MODELING AND ANALYSIS OF TRANSIENT PERFORMANCE OF PROTECTION SYSTEMS USING DIGITAL PROGRAMS

A Special Publication by IEEE Task Force on Modeling of Protection and Control of the IEEE Working Group on Modeling and Analysis of System Transients Using Digital Programs

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Abstract: This chapter of the Special Publication provides general guidelines and summarizes the work done by various researchers and industry experts in modeling of protection systems for use in digital simulations of power system transients. Because digital modeling of protection systems in the electromagnetic transients programs is a relatively new procedure, this report lists some of the uses, advantages, disadvan tages, and limitations of modeling of protection systems. This report includes some models of instrument transformers and the possible need to model instrument trans formers. The modeling of electro-mechanical, static (electronic), and microprocessor- based digital relay is also presented. References and a bibliography are included..

Keywords: Modeling of Protection Systems; Simulation of Protection Systems; Dis tance Relay Models; Electromagnetic Transients Program (EMTP); Simulation; Current Transformer Models; Capacitor Voltage Transformer Models; Relay Models **.** .

1. OBJECTIVES

A vast majority of the components that constitute a modern electrical power system have been successfully modeled for transient studies. One exception to this rule is protective relays. The first purpose of this report is to develop general guidelines for the modeling of electric power system protection functions for use in any version of electrical transient simulation programs. The second purpose of this report is to list some of the advantages and uses of modeling of protection systems. In the interest of objectivity, also listed are some disadvantages and limitations of modeling. The third objective of this report is to develop a bibliography and list some references.

There are many versions of the ElectroMagnetic Transients Programs (EMTPs), such as the Electric Power Research Institute /Development Coordination Group EMTP, the Canadian/American EMTP or Alternative Transients Program (ATP), and the Manitoba High Voltage DC Research EMTDC. The Task Force has worked to keep the modeling guidelines sufficiently general so this report is applicable to all versions of EMTP. In this report the term EMTP is employed as a generic term and does not refer to any specific program or product.

2. BACKGROUND & HISTORY

2.1. Partial History of Protection System and Relay Modeling

Modeling and simulation of the high-voltage sections of electric power systems have been common engineering practices for more than thirty years. Computer models of major system components, such as transmission lines, transformers, cables, and circuit breakers, are available in the literature or are a part of a simulation package such EMTP. Control systems, which affect the operation and connectivity of the high-voltage power system, have been modeled to a lesser extent. As Greenwood states:

> Measuring the transient behavior of power apparatus in power systems is often difficult, always expensive and occasionally it is hazardous to the equipment involved. Yet we need to know how components will behave when switching operations, faults and lightning activity occur on the system if we are to have a reliable, secure system. Also, if apparatus fails in service we need to have a better way to improve the design and eliminate future failures than simple cut and try. Modeling is a potential solution to both of these problems.
>
> . . . However, a model is not an end in itself but a means to an end. The end is predicting how a component or system will behave when subjected to a pre scribed transient stimulus. To determine this response requires that the model be evaluated. This nearly always requires the aid of a computer [1].

An electric power protection system consists of three major parts: instrument transform ers (current, wound electromagnetic voltage, and capacitor voltage transformers), protective relays, and circuit breakers. The instrument transformers lower the power system voltages and currents to safe working levels. The protective relays receive information about the high-voltage power system via the instrument transformers. The relays make decisions whether the power system is in a healthy state or an unhealthy state. The relays send signals to circuit breakers that interrupt the large currents and voltages associated with power systems. The modeling of circuit breakers is not discussed in this report, but is fully discussed in the technical literature.

Protection systems are critical power system components and their behavior is an important part of power system response to a transient event. Actual power systems and their protection systems operate in a closed-loop manner. The power system influences the protection system through the instrument transformers. The protection system can modify the topology of the power system by opening and closing circuit breakers. One major purpose of protection system modeling is to represent this closed-loop interaction. Closed-loop modeling presents an improved method for analyzing the performance of the power system under transient conditions. For more details se [2], [3],[4] and [5].

2.2.Partial History of Protection System and Relay Modeling.

One of the earlier works on power system protective equipment modeling is given in [6] by Wright and Charalambous. This work employs analog models of the required components. Analog models of current transformers (CTs), summation transformers, and pilot wires have been built. An electromechanical relay's equation is simulated on an analog computer. The digital computer method is not adopted because of the length and complexity of the problem.

An over-current relay was one of the first classes of protective relays modeled. Schweitzer and Aliaga developed and tested a programmable time-parameter relay algorithm suitable for use as a microprocessor-based time over-current relay. These authors also developed operating equations and the reset characteristics [7]. Peng, et.al., took a significant step when they derived a dynamic state-space model of an electro-mechanical distance relay. The authors showed that their state-space model responded correctly to pre-fault and during fault (steady-state) conditions[8].

Domijan and Emami expanded on the work by Peng by developing the methods to input this state-space model of a relay to the EMTP [9]. They used the original TACS portion of the ATP version of EMTP. These authors used the Laplace "s" domain approach to input the state space equations to the EMTP. They then proceeded to investigate the transient behavior of this relay to a forward and reverse fault.

Garrett, Dommel, and Engelhardt [10], developed a protection system model under transient conditions, and showed how both near-operation and near mis-operation of relays could be made visible from simulations. Peterson and Wall took a slightly different approach [11]. They viewed relays as digital filters and worked in the "z" domain. A new version of the EMTP was written for use on a personal computer [12]. They modeled an electro-mechanical non-directional and directional over-current relay. The third relay studied was a commercially available electronic "pilot wire" relay that uses sequence components. The over-current and pilot-wire relay models were used in EMTP-PC simulations of relay responses to fault conditions.

Engineers at a Saskatchewan utility developed and investigated an improved method of testing Voltage polarized mho relays [13]. Part of this process was to model relays using dedicated measuring elements. The fault quantities were generated by a fault simulation program that ran on a mainframe computer and was linked to the PC. The computer simulation used the same equations as the physical relay did, as inputs to the comparator circuits.

Lauger, et.al., discuss a computer program used to investigate the behavior of distance relays at the system operating frequency [14]. The authors list several different distance relays that are simulated, but few details are given.

Ryan studied the effect power swings have on one out-of-step (OOS) relay [15]. In this study Ryan wrote a computer program in BASIC to calculate the reach of a variable- characteristic offset mho relay. This study calculated test quantities to apply to a commercial relay test set. In another study the same author developed a BASIC computer to calculate steady-state voltages and currents for polarized mho relay testing [16]. This computer program showed the expanded characteristic of these relays.

McLaren has reported on the use of an engineering work station and a relay model [17]. Gustausen, et. al., [18] developed a generator protection scheme using the EMTP.

Chaudhary, et.al., [19] developed, validated, and implemented a transformer differen tial relay with features of percentage and harmonic restraint. Wilson and Nordstrom [20] developed a model of a digital distance relay with sperate sub-models for a low- pass anti-aliasing filter, an analog-to-digital converter, a Fourier detector, and a zero-sequence compensated quadrature-voltage polarized mho measuring unit. The physical relay and the relay model were subjected to the same EMTP-generated waveforms. The responses were similar.

Mooney, et. al., [21] developed models for relays and show some good reasons for developing relay models. Chaudhary has studied the EMTP modeling of instrument transformers, modified one version of EMTP to accept FORTRAN programming, and modeled an electronic distance relay, and other relays [22]. Perez, et. al., [23] devel oped general mathematical models of protective relays for dynamic simulations. The mathematical models discussed were not directly intended for computer implementation and were not intended for transients studies.

Simpson and Humpage [24] describe a software system for electromagnetic transient analysis based on the z plane transform sequence.

McLaren, et. al., [25] has used the same waveforms to test a software model of a digital relay an a physical proto-type of the same relay. The authors state even if the digital algorithms of the relay are completely known, there still is uncertainty. The level of accuracy achieved is satisfactory for all but the most extreme cases.

Glinkowski, et.al., [26, 27] modeled electro-mechanical relays, which are discussed in detail in Section 5.1 of this report.

Calero, Hart, et.al., [28, 29] describe the tests involved in developing a new algorithm and eventually a new relay.

Wall and Johnson [30] used Transient Analysis of Control Systems (TACS) functions to model digital relays as an educational tool for investigating relaying concepts. The authors grouped the relay functions to be modeled into instrumentation dynamics, anal of signal conditioning, sampling and conversion, magnitude and phase computation, relay algorithm, trip logic, and switch operation. Kezunovic and Chen [31] combined EMTP and MATLAB to model protective relays. Relays were modeled in the MATLAB simulation software and connected to EMTP through an interaction buffer.

3. APPROACHES, ADVANTAGES, & DISADVANTAGES

The modeling of electric power protection and control systems is similar to the model ing of any other power system component. A practicing engineer or researcher must ask the question of what is the model going to be used for? Will the model be used only in steady-state simulations? What level of modeling accuracy is needed? Should the model predict relay time-of-operation within 1 ms or 10 ms? Is the objective of modeling to test a new measuring technique or method of estimating power system phasors in an environment where "moderate" modeling accuracy is acceptable?

What is our budget for developing a model? The Task Force believe there is a direct relationship between the accuracy of the model and the cost of producing any new model. Very accurate and representative models can be developed if a physical relay can disassembled, every component investigated, and, for digital relays, all the features of the software discovered. On the other hand, models of limited accuracy may be developed from available published information.

3.1.Modeling Approaches.

In developing a computer equivalent of a protective relay, there are at least two possible approaches. One approach would be to model every electronic, electro-mechanical, and software component of the relay. If the model is intended to accu rately represent all aspects of a physical relay, the model may be very complex and would require longer simulation times. Interactions between components would have to be investigated.

The second approach is to develop more abstract models, which behave in a similar manner to the relay within specified and clearly understood bounds. In electronics this is called "macro-modeling" [32]. The differences between the two approaches can be illustrated by an example. Microprocessor-based digital relays usually have low-pass input filters on all current and voltage inputs. The purpose of the filters is to limit noise introduced into the relay and prevent alaising. Assume the filter is constructed from discrete components and is not a digital filter. One approach would be to obtain the circuit diagram and physical lay-out and use standard EMTP (or SPICE) models for the resistors, capacitors, inductors, or operational amplifiers. A second approach would be to obtain the characteristics of the filter, the number of stages, the 3-dB point, and the signal level loss. The filter characteristics could be used to develop a moderately accurate filter model using S-plane modeling features in the Transient Analysis of Control Systems.(TACS) section of many versions of EMTP.

A model does not have to represent all performance specifications of a relay. For example, a model of any auxiliary relay in the trip circuit will not normally be needed. It may be necessary to model the time delay introduced by an auxiliary relay, but not model the current carrying capacity of the relay contacts. Another example of a component that may not need to be modeled are electro-mechanical targets.

3.2.Uses and Advantages.

The uses and advantages of computer modeling of protective relays are many. Relay modeling, when performed using digital techniques, complements and enables improvement in the experimental testing procedures over what was available in the past. Many utilities do not have high-voltage laboratories for testing the transient response of power system components, such as power transformers, and have to rely on modeling for transient simulations. Digital simulation techniques provide for very efficient and flexible execution of a large number of test cases.

Use of relay laboratories offers the ultimate in testing, but the costs are high. Several large utilities have built relay testing laboratories that subject commercial relays to transient waveforms [33, 34, 35]. The use of relay models would allow smaller utilities to participate in transient simulations of relay responses. Relay simulations using the model could be done on a personal computer, which is an integral part of the relay engineer's work station. If the model of relay were supplied by the manufacturer, there would be few questions about model accuracy.

A relay model could be used by a relay applications engineer to select a relay measur ing principle and to check relay settings. The relay settings can be optimized, i.e., the appropriate security and dependability margins can be determined by seeing how close the relay comes to operation, as opposed to the "go/no go" results of conventional tests. With accurate models a relay engineer can investigate how different relay measuring principles work for a particular power system protection application. The simulations can be performed without the need for the actual relay and the test equipment or an expensive laboratory required to drive the relay. The issue of access involves only the simulation software and hence a potential reduction in the cost of testing, particularly if the test has to be repeated or performed with another set of input signals.

An important use of computer modeling would be in the analysis of protection system mis-operations. A systems analyst can gain insight to the relaying process and help the analysis of power system disturbances and blackouts. Computer modeling can automate the calculation of the response of every relay measuring element to a large number of simulated fault conditions.

A model could be used to look inside a relay and determine a probable cause for a mis- operation. The simulation could be accomplished by one person, before the relay test technicians are sent to the substation. Simulations may point to specific relay inputs, relay circuits, or system conditions to investigate further in the field.

Representative relay models will be a valuable teaching tool. University students, test technicians, beginning and experienced engineers can gain insight. In the computer laboratory students can see the differences between steady-state, dynamic, and transient testing. The monitoring of relay responses to different faults or operational conditions on the high voltage section of the computer simulation would add experience and motivation.

Manufacturers of protective relays could use relay models as one stage in their new relay development process. Relays models could help evaluate the transient response of different filters, methods of estimating phasors, directional units, or promising measuring techniques. Modeling would precede the building a physical prototype of a new relay. Use of a model would offer the manufacturer the option of investigating relay response before a prototype relay is built. In fact, during the development of a microprocessor relay algorithm, the algorithm is tested extensively on fault data first before the prototype relay is built.

The power systems researcher could use models to evaluate new digital signal processing techniques for protective relaying. With complete closed-loop simulations, researchers could evaluate the use of different types of lowpass filters, analog-to-digital converters, electro-mechanical spring constants, detectors, or traveling-wave relay techniques.

3.3.Disadvantages and Limitations.

Several factors must be considered before relay and protection system modeling can be widely and safely used. A major disadvantage is that accurate relay models can be difficult to develop and verify. Improved understanding of relay performance can only be achieved with a significant investment of time and effort. The modeling of relays has not been a common practice in the past. Significant investigation is needed to better understand this new approach.

A problem with relay modeling is the lack of detailed information. Relay manufacturers are understandably reluctant to divulge sensitive information about inner workings of their product. The possibility always exists of competitors using reverse engineering techniques to discover sensitive information. A person attempting to model a relay may have to make informed guesses about many details.

A relay model may have to be very large to incorporate all elements of the physical relay. A large model probably will require increased computer execution time. Simplifications of a large model will raise questions of accuracy. Will a reduced relay model accurately mimic the actions of a physical relay? Oversimplifications in model ing can lead to erroneous conclusions, with far-reaching consequences.

For instance, the relay modeling may be based on readily available phasor modeling of the power system faults and relay operating characteristics. Phasor methods leads to the widely used symmetrical component representation of faulted power systems. This also may lead to relay modeling using only phasor representation of the relay operating characteristic. Modeling relay using only phasor methods is generally not sufficient especially for predicting relay time-of-operation to within 1 ms.

In a later section, this report discusses modeling microprocessor-based relays as interconnected modules. The different modules model an input lowpass filter, an analog-to-digital converter, etc. A practitioner must first verify the different modules, and then verify the accuracy of the assembled modules. In the physical relay there may be interactions between the modules that are not modeled in the assembled larger model. In the modeling of microprocessor-based relays, the analog-to-digital converter (ADC) must be modeled. The model of the ADC may sample any input signal at the same point-on-wave every time. The physical relay may sample input signals at varying points-on-wave.

A relay model may not include hardware limitations such as component tolerances, component value change with temperature, etc. A model may not include interaction with external hardware devices, such as contact bounce from inputs, outputs, control signals and power supply transients.

The cost of relay modeling and the oversimplification problem require that a full understanding of the limitations of relay modeling is achieved. As is well known, the models are only as good as we make them to be. The models are always approximations of the actual phenomena, and as such, do require careful validation and evaluation.

Computer investigations of relaying problems will not easily replace the need for on-site and laboratory testing. Simulations may point to specific relay inputs, relay circuits or system conditions to investigate further in the field. As a final point, a model does not replicate actual training experiences and does not include human-machine interactions.

4. MODELING GUIDELINES FOR INSTRUMENT TRANSFORMERS

To determine the proper operation of protection systems during transient phenomena, an accurate representation of instrument transformers is needed. The fast operational requirements of relay protection schemes raises concerns about the accurate output of the instrument transformers, which provide inputs to the relay systems. The steady- state performance of instrument transformers is well known, the transient performance is covered by IEC Standards 185 and 186. Frequency response is not covered by standards. Studies related to the performance of instrument transformers under transient conditions have shown the following areas of concern [36, 37]:

a) The saturation of current transformers reduces the magnitude of the secondary current, and hence the operating force or torque of the relays. The reduced tongue (force) increases the operation time of the relay, and reduces the reach of the relay.

b) The saturation of current transformers affects the zero-crossings of the current wave. This saturation will affect schemes that depend on the zero crossings, such as phase comparators.

c) The relaxation current in the current transformer secondary is the current that flows when the primary circuit is de-energized. This current is more pronounced in the case of current transformers with an anti-remanent air gap. The relaxation current can delay the resetting of low-set overcurrent relays and also cause the false operation of breaker failure relays.

d) Electromagnetic (wound) voltage transformers and capacitor voltage transformers (CVTs) can be subjected to ferro-resonance. This phenomenon leads to overvoltages, which in turn, can lead to mis-operation and (thermal and dielectric) failure.

e) The reduction of the primary voltage to zero creates a subsidence transient on the CVT secondary, because of the stored energy in the capacitive and inductive elements. This subsidence transient affects the speed of the protection scheme and can cause relay mis-operation for reverse faults.

The North American Reliability Council (NERC) publishes a yearly document entitled, *System Disturbances*, which is a review of selected Electric System Disturbances in North America. A majority of the disturbances are related to the failure of the protection system, especially after one contingency has occurred. For several years this document [38] has emphasized the following:

> "The use of increasingly complex protection systems demands careful planning, contingency analysis, personnel training, and ongoing review. . . Design protection systems and breaker testing to mimic actual conditions as closely as possible, and to test relays as part of the entire protection system."

Thus, it can be important to model instrument transformers in a simulation of a protection system.

This section presents a summary of the works performed during the last few years to develop accurate models of current transformers, and capacitive voltage transformers. Wound voltage transformers are not included because their models have been employed in EMTP-type programs for several decades.

The next two sections detail the models proposed for CTs and CVTs, as well as validation tests. Some remarks about the works reviewed for this section are included in the last section.

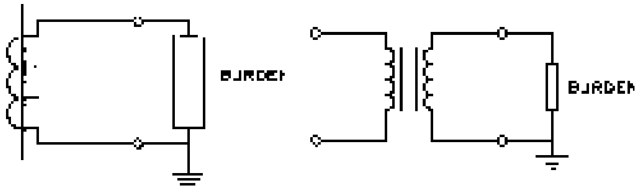

Fig. 1 Schematic Diagram of a Current Transformer.

4.1.Current Transformers.

A CT transforms the line current to a low current suitable for relaying applications. Figures 1 and 2 show a schematic diagram and a detailed model of a CT [36, 37, 39, 40].

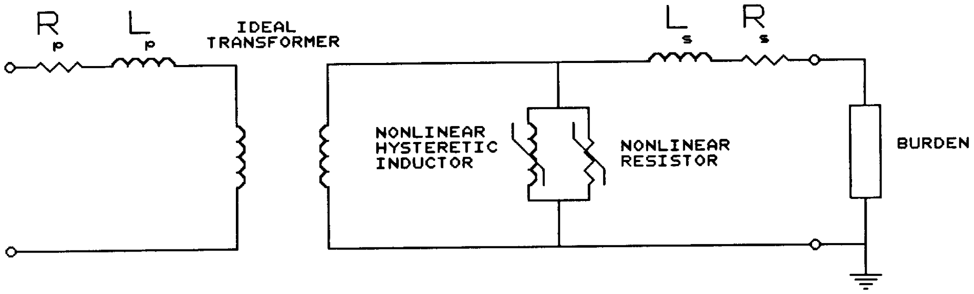

Fig. 2 Detailed Model of a Current Transformer

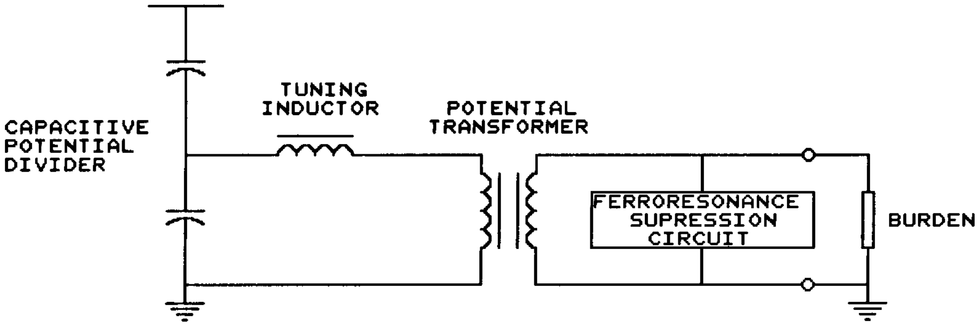

Fig. 3 Schematic Diagram of a Capacitive Voltage Transformer

One of the main concerns in this model is the representation of the nonlinear magnetization characteristic. Under normal operating conditions, a CT operates below the saturation flux density (the knee) and the exciting current drawn is small. Under heavy fault conditions saturation may be reached. The magnetization characteristic should include the hysteresis loop and simulate minor loops. Due to the high rema nence flux that may be left on the core after a fault is cleared, a distorted current waveform might be presented to the relay when the circuit is reclosed. The ability to incorporate remanent flux in a model is critical.

Different models presented in the literature could slightly differ from that depicted in Fig. 2, i.e., the model proposed in [36] does not incorporate the core losses, while some models proposed in [40] do not consider hysteresis for the magnetization characteristic.

Validation tests have shown that this model can reproduce with good accuracy [36, 37, 39, 40]:

- the rise of the flux in the core during a fault with maximum dc offset
- the behavior of the flux-current loops under transient conditions
- the actual secondary current which can differ severely from the ideal one
- the effect of the remanence on the onset of saturation.

4.2.Capacitive Voltage Transformers.

A CVT transforms the line voltage to low voltage through a sequence of capacitive potential dividers and an electromagnetic voltage transformer (VT). A schematic diagram of a CVT is depicted in Fig. 3.

A relatively heavy current is drawn from the protective device when the burden is an electro-mechanical relay, in such a situation a large error can result. To avoid this problem the loading effect on the capacitive divider is tuned by a compensating reactor on the primary side of the VT. In addition, a system composed by capacitors and iron-cored inductors is subject to possible ferroresonant oscillations because of the possibility of resonance between the capacitors and a particular value of the nonlinear reactor. Therefore, ferro-resonance suppression devices are incorporated in the CVT [43]. The detailed model of a CVT is shown in Fig. 4.

The model depicted in Figures 3 and 4 incorpo-

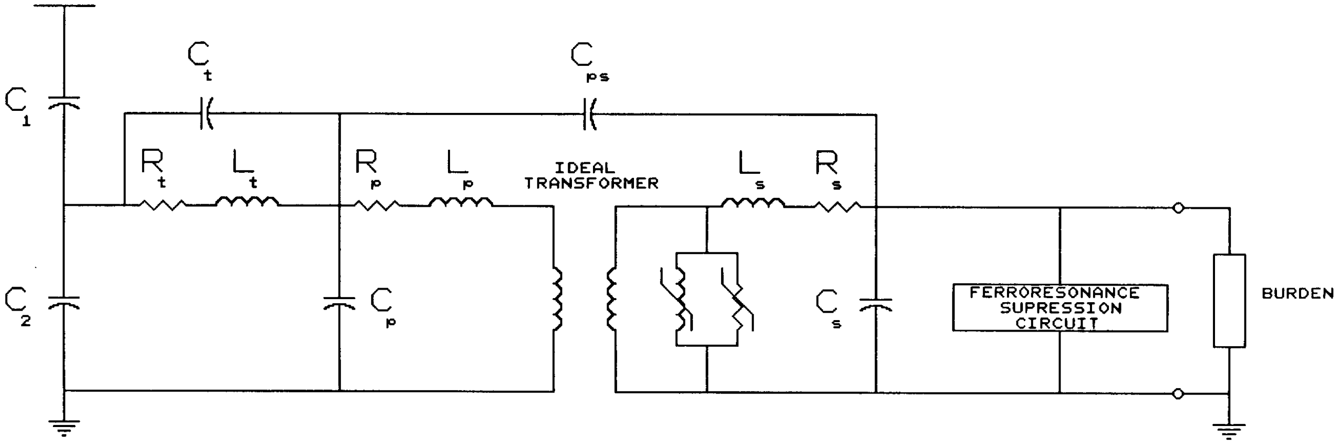

Fig. 4 Detailed Model of a Capacitive Voltage Transformer

rates capacitances. Sensitivity studies have shown the influence of some of these capacitances, mainly those of the VT primary winding to ground and of the compensating reactor [43].

Validation tests performed without stray capacitances have shown that the model can reproduce the subsidence transients and the ferro-resonance behavior, see [36] and [39].

The subsidence transients have a major effect on the relay behavior. Simulation results show that [36]

- the subsidence transient has the largest magnitude and lasts the longest time when the fault occurs at a primary voltage zero
- the magnitude of the subsidence transient increases with an increased burden
- a similar behavior is obtained when the values of the divider capacitances are decreased
- the magnetization inductance has a negligible effect on the subsidence transients.

4.3.Limitations of Models of Instrument Transformers

The main subject of this section of this special publication is modeling of instrument transformers for their representation in digital programs. However, it is worth mentioning that several solution methods have been developed to simulate the proposed models, depending on the tool used for simulation. For those models developed for simulation by means of either EMTP or ATP, see [36], [37], [39] and [40], the solution methods are those implemented in these programs. In reference [39], two methods using iterative and non-iterative algorithms are presented for simulation of instrument transformers by means of EMTDC.

The incorporation of winding capacitances (HV to ground, HV to LV, and LV to ground) in both CT and CVT models would increase the frequency range for which models are valid. Without these capacitances the frequency range is restricted to 3 kHz, approximately.

Identification of parameters is one of the main research areas in modeling of instrument transformers, mainly for those cases in which winding capacitances could be important, see [41] and [42].

The CVT model can be improved if the transient response to overvoltages is to be simulated too. If this effect has to be taken into account, a gap protection circuit should be included in the CVT model, see [37] and [41]. This circuit can be easily represented using capabilities available in programs like EMTP or ATP.

5. MODELING GUIDELINES FOR RELAYS

5.1. Electro-Mechanical Relays

Electro-Mechanical Relays relays are difficult to model because they involve complex combination of mechanical, electrical, as well as magnetic phenomena. Another difficulty is that the operating time characteristics of

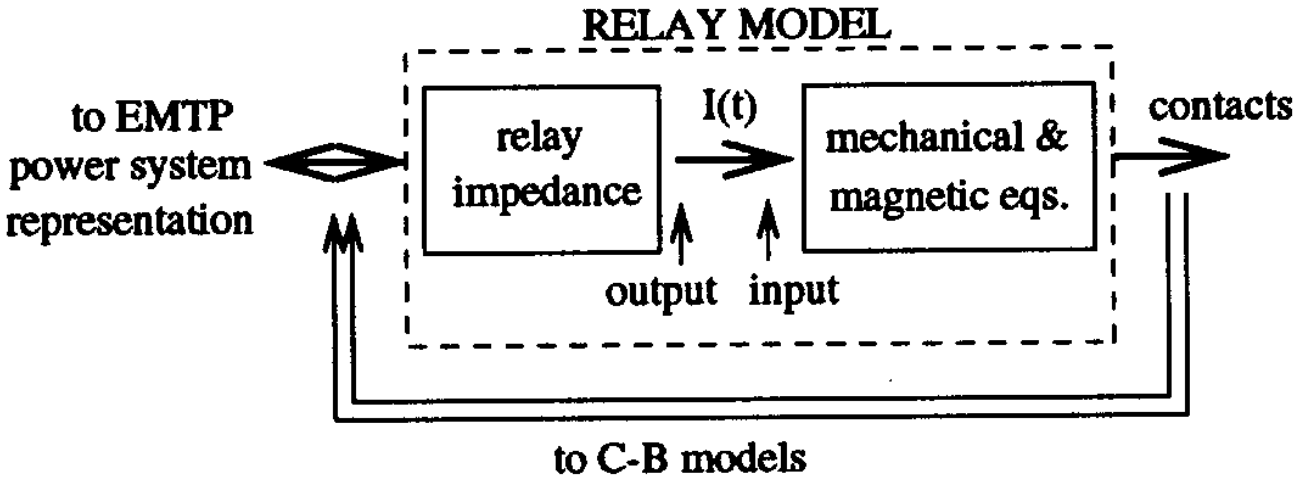

Fig. 5 Diagram of relay model showing combination of electrical, magnetic, and mechanical properties

an electro-mechanical device are not fully repeatable and they involve some statistical spread.

5.1.1 Modeling

In references [26] and [27] the authors describe modeling of electro-mechanical type-50 overcurrent relays as three subsystems: electrical, mechanical, and magnetic. The schematic representative is shown in Figure 5. This mathematical model offers some advantages. For example, the three subsystems can be developed separately and combined as desired. One could also use only part of the model, say relay impedance, if the complete, full-blown representation is not necessary.

The electrical modeling involved representing the relay burden impedance as a function of frequency and magnitude of the input current (Figure 6). Because the relay can saturate at high current levels, the non-linearity of the burden has to be represented. In [26] and [27] this non-linearity was modeled as one lumped nonlinear inductance and the comparison between the model and experiments were very satisfactory. The linear part of the electrical equivalent circuit was synthesized from frequency scan tests at very low current levels to avoid saturation.

The mechanical action of the relay was simplified to a second order system involving mass, spring, and dashpot. A free-body diagram was drawn and the mechanical forces, together with the magnetic force due to the current flowing in the relay coil, were summed up to zero. The mass, spring constraint, and friction constant were estimated from direct measurements of the relay components.

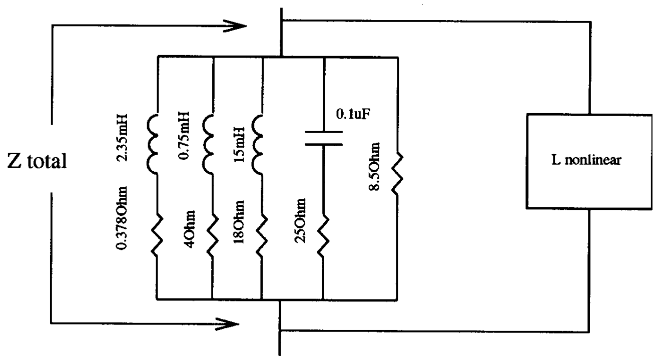

Fig. 6 Equivalent circuit of armature relay impedance

The magnetic force acting on the armature or plunge of the device was calculated from the magnetic subsystem of the model. In there the current through the coil was considered as an input. With known number of turns the magnetomotive force MMF was determined. The reluctance of the magnetic structure was calculated for the dimensions of the device and known magnetic properties of the material. The analytical expression of the reluctance included the time-varying air gap of the device when the armature (or the plunger) was in motion.

An example of the mechanical and magnetic part of the relay model is shown in Figure 7, as a block diagram. The complete model was consequently implemented in ATP/EMTP using a combination of electrical circuit modeling (for electrical subsystem, Figure 6) and TACS devices (for mechanical and magnetic subsystems, Figure 7). The model was verified extensively against the experimental results of the transient testing of actual relays in digital Power System

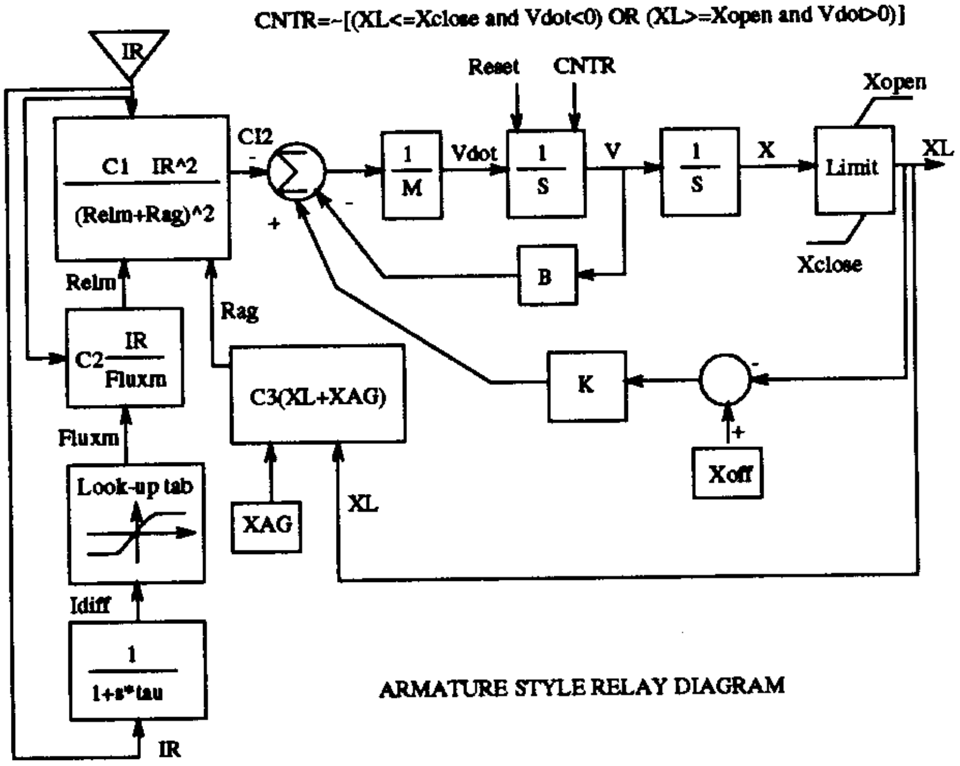

Fig. 7 Block Diagram of Armature Relay Model

Simulator (PSS) for a variety of power system transient fault conditions. The agreement between the operating times of the model and the actual device was typically within 2 to 3 milliseconds.

5.1.2 Electro-mechanical relays - incorrect modeling

As was pointed out in Sec. 3.1, steady-state phasor representations cannot be used for transient modeling. The following paragraphs discuss one example of incorrect modeling for **transient** response of over-current relays.

Typically the operating curves for the time-overcurrent relays are given as follows:

$$t_{operate} = \frac{K * TSM}{(I - 1.0)^n} \qquad (1)$$

where:

K is a constant for a particular relay

TSM is the Time Setting Multiplier

I is the ratio of the current seen by the relay to the pickup setting of the relay (rms values)

n is an exponent varying from 2 to 9, depending on the inverse characteristic of the relay

If this model is implemented in EMTP, the time-to-operate will be given correctly for the **steady-state** case where a particular fixed value of current (rms) greater than the pickup setting of the relay will result in a particular fixed operating time for the relay. Thus, assume that for a 200% overload current the time-to-operate of this particular relay tap setting is 2 seconds. If, a time-varying current is applied to the relay, an overload of 200% for a duration of 80% of the time-to-operate (1.6 s), and continuously repetitive (75% duty-cycle on for 1.2 sec. and off for .4 sec.), the relay model will not give a trip indication. This is because the dynamic equations of the relay have not been represented - the resetting of the relay has to be simulated. If, however, the dynamic equations of the relay are written as follows [44]:

$$F_{operate} = a\ddot{x} + b\dot{x} + cx \qquad (2)$$

Foperate is the applied force (proportional to current squared) minus the restraint force

x is the distance traversed by the contact

a,b,c are constants to be determined by the user

K is the threshold of operating force

The differential equation can be modeled as a second order transfer function in TACS, after taking the Laplace transform of Eq. 2. Thus, the distance traversed by the moving contact is given by the following second order transfer function:

$$x = \frac{F_{operate}}{as^2 + bs + c} \qquad (3)$$

When the distance traversed by the armature is more than the contact separation, the relay operates. Because of saturation, the relay has a definite minimum time of operation and implies the use of a maximum limit on the operating force. To simulate the reset action of the relay, a negative minimum limit on the operating force is allowed.

When the current falls below a threshold, the applied force will be negative and the distance traversed by the contact will be reduced. For the 75% duty cycle overload (200%) current waveform, the trip should then occur, the exact time-to-trip depending on the particular relay and hence the constants of the above equation. An excellent treatment of this subject can be found in [45].

Similarly, if a thermal overload relay is being modeled, the reset characteristics of the particular relay determined by the thermal time-constants must be simulated for an accurate and realistic model.

5.2.Electronic Relays.

Static relays are those relays that employ solid state components such as transistors, diodes, gates, flip-flops, comparators, counters, level detectors, integrators, etc. Static relays were mainly developed in the 1960's through to the early 1990's. They are the next evolutionary step after electromagnetic relays. The main advantages of these relays over the electromagnetic type are the better performance and characteristics, e.g., higher speed with greater accuracy and sensitivity in distance relays [46]. A definition of static relay is "A relay in which the designed response is developed by electronic, magnetic, or other components without mechanical motion" [47].

In general static relays tend to be more complex than electromagnetic relays and therefore the modeling of static relays is among the most difficult of all relays to model. The main tool available is the Transient Analysis of Control Systems (TACS) portion of the EMTP. TACS has extensive capability to model comparators, accumulators, integrators, time delay elements, limiters, etc. TACS also has the capability to model simple FORTRAN statements, e.g., logical operators (.OR., .AND., .NOT.), relational operators (.EQ., .NE., .LT.), etc. TACS at present cannot perform IF THEN, GO TO, and DO Loop operations. However, it is possible to compile and link use defined specific FORTRAN routines in EMTP. Thus, the computational tools to simulate complex static relays are available. It should be mentioned here that the initialization of the TACS components (comparators, etc.) may take one or two cycles (depending on the time constants of the particular component) of pre-fault simulation before the transient is initiated.

One of the earliest computer models of a static relay was developed by Garrett [48]. The specific static relay modeled was the Westinghouse Canada SD-2H, for phase-phase fault detection (distance relay). The general approach was to develop a separate standalone FORTRAN subroutine was written for each major relay component, such as a transactor, a block-average phase comparator, a series R-L-C filter, etc. The state (differential) equations for each of the components were derived. From the state equations using the central difference equation, the algebraic transition equations were developed. The algebraic equations were solved using Gaussian elimination. The model for the SD-2H was developed paying careful attention to the Q of the input filter circuit. The Q values for the memory and the "IZ-V" input filter were not known - no tests had been conducted. The values for Q of the filters were chosen heuristically, i.e., the memory filter's Q had been set large enough (QM=5) to ensure relay operation for close-up forward faults. The "IZ-V" input filter's Q was set just large enough (QH=10) to prevent the zone 1 under-reaching elements from operating for bolted faults at the remote-end bus. The high Q of the "IZ-V" input filter, however, was found to produce such a strong memory effect that the polarizing-input memory was rendered largely ineffective. This experience demonstrates the importance of either transient testing or transient simulation for proving the performance of relays using memory polarizing. (This phenomenon may also apply to externally-polarized mho relays, thus requiring transient testing.) This valuable experience from [48] is cited to alert the reader to the need for careful testing of the relay model with regard to expected behavior and to the need for obtaining important relay parameters for use in the model.

Another static relay, the GE SLY12C was modeled in EMTP mainly employing TACS components. The SLY12C is a static mho phase distance relay intended for the protection of transmission lines. Details of the relay modeling can be found in [50] and [51]. Because, most of the values of the filter circuits were known, the difficulties mentioned above from [48] were not encountered in simulating the relay. The relay model had a tendency to overreach during the verification of the steady-state testing of the mho characteristic. One reason for this overreach could be the initialization of all the TACS variables for the fault at t=0.0-. The magnitude of the overreach varied from 1.06 to 1.11 for various magnitudes of line impedances at different angles of 65 , 45 , 25 , 15 , and 0 . The maximum overreach of 1.11 assumes the form of an ON-OFF trip pulse and not of a continuous trip signal. A similar effect was observed when testing the M2 function forward offset MHO characteristic., the transactor transfer function gains were multiplied by a factor of 0.9 times its theoretical computed gain. This compensates for the tendency of the relay model to overreach during steady-state fault conditions, which gives the relay a measure of security, to avoid tripping for a fault at the end of the line (overreaching zone 1).

Therefore, the results of [48] and [49] reflect the importance of the filter circuits in the development of the exact relay model. The results also indicate the necessity of 1 or 2 cycles of pre-fault simulation. One definition of "generic" relay models is relay models that share the same general principles of operation as the actual relays (e.g., mho relays based on block-average phase comparison) but omit details such as input filtering or input sensitivity levels [48]. Generic modeling can be quite useful for studying basic protection concepts, and can be used for modeling the less-important relays in a protection scheme (e.g., some supervisory relays, auxiliary relays, etc.). The importance of the particular scheme and purpose of the study will determine the level of detail required in the modeling of the relay. For example, if the study is being conducted to determine the security and dependability of the critical high-voltage tie to the major load center, then a detailed relay model is required.

5.3.Microprocessor-Based Relays.

Many digital distance relays are modern realizations of proven electro-mechanical distance relay designs. Modern digital relays use familiar distance measuring (or estimation) principles such as the familiar mho circle, which is a steady-state (phasor) concept. To use obtain phasor values of power system voltages and currents, many digital relays first have to sample (digitize) the input voltages and currents, then recover the estimates of the phasor values. To prevent aliasing, digital relays must have an input anti-aliasing (low-pass) filter.

In light of the above discussion, a model of a digital distance relay could be divided into four sections or submodels. The first section could consist of the input auxiliary transformers (if any) and the anti-aliasing low-pass filter. Next could be the model for the analog-to-digital conversion process. The third section could be the Walsh function or Fourier detector that estimates fundamental frequency (phasor) information. Details of modeling of the first three sections are given in [51]. The relay measuring principle, which is discussed below, could be the final section modeled from available R-X diagram information. Figure 8 shows the structure of the models.

The models of the mho measuring units presented here are based on available published information [52, 53, 54, 55]. The circular mho relay characteristic is developed from comparisons made between two different inputs. The inputs are called S1 and S2. As Kennedy pointed out, for steady-state modeling all we need to know are the equations for the two inputs to the comparator [57]. In this report the S1 signal is called the operating signal and S2 the polarizing. The trip decision can be made with an amplitude or phase angle comparison criteria.

Models of both an uncompensated, self-polarized and a zero-sequence compensated, quadrature-voltage polarized mho measuring units were constructed. For a phase A self-polarized mho characteristic, the two inputs are:

S1 = IaZcg - Vfa
S2 = Vfa

For a phase A zero-sequence compensated quadrature-voltage polarized mho characteristic, the two inputs are:

S1 = (Ia - kI0)Zcg - Vfa
S2 = Vfbc

where:
I = secondary current
k = zero-sequence compensation factor
= (Z0 - Z1)/3*Z1. Z0 = zero-sequence transmission line impedance
Z1 = positive-sequence line impedance

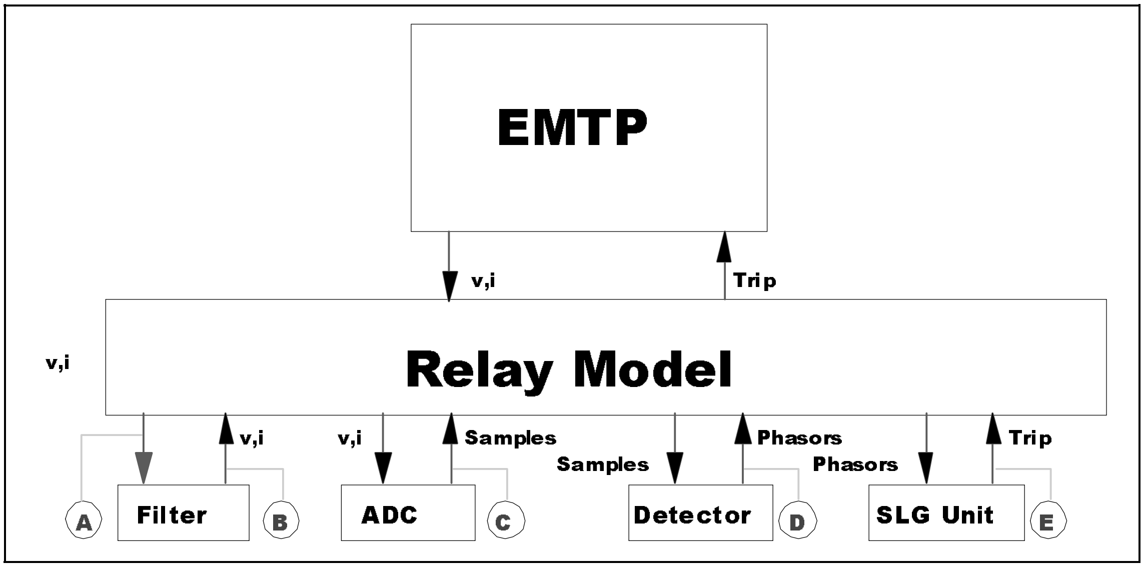

Figure 8. Modeling Structure.

Zcg = relay replica impedance
Vf = voltage at the relay location

Following is an example of an ATP Model's language listing of a self-polarized phase-A-to-ground measuring unit. It is not the Task Forceís intent to recommend one version of EMTP over another. The Models language is similar to Fortran and the model listed here can be translated into other high-level languages using the following guidelines. Here vr, vj, ir, and ij are vectors of dimension 4 with component ordering of phases A, B, C, and zero sequence. Lower case r means the real components with j for the imaginary parts. The replica impedance vector is called zcg. The real part is the first component and the imaginary part is the second. Two or three dashes indicate a comment. The model for a self-polarized phase-B-to-ground (and C) measuring unit can be obtained by symbolic permutation (a to b, b to c, c to a).

The model listed below uses angle comparison logic. The first sections of the listing define the input, internal, and output variables. In the execution (EXCEC) section the real and imaginary portions for the IZ-V operate signals are calculated. The angle of the phase A operate signal, called operangleA, is calculated by the ATAN2 function. An IF statement protects this operation from division by zero. Next the angle of the polarization signal, called polangleA, is calculated from the input phasor arrays vr (real part) and vj (imaginary). Next the difference between the operate and polarizing signals (diffangleA) is calculated. Finally an IF statement sets the "trip bus: variable tripA to 1.0 if the difference angle is between 90 and 270 (in radians). In a complete model, the values of vr and vj would be calculated by the proceeding detector section.

```
MODEL Angle_SLG1
 INPUT
  vr[1..4], vj[1..4]
  ir[1..4], ij[1..4]
  zcg[1..2] ---Line impedance.
  k[1..2] --- Zero sequence factor.
 DATA
  printcontrol --- Controls listing file.
 VAR
  operator, operateAj --- Operate signals.
  operangleA, polangleA --- Angles
  diffangleA --- Difference angles.
  tripA --- Individual trip signals.
 OUTPUT
  tripA
 INIT -- Initialization section
 tripA:=0.0 -- Reset the trip bus
 ENDINIT
 EXEC --- Execution section
-- Real part parts of the operate signals.
 operator:=ir[1]*zcg[1]-ij[1]*zcg[2]-vr[1]
-- Complex parts of the operate signals.
 operateAj:=ij[1]*zcg[1]+ir[1]*zcg[2]-vj[1]
--Find the angle of the operate phasor.
 IF ((operateAj-0.0) AND (operator=0.0)) THEN operangleA:=0.0
 ELSE operangleA:=ATAN2 (operateAj,operateAr) ENDIF
--- Self polarizing voltages, V-A polarizes A phase.
  IF((vr[1])=0.0 AND ((vj[1])=0.0)) THEN operangleA:=0.0
  Else operangleA:= ATAN2 ((vj[1]), (vr[1])) ENDIF
---Decision making angle comparison logic.
 diffangleA:=ABS(operangleA-polangleA)
 IF((diffangleA>4.7124) OR (diffangleA < 1.5708))
 THEN tripA:=1.0 ELSE tripA:=0.0 ENDIF
 ENDEXEC
ENDMODEL ----END Model Angle_SLG1a
```

The model of a compensated polarized relay is discussed by Wilson [58]

5.4.Validation of Models.

The only known way of validating relay models of existing relays is through laboratory testing. First, the actual relay is tested for various inputs and relay operation/no operation and if applicable, relay time-of-operation is noted. Then, the same inputs are applied to the relay model and the relay model operation/no operation and if applicable, the relay time-of-operation are noted. Comparison of the actual relay behaviour to the relay model behaviour determines the validation of the relay model. There are three main types of transient simulators: analog simulators (transient network analyzer or TNA), real-time digital simulators, and playback digital simulators. These simulators are described in this section.

The TNA consists of scaled analog models which represent, up to a few kHz, the transient behavior of the actual power system components. The models are accurate and can represent the magnetic non-linearities of the transformers and reactors. Because of physical models, the influence of remanence in transformers, which can pass unobserved in a digital simulation, has been observed and studied. The TNA output is amplified and fed to the relays under test. The relay characteristics can be tested with various currents and voltages, including the effects of dc offset. Then identical currents and voltages are supplied to the relay **model** and the time-to-operation and no-operation are analyzed and compared to the **actual** relayís performance. Some of the disadvantages of TNAs are that the study is limited to the available parameters of the transmission line and transformers and not all configurations can be tested.

Development of digital simulators for relay testing has enabled a flexible and accurate environment for testing of digital relays and relay models. Fault waveforms can be simulated using an electromagnetic transient program (EMTP).

These waveforms can be utilized to test relay models by directly interfacing the models to the EMTP. The actual relays can be tested by converting sampled waveforms into analog signals and amplifying them to the levels required by the relays. This is accomplished with digital-to-analog converters and power amplifier interfaces available in the digital simulator designs.

Once the digital simulator environment is available, a number of hardware and software tools can be developed to support testing of relays and relay models. The real question is what should be the methodology for verification of relay models. One obvious approach is to compare relay model responses with the responses obtained from an actual relay. This assumes that the model of an actual relay is made available and needs to be verified. For now, this approach will be further discussed.

The first group of tests is related to characterization of the phasor model of a relay. This reduces to verification of the operating characteristic of an actual relay since this characteristic is a phasor concept. After the relay characteristic is verified, the second group of test can be performed to verify transient behavior of an actual relay. In this case, an application has to be defined and a relay response to a fault has to be determined. This response is characterized with the relay trip/no trip indication and the operating time.

Once the test results are obtained, the relay model can be verified using these results as a reference. The relay model can be subjected to the same test waveforms and the responses can be compared.

The operating characteristic verification may be easier to perform since a two equivalent phasor representation of the power system model can be used. However, the application tests involving fault transients may be performed utilizing a variety of power system models and conditions.

5.5Limitations of the Section 5.3 Model.

The main limitation of relay models may be the level of the approximation used to represent an actual relay. The existing practice in the industry is for relay manufacturers to make available only limited information regarding relay design and its behavior. This is particularly true with the new microprocessor-based design that may be fully described with a software description, but the manufacturers do not provide this description since it would enable others to fully reproduce the relay design. Most of the information provided in the manuals relates to the phasor description of the relay behavior. This information is given in a form of operating characteristics and related phasor equations. On the other hand, this description is not sufficient for a full description of the relay behavior under transient conditions. As mentioned earlier in Section 5.2, the filter parameters play a critical role in determining the transient behavior of the relays.

It is important to recognize that the limitations of relay models are relative depending on the purpose of using these models. If the purpose is to provide general education about relay designs and behavior, phasor-based models can suffice. If the purpose is to determine actual behavior of a relay under fault condition, the phasor-based models cannot be recommended and more detailed models including filters

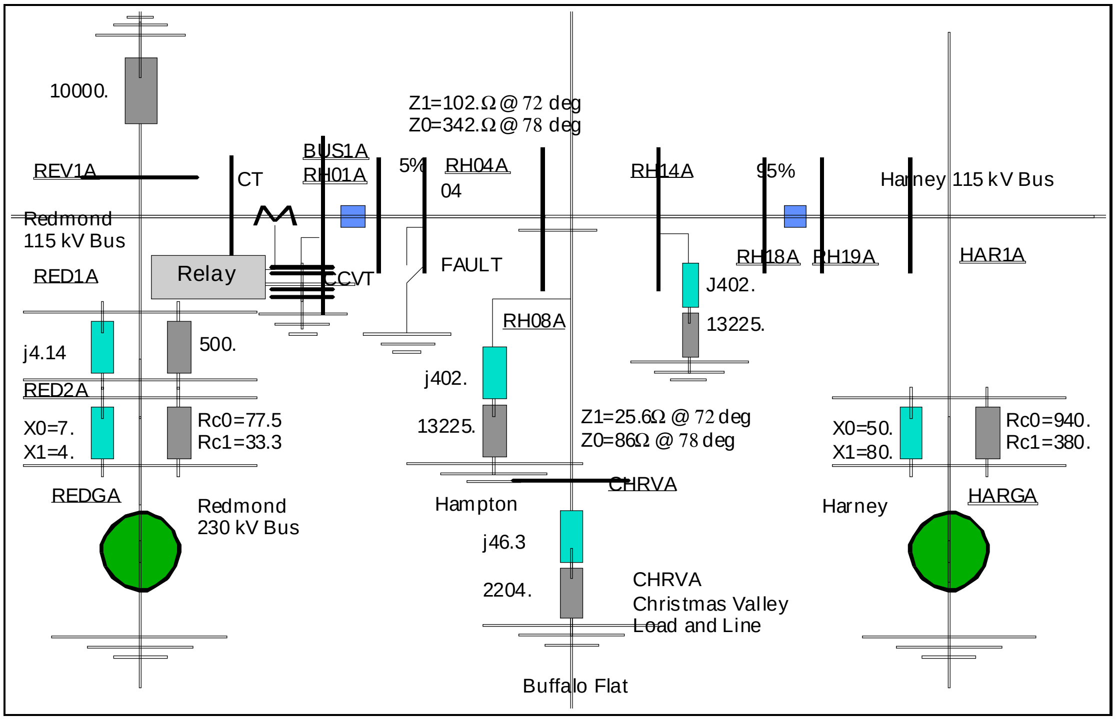

Fig. 9 A Section of BPA Power System

are required.

6. CASE STUDIES

6.1. EMTP Simulations of Distance Relay Testing

This section includes EMTP/ATP modeling of the following:

1. A section of Bonneville Power Administration (BPA) power system shown in Figure 9,
2. Current transformer modeling shown in Figure 10,
3. CVT modeling shown in Figure 11,
4. Voltage transformer (VT) modeling shown in Figure 12, and
5. Electro-mechanical distance MHO Type relay modeling as shown in Figure 13.

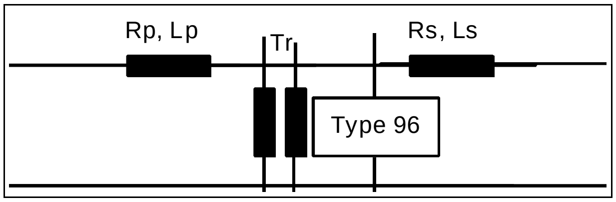

Fig. 10 Current Transformer Model

The relay model was at the substation (RH01A) protecting the Redmond-Harney line. Single-phase-to-ground faults were simulated at the Redmond-Harney line (location RH04A) and at the substation (RH01A) as shown in Figure 9.

Relay test simulations included five test cases:

1. Steady-state relay tests
2. Symmetric single-phase-to-ground fault at the 115 kV line (location RH04A) with CVTs,
3. Asymmetric single-phase-to-ground fault at the 115 kV line (location RH04A) with CVTs,
4. Symmetric single-phase to ground faults at the substation (location RH01A) with VTs, and
5. Symmetric single-phase-to-ground fault at the substation (location RH01A) with CVTs.

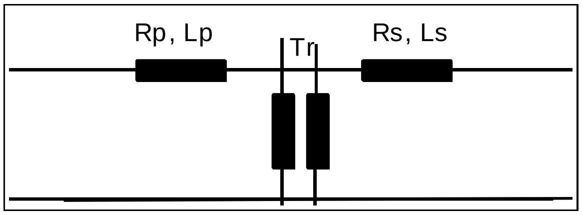

Fig. 12 Voltage Transformer Model

6.1.1 Steady-state Relay Tests

These simulations included testing the distance relay modelís steady-state characteristic to verify that the relay has a mho characteristic. The results are shown in Figure 14. Filled dots represent the operating region, while open dots represent the non-operating region.

6.1.2 Symmetric and Asymmetric Single-Phase to Ground Fault at the Line (location RH04A) with CVTs

These simulations were performed to evaluate influence of the CT saturation on the relay operations. To obtain a symmetric fault, the circuit breaker was closed at the voltage peak. The CVT primary and secondary voltages are shown in Figure 15. An asymmetric fault was initiated by closing the circuit breaker at the voltage zero. The CVT primary and secondary voltages are shown in Figure 16. A symmetric fault did not cause CT saturation as shown in Figure 17, while the asymmetric fault did cause CT saturation as shown in Figure 18.

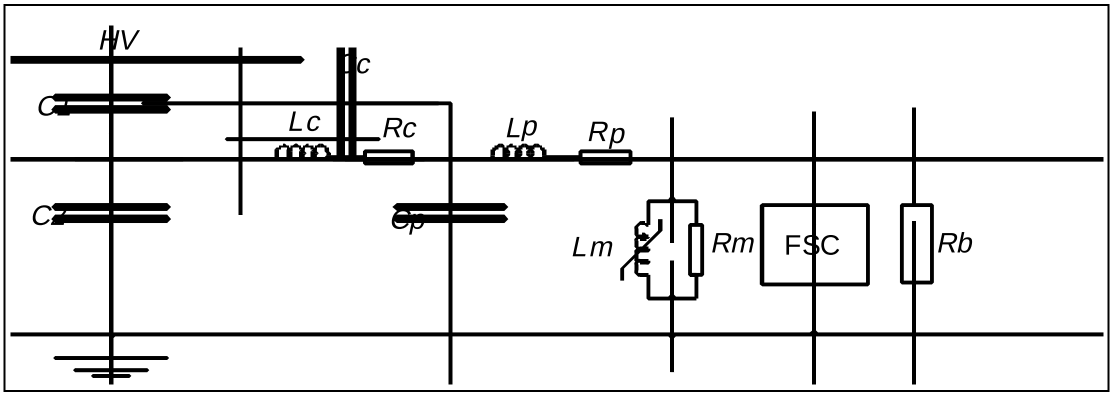

Fig. 11 Capacitor Voltage Transformer Model

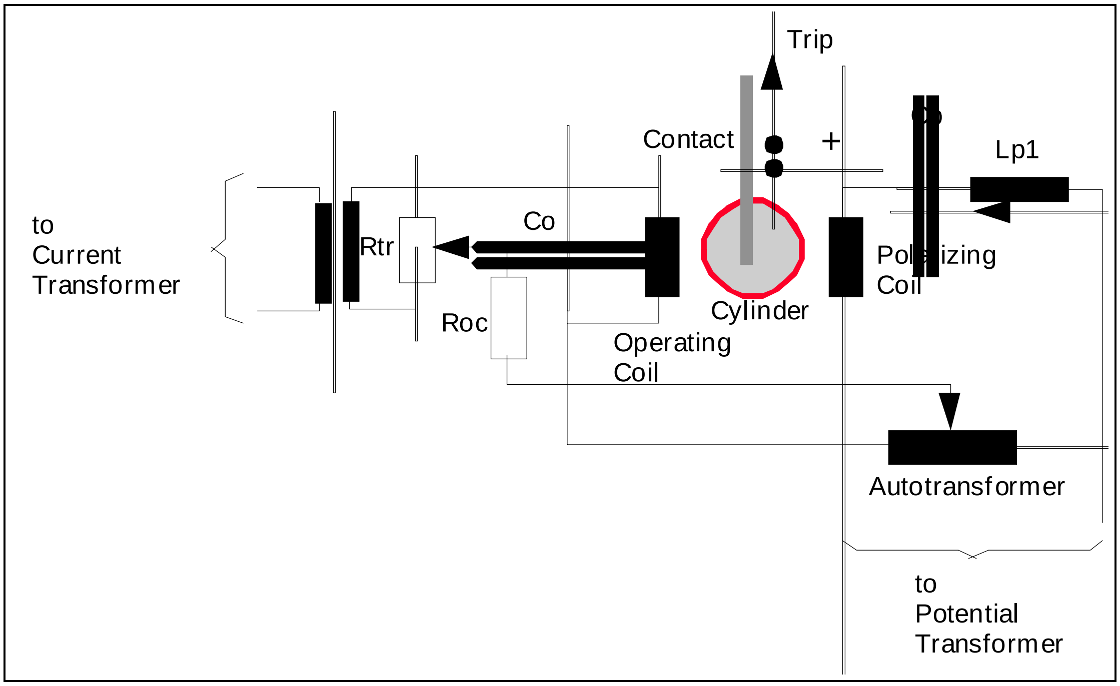

Fig. 13 Electro-mechanical MHO Distance Relay Model.

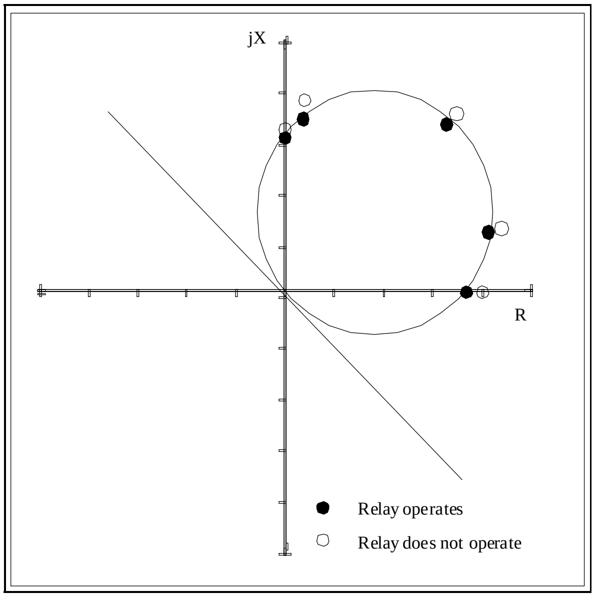

Fig. 14 Distance Relay Characteristic (ATP simulations of the relay steady-state tests).

Relay operation for both cases was monitored by calculating the relay contact speed and electro-mechanical torque. These parameters are shown in Figures 19 and 20. To perform the comparison, waveforms in Figures 19 and 20 are aligned by shifting the symmetric fault by a quarter-cycle. It is evident that asymmetric fault causes faster relay response until the CT saturates. When the CT saturates, the relay speed and torque decreases

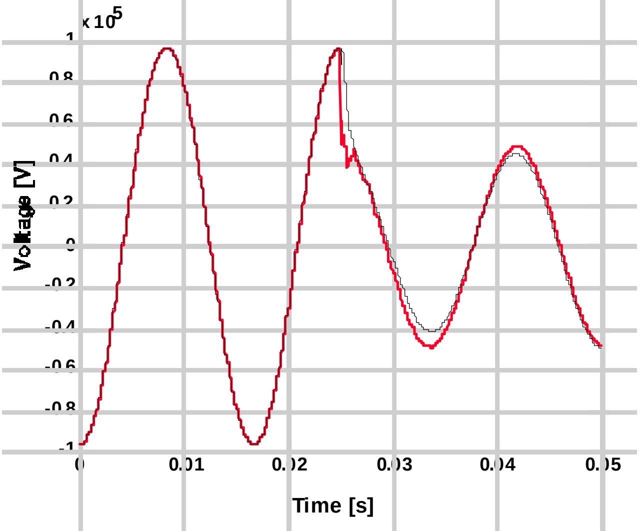

Fig. 15 The CVT Primary and Secondary Voltages for Symmetric Faults on the Line (location RH04A).

6.1.3 Symmetric Single-Phase to Ground Fault at the Substation (location RH01A) with VTs and CVTs

To compare VT and CVT instrument transformer influence on distance relay operations, a symmetric single-phase-to-ground fault was simulated at location RH01A. Though the fault is symmetric, the CT secondary current is distorted due to higher fault current at location RH01A, as shown in Figure 21. The VT and the CVT secondary voltages are given in Figure 22.

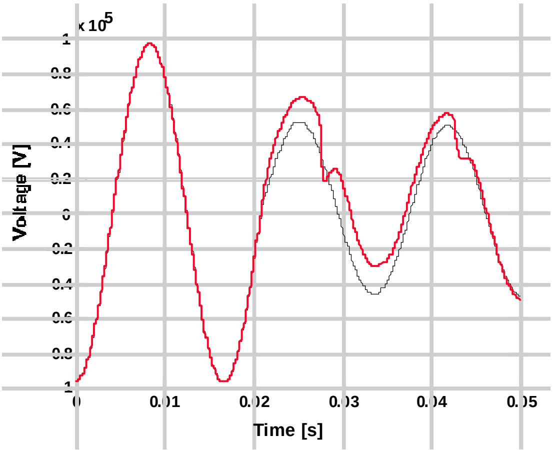

Fig. 16 The CVT Primary and Secondary Voltages for an Asymmetric Fault on the Line (location RH04A)

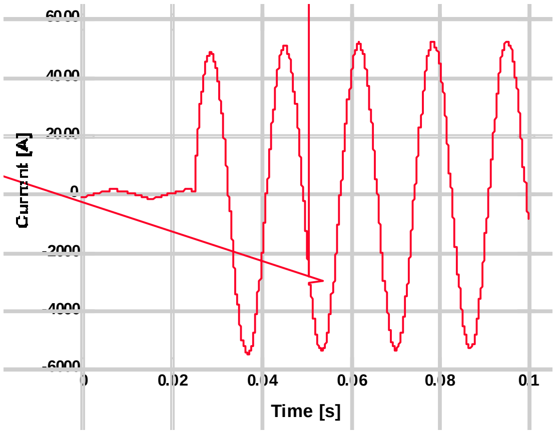

Fig. 17 The CT Primary and Secondary Currents for a Symmetric Fault on the Line (location RH04A)

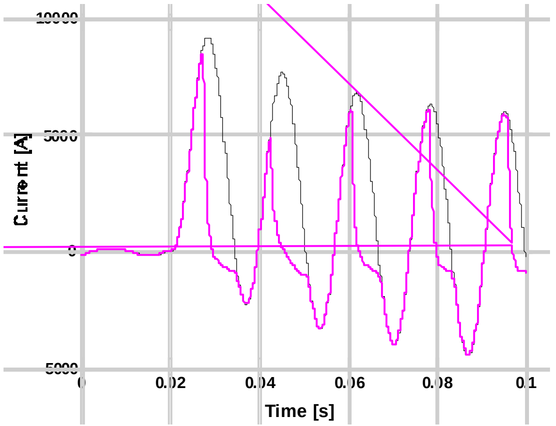

Fig. 18 The CT Primary and Secondary Currents for an Asymmetric Fault on the Line (location RH04A).

The VT secondary voltage drops quickly to zero when the fault occurs, while the CVT secondary voltage oscillations decrease to zero. The CVT secondary voltage without a relay and with the resistive burden is presented in Figure 23. The secondary voltage decreases to zero much faster. The relay contact speed and electro-mechanical torque are given in Figures 24 and 25. The peak torque and the average torque developed by the relay fed from the VT is higher than the relay fed from the CVT. Therefore, VTs cause faster relay response.

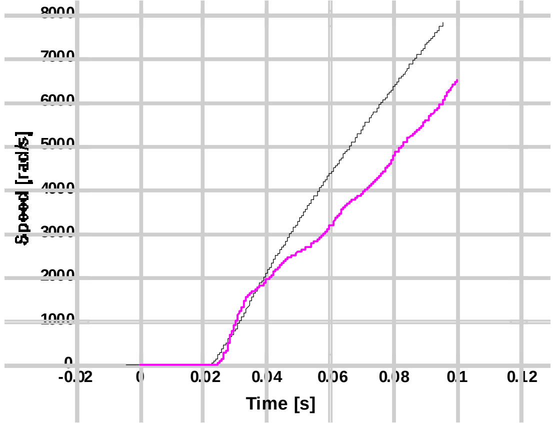

Fig. 19 Relay Contact Speed for Symmetric and Asymmetric Faults on the Line (location RH04A)

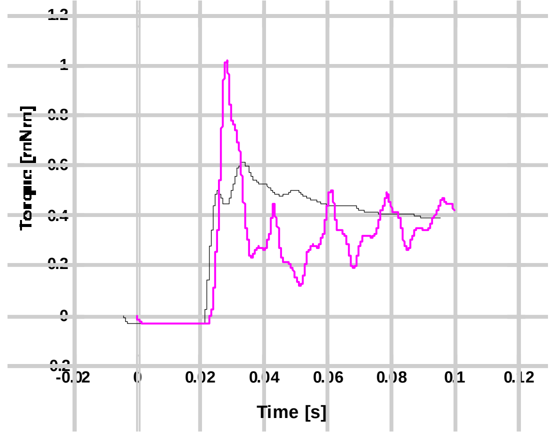

Fig. 20 Relay Electromagnetic Torque for Symmetric and Asymmetric Faults on the Line (location RH04A)

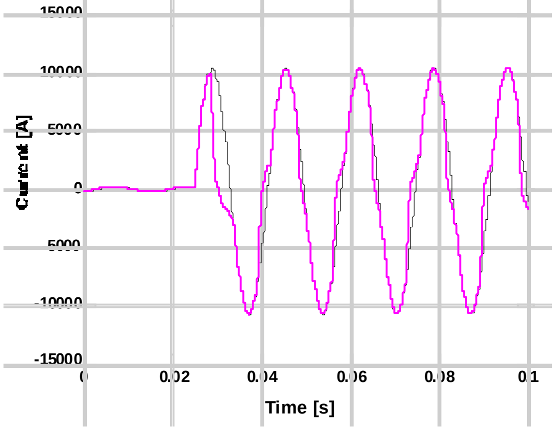

Fig. 21 The CT Primary and Secondary Currents for a Symmetric Fault at the Substation (location RH01A)

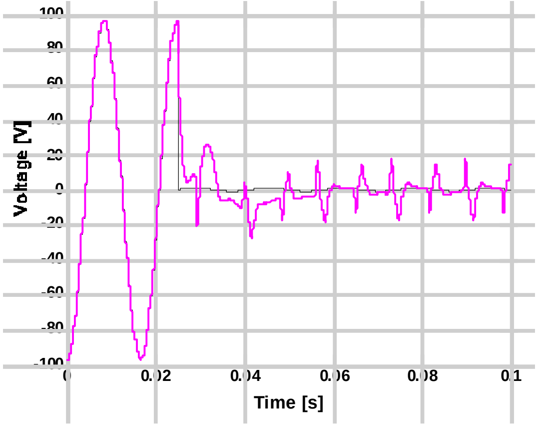

Fig. 22 VT and CVT Secondary Voltages for a Symmetric Fault at the Substation (location RH01A)

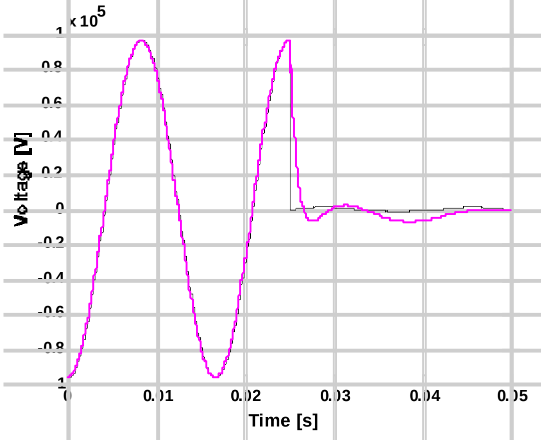

Fig. 23 The CVT Primary and Secondary Voltages Without Relay Burden and with the Resistive Burden for Symmetric Fault at the Substation (location RH01A)

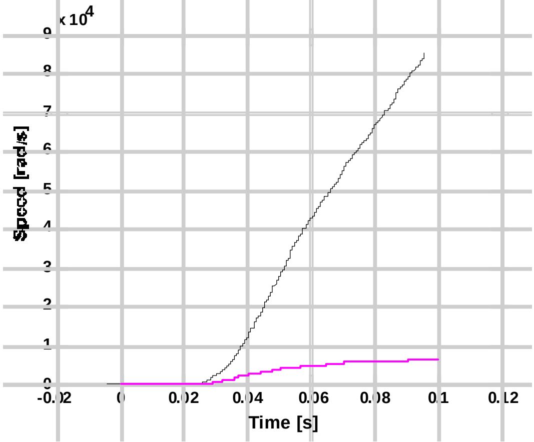

Fig. 24 Relay Contact Speed When using a VT and a CVT for a Symmetric Fault at the Substation (location RH01A)

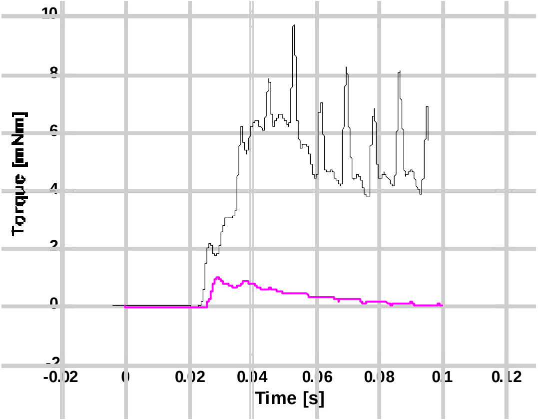

Fig. 25 Relay Electro-mechanical Torque for Using a VT and a CVT for a Symmetric Fault at the Substation (location RH01A

7. RECOMMENDATIONS FOR FUTURE WORK

The IEEE PES Power System Relay Committee (PSRC) has formed Working Group I-17 to continue the development of relay models. This Task Force will concentrate its future efforts on the power system effects caused by protection and control circuits. Simply stated, PSRC will develop relay models and this Task Force will use these models in studies of the high-voltage effects of protection and control. For example, future studies could be of: the system effects of tripping and reclosures on transmission lines of various voltage levels, effects of reclosing a series-compensated line, the interaction of shunt capacitor bank protection and control with high-voltage system effects and possible breaker switching problems.

One limitation of this research published to date is that only few relays have been modeled. Often the model is compared to a physical relay on only one electrical system. A next step would be to compare the available models and physical relays on different electrical systems. The electrical system could be a 230 or 345 kV system, of shorter length, transformer terminated, or near a generating station.

With the material summarized in this Special Publication, many possibilities for future research and development exist. Some suggested areas for study are listed below:

1. An aspect of the original charter of this Task Force was control circuits. A possible task would be to take models of distance, back-up, and bus relays and assemble a "total protection and control package." This model could include relay models from PSRC and models of a typical power circuit breaker control scheme by this Task Force.

2. One area for future research is to determine proximity to a relay operation. Souillard, during the 1980 General Discussion of CIGRE Group 34, made the following statement on this point:

"By its nature, a protection (device) emits an on/off signal. For this reason it is difficult to know whether an operation which gave a correct state is close to the change of state, or not, we do not have, as in an analog output device, a means of following up as a function of variation of parameters to permit the application of interpolation or extrapolation principles, for envisaging the changes and limiting the number of tests. When the output device is of an "on/off" type, it is therefore appropriate to undertake a very fine investigation, to detect all the points missed in the examination.

"Even when many tests are conducted, the various relay outputs (and other binary signals) which are combined in the scheme logic must be examined individually. This is because the scheme logic tends to obscure the existence of marginal operating conditions. Careful examination of the critical steps in the scheme logic is required to avoid overlooking potential mis-operation". [59]

Reference [48] has introduced the technique called "numerical logic replacement" (NLR), which makes both near-operation and near mis-operation visible from simulations; e.g., how close a timer was to issuing a trip. To prove security and dependability of a protection scheme or a relay a few thousand fault tests and simulations are carried out. This NLR technique contains the potential to reduce the number of simulations. The relay models developed should endeavor to incorporate this feature.

3. This publication has summarized the modeling of two electro-mechanical, one electronic and one digital relay. The digital relay used the mho type of measuring principle. Many other relays and distance measuring principles exist. Recommended future research would be to develop models of other measuring principles of distance relays such as compensator distance, the quadrilateral characteristic, lenticular, and other principles.

4. If only single-line-to-ground measuring units were modeled, develop models of three- phase and phase-to-phase units. All known commercial distance relays contain a three- phase-fault measuring unit. Many relays contain overcurrent fault detectors. Given the techniques summarized here and listed in the technical literature, modeling of these additional units could be done.

5. Portions of this publication summarized modeling of the relay measuring units. A commercial distance relay contains programming that interconnects the operation of over- current fault detectors, the measuring units, and communications circuits. This logic could be mimicked by using parallel statements written in some high-level language.

6. A needed step in model verification is for a relay model to duplicate an actual mis- operation of the physical relay.

7. Modeling of current-only and traveling-wave relaying of transmission lines would be a useful addition to the field of the analysis of distance relaying.

8. Develop the structure to have two relay models working in parallel. Many series compensated transmission lines are protected by two relay systems operating in parallel. The two types may be a distance type of relay, a traveling wave relay, or a current only (phase comparison) type of relay. Models exist for the protection of the high-voltage series capacitors [60]. With the above developments, the entire protection system of a series compensated line could be studied.

9. Modern protective relaying makes extensive use of the engineering fields of digital signal processing and parameter estimation [61]. Relay modeling presents an excellent way to study the effects of new forms of signal processing. Before building an engineering prototype, the effects of a different low-pass filter or detector could be studied on a PC. Signals of interest could be brought from within the relay model into the main electrical part of EMTP and finally to a plotter file. The various signals could then be displayed visually by using an auxiliary program.

10. Detailed studies of relay response to waveforms with sub-synchronous frequencies could be performed using relay models. It would be possible to assess the model response to a 30 or 40 Hz signal using the simulation techniques discussed in this Special Publication and in the literature. The effects of various types and frequency response of filters and several different measuring principles could also be studied.

11. Many transmission systems included transmission lines that are parallel. Due to environmental constraints, two transmission lines often share the same supporting structures. The lines may be only 20 to 30 feet apart. With close separations, mutual coupling is more pronounced. Relay models could be used to study the relay response of two closely coupled transmission lines.

12. Relay modeling presents many opportunities to train the relay engineers of the next generation. Using the techniques summarized here, educators could have students investigate how modern relays work.

13. The development of relay models for use within EMTP should aid future researchers in developing models for stability studies. Without models of distance relays present stability studies use estimated, fixed relay response times. Physical relays may respond more quickly than the fixed time models now used. With accurate relay models, the simulations could be run "closed loop" with the relay models tripping the PCB models. The improved modeling may lead to higher power transfer limits.

14. An area of research will be whether a stable phase angle reference would be useful as a system-wide standard. This reference may allow the relay to determine if the input quantities are suffering from a voltage or current inver-

sion [62].

15. There have been articles written about current research on "global relaying" [63, 64]. "Line relaying" is the presently practiced protection philosophy where the relays use locally available quantities. Global relaying is where power system-wide quantities, such as an unvarying angle reference, are used. A precise timekeeping network could easily provide a reference time marker indicative of a constant phase angle (for constant frequency systems). For example, a new relay could use this global reference to determine if the current has just inverted.

16. A major disadvantage to existing designs of series capacitors is that the value of the capacitance is fixed. Several years ago the Electric Power Research Institute (EPRI) started a project called Flexible Alternating Current Transmission System (FACTS). One possibility would be a series capacitor bank with variable capacitance. One way to accomplish this would be by paralleling the capacitors with an inductor in series with an electronic switch such as a silicon controlled rectifier (SCR). The firing angle of the SCR would vary the amount of inductance that would cancel a variable percentage of the parallel capacitance. New models may have to be developed for this part of the study.

17. A critical section of any relay is the detector section. In many relays a Fourier detector that has a window of one cycle is used. Investigations of the effects of different window sizes would be a useful addition to the literature.

18. The wavelet transformation may produce a different estimate of the fundamental frequency phasor information during transient periods [65]. Previous work on a transform with variable window size has been reported [66]. A detector section that uses the wavelet concept could be written for the relay model.

19. Model reported in the literature use a simple model of the analog-to-digital converter, namely a leading-edge, infinite-precision model. The effects of finite word length and conversion error could be included in future work.

8. CONCLUSIONS

The material reported in this Special Publication summarizes a first step in the modeling of relays. The modeling of protection and control devices and circuits has progressed since this Task Force was formed. Several researchers have obtained initial favorable comparisons between relay models and physical relays. More models of protective relays that can be used in transient simulation software, such as the many versions of EMTP, are available. The demonstrated accuracy level of the models varies. If the modeling had not been successful, then the use of relay modeling would not merit further research. Further research will be needed to verify reliability and accuracy of the models for several different relays.

Modeling of protection systems in digital programs is a relatively new procedure. As with all new ideas and procedures, there is a time lag between initial skepticism and acceptance. This Task Force's report has aimed to summarize the work done in this area and provide general guidelines to assist an engineer in modeling protection systems. In the interest of objectivity sections on the advantages and disadvantages of modeling of protection systems are included.

Computer modeling is not meant to replace laboratory or field testing. Relay and control system modeling complements testing of the physical device. Before a relay is placed in service, it must be thoroughly tested in the laboratory or field to insure the highest reliability. Modeling is a useful adjunct to testing in designing new relays, relay application studies, engineering education, and mis-operation analyses.

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