Using COMTRADE Records to Test Protective Relays

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INTRODUCTION

This purpose of this paper is to demonstrate how to use COMTRADE records to test protective relays. COMTRADE records that have been captured by numerical relays and digital fault records during actual system events are of particular interest since these provide the ability to test protection for critical faults or disturbances such as an out-of-step condition that are difficult to create using off the shelf test set software. Utilities and other customers can build a library of test cases.

This paper shows how to use COMTRADE records to test transformer differential protection, loss of field protection and out-of-step protection.

Differential Relay Operation during Transformer Energization

The first example is the case of transformer differential protection operating during energization due to low second harmonic current content in the inrush current. This event was recorded by the numerical relay protecting a 400 MVA 230/115 kV auto-transformer that was energized from the high side while the low side was open. The auto-transformer is connected to a 230 kV straight bus through a motorized disconnect switch. The CTs are wye connected on both sides. The 230 kV CTs are on the transformer bushings connected with the full ratio (1200:5). Note that the tertiary winding feeds the station service load but does not have CTs connected to the bank differential.

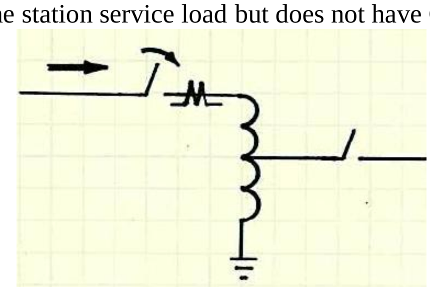

Figure 1. Auto Transformer Energization from High Side

This is an excellent case to use the COMTRADE record captured by the relay since you can test transformer differential protection to ensure it does not operate during inrush for many applications; that is, most two winding transformers and auto banks with five amp rated CT secondary values on the high side.

Figure 2 shows there was very little restraint current and high magnitude differential current in B Phase during the transformer energization. The trip occurred when the ratio of B Phase 2nd harmonic to fundamental current dropped too low.

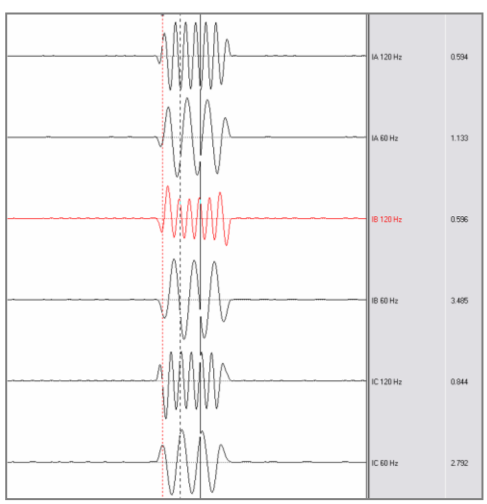

Figure 2. High Side CT Secondary Fundamental versus 2nd Harmonic Current

The relevant current phasors measured by the relay at the time of the trip along with the 2nd harmonic contents are listed below in Figure 3.

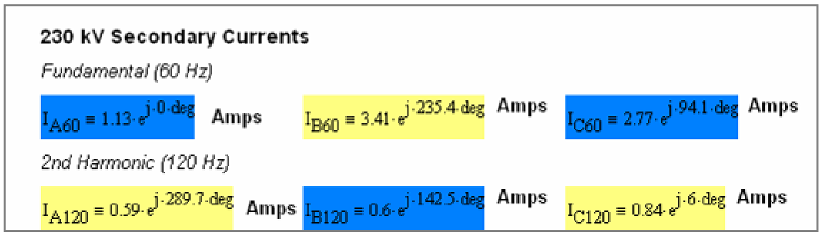

Figure 3. Current Phasors Measured at the Relay with 2nd Harmonic Current

The numerical transformer differential relay that tripped uses internal zero-sequence current compensation to prevent unwanted operations during external ground faults since the current transformers are connected wye and the transformer is an auto bank. Calculating the phase-to-phase current automatically eliminates zero-sequence current as follows:

$I_a = I_1 + I_2 + \mathbf{I_0}$
$I_b = a^2 I_1 + a I_2 + \mathbf{I_0}$
$I_c = a I_1 + a^2 I_2 + \mathbf{I_0}$

$I_{ab} = I_a - I_b = I_1 (1 - a^2) + I_2 (1 - a)$
$I_{bc} = I_b - I_c = I_1 (a^2 - a) + I_2 (a - a^2)$
$I_{ca} = I_c - I_a = I_1 (a - 1) + I_2 (a^2 - 1)$

If the transformer differential relay uses phase-to-phase current to eliminate zero-sequence current then I_{bc} is the most depleted of 2nd harmonic content and also corresponds to the phase that actually tripped (B-Phase). Figure 5 illustrates the following signals:

- I_{bc}
- fundamental component
- 2nd harmonic content
- *ratio of 2nd harmonic to fundamental*

The ratio decreases in magnitude over the first two cycles following energization. The relay tripped at the point when the ratio dropped to 14 percent. *Note that transformer differential relays are typically set to restrain at 15 percent.*

$$\text{Ratio} = \left| \frac{I_{diff}^{2nd}}{I_{diff}} \right| \bullet 100\%$$

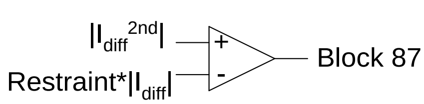

Figure 4. Current 2nd Harmonic Restraint Logic

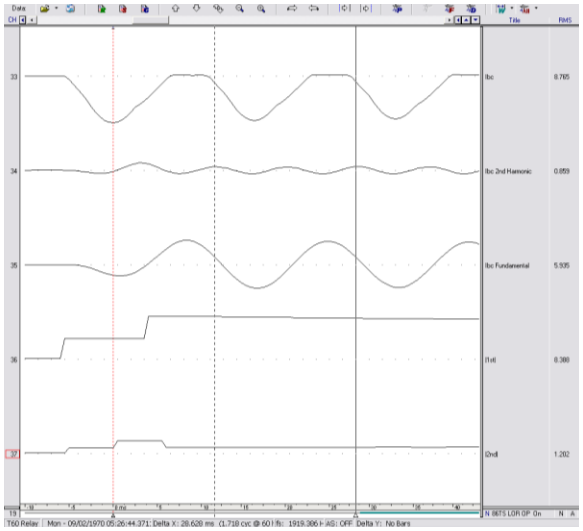

Figure 5. Current Phasors Measured at the Relay with 2nd & 4th Harmonic Current

Test Requirements

You will need a three-phase test set that can playback COMTRADE records. Three current channels are required. Connect the three-phase test set to the relay as shown in Figure 6A below.

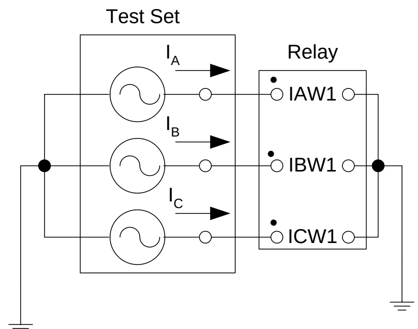

Figure 6A. Test Connections

Figure 6B shows off the shelf software available to playback this particular COMTRADE record through the test set to the relay.

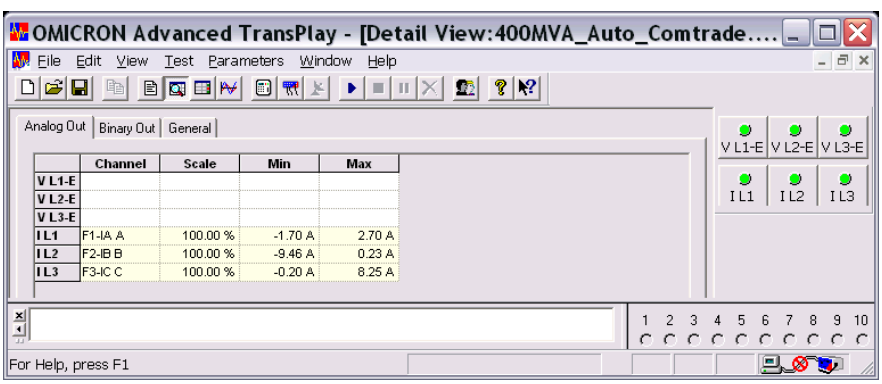

Figure 6B. Test software

Test Procedure

1. First playback the inrush case to the relay with harmonic restraint disabled.
2. The relay should trip when harmonic restraint is disabled.
3. If the relay trips then playback the inrush case again with harmonic restraint enabled.
4. The relay should not trip when harmonic restraint is enabled.

Figure 7 shows the corresponding flowchart.

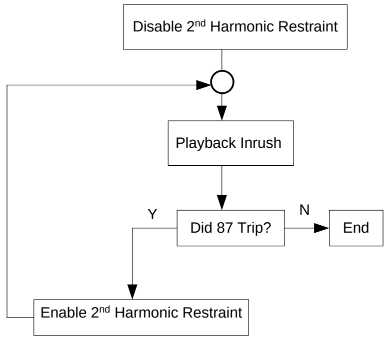

Figure 7. Transformer Inrush Test Procedure Flowchart

Advanced Test – Adjusting the Level of 2nd Harmonic Content

It is possible to reduce the amount of 2nd harmonic content present in the inrush current during the injection test. You can reduce the level of 2nd harmonic current until the restraint no longer blocks the differential protection. For example, 10 percent is typically the minimum level acceptable to set the 2nd harmonic restraint, otherwise if it were set lower tripping might be significantly delayed for heavy internal faults due to harmonics generated by CT saturation. The software shown below in Figure 8 illustrates this process:

1. First isolate the fundamental component and 2nd harmonic component in B-Phase current (I_B).
2. Next multiply the 2nd harmonic content by a factor to reduce its magnitude to the pickup level selected for the 2nd harmonic restraint. For this particular case the minimum pickup is 10 percent. Therefore, the multiplication factor is 0.7 (i.e., $\frac{10\%}{14\%}$).
3. Re-assemble the B-Phase current by adding the fundamental and 2nd harmonic back together (Depleted IB in the case of Figure 8).
4. Finally inject the adjusted current into the relay.

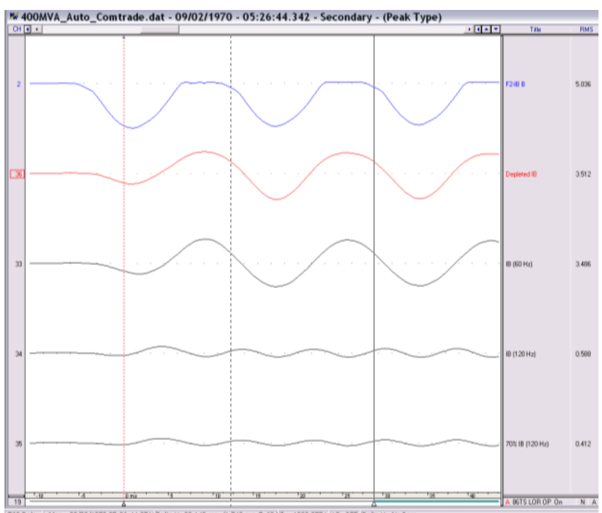

Figure 8. Adjusted Inrush Current

Loss of Field Generator Protection Operation

The second example is an actual loss-of-field captured by a numerical generator protection relay. The event is shown in Figure 9 below.

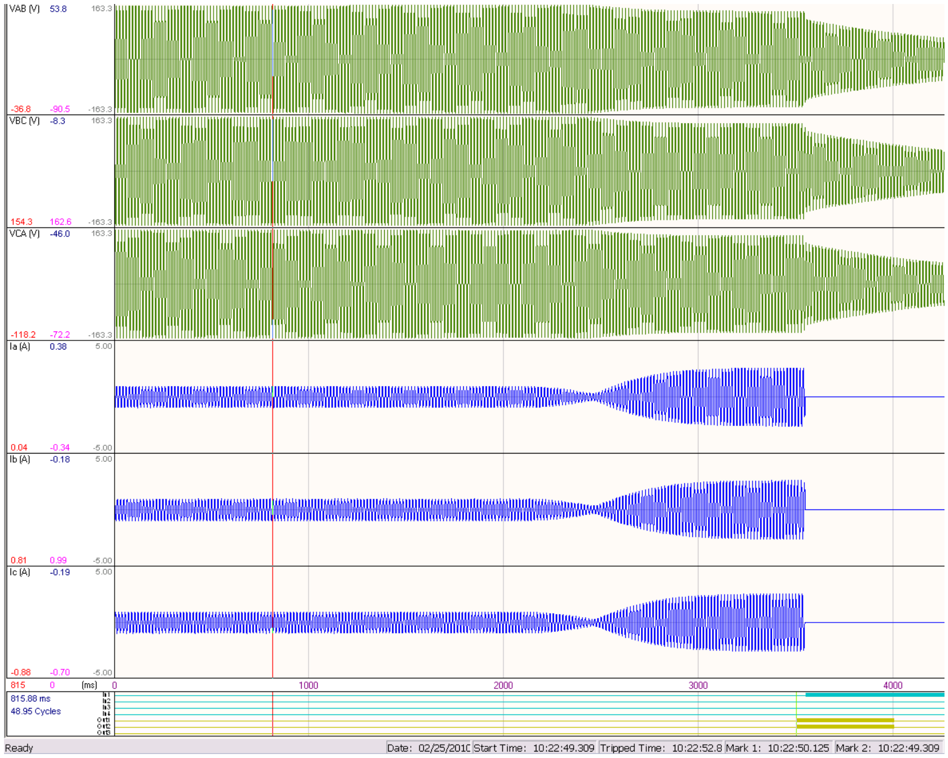

Figure 9. Generator Loss of Field

The numerical relay that tripped and captured the event was configured for 115 volts line-to-line and 5 amps secondary. The maximum current measured by the relay during the event was 1.9 amps secondary (i.e., lightly loaded). Figure 10 shows the impedance trajectory (Z_{AB}) corresponding to the loss of field. It is simpler to view one phase-to-phase impedance since the loss of field is a balanced three-phase event. Note that the scale in the impedance diagram is kilo-ohms. Figure 10 shows the corresponding points in time in the current channels. Table 1 shows the corresponding timeline. The impedance trajectory does not have a constant velocity. *This is an excellent test because it is an actual loss of field that entered the LOF operating characteristic along the bottom of its boundary*. Figures 12A and 12B illustrate that this is the case when loss of field occurs while the generator is lightly loaded.

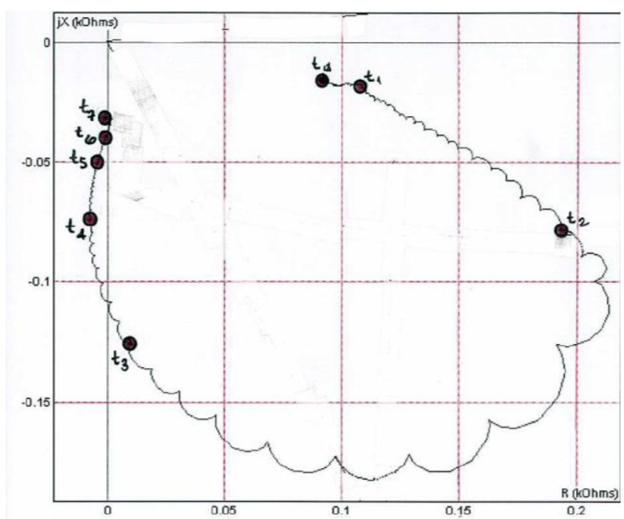

Figure 10. Loss of Field Impedance Trajectory

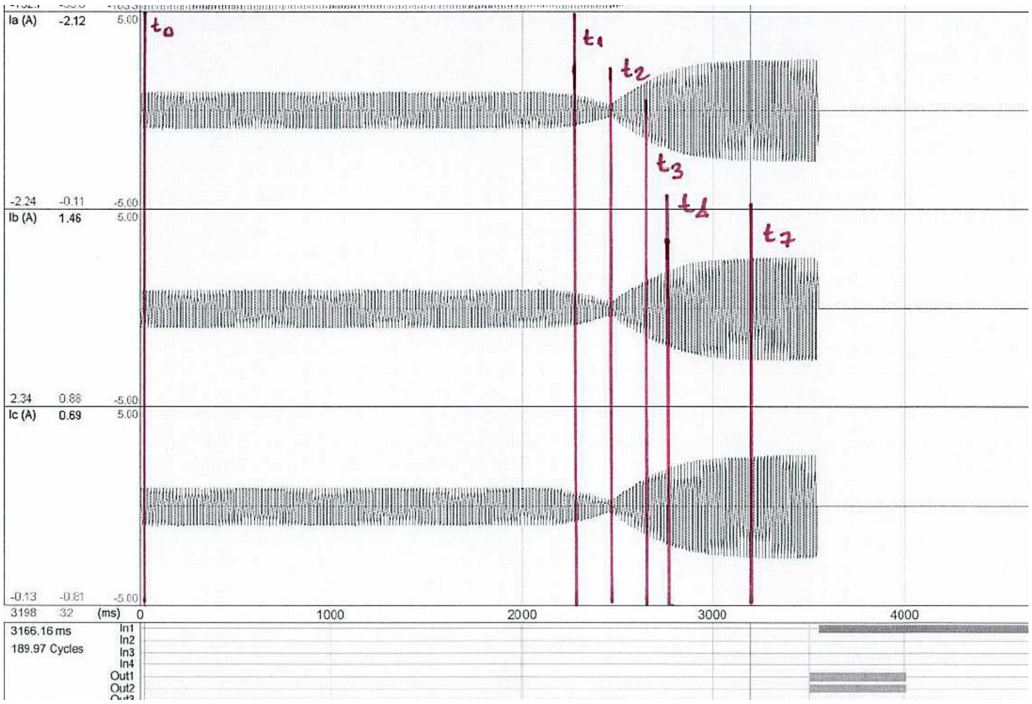

Figure 11. Loss of Field Current Channels

Table 1. Loss of Field Timeline

t_0	0 cycles
t_1	135 cycles
t_2	145 cycles
t_3	150 cycles
t_4	155 cycles
t_5	160 cycles
t_6	165 cycles
t_7	190 cycles

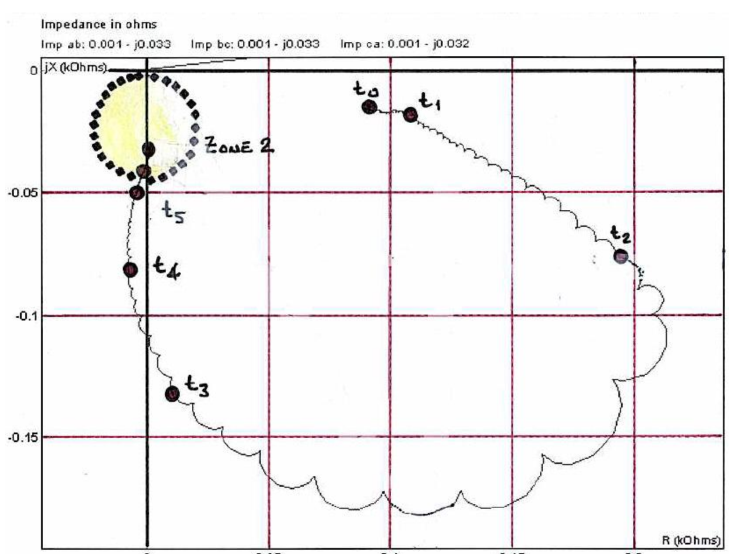

Figure 12A. Loss of Field Impedance Function Characteristic Impedance Trajectory

Figure 12A shows a loss of field impedance characteristic superimposed on the trajectory. The characteristic has an offset equal to three ohms secondary and a diameter of 32.5 ohms secondary (see Figure 13).

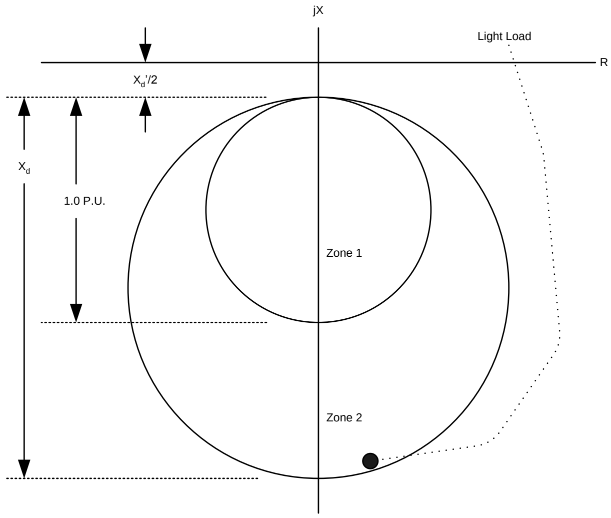

Figure 12B. Loss of Field Impedance Trajectory during Light Load

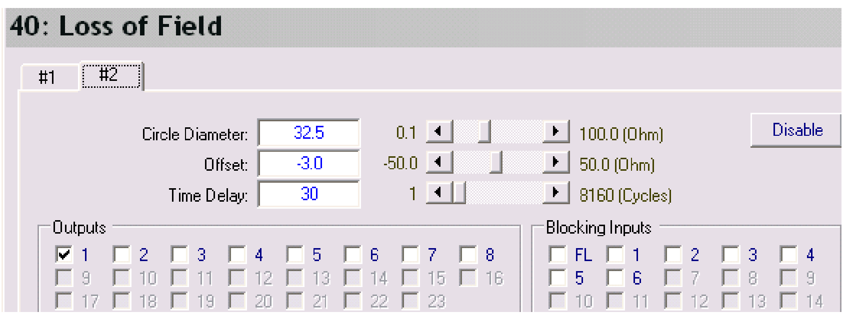

Figure 13. Loss of Field Zone 2 Impedance Settings

Test Requirements

A three-phase test set that can playback COMTRADE records is needed. Three voltage channels and three current channels are required. Connect the three-phase test set to the relay as shown in Figure 14.

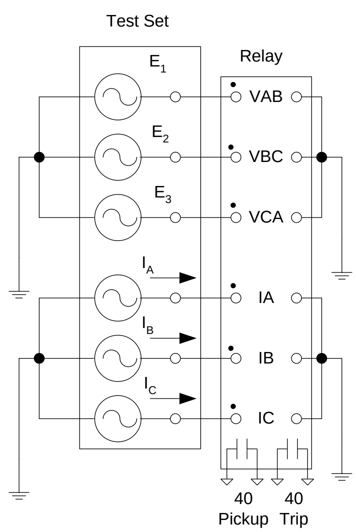

Figure 14. Test Connections

Test Procedure

1. Configure the relay so that one output closes when the 40 function first picks up (O1) and another closes when the 40 function trips (O2).
2. Connect the two outputs to the test set such that O1 starts the timer and O2 stops the timer.
3. Playback the loss of field case to the relay.
4. You can measure the time required for the function to operate.

Advanced Test – Adjusting the Impedance Trajectory

This test case is much more useful and can be applied to a much wider number of applications if you can adjust the loss of field impedance trajectory. One simple example is to double the current magnitude. Figure 15 shows a screenshot of commercially available software that allows the user alter voltage and current signals. Channels I_a', I_b' and I_c' are twice the value of I_a, I_b and I_c.

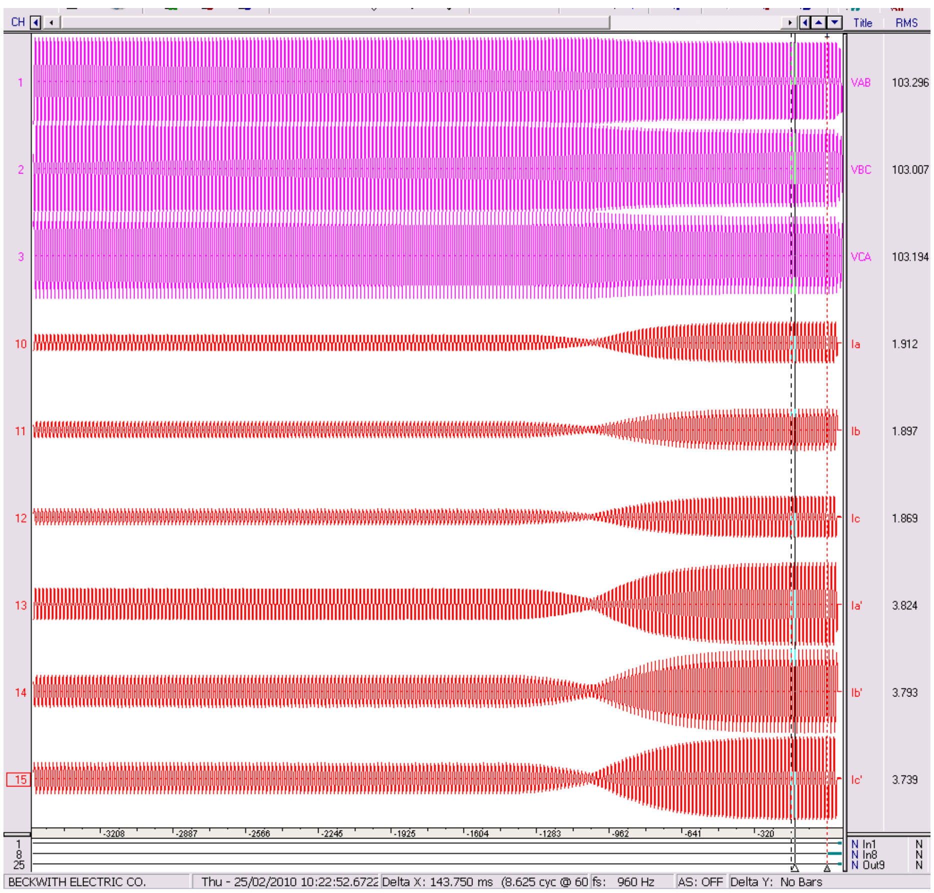

Figure 15. Multiplying the Current Channels

Figure 16 shows the corresponding loss of field impedance trajectory as well as the original for comparison.

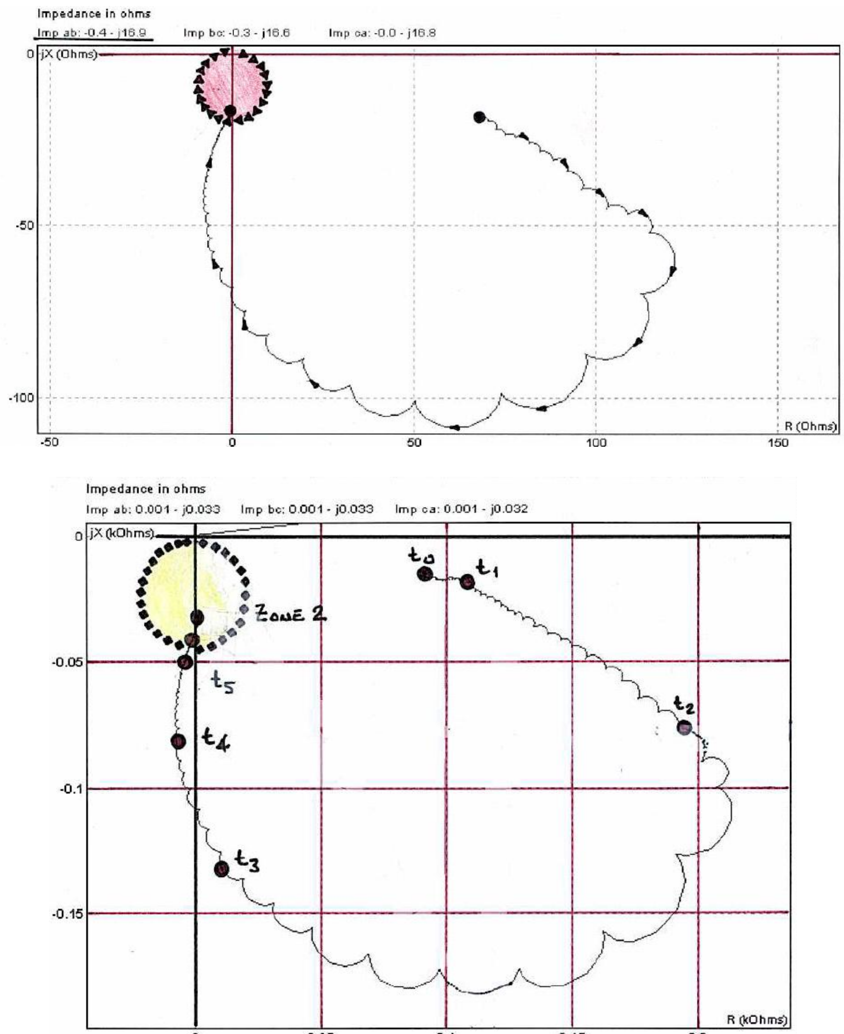

Figure 16. Adjusted Impedance Trajectory versus Original

You can use this COMTRADE record to test any loss of field characteristic by simply scaling the channels.

Out-of-Step Condition Followed by System Fault Simulation

The final example is the simulation of a fast out-of-step condition that slipped three poles then evolved into a resistive single line-to-ground fault on A-Phase. The slip frequency was 10 Hz. The period of the swing is calculated as follows:

$$T = \frac{1}{f_{slip}} = 100 \text{ milliseconds (6 cycles)}$$

Figure 17 shows the three-phase voltage and current to be injected into the relay for this event. The maximum current is 10 amps secondary which occurs during the swing not the ground fault.

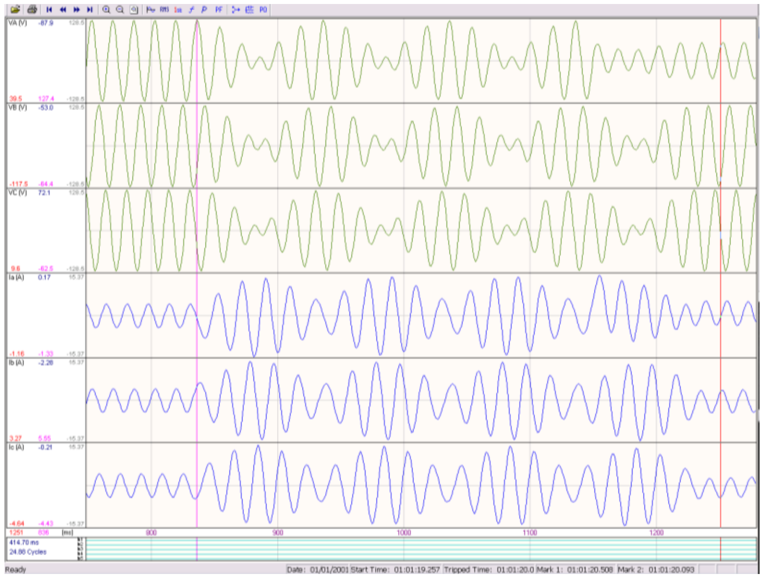

Figure 17. Out-of-Step (OST) followed by Single Line-to-Ground Fault

Figure 18A shows the out of step impedance characteristic for this test. Figure 18B shows the corresponding settings. The out-of-step protection is set to count three pole slips then trip when the impedance trajectory exits the mho characteristic.

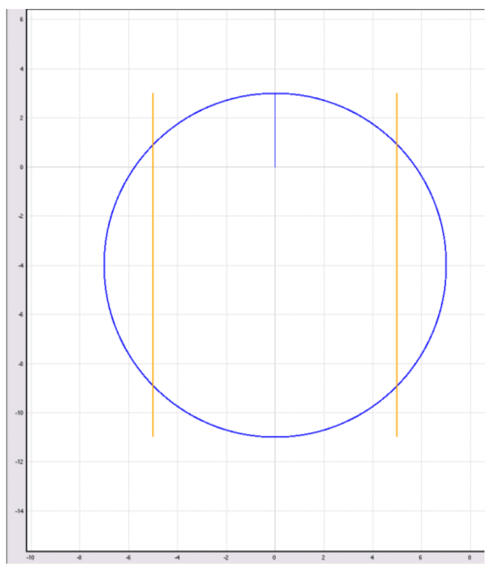

Figure 18A. Out-of-Step Impedance Characteristic

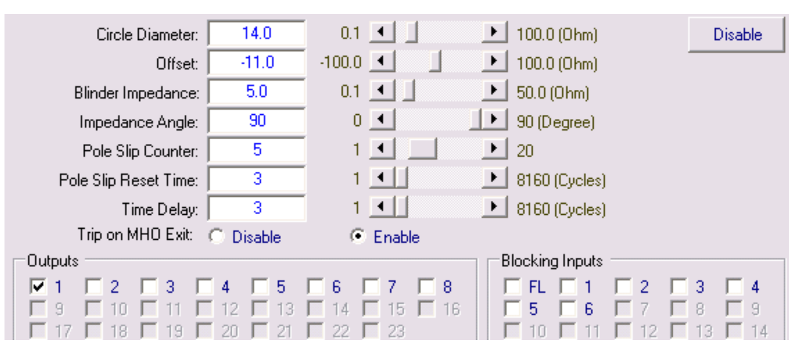

Figure 18B. Out-of-Step Impedance Settings

Figure 19 shows the impedance trajectory for the out-of-step condition (•) followed by the ground fault (♦) and is superimposed over the OST characteristic. The arrows (▶) show the direction in which the trajectory is moving. The markers for t_1 through t_7 are one cycle apart in time. The markers for the ground fault are also one cycle apart in time as well. Examination of the trajectory reveals that the relay should operate in approximately 18 cycles for this simulation (i.e., after the third slipped pole).

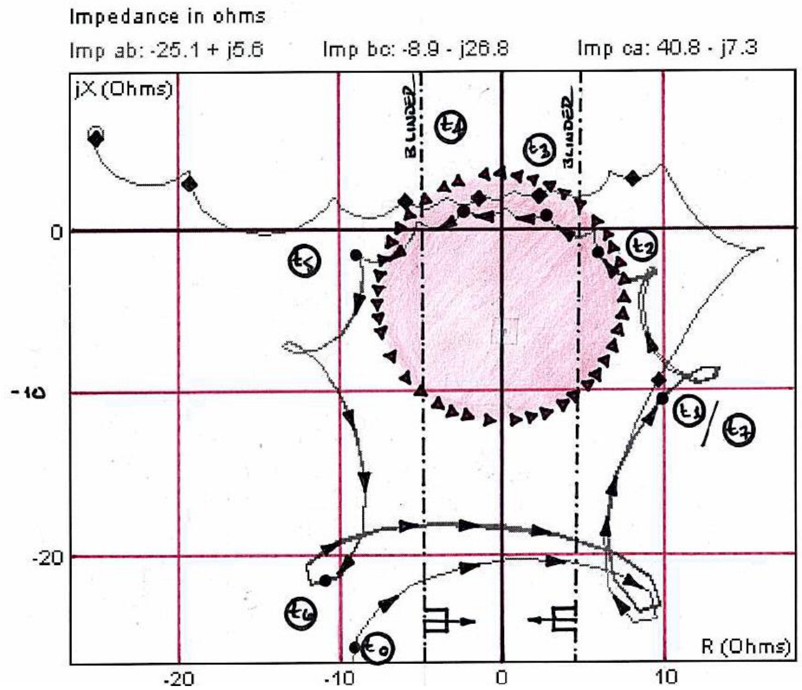

Figure 19. OST Function Characteristic Impedance Trajectory

Figure 20 shows the corresponding P-Q trajectory for this event.

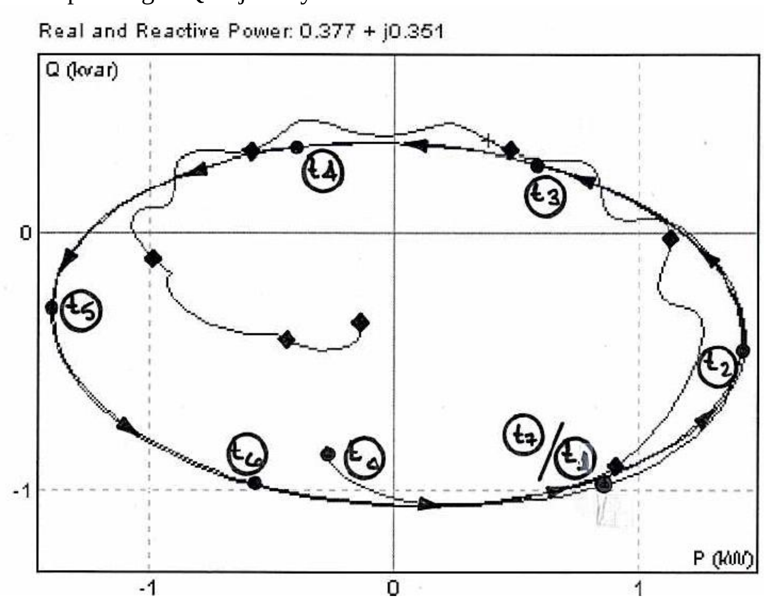

Figure 20. OST P-Q Trajectory

Test Requirements

A three-phase test set that can playback COMTRADE records is needed. Three voltage channels and three current channels are required. Connect the three-phase test set to the relay as shown in Figure 21.

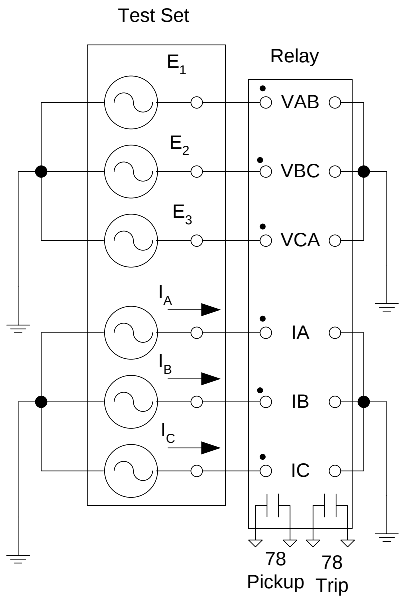

Figure 21. Test Connections

Test Procedure

1. Configure the relay so that one output closes when the 78 function first picks up (O1) and another closes when the 78 function trips (O2).
2. Connect the two outputs to the test set such that O1 starts the timer and O2 stops the timer.
3. Playback the out-of-step case to the relay.
4. You can measure the time required for the function to operate, which should be 18 cycles.

CONCLUSIONS

This purpose of this paper is to demonstrate how to use COMTRADE records to test protective relays. COMTRADE records that have been captured by numerical relays and digital fault records during actual system events are of particular interest since these provide the ability to test protection for critical faults or disturbances such as an out-of-step condition that are hard to create using off the shelf test set software. *Utilities and other customers can build a library of test cases.* COMTRADE records are also an excellent means of playing back a complex simulation such as the out-of-step condition discussed in this paper.

The first case uses a COMTRADE record captured by a numerical transformer relay to ensure your protection does not operate during inrush. This case is suitable for many applications; that is most two winding transformers and auto banks with five amp rated CT secondary values on the high side.

The second example is an actual loss-of-field captured by a numerical generator protection relay.

The third example is the simulation of an out-of-step event followed by a resistive ground fault.

The paper also demonstrates that by altering voltage and current channels in a COMTRADE record you can use the event to test a much wider range of applications.

ABOUT THE AUTHOR

Steve Turner is a Senior Applications Engineer at Beckwith Electric Company. His previous experience includes working as an application engineer with GEC Alstom, an application engineer in the international market for SEL, focusing on transmission line protection applications. Steve worked for Progress Energy, where he developed a patent for double-ended fault location on transmission lines.

Steve has both a BSEE and MSEE from Virginia Tech University. He has presented at numerous conferences including: Georgia Tech Protective Relay Conference, Western Protective Relay Conference, ECNE and Doble User Groups, as well as various international conferences. Steve is a senior member of IEEE.