Northeastern US Oscillation Detection and Recording Project

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David B. Bertagnolli[a], Xiaochuan Luo
ISO New England

James W. Ingleson, Joe H. Chow[b], J. Gregory Allcorn
New York ISO

Mark Kuras
PJM Interconnection

Harish I. Mehta, Dick Dickens, James P. Hackett
Mehta Tech, Inc.

Abstract

Occasional oscillations have been observed and reported in our area over a period of years. One of the modes of interest to us has a frequency in the vicinity of 0.5 Hz, and seems to be an oscillation across the NY-NE Interface. Acting as a group, three ISOs in the Northeastern US initiated a project to design and implement a trigger for certain of our dynamic swing recorders (DSRs), a trigger specifically designed to detect oscillations in power system frequency. While this triggering capability has only been in service for less than a year, the performance of the trigger appears to be very good. We are collecting data when these oscillations occur and hope to eventually correlate our experience with changes in system configurations or conditions

In this paper we will describe the objective of this project, the specific phenomena that we want to detect, how the trigger was specified and implemented, and, in general terms, how our trigger algorithm works. We will also show some data that have been collected and discuss the results to date.

1. Introduction

In 1990, the New England Power Pool (NEPOOL) installed a dynamic swing recorder (DSR) at the Northfield 345 kV substation in Massachusetts to capture frequency and line flow data [1,2]. This device successfully implemented a flexible triggering

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[a] Contact Author: D. Bertagnolli (413-535-4330), dbert@iso-ne.com

[b] Also Professor of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute

mechanism that was adapted, or “tuned” to capture events of interest. Over the years this recorder, mainly through the rate of frequency change trigger, accidentally captured several records that showed sustained oscillations. These oscillations were in the range of 0.25 to 1.0 Hz, which is also the frequency range at which transient stability simulations indicated the system would oscillate. It was apparent over a period of years that NY and NE Areas participated in 0.25 Hz oscillations together, however 0.5Hz seemed to be a mode of oscillation of NE against NY. Because the nature of these oscillations is not well understood, NEPOOL needed a reliable detection mechanism. Recording these types of phenomena would provide insight into how often these oscillations occur, how long the oscillations persist, and their magnitude.

Because the Northfield recorder was so successful, NEPOOL selected Mehta Tech Inc., the recorder supplier, to develop an oscillation trigger using the Northfield recorder as a host platform. The NYISO supported this development by developing an oscillation trigger algorithm and replicating the oscillation trigger on a Mehta Tech unit at Edic. Figure 1 shows the locations of the Northfield and Edic substations and a future installation at Athens substation. Also shown in Figure 1 are the locations of seven Mehta Tech IEDs located on the New England transmission system and one on the PJM transmission system. These IEDs are capable of providing time-synchronized frequency measurements. They, however, are not yet equipped with the oscillation trigger logic.

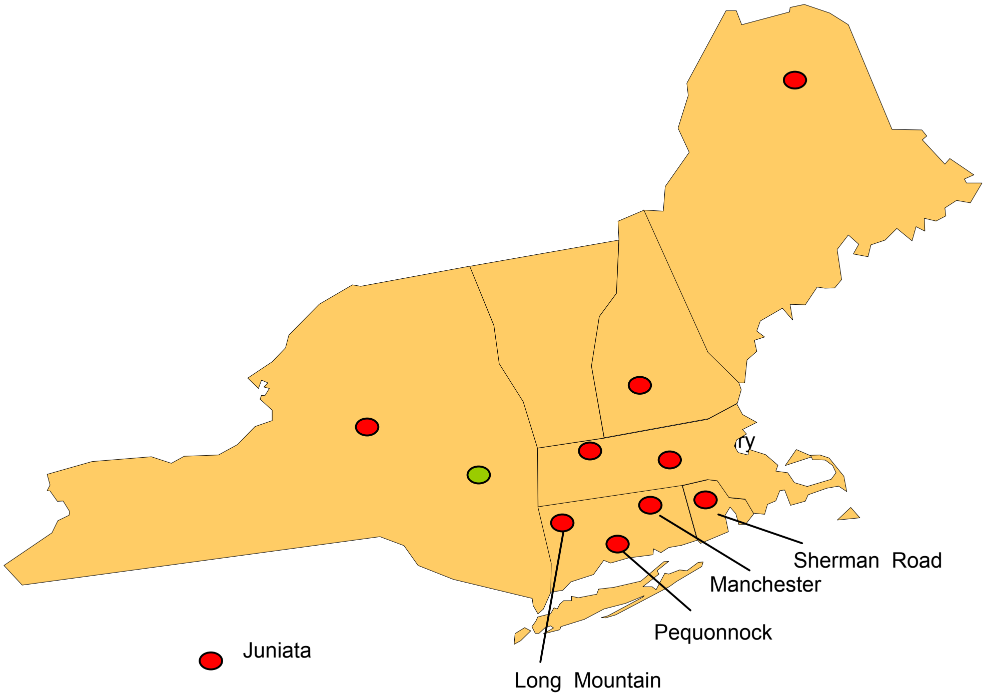

Figure 1. Map of New England and New York showing locations of various recording devices

2. Northfield and Edic DSRs

These DSRs are implemented using a Mehta Tech TRANSCAN DFR/DSR hardware platform, configured through software to meet the specific requirements for the swing recorder (see Figure 2 for a TRANSCAN block diagram). The recorder receives a precise time reference from a satellite clock and has the capability of handling a large amount of input data (up to 64 channels at up to 96 samples per cycle) and, most important of all, software based triggering with remote access (via modem) to the recorded data as well as to all triggering software and parameters. The recorder is equipped with host processor, RAM memory, hard disk, modem, data collection modules and multiple digital signal processors (DSP's). Parameters used to control operation of the recorder (triggering thresholds, length of events, etc.) reside in non-volatile memory (EEPROM) and are copied into RAM when the recorder is powered-up or re-booted. Changes to these parameters can be accomplished without visiting the substation using the master station and telecommunications.

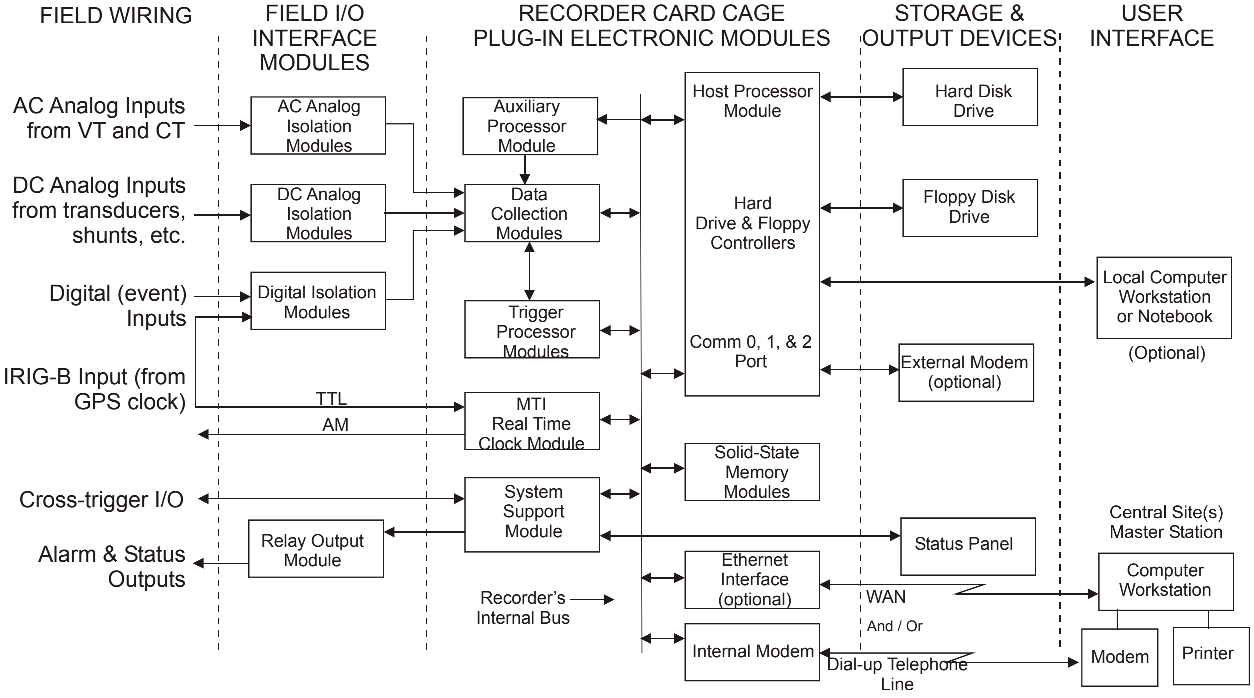

Figure 2 TRANSCAN Recorder system block diagram

The initial system specification required triggering on absolute frequency, rate-of-change of frequency, rate-of-change of voltage, power deviation, etc. To meet these requirements, several enhancements to the original fault recorder design were made. First, the original trigger processor was replaced with a more powerful DSP module.

Second, the capability to use multiple trigger processors was added to the recorders' software. Finally, the ability to retain data at a slower rate while using a higher collection/processing rate for triggering was implemented. These enhancements made the required triggering possible and offered the capability to add any new triggers that might be desired.

In the frequency deviation detection trigger, the incoming analog signal is converted to a phasor quantity. The consecutive phasors are compared to determine the change of phase over time to determine frequency. The frequency is averaged using a low pass filter with a bandwidth of 3 Hz. Triggering occurs when the absolute value of the calculated frequency exceeds the quantity entered for Frequency Band Hertz difference.

In the rate-of-change of frequency trigger, the incoming analog signal is converted to a phasor quantity. The consecutive phasors are compared to determine the change of phase over time to determine frequency. Frequency is averaged with a lowpass filter with a 3 Hz bandwidth. From these values, the rate of change of frequency is determined. Triggering occurs when the absolute value of the calculated rate of change of frequency exceeds the quantity entered for *df/dt* in Hertz per second and persists for longer than the period of time (expressed in milliseconds) entered for *df/dt* delay.

The trigger algorithms that were developed included considerable sophistication for filtering, time response, numeric analysis, etc. This sophistication allowed the trigger parameters to be tailored for the particular substation at which the devices would be installed. For example, the first recorder was installed at a substation to which four pump storage units were connected. The tripping of each unit caused a very fast but brief change in the system frequency which would trigger the recording of an event. The parameters associated with each trigger (time delay, reset, etc.) were set to reduce the number of these events being captured. Trigger blocking capability was also provided and could be used to further reduce the number of unwanted events being captured.

The Northfield DSR was configured to use measurements on only one phase, although the basic design permits the use of all three phases. This was done because stability simulations assume that the post-fault response of the power system is balanced in the three phases. This feature has provided very good results and reduces, by two-thirds, the amount of data needed to process and store.

Additional processing was required at the master station beyond the capabilities normally provided with a fault recorder. Automatic polling and plotting was provided so that the swing recording system did not have to be attended frequently. Software was also provided to convert the recorded data into a format compatible with the simulation software.

Detailed descriptions of the Northfield and Edic DSRs are given in Figure 3.

1. System Description

1.1	Type	Dynamic Swing Recorder
1.2	Name	TRANSCAN™ Recorder System
1.3	Manufacturer	Mehta Tech Inc.

2. Input

2.1	No. of Input Channels	
2.1.1	Northfield	5 analog, 16 digital
2.1.2	Edic	10 analog, 8 digital
2.2	Triggering Quantity	Programmable
4.3	Trigger Levels	Adjustable
2.4	Frequency Resolution	0.1 mHz (uses 12 bit A/D: 11 bit + sign)

3. Output

3.1	Measured Quantities	
3.1.1	Northfield	1 bus voltage, 2 line and 2 transformer currents
3.1.2	Edic	2 line voltages, 8 line currents
3.2	Calculated Quantities	Programmable
3.3	Sample Rate	Presently programmed to 48 samples per cycle (2880 Hz)
3.4	Pre-trigger Coverage	Programmable
3.5	Minimum Event Coverage	Programmable
3.6	Maximum Event Coverage	Programmable
3.7	Post Event Coverage	Programmable

3.8 Data Storage & Retention Period

Data is stored in RAM and automatically transferred to a hard drive for on-site non-volatile storage. Operation of hard drive is not essential to capturing a record. Data may be down-loaded and stored indefinitely off-site.

4. Triggers

4.1 Triggers currently active

4.1.1 Northfield

Frequency Over and Under, Frequency Rate-of-change, Frequency Oscillation

4.1.2 Edic

Frequency Over and Under, Frequency Rate-of-change, Frequency Oscillation

5. System Features

Multiple Digital Signal Processors (DSPs) provide fast calculations between sample points. DSP software calculates phasor quantities and provides signals to initiate event storage.. Storage of only primary measured quantities (voltage, current, digital inputs) and exact emulation of DSPs on the master station provides exact re-creation of system events and triggering. Each event record contains GPS/GOES time signal encoded in IRIG-B format for sub-millisecond accuracy.

6 Installation & Upgrades

6.1 Northfield

Installed in 1990 with major upgrades in 1994 and 2002 to permit implementation of new features and functions, resulting in the Northfield DSR being of current generation technology.

6.2 Edic

Installed in 1991 with a major upgrade 2003 to permit implementation of new features and functions, resulting in the EDIC DSR being of current generation technology.

Figure 3. Northfield (ISO-NE) and Edic (NYISO) DSR descriptions

3. Adaptive Oscillation Trigger

3.1 Specifications

1. The trigger must initiate recording when phenomena of interest are detected. The phenomena of interest are persistent oscillations in the range of 0.25 to 1.0 Hz and of such magnitude to cause significant deviations of power flow on the transmission system.

2. The pre-trigger and post-trigger recording time must be sufficient to capture the beginning and the end of the oscillation. If the trigger condition is detected again while recording is in progress, recording should continue until the magnitude of the oscillation drops to a level that no longer meets the trigger conditions.

3. The oscillation records should be retrieved to the master station through modem over dedicated telephone lines. The user should be able to modify the settings of oscillation trigger at the master station, and upload the configuration of oscillation trigger to the remote recorder through modem over the telephone lines.

4. For further analysis, the recording data that is originally in Mehta Tech format should be converted to PSS/E RAWC format so that Prony analysis can be used to analyze the oscillation frequency and damping ratio. Converting to PSS/E RAWC format also provides the ability to benchmark the dynamic simulation using the PSS/E with the actual recordings.

3.2 Design Concept

The oscillation trigger needs to be designed to selectively detect only median to high level of lightly damped oscillations with periods of 0.25 to 1 Hz. An example of such an oscillation is shown in Figure 4a [1]. Other events that cause large transients but well-damped oscillations, such as the loss of generation event shown in Figure 4b [2], should not cause the oscillation trigger to initiate recording, because such events are detected by the *df/dt* trigger.

Two of the main criteria in the oscillation trigger design are:

1. The trigger is to detect lightly damped oscillatory modes in the frequency variable with median to high peak-to-peak amplitude. Thus the trigger needs to be adaptive with respect to the amplitude of the oscillation, so that the rate of decay, which determines the damping, is properly accounted for.
2. The computation for determining the triggering should be minimal, so that the real time computer code can be readily executed in the DSP of a dynamic swing recorder, which usually has many other functions to perform.

The schematic of the proposed oscillation trigger is shown in Figure 5. The running average of the system frequency, f_{ave} , is first subtracted from the frequency variable.

Then the signal is sent through a lowpass filter to remove any noise components. For ease of implementation, an FIR (finite-impulse response filter) is used.

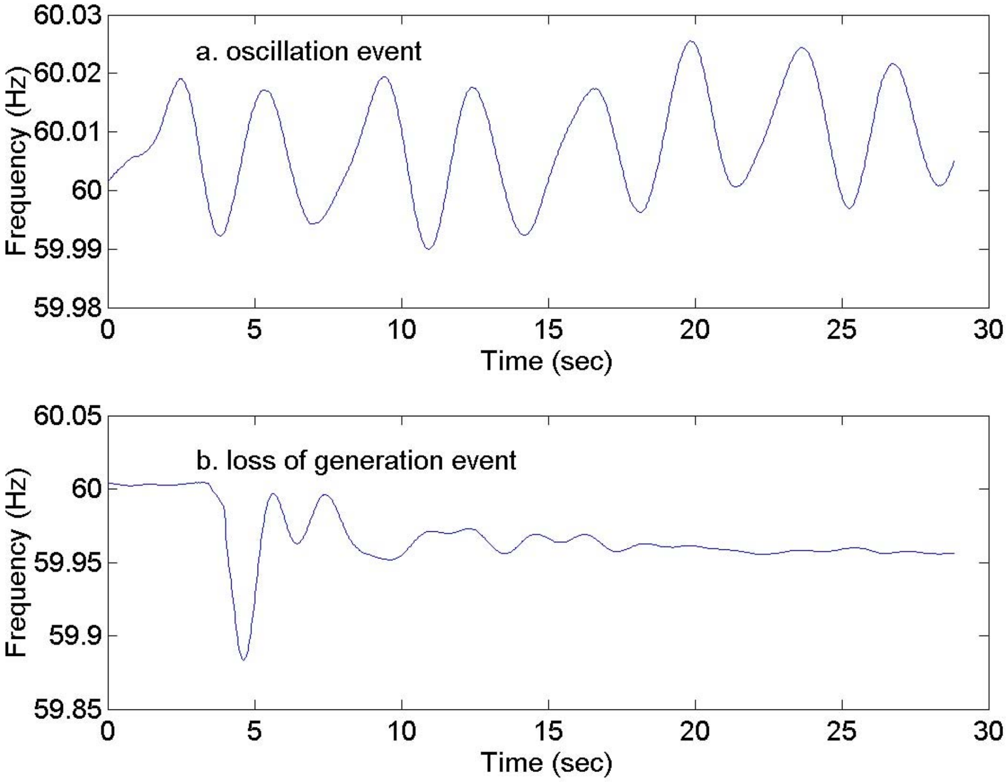

Figure 4. Recorded event at Northfield, (a) an oscillation event, and (b) a loss of generation event

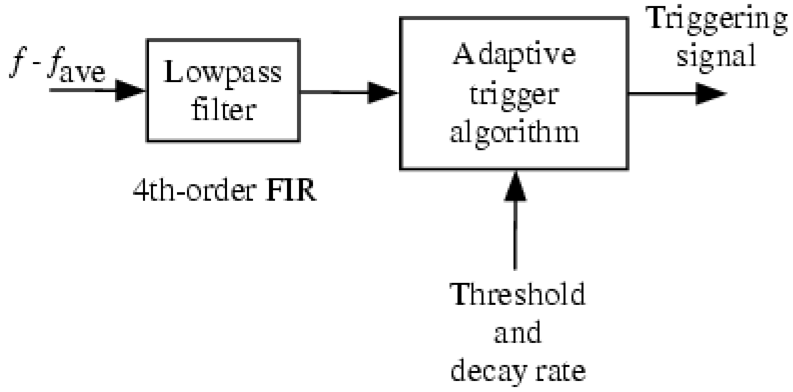

Figure 5. Schematic of the Adaptive Oscillation Trigger

The design of the adaptive oscillation trigger is based on an ideal decaying sinusoidal signal as shown in Figure 6, in which the time axis is normalized with respect to the oscillation period and the amplitude is scaled to represent a maximum of about 20 mHz. A decay envelope is established, which is determined by the damping ratio of the oscillation. This decay envelope is defined by the initial peak *A* and the ratio of the successive peaks *r* = *A/B*. The initial peak *A* is determined using a simple peak searching algorithm and thus is a function of the specific disturbance. The ratio *r* is a user input, which can be tailored to the detection objective. For example, if a damping ratio of 0.1 is deemed appropriate, then *r* can be set to 0.532. To prevent the oscillation trigger from detecting spurious low-level noise-like oscillations, a threshold can be specified such that the trigger will stay dormant when the frequency variation is below the threshold.

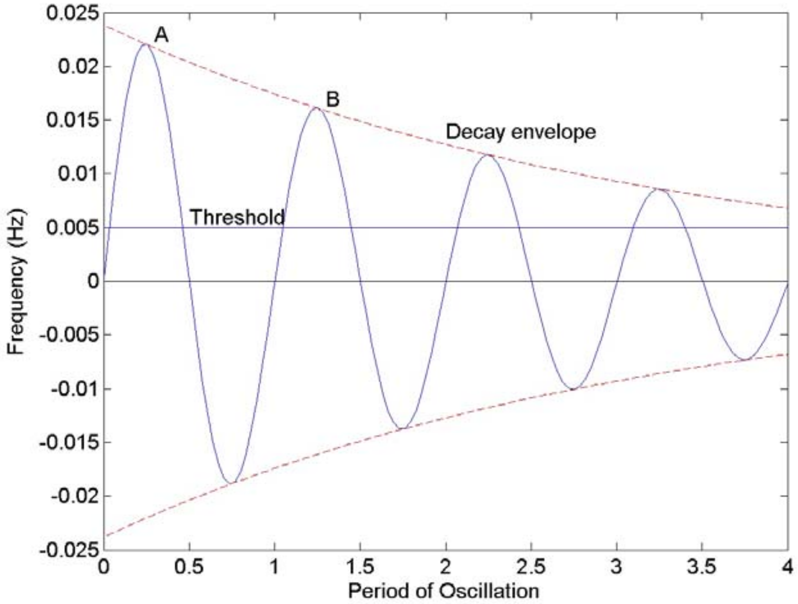

Figure 6. Oscillation trigger design concept

Once a frequency excursion beyond the threshold is detected, the algorithm will determine, as the data is being recorded, the first peak *A*. From the peak *A* and the ratio *r*, the decay envelope can be determined. The algorithm then proceeds to detect the subsequent peaks of the oscillations. In the ideal situation, only the next peak is needed to determine whether the oscillation remains within the envelope. In a practical situation with non-ideal oscillatory signals, if two out of the three successive peaks exceed the decay envelope, the algorithm will send out a triggering signal to record the data. In a simulated testing of the algorithm, the oscillation trigger was successful in detecting oscillation events such as those similar to that in Figure 4a, as well as not triggering on loss of generation events such as those similar to that in Figure 4b.

The recordings have been evaluated for oscillations. Analysis of the recordings has shown the oscillation trigger algorithm to be robust for our application. It is considerably simpler for real-time applications than algorithms proposed in published literature [4] intended for post-processing data.

3.3 Implementation

The incoming signal, galvanically isolated, is digitized to 12 bits, which includes a sign bit. The signal is converted into a phasor, which is used to derive the frequency. To enhance computational resolution, the expected 60 Hz is subtracted from the signal to obtain the frequency deviation. The frequency deviation signal is then passed through a bandpass filter with a bandwidth of 0.2 Hz to 3 Hz.

The oscillation trigger involves finding the peaks (positive and negative) of the frequency and determining the peak-to-peak variation. The first threshold is user settable. Once it has been violated, the new threshold is computed to be a fraction of the last value. When this threshold falls below a user settable minimum, the detection algorithm is reset. The peaks are counted (an up/down counter) and when enough peaks have been detected a signal is issued. This and all other signals appear to the main DSP as event inputs and are subjected to event triggering conditions. If no peak is detected within a user settable time limit, the detector is reset.

3.4 Field Testing and Set-Up

The Oscillation Trigger was installed at Northfield DSR in November 2002. Table 1 lists the major parameters that are currently used at Northfield DSR.

Table 1. Major Parameters at Northfield DSR

Pre-trigger data	21 buffers (29.867 seconds)
Post-trigger data	21 buffers (29.867 seconds)
Over/Under Frequency Deviation trigger	80 mHz
Rate-of-change Frequency trigger	20 mHz/second
Oscillation Trigger:	
Original Threshold	10 mHz
Peak Decay Ratio	0.3
Peak Counter	4

Each buffer of Northfield DSR is 65,536 bytes. With 21 buffers of pre-trigger data and 21 buffers of post-trigger data, the size of each record is 2.688 MB.

Before installing the oscillation trigger, the pre-trigger data was set to 3 buffers, which is approximately 4.3 seconds. This pre-trigger data is good enough for the over/under frequency trigger and frequency rate-of-change trigger. However, it was found out that 4.3 seconds of pre-trigger data was too short to capture the startup of the oscillation. Therefore the pre-trigger data was adjusted to 21 buffers, which is about 29.867 seconds. Records at Northfield have shown that this amount of pre-trigger data has recorded the startup of the oscillation adequately. The process of field testing and set-up is being repeated at Edic.

Right after the installation of the oscillation trigger, the Original Threshold was set to 30 mHz (changed to 20 mHz two weeks later) and the Peak Decay Ratio was set to 0.1. The oscillation trigger recorded no data in that month. The Original Threshold was then changed to 5 mHz and the Peak Decay Ratio was changed to 0.3. Too many records were captured by the oscillation trigger after the change and the hard drive of the DSR was filled up quickly. By trial and error, the current setting, Original Threshold at 10 mHz and Peak Decay Ratio at 0.3, has captured necessary system oscillation information without losing important data and without getting excessive amount of data.

4. Recorded Event Analysis

Many events were recorded at Northfield and at other locations since the oscillation trigger was installed. For this investigation, we classify the records into three categories: events captured by the rate of change of frequency trigger but not by the oscillation trigger, events recorded by the oscillation trigger only, and events recorded by multiple triggers. In the following, we show some representative events.

4.1 Events Captured by Rate-of-Change of Frequency Trigger

Most of the recording events were initiated by the rate of change of frequency trigger, caused by the sudden loss of a generator. Figures 7 and 8 show the frequency traces from a number of locations in the system for the loss of a 900 MW unit within the New England area. The initial drop in frequency was followed by a few well-damped oscillations, indicating that the system has been designed to "absorb" such type of disturbances. These oscillations, although large in amplitude, did not arm the oscillation trigger, because they decayed too fast.

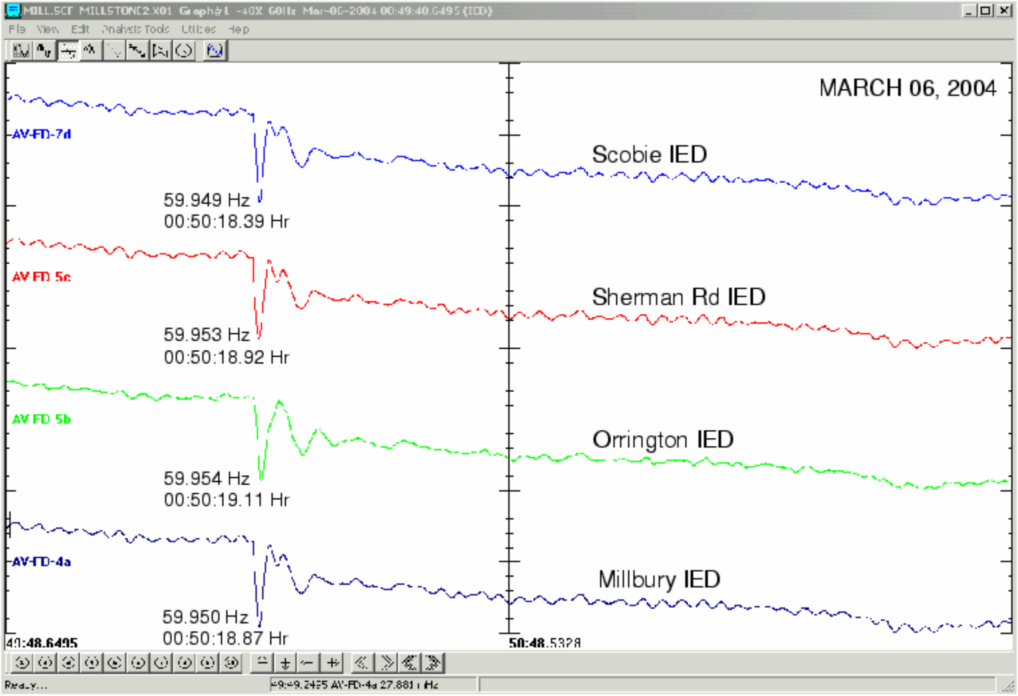

Figure 7. Loss of generation in New England, recorded at four different IEDs

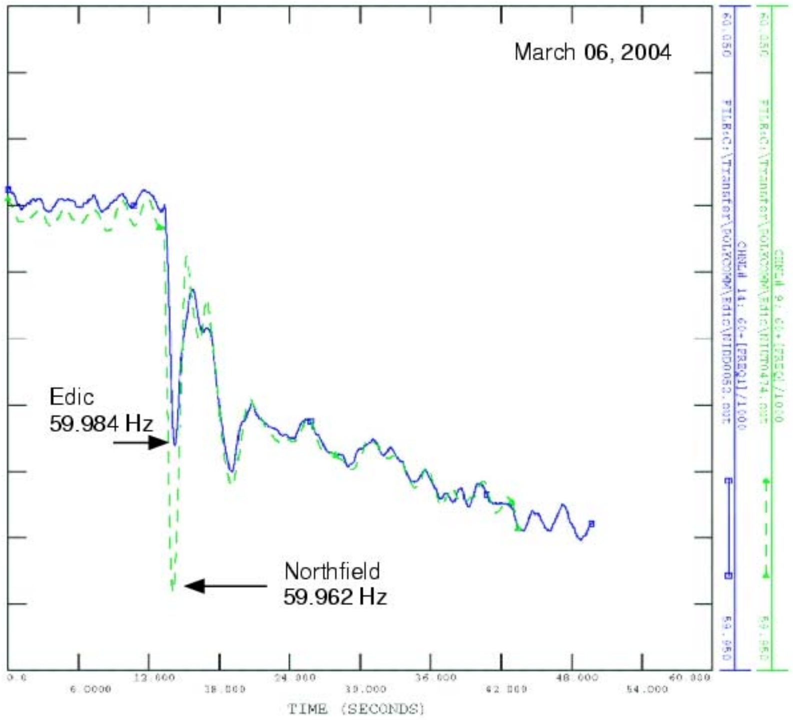

Figure 8. Loss of generation in New England, recorded at Northfield and Edic

4.2 Events Captured by the Oscillation Trigger Only

The Northfield DSR was able to capture a number of events based on the oscillation triggers only, three of which are shown in Figures 9-11. The magnitude of the oscillations was typically 10 mHz peak to peak, with periods ranging from 1.5 to 2 seconds. The oscillations seemed to be spontaneous and sometimes lasted as long as one minute. They are more likely to appear during light load period. The cause of these oscillations is not known. Although these oscillations have not cause any equipment outage, ISO-NE has initiated studies to investigate these oscillations and the application of power system stabilizers to damp these oscillations. In the meantime, the continuing monitoring of these oscillations is crucial to the power system operation.

4.3 Events Captured by Both Triggers

A few events were also captured in Northfield by both the oscillation trigger and the rate-of-frequency change trigger. These events were often external to New England, but not too distant from it. Such events cause a sudden frequency change and the oscillation does not damp out until several periods later. Therefore both the rate-of-change frequency trigger and the oscillation trigger captured such events. One of these events is shown in Figure 12. The frequency traces for Northfield, Edic and Juniata were manually aligned in Figure 12 because the clocks at each substation were not synchronized to each other at that time.

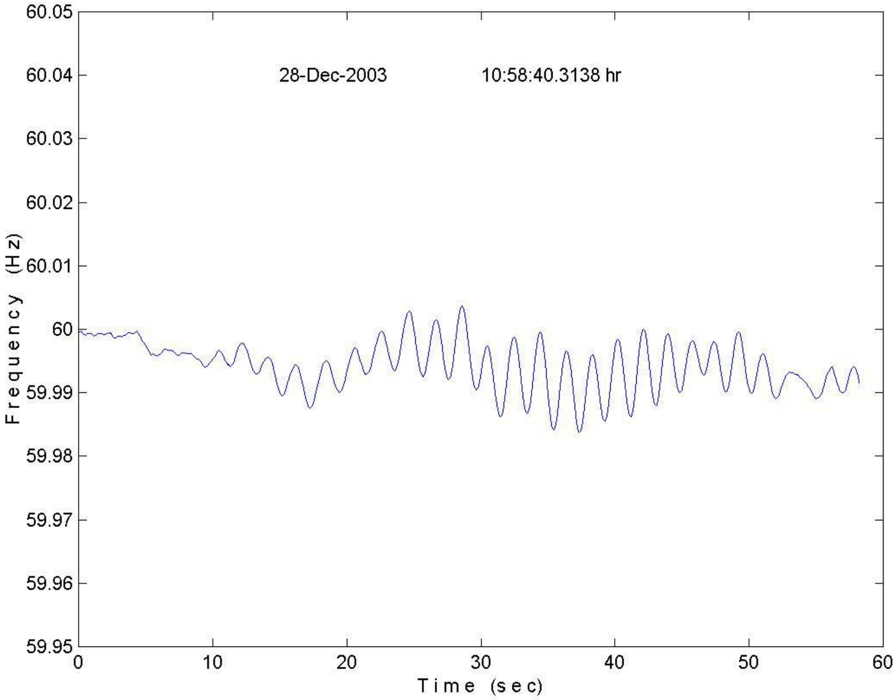

Figure 9. “0.5 Hz” Oscillation, Recorded at Northfield

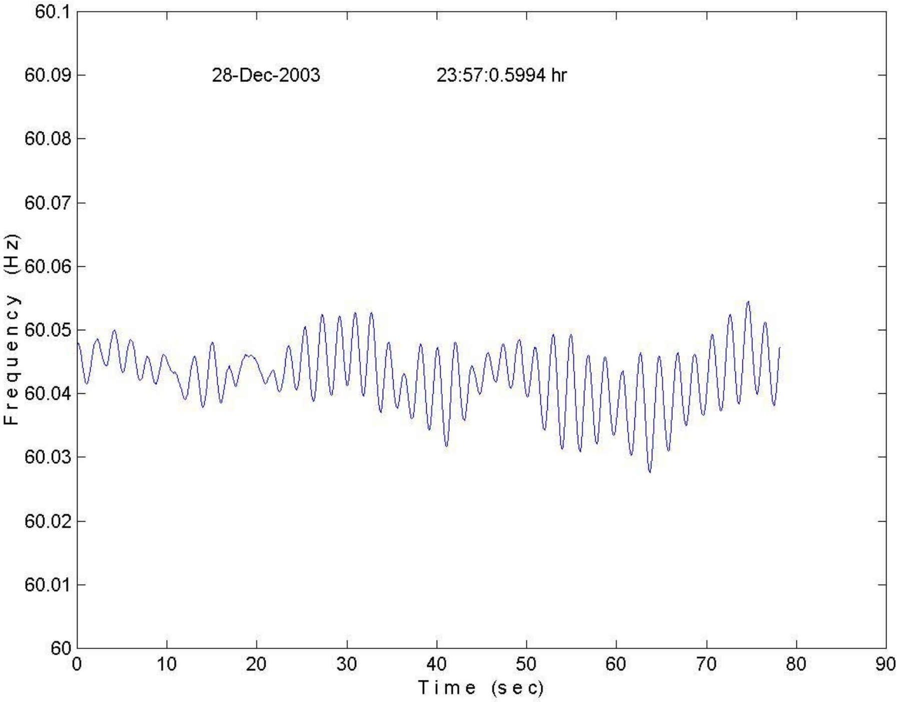

Figure 10. “0.5 Hz” Oscillation, Recorded at Northfield.

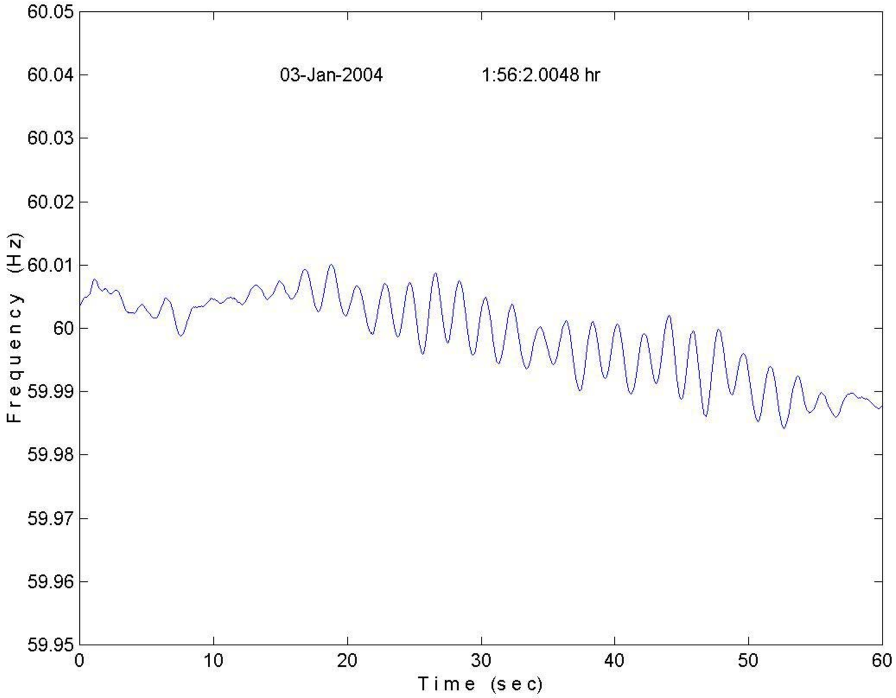

Figure 11. “0.5 Hz” Oscillation, Recorded at Northfield.

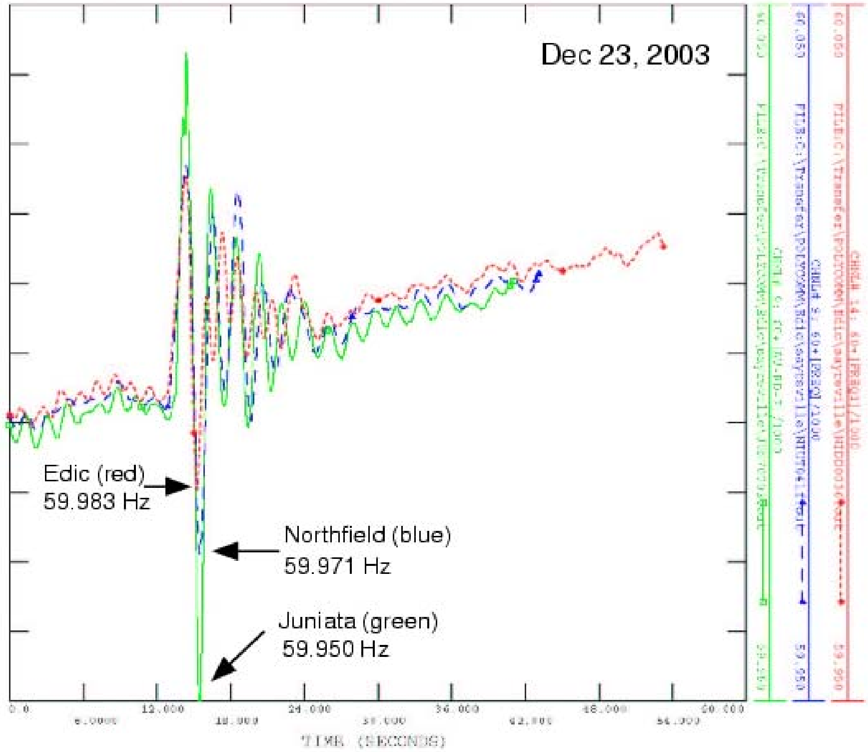

Figure 12. Event external to New England and New York

4.4 Observations of the Triggering and Recorded Events

1. The oscillation events can occur without high *df/dt* and frequency change. Thus the oscillation detector will allow capture of events that other triggers may not.
2. Df/dt and frequency change events can occur without oscillations. Therefore, all three frequency triggers (change, df/dt and oscillation) are important.
3. It is possible to discriminate between the types of events such that reliable detection of both types of events is possible.
4. It is possible to adjust (tune) the triggers appropriately, allowing the triggers to supplement each other.
5. The oscillation trigger was proven to operating using a data collection rate of 2880Hz. More testing would be required to prove the reliable operation of the triggers when using significantly lower data collection rates.
6. The oscillation trigger algorithm is validated by recording events.
7. The periodic review of records and events by associated parties is an effective means of validation
8. Wide area monitoring applications do not always require continuous recording or dedicated high speed communications.
9. Valuable power system disturbance information was recorded by swing recorders implemented using both the dedicated (DSR) and multi-function (DFR/DSR) platforms. We conclude oscillations and frequency anomalies can be detected and appropriate records can be gathered using generalized fault recording equipment.
10. It seems that the measurements taken by these recorders can provide an affordable wide area monitoring capability. This apparent finding needs to be analyzed as we set new goals for wide area monitoring.

5. Conclusions and Future Work

The oscillation trigger works well. Already the oscillation trigger has made us aware of short periods of system oscillations of which we otherwise would not have been aware. Using this trigger we expect to be able to correlate the times of oscillations with known system changes. This successful project is a model of industry teamwork involving generation owners, transmission owners, ISOs, university, and a manufacturer. It is the culmination of a multiparty activity over a significant period of time, covering vital NPCC areas (ISO-NE and NYISO) with visibility from Maine to NY and to PA (PJM). This project is a positive example that is worthy of note.

Through experience with the oscillation trigger and in our discussions during regular conference calls of our group, several areas of future work have been suggested:

1. We would like to investigate changing to a lower sampling rate and longer recording length. In the future, we expect be able to move to continuous recording, although triggers will remain important, to call our attention to events of interest.

2. The field validation process used has been demonstrated to be as valuable as the definition and design phases of the project.

3. The ability to plot recordings from multiple locations on a common time axis is very powerful and has been revealing. This process however is at this point involves several steps. We are evaluating ways to make this process more convenient.

4. We need to better document our scaling of all quantities recorded so we can more easily compare recordings from different recorders.

5. Although all of the subject recorder locations have satellite synchronization, there are still some issues to resolve in plotting multiple recordings on the same time axis.

6. We intend to continue to attempt to find correlations involving the system oscillations. For example, is the occurrence of oscillations correlated with load or system configuration, or generators in service? Likewise, can we find any correlations involving the frequency or magnitude of the oscillations?

Acknowledgements

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