Transformer Protection – An Analysis of Field Cases

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ABSTRACT

The algorithms used in a microprocessor relay are a set of equations that comprise a mathematical model of the relay. The model residing in the relay processes the sampled currents and/or voltages input to the relay. When executed as a program in MATLAB®, the model can process the current and/or voltage samples of a simulation or the samples recorded in an event report to obtain the internal response of the relay. Consequently, the model doubles as both a design and a diagnostic tool in difficult applications. This paper shows how a transformer differential relay model is used with a simulation to determine what degree of CT saturation can be tolerated. The model is then used with the unfiltered samples obtained from field event reports to determine remedial settings.

INTRODUCTION

Microprocessor relays execute algorithms which are mathematical procedures that reside in the EPROM of the relay. The algorithms are a set of equations that comprise a mathematical model of the relay. The model accepts a set of sampled currents and/or voltages and produces the relay's internal response. In the relay, the model operates on the actual input samples. It can also reside in a computer program where it accepts a set of prerecorded samples of a simulation or the raw unfiltered samples of the event report. Consequently, the model is a design tool that doubles as a valuable diagnostic tool. This paper shows how a transformer differential relay model is used with a simulation to determine what degree of CT mismatch can be tolerated. The model is also used with the unfiltered samples obtained from field event reports to analyze the following cases:

- Differential response during high through fault current,
- Settings that will tolerate low current differential currents,
- Faulty CT wave form which caused a differential trip,
- Relay response to variation of the 2^{nd} harmonic content of transformer inrush currents found in individual phases.

Setting procedure and practices are then reviewed in light of the analysis of field cases.

THE RELAY MODEL

It is convenient to refer to the microprocessor transformer differential relay algorithms and logic collectively as the model. In the relay, the model is in machine code obtained from a C-language compiler. In the computer, the model is a set of equations in a MATLAB program. MATLAB is an interactive system whose basic data element is a matrix that does not require dimensioning. It allows you to solve numerical problems in a fraction of the time it would take to write the program in Fortran or C. The program reads an array of 260 unfiltered samples of each of six relay currents from an event report when the file name is entered. The samples constitute 1.25

cycles of pre-fault and 15 cycles of post-fault data. The TRCON, TAP1, TAP2, PCT2, SLP1, and O87P settings are also read. The program then calculates and plots the winding 1 and winding 2 currents, the percent differential operating current, the harmonic restraint, and the trip signal for each phase as a function of time. An alternate version reads and processes the current samples derived from a CT simulation. Figure 1 shows the filtering, tap scaling, and connection compensation for the currents of winding 1. An identical process is executed for winding 2 currents. Figure 2 shows the signals processed by the differential and harmonic blocking functions.

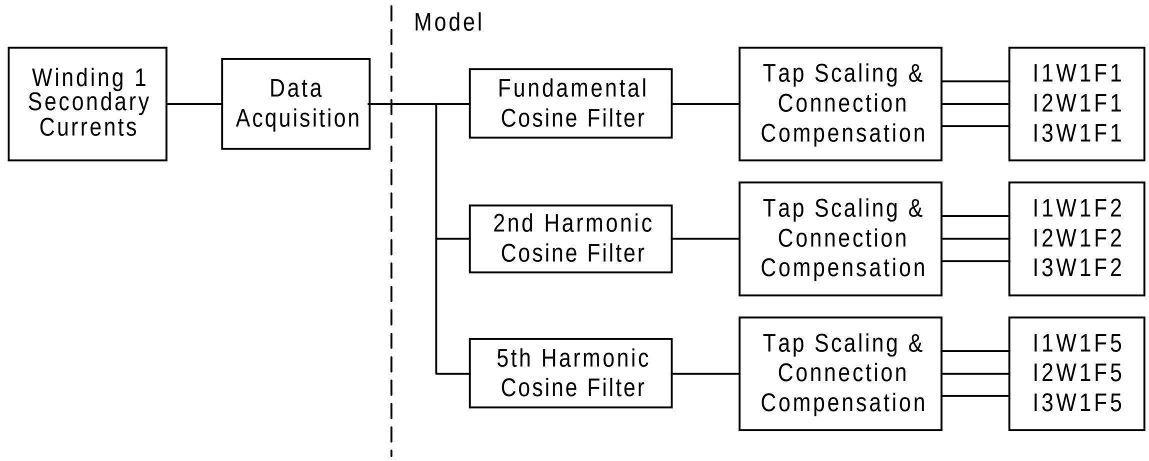

Figure 1: Data Acquisition and Filtering for Winding 1 Currents

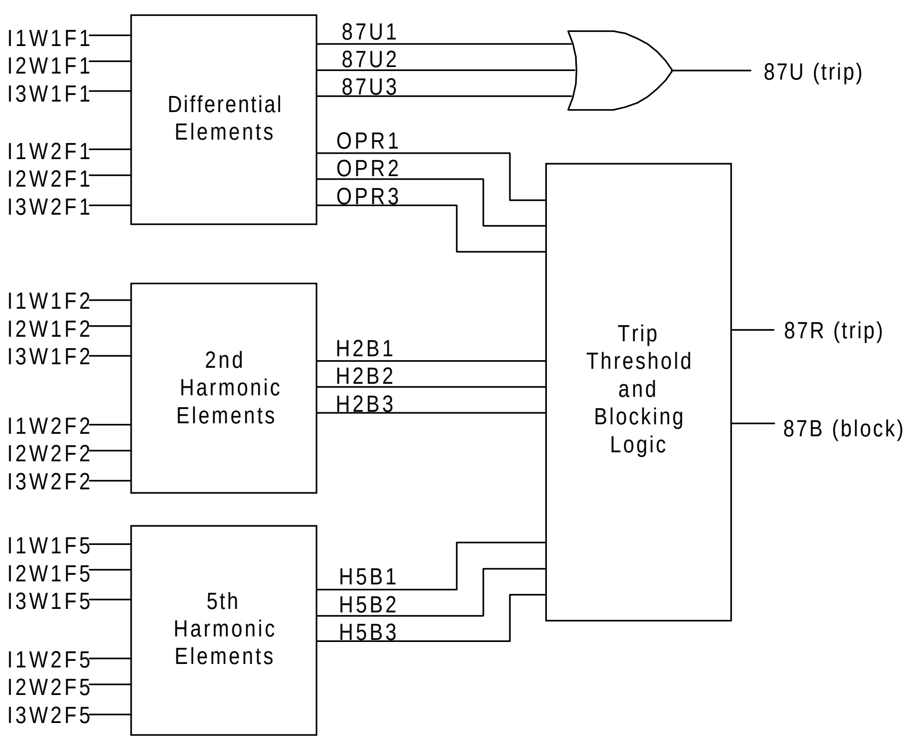

Figure 2: Differential and Blocking Elements

As shown in Figure 1, 16-sample/cycle cosine filters[1] extract the fundamental, 2^{nd} harmonic, and 5^{th} harmonic current phasor component. The components are then combined and scaled according to the tap and the transformer connection settings, TAP1, TAP2, and TRCON. The compensation for the setting TRCON = DABY is shown below where Vaw1, Vbw1, Vcw1, Vaw2, Vbw2, and Vcw2 are the fundamental current phasors of windings 1 and 2. A similar tap scaling and connection compensation is also calculated for the 2^{nd} and 5^{th} harmonic phasor components.

```
function [I1W1, I2W1, I3W1, I1W2, I2W2, I3W2] = daby(Vaw1, Vbw1, Vcw1, Vaw2, Vbw2, Vcw2)
% DABY returns wye currents for W1 and delta currents for W2

global TAP1 TAP2

% Winding 1 delta connection including tap

I1W1=Vaw1/TAP1;
I2W1=Vbw1/TAP1;
I3W1=Vcw1/TAP1;

% Winding 2 wye connection including tap

I1W2=(Vaw2-Vbw2)/TAP2/sqrt(3);
I2W2=(Vbw2-Vcw2)/TAP2/sqrt(3);
I3W2=(Vcw2-Vaw2)/TAP2/sqrt(3);
```

The operating and restraint quantities are derived as shown in the code below. The compensated winding 1 and winding 2 currents of each phase are added, and the magnitude of the result forms the operating signals IOP1, IOP2, and IOP3. The restraint signals IRT1, IRT2, and IRT3 are the average of the winding 1 and winding 2 currents. The ratio of these two quantities can then be compared to the percentage slope threshold setting SLP1.

```
% Operating & Restraint Signals

IOP1=abs(I1W1F1+I1W2F1);
IOP2=abs(I2W1F1+I2W2F1);
IOP3=abs(I3W1F1+I3W2F1);

IRT1=(abs(I1W1F1)+abs(I1W2F1))/2;
IRT2=(abs(I2W1F1)+abs(I2W2F1))/2;
IRT3=(abs(I3W1F1)+abs(I3W2F1))/2;

% Ratio of the Operate to Restraint Signal

OPR1=IOP1./IRT1;
OPR2=IOP2./IRT2;
OPR3=IOP3./IRT3;
```

Similar operating quantities are calculated for the harmonic components as shown for the 2^{nd} harmonic currents in the following code. The ratio of the harmonic currents to the fundamental can then be compared to the percentage 2^{nd} harmonic setting PCT2 and the percentage 5^{th} harmonic setting PCT5.

```
% Ratio of 2nd Harmonic to Fundamental

IOP1F2=abs(I1W1F2+I1W2F2);
IOP2F2=abs(I2W1F2+I2W2F2);
IOP3F2=abs(I3W1F2+I3W2F2);

H2R1=IOP1F2./IOP1;
H2R2=IOP2F2./IOP2;
H2R3=IOP3F2./IOP3;
```

MODEL OUTPUT

The output for each event is a plot of the CT currents in winding 1, a plot of the CT currents in winding 2, and the relay response for each phase. The relay response is a plot of the ratio of the fundamental differential to the restraint signal (OPR1, OPR2, or OPR3) and the ratio of the 2^{nd} harmonic differential to the fundamental (H2R1, H2R2, or H2R3) versus time. A trip asserts when the operate signal exceeds the slip threshold SLP1 for a predetermined sample count, and the harmonic signal is below the harmonic threshold PCT2. To produce a trip, the operating current must also exceed the minimum operating setting O87P. The thresholds SLP1 and PCT2 are also shown. The current samples and settings are read from an event report as in the sample shown below.

SAMPLE EVENT REPORT (PARTIAL)

```
S/N 96320037                            Date: 11/12/97   Time: 13:39:31.493
CLRKSVIL BK2


FID=SEL-587-R105-V5a-D950929

                                                        Relay Elements    OUT IN

           Winding 1                  Winding 2         555555 555555 888   A
           Amps Sec                   Amps Sec          111000 111000 777 13L 1
                                                        PQNPQN PQNPQN URB &&R &  Sample
  IRW1   IAW1   IBW1   ICW1   IRW2   IAW2   IBW2   ICW2 111111 222222   L 24M 2  number
   -
   -
   0.5   -1.5    3.3   -1.3    0.3    0.1    0.2    0.1 ...... ...... ..* ... . 53
   0.3   -0.5    1.2   -0.4    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.2    0.1   -0.1    0.2    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.2    0.1   -0.1    0.2    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.2    0.1   -0.1    0.2    0.4    0.2    0.2    0.1 ...... ...... ..* ... .
   0.3    0.2   -0.1    0.2    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.3    0.2   -0.1    0.2    0.4    0.2    0.2    0.1 ...... ...... ..* ... .
   0.3    0.4    0.2   -0.2    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.2    1.3    1.2   -2.3    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.2    2.4    2.1   -4.3    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.0    2.9    2.7   -5.6    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.0    2.1    4.1   -6.1    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.2    0.7    5.3   -5.8    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.2   -1.0    5.8   -4.6    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.4   -2.1    5.3   -2.8    0.3    0.1    0.2    0.1 ...... ...... ..* ... .
   0.4   -2.1    4.4   -1.9    0.3    0.1    0.2    0.1>...... ...... .** .3. . 68

   0.4   -1.5    3.0   -1.1    0.3    0.1    0.2    0.1 ...... ...... .** .3. . 69
   0.3   -0.4    1.0   -0.2    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.3    0.3    0.0    0.0    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.1    1.2    1.0   -2.0    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.1    2.2    2.0   -4.1    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
  -0.1    2.7    2.5   -5.2    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
  -0.1    2.0    3.8   -5.8    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.1    0.7    5.0   -5.6    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.1   -1.1    5.4   -4.3    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.3   -2.1    5.1   -2.6    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.5   -2.0    4.2   -1.7    0.3    0.1    0.2    0.1 ...... ...... .** .3. . 84
```

```
   0.3   -1.4    2.8   -1.1    0.3    0.1    0.2    0.1 ...... ...... .** .3. . 85
   0.2   -0.3    0.7   -0.2    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.2    0.1   -0.2    0.4    0.3    0.1    0.2    0.1 ...... ...... .** .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.2    0.1   -0.2    0.3    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.2    0.2   -0.1    0.1    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.1    1.1    0.8   -1.8    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.1    2.1    1.8   -3.8    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
  -0.1    2.6    2.3   -5.0    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.0    2.0    3.6   -5.6    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.1    0.7    4.8   -5.3    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.2   -1.1    5.3   -4.0    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.4   -2.1    4.9   -2.4    0.3    0.1    0.2    0.1 ...... ...... ..* .3. .
   0.3   -2.0    3.9   -1.6    0.3    0.1    0.2    0.1 ...... ...... ..* .3. . 100
   -
   -



Event: TRP3             Targets: 87 B C                Duration:   0.50 cyc
Winding 1 Currents (A Sec), ABCQN:    1.6    3.1    3.3    2.8    0.1
Winding 2 Currents (A Sec), ABCQN:    0.0    0.0    0.0    0.1    0.0

RID   =S/N 96320037
TID   =CLRKSVIL BK2
MVA   = 45.0     VWDG1 = 117.50   VWDG2 = 21.60
TRCON = YY       CTCON = YY       CTR1  = 100      CTR2  = 600
DATC  = 15       PDEM  = 2.2      QDEM  = 0.5      NDEM  = 0.5
TAP1  = 2.21     TAP2  = 2.00
IN1   = 52A1     IN2   = NA
O87P  = 0.4      SLP1  = 40       SLP2  = OFF
U87P  = 4.0      PCT2  = 15       PCT5  = OFF
TH5   = 0.3      TH5D  = 180.000  IHBL  = Y
50P1P = OFF      50P1H = 18.1
51P1P = 4.0      51P1C = U3       51P1TD= 2.00     51P1RS= Y
50Q1P = OFF
51Q1P = OFF
50N1P = OFF      50N1H = OFF
51N1P = OFF
50P2P = OFF      50P2H = 3.5
51P2P = OFF
50Q2P = OFF
51Q2P = OFF
50N2P = OFF      50N2H = OFF
51N2P = 0.5      51N2C = U3       51N2TD= 8.00     51N2RS= Y
LTRP  = N        TDURD = 10.000
TXPU  = 10.000   TXDO  = 0.000    TYPU  = 0.000    TYDO  = 3600.000
NFREQ = 60       PHROT = ABC
```

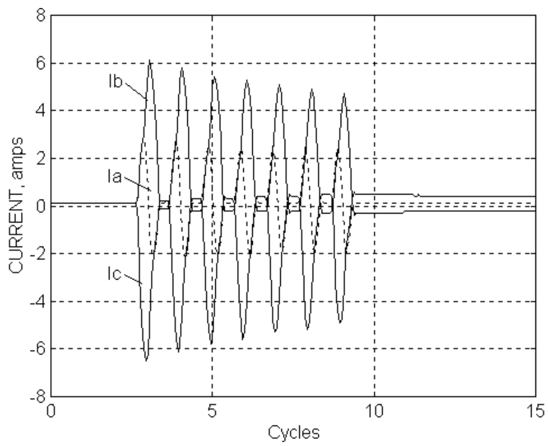

Figure 3: Current in Winding 1

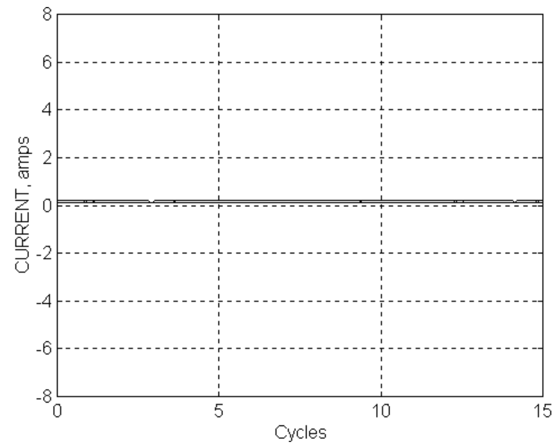

Figure 4: Current in Winding 2

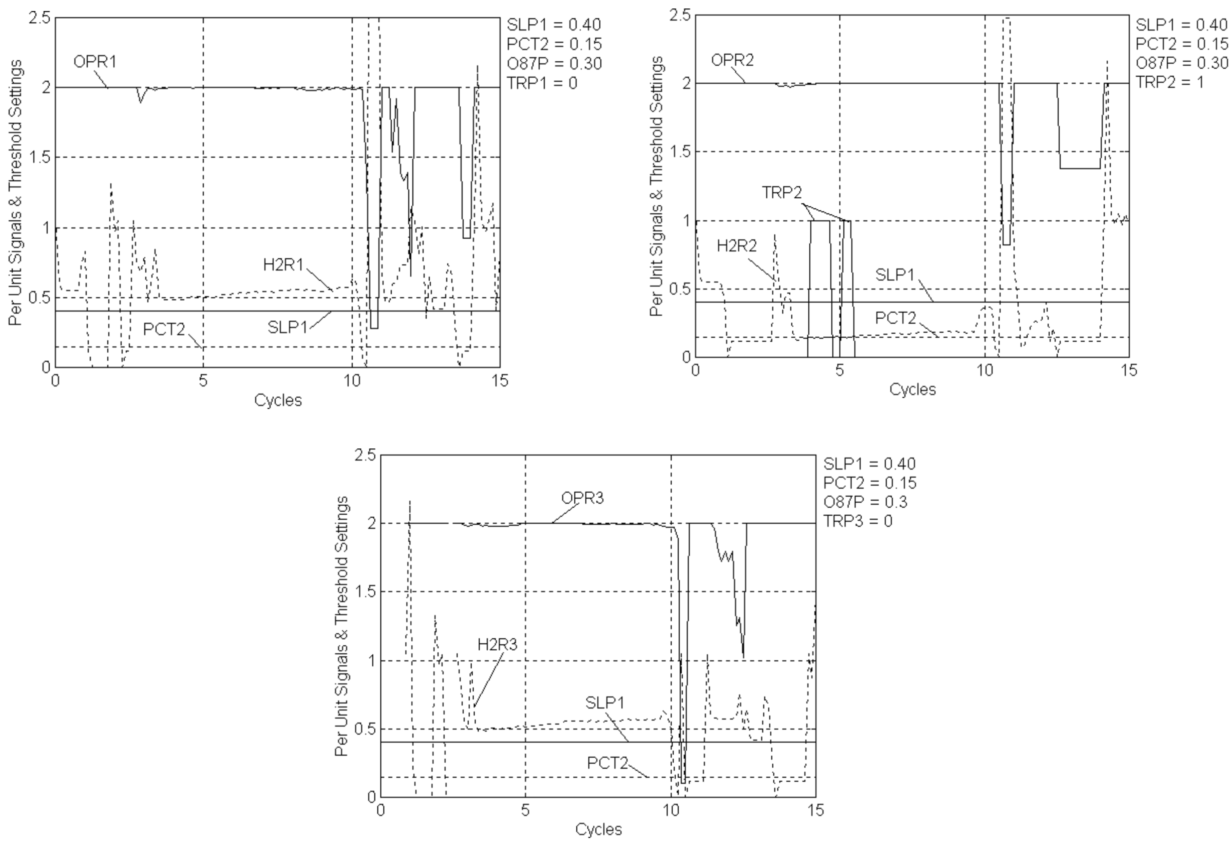

Figure 5: Relay Response in Phases A, B, and C

Case A: Trip During Inrush in a Delta-Wye Transformer - Figures 3 - 5

A trip occurs in B-phase due to a low content of 2nd harmonic. The trip occurs for the inrush current shown in Figure 3 where B and C appear equal in magnitude but opposite in phase. The 2nd harmonic is reduced in the subtraction of currents for the delta compensation. The problem is prevented by selecting the option to block the trip for the harmonic restraint in any phase.

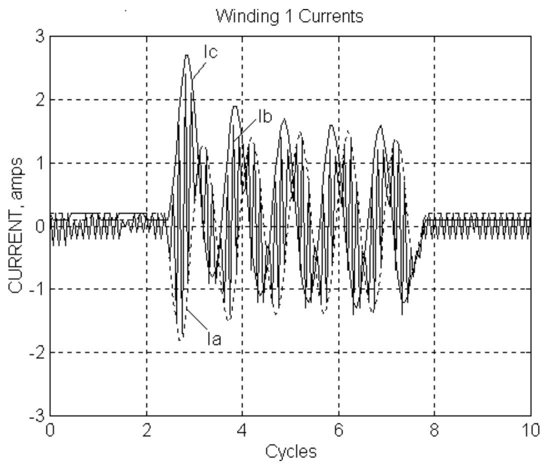

Figure 6: Current in Winding 1

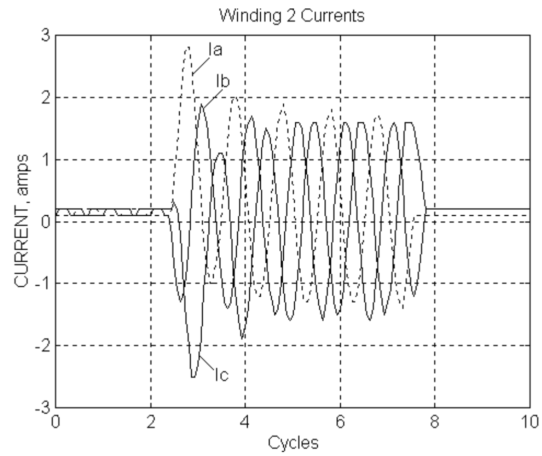

Figure 7: Current in Winding 2

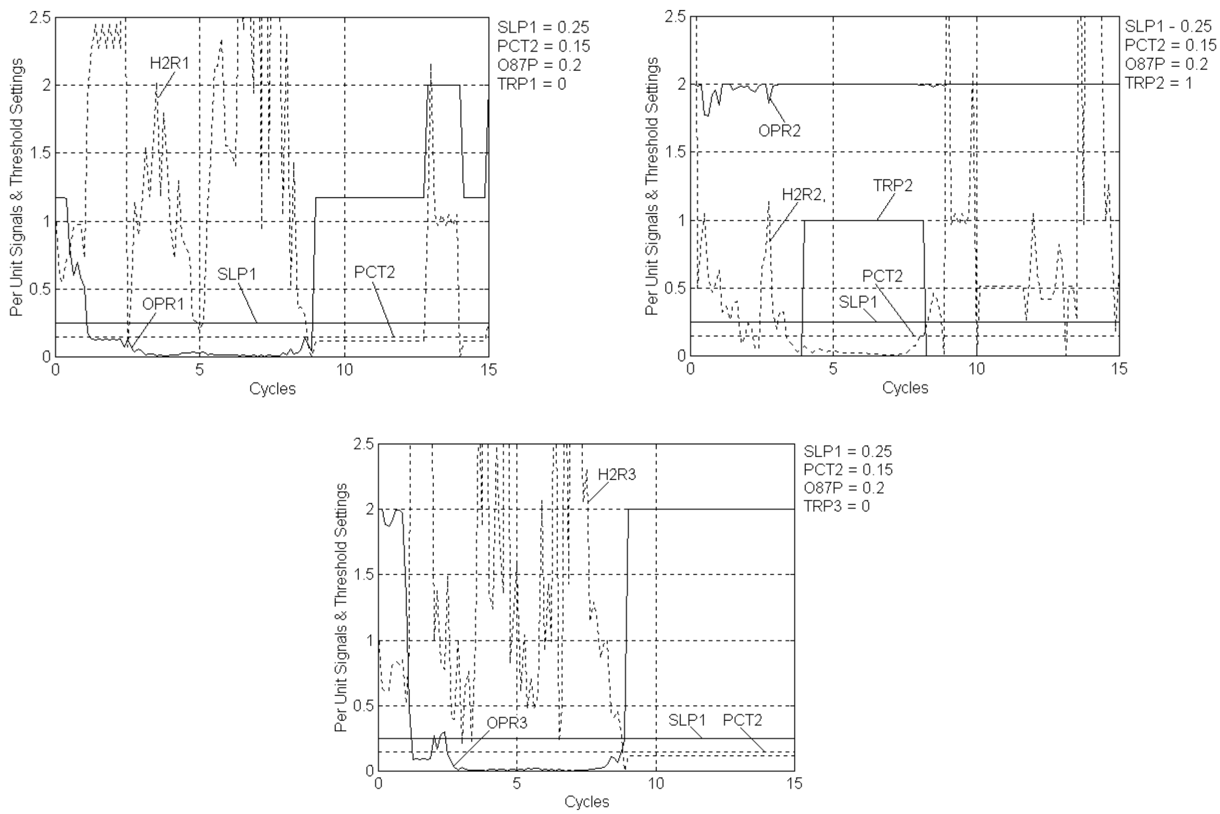

Figure 8: Relay Response in Phases A, B, and C

Case B: Differential Trip Caused by Faulty CT - Figures 6 - 8

This event captured a trip with normal load current caused by a faulty C-phase CT in winding 1. The intermittent current is evident is Figure 6. The B-phase relay response shows the differential signal OPR2 at the maximum value of 2 and the trip signal as a result of the faulty CT.

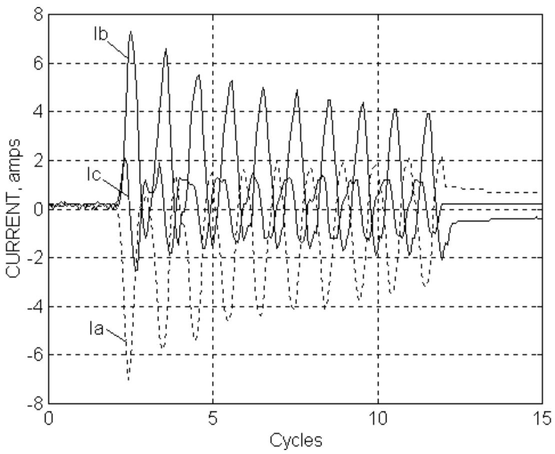

Figure 9: Current in Winding 1

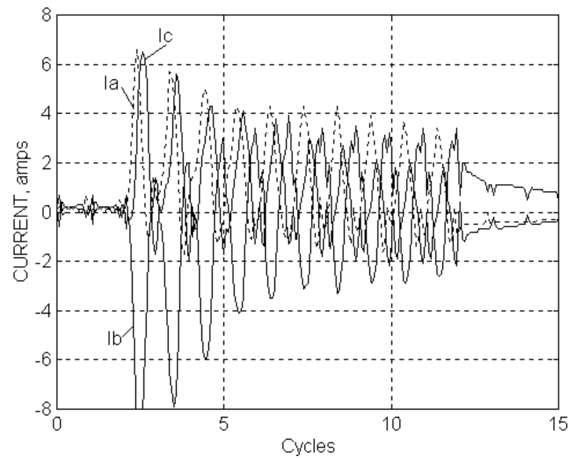

Figure 10: Current in Winding 2

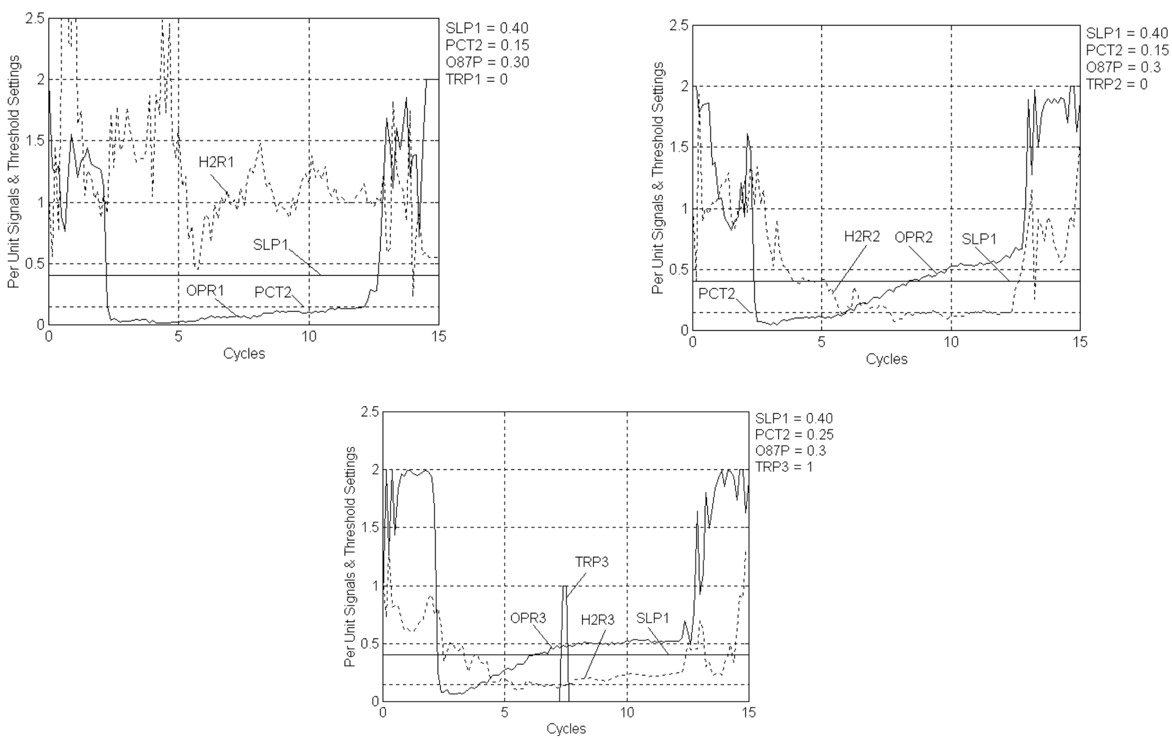

Figure 11: Relay Response in Phases A, B, and C

Case C: The Strange Case of the Growing Differential - Figures 9 - 11

As shown in Figures 9 and 10, the relay is subjected to the inrush current of a downstream arc furnace transformer. The Phase B and C differential current grows to exceed the 40 percent slope. The 2nd harmonic restraint blocks the trip in Phase B, but drops below the 15 percent setting to allow a trip in Phase C. The winding currents are distorted by the presence of a static var compensator as evidenced by the notches. As yet, no satisfactory explanation has been found for the differential current. However, the model shows that raising O87P to 0.5 prevents the trip.

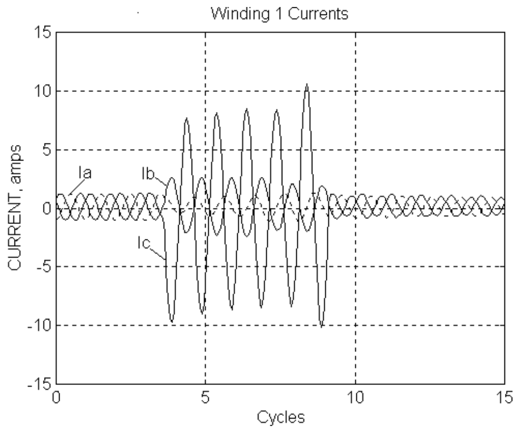

Figure 12: Current in Winding 1

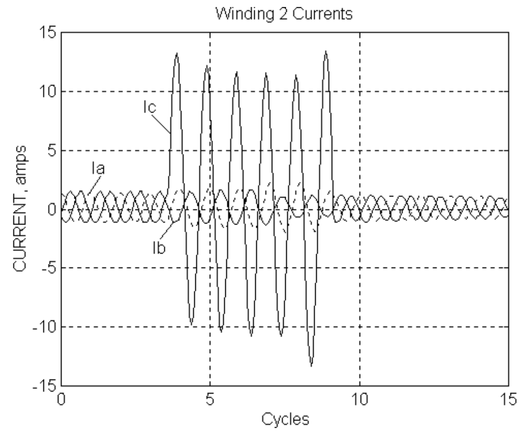

Figure 13: Current in Winding 2

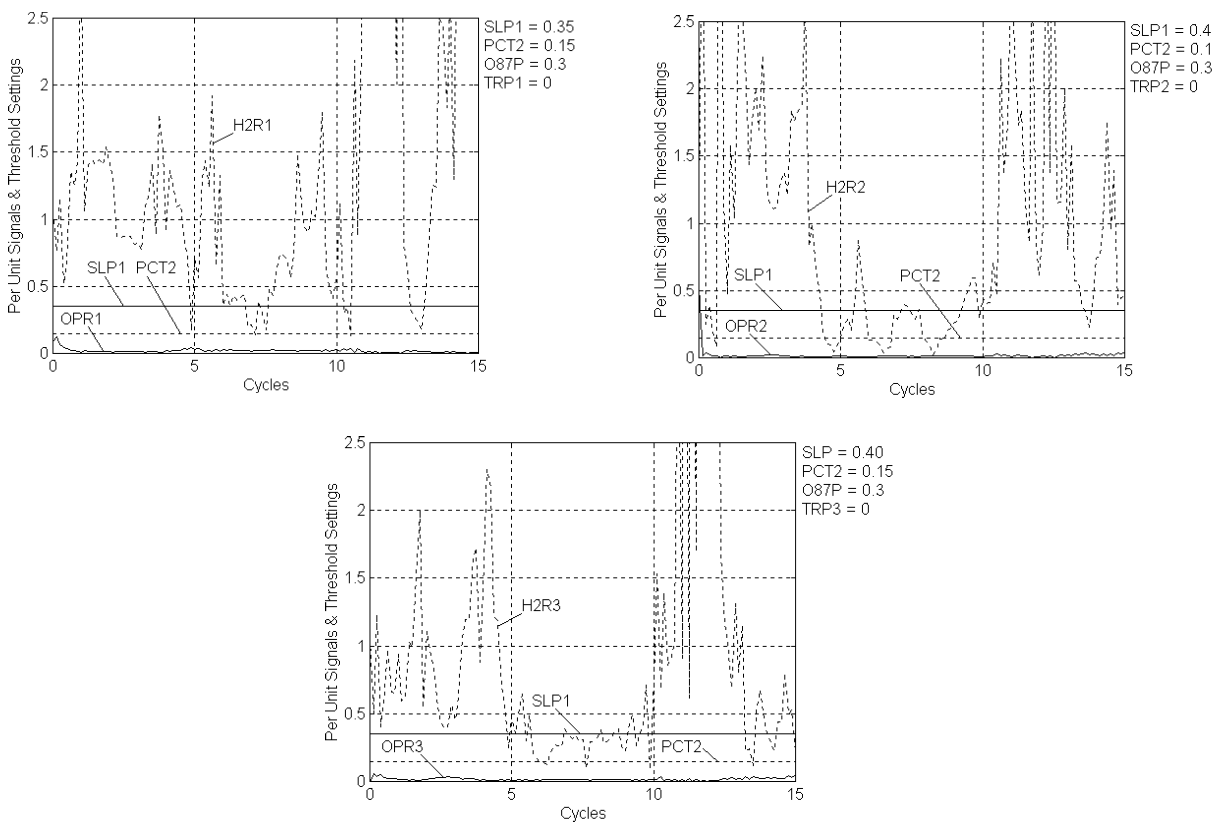

Figure 14: Relay Response in Phases A, B, and C

Case D: The Nominal External Fault - Figures 12 - 14

The currents in windings 1 and 2 (Figures 12 and 13) were the result of a C-phase fault external to the zone of a 112 MVA, 161/69 kV, YY connected transformer. The relay response in Figure 14 shows that percent differential signals OPR1, OPR2, and OPR3 are virtually zero. The case illustrates the expected performance using adequately rated CTs.

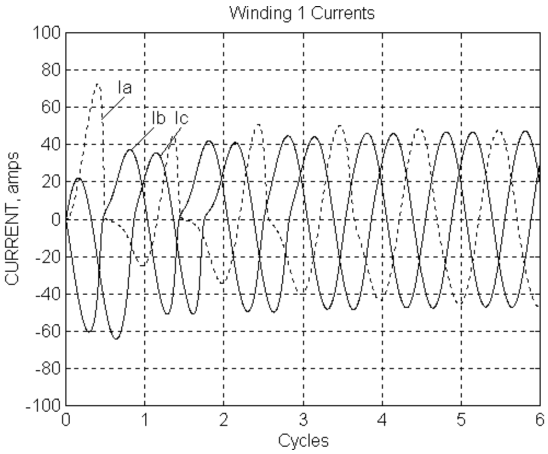

Figure 15: Currents in Winding 1

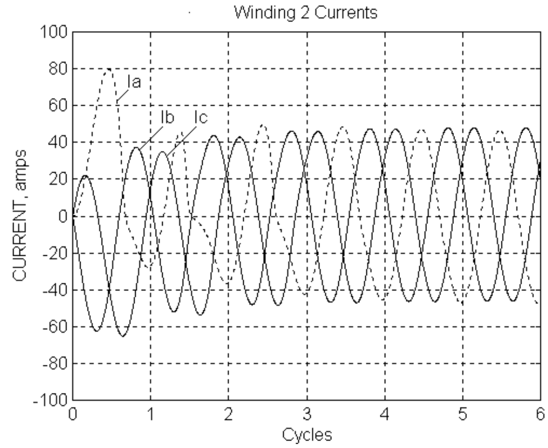

Figure 16: Currents in Winding 2

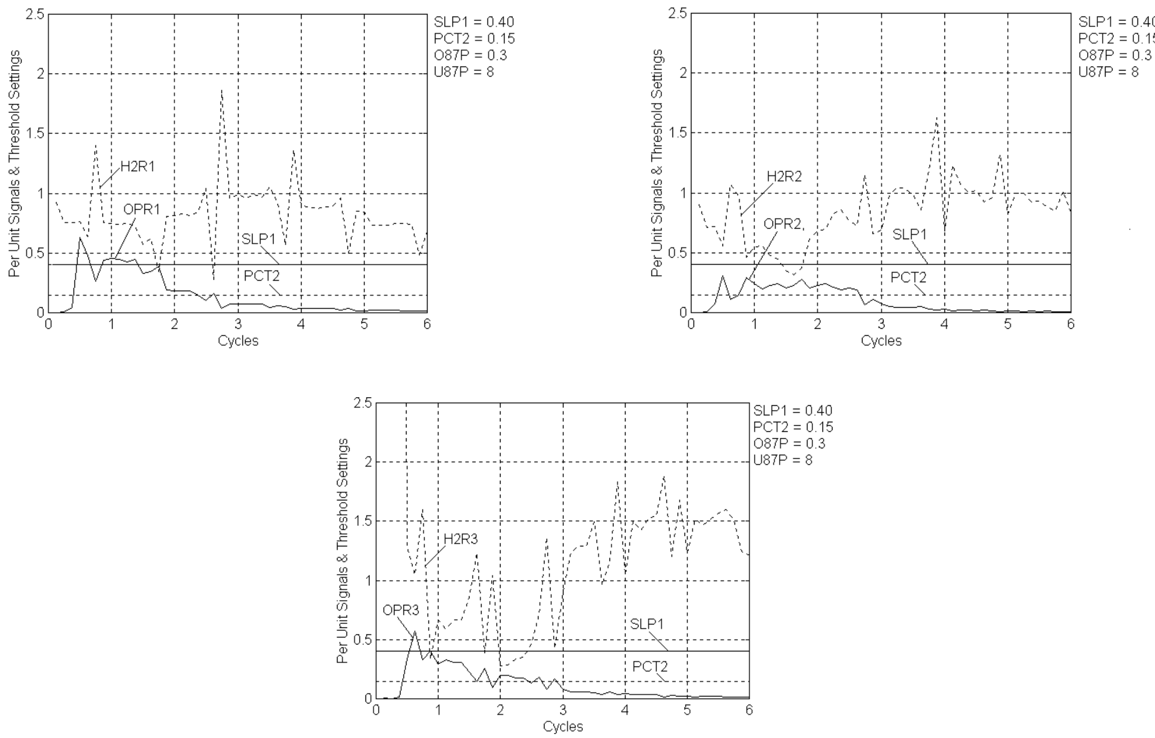

Figure 17: Relay Response in Phases A, B, and C

Case E: CT Simulation of a Three-Phase External Fault - Figures 15-17

The currents in windings 1 and 2 are a simulation of a 4000 amp, three-phase fault external to a 112 MVA, 169/69 kV, YY transformer. The high-side CTs are C400, 600:5 CTs with a 2.5 ohm burden. The low-side CTs are C400, 1200:5 CTs with a 1.5 ohm burden. No trip is observed, since the differential current is not enough to exceed the slope setting SLP1 for the required sample count. However, the Phase A operate current IOP1 (not shown) reaches 7.4 per unit of tap for five samples with the unrestrained trip threshold U87P set at 8. The case shows that a 3.0 ohm burden would have caused the unrestrained trip.

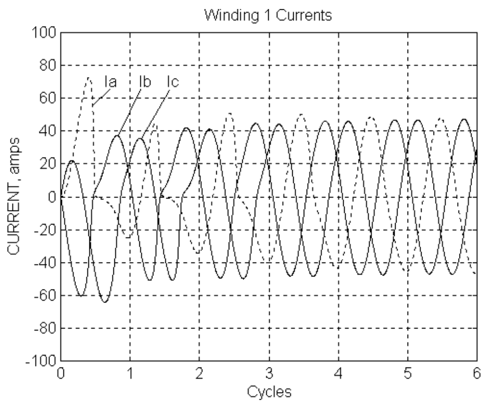

Figure 18: Currents in Winding 1

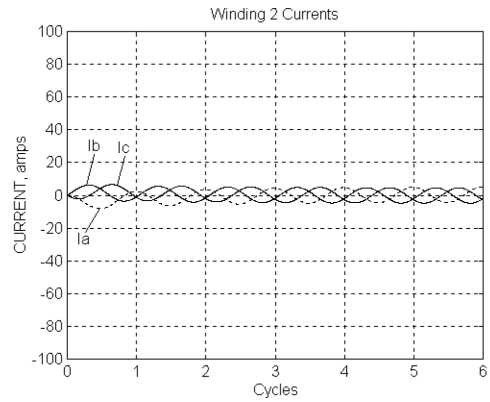

Figure 19: Currents in Winding 2

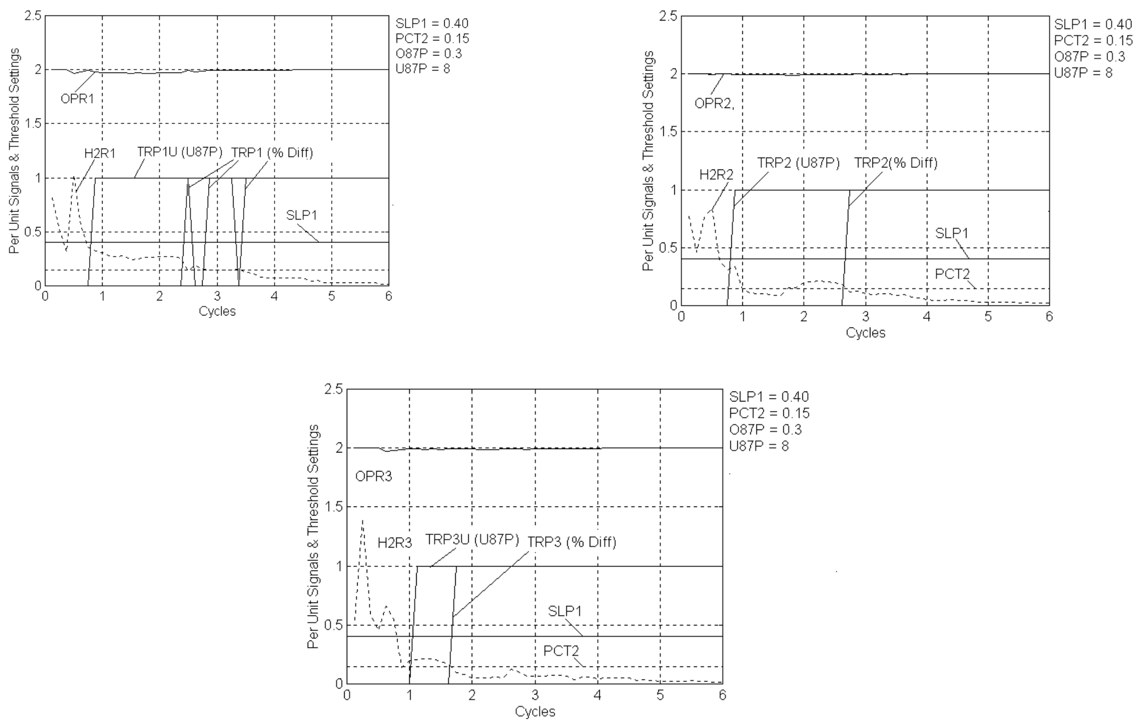

Figure 20: Relay Response in Phases A, B, and C

Case F: CT Simulation of a Three-Phase Internal Fault - Figures 18 - 20

The currents in windings 1 and 2 are a simulation of a 4000 amp, internal three-phase fault in the !69/69 kV, YY transformer. As in the previous case, the high-side CTs are C400, 600:5 CTs with a 2.5 ohm burden. The low-side CTs are C400, 1200:5 CTs with a 1.5 ohm burden. The relay produces a differential trip in each phase. However, the high 2^{nd} harmonic content caused by the excess saturation in the high burden CT delays the trip. Note the pickup and dropout of the A-phase differential element. Although the differential trip is delayed, the unrestrained element U87P demonstrates its value by supplying the fast trip in each phase.

Conclusions

1. It is convenient to consider the microprocessor transformer differential relay algorithms and logic collectively as a model. In a relay, the model processes the actual sampled input currents. In a computer, the model is a set of equations in a MATLAB program and processes the current samples of a simulation or the recorded samples in an event report.
2. The model shows that delta connection compensation can lower the 2nd harmonic content of the resultant current in one phase to less than a 15 percent restraint threshold. Accepting the option to block the trip for restraint in any phase prevents nuisance tripping.
3. The model shows that a transformer differential relay with harmonic restraint can tolerate a degree of CT saturation caused by the dc offset of an asymmetrical external fault. The 2nd harmonic blocks to prevent a false trip.
4. The model shows that tripping in the presence of CT saturation during the dc offset for an internal fault is delayed by the harmonic restraint. However, the unrestrained differential element provides the fast trip.
5. The model provides a valuable insight into the internal behavior of a relay in a wide range of field events and applications.

References

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Biography

Stanley (Stan) Zocholl has a B.S. and M.S. in Electrical Engineering from Drexel University. He is an IEEE Life Fellow and a member of the Power Engineering Society and the Industrial Application Society. He is also a member of the Power System Relaying Committee and past chair of the Relay Input Sources Subcommittee. He joined Schweitzer Engineering Laboratories, Inc. in 1991 in the position of Distinguished Engineer. He was with ABB Power T&D Company Allentown (formerly ITE, Gould, BBC) since 1947 where he held various engineering positions including Director of Protection Technology. His biography appears in Who's Who in America. He holds over a dozen patents associated with power system protection using solid state and microprocessor technology and is the author of numerous IEEE and Protective Relay Conference papers. He received the Best Paper Award of the 1988 Petroleum and Chemical Industry Conference and the Power System Relaying Committee's Distinguished Service Award in 1991.