COMPUTER-BASED RELAY MODELS SIMPLIFY RELAY-APPLICATION STUDIES

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INTRODUCTION

How can we be sure a particular relay is suitable for a given application? For common or simple applications, the relay instruction manual or application guide may provide the answer. For unusual or complex applications, we may need to test the relay performance.

Early in an application study, computer simulation of the relay may be a valuable preliminary step to performance testing. Relay simulation may allow its design and/or settings to be optimized. This minimizes surprises during performance testing thus increasing the efficient use of test equipment.

This paper describes some of the benefits of using a computer simulation of a relay. It includes an example of simulation for an unusually difficult protection application which gave the user and manufacturer confidence to proceed with final design and initial settings for an exhaustive series of performance tests. The authors hope that computer simulation of relay performance will be increasingly used, and that computer-based relay models will become increasingly available to answer preliminary application questions.

BACKGROUND

Simple devices such as Variacs and load boxes are useful for checking steady-state performance. Steady-state tests demonstrate that a relay performs in accordance with its design characteristics. These tests, therefore, are helpful for acceptance, commissioning or maintenance purposes. However, since faults are transient, transient tests are the final arbiter of whether a particular design or settings are suitable.

For some applications, a user may perform simplified transient tests called "dynamic state", "pseudo-transient" or "phasor" tests. Commercially available test equipment can switch between various steady-state conditions such as pre-fault, fault, post-fault, etc. The test signals contain only fundamental frequency phasor quantities, except at the instant of transition from one state to another. These tests have been widely applied for checking relay applications [1,2,3]. Although the equipment for dynamic state testing is more readily available and less expensive than that required for full transient testing, it has its limitations. The test signals do not include the non fundamental frequency components (such as dc offset, or harmonics) that may be present during a fault, and they do include very high di/dt components which are not present during a fault. Therefore, these test may not always be valid [2,3,4].

When dynamic state tests are not suitable, full transient tests are required. The equipment required for the transient tests is expensive and requires considerable effort to set up and operate [5,6]. However, it is still much easier to test a relay by applying signals from a simulated system than by staging tests on the actual power system. It is easier still to simulate the relay as well as the power system.

Relays may be simulated in terms of their steady-state characteristics or as dynamic elements. In the steady-state, a computer program may represent their operating and polarizing quantities. A fault program may calculate the phasor quantities which would be presented to the relay under steady-state fault conditions. This sort of representation is useful mainly for distance relays which have a wide variety of operating and polarizing signals.

The simulation is useful to check the effect of system conditions, fault resistance and load conditions [7]. Users can make up their own computer-based models of relays [8] or use commercially available programs [9]. The computer-based model of the steady-state representation of distance relays is helpful to compare the performance of different types of distance relays under known influencing factors. This type of representation, however, does not determine the transient performance of the relay under transient system conditions. For such determination, a transient model of the relay is required.

A transient model of the relay would model its performance in detail. In the case of digital relays, it is fairly simple to use the same algorithm as is used in the relay, but there are other factors which must also be included. The anti-aliasing input analog filters and the effect of sample and hold or skew in the samples must also be considered. Output relay delays are also important.

Common to both the steady-state and transient relay models is the capability to plot the output in a way that is not possible with actual relay tests which are usually go or no go tests. With computer simulation it is usually possible to see how close one is to the boundary of operation. This form of output is valuable in determining the effectiveness of a particular application or setting.

COMPUTER-BASED RELAY MODELS

Researchers often test new digital relay algorithms by supplying them with simulated fault signals. Early in development, these algorithms are no more than pieces of program code running in a computer. They are computer-based models of a possible future relay. Technical papers describing the algorithms performance, such as Reference 10, contain charts showing how fast they sense faults, and how dependable and secure they are. These charts usually show a boundary of operation and the distance of a measured parameter from that boundary.

A simple example of a computer-based model may be made with almost any type of commercial mathematical program. Consider a model of a time-overcurrent relay which operates according to the following formula:

$$t = A/(M^p-1) + B$$

Where t is the time to operate, A, B and p are constants, and M is the multiple of pickup current that is presented to the relay. This formula gives the operating time of a relay if the current that is presented to it is constant (i.e., if M is constant). If M is variable during the measuring time of the relay, the time to operate can be calculated by measuring the total travel of the relay disk at any instant, which is given by the formula:

$$Trvl = \int F(M)\, dt + Trvl_0;$$

Where $F(M) = 1/((A/M^p-1) + B)$ and $Trvl_0$ is the initial position of the disk.

The background to this formula is given in Reference 11. When the disk has traveled through its complete range, a trip signal is given. If the magnitude of fault current changes during the travel, the velocity of travel varies accordingly. The formula for travel may be easily written on a commercial mathematical program and response to a given fault current plotted.

The output of a simple simulation is shown on Figure 1 where a time-overcurrent relay model is subjected to a constant current for a certain time just short of the expected operating time. The disk travel is plotted against time. It can be seen how the travel approaches the boundary of operation and then starts decreasing after the current is stopped. This plot is a representation of a time-overcurrent relay modeled on a Mathcad file with only a few lines of code. It is interesting to note that the margin of non-operation is clearly shown, providing much more information about the relays performance than if it had simply not operated for the given test signal.

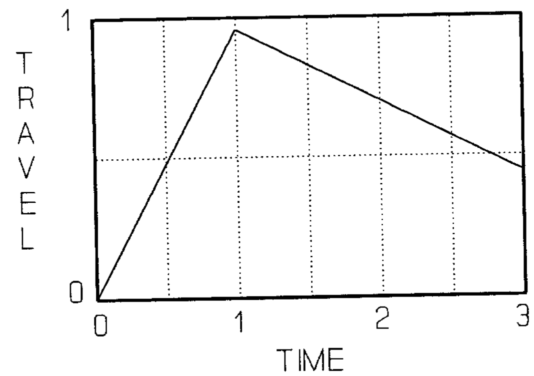

Figure 1: Plot From Mathcad Simulation of Time-Overcurrent Relay

The Mathcad model of an overcurrent relay may be supplied with current waveforms derived from almost any source. The source used to generate the response shown in Figure 1 was developed within Mathcad itself. Mathcad can be used to develop complex waveforms such as currents including dc components or harmonics. Other programs, such as EMTP, are more readily used to derive the currents and voltages presented to relays during faults on large power systems.

EMTP-derived relaying signals are widely used in transient tests to evaluate the response of digital protection algorithms and of analog relay systems. This type of signal may also be used as a source for relay model simulations. In the late 1980's, researchers started developing computer-based models of electromechanical and solid-state analog relays.

For example, in 1987, Garrett proposed digital simulation of relays as an alternative to testing the actual relays on a model power system simulator [12]. He recognized the benefit of avoiding the need for expensive test equipment required for model power system tests. He also recognized the value of relay simulations providing the opportunity to see the margin of dependability or security of a relay, instead of a simple "trip" or "no trip" response. He proposed the concept of "numerical replacement logic" to show these margins.

With numerical replacement logic, the state of the relay output is represented by a continuous analog quantity, instead of a two-state "on/off" quantity. Garrett referred to the analog output as a pseudo-output which would indicate the degree to which the relay is on or off. The positive value of the pseudo-output indicates a closed output contact, and a negative value indicates an open contact. A small negative value indicates that a contact is open, but not far from closing.

Garrett developed models of solid-state analog relays in a dedicated program written in FORTRAN 77 code. Today, powerful, commercially available mathematical programs may be used instead of dedicated programs to develop relay models. For example, MATLAB, distributed by The Math Works Inc., is a high powered numerical computation and visualization software package.

The MATLAB software combines signal processing, numerical analysis, matrix calculations and graphics into an easy-to-use processing package. Problems and solutions are presented as they are written mathematically. The program is an interactive system whose basic elements are matrices which do not require dimensioning. This allows for the processing of numerous calculations and solutions in a relatively short period of time.

MATLAB Relay Simulation

Figure 2 shows a block diagram of the relay modeling process. Digitally sampled data (23,040 samples per second) is derived using an EMTP model of the power system. Currents and voltages are extracted from the EMTP output file for the particular nodes of interest to an ASCII data file. The sample rate is reduced to 7680 samples per second using a MATLAB program which decimates the digital data to remove any aliasing effects. The 7680 sample per second data is used in the MATLAB relay simulation.

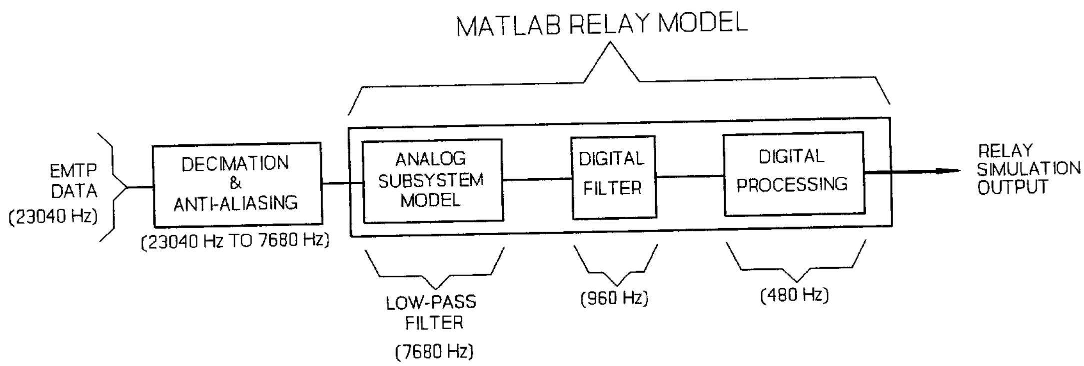

Figure 2: MATLAB Relay Model Block Diagram

The model includes the analog filter, the digital filter, and critical relay algorithms. The input data used by the relay model is processed the same manner as the actual relay and provides graphical outputs for the overcurrent elements, distance elements, phase selection logic, and sequence components. A brief description of each step of the simulation process follows.

The relay model processes the sampled data through an analog filter model which is equivalent to the analog filter used in the actual relay. The output of the analog filter model is the 16 sample per cycle data used by the digital filter. This is equivalent to the analog filtering and analog to digital conversion process performed in the relay (analog subsystem model shown in Figure 2).

The 16 sample per cycle data output from the analog subsystem model is processed by the digital filter model. The performance of the digital filter model is identical to the digital filter used in the actual relay. The output of the digital filter model is used by the relay model algorithms. The relay algorithms are processed eight times per cycle, as in the actual relay.

The relay model performs the same algorithms and calculations as the true relay, therefore, settings are required. The relay model settings are nearly the same as the actual relay. Figure 3 shows an example of the relay simulation settings. As in the actual relay, settings for overcurrent elements, distance elements, and directional elements determine how the relay responds to given fault conditions.

```
ID    = BCH 5L41 - CBN TERM : 75
R1    =   0.80  X1    =  10.01  R0    =   6.17  X0    =  37.25
LL    = 271.19  CTR   = 500.00  PTR   =4500.00
Z1P   =   0.90  Z2P   =  30.00  Z3P   = -30.00  Z4P   =  50.00
50PP1=    3.00  50PP2=    2.00  50PP3=    1.00  50PP4=    2.00
Z1MG  =   0.90  Z2MG  =  30.00  Z3MG  = -30.00  Z4MG  =  50.00
XG1   =   0.90  XG2   =  30.00  XG3   = -30.00  XG4   =  50.00
RG1   =   6.00  RG2   =   6.00  RG3   =  -6.00  RG4   =  40.00
50L1  =   3.00  50L2  =   2.00  50L3  =   0.50  50L4  =   2.00
50G1  =   1.20  50G2  =   0.50  50G3  =   0.25  50G4  =   0.25
50Q1  =   1.20  50Q2  =   0.60  50Q3  =   0.25  50Q4  =   0.25
K01M  =   0.92  K01A  =  -6.60  K0M   =   0.92  K0A   =  -6.60  T     =   0.00
EOSS  =      N  OSBD  =  30.00  OSTD  =  10.00  TOWOD=   20.00
X3P5  =  32.00  X3M5  = -20.00  R3P5  =  10.00  R3M5  = -10.00
X3P6  =  34.00  X3M6  = -22.00  R3P6  =  12.00  R3M6  = -12.00  50ABC=    0.50
ELE   =      Y  ZLF   =  10.00  ZLR   = -10.00
PLAF  =  30.00  NLAF  = -30.00  PLAR  = 150.00  NLAR  = 210.00
Z2F   =   0.00  50QF  =   0.60  Z2R   =   0.50  50QR  =   0.25  a2    =   0.06
Z2PD  =   0.00  Z3PD  =   0.00  Z4PD  =   0.00
Z2GD  =   0.00  Z3GD  =   0.00  Z4GD  =   0.00
50H   =  12.60  50M   =   1.00  50PO  =   0.05  59QL  =  14.00  59PL  =  14.00
ELOP  =      Y  LOPD  =   3.00  SPOD  =  20.00  3POD  =   0.25
```

Figure 3: MATLAB Relay Model Settings

The simulation provides two types of graphical outputs. The first, as shown in Figure 4, shows the status (on or off) of various elements within the relay model (refer to Appendix 1 for a key the MATLAB relay model element output). This graph is similar to an event recorder showing status of several elements during a fault simulation. This output is useful for showing when measured quantities pass set thresholds. However, the type of graph shown in Figure 4 does not show the margin between the measured quantity and the threshold settings as demonstrated by the "pseudo-output" of Garrett's model.

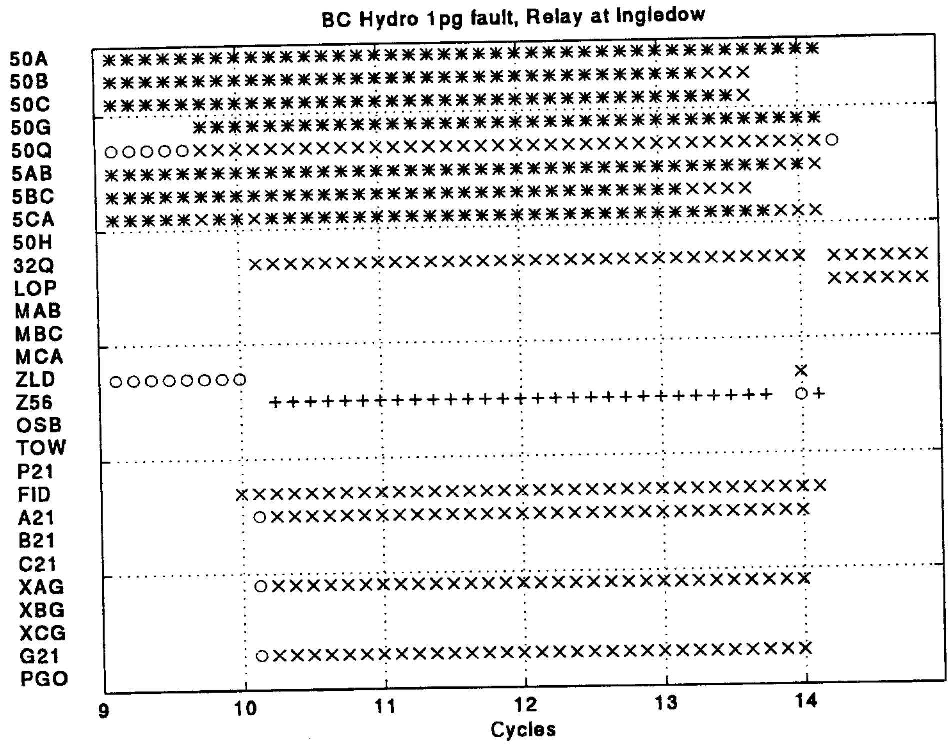

Figure 4: MATLAB Relay Model Element Output

Margins are shown by a second type of graphical output as shown in Figure 5. This figure shows the measured impedances of the A-phase, B-phase, and C-phase to ground mho-distance elements for an internal phase-to-ground fault. The vertical axis is the distance element measured impedance in secondary ohms. The horizontal axis is time in cycles. The horizontal dash-dot lines shown in Figure 5 indicate the set thresholds of the various distance element zones.

This type of plot shows the measured impedance for all of the ground distance elements. Even though the B-phase and C-phase ground distance elements show a negative measured impedance, they are blocked by directional elements and do not operate. This is shown in Figure 4, only the A-phase ground distance element operates.

As described in Reference 13, a single measured value of impedance may be used to determine whether the impedance lies within a mho element characteristic which plots as a circle on an R-X diagram. Thus, the distance between the measured impedance and the threshold shown in Figure 5 may be used to determine a margin between operation of various elements for a given fault simulation.

The data on these graphs allow optimizing the relay settings to accomplish the best possible performance for the application. The relay is also evaluated on the basis of whether or not it can meet the application requirements. Relay sensitivity, selectivity, and security for different fault types, locations, and system operating conditions are also evaluated.

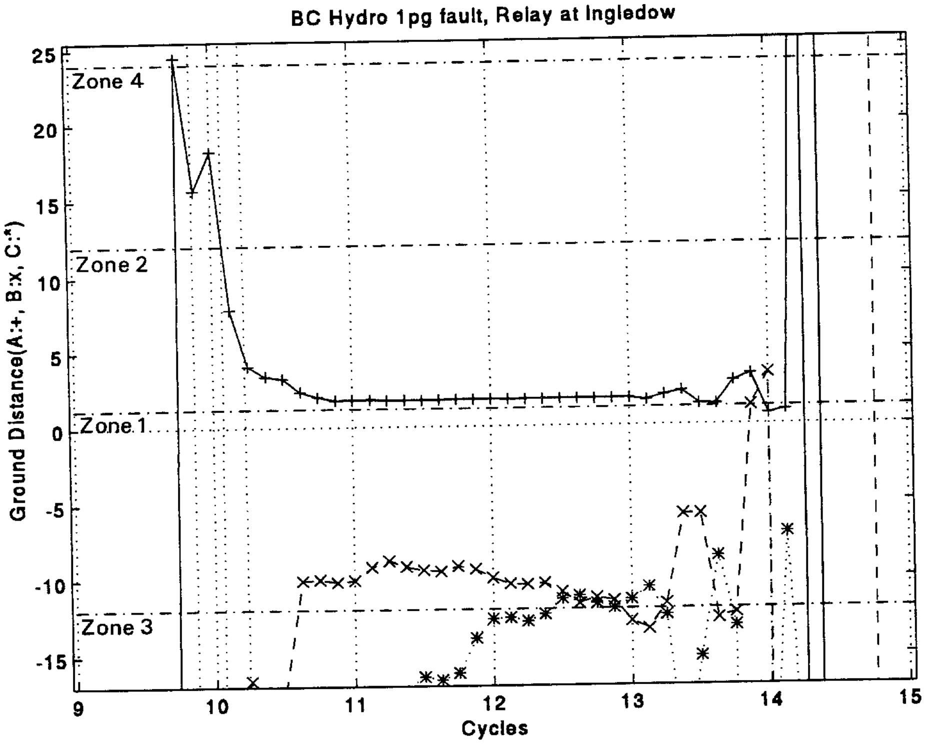

Figure 5: MATLAB Relay Model Ground Distance Element Reach Plot

APPLICATION ON B.C. HYDRO 500 kV LINES

The MATLAB relay model was used for application studies on three B.C. Hydro 500 kV transmission lines. These lines are part of a common 500 kV transmission system as shown in Figure 6. The bold lines shown in Figure 6 are the new lines and substations involved in this project.

The Williston-Kelly Lake project involves the addition of 5L13 in parallel with existing circuits 5L11 and 5L12. 5L13 is being added to increase North-South power transfer capability, and decrease the possibility of a North-South system separation. This also required 5L13 be equipped with single-phase tripping and reclosing. Line 5L13 is to be series compensated with a mid-point series capacitor bank.

The two new lines, 5L40 and 5L41, result from looping existing circuit 5L41 into Clayburn substation. This project will strengthen the existing 230 kV transmission system in the Fraser Valley area.

The protection of the three transmission lines (5L13, 5L40, and 5L41) introduce some difficult and unusual protection challenges. These include:

- Series compensation, which in the case of 5L41 is a non-midline location, with approximately 58% compensation. The compensation is expected to be increased to 75% in the future.

- Single-pole tripping and reclosing coupled with the requirements of faulted phase selection and tripping for high resistance (300 Ω) ground faults.

- Unequal transmission line phase transpositions on 5L40 and 5L41. This causes high pre-disturbance, load-derived, negative- and zero-sequence current flows.

The protection of the three transmission lines is further complicated by several control features.

- Bypass sequence of the capacitor banks where only the faulted phase is bypassed during a single-pole reclose operation and time reinserted after the transmission line is successfully reclosed. This causes a series imbalance in the line after reclosure until the capacitor is re-inserted.

- Point-on-wave closing of line circuit breakers to reduce switching surges (in lieu of applying closing resistors).

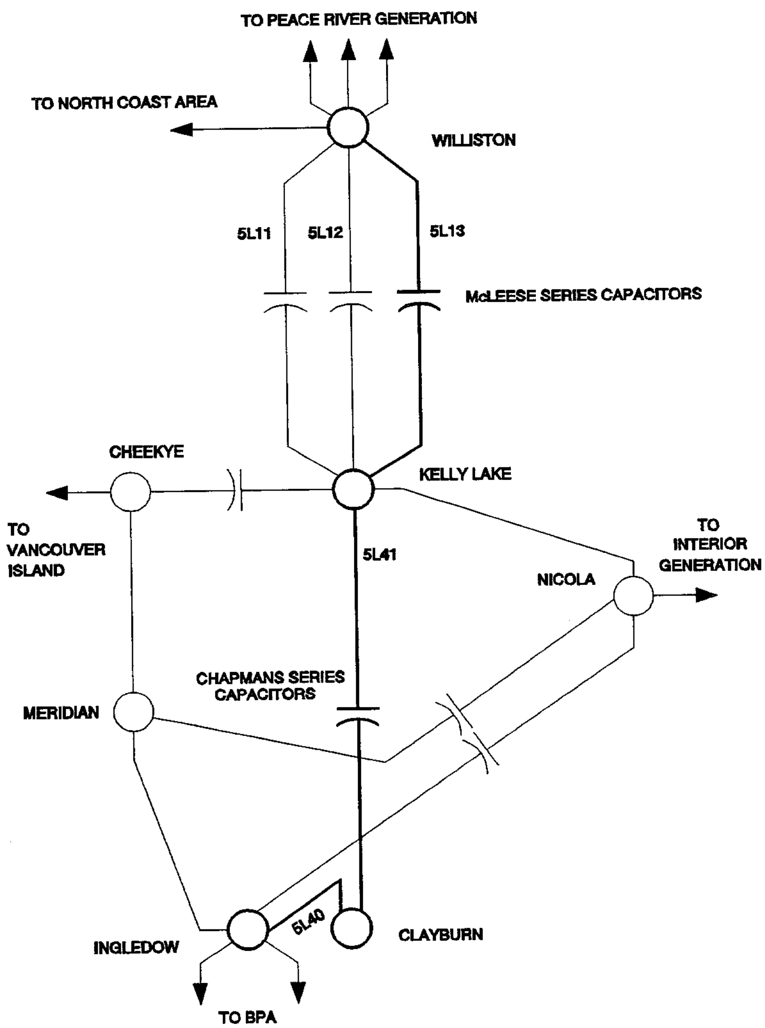

Figure 6: B.C. Hydro 500 kV System (Simplified Representation)

Simulation and results

EMTP fault cases used in the MATLAB relay model simulations cover a wide range of relay performance issues and system operating conditions. These included single-phase to ground faults with fault resistance up to 300 Ω, high load-flow conditions, series compensation, and single-pole trip conditions considering both correct phase selection and security during the open-pole period.

The MATLAB simulation allows the engineer to determine exact performance issues and problems. For example, one can determine the response of a distance element which may cause a potential misoperation due to overreaching caused by system transient conditions. Quantities can be observed which determine the relays ability to detect certain fault conditions, in this case, fault resistance of up to 300 Ω. Settings for particular elements can also be optimized.

This is all accomplished before relay performance tests start. Therefore, when the relay is subjected to a full performance test, settings for particular elements are already optimized. The internal relay logic is tested - not the settings.

Following are three examples of how the MATLAB simulation helped optimize relay settings and gauge relay performance before performance tests were done.

Example I

The purpose of this example is to show how the MATLAB relay model is used to set the Zone 1 phase distance elements. The Zone 1 distance element must be set so as not to trip for external faults.

This example shows the 75% compensation level on the 5L41 line. With this level of series compensation, the positive-sequence line impedance is 2.5 Ω secondary.

The MATLAB relay simulation phase distance element plot is used to determine the minimum measured impedance for out-of-section faults, close-in to the remote bus. These plots show a fault initiation at a particular point on the A-phase voltage wave. Analyses are also performed for different points on wave to compare results and determine the optimal setting for the Zone 1 distance element. The horizontal dash-dot line shown in the following figures give the actual Zone 1 distance element settings at the respective line terminal. The vertical axis is the measured impedance in secondary ohms. The horizontal axis is time in cycles.

Figure 7 shows the phase distance element reach plot for an out-of-section, three-phase fault near the Kelly Lake bus as viewed from Clayburn.

Figure 8 shows the phase distance element reach plot for an out-of-section, three-phase fault near the Clayburn bus as viewed from Kelly Lake.

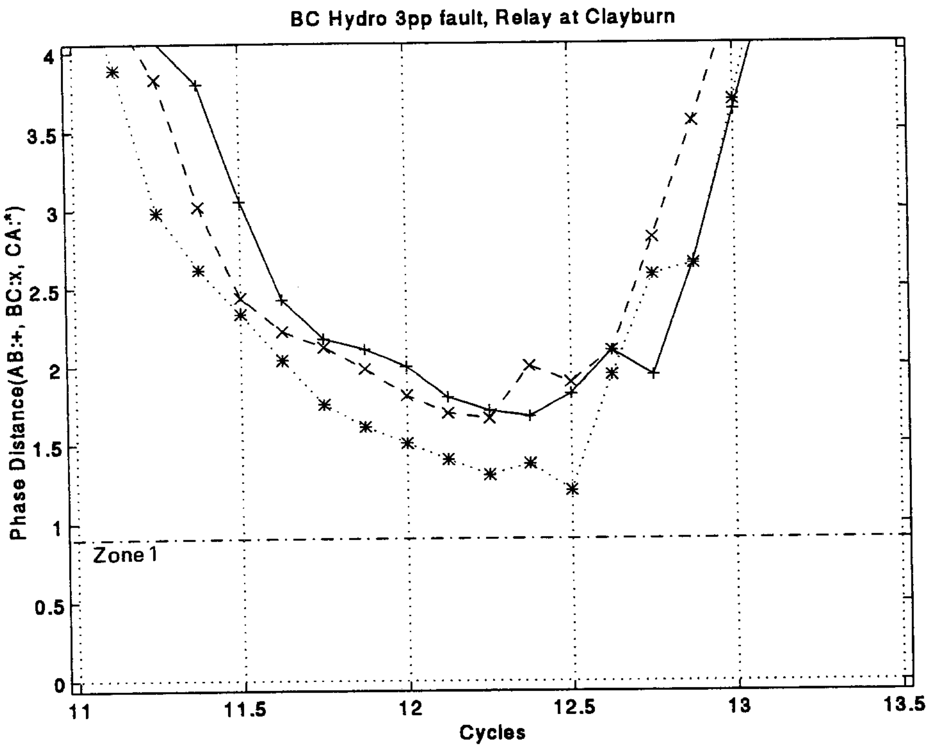

Figure 7: Phase Distance Element Reach Plot: Clayburn Terminal

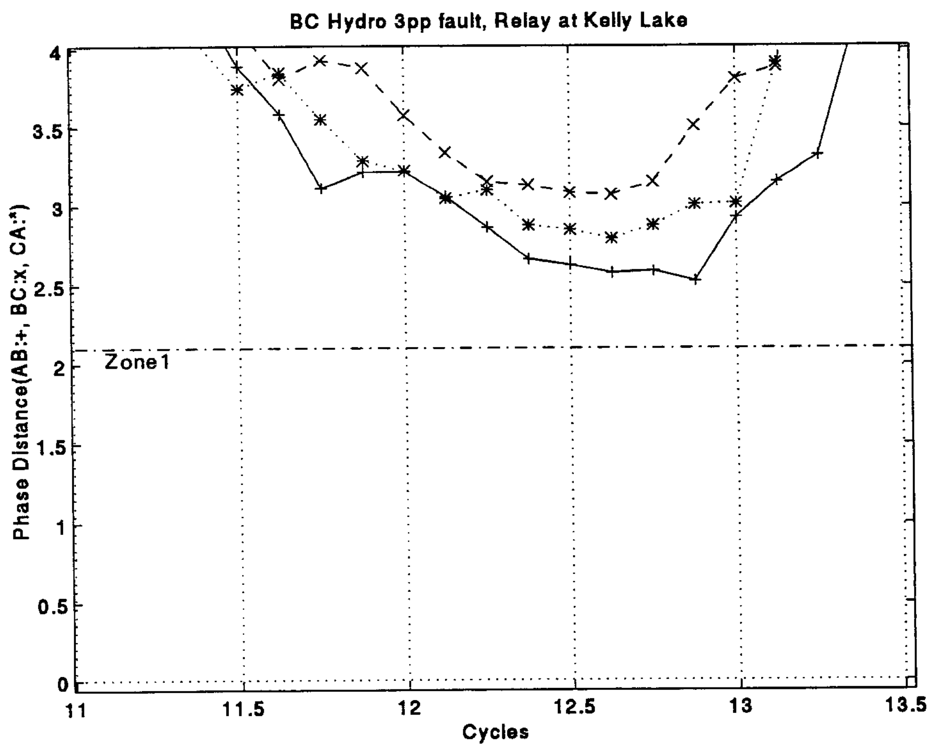

Figure 8: Phase Distance Element Reach Plot: Kelly Lake Terminal

Notice that each of the phase-phase distance elements at both of the line terminals measure a different impedance to the fault point. This difference is as much as 0.4 Ω. This is caused by the uneven transposition of the line due to the new line terminations at Clayburn substation.

Also, the measured impedance for a fault at remote bus differs from each line terminal. The measured line impedance from Clayburn is actually much less than the expected positive-sequence line impedance. The minimum measured impedance is approximately 1.2 Ω. From the Kelly Lake terminal the minimum measured impedance is as expected (approximately 2.6 Ω). This is due to the transient response of the series capacitors, coupled with the difference in the sources at Kelly Lake and Clayburn.

From these two plots, we are able to determine the actual measured impedance and set the Zone 1 element less than the measured impedance shown by the plots.

Example II

Figures 9 and 10 show plots of the negative-sequence directional-element calculation. Figure 9 shows the measured negative-sequence source impedance for fault directly in front of the Williston terminal of the 5L13 line. Figure 10 shows the same type of plot for a fault at the end of the line.

In both figures, the broken lines show the thresholds of the reverse (upper line) and forward (lower line) negative-sequence directional element. The vertical axis is the measured negative-sequence impedance. The horizontal axis is time in cycles.

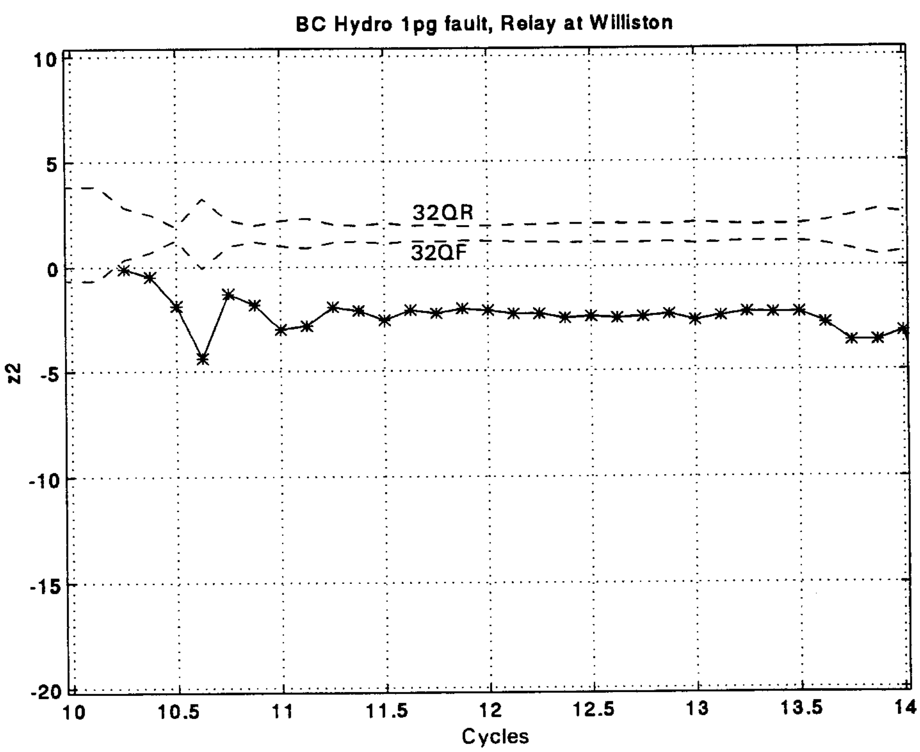

Figure 9: Negative-Sequence Directional Element Plot - Close-in Fault

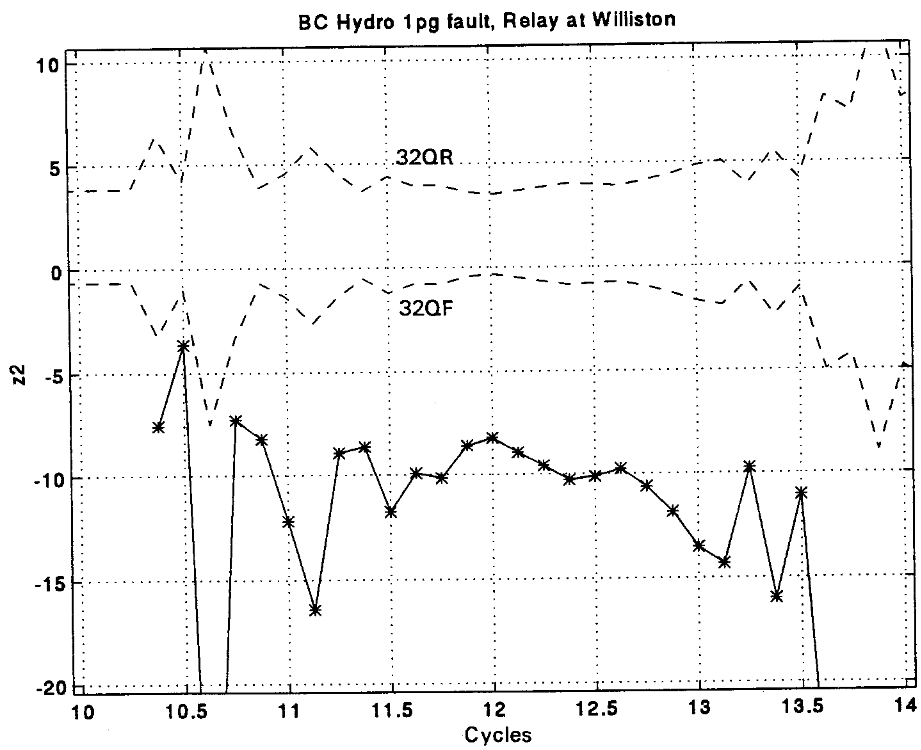

Figure 10: Negative-Sequence Directional Element Plot - Remote Fault

The principle on which these elements operate, by measuring the negative-sequence source impedance, is explained in Reference 13. In both figures, the measured impedance is less than the threshold for the forward element, indicating that the directional element correctly sees a forward fault.

We would expect the negative-sequence source impedance for these faults to be approximately the same. However, due to the parallel line configuration, the negative-sequence currents for the remote fault are split between the three lines, thus causing a larger apparent negative-sequence source impedance. The graphical presentation of the negative-sequence source impedance illustrates how the negative-sequence directional element operates and improves the utility engineers understanding of how to set the directional element.

Example III

Our final example shows an interesting condition that exists due to the series capacitor control sequence following a trip-reclose line operation. Briefly, for any line trip condition, one or more phases are of the series capacitor is bypassed during the open-pole period and re-inserted after the line has successfully reclosed.

Figure 11 shows a plot of positive-sequence impedance trajectory (shown by an "*") on an R-X type diagram for a three-pole trip and reclose operation. When the capacitor is re-inserted, the positive-sequence impedance oscillates for a number of cycles before it reaches a steady-state condition. The arrows in Figure 11 show the direction the positive-sequence impedance trajectory moves for the fault condition and the load oscillations. The impedance circles shown are the steady-state characteristics of the various mho-distance elements and are provided for illustration only.

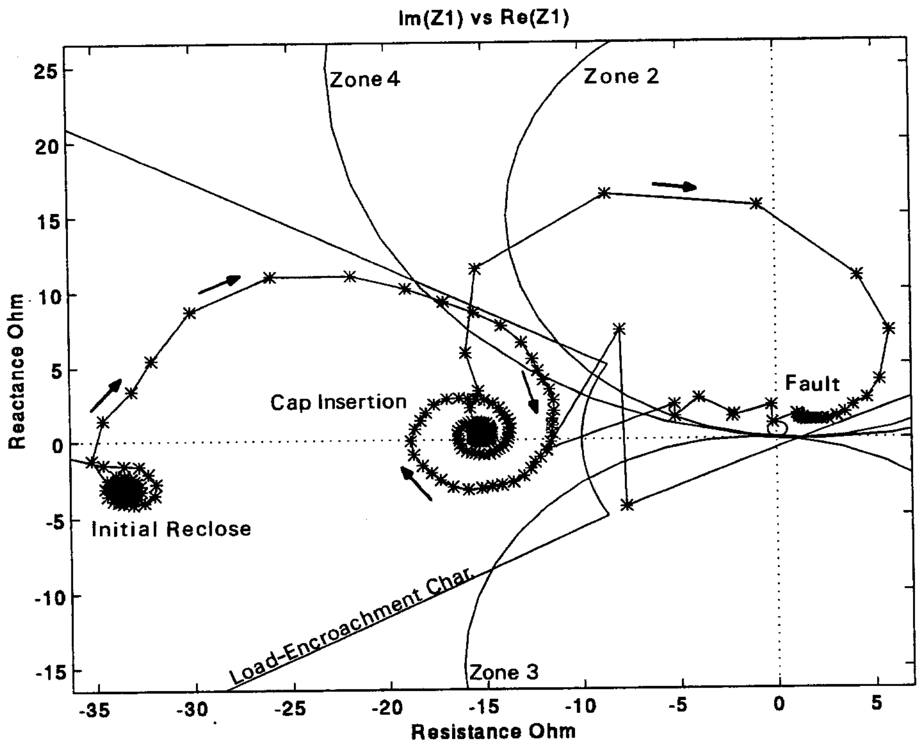

Figure 11: Positive-Sequence Impedance Plot

Initially this occurrence does not appear to have a critical impact on the protective relaying aspects. However, Figure 12 shows the phase-distance reach plot at the time of capacitor re-insertion. Notice that the Zone 2 distance element is very close to operating and that the measured impedance is actually less than the Zone 4 setting threshold.

From Figure 11 we observe that the positive-sequence impedance stays within the load-encroachment characteristic. This prevents the phase-distance elements from operating on the load oscillations.

Figure 13 shows the MATLAB relay model element output. Notice that no phase distance elements have operated. Again, this is due to the load-encroachment logic properly blocking them on the load swing.

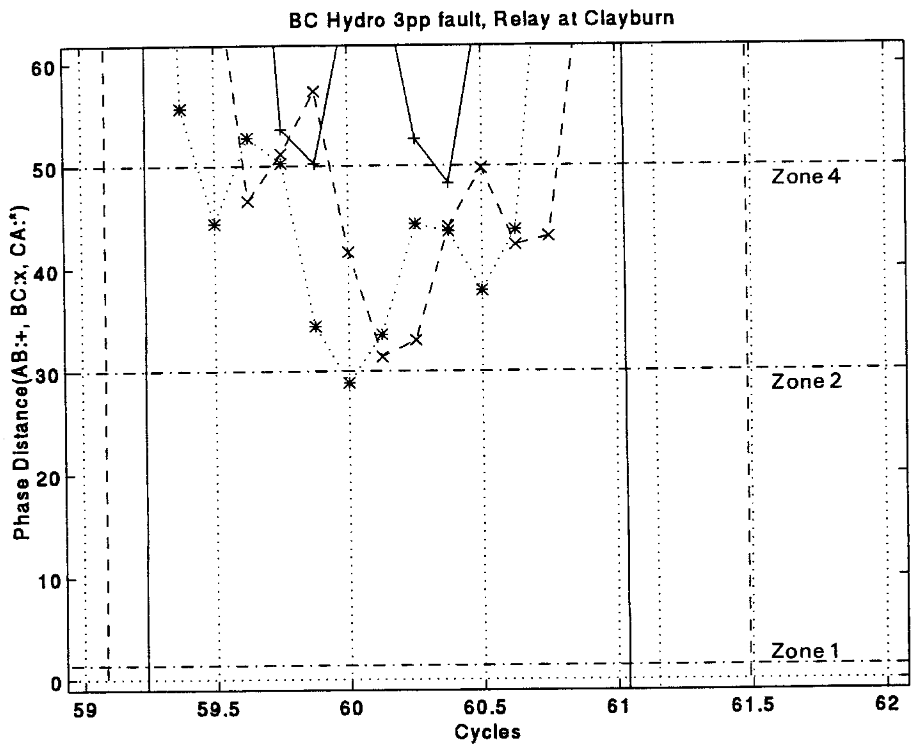

Figure 12: Phase Distance Reach Plot - Capacitor Insertion

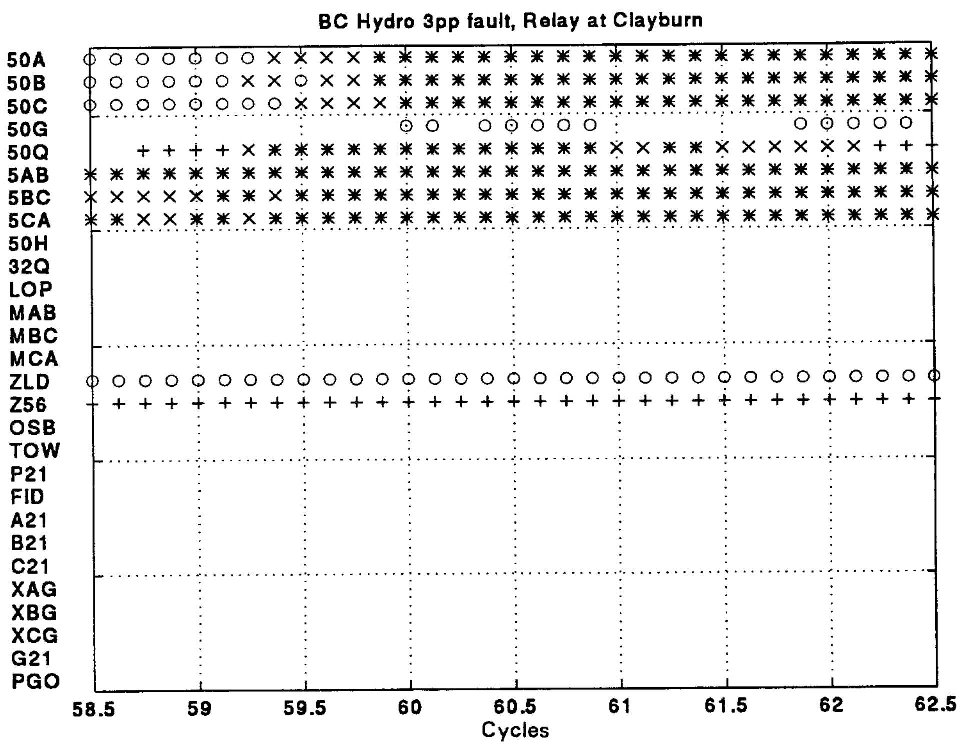

Figure 13: MATLAB Relay Model Element Plot - Capacitor Insertion

Model Verification

The relay model is verified using the same EMTP fault cases as those in the relay simulation tests. The EMTP output data is converted to a COMTRADE [14] format sampling at 3840 samples per second. The sampled data are converted to a low-level (±5 volt) analog signal using a 16-bit digital-to-analog convertor. The analog signals are connected to the same input in the relay as the isolation transformer secondaries. Therefore, the low-level analog signals are subject to all the same processing and conditioning for a nominal input (67V and 5A). Figure 14 shows a block diagram illustrating the test setup and also shows the conventional full-level input.

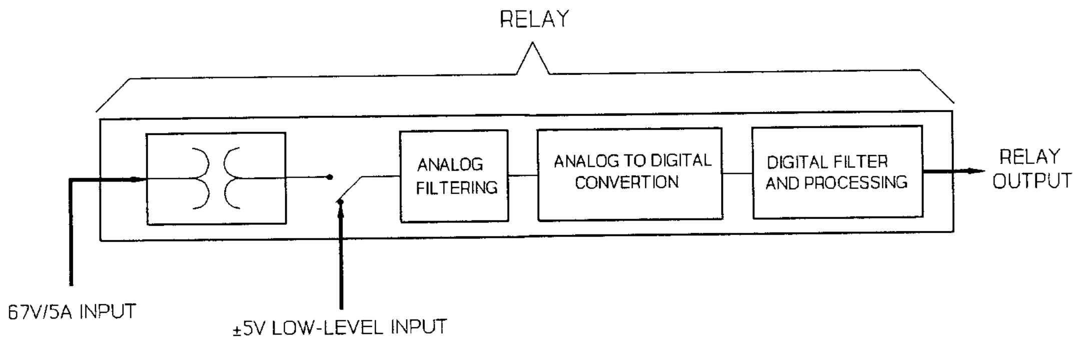

Figure 14: Model Verification Block Diagram

The performance tests verified the simulation results. In nearly all cases the relay simulation showed the same result as the actual relay. However, where the relay simulation only showed relay-element measuring response, the performance tests verified all relay logic and algorithms.

To illustrate how closely the relay model represents the actual relay response, the relay and model are set to a value which corresponds to the minimum calculated impedance shown in Figure 7. The Zone 1 element is set at 1.4 Ω secondary for this example. However, note that this setting would not be used in the actual application.

Figure 15 shows the four sample per cycle event report for this fault. The Zone 1 CA-phase distance element picks-up for a short period of time (as shown by a "1" in the ZCA column). Figure 16 shows the MATLAB relay model element output for the same fault. Notice that the relay model also shows the CA-phase distance element picking up in Zone 1 (as shown by "*" in the MCA row).

```
BCH 5L41 - CLAYBURN 75%                    Date: 08/30/93     Time: 13:04:38.265

FID=SEL-321-R100-V656112-D930210

  CURRENTS (pri)                   VOLTAGES (kV pri)        RELAY ELEMENTS   OUT   IN

                                                          ZZZZZZO  555566L 1357 1357
                                                          ABCABCO  31110770 &&&& &&&&
  IR     IA     IB     IC      VA       VB       VC       BCAGGGS  2NQPPNQP 2468 2468
                                        .
                                        .
 -65   1293    533  -1890  -172.1    -72.0    251.1 .......  ....M...  ....  ....
 100  -1570   1398    273   181.3   -233.3     59.9 .......  ....M...  ....  ....
  35   -205   -663    903   136.6     35.5   -179.9 .......  ....M...  ....  ....
 -73   1253    343  -1668  -110.4    182.9    -79.6 ..2....  ....M...  .4..  ....

  13  -1753   1195    570  -118.2     22.1    104.6 222....  Q...M.2.  .4..  ....
  33   -860  -2423   3315    41.8   -140.0    102.6 222....  Q...M.2.  .4..  ....
 -73   3445  -2463  -1055   108.7    -42.4    -79.4 222....  Q...M.2.  .4..  ....
 -43   1400   3383  -4825   -22.0    113.4    -95.0 222....  ....M...  .4..  ....

  73  -4480   4003    550   -87.4     37.7     65.0 222....  ....M...  .4..  ....
  23  -2450  -3175   5648    20.6   -103.3     86.4 222....  ....M...  .4..  ....
 -63   4615  -5040    363    72.8    -31.0    -58.3 222....  ....M...  .4..  ....
 190   3273   2183  -5265   -18.1    104.0   -106.6 221....  ....M...  BB.8  ....
                                                      |_______________________________ Zone 1
-153  -3725   4918  -1345  -101.2     19.9    110.4 222....  ....M...  BB.8  ....      CA-phase
-275  -3473   -218   3415    72.3   -160.2     88.4 222....  ....M...  BB.8  ....      Operation
 110   1348  -3835   2598   142.3     31.5   -197.6 222....  ....M...  BB.8  ....
  60   3405  -2078  -1268  -154.5    228.9    -55.5 222....  ....M...  BB.8  ....

   3   1138   2303  -3438  -169.7    -73.6    249.3 222....  ....M...  BB.8  ....
 115  -2928   3250   -208   200.3   -250.4     59.7 22.....  Q...M.2.  BB.8  ....
 135  -2295   -850   3280   185.2     79.0   -264.8 .......  ....M.2.  BB.8  ....
-148   1950  -3305   1208  -216.8    261.0    -53.5 .......  ....M...  BB.8  ....
```

Figure 15: Relay Event Report - Remote Three-Phase Fault

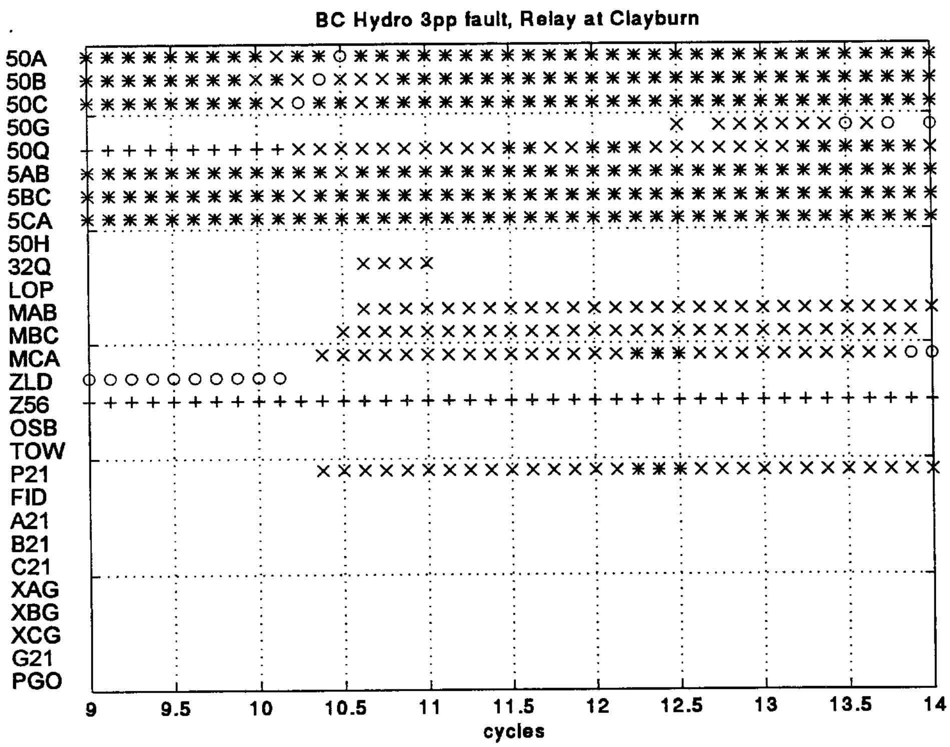

Figure 16: MATLAB Relay Model Element Output - Remote Three-Phase Fault

In some cases, as shown in Figures 15 and 16, the actual relay did not behave exactly like the MATLAB relay model. This is attributed to differences in sampling the waveform. The actual relay randomly samples points on the analog waveform 16 times per power system cycle. The MATLAB relay model uses the same data points time after time. Therefore, there are differences in digital data comparison between the two systems. One way to get a broader response from the model, is to initiate the fault with different relationships to the sampling clock.

SOME USES FOR RELAY MODELS

Utility relay engineers are often faced with the question "Can we have a three terminal line from here to there and there?", "Can we increase the series compensation on this line?", "Can we operate the power system in such and such a fashion?". These sort of questions are usually in the very early stages of considering particular options in power system development. It is often not practical to proceed with extensive and expensive relay performance testing to answer such questions. If computer-based models of various types of relays were available, it would be relatively easy to assess the performance of various types of protection under the condition to be studied.

Invariably, as existing power systems are stressed to their limit there are trade offs between operating speed and security for the associated protection systems. With the techniques described, these trade offs can be assessed with the relay models available.

In addition to new proposed system changes, system disturbance analysis can be extended by using field data to play back through the model. Field data could be in the form of digitally recorded information from a digital fault recorder or from an event record generated by the protective relay.

With increasingly complex protective relays available, utility engineers to a degree, are becoming relay development engineers given the range of adjustment and flexibility offered. The graphical presentation of measured quantities and thresholds help technicians and engineers understand how the relay works. They can "see inside" the relay. The model is a valuable training tool for all involved in application, design, testing, and maintenance of protection systems.

Occasionally, there may be a benefit even with routine applications which can be tested as to their desired result in the engineer's office prior to release to production.

FUTURE PROSPECTS

The relay models discussed so far have all been of the "open loop" variety. The fault simulation on the power system is not directly controlled by the relay response. The relay response (such as opening of circuit breakers) is estimated and then implemented in the data file defining the EMTP simulation. The EMTP simulation is then played back to the relay model, and the validity of the first estimation is checked. The process may sometimes require additional simulations to match the exact effect of the relay action on the power system.

It is preferable that the relay model and power system interact with each other during the fault simulation so that at each step during the power system transient solution, the effect of the relay model is taken into consideration. This interaction has at least two benefits:

- The occasional need for iteratively modeling the fault simulation to match the relay response is eliminated.

- The effect of the relay on the measured signal is taken into account. This effect cannot be shown with the relay model independent of the system model. For instance, the burden of an electromechanical inverse time-overcurrent relay is nonlinear. If the effects of ct saturation were to be included as part of the power system simulation, the nonlinear burden of the relay would also have to be included as part of the system model. The effect of ct saturation would then be properly represented in determining the relay performance.

Researchers are now expending a considerable amount of work to incorporate computer-based relay models into EMTP to work in an interactive way [15,16]. This work will allow simultaneous observation of both the transient signals effect on the relay and the relays effect on the state of the power system. Simulation of the interaction between the relay model and the power system will be similar to the type of closed looped performance testing of actual protection systems with digital model power systems that have just recently become available [6].

There are several impediments to the production use of relay models, not least of which is the proprietary nature of many of the protection algorithms used by relay manufacturers. It is difficult to see how program modules representing the relay could be released into the public domain. However, it should be possible for manufacturers to release "black box models" or equivalents of their relays for public use.

CONCLUSION

Computer-based models of relays are a relatively new tool in power system protection. This new tool is valuable:

- to reduce the need for transient testing of the relay. Since there are subtle differences between the models and the actual relay, transient testing is not eliminated, but time spent during such testing is reduced.

- to provide insights into the transient performance, which have never been available before. These insights lead to more reliable designs, applications, and settings.

- as a training tool to help users understand how the relay works.

The relay model offers an inexpensive alternative to model power system testing. When new operating conditions arise or complex system configurations are proposed, the impact of these changes on the protective relaying can be easily analyzed.

The effect of long-term system conditions (e.g., power-swings and single-pole open periods) can be examined. The response of the relay can be monitored for the entire time the condition exists, not just a "snap-shot" of when the fault occurs or power-swing starts.

Production versions of relay models which are able to interact with power system simulations are not widely available. It is probable that further research will increase the availability of such models. These models will be even more valuable then the existing "open loop" models.

When relay models are available to the end users, application and performance questions to manufacturers may be reduced. The benefits mentioned above will be more easily available to all. There are technical difficulties in making proprietary designs and algorithms available to the public in computer-based models. End user demand, and advances in code protection techniques and may help speed the resolution of these technical difficulties.

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APPENDIX 1 - SYMBOL DEFINITIONS FOR THE MATLAB RELAY MODEL ELEMENT PLOT

Overcurrent Elements

50A, 50B, 50C : Single-phase Overcurrent Elements, Ground Distance Supervision
5AB, 5BC, 5CA : Phase-phase Overcurrent Elements, Phase Distance Supervision
50G : Residual Overcurrent Elements, Ground Distance Supervision and Residual Overcurrent Levels
50Q : Negative-Sequence ($3I_2$) Overcurrent Levels

- * (asterisk) - Zone 1
- x (cross) - Zone 2
- + (plus) - Zone 3
- o (circle) - Zone 4

50H : High-set Phase Overcurrent Elements

- x - A-Phase Pickup
- + - B-Phase Pickup
- o - C-Phase Pickup
- * - Pickup on any two phases

Negative-Sequence Directional Element

32Q : x - Forward
o - Reverse

Loss-of-Potential Condition

LOP : x - Loss-of-Potential

Phase Distance Elements

MAB, MBC, MCA : * - Zone 1
x - Zone 2
+ - Zone 3
o - Zone 4

Load-Encroachment Logic Condition

ZLD : x - Load OUT Pickup
o - Load IN Pickup

Out-of-Step Positive-Sequence Impedance Elements

Z56	: +	- Zone 5 Pickup
	o	- Zone 6 Pickup

Out-of-Step Blocking Logic

OSB	: x	- Out-of-Step Block

Out-of-Step Tripping Logic

TOW	: x	- Trip on Way In and Out
	+	- Trip on the Way Out
	o	- Trip on the Way In

Phase Distance Element Output

P21	: *	- Zone 1
	x	- Zone 2
	+	- Zone 3
	o	- Zone 4

Faulted Phase Selection Logic

FID	: x	- A-Phase Selection
	+	- B-Phase Selection
	o	- C-Phase Selection

Mho Ground Distance Element

A21, B21, C21	: Mho Ground Distance Element
XAG, XBG, XCG	: Quadrilateral Ground Distance Element
G21	: Ground Distance Output (Mho or Quadrilateral)

*	- Zone 1
x	- Zone 2
+	- Zone 3
o	- Zone 4

Pole-Open Indication

PGO	: x	- A-Phase Open
	+	- B-Phase Open
	o	- C-Phase Open
	*	- All Poles Open