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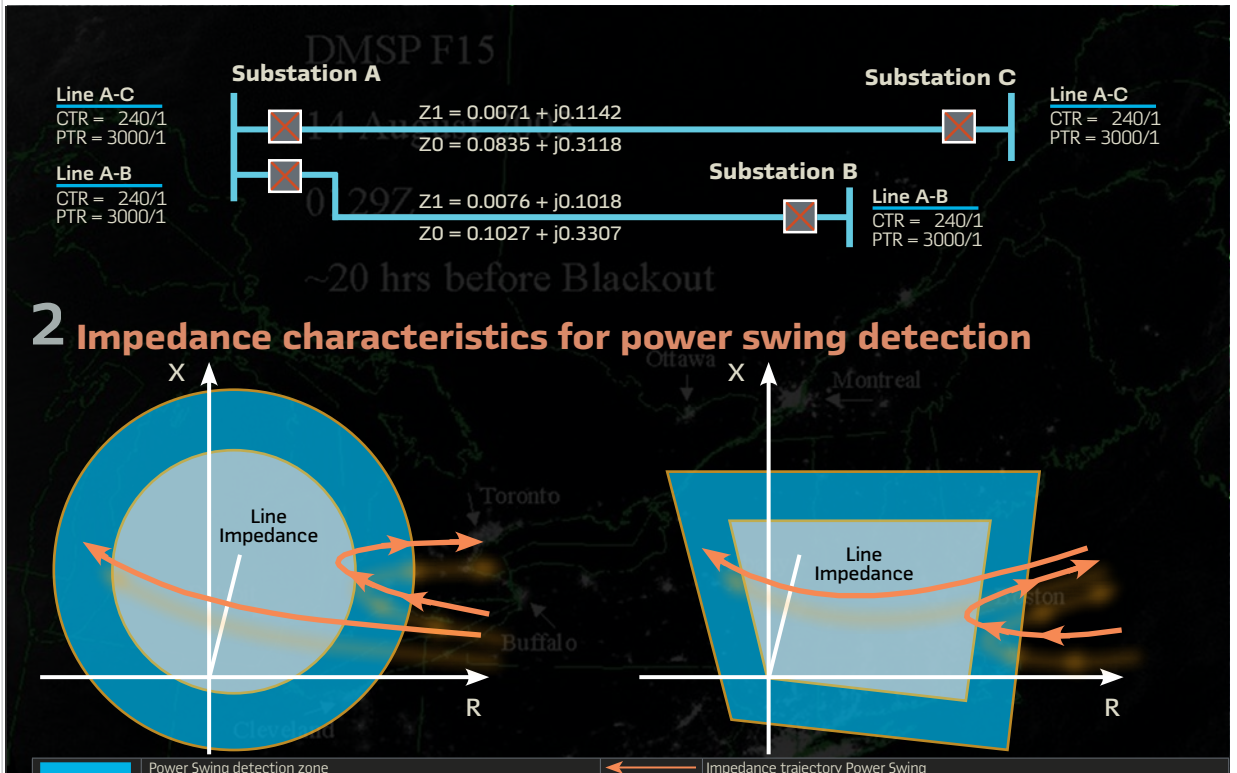
# Testing Relay Performance During the 2003 Blackout

On August 14th, 2003, stable and unstable power swings occurred on the Northeast Power Coordinating Council (NPCC) bulk transmission system. Distance protection relays tripped out on some of the lines during stable power swings. These events contributed to the blackout of many parts of the northeast United States and Canada that occurred

on that date, and brought to attention the need to evaluate Power Swing protection for bulk transmission systems. The NPCC created a team to investigate the event, analyze relay operation, and recommend improvements to the line distance protection performance for such events.

## 1 Topology and parameters of the transmission system

Note: Impedance are Per Unit on a 100MVA Base. Voltage = 345.0 kV



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**Edward Krizauskas** received a BS in Electrical Engineering from the Pennsylvania State University in 1985, and a Master of Engineering in Electric Power Engineering from the Rensselaer Polytechnic Institute in 1990. Ed has worked as a distribution engineer for the New England Electric System, as a transmission planning engineer for the Atlantic Electric Corporation and as a protection and control engineer for the New York State Electric and Gas Corporation. Ed has chaired or served on various IEEE Power System Relaying Committee working groups, and has co-authored several technical papers. Ed is a registered professional engineer in New York State and in Pennsylvania.

THE NPCC REQUESTED THAT studies be conducted to determine if line protection systems can be installed to operate as follows:

- line distance protection needs to be blocked when stable power swings are experienced on the lines

- some lines need to trip out during unstable power swings to separate electrical systems that would be spinning apart from each other to avoid more widespread system separations and outages

The NPCC System Studies working group SS-38 simulated the network conditions during the Blackout (August 14th, 2003, 16:05:55) for two of the bulk transmission lines that terminate at three different substations. The simulations approximate the power swings that occurred on those lines, which gradually evolved from stable to unstable (out-of-step).

For this article, the subject substations will be called Substation A, Substation B and Substation C. The topology and parameters of the subject bulk transmission system are shown in Figure 1.

Test plans were developed to check the performance of distance relay elements for the conditions that led to the blackout based on the SS-38 data. The tests explored whether various methods available in distance protection relays would be capable of providing adequate protection, and determine which protection option would provide the best possible solution.

**Conventional Power Swing Detection Methods:** For distance protection relays, a common criterion to differentiate a power swing from a fault is the speed of the change of measured impedance. When a fault occurs, the measured impedance jumps instantaneously from load impedance area to the fault detection zones. In the case of an OOS condition the measured impedance will “travel” on a trajectory in the R/X plane with a speed that is much slower than that

caused by a fault. In distance relays, the speed of impedance change is normally measured by the time it takes to pass a certain length. Most power swing detection methods use this principle.

**Concentric Characteristics:** The simplest method of speed measurement is by monitoring the elapsed time of the impedance trajectory passing a zone between two impedance characteristics. These two characteristics are usually designed in such a way that one is concentric around the other. Some typical characteristics are shown in Figure 2. These two additional characteristics (outside the protection zones) can be used exclusively for the purpose of power swing detection, and can lie concentric to the existing distance protection characteristics.

The advantage of these concentric characteristics is that power swings can be detected before the measured impedance trajectories enter the protection tripping zones. Although setting the relay is relatively simple, it is not easy to calculate proper setting parameters for the two characteristics. A sophisticated grid analysis is normally required. One limit for applying the concentric characteristics is that the resistive reach of the outer characteristic cannot extend into the load area. This becomes a very limiting requirement, especially for long and heavily loaded transmission lines.

**Blinder Schemes:** The blinder scheme, as shown in Figure 3, is based on the same principle of measuring the traveling time of an impedance trajectory passing a blinder zone. The time measurement starts when an impedance trajectory crosses the outer blinder and stops when the inner blinder is crossed. If the measured time is longer than a prescribed setting, a power swing condition is detected.

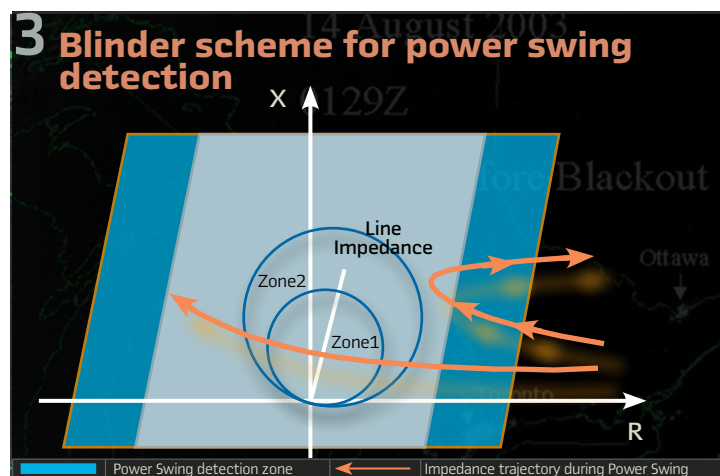
If the blinders are set at an angle parallel to the line impedance, they are optimized for measurement of out of step impedances, because its trajectory will in most cases enter

## The tests evaluated the performance of distance protection relays under stable and unstable power swings that contributed to the northeast blackout of August 14, 2003.

the protection zones at an angle nearly 90 degrees to the line angle. The big advantage of the blinder scheme is that the blinders can be used independent of the protection zone characteristics. An advantage of this scheme is that the load impedance can lie inside the blinder impedances. The disadvantage, again, is that it is not easy to calculate the correct settings for the blinders, and a sophisticated grid analysis may be required.

**Protection Philosophy during Power Swings:** During a power swing, whether stable or unstable, the impedances measured by distance relays may move into the protection zones and cause unwanted relay operations.

If the power swing is stable, it is normally desired to block the relay





## The PSB function prevents distance protection functions from tripping during power swings.

from operation. On the other hand, if the power swing becomes unstable, proper fast remedial actions have to be taken to restore system stability. Power swing detection relays at carefully selected locations would be preferred to separate the systems in order to prevent further line distance relay operations and further deteriorate system stability.

Meanwhile, any fault occurring on the protected line during the condition of a power swing, needs to be reliably identified and promptly cleared. The sensitivity of distance protection to detect faults on the protected line cannot be compromised by power swing detection elements.

A number of utilities do not provide any means to prevent operation of distance protection elements during power swings. They accept the possibility of unpredictable separations of the network instead of implementing a complex power swing blocking and tripping scheme where power swing tripping would only be implemented on one particular line. However, if the distance protection elements operate during a power swing event, it can be assumed that the system voltages on both sides of the open line terminal breaker(s) are more than 60 degrees out of phase. Normally if the power swing impedance enters the distance protection zone, the voltages would be closer to 180 degrees out of phase. Thus, the voltage across the open line terminal breaker(s)

would exceed rated system voltage, and could be as high as twice rated system voltage. Therefore, if the utility chooses not to implement a complex power swing blocking/tripping scheme, they would be required to install line terminal breakers with voltage ratings that are twice rated system voltage!

### Advanced power swing detection

The need for sophisticated system studies can be eliminated using advanced methods developed for power swing detection in distance protection relays. One such algorithm consists of two modules, working in parallel. The first module uses concentric polygon characteristics. A setting is not needed, because the outer characteristic has small constant impedance (1 ohm based on 5A) to the outside of the fault detection area. This module is designed to detect slow impedance movements (< 5 ohm/s) during a low-frequency power swing. Once measured impedance trajectories enter the power swing detection zone, a timer set at 30 ms is started. A power swing is detected if the timer elapses before the fault detection zone is passed.

The second module is designed and optimized to detect fast impedance movements for the power swing frequency as high as 7 Hz. This module is the core of the power swing detection and blocking function, and is based on continuous impedance calculation of three modified loop impedances. The module continuously monitors the measured impedance trajectories to detect any potential power swings. The algorithm is based on the fact that a power swing can be best detected by analyzing its impedance trajectory behavior in a certain time window. Power swing impedances generally move in elliptical trajectories, which can be further analyzed to determine if the power swing is stable or unstable. The structure of the power swing module is illustrated in Figure 9. The continuous

measurement of the load impedance means that every 5 ms impedance calculations for three loops are performed and checked for continuity and monotony.

The correct trending checks if the resistance changes at least 50 milliohms during each calculation. If this condition is fulfilled for six consecutive calculations, a power swing "suspicion" is established.

The continuity test checks that the change rate of the impedance in R and in X is not beyond a limit, thus it guarantees that the impedance trajectory has a uniformly smooth movement without abrupt changes. The limit is not fixed; instead it is calculated based on previously calculated values. This leads to a dynamic calculation of the limits, and an automatic adaptation to the traveling speed of a power swing trajectory.

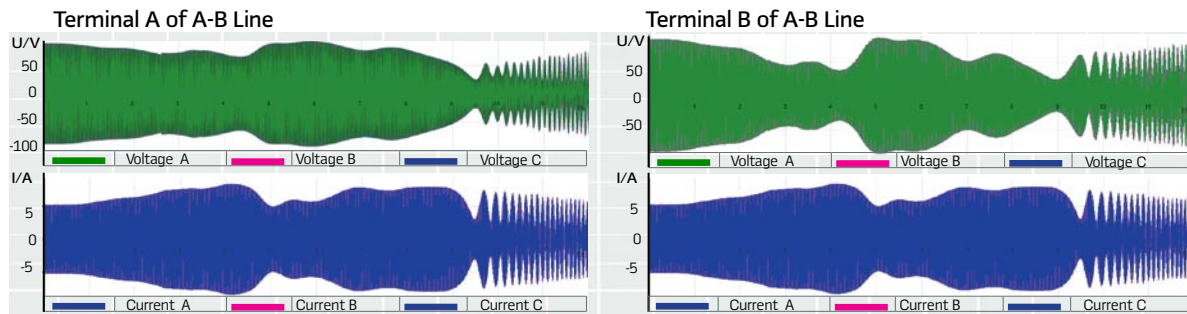
The dynamic adaptation to the traveling speed of a power swing trajectory enables the function to detect fast swings with frequencies up to 7 Hz. If both continuity and monotony conditions are fulfilled, a power swing can be detected even before the impedance trajectory enters the power swing detection zone. In general, a power swing can be detected in 30 ms (6 consecutive calculations of 5ms) after it starts. Once the impedance trajectory moves into the power swing detection zone, the distance protection functions can be blocked if the power swing blocking (PSB) element is enabled. Meanwhile, if the continuity condition is not fulfilled for six consecutive calculations and the measured impedance is within the protection zones, then a fault is assumed to have occurred. In this case, the distance protection functions are activated immediately.

**Relays were able to trip for faults during a power swing.**

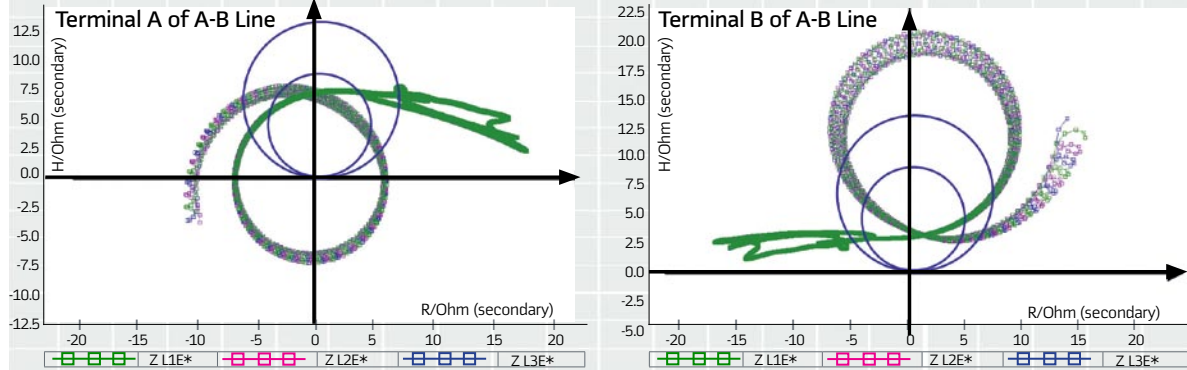


Yuchen Lu received his B.S.(1999) and M.S.(2002) in Electrical Engineering from Shanghai Jiao Tong University in Shanghai, China. From 2002 to 2007, he studied at Washington State University and University of Idaho, USA. He received his Ph.D.(2007) in Power Systems and Power Electronics at University of Idaho. Since 2007, he joined Siemens as a Power System Protection & Control engineer. Yuchen is a member of IEEE.

### 4 Waveforms - A-B line

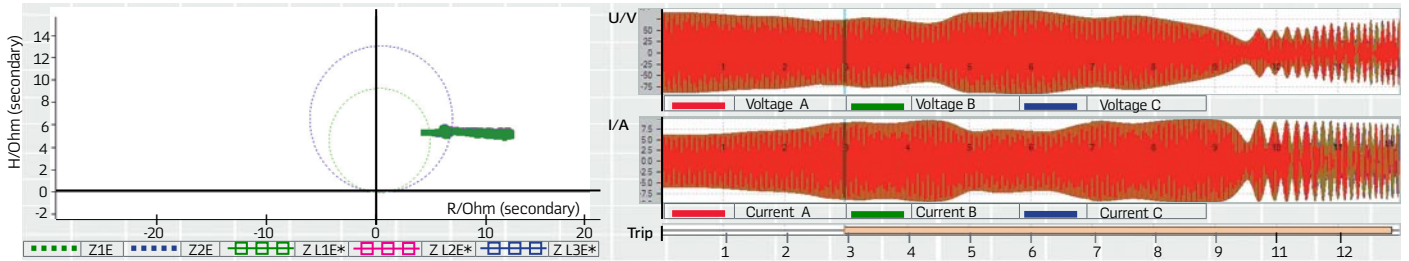


### 5 Impedance - A-B line



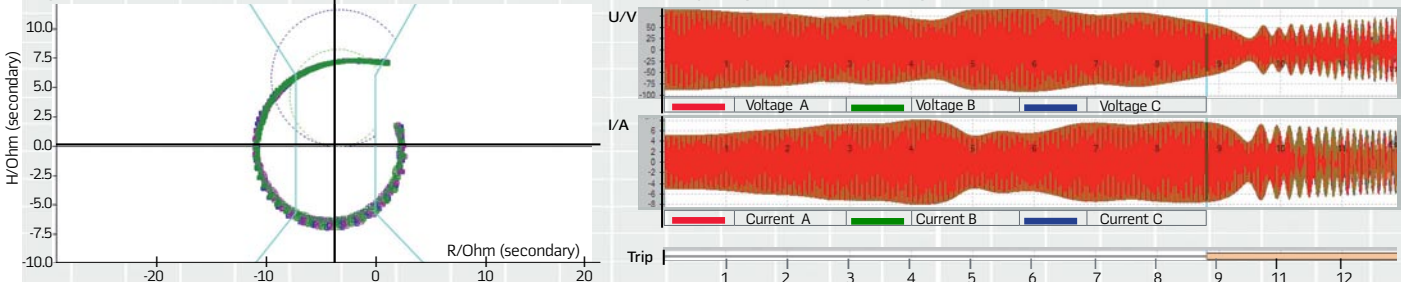
### 6 Case 1: LEB, PSB, and OST Disabled

Impedances from the fault record at Terminal A of Line A-C Relay response during the power swing simulation at Terminal A of Line A-C



### 7 Case 2: LEB Enabled, PSB and OST Disabled

Impedances from the fault record at Terminal A of Line A-B Relay response during the power swing simulation at Terminal A of Line A-B



**Methods and procedures**  
**Power Swing Test Data:** The COMTRADE files used in the tests were converted from the fault simulation data provided by the NPCC SS-38 working group. The COMTRADE files used throughout the tests are as follows:

- *Terminal A of Line A-B:* "A-to-B.cfg"
- *Terminal B of Line A-B:* "B-to-A.cfg"
- *Terminal A of Line A-C:* "A-to-C.cfg"
- *Terminal C of Line A-C:* "C-to-A.cfg"

The COMTRADE files are plotted in Figures 4 & 5. Figure 4 shows the waveforms of voltages and currents measured at terminals A/B. In the figures, the magnitudes of the voltage and current oscillations during the power swings can be clearly seen. Moreover, by observation of the frequency of the oscillations, one can roughly determine where the power swing is stable and where it becomes unstable.

A power swing can be more precisely represented by its impedance trajectories. Figure 5 shows the impedance trajectories measured by the distance relay at terminals A/B. For clarity and illustration purposes, only the stable part of the power swing and the first cycle of the unstable part of the power swing are plotted in the R/X plane. Each impedance trajectory starts

moving from the load zone at the beginning of the power swing. It approaches and occasionally enters the protection zones as can be seen in the plots. During the stable part of the power swing, the impedance moves but stays on its side. It never travels across the X axis on the R/X plane. Using this criterion, it can easily be seen in the plots at what point the power swing becomes unstable.

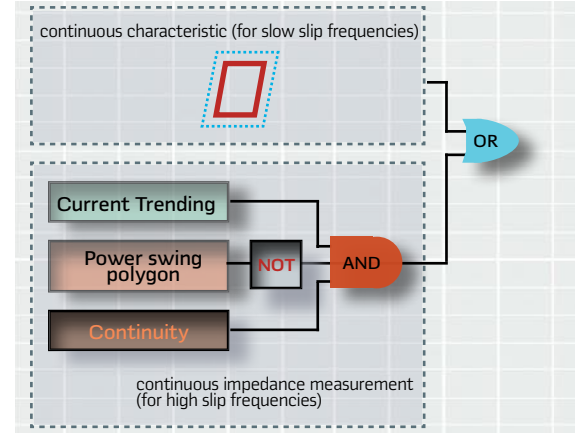
**Test Procedures:** In the tests, the distance protection relay was connected to a test set capable of playing COMTRADE files. The COMTRADE files were played by the test set to apply the power swing voltages and currents to the voltage and current terminals of the relay. The relay operation and timing were carefully recorded.

*The following functions in the relay were tested:* Load Encroachment Blinders (LEB), Power Swing Blocking (PSB), and Out-of-Step Trip (OST). The relay was programmed separately with mho and quadrilateral characteristics, and each was tested individually. These characteristics were tested for each of the line terminals for the two lines. Thus, for each line terminal (*Terminal A of Line A-B, Terminal B of Line A-B, Terminal A of Line A-C, and Terminal C of Line A-C*), five test cases out of 20 are performed:

- **Case 1:** LEB, PSB, and OST are all Disabled. The relay has only

## 9 Components:

The new power swing detection function



normal distance protection functions. How the power swing affected a "normal" distance relay that was not equipped with power swing detection was tested.

■ **Case 2:** LEB is Enabled, but PSB and OST are Disabled. It is a common practice for distance relays to use additional LEB to prevent load encroachment. However, would this be enough to prevent an unwanted relay operation during the power swing?

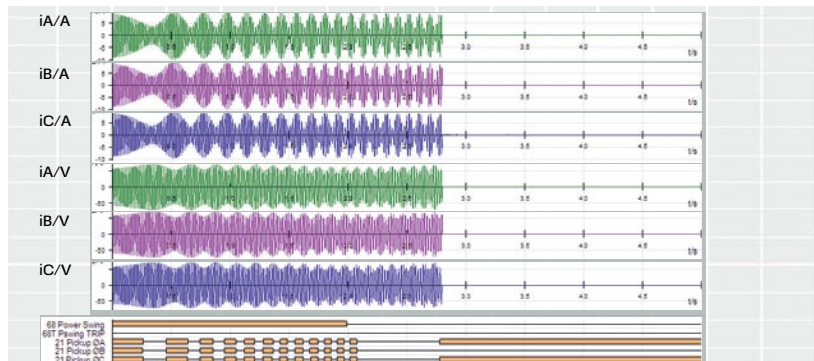
■ **Case 3:** PSB is Enabled, but LEB and OST are Disabled. Ideally, with PSB function enabled, the distance relay should be able to reliably detect the power swing and block tripping.

■ **Case 4:** PSB and OST are Enabled, LEB is Disabled. Ideally, when PSB and OST are both enabled, the relay should block tripping during a stable power swing. As soon as an unstable power swing is detected, OST function should be activated to permit tripping.

■ **Case 5:** PSB with concurrent line faults. Various cases of power swing blocking functions with concurrent line faults were performed. The PSB function should by no means compromise the sensitivity of fault detection or the speed of fault clearance of the distance protection elements.

## 8 Case 3: PSB enabled, LEB & OST disabled

Fault record during the power swing simulation at Terminal B of Line A-B



Tests of relay fault detection capability during power swings were simulated.

## The tests showed that the use of a Load Encroachment Blinder did not prevent the distance protection elements from tripping during stable or unstable power swings.

### Test results

**Case 1: LEB, PSB, and OST Disabled** - Typical relay responses to the tests are shown in Figure 6. As expected, the relay tripped during the stable portion of the power swing once the impedance trajectories entered the protection zones. This occurred for both mho and quadrilateral protection elements.

**Case 2: LEB Enabled, PSB and OST Disabled** - Many distance relays provide the conventional Load Encroachment Blinders (LEB), whose major task is to prevent unwanted relay tripping when system is heavily loaded and load impedances approach the distance protection zones in the R-axis direction. In the case of these circuits, Load Encroachment Blinders were also needed to be used in order to comply with NERC loadability requirements for the lines. The tests performed aimed to evaluate the effectiveness of LEB function in blocking the power swing impedances.

The first test was performed for Terminal A of Line A-B. In Figure 7, it can be seen the LEB blocked relay tripping during most of the stable portion of the power swing. The relay tripped 8.808 seconds after initiation of the power swing, which is close to the point where the power swing becomes unstable. By further analyzing Figure 7, it can be seen that during the first 8.808 seconds of the power swing, the swing impedances happened to be inside the LEB! Furthermore, with LEB enabled, the relay still tripped during the stable portion of the power swing, even though at the moment that the relay tripped the swing was close to becoming unstable.

Another test on LEB was performed at Terminal B of Line A-B. The relay tripped at 4.104 second

during the stable power swing because the impedance trajectories moved out the blinder region and into the protection zones.

Changing the setting of the load blinder to be able to block tripping of the stable swing was considered. The setting required to prevent tripping for stable power swings significantly encroached upon the tripping characteristic of the relay.

Based on the test results and the setting limitations, it was concluded that LEB may not be a reliable solution for PSB during stable power swings.

**Case 3: PSB Enabled, but LEB and OST Disabled**-All the test results showed that the PSB function successfully and consistently blocked the relay from unwanted tripping during the stable portion of the power swings. For the unstable swings, the PSB function blocked the first three to nine swing cycles of the unstable portion of the power swing before the relay tripped. In two of the tests, the relay was blocked from tripping during the entire power swing. The PSB function for the relay at Terminal B of Line A-B did not trip during the entire stable portion of the power swing. Moreover, it blocked tripping during the first nine cycles of the unstable portion of the power swing. Figure 8 provides more details on the status of the protective relay elements both during the power swing and at the moment that the relay tripped.

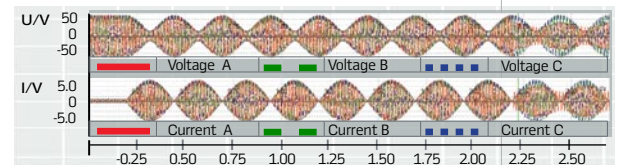
**Case 4: PSB and OST Enabled, LEB Disabled** - In all these tests, the relay tripped at the moment that the power swing evolved from stable to unstable.

**Case 5: PSB with Concurrent Line Faults** - The relay was programmed with the impedance settings shown below. Simulated

power swing data was applied to the relay (other than from the COMTRADE simulations of the SS-38 data). A 4 Hz unstable power swing was applied to the relay, and a SLG fault was simulated during the 8th swing cycle. Figure 10a shows that the relay detected the fault and tripped without any additional time delay. As shown in Figure 10b, the relay tripping time was recorded as 20.6 milliseconds.

All the test results showed the PSB function in the relay did not compromise the protection functions to detect faults on the protected line. The relay maintained a high sensitivity to the faults even during the unstable high slip-frequency portion of the power swing.

### 10a Case 5: PSB with line faults Relay response for: SLG fault simulation during an unstable power swing



### 10b Relay fault record for: Tripping during SLG fault simulation

