Matlab® Analysis of Braytown Transformer Differential Inrush Misoperation

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Abstract

This paper describes the analysis of a transformer bank differential misoperation. The only information available was local differential relay target indication and a digital fault recording from a remote DFR. The subsequent analysis used the Matlab®[1] (software by The MathWorks, Inc.) environment to plot total harmonic distortion (THD) with operating fundamental to show why the single-phase differential (GE STD) operated. The analysis points out the vulnerability of transformer differential relay schemes that use independent fixed percentage harmonic restraint to block false operation on bank energization. A corollary presented is the possibility of "cross-blocking" schemes improperly restraining on energization of a faulted transformer bank. The Matlab® code used for analysis is available at http://www2.msstate.edu/~rwp1/matlab/ and is included is this paper's appendix.

Background

On March 19, 1999, a static wire on TVA's Elza-Braytown-Huntsville 161kV line fell into and faulted the line which was subsequently tripped by relay action. The auto-sectionalizing scheme at Braytown operated, and the Huntsville terminal attempted to radially pick up the two Braytown transformers and load by time-delay dead-line reclosing. When the Braytown substation was re-energized, the C-phase transformer differential relay operated to trip and lock out the transformer banks. Total load on the transformer banks just before the trip (according to metering data) was (14.8 + j1.2) MVA.

The two Braytown transformer banks are three-phase,161kV:69kV:13kV Y:y:d with both wye-connected windings grounded. Each bank is rated 25/33.3/41.7 MVA. Differential protection for both banks is provided by a set of three solid-state single-phase transformer differential relays with percentage and harmonic restraint, General Electric type STD16C. Delta-connected transformer bank bushing CTs are paralleled for the 161kV current input, while 69kV feeder breaker CTs also connected in delta provide the 69kV current input. 13kV load is station service only and is not included in the differential circuit.

[1] "Matlab" is a registered trademark of The MathWorks, Inc. For more information, see http://www.mathworks.com)

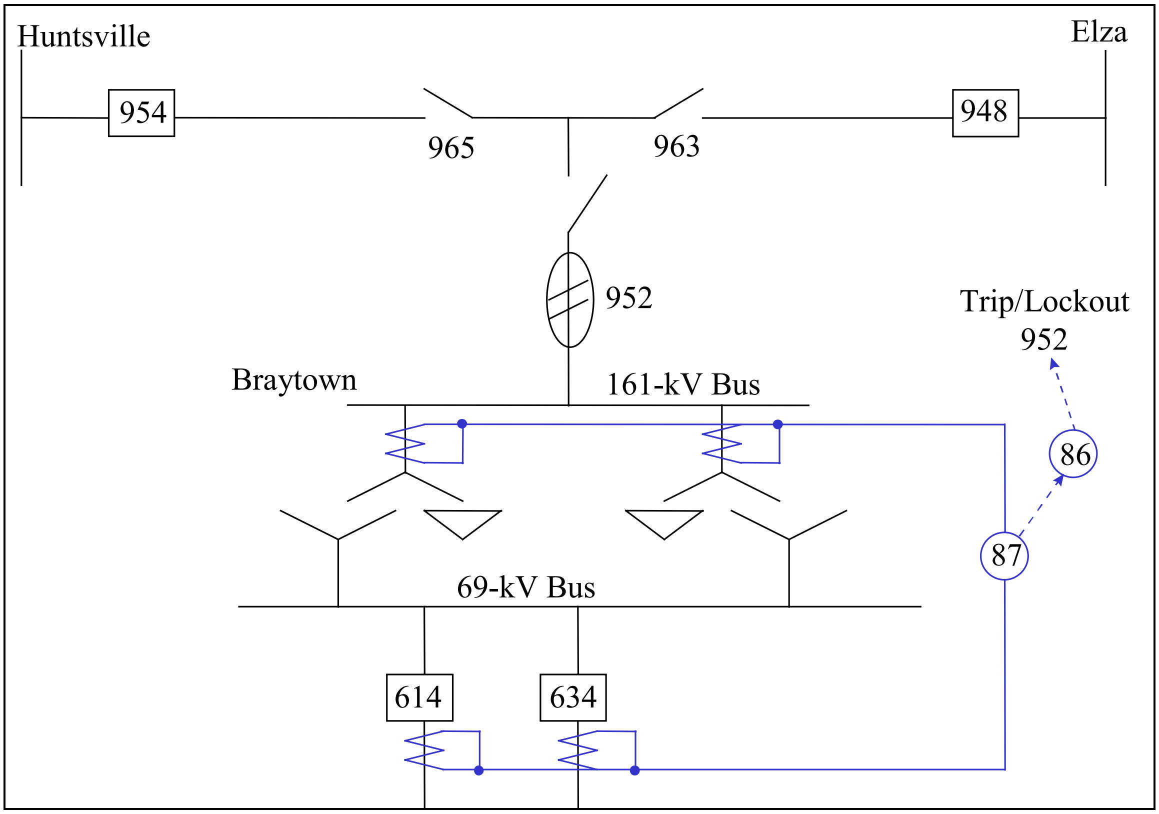

Figure 1. Braytown 161-69kV Substation

Analysis

These differential relays are intended to be resistant to misoperation on inrush while maintaining their ability to properly detect and operate for an actual transformer fault that may occur simultaneous with the inrush event (energizing a faulted transformer). However, harmonic inrush was the suspected culprit, and tap settings were raised to decrease the relays sensitivity to inrush, although it was not actually proven that inrush was the cause.

The instruction manual for the STD16C relay states that the relay should "restrain with greater than twenty percent second harmonic but will operate with second harmonic equal to twenty percent or lower."[2] (The C-phase differential relay was bench tested with no problems found.)

The missing piece of information was the actual currents seen by the differential relays. With no oscillograph at the Braytown substation, there was no way locally to determine the reason why the differential relay operated. However, the Huntsville terminal station did have a digital fault recorder, and fortunately it did record an event at the exact time that the Huntsville terminal breaker reclosed to energize the Braytown station (see Figure 2).

[2] General Electric, Instructions GEK-45307C, Transformer Differential Relays with Percentage and Harmonic Restraint - Types STD15C and STD16C, p.15. The relay actually will restrain on all harmonics above fundamental, but the percentages of harmonics above the second are typically negligible.

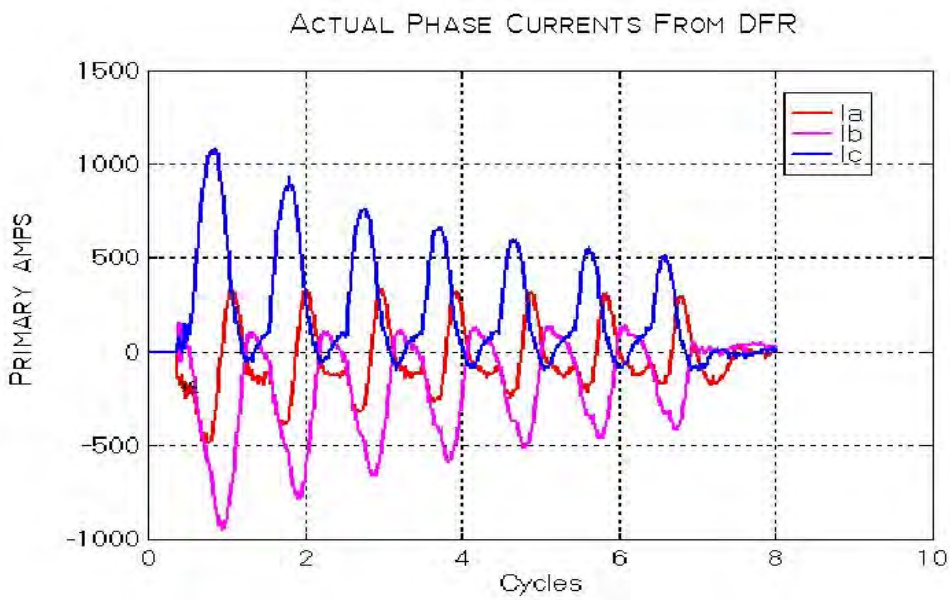

Figure 2. Phase currents at Huntsville terminal for Braytown inrush.

This raw data was exported into a data file, and Matlab® was used to analyze the waveforms. A sliding window DFT algorithm was used to calculate the second harmonic content of each current (see Figure 3).

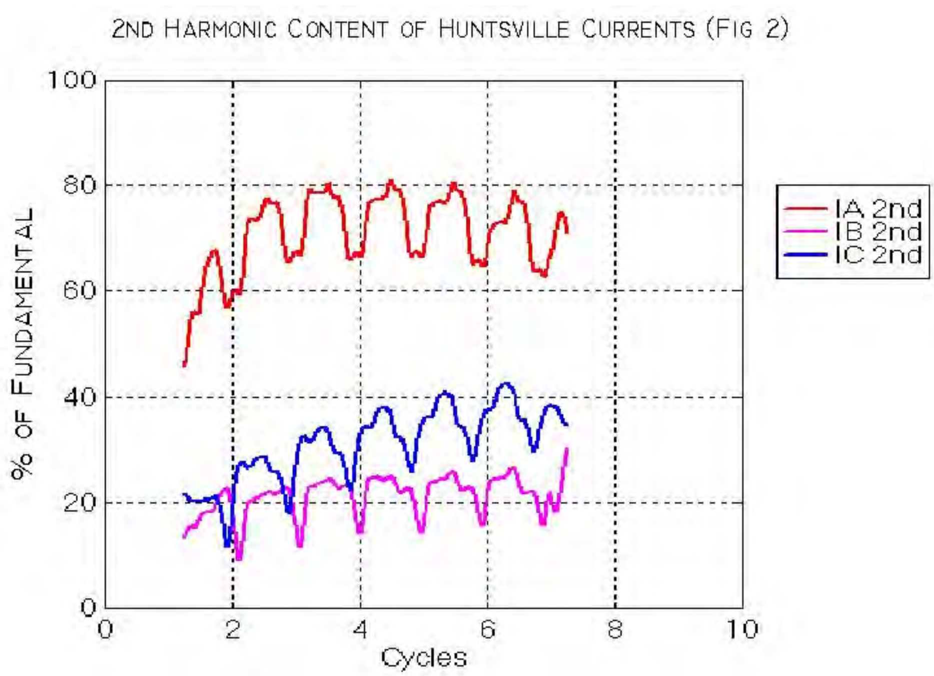

Figure 3. Percent 2nd harmonic in Huntsville Currents.

Note that all three currents had around 20% or greater second harmonic during the length of the event (Figure 3). It was then deduced that the harmonic restraint characteristic of the C-phase relay may have been somewhat higher than 20%.

However, this was an erroneous deduction. It was realized that the currents at the Huntsville terminal were the phase currents, while the currents seen by the differential relays at Braytown were provided by delta-connected CTs. Thus, the waveforms above were not those seen by the relays.

Figure 4 illustrates in more detail the delta CT connection of the currents to the differential relays at Braytown. It can be seen that the relay labeled C-phase is actually seeing the difference between the C-phase and B-phase currents (`Icb`).

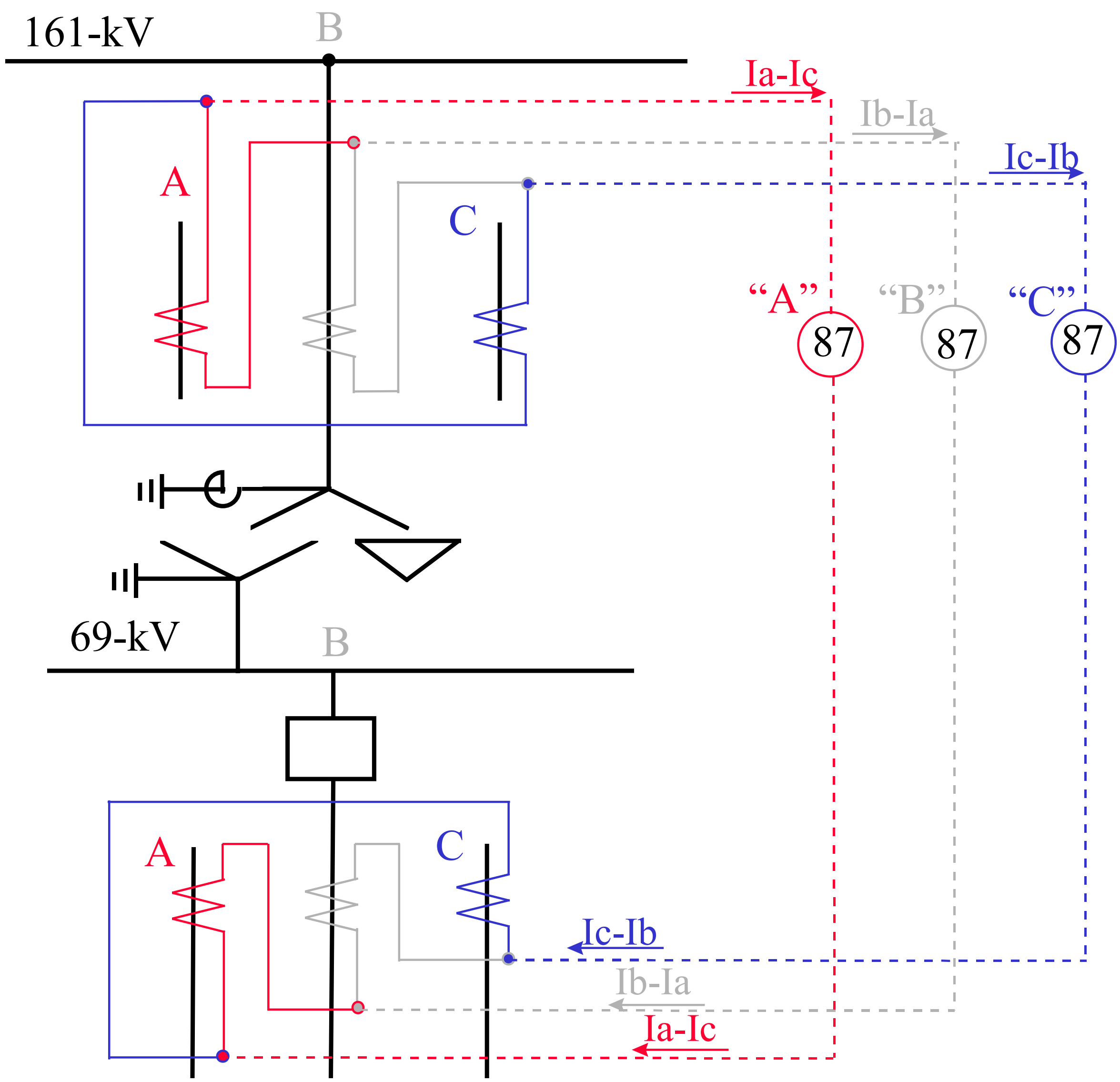

Figure 4. Delta-connected CTs providing current to differential relays

The delta currents seen by each relay were then calculated by simple sample-by-sample subtraction of the currents. Figure 5 illustrates the results. Matlab® was again used to compute the 2nd harmonic content of each relay current (Figure 6).

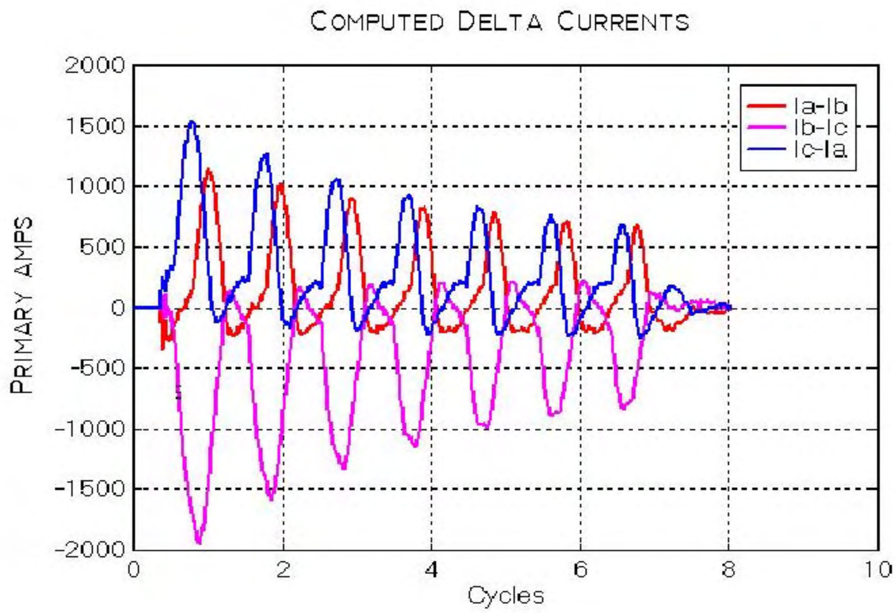

Figure 5. Computed Delta Currents at Braytown.

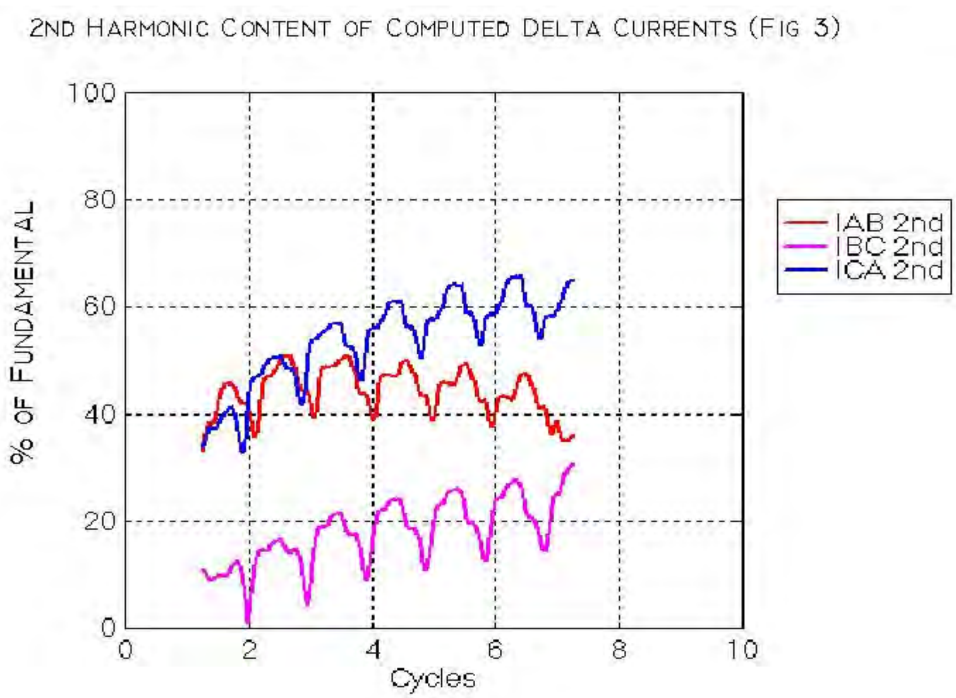

Figure 6. Percent 2nd harmonic in Delta Currents.

Referring to Figure 6, note that while the `Iab` and `Ica` currents both had greater than 45% second harmonic, the `Ibc` current had less than 15% harmonic for around 1 cycle and less than 20% for 2 or more cycles. This is due to the subtraction effect of the delta connection. Figure 7 shows the harmonic analysis of the “C-phase” differential current (actually BC current). It can be seen that the total harmonic calculation (THD) added little to the 2nd harmonic content and would basically have a smoothing effect on the 2nd harmonic content. There was not enough total harmonic content to restrain the relay. Figure 7 also shows the amount of fundamental current in the BC current. Ample 60Hz content was available to operate the relay. Without digital oscillographic data from Braytown, we were unable to analyze and account for the 69kV currents that would have been present in some distorted form due to connection of load.

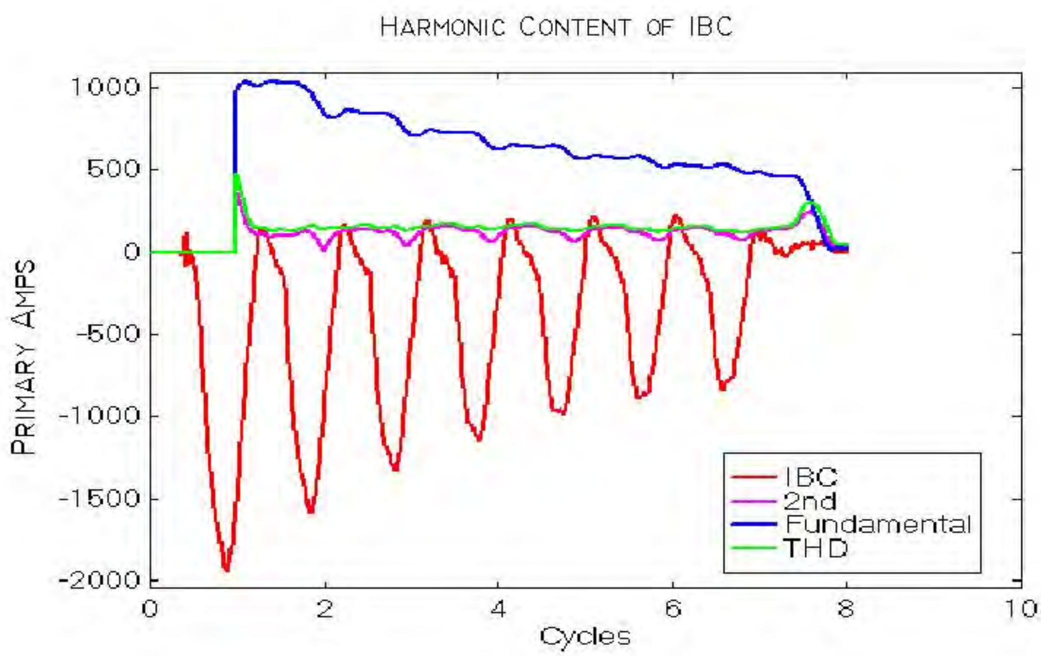

Figure 7. Harmonic analysis of BC current

From this analysis, the differential relay trip at re-energization was determined to be a misoperation due to lack of harmonic restraint on inrush currents.

Solutions

With the cause of operation determined, a few different solutions were considered. Having already considered the method of raising taps (which only provides a very small increase in security while decreasing sensitivity), the next method was to determine if the harmonic restraint setting of the existing STD16C could be lowered. It is known that other electromechanical transformer differential relays with harmonic restraint have different second harmonic thresholds. For example, the Westinghouse HU-1 is factory set for 15% second harmonic, and it can be lowered to 7.5%[3]. The BDD relay, also made by GE, has a second harmonic threshold of 35%.

[3] Elmore, W.A., ABB Protective Relaying Theory and Applications, Marcel Dekker, Inc., New York, 1994, p. 151.

The manufacturer was contacted concerning the STD16C relay, and it was discovered that it is not possible to modify the second harmonic restraint threshold of the STD16C by more than 1-2%[4].

With the relay harmonic restraint setting fixed at 20%, the only other realistic option to avoid misoperation on inrush considered was to replace the relay with a relay using a more secure method of harmonic restraint. This was the option chosen (although it had not yet been installed at the time of writing this paper).

One method being used by manufacturers of three-phase microprocessor transformer differential relays is known as "cross-blocking." Cross-blocking is simply blocking all three differential elements from operating if any one of them detects an inrush condition. The obvious pitfall to this technique occurs when energizing a transformer bank with one phase faulted. If either of the other two phases differential relays detects inrush and declares a restraint then all relays are blocked from operating until the inrush currents have subsided. Many of the newer relays have a high-set overcurrent element that is not restrained by the inrush detection smarts. This element would provide protection for energization of the faulted transformer in the event the fault current was excessively high enough. This still provides no protection for the lower magnitude currents that may be present upon energizing a faulted transformer. Our desire is to de-energize the transformer bank before those lower magnitude fault currents become higher magnitude fault currents possibly moving us from a minimally damaged transformer to a severely damaged transformer. The obvious benefit to this method is that misoperations on inrush when one phase has low levels of restraint quantity is avoided.

The author's evaluation of other different methods of inrush restraint in an attempt to pick a replacement relay is the subject of a paper by the authors in the 54th Annual Protective Relaying Conference[5]. A copy can also be obtained via the Internet at http:\\www2.msstate.edu\~rwp1\matlab\paper.

Conclusions

From this paper two very important points should be taken. First, it can be seen how important digital fault recorders are to the analysis of system disturbances, especially for those events where relays are suspected to have misoperated. One event report from a remote digital fault recorder provided the key to analyzing this event, and has led the utility to reevaluate its transformer protection standard.

[4] It is possible to modify other versions of the STD relay, such as the STD25D. The STD99 has a fixed second harmonic restraint threshold of 12%.

[5] Patterson, R.W., McCannon, W.P., Kobet, G.L., "A Consideration of Inrush Restraint Methods in Transformer Differential Relays", paper presented to the 2000 Georgia Tech Fault and Disturbance Analysis Conference.

Without digitally captured waveforms, analysis of this detailed nature is nearly impossible.

Second, the power of tools like Matlab® is evident in its ability to allow us to analyze and present results in this fashion. Sliding DFT algorithms similar to those used by the relay manufacturers in newer microprocessor relays can be modeled and their performance evaluated with actual captured waveform data. This gives us the ability to determine with confidence how and why our protective relays operate (or fail to operate) under fault or other transient conditions.

Appendix

Matlab® version 4.0 code script file used in the analysis:

```
% FFT sliding window to plot 2nd harmonic content of Braytown
% differential currents.
%
% Input signal as IA, IB & IC from the file bray.m
%
% Russell Patterson
% rwpatterson@tva.gov
% http://www2.msstate.edu/~rwp1
% June 1999
%
%
clear  % clear all variables

bray;           % this loads the 3 current waveforms
IAB = Ia-Ib;    % this creates the delta currents
IBC = Ib-Ic;
ICA = Ic-Ia;
N = 100;        % samples per cycle of digital recorder
P = 600;        % number of points desired for plot output (6 cycles)


M = length(IAB)-N;   % number points for the output vectors
for i = 1:M
 t(i) = i;   % fill vector t to simplify plotting
end

for i = 1:M
 for j = 1:N
  WINDOW_of_IAB(j) = IAB(i+j-1);   % fills the current 100 sample point
  WINDOW_of_IBC(j) = IBC(i+j-1);   % window
  WINDOW_of_ICA(j) = ICA(i+j-1);
 end
 FFT_of_WINDOW_IAB = fft(WINDOW_of_IAB);  % 2nd harmonic calc. For IAB
 MAG_of_FFT_IAB = abs(FFT_of_WINDOW_IAB);
 mysecond_IAB(i) = MAG_of_FFT_IAB(3)/MAG_of_FFT_IAB(2)*100;

 FFT_of_WINDOW_IBC = fft(WINDOW_of_IBC);
 MAG_of_FFT_IBC = abs(FFT_of_WINDOW_IBC);
 mysecond_IBC(i) = MAG_of_FFT_IBC(3)/MAG_of_FFT_IBC(2)*100;

 FFT_of_WINDOW_ICA = fft(WINDOW_of_ICA);
 MAG_of_FFT_ICA = abs(FFT_of_WINDOW_ICA);
 mysecond_ICA(i) = MAG_of_FFT_ICA(3)/MAG_of_FFT_ICA(2)*100;
end



% plot resulting 2nd harmonic points with each waveform
figure
subplot(3,1,1);
plot(t(1:P),mysecond_IAB(1:P),t(1:P),IAB(1:P));
ylabel('IAB');
title('Braytown GE STD Differential Inrush Trip - Second Harmonic
Content');

subplot(3,1,2);
plot(t(1:P),mysecond_IBC(1:P),t(1:P),IBC(1:P));
ylabel('IBC');
```

```
subplot(3,1,3);
plot(t(1:P),mysecond_ICA(1:P),t(1:P),ICA(1:P));
ylabel('ICA');
xlabel('Data Points at 100 samples/cycle');

% now plot each separately
figure
plot(t(1:P),mysecond_IAB(1:P),t(1:P),IAB(1:P));
xlabel('Data Points at 100 samples/cycle');
ylabel('IAB');
title('Braytown GE STD Differential Inrush Trip - Second Harmonic
Content');

figure
plot(t(1:P),mysecond_IBC(1:P),t(1:P),IBC(1:P));
xlabel('Data Points at 100 samples/cycle');
ylabel('IBC');
title('Braytown GE STD Differential Inrush Trip - Second Harmonic
Content');

figure
plot(t(1:P),mysecond_ICA(1:P),t(1:P),ICA(1:P));
xlabel('Data Points at 100 samples/cycle');
ylabel('ICA');
title('Braytown GE STD Differential Inrush Trip - Second Harmonic
Content');

t=t/100;  % to put x-axis in cycles
% now plot the three 2nd harmonic plots together vs. cycles
figure
plot(t(1:P),mysecond_IAB(1:P),'b',t(1:P),mysecond_IBC(1:P),'r',t(1:P),mys
econd_ICA(1:P),'b');
xlabel('Cycles');
ylabel('2nd harmonic in % of fundamental per-phase');
title('Braytown GE STD Differential Inrush Trip - Second Harmonic
Content');
```

Biographical Sketches

Gary Kobet is a Project Specialist, System Protection for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. His responsibilities include scoping relaying schemes on transmission and generation projects, as well as relay setpoint calculations. He has performed transient studies using EMTP for breaker TRV studies and switching surge overvoltages. Previously he worked as a field engineer and as Power Quality Specialist. Mr. Kobet earned the B.S.E. (electrical) from the University of Alabama in Huntsville in 1989 and the M.S.E.E. from Mississippi State University in 1996. He is a member of Eta Kappa Nu, Tau Beta Pi, and is a registered professional engineer in the state of Alabama.

Russell W. Patterson is a Project Specialist, System Protection for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. He is responsible for reviewing and making protective relaying recommendations on new construction and retrofit projects for the generation and transmission system. Russell also has responsibility for protective relaying and control settings and field support. Prior to his position as Project Specialist Russell was TVA's Power Quality Manager responsible for field and customer support on PQ related issues and disturbances. Russell has performed transient simulations using EMTP for breaker Transient Recovery Voltage (TRV) studies including recommending mitigation techniques. Mr. Patterson earned the B.S.E.E. from the Mississippi State University in 1991 and has completed all coursework toward the M.S.E.E. at Mississippi State University. Russell is a registered professional engineer in the state of Tennessee.