for the second cycle. The ramping occurs because the cosine and sine components for each phase are declared to be zero before time t=0. The positive-sequence current magnitude remains at the above value because there is no change in the a phase current between the first two cycles. The negative sequence magnitude “hops” until it settles down at zero
Figure 4.1 Positive (I₁) and Negative (I₂) Sequence Current Magnitudes During Normal Operation and During a Disturbance

during the second cycle. These occurrences are typical of positive- and negative-sequence current magnitudes during normal operation, i.e., the positive-sequence magnitude converges to the rms magnitude whereas the negative-sequence magnitude converges to zero.

When the a and b phase angles are switched at the beginning of the third cycle, the magnitudes of the positive- and negative-sequence currents act completely opposite of each other and their magnitude values switch—the positive-sequence magnitude goes to zero while the negative-sequence magnitude goes to the rms value of 0.707. This behavior is expected of the positive- and negative-sequence current magnitudes during such an imbalance. In the case of the positive-sequence current, the result (after
multiplying the phase currents by the transformation matrix components) is three phasors
with the same magnitude and 120° apart from each other. Thus, if the three phasors are
added together, the result is zero. In the case of the negative-sequence current, the result
is three phasors with the same magnitude and the same angle. Thus, adding the phasors
together and dividing by three results in one phasor of magnitude 0.707. Normal
operation resulted in the reverse effect.

As mentioned in Chapter 2, the algorithm also contains a variable which sums up
all the \((I_2^2)T\) calculations when the negative-sequence current magnitude has exceeded
a certain value, which indicates an unbalanced condition. Thus, a test had to be performed
to verify correct calculation of this summation term. At each sample point, the algorithm
would check to see if the negative-sequence current magnitude exceeded a certain trip-
current pickup value, which was usually four percent of the base current setting (0.707).
When the negative-sequence current magnitude exceeded this value, it was squared and
multiplied by the time difference between sampled data points (32 samples/cycle \(*1/60\)
seconds(1 cycle)), and then added to a summation variable. At the conclusion of the
simulation, the summation variable would be outputted by the algorithm.

Figure 4.2 shows the test performed to verify correct calculation of the above
variable. Normal operation is simulated in the first 8 cycles. The a and b phase angles are
switched in the next 12 cycles, and the final 8 cycles show a return to normal operation.
The input file for this test, GEphinp.m, as well as the recursive algorithm are included in
Appendix B. Also included is the output file for this test, GEphinp.out, which shows a
summation value of 0.0977 for this test. By knowing that the disturbance occurs
approximately for a period of 12 cycles, or 0.2 seconds, the \((I_2^2)T\) term can be calculated:

\[
I_2^2 \cdot T = (0.707)^2 \cdot (0.2 \text{ sec}) = 0.5 \cdot 0.2 = 0.1
\]  \hspace{1cm} (4.2)

Thus, it has been verified that the algorithm works correctly. It should be noted that a real disturbance would typically last much longer than 12 cycles, which explains why the negative-sequence current constant \((K)\) is set between 4 and 8.
CHAPTER 5: CONCLUSIONS

The test results show that the test setup was very reliable, and that this type of setup can be used not only to test protective functions, but also for studies that require realistic generator behavior with a high degree of reliability. This is confirmed by generator impedance trajectories for all the operating conditions and simulated faults. Also, the tests have shown that the LOE function in EX2000 is credible, and can be relied upon as independent protection providing redundancy for the main protective system. In the future, other EX2000 protective functions should also be tested to verify their reliability. The results also show that the negative sequence current algorithm is also very reliable and is worthy of implementation.
REFERENCES


APPENDIX A:

DGP AND EX2000 OUTPUT PLOTS
Figure A.1a) EX2000 Inner Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=0.125

Figure A.1b) DGP Inner Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=0.125
Figure A.2a) EX2000 Outer Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=0.125

Figure A.2b) DGP Outer Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=0.125
Figure A.3a) EX2000 Inner Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=0.125

Figure A.3b) DGP Inner Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=0.125
Figure A.4a) EX2000 Outer Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=0.125

Figure A.4b) DGP Outer Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=0.125
Figure A.5a) EX2000 Inner Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=0.125

Figure A.5b) DGP Inner Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=0.125
Figure A.6a) EX2000 Outer Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=0.125

Figure A.6b) DGP Outer Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=0.125
Figure A.7a) EX2000 Inner Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=1.25

Figure A.7b) DGP Inner Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=1.25
Figure A.8a) EX2000 Outer Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=1.25

Figure A.8b) DGP Outer Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=1.25
**Figure A.9a)** EX2000 Inner Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=1.25

**Figure A.9b)** DGP Inner Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=1.25
**Figure A.10a)** EX2000 Outer Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=1.25

**Figure A.10b)** DGP Outer Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=1.25
Figure A.11a) EX2000 Inner Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=1.25

Figure A.11b) DGP Inner Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=1.25
Figure A.12a) EX2000 Outer Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=1.25

Figure A.12b) DGP Outer Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=1.25
Figure A.13a) EX2000 Inner Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=12.5

Figure A.13b) DGP Inner Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=12.5
Figure A.14a) EX2000 Outer Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=12.5

Figure A.14b) DGP Outer Function Output Plot for 100% Load, 0.05 pu Sys. Imp., and Inertia=12.5
Figure A.15a) EX2000 Inner Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=12.5

Figure A.15b) DGP Inner Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=12.5
Figure A.16a) EX2000 Outer Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=12.5

Figure A.16b) DGP Outer Function Output Plot for 100% Load, 0.2 pu Sys. Imp., and Inertia=12.5
Figure A.17a) EX2000 Inner Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=12.5

Figure A.17b) DGP Inner Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=12.5
Figure A.18a) EX2000 Outer Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=12.5

Figure A.18b) DGP Outer Function Output Plot for 100% Load, 0.4 pu Sys. Imp., and Inertia=12.5
Figure A.19a) EX2000 Outer Function Output Plot for 50% Load, 0.05 pu Sys. Imp., and Inertia=0.125

Figure A.19b) DGP Outer Function Output Plot for 50% Load, 0.05 pu Sys. Imp., and Inertia=0.125
Figure A.20a) EX2000 Inner Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=0.125

Figure A.20b) DGP Inner Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=0.125
Figure A.21a) EX2000 Outer Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=0.125

Figure A.21b) DGP Outer Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=0.125
Figure A.22a) EX2000 Inner Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=0.125

Figure A.22b) DGP Inner Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=0.125
Figure A.23a) EX2000 Outer Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=0.125

Figure A.23b) DGP Outer Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=0.125
Figure A.24a) EX2000 Outer Function Output Plot for 50% Load, 0.05 pu Sys. Imp., and Inertia=1.25

Figure A.24b) DGP Outer Function Output Plot for 50% Load, 0.05 pu Sys. Imp., and Inertia=1.25
Figure A.25a) EX2000 Inner Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=1.25

Figure A.25b) DGP Inner Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=1.25
Figure A.26a) EX2000 Outer Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=1.25

Figure A.26b) DGP Outer Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=1.25
Figure A.27a) EX2000 Inner Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=1.25

Figure A.27b) DGP Inner Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=1.25
Figure A.28a) EX2000 Outer Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=1.25

Figure A.28b) DGP Outer Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=1.25
Figure A.29a) EX2000 Outer Function Output Plot for 50% Load, 0.05 pu Sys. Imp., and Inertia=12.5

Figure A.29b) DGP Outer Function Output Plot for 50% Load, 0.05 pu Sys. Imp., and Inertia=12.5
Figure A.30a) EX2000 Outer Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=12.5

Figure A.30b) DGP Outer Function Output Plot for 50% Load, 0.2 pu Sys. Imp., and Inertia=12.5
Figure A.31a) EX2000 Inner Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=12.5

Figure A.31b) DGP Inner Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=12.5
**Figure A.32a)** EX2000 Outer Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=12.5

**Figure A.32b)** DGP Outer Function Output Plot for 50% Load, 0.4 pu Sys. Imp., and Inertia=12.5
Figure A.33a) EX2000 Outer Function Output Plot for 30% Load, 0.05 pu Sys. Imp., and Inertia=0.125

Figure A.33b) DGP Outer Function Output Plot for 30% Load, 0.95 pu Sys. Imp., and Inertia=0.125
Figure A.34a) EX2000 Outer Function Output Plot for 30% Load, 0.2 pu Sys. Imp., and Inertia=0.125

Figure A.34b) DGP Outer Function Output Plot for 30% Load, 0.2 pu Sys. Imp., and Inertia=0.125
**Figure A.35a)** EX2000 Outer Function Output Plot for 30% Load, 0.4 pu Sys. Imp., and Inertia=0.125

**Figure A.35b)** DGP Outer Function Output Plot for 30% Load, 0.4 pu Sys. Imp., and Inertia=0.125
Figure A.36a) EX2000 Outer Function Output Plot for 30% Load, 0.05 pu Sys. Imp., and Inertia=1.25

Figure A.36b) DGP Outer Function Output Plot for 30% Load, 0.05 pu Sys. Imp., and Inertia=1.25
Figure A.37a) EX2000 Outer Function Output Plot for 30% Load, 0.2 pu Sys. Imp., and Inertia=1.25

Figure A.37b) DGP Outer Function Output Plot for 30% Load, 0.2 pu Sys. Imp., and Inertia=1.25
Figure A.38a) EX2000 Outer Function Output Plot for 30% Load, 0.4 pu Sys. Imp., and Inertia=1.25

Figure A.38b) DGP Outer Function Output Plot for 30% Load, 0.4 pu Sys. Imp., and Inertia=1.25
Figure A.39a) EX2000 Outer Function Output Plot for 30% Load, 0.05 pu Sys. Imp., and Inertia=12.5

Figure A.39b) DGP Outer Function Output Plot for 30% Load, 0.05 pu Sys. Imp., and Inertia=12.5
Figure A.40a) EX2000 Outer Function Output Plot for 30% Load, 0.2 pu Sys. Imp., and Inertia=12.5

Figure A.40b) DGP Outer Function Output Plot for 30% Load, 0.2 pu Sys. Imp., and Inertia=12.5
**Figure A.41a)** EX2000 Outer Function Output Plot for 30% Load, 0.4 pu Sys. Imp., and Inertia=12.5

**Figure A.41b)** DGP Outer Function Output Plot for 30% Load, 0.4 pu Sys. Imp., and Inertia=12.5
APPENDIX B: PROGRAM LISTINGS

B.1 Control Malfunction Input Data File (Example)

C EMTP Program for GE circuit
BEGIN NEW DATA CASE
C ..................MISCELLANEOUS DATA..............................
C 3456789012345678901234567890123456789012345678901234567890
C DeltaT  TMax  XOPT  COPT  Epslin  TolMat  TStart
6.68E-5   4.0   60   60
C IOut  IPlot  IDoub1  KSSOut  MaxOut  IPun  MemSav  ICat  NEnerg  IPrsUp
  6   401   1   1
TACS HYBRID
C Z block
C 3456789012345678901234567890123456789012345678901234567890
  VR +V2
  VF +dVF +UNITY    1.
C S block
  1V2  +V1 +UNITY  -V3    400.
     1.
     1.  .02
  1V1  +Vdc    1.
     .52359878
     1.  .03
  1dVF  +VR    1.
     1.
     1.  .015
  1V3  +dVF    1.
     0.  .03
     1.  .5
C 3456789012345678901234567890123456789012345678901234567890
90THEVA    60.
90THEVB    60.
90THEVC    60.
88VT_A  66+THEVA    60.
88Vdc  =1.925
C 88Vdc  =(ABS(Vt_A))*SQRT(3/2)/(34500)
C TACS Output
  33
C TACS IC
C 345678901234567890
77Vdc  1.925
77THEVA  0.
77THEVB  -24395.18
77THEVC  24395.18
77dVF    0.
77VF    1.
77V2  0.
77Vr  0.
77V1  1.
77V3  0.
BLANK CARD TERMINATES TACS DATA
C ..................CIRCUIT DATA..............................
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C BUS1 BUS2 BUS3 BUS4 R L C
THEVA BUS11A 0.1E-5 1.0 1
THEVB BUS11BTHEVA BUS11A 1
THEVC BUS11CTHEVA BUS11A 1
BLANK CARD TERMINATES CIRCUIT DATA
C ..................SWITCH DATA.................................
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C BUS1 BUS2 TCLOSE TOPEN
BUS11ABUS12A -1. 9999.
BUS11BBUS12B -1. 9999.
BUS11CBUS12C -1. 9999.
BLANK CARD TERMINATES SWITCH DATA
C ..................SOURCE DATA.................................
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C BUS VOLTAGE FREQUENCY ANGLE
14BUS12A  28.17E+3  60.  0. -1. 9999.
14BUS12B  28.17E+3  60. -120. -1. 9999.
14BUS12C  28.17E+3  60.  120. -1. 9999.
59THEVA  28.17E+3  60.  11.
THEVB
THEVC
PARAMETER FITTING  1.
C CLASS 3 S.M. DATA CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
1 1 1 4 1.0 1.0  229.741  34.5  1821.1
  0.004  0.093  2.134  2.050  0.320  0.479  0.224  0.217
  3.7970  0.438  0.033  0.070  0.103
1 1 1.25
C 1  1.502.2206
C 1  1.  250.
BLANK CARD TERMINATES MASS DATA
C 1 1
BLANK CARD ENDING OUTPUT
C TACS INPUT CARDS
C BUS KI
71VF
FINISH
BLANK CARD TERMINATES SOURCE DATA
C ..................OUTPUT REQUESTS..............................
C BUS BUS BUS BUS BUS BUS BUS BUS BUS BUS THEVA THEVB THEVC
BLANK CARD TERMINATES OUTPUT REQUESTS
BLANK CARD TERMINATES PLOT REQUESTS
BLANK CARD TERMINATES EMTP SOLUTION-MODE
98
B.2 Stable/Unstable Case Input Data File (Example)

C Transient stability analysis for test system. Stable case.
BEGIN NEW DATA CASE
C ........................................ MISCELLANEOUS DATA ..........
C DeltaT<--TMax<--XOpt<--COpt<--Epsiln<-TolMat<-TStart
6.68E-5 4.0
C --IOut<--IpPlot<--IDouble<--KSSOut<--MaxOut<--IPun<--MemSav<--ICat<--NEnerg<--IPrSup
 6 401 1

TACS HYBRID
C Z block
C 34567890123456789012345678901234567890123456789012345678901234567890
Vr  +V2 1.
Vf  +dVf +UNITY 1.
C S block
1V2  -V1  +UNITY  -V3 400.
  1.
  1.02
1V1  +Vdc 1.
  .52359878
  1.03
1dVf  +Vr 1.
  1.
  .015
1V3  +dVf 1.
  0.03
  1.5
C 3456789012345678901234567890123456789012345678901234567890
90GEN3A  60.
90GEN3B  60.
90GEN3C  60.
C RMS VALUE
88Vt_A  66+GEN3A 60.
C Simulation of an ideal three-phase transformer-rectifier arrange.
88Vdc  = (ABS(GEN3A)+ABS(GEN3B)+ABS(GEN3C))*SQR(3/2)/(13800)
C TACS Output
33
C TACS IC
C 345678901234567890
77Vdc  1.732051
77GEN3A  0.
77GEN3B  -9758.074
77GEN3C  9758.074
77dVf  0.
77Vf  1.
77V2  0.
77Vr  0.
77V1  1.
77V3  0.
BLANK CARD TERMINATES TACS DATA
C ..........................Circuit Data  ......................
C Bus-->Bus--><--------<--------R<-------------L<--------R<-------------L<--------R<--------L

99
51THEVA BUS7A  .13 23.71
52THEVB BUS7B  .06 39.99
53THEVC BUS7C  

C Bus--->Bus--->Bus---><---R----L----C----R----L----C----R----L----C--
1BKRI1A BUS12A 2.914240.834.26247
2BKRI1B BUS12B 2.370719.587-06032.993440.714.27339
3BKRI1C BUS12C 2.317816.307-01532.370719.587-06032.914240.834.26247

C Bus--->Bus--->Bus---><---R----L----C----len 0 0 0<-----Blank-----
-1BUS7A BUS1A 0.3167 3.222.00787 144.4 0 0 0
-2BUS7B BUS1B 0.0243 .9238 .0126 144.4 0 0 0
-3BUS7C BUS1C  

C Bus--->Bus--->Bus---><---R----L----C
BUS12ABUS13A  70.16
BUS12BBUS13BBUS12ABUS13A
BUS12CBUS13CBUS12ABUS13A
BUS13A  221.41 38.26
BUS13B BUS13A
BUS13C BUS13A

C Saturable transformer components.

TRANSFORMER DELTAB 9999

C <-Bus1<-Bus2<---------<---Rk<-Lk<---Nk
1GEN33AGEN33B  .1263 13.8
2BUS1A  35.08132.79

TRANSFORMER DELTAB DELTBC
C <-BUS1<-BUS2
1GEN33BGEN33C
2BUS1B

TRANSFORMER DELTAB DELTCA
1GEN33CAGEN33A
2BUS1C

BLANK CARD TERMINATES CIRCUIT DATA

C ..................................................SWITCH DATA....................

C Bus--->Bus---><---Tclose<---Topen<
GEN3A GEN33A -1. 9999. 1
GEN3B GEN33B -1. 9999. 1
GEN3C GEN33C -1. 9999. 1
BUS1A BKR1A -1.E-3 200.E-3
BUS1B BKR1B -1.E-3 200.E-3
BUS1C BKR1C -1.E-3 200.E-3
BUS12A  100.E-3 9999.
BUS12B  100.E-3 9999.
BUS12C  100.E-3 9999.

BLANK CARD TERMINATES SWITCH DATA

C ..................................................SOURCE DATA.....................

C Bus---><---Amplitude<---Frequency<---T0<Phi0<---Tstart<---Tstop
14THEVA 187.79E3 60. 0. 0. -1. 9999.
14THEVB 187.79E3 60. -120. 0. -1. 9999.
14THEVC 187.79E3 60. 120. 0. -1. 9999.

C Dynamic synchronous machine

C Bus---><---Volt<---Freq<---Angle
59GEN3A 11267.65 60. -28.00

100
GEN3B
GEN3C
C Electrical parameters of machine
1 1  2  1.  1.  200.  13.8  935.016  1000.  1440.

1.65  1.55  1.55  1.70  1.55  1.605  .15
.000001  1.64  1.49  1.526
1.4  0.001096  0.000742  0.0131  0.0540
1  1.  1.81128
BLANK CARD TERMINATING MASS DATA
C  1  1
BLANK CARD TERMINATES SYNCHRONOUS MACHINE OUTPUT REQUESTS
C Bus-->-----<KI
71 Vf
FINISH
BLANK CARD TERMINATES SOURCE DATA
C ................................OUTPUT REQUESTS............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
GEN3A  GEN3B  GEN3C
BLANK CARD TERMINATES OUTPUT REQUESTS
BLANK CARD TERMINATES PLOT REQUESTS
BLANK CARD TERMINATES EMTP SOLUTION-MODE
B.3 Impedance Trajectory m-files

konginp.m

% Command file for kong.
% diary konginp.out
q=1;
% generator parameters
kva=229741;
kv=34.5;
samp=33;
tlip13s5; % call m-file for 0.05 per unit case
%7921=4 second sim., 11848-6 sec.sim., 15907-8 sec. sim.
for k=1:samp:15907
    kongrec;
end
plot(zr,zi,'-');
hold;
q=1;
tlip13s2; % call m-file for 0.2 per unit case
for k=1:samp:15907
    kongrec;
end
plot(zr,zi,'-');
q=1;
tlip13s4; % call m-file for 0.4 per unit case
for k=1:samp:15907
    kongrec;
end
plot(zr,zi,'-');
impcirc; % impcirc.m creates protection circles

kongrec.m

% File to convert voltage and current data to impedance data.
b=kva/((sqrt(3))*kv); a=kv*1000/(sqrt(3));
sumvc=0; sumvs=0; sumic=0; sumis=0;
for j=k:(k+samp-1)
    sumvc=sumvc+(vimax(j,2)/a)*cos(j)*2*pi/samp);
    sumvs=sumvs+(vimax(j,2)/a)*sin(j)*2*pi/samp);
    sumic=sumic+(vimax(j,3)/b)*cos(j)*2*pi/samp);
    sumis=sumis+(vimax(j,3)/b)*sin(j)*2*pi/samp);
end
vc(q)=sumvc*2/samp;
vs(q)=sumvs*2/samp;
ic(q)=sumic*2/samp;
is(q)=sumis*2/samp;
vph=vc(q)-i*vs(q);
iph=ic(q)-i*is(q);
zh=vph/iph;
zr(q)=real(zh);
zi(q)=imag(zh);
sph=vph*(conj(iph));
sr(q)=real(sph);
si(q)=imag(sph);
q=q+1;

impcirc.m

% File which plots the impedance circles
x=[-1.067 -1.065 -1.06 -1.05 -1 -.95 -.9 -.85 -.8 -.75 -.7 -.65 -.6 -.55 -.5 -.45 -.4 -.35
-.3 -.25 -.2 -.15 -.1 -.05 0 .05 .1 .15 .2 .25 .3 .35 .4 .45 .5 .55 .6 .65 .7 .75 .8 .85
.9 .95 1 1.05 1.06 1.065 1.067];
for kk=1:49
    % plotting large circle
    y(kk)=sqrt(1.1385-x(kk)^2)-1.184;
    z(kk)=-y(kk)-2*1.184;
end
plot (x,y)
plot (x,z)
f=[.5 .49 .48 .47 .46 .45 .4 .35 .3 .25 .2 .15 .1 .05 0
.05 .1 .15 .2 .25 .3 .35 .4 .45 .5 .46 .47 .48 .49 .5];
for h=1:29
    % plotting small circle
    bb(h)=sqrt(.25-f(h)^2)-.617;
    c(h)=-bb(h)-2*.617;
end
plot(f,bb)
plot(f,c)
grid
xlabel('Resistance(pu)')
ylabel('Reactance(pu)')
B.4 Negative-Sequence Overcurrent Function m-files

GEphinp.m

% Input file
K=32; % 32 samples/cycle
sum3=0;
th=2*pi/K;
% Normal operation for the first eight cycles.
for cyc=1:2
    for j=(1+(cyc-1)*32):(32*cyc)
        x(j)=(0.01667*(j-1)/32);
        ia(j)=1*sin(120*pi*x(j));
        ic(j)=1*sin(120*pi*x(j)+2*pi/3);
    end
    GERecur2; % Recursive algorithm used.
end
% A disturbance for 12 cycles (the angles of ia and ib switched.
for cyc=3:4
    for j=(1+(cyc-1)*32):(32*cyc)
        x(j)=(0.01667*(j-1)/32);
        ia(j)=1*sin(120*pi*x(j)-2*pi/3);
        ic(j)=1*sin(120*pi*x(j)+2*pi/3);
    end
    GERecur2;
end
% Back to normal operation.
%for cyc=21:28
%    for j=(1+(cyc-1)*32):(32*cyc)
%        x(j)=(0.01667*(j-1)/32);
%        ia(j)=1*sin(120*pi*x(j));
%        ic(j)=1*sin(120*pi*x(j)+2*pi/3);
%    end
%    GERecur2;
%
% If the K constant is exceeded, a warning is outputted.
if dummy == 1
    disp('THERMAL LIMIT EXCEEDED')
end
% The sum of I2^2*dt is outputted and the magnitudes are plotted.
sum3
plot (x,ia), hold
plot (x,ic)
plot (x,magpa,*')

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plot (x,magna,'+')
grid
xlabel('Time(s)')
ylabel('per unit current')
%title('Figure 1. |I1| (*) and |I2| (+)')

GErecur2.m

% Recursive method for calculating positive and negative sequence current.
for j=(1+(cyc-1)*32):(32/K):32*cyc
    % The difference between cycles are calculated for
    % each phase.
    if (cyc > 1)
        dya=ia(j)-ia(j-32);
        dyc=ic(j)-ic(j-32);
    else
        dya=ia(j);
        dyc=ic(j);
    end
    % The cosine and sine terms start out at zero.
    ua(1)=0; va(1)=0; gc(1)=0; hc(1)=0;
    % The recursive method calculates the next values
    % for the a and c phase current phasors.
    ua(j+1)=ua(j)+(sqrt(2)/(K))*(dya*cos(j*th));
    va(j+1)=va(j)+(sqrt(2)/(K))*(dya*sin(j*th));
    gc(j+1)=gc(j)+(sqrt(2)/(K))*(dyc*cos(j*th));
    hc(j+1)=hc(j)+(sqrt(2)/(K))*(dyc*sin(j*th));
    % The phasors are then formed.
    iaph(j)=ua(j+1)-i*va(j+1);
    icph(j)=gc(j+1)-i*hc(j+1);
    q1=-.5+i*.866;
    q2=-.5-i*.866;
    % The positive and negative sequence currents are
    % calculated.
    iapos(j)=(iaph(j)*(1-q1)+icph(j)*(q2-q1))/3;
    ianeg(j)=(iaph(j)*(1-q2)+icph(j)*(q1-q2))/3;
    % The phasors are separated into real and imaginary
    % parts and the magnitudes are taken.
    ipr(j)=real(iapos(j));
    ipi(j)=imag(iapos(j));
    inr(j)=real(ianeg(j));
    ini(j)=imag(ianeg(j));
    magp(j)=sqrt(ipr(j)^2+ipi(j)^2);
    magna(j)=sqrt(inr(j)^2+ini(j)^2);
    % If the negative sequence current magnitude exceeds

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% a certain value (4% of .70711), then $I_2^2 dt$ is
% calculated. This value is then added to the sum of
% the previous disturbances.
if ($(\text{magna}(j)) > .02828$
  $t\text{dis}=x(j-1)$;
  $\text{sum3}=\text{sum3}+((\text{magna}(j))^2)*(x(j)-t\text{dis})$;
% If the sum exceeds a constant K, then a
% variable is set to 1 and this causes the
% output of an alarm.
if $\text{sum3} > 6$
  $\text{dummy}=1$;
end
end

GEphinp.out

% Output file.
\text{sum3} =

0.0977

Current plot held
>> exit
APPENDIX C: WIRING DIAGRAMS

Figure C.1 Crown Amplifier Output Diagram

Figure C.2 PT Connection Diagram
The Crown Amplifiers are mounted in a bracket in the Power Systems Lab, with the outputs located in between the first and second amplifiers (as shown by Figure C.1) and above the playback system microcomputer. The PTs are also mounted in a bracket close to the amplifiers. It should be noted that these PTs should not be connected to the Crown Amplifier outputs until after the amplifier gains are set to a level close to its final setting. This ensures that the PTs will not experience any DC offset.
Figure C.4 PT and Doble Output Connections and DGP Input Connections

Figure C.3 shows the necessary connections per phase for proper use of the Doble Transient Current Sources. The positive input signal is one of the phase currents (a, b, or c) from the Crown Amplifiers, and the negative input signal is the ground signal from the Crowns. Figure C.4 shows the necessary connections for proper use of the DGP. The DGP requires three phase voltage inputs with three neutral voltage inputs, as well as three phase current inputs with only one neutral current input. The three negative current leads from the Dobles were connected together to form one neutral current input to the DGP.
Figure C.5 shows the necessary connections for proper PTCT Card use. The current inputs and outputs show that the DGP and EX2000 are connected in series (the Dobles connected to the positive terminals and the negative terminals fed to the DGP), in order that they view the same input current. The EX2000 only requires two phase-to-phase voltage inputs (V12 and V23). Thus, only the three phase voltages are required and a ground voltage need not be connected, as shown in the figure.
VITA

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