An Examination of Possible Criteria for Triggering Swing Recording in Disturbance Recorders

By

Leonard Swanson & Jeffrey Pond, National Grid USA

Rich Hunt, NxtPhase T&D Corporation

Presented at the

2005 Fault and Disturbance Analysis Conference

Georgia Tech

Atlanta, Georgia

April 25th – 26th, 2005

Introduction

Before the August 14, 2003 blackout, the digital recording equipment (DRE) used by National Grid USA was configured to capture transient faults through the application of magnitude triggers on voltage and current channels. Many events, including a significant power swing, surrounded the August 14th blackout. Many of the transient recording devices triggered during these events. However, because the devices triggered based on local, transient events, and produced only records of short duration, making a determination as to how this power swing affected the protection system was very difficult. There was one digital recording equipment installation that included long-term recording capability. This device was configured to capture a swing event using magnitude and rate-of-change triggers on the system frequency. This swing recording function did succeed in capturing the events of August 14th. The analysis that followed revealed a need to using long duration records to develop an understanding of events such as the blackout. National Grid determined a need to institute a consistent methodology for identifying and capturing information on power swings using digital recording equipment.

The goal of this paper is to show the process by which National Grid is developing a common methodology of setting swing recording triggers across its system, by examining the various types of triggers that can be applied. Industry work has focused on frequency rate-of-change and oscillation triggers, and National Grid considers this work to be a great foundation for the application of these triggers within the system. However, the possibility of triggering on other conditions, such as power flow, or impedance, has not been studied as thoroughly. For any trigger applied for swing recording, a key consideration is how to apply the triggers for "secure" recording to optimize the recording of swing events, where the triggers are set to capture events but not set so sensitive that a record is generated for all transient events. In the process of examining the application of triggers it is expected also for the authors to obtain a better understanding of what measurable phenomena occur during a swing event.

For modern digital recording equipment, any trigger condition can be used to initiate a long-duration swing recording. With a goal of secure recording, some triggers cannot distinguish between transient events and power swing events. Therefore, a discussion of the various quantities and triggers will be discussed in the report identifying those which could be applied to capture a swing event.

Definitions

Recording equipment is typically installed to record fault information. Initially, the information recorded was instantaneous data of short duration. This was due to the need to explain the impact of transient events on the protection system, and to the limitations of the recording equipment. Modern recording equipment can capture a variety of information, over a longer time period. When configuring such a recorder, an understanding of the type of fault to capture is necessary. Faults can be broadly broken down into power equipment faults, and power system faults. Throughout the paper, we'll use the general terms "fault" to indicate a power equipment fault, and "disturbance" or "swing" to indicate a power system fault.

Power equipment faults are short-term, rapid events, generally indicating the instantaneous failure of a piece of equipment or other unpredictable event, such as short circuits, lightning strikes, insulator failures, and similar phenomena. The protection system is designed to identify and isolate these faults rapidly, and DREs are designed to create recording based on their occurrence.

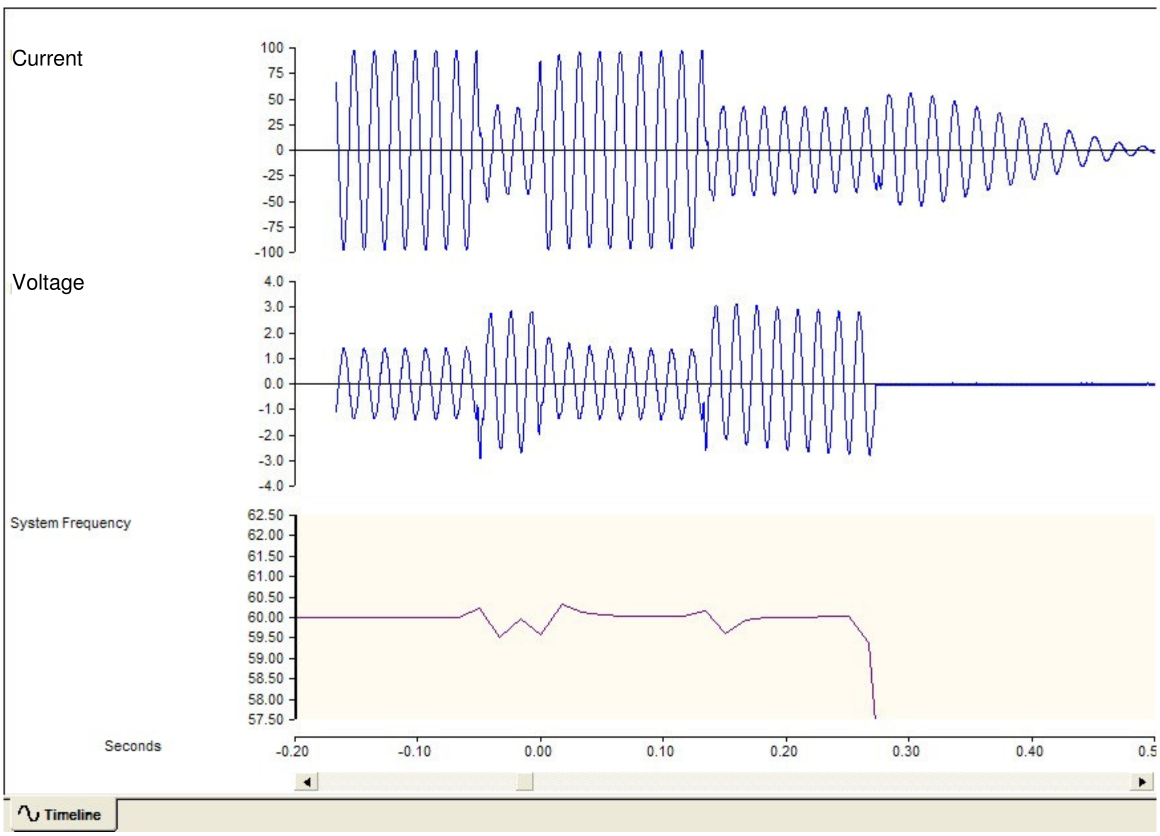

Figure 1: Power equipment fault record

In general, a power equipment fault causes an instantaneous increase in current magnitude, decrease in the voltage magnitude, increase in power, local change in frequency, decrease in measured apparent impedance, and changes in symmetrical component quantities, and is fairly localized in impact on the system. A criteria based on any one of these impacts can be used to determine the presence of a fault, and trigger a fault recording. Specifically, NERC guidelines require the use of an overcurrent trigger and undervoltage trigger to identify power equipment faults. Initiating a recording when current exceeds 120% of maximum line loading is one possible way to capture power equipment faults. Analyzing power equipment faults typically requires looking at instantaneous current and voltage data captured at a high resolution, so a sampling rate of 2000 to 6000 Hz is typical. Recording of power equipment faults is used to verify the operation of the protection system, which should clear faults in a matter of cycles, so record lengths are typically in the range of 20 cycles to 10 seconds.

Power system faults indicate a disturbance in the power system itself, caused by events such as loss of generation, loss of transmission, or out of step conditions, and may occur for several minutes of time. Power system faults tend to be system-wide faults as opposed to local faults, and are more commonly described as disturbances or power swings.

Power system faults are a three-phase symmetrical phenomenon, and are an indication of a possible instability in the power system. System stability is classified by angle stability, frequency stability, and voltage stability, with real and reactive power transferred being a consequential measure of stability. Of practical importance for recording, these faults manifest themselves as significant fluctuations, lasting from several seconds to several minutes, in current, voltage, real and reactive power, frequency, and measured impedance.

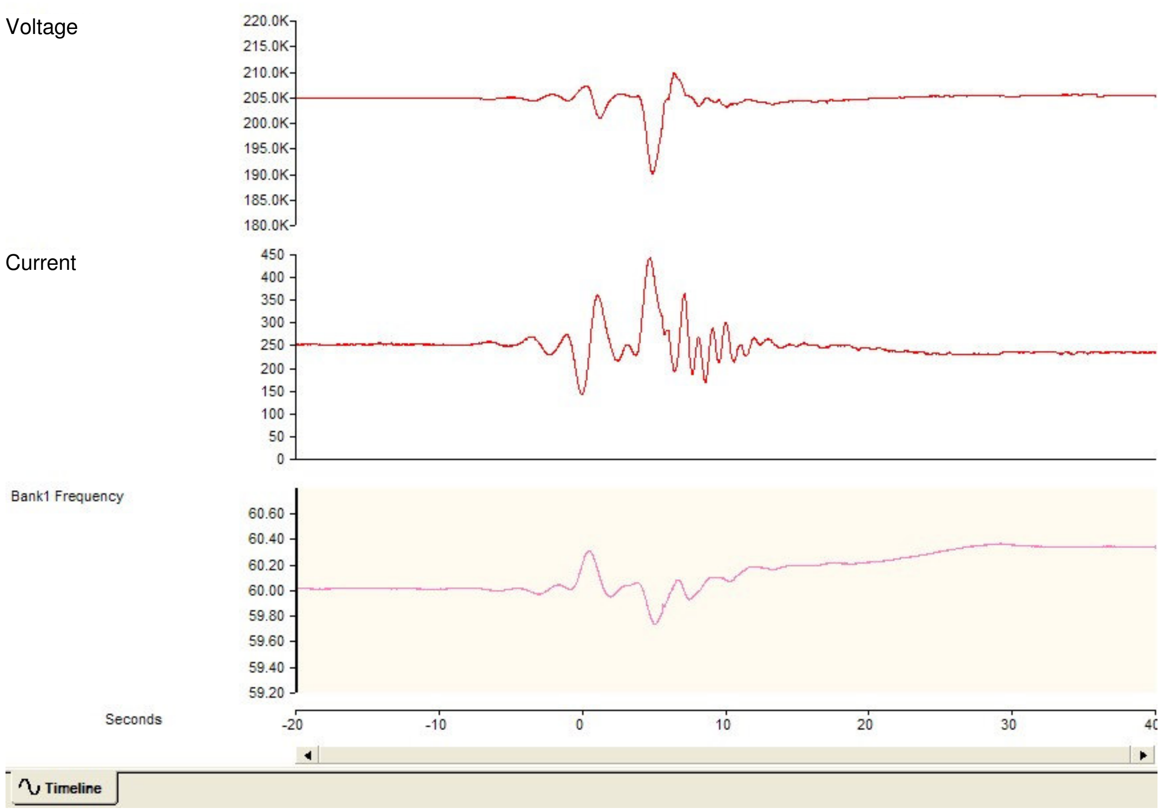

Figure 2: Power system fault (swing) record

Triggering to specifically capture only a power system fault is very difficult. Magnitude triggers and rate-of-change triggers, even when applied on power, frequency, or impedance measurements, may trigger for equipment faults, causing excessive recordings. It is the purpose of this paper to suggest several possible criteria to securely identify a power system fault. For this type of disturbance, the analysis of events is based on impacts to system stability and power transfer capability, which requires the study of current, voltage, frequency, real and reactive power, and impedance. The analysis consists of looking at fluctuations or incongruities over a time interval of seconds or minutes, so a sampling rate of 20 to 60 Hz is adequate. Record lengths need to be in the range of 30 seconds to 5 minutes to adequately capture an event. NERC regional coordinating council guidelines typically require a sampling rate of at least 30 Hz, and a record length of 3 to 5 minutes.[1]

Dynamic Swing Recorder – Digital recording equipment (DRE) is any digital equipment that can be used to capture data used to analyze faults on the power system. DREs may be capable of triggering for and recording both power equipment faults and power system faults. A Dynamic Swing Recorder (DSR) is a DRE device that has the capability to record data to analyze power system fault events. A DSR is a digital device, so the DSR is subject to issues involving measurement accuracy, analog-to-digital conversion, sampling rates, and data storage requirements. While beyond the scope of this paper, these factors must be considered when developing triggers to capture power system faults. The DSR must at least capture bus voltage, line current, real and reactive power flow, and system frequency.

Recording Power System Faults

There are several good reasons for recording disturbances or swings on the power system. One reason is identical to that of fault recording: analysis of system performance after an event. The goals are determining the cause of the event, identifying the performance of the system and individual components in the system, correcting protection system and control deficiencies, and reducing the risk of recurring misoperations.[2], [3]

A second reason is to improve system simulations, and the overall operation of the system. Measurements of the actual response of the power system can be used to benchmark system simulation models, to learn system behavior when confronted with sudden losses of generation or load, and to obtain experience in recognizing disturbances. The obvious long-term goal is to improve the system in terms of reliability and transfer capabilities.[4]

Because a power system fault is a system-wide event, swing recording is only truly beneficial when the recording gives a picture of the entire utility system during an event. Part of achieving this picture is to install DSRs at specific locations across the system. However, the actual method used to trigger for and record disturbances impacts the ability to acquire a complete system picture. Looking at just the issue of recording, there are three basic methods of recording power system faults: discrete recording, continuous recording, and wide-area recording. Each of these methods has advantages and disadvantages, and each method has been successfully employed to capture power system faults.

Discrete recording captures a record of a specific length when a trigger occurs. Triggers are set to capture a recording for disturbances as measured at the recording location. Records are typically from 2 to 5 minutes long. Records should be stored in non-volatile memory in the recorder, and the recorder should be able to store in memory records for the last 30 days. Data in the recorder should include directly measured current and voltage, as well as derived quantities including frequency, real and reactive power, and impedance. A system-wide picture is achieved by retrieving records from each DSR on the system, and manually combining the record together at a central location.

The advantages to discrete recording are that the DSR are set for local triggers only, no communications with other DSRs is required, and a finite number of compact recordings simplify data storage and data management. Providing a descriptive name for records, such as defined in "*File Naming Convention for Time Sequence Data, Final Report of IEEE Power System Relaying Committee Working Group H8*", [5] simplifies retrieval of records for a specific event. The disadvantages of discrete triggers are the possibility of not recording data for an event due to record limitations, and of not triggering locally for a system-wide event. Additionally, recorders may be limited by record length, storage capacity, and the recorder ability to process multiple records simultaneously, leading to the possibility of not capturing some event data. There is always a concern that a power system fault may not be detected by a local trigger, losing part of the system-wide picture. All DSRs need to be accurately time synchronized to be able to identify and match records.

Continuous recording continuously captures all data for all analog channels Triggers may be applied to identify key points in the record. Continuous recording typically stores the last 30 days of data in non-volatile memory, and only stores the measured current and voltage. A system-wide record is achieved by retrieving data from each DSR, and manually combining the data together at a central location.

The advantage to continuous recording is that no event data is missed, because all data is captured. There are practical challenges to continuous recording. The storage requirements for 30 days of data can be as high as 1GB of memory per channel. This requires large local storage capabilities, and increases the time required to retrieve data remotely through communications channels. Additional processing of the recorded data may be required to get derived information such as frequency, power, and impedance. Individual data points must be time-stamped, which is part of the high data storage requirements. Finding desired data for an event is difficult if some kind of triggering is not used. The data is locally recorded, so getting a system-wide picture requires manually combining records from various DSRs. Accurate time synchronization is a must to tie data from different DSRs together.

Wide-area recording uses a local trigger for an event at one DSR to trigger, via communications, all other DSRs on the system. All the DSRs create a discrete recording, or trigger a continuous recording, for the same instance in time, with the records automatically retrieved to a central location. The advantage to wide-area recording is system-wide data is captured on a local trigger, so complete pictures of disturbances are always acquired. Wide-area recording requires a reliable communications network, with a high speed network preferred, and requires accurate time synchronization of all DSRs.

Channels and Triggers for Power System Faults

DSRs typically measure, derive, and record many analog quantities. These quantities may include directly measured current and voltage, and values derived from the measured current and voltage, such as real and reactive power, frequency, impedance, power factor, and symmetrical components. Changes in any one of these quantities may be used to trigger a swing recording. When attempting to securely record disturbances, triggers can only be set with an understanding how each analog value behaves during a fault, during a swing, and during normal load fluctuations, and with an understanding of the types of triggers that are typically available in a DSR. A brief review of system behavior during faults, disturbances, and load fluctuations will help determine appropriate triggers to use to securely record a power system fault.

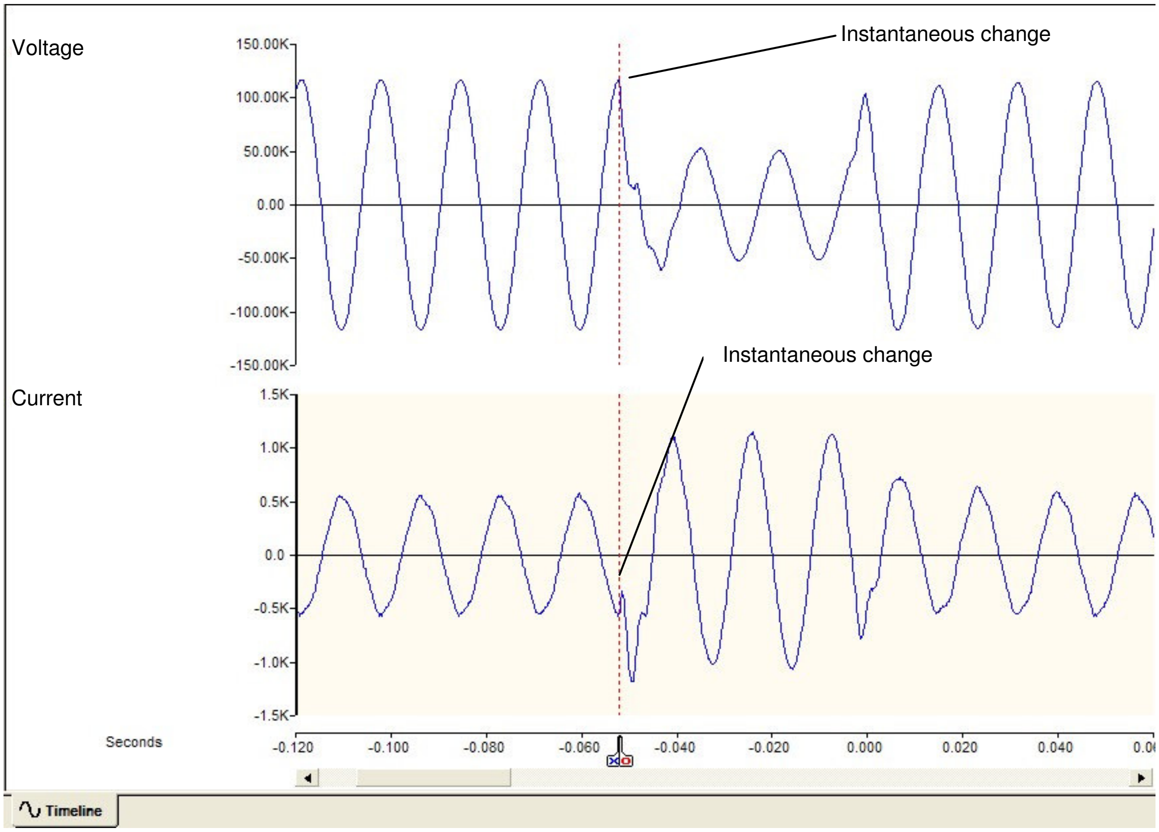

Figure 3: Power equipment fault – speed of fault inception

Power Equipment Fault: Figure 3 shows the voltage and current recorded during a typical power equipment fault. The key to note is that the current and voltage magnitude changes instantaneously during this fault event. Therefore, other derived analog quantities, including real and reactive power, frequency, impedance, and symmetrical components will change instantaneously as well. The direction of current and voltage, and all derived quantities, may change as well, and will change instantaneously. Depending on the nature of the fault, the system frequency may fluctuate quite rapidly around the occurrence of the fault.

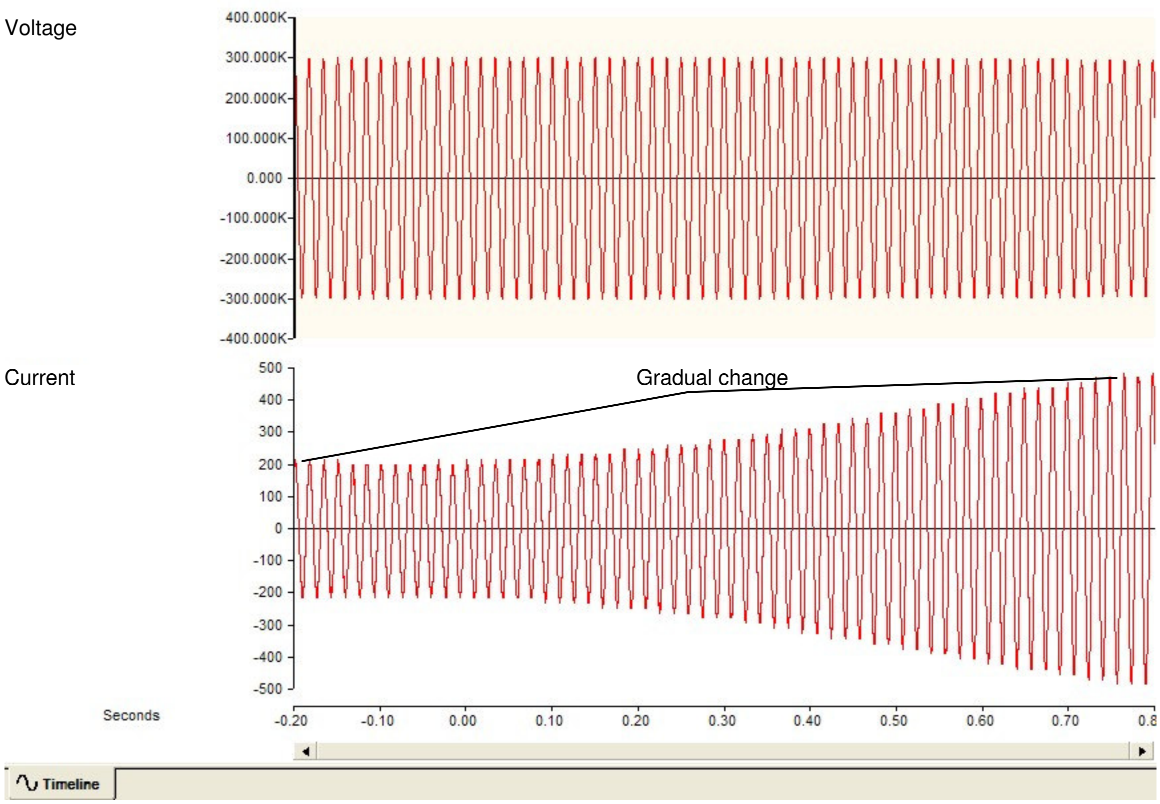

Figure 4: Power system fault – speed of fault inception

Power system faults: Figure 4 shows the voltage and current for a wide-area disturbance, captured at the fault recording sampling rate. The current magnitude is slowly increasing (from 200 amps to 450 amps in 1 second). While not evident from this graphic, the voltage magnitude is slowly changing, and the direction of both voltage and current is changing. As a practical result, real and reactive power, system frequency, and impedance are all changing. During such a disturbance, the voltage and current magnitudes may increase and decrease, and the direction of voltage and current, may change several times. Because this event is symmetrical three-phase event, only the positive sequence components of the current and voltage will be changing during a disturbance.

Load fluctuations: Load fluctuations are very similar to power system faults, in that changes are relatively slow. However, the change is normally significant only in current, not voltage, though changes in the direction of power flow are possible. The magnitude of change in the current will probably not be as high as that seen during a power system fault. Also, changes tend to occur only once during a specific time interval.

Of equal importance in secure triggering for power system faults is selecting the correct triggering method. The types of triggers typically available can be applied to any analog quantity. Triggers also include a settable time delay, typically used to ensure that a trigger condition truly exists.

Magnitude: magnitude triggers assert when the desired quantity exceeds (for a high magnitude trigger) or decreases below (for a low magnitude trigger) a set magnitude. Magnitude triggers may be applied on any of the analog quantities.

Rate-of-change: Rate-of-change triggers assert when a desired quantity exceeds a set rate-of-change. Typically, positive and negative rate-of-change triggers are provided. Rate-of-change triggers may be applied to any of the analog quantities previously described, except power factor. When setting rate-of-change triggers, it is important to understand how the rate-of-change is calculated in the recorder. The recorder may calculate a derivate of the measured quantity, or it may be simply subtracting two values over a defined time interval. The method may impact time delay settings.

Oscillation: Oscillation triggers are designed to detect oscillations in the system frequency. Oscillation triggers are designed to operate when small oscillations in the frequency, in the 0.25 – 1.0 Hz range, occur, and to not operate when major disturbances, such as loss of generation, occur. One such oscillation trigger is described in "*Northeastern US Oscillation Detection and Recording Project*" [6]. Oscillation triggers are applied to frequency only.

External inputs: A DSR may also trigger a recording based upon a binary input to the DSR from external devices. A recording can be triggered when the input asserts or de-asserts. External inputs may be received via digital input channels, or via communications. For disturbance recording, external triggers may include out-of-step protection functions, long over-reaching distance protection (Zone 3), manual initiation from system operators, or wide-area recording triggers.

Logic triggers: logic triggers use Boolean logic, or other programmable logic, to trigger a recording when a certain set of conditions is met. This allows trigger conditions to be supervised by equipment status, or to only trigger when certain measurement states exist. Logic triggers can be used with any analog quantity or any other trigger state.

When looking at the behavior of the system during faults, swings, and load fluctuations, and at the possible triggers, the use of some analog quantities and trigger combinations for swing recording can be eliminated by inspection. Table 1 lists the combinations of analog quantity and trigger type, and describes the inspection process when considering the suitability of a trigger for secure swing recording.

Table 1: Trigger possibilities

	Magnitude	Rate of change	Oscillation
Current	Triggers for faults	Triggers for faults and load	N/a
Voltage	Triggers for faults	Triggers for faults	N/a
Power	Triggers for faults and load	Possible	N/a
Frequency	Possible	Possible	Possible
Impedance	Possible	Possible	N/a
Symmetrical components	Triggers for faults and load	Triggers for faults and load	N/a

From this list, it is easy to see some trigger conditions that can possibly be used for secure recording of power swings. These include the rate-of-change of real and reactive power, the rate-of-change of frequency, frequency magnitude, frequency oscillation, impedance magnitude and rate-of-change, logic triggers, and external triggers. These possible trigger conditions will be analyzed in this paper, except for oscillation triggers. The use of oscillation triggers has been well described in "*Northeastern US Oscillation Detection and Recording Project*" [6] and "*Triggering Tradeoffs for Recording Dynamics*" [7], and was recently presented at this conference.

Possible Triggers for Power System Faults

When reviewing possible triggers for power swings the engineer must consider what he or she wants to capture. As discussed power equipment and power system faults cause changes in real and reactive power, apparent impedance, frequency, and voltage and current channels. From the preceding analysis of possible triggers it is evident that any type of magnitude trigger is best applied to power equipment faults where the abrupt changes caused by these faults have a short term effect on the above quantities. When the faulted equipment is removed from service the system again stabilizes as it achieves equilibrium. The slower speed recording is needed to capture the subsequent system fault that will occur in the event that equilibrium is not achieved and generators start to oscillate. In this instance the power, frequency, and analog quantities will change over a longer period of time, usually one second or greater. The rate-of-change trigger algorithms are better suited to capture these events. The data obtained from early monitoring systems suggests that triggering capability including power flow (real and reactive), oscillation and frequency oscillation be utilized, corresponding to system disturbances or inadequate stabilization, indicative of potential system failure [13]. The ability to time synchronize the data reliably will allow better analysis of the records obtained from various sites and help provide a clearer understanding of the event.

<u>*Power Rate-of-Change*</u>: When discussing a power system fault, the amplitude of the active power flow change is generally used to determine the severity of the event. For example, the August 14th event involved a 9000 MW power swing in the Northeast. The sign of the real power flow change can help determine the location of the event.[3]. Over a longer time frame the voltage and reactive power flow measurements can be used to help to indicate the weak parts of the system in terms of reactive power support [3].

When a generator unit trips or load is lost there is an abrupt change in power flow on the power system local to the event [7]. A magnitude trigger could be applied, however the abrupt change is typically related to a transient disturbance and quickly returns to normal after the transient condition. Also, a magnitude trigger will be less sensitive the farther away the DSR is from the actual event. A better trigger choice is a rate-of-change trigger on active power flow.

A power system fault occurs over a longer period of time and during this disturbance the power flow will change. The rate-of-change of power flow will be larger near the local event, but will be smaller the further away from the disturbance. Also, during a system disturbance there will also be a small change in reactive power as well. The positive and negative rate-of-change triggers for capturing power system faults can be applied on reactive power as well.

The setting of the trigger can be determined by power system simulation studies for various operating contingencies. These studies will generally provide settings for the smaller magnitude routine power swings. It is also possible to set the triggers by experience. The method is to set the triggers fairly sensitively, capture some records over time, and adjust the triggers to increase the recording security. This experience based method may be necessary even when empirically determining settings to achieve secure triggering.

Another consideration for the application of a power rate-of-change trigger is that during persistent oscillations in the range of 0.25 to 1.0 Hz, that are of sufficient magnitude can cause significant deviations of power flow on the transmission system [6] [8]. In this case the power rate-of-change trigger can be applied as an alternative to the oscillation trigger.

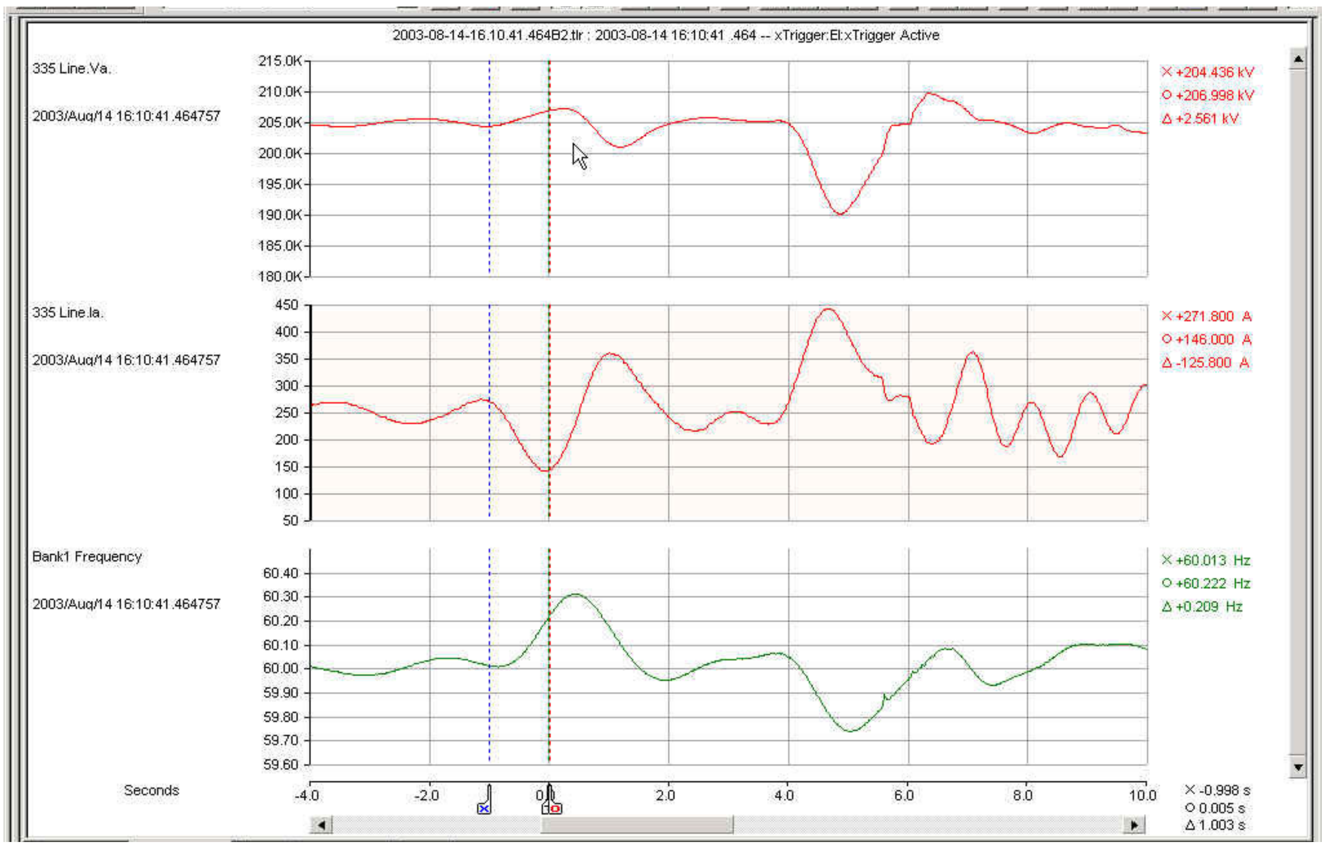

Figure 5: Voltage and Current quantities from August 14, 2003 swing event

To use a rate-of-change trigger for power and to utilize it as an alternative to an oscillation trigger requires that the setting be small enough to detect minor fluctuations in power but have it set such that it does not trigger for power equipment faults. Analysis of the recorded power swing from the August 14 blackout, as shown in Figure 5, leads to a possible trigger setting. Disturbance record analysis tools were used to measure the delta value in voltage and current over one second in the area with the smallest slope. Since the rate-of-change algorithm in this disturbance recorder calculates power per phase, a single voltage and current was used to determine a possible trigger value. A value of 0.322 MVA was the minimum change over one second calculated from the record of Figure 5. In determining a ROC setting from this value a for the power trigger setting of 0.3 MVA per second can be used as a starting point.

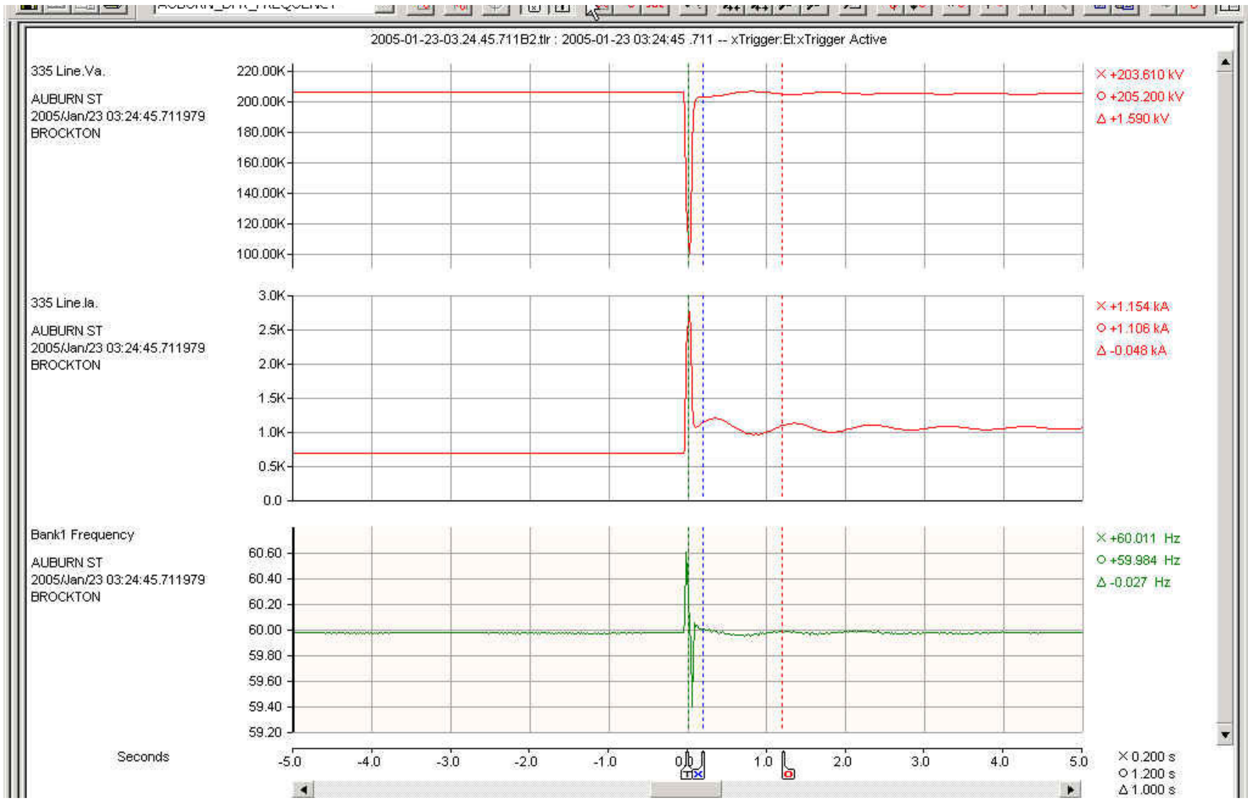

Figure 6**: Voltage and Current quantities from power equipment fault**

The real power rate-of-change trigger should be secure, so this trigger should not operate for a power equipment fault. The trace of Figure 6 is a power swing recording from an equipment fault close to the recorder location. The minimum power rate-of-change was determined by selecting the region with the smallest slope, with a calculated value of 0.076 MVA. Therefore, based on these two events the disturbance recorder is set securely, such that swing records are not generated for power equipment faults, and will be generated for power system faults.

Frequency Rate-of-Change: When a disturbance occurs there is a corresponding change in frequency, typically resulting from the tripping of a generator or the loss of a significant interconnection. Disturbances due to load loss and other causes are less frequent [10].

When a generator output is lost to the interconnection the frequency immediately begins to fall [10]. In the same way when load is lost the frequency on the interconnection begins to rise. Generators connected to the system will change speed adjusting to the new system balance. The resulting post-fault rotor angle oscillation leads to power swings [9]. During these oscillations system frequency is changing and this change is a measure of how much generation or load was removed or added in the interconnected system [3]. The slope of the local system frequency variation on its first "swing" can be used to assess how close a disturbance is located to the DSR.

The frequency rate-of-change trigger set properly is able to detect frequency transients from sudden losses of generation or load [7]. New York ISO and New England Independent System Operator have experience with using frequency rate-of-change triggers which are presently set at 20 mHz per second, with time delays in the range of 500 to 700 ms. However, the New York ISO has found that a frequency step or "delta" frequency trigger is superior to a frequency rate-of-change trigger for capturing loss of generation and loss of load incidents with less sensitivity to distance from the recorder. A report is being prepared on this now, and is intended for submission to the next FDA Conference.

Impedance: The apparent impedance of a transmission line changes during power system or equipment faults. The apparent impedance decreases as power flow increases or voltage decreases [9]. Research suggests an impedance trigger is effective especially for swings located at the electrical center.[9]

The apparent impedances can be used to evaluate the locations and impacts of system disturbances [3]. Effective application of the impedance trigger can aid in the evaluation of protection system performance by aiding the engineer in locating weaknesses in the application of impedance relay settings, particularly large over-reaching distance zones, and out of step tripping or blocking functions

The challenge with an impedance trigger is distinguishing between an equipment fault and a system fault. A pure magnitude trigger is inadequate. The magnitude trigger is typically a positive sequence impedance circle centered on the R-X origin. An impedance circle large enough to capture a power system fault is always large enough to capture a power equipment fault. Therefore, an impedance rate-of-change trigger is a better choice, as it is possible to distinguish between the instantaneous change in impedance of an equipment fault versus the slower change of a system fault.

The impedance rate-of-change requirement should look at the impedance change over a time period longer than the normal expected clearing time for power equipment faults. Looking at the change in impedance over a time of 8 cycles should be sufficient for faults at most transmission voltage levels. The minimum rate-of-change setting should be slightly larger than changes due to typical load fluctuations. If the DRE includes a maximum allowable rate-of-change, the magnitude for this setting should be less than the difference between normal load and the apparent impedance of a Zone 1 line fault.

An impedance rate-of-change trigger should only operate for fault events, and not simple load wings, so it is typical to supervise the rate-of-change trigger with an impedance circle. The use of impedance magnitude supervision limits the impedance trigger to only capturing events where the DRE is close to the electrical center of the event.

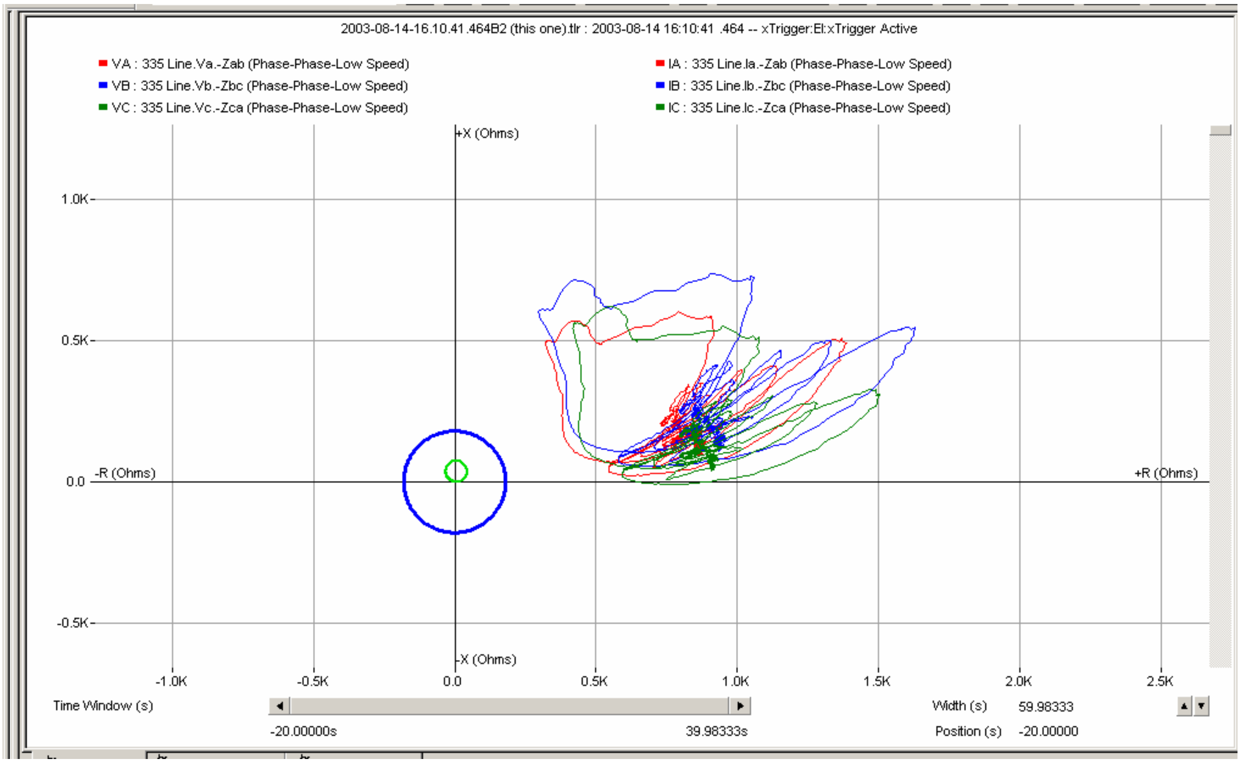

Figure 7: Impedance trigger for power swing event

National Grid plans to apply an impedance rate-of-change trigger. This specific DRE uses an impedance magnitude supervision zone. Setting this zone at maximum line loading results in the characteristic shown in Figure **7**. The impedance data of Figure 7 was recorded during the blackout of August 14th, 2003. The electrical center of the power system fault was located a great distance from the location of this DRE. The impedance rate-of-change trigger would not operate for this event. An impedance trigger is therefore only practical to use when the electrical center of a disturbance is close to the recorder location.

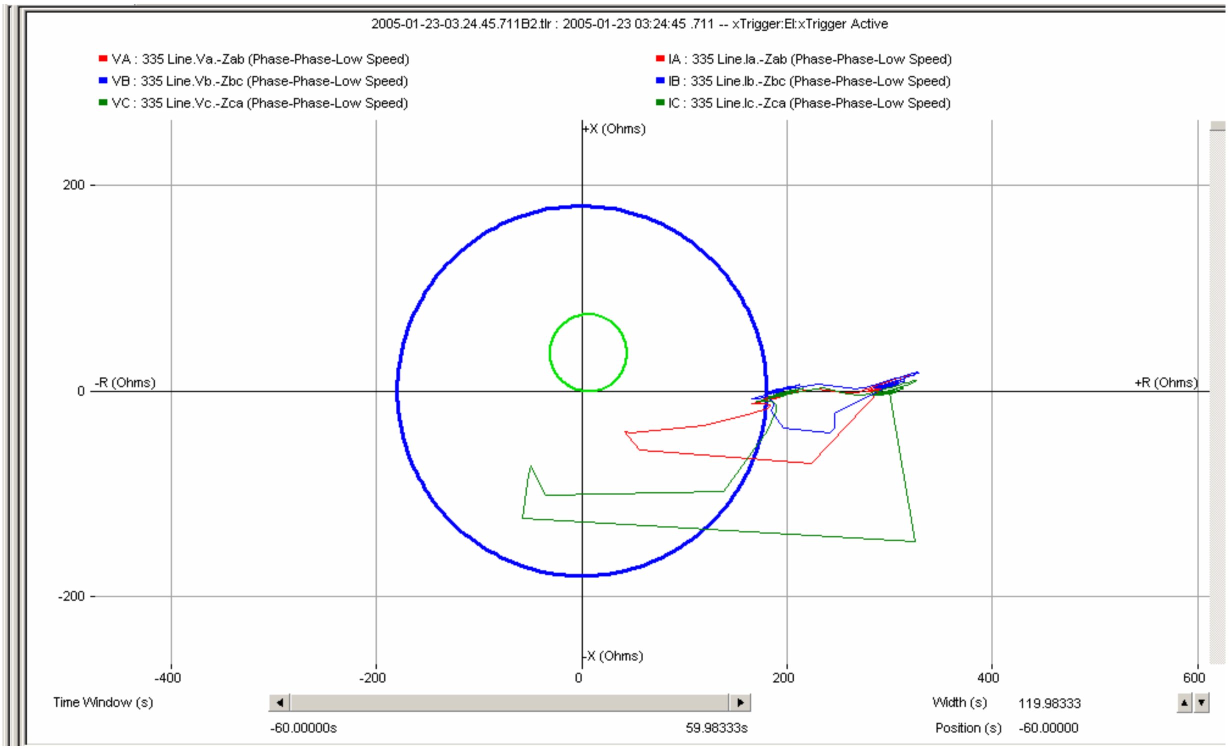

Figure 8: Impedance trigger for local fault event

For faults where the DRE is close to the electrical center of the fault, an impedance trigger is useful. Figure 8 shows a power equipment fault captured by the same DRE as in Figure 7. The fault is on a transmission line connected to the bus where the DRE is located. Therefore, the impedance trigger set for maximum line loading is adequate to detect a power swing for an event located close to the station. Therefore, the best use for an impedance trigger is to verify the performance of distance protection elements, or out of step tripping or blocking elements.

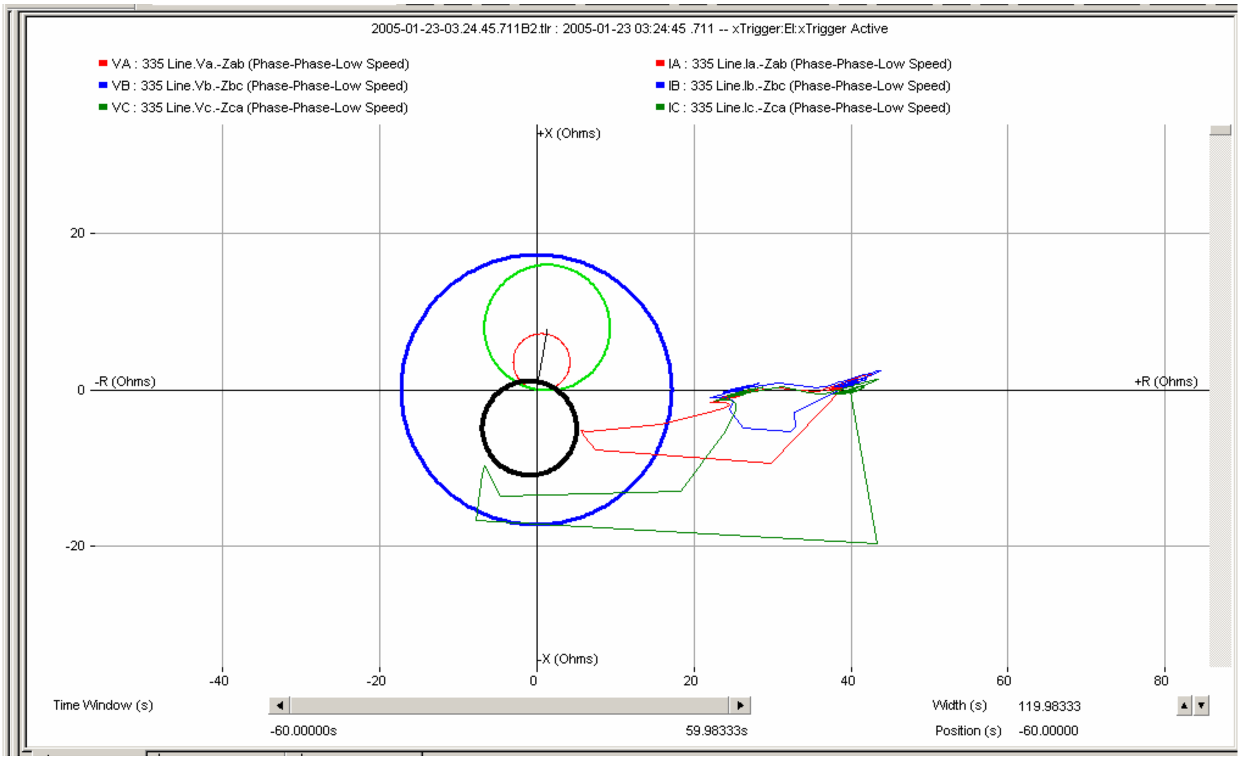

Figure 9: Impedance trigger for protection system verification

Figure 9 shows the same event as in Figure 8, with the impedance trigger set to verify protection system performance. The triggering magnitude is set slightly larger than the largest forward or reverse distance protection zone for a specific line. This record documents the correct performance of the protection system for an event: the fault did not enter an operating zone, and the relay did not operate.

National Grid plans to use impedance rate-of-change triggers, set with a magnitude supervision zone of 20% greater than the largest distance protection zone, and a minimum rate-of-change of 5 ohms (secondary) per 8 cycles.

Future Triggers to consider: The triggers under discussion in this paper are all based on individual analog quantities. There are other possible triggers for securely recording power system faults that are beyond the scope of this paper. The most obvious of these triggers is to use external devices, such as the operation of out of step tripping or blocking relays or wide-area recording triggers, to initiate a recording.

A type of trigger that is available in a modern DRE is a logic trigger that operates on the status of analog triggers and digital inputs. The logic trigger allows a combination of several analog channels to distinguish between power equipment faults and power system faults. For example, one possible use of a logic trigger is to supervise single analog quantity swing triggers with the presence of negative sequence voltage. Negative sequence voltage is quite sensitive to unbalanced conditions, and negative sequence voltage is only available during an unbalanced fault event. A logic trigger can be used to permit a swing recording only when no negative sequence voltage trigger exists. This type of trigger ensures that a swing recording will only occur when a symmetrical event occurs, and adds some additional security to swing recording.

Application

The goal of National Grid in the application of triggers for swing recording is to enhance our knowledge of the interconnected power system. Typically at National Grid, fault recording has been handled by the Protection Engineering Group for the purpose of evaluating protective relay performance during post-fault analysis. Power swing recording has typically been handled by the respective Independent System Operators for the parts of the National Grid system. However, the Transmission Planning Group at National Grid is responsible for engineering a transmission system that can achieve equilibrium after a power equipment fault or stable power system fault. Transmission Planning could use recorded swing data to verify system performance and system stability models. For specific contingencies, Transmission Planning can use system stability models to determine appropriate trigger settings to capture power swing events.

From the perspective of Transmission Planning, the desired goal of a dynamic swing recording trigger is to capture unusual events that are usually 2nd or 3rd contingencies. A 2nd or 3rd contingency event may cause a major impact on system stability. Examples of such major events the Transmission Planning Group is interested in are loss of major generation at two points in the system simultaneously or the loss of two major transmission lines simultaneously. Swing records for these events can provide the transmission planning engineers with valuable insight on system stability that will aide in design of the power system. In addition the use of dynamic swing recording equipment in National Grid bulk power stations will provide a valuable backup recorder that can support the Independent System Operators in the event of another wide area blackout, such as that of August 14, 2003.

As a result of what we learned from the performance of our digital recording equipment after the August 14, 2003 blackout, National Grid committed to a five year program of investment in our existing DFRs and new DREs to monitor the transmission system. The new DREs have the capability of setting triggers to capture transient and swing events, and also provide a level of continuous recording as well. As part of this program, National Grid is also installing disturbance recording devices in several important non-bulk power transmission stations as well as the bulk power system stations. We believe that the swing recordings from this disturbance monitoring equipment will give the Transmission Planning Group valuable insight on power system response to a swing event and the recordings can be used to verify the stability model.

The final list of substations, recording requirements, and triggers settings, are not yet complete. Transient and power swing recording requirements are currently being reviewed by the Northeast Power Coordinating Council (NPCC). The decision on how many and where to apply DSRs has not been determined. The NPCC final recommendations will provide criteria as to what level of recording is needed to effectively monitor the bulk power system.

National Grid has little experience in the application of triggers for power swing recording. However, through research we have learned that even with good trigger logic, it is natural for a system disturbance monitor to capture many routine records and occasionally miss an important disturbance regardless of sensitivity, reliability, and versatility [11]. This suggests that the best approach in the application of triggers is to use all available triggers in disturbance recorder equipment to maximize the opportunity of recording a system event. The challenge will be to set these triggers secure enough as to not generate an abundance of records that are related to normal switching events or transient conditions that are properly cleared, yet to set them to dependably trigger for power system faults.

National Grid realizes that enabling dynamic swing recording in all transmission stations that have DRE equipment is not a necessity, but we realize that it is a method of providing recording dependability, as at any time there may be a swing recorder that will fail to trigger for an event. The company plans to apply the rate-of-change (ROC) triggers for impedance, frequency, and power in installed disturbance recording equipment in the company's bulk power stations. It is our opinion that the ROC trigger is a better suited for the capturing of power system faults compared to the magnitude trigger. In addition when DRE is purchased which has an available frequency oscillation trigger it will be considered. As discussed earlier the power ROC trigger can be successfully used as an alternate to the oscillation trigger. Dynamic swing recording triggers may also be applied at non-bulk power facilities that have an inter-connection to an Independent Power Producers generation facilities.

The disturbance recording equipment currently being purchased by National Grid allows for the application of the frequency rate-of-change trigger on two sources per recorder. It is our intention to apply these to potential circuits with a preference for monitoring the bus potentials. The trigger setting will be that used by the NY ISO, 20mHz per second. The NYISO also has published the results of their experience with the oscillation trigger as well and it will be considered for use when available. When applying the oscillation trigger, National Grid will use the same 0.25Hz setting as used by NY ISO for the oscillation trigger.

Power ROC triggers can be used for real and reactive power. National Grid will use the ROC trigger for real power only. It is our opinion, based on observed recordings of real and reactive power flows, it will not be possible to set a reactive power rate-of-change trigger securely, since, VARs on the power system tend to vary during light load periods. At least two transmission circuits will be selected for application of the power rate-of-change trigger in each bulk power station. As experience is obtained with this trigger it may be applied to more circuits, as research indicates this trigger may be an effective substitute to the frequency oscillation trigger.

The Impedance ROC trigger will be applied in National Grid's bulk power stations as well. The trigger will initially be applied at each monitored voltage level in bulk power stations. The goal of using the impedance trigger will be to verify the correct performance of distance protection elements during power system faults and during maximum load periods.

The Transmission Planning Group will run simulations in the transient stability model to determine a base for developing 'rate-of-change settings for power and impedance based on these contingencies. However, we will also use the swing recording obtained from the one DRE during the August 14, 2003 blackout, and recordings from two other system events where a power swing recording was generated to determine some general setting guidelines. It is our opinion that since this device was far removed from the center of the events that caused the blackout that it will provide valuable insight into what the possible trigger settings should be to capture system response remote to a power system and power equipment fault.

Summary

Through this evaluation of possible triggers National Grid has learned that in order to establish setting criteria for swing recording triggers it is best to run some transient stability simulations models, taking into account the type of events where a dynamic swing recording will help to better analyze a power system fault. However, experience in the application of these triggers is needed to fine-tune each application of triggers. Since many of the triggers will be set on second and third contingency cases per Transmission Planning criteria, the setting review will take time.

The DRE triggering algorithms need settings that dependably and securely detect unusual system events in the presence of normal power system events such as switching, customer load changes, and other routine operations [7]. However, research suggests that it is best to set trigger levels to be dependable (sensitive) for new installations in order to benchmark system response, because there is little recorded experience working with triggers, with the exception of frequency rate-of-change and oscillation triggers. Each application of triggers should be monitored and tuned with at least several weeks of continuous data from the DRD site, with the triggers set intentionally to be dependable [7]. A dependable trigger setting will allow for the evaluation of system events for comparison to the stability model. Then as data is collected and analyzed to increase the security of the triggers in order to capture only those desired abnormal system events.

Transient recordings will be sufficient to analyze the majority of power system events. Swing recordings will be occasionally analyzed for the unusual system events that need to be explained further. These swing records will also provide a backup recording to ISO installed dynamic swing recorders, because it is possible for a swing recorder to not capture an event when needed because the triggers did not sense the event or there was a failure of a DRE.

National Grid's Protection Engineering Group will work with the Transmission Planning Group to determine rate-of-change trigger settings that should capture the 2nd and 3rd contingency events of interest. Initially, however, the trigger settings discussed in the paper will be used for a few circuits in selected locations so that the value of the captured data can be determined. The power rate-of-change trigger will be used to capture larger area system events, where the impedance rate-of-change trigger will be utilized to evaluate protection system performance. The trigger settings will be fined tuned as experienced is gained and the settings become more secure. Once the settings methodology is developed and proven, the monitoring program will be expanded to include all disturbance recording equipment that is capable of dynamic swing recording.

References

[1] MAAC Requirements for Installation of Disturbance Monitoring Equipment, document B-6, MidAtlantic Area Council – MAAC – 2001.

[2] Benefits of Power Swing Recording, A. Klimek, R. Baldwin, 7th Annual Georgia Tech Fault and Disturbance Analysis Conference, April 26-27, 2004.

[3] Dynamic Data Recording in the New England Power System and an Event Analyzer for the Northfield Monitor, A. Bykhovsky, J. H. Chow, VII Symposium of Specialists on Electric Operational and Expansion Planning (SEPOPE), Curitiba, Brazil, May 2000.

[4] Long Term Recording, D. Bertagnolli, 4th Annual Georgia Tech Fault and Disturbance Analysis Conference, May 1, 2001.

[5] File Naming Convention for Time Sequence Data, Final Report of IEEE Power System Relaying Committee Working Group H8, IEEE Power Engineering Society Power System Relay Committee Report.

[6] Northeastern US Oscillation Detection and Recording Project, D. B. Bertagnolli, X. Luo, J. W. Ingleson, J. H. Chow, J. G. Allcorn, H. I. Mehta, D. Dickens, J. P. Hackett, 7th Annual Georgia Tech Fault and Disturbance Analysis Conference, April 26-27, 2004.

[7] Triggering Tradeoffs for Recording Dynamics, R. P. Schulz, B. B. Laios, IEEE Computer Applications in Power, April 1997.

[8] Dynamic Recording Devices (DRD) in New England Power Pool, D. Bertagnolli, X. Luo, R. Kowalski.

[9] Analysis of Angle Stability Problems: A Transmission Protection System Perspective, S.A. Soman, T. B. Nguyen, M. A. Pai, R. Vaidyanathan, IEEE Trans. On Power Delivery, Vol. 19, No. 3, July 2004, p 1024-1033.

[10] Decline of Eastern Interconnection Frequency Response, J. Ingleson, M. Nagle, 2nd Annual Georgia Tech Fault and Disturbance Analysis Conference, May 3-4, 1999.

[11] An Oscillation Detector Used in the BPA Power System Disturbance Monitor, J. F. Haure, F. Vakili, IEEE Trans. On Power Systems, Vol. 5, No. 1, Feb 1990, p 74-79.

[12] Report: Dynamic Disturbance Recording in New York, Approved by the TPAS at the May 4-5, 1999 Meeting.

[13] Disturbance Recorders Trigger Detection and Protection, R. J. Murphy, IEEE Computer Applications in Power, January 1996.

About the Authors

Jeffrey Pond has been an employee of National Grid USA for 24 years. He is a Lead Technician on the Substation Systems Integration Team, where he is responsible for the selection and configuration of disturbance recording equipment and RTUs. He has implemented a program to automatically retrieve transient event data from relays and fault recorders. Previously Jeff worked for the Relay and Telecommunications Operations Group, where he was responsible for commissioning, maintaining, and troubleshooting protection and control systems. He also assists the Protection Engineers in performing post-fault analysis of transmission system operations.

Jeffrey received an Associate degree in Electrical Engineering Technology from Wentworth Institute of Technology, in Boston, MA, and a Bachelor of Science degree in Business Management from Lesley University in Cambridge, MA. He is a member of IEEE and is active in several working groups of the Power System Relaying Committee.

Len Swanson has been an employee of National Grid USA for 10 years. He is a Lead Senior Engineer in the New York Protection Engineering Group, where he is responsible for the designing protections systems, performing post-fault analysis of system operations and involved with the selection and configuration of disturbance recording equipment. Previously Len worked for Cutler-Hammer in the Distributed Generation Group responsible for designing and commissioning of small generation projects and PG&E National Energy in the Engineering Group responsible for electrical support for the existing and new generating plants.

Len received a Bachelors Degree in Electrical Engineering from Gannon University in Erie, PA, and a Masters Degree in Electrical Engineering from Northeastern University in Boston, MA. He is a member of IEEE and a registered professional engineer in MA and PA.

Rich Hunt, M.S., P.E. is presently a Senior Field Application Engineer for NxtPhase T&D Corporation, responsible for technical marketing, technical sales, and technical support of optical current and voltage sensors, and protective relays and fault recorders. Rich has over 10 years of utility experience at Virginia Power and the University of North Carolina, as well as over 6 years of industry experience. Rich earned his M.S.E.E at Virginia Tech under the guidance of Dr. Arun Phadke, with a thesis topic entitled “Hidden Failure in Protective Relays: Supervision and Control”. Rich is a member of the Main Committee of the IEEE PSRC, and is a Professional Engineer licensed in the Commonwealth of Virginia.