

# Considerations for Use Of Disturbance Recorders

## A report to the System Protection Subcommittee of the Power System Relaying Committee of the IEEE Power Engineering Society

**Abstract:** The working group for use of disturbance recorders was given the assignment to develop a report to the System Protection subcommittee of the IEEE Power System Relay Committee. The paper discusses the types of recording devices available to capture disturbances on the power system, and the analog and binary inputs that will help an engineer analyze these disturbances.

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# Considerations for Use of Disturbance Recorders

## 1. Introduction

Recording devices have existed for many years, from the first ink chart recorders, often referred to as perturbographs, to the digital recording equipment available today. Modern digital equipment has the capability to monitor a larger number of analog and binary inputs that could not be monitored in the earlier disturbance recording devices. The introduction of microprocessor relays provided another method of disturbance recording. The increased capability of disturbance recording devices and microprocessor relays with disturbance recording capability, have created analysis challenges for the engineer.

There are a number of considerations when installing disturbance recording and monitoring equipment that an engineer must consider. First the type of event to be monitored must be identified. Is the equipment to be used for recording power system faults to verify protection system performance or is the device to be used to monitor power swings on the system. Once the type of power system event is identified the engineer must then consider the sampling frequency, type of event triggers, record length, and the analog and binary inputs that are to be monitored in order to select the best disturbance recording device. The last thing an engineer must consider is the limitations and errors that may be introduced into the records due to the characteristics of the sensing equipment.

This report discusses the application of disturbance monitoring equipment. The disturbance recorder sampling frequency, record length, and types of triggers are discussed. The characteristics of sensing the analog sensing elements (current and voltage transformers), and the errors that may be introduced will be discussed. Binary input sources and the associated errors are also discussed. Suggestions for the recorder inputs, the need for time synchronization and the requirements for analysis of the data for a disturbance are discussed.

## 2. Purpose

The purpose of this report is to provide a general understanding of the considerations required for the selection and application of disturbance recording equipment. The report describes errors due to the characteristics of the analog and digital inputs. In addition, the required inputs necessary to effectively capture a power system event will be presented. Examples of records illustrating the types of data displays are provided to help the reader understand the concepts presented. The paper does not discuss the deployment of disturbance recorders to meet the standards of NERC.

## 3. Definitions and Acronyms

The following terms are often found when discussion takes place regarding disturbance recording. This list provides a brief description of the equipment as well as the preferred usage. Terms beginning with an asterisk (\*) are included in the Equipment Terminology categories chart (Figure 1).

\* **Digital Fault Recorder (DFR)** - records instantaneous values (waveforms) of current and voltages, sampled many times per cycle, for time periods on the order of a second. May also record computed quantities. Developed for the purpose of analyzing system protection operations and circuit breaker performance.

**Disturbance** - Any perturbation to the electric system. Other definitions are provided but are not related to electric system disturbance recording. (IEEE 100, The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition, 2000)

**Disturbance Recorder or Disturbance Recording Equipment** - General name for non-continuous power system time sequence data recording equipment, which includes the DFR, the DDR, and the SER. Many types of modern recording equipment include DFR, DDR, and SER functions, and it is recommended that the term Disturbance Recorder be used for such integrated equipment.

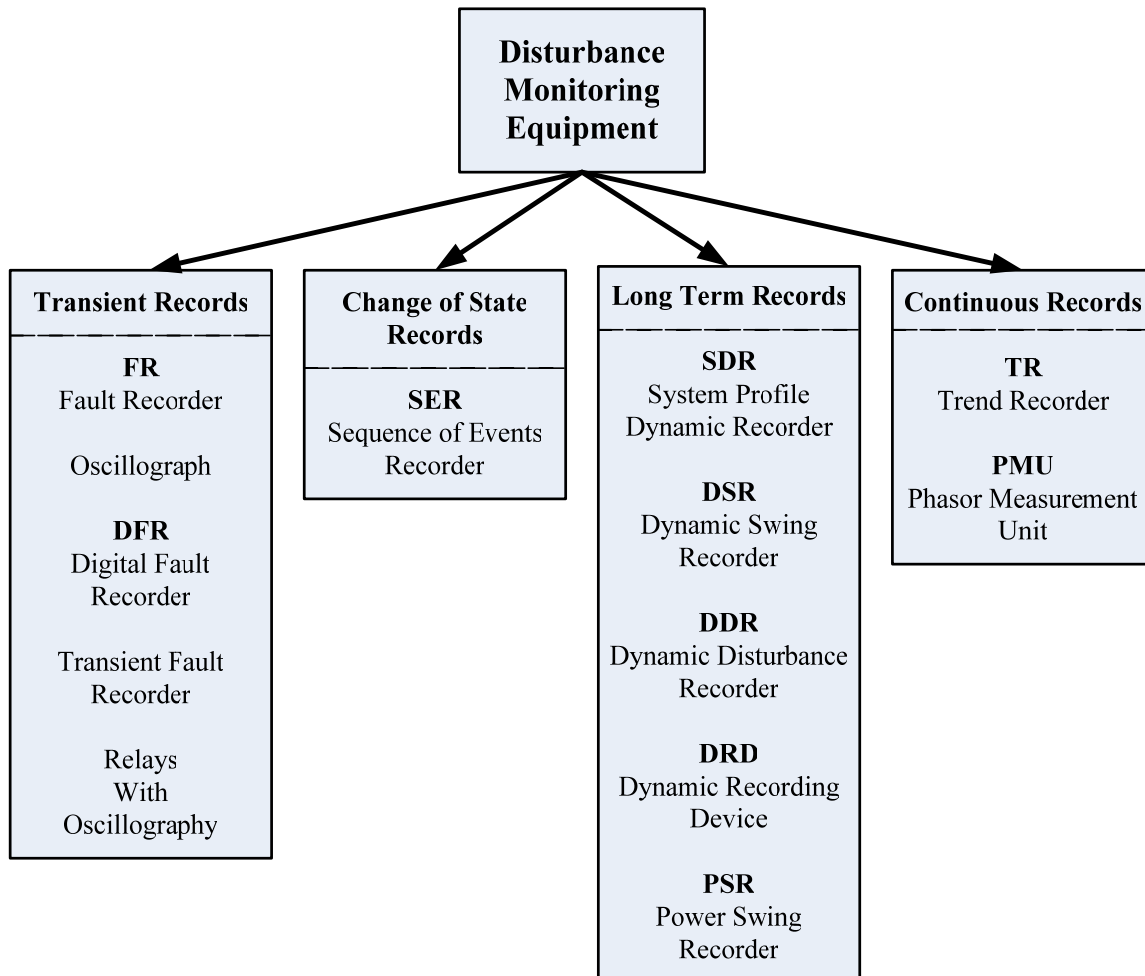


Figure 1 Equipment terminology categories

**Disturbance Monitoring Equipment** - Same as Disturbance Recorder, above. Disturbance Recorder is the preferred term. (NOTE: NERC Planning Standards 1997 uses Disturbance Monitoring Equipment as the general term, which includes DFR, DDR, and SER equipment.)

\* **Dynamic Swing Recorder (DSR)** – records frequency, phase angle, and or rms values of power system quantities such as voltage magnitude, current, MW, MVAR, etc., sampled or calculated many times per second, e.g. 6 to 60 samples per second or more. Record duration is

generally on the order of a minute or more. Developed for the purpose of analyzing complex power system events and for recording the dynamic response of power systems to disturbances. Due to the many terms that have been applied to such devices, it has been found necessary to include the word “swing” to insure understanding.

\* **Dynamic Disturbance Recorder (DDR)** – Same as DSR, above. DSR is the preferred term.

\* **Dynamic Recording Device (DRD)** - Same as DSR, above. DSR is the preferred term.

\* **Fault Recorder** – A general term that encompasses all recording devices capable of capturing a fault on the power system. This equipment includes, and is not limited to, oscillographs, digital fault recorders, protective relays, and transient recorders.

**Intelligent Electronic Device (IED)** – General term for digital or microprocessor based equipment that is used in the electrical system. These devices include relays, meters, DFRs, DSRs and programmable logic controllers (PLCs).

**Oscillograph** - Early fault recorder which generally used light beams writing on photo-sensitive paper or film. Since this term is firmly established, engineers frequently use "oscillograph" or "oscillography" when they are in fact referring to a DFR or to digital fault recording. Very few operative oscillographs remain, primarily because the special photo-sensitive paper has gone out of production.

\* **Phasor Measurement Unit (PMU)** – Device that records phasor quantities and accurately references them to a standard time signal. (See IEEE Standard 1344-2006 for more details.)

\* **Power Swing Recorder (PSR)** - Same as DSR, above. DSR is the preferred term.

\* **Sequence-of-Events Recorder (SER)** - records sequence and time-of-day of digital events, such as contact operations. Developed for the purpose of analyzing operations of control and protection systems.

\* **Transient Fault Recorder** – Often referred to as DFR, above. Transient fault recorder records surges and lightning strikes.

\* **Trend Recorder (TR)** – A long term recorder of the system parameters of interest.

## 4. History

The capability of disturbance monitoring equipment has improved due to advances in technology. The number of data inputs has increased with the advances in increased processing power of modern digital technology. The amount of information available to the engineer today from the types of recording devices and associated analysis tools allows for a more thorough analysis of power system disturbances. Prior to the advent of fault recording equipment, utility engineers relied on limited data such as relay targets and visual evidence of fault damage to determine whether the protective systems worked correctly.

Early fault recorders, or light beam oscillographs, provided valuable information for analysis of faults and the protective systems; however, they were limited in that they could only monitor a few analog channels. However, the engineer had more information to compare with target data and visual evidence of fault damage. As technology advanced, the digital fault recorders of today evolved to capture analog and binary inputs. Examples of typical point densities today for centralized systems are 18 analog/36 digital inputs or 64 analog/128 digital inputs.

Early disturbance (power swing) recorders were in the form of the continuous monitoring equipment using magnetic tape media. These units captured data anywhere from several seconds up to three hours, depending upon the location of the data on the tape relative to the end of the reel.

Retrieval of the records (paper charts or film) from the early fault and disturbance records required a technician to visit the substation or power plant to collect the records. Modern digital fault recorders now have communications capability allowing for remote retrieval of the records, reducing the time it takes to get a record back for analysis and allowing the protection engineer to perform a disturbance investigation quicker. The ability to retrieve the records remotely and the technology advances in disturbance monitoring, i.e. larger electronic records have increased the storage and communications time requirements for the retrieved records

Time stamping and time synchronizing of records is a necessary task of today's disturbance recorders. Global Positioning System (GPS) satellites provide in the GPS IRIG-B (and other) time code formats the ability to synchronize and time stamp the disturbance records of DFRs, protective relays and other recording equipments.

## 5. Types of Disturbances of interest to protection engineers

There are typically four types of disturbance or event records of interest to a protection engineer. These are categorized by the event duration as follows:

**5.1. Transient** - These are very short in duration and typically include faults that are cleared immediately by circuit breaker operation. These events are generally no longer than 8 cycles for high speed clearing and 16 cycles for sequential line clearing. These events are usually analyzed to determine correct protection operation, fault location, or verification of system model parameters.

**5.2. Short Term** - These generally include all other time-delayed fault clearing and reclosing events where the system operation (stability) is not affected. These events are typically 20 to 60 cycles in length but may be longer if multiple protection operations are required to clear the fault. These events are usually analyzed to determine correct protection operation, fault location or verification of system model parameters.

**5.3. Long Term-** These include those events that affect system stability such as power swings, frequency variations and abnormal voltage problems. These events are usually analyzed to determine causes of incorrect system operations. Data management techniques are employed to process a number of samples and record the value for the parameter of interest. Record length parameters may be defined.

**5.4. Steady State -** There are steady state disturbances where system operation is not threatened, but power quality is affected. This may include harmonics or sub-harmonics produced by the load and/or the interaction between power system's components. Depending upon the type of phenomena being analyzed, higher sample rates may be required to capture the events and data of interest. Record length parameters may be defined.

## **6. Disturbance Recording Considerations**

As microprocessor technologies are applied to the power system in the forms of protective relays, energy management devices, digital fault recorders and phasor measurement units, the amount of data collected that can be available for use to analyze the operation of the power system grows due to the number and increased capabilities of these devices. For example, protective relays monitor current(s) and voltage(s) to make decisions based on the settings to clear faults on the power system by opening associated protection equipment. The microprocessor relay of today is also capable of recording the fault and event data, collecting and continuously transmitting the instantaneous analog quantities to an energy management center.

Issues relating to the application of disturbance recording equipment are:

- The specific event to capture
- The available data sources; analog and binary
- Characteristics of sensing equipment
- Required sampling rate to capture desired events
- Application of triggers necessary to capture the desired event
- The storage capacity of each device.
- Communication method associated with each recording device.
- Frequency of record retrieval necessary to minimize losing records.

The above issues are important whether an engineer is interested in determining the cause and severity of a fault and if the associated protective devices functioned as required, or desires to measure the dynamic response of the system during power swings, obtain power quality information, or analyzing records to determine the cause of a wide area disturbance such as the blackout that occurred on August 14, 2003. The engineer needs to consider the issues for any type of event to capture.



The three primary types of recording are:

- High-speed disturbance recording
- Low-speed disturbance recording
- Steady State (continuous) recording

These types of recording allow the engineer to capture data for analysis of most events on the power system and are discussed in the following sections.

### **6.1. High-speed Recording**

High-speed recording is used to capture the individual samples of the currents and voltages measured by the device with a sampling frequency high enough to display power system faults and transients. A recording is typically initiated when the magnitude of an analog quantity increases above or decreases below a specific value. High-speed recording is used to capture transient events, which are short in duration, with the recorder record length typically set for one to two seconds. Sampling frequency is important when selecting a high-speed recording device. If an engineer desires the ability to detect a breaker re-strike condition then a high sampling rate is needed.

High-speed recording is available in disturbance recorders, and microprocessor based protective relays. Care must be taken when choosing the appropriate device to capture high-speed data, as significant differences exist between DFRs and relays in terms of triggering methods, types of triggers, the sampling rate at which records are stored, the length of the record, and the filtering applied in the capture of the relay.

Microprocessor based protective relays with recording capabilities are being used for fault analysis. These records provide valuable information about the protective functions of the relay. However, when considering using a microprocessor relay as a fault recorder the engineer must evaluate the sampling rate at which records are stored, the length of the record, and the filtering applied in the capture of the relay. Many early relays filtered the analog data so that only the 60 hertz component of the waveform was captured, then is displayed using a smooth curve fitted algorithm.

Figure 2 is a transient event captured by high-speed recording, showing analog voltage and current waveforms and the change of state information for selected equipment operations as signified by a contact transition.

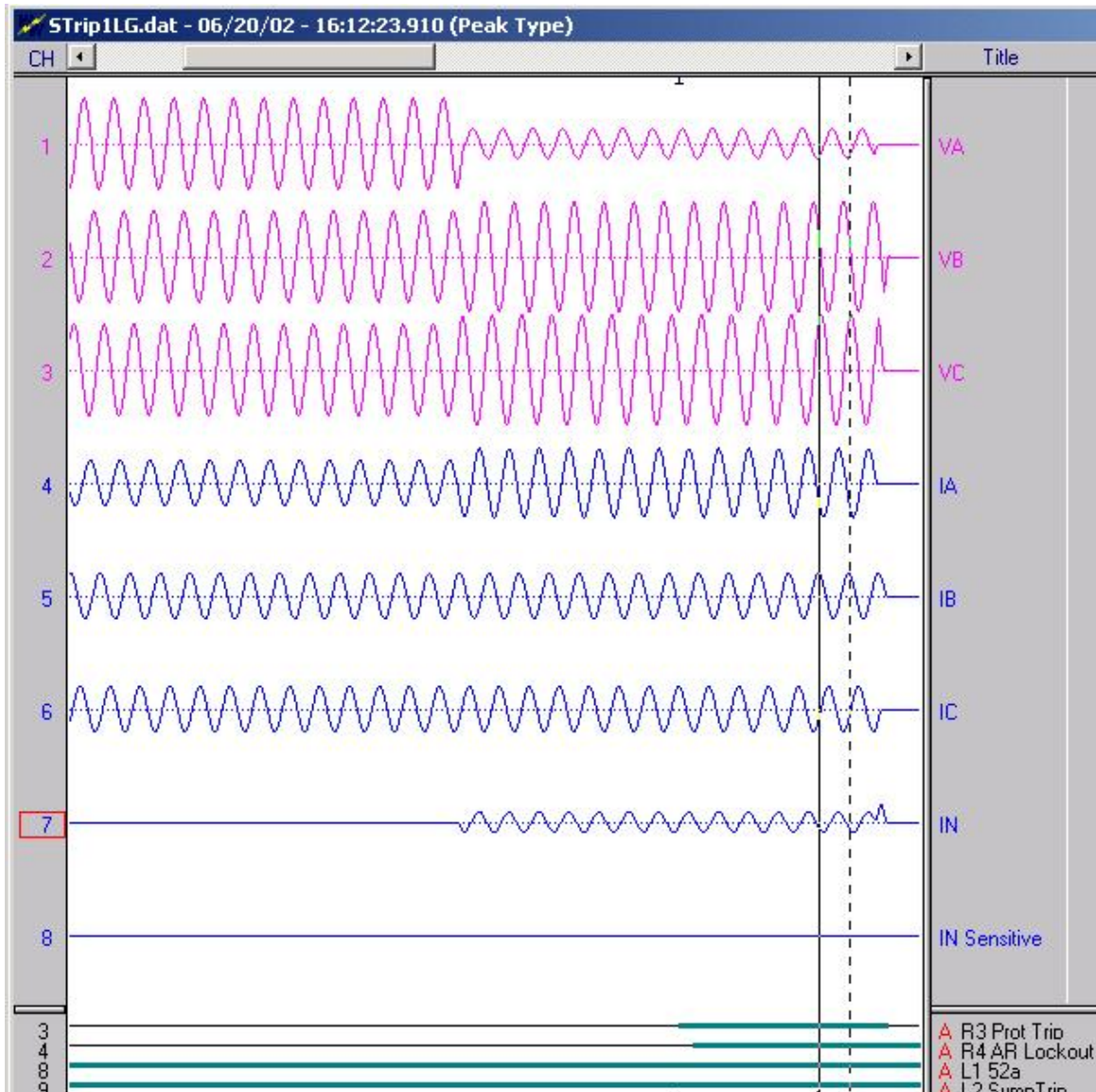


Figure 2 Transient record including binary state change information

## 6.2. Low-Speed Disturbance Recording

Low-speed recording is typically used to capture short term and long term disturbances, such as a power swing. Data is typically captured at a rate between 2 times per cycle and 1 every 2 cycles. The data captured is phasor or RMS data, not sampled data. Recording length is typically in the range of 60 to 180 seconds, but can be as long as 1 hour. Examples of these records are shown in Figures 3 and 4. Figure 3 shows a low-speed recording of 10 seconds in length, and Figure 4 shows a series of the 30 second data scans from SCADA remote terminal units over the period of 1 hour. Typical triggers for these functions include frequency rate-of-change triggers, power rate-of-change triggers, and system frequency oscillation triggers.

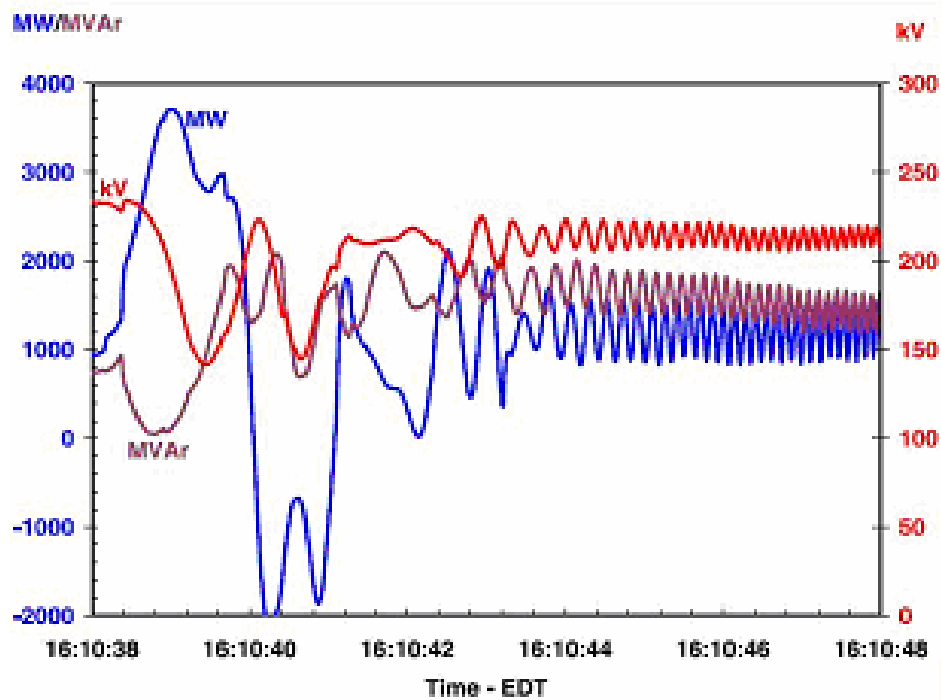


Figure 3 Low-speed disturbance record, short duration

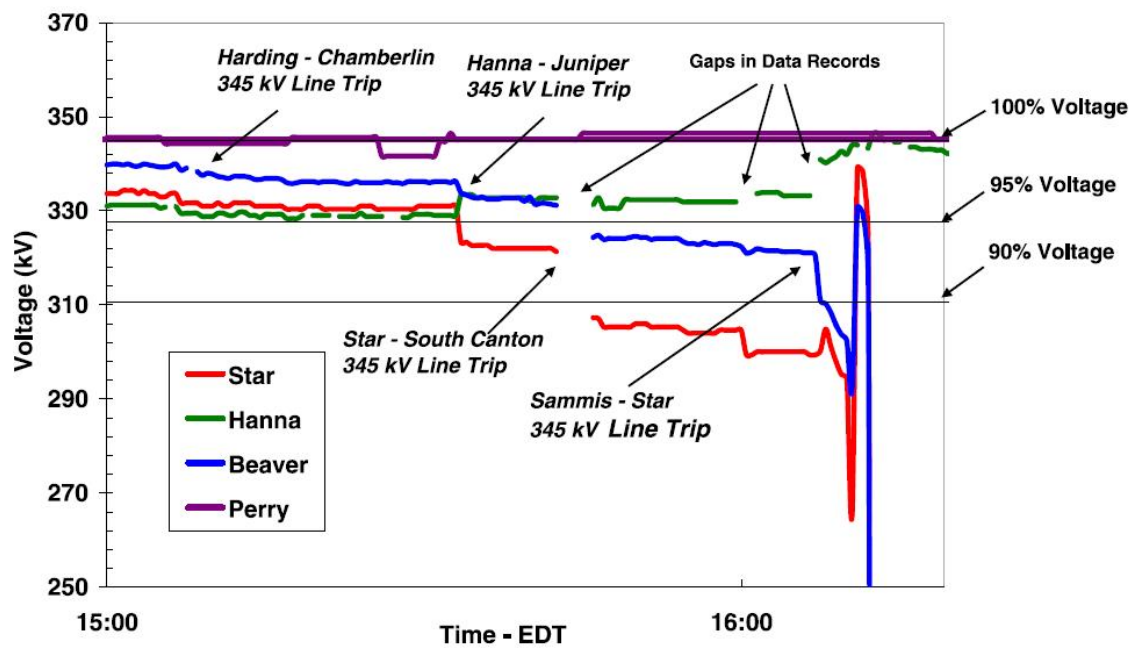


Figure 4 30 second scans of SCADA data from 4 locations

### **6.3 Steady State Recording**

Steady state or continuous recording, which is often referred to as trend recording captures average analog quantities such as maximum and minimum values and are usually stored in a file with several days of data. Other quantities monitored include harmonics or sub-harmonics produced by the load and/or the interaction between power system components, voltage sags and swells. Phasor Measurement Units are considered steady-state recording devices, which collect the system state information over a wide area. Depending upon the type of phenomena being analyzed, higher sample rates may be required to capture the events and data of interest.

### **6.4. Distributed Recording**

The increasing population of recording devices makes available more records for the analysis of a disturbance. These devices include digital fault recorders, dynamic swing recorders, protective relays, and multi-function meters. The number of available recording devices leads to the idea of a distributed recorder that collects data from multiple analog inputs and recording devices to combine into one record for a specific location.

Distributed recording takes on two basic forms. One form involves the physical design of the recorder, which places modules for analog inputs and possibly digital inputs at various locations in the substation, and connects these input modules to a central unit. The central unit then operates in the same manner as any recording device. The second form of distributed recording is a virtual form, with a central unit retrieving, and combining recorded data from a variety of recording devices. The virtual form of recording provides some challenges in creating a combined record, as the individual devices will use different triggers and triggering methods, time synchronization, record length, sampling rate, and storage capability. Also, there will be duplication of analog channels for the same event.

### **6.5. Periodic Measurement Logging**

Planning studies and short and long-term load forecasting require the recording of system parameters over long periods of time. The recording device should be able to store the values of a user-defined set of parameters for every logging interval. This interval and the parametric algorithms define the sampling rate of a trend recording.

The measurement log file can contain user settable number of entries. For example, a record with 3072 entries is equivalent to 32 days of logging when using a sampling interval of 15 minutes. Once the log file has reached its maximum length it will wrap around to the beginning and overwrite the oldest entries in the file. For each parameter the minimum, maximum, and average RMS values that occurred during the previous interval might be required to be recorded.

### **6.6. Time Synchronization**

Several vendors manufacture master time devices (GPS clocks) which support different standardized time synchronization protocols. IRIG-B is the more commonly supported standard time code format that has been widely accepted by the electric utilities and is supported by most modern electronic devices with recording capability.

There are two common ways of synchronizing various devices to the same GPS clock source:

- Synchronization over direct connection
- Network synchronization

Synchronization of IEDs utilizing a direct connection requires each device to have a GPS or IRIG-B communications port in order to connect it to the master clock. Having a permanently connected GPS/IRIG-B source provides an accurate reference for the device's internal clock

In the past, GPS clocks with uncertainties of 1 millisecond were common, but at the time of this report, GPS clocks with accuracies of 1 microsecond are the standard offering. At the 1 microsecond level, the uncertainty introduced by the GPS clock is negligible compared to other uncertainties. However, an IRIG-B network can introduce an uncertainty (delay) of up to 1 millisecond. [23] With careful design the uncertainty of the IRIG-B network can be kept to a minimum. The largest contributor to uncertainty and delay in recorded observations is the response of the recording devices themselves. Internal device delays are primarily due to filtering, and may be 4 milliseconds or more. At the time this report was being written, the PSRC working group I11 Timing Considerations for Event Reconstruction is investigating this area and will produce a report.

The network synchronization method eliminates the problem of dedicated interconnection with the master clock by allowing the individual device's internal time clock to be synchronized over the substation LAN with the network time-synch master using the methods specified by the protocol. This method however introduces a potential error due to the processing delays within the LAN.

### **Universal Coordinated Time (UTC)**

GPS clocks provide outputs which are synchronized to the international standard time scale called UTC. When UTC is provided with no offset, the letters UTC are often used in the place of a time zone. There is a potential for confusion because UTC is really the standard time scale. When the letters UTC are used as a time zone, it should be understood that no offset has been applied. Other terms for this are Zulu time, UTZ or Greenwich Time. The working group suggests that Zulu time, UTC without offset, be used for disturbance recording to avoid all the misunderstandings introduced by local time zones and particularly introduced by shifting to daylight savings time.

### **Local Time Zones and Daylight Savings Time**

GPS clocks are also capable providing time outputs which are UTC time scale with offset applied for local time zones such as Eastern Standard Time (EST). GPS clocks are also capable of shifting to Daylight Savings Time on pre-programmed dates. The working group suggests that such local shifts and daylight savings shifts not be used in power system disturbance recording as a number of large utilities now cross time zones.

## **7. Equipment types**

The following descriptions are of equipment types that may be used to record and collect data about disturbances as they occur on the power system.

### **7.1 Fault Recorder (FR)**

Fault recorders have been in use for a number of years and have evolved from analog recording devices which utilized light sensitive paper to digital signal processing and recording techniques

to produce digital records that can easily be collected, transmitted, stored, printed and analyzed. This report focuses on the digital techniques used by modern equipment to obtain and analyze disturbance data. The term fault recorder encompasses both analog and digital techniques as well as other devices that are capable of capturing and recording a disturbance on the power system. These devices are also referred to as Transient Recorders (TR).

A fault recorder typically contains directly measured analog channels, as well as event or binary channels. This allows the recorder to capture the time sequence of analog power system quantities, along with breaker contacts, logic state changes, event contacts, etc. Modern recorders typically include calculated analog quantities and logic functions to ensure pertinent power system information is captured during an event. Triggering to start the capture of data can typically be directly based on changes in analog quantities, digital inputs, or logic.

Information from fault recorders can be used to confirm the occurrence of a fault, determine the duration of a fault, measure the magnitude of fault quantities of current and voltage, determine the location of a fault, define the nature or type of fault, assess performance of relays, and assess circuit breaker performance. An engineer experienced with fault recorder records can often recognize faults due to lightning strikes, insulator contamination, tree faults, restrikes and other common faults causes, from their distinctive "signature" on a fault record.

A typical fault recorder installation may not include all of the currents for a specific line. However, analysis software may provide the ability to replicate the missing channel from other monitored sources.

Triggering of the fault recorder may be by internal triggering measurements, contact inputs or Boolean expressions of a combination of direct, or calculated measurements, and the status of the contact inputs.

## **7.2 Protective Relays with Oscillography and Event Recording**

Numerical digital relays can also generate sequence of events based on their individual relay elements and digital or contact inputs. They may also be programmed to recognize and record events in situations where they do not initiate a trip.

A drawback to relays as recording devices is having the data distributed in many devices instead of combined in one device. Time synchronization of all the relays, and other recording devices, is a significant, gathering and combining all data from these individual sources is a manual activity. There are likely also differences in the triggering method, sampling rate, and record length to consider.

Triggering of the recording function within the relay is programmable and based on the internal measuring elements within the device. Typically these records are limited to the “zone of protection” associated with the device.

## **7.3 Dynamic Swing Recorder (DSR), including Phasor Measurement Unit (PMU)**

DSRs are useful for disturbance analysis, investigating system oscillations, quantifying sudden changes in power system parameters, and obtaining data for verifying stability models. Since the data of interest is changes in power system over time, DSRs normally store data in as RMS or phasor values, as opposed to directly sampled data as found in digital fault recorder. DSRs

generally capture data from twice a cycle, up to once every 10 cycles. DSRs are normally used for low-speed disturbance recording, and capture records that are typically from 1 minute to 1 hour in length.

DSRs may be a separate device, or integrated with a modern digital fault recorder. The phasor data capture by the DSR may be synchrophasor data, as defined by the IEEE Std. C37.118 [20], or a phasor measurement unit (PMU) may also function as a DSR. To meet the requirements of C37.118, the DSR must be time synchronized to a with a microsecond resolution as opposed to the typical millisecond resolution used for most DFR applications.

Longer term recorders also have particular applications within a power plant location to capture those cascading or trending events that might evolve over many seconds or hours that would otherwise be lost until the fault actually operated normal triggers.

#### **7.4 Power Quality Monitor (PQM)**

Power Quality Monitors are designed to record power quality parameters such as voltage dips, flicker, and harmonic content. They often compute and record industry standard measures for power quality. Power Quality monitors often are normally set up for continuous recording at a relatively low sample rate. They may be configured to switch to a higher sampling rate when triggered to do so.

#### **7.5 Continuous Monitoring Equipment (CME)**

This type of equipment tended to be reel-to-reel continuous recording magnetic tape machines. The modern form of this equipment uses high capacity memory and initiates an alarm when an abnormal event occurs, indicating a meaningful record is available for retrieval.

#### **7.6 Sequence of Event Recorders (SER)**

A Sequence of Event Recorder's function is to gather and time tag operational data from substation equipment (e.g., relays, circuit breakers, transformers), control schemes (manual and automatic) as they react to a system event. This series of sequential, individual events can be from a switching operation, fault, or misoperation and can be contained within a single substation, a line and associated substations, a utilities system, or several interconnected systems. This data allows the chain of events to be studied for the cause (or causes) of the misoperation and the linkages between individual actions and effects.

Sequences of Events Recorders have improved over the years by becoming smaller, less expensive, while increasing their capacities for data points and storage. This allows them to be applied in stations that are smaller, both in terms of KV and equipment, than was considered economically practicable in the past. Time tagging has improved with the widespread use of Global Positioning Satellites (GPS) and Universal Time Code (UTC). One area that has not changed however is the time resolution of SER's beyond a millisecond.

Many modern Intelligent Electronic Devices (IEDs) include sequence of events functions that record the triggering sequence of individual elements or commands specific to the device. However, without an overall (i.e. substation level) SER it is often difficult to piece together all of the information from these individual devices, especially for a large disturbance. For that reason alone, SER's that monitor an entire substation will continue to be useful devices.

## **8. Data requirements for analysis of disturbances**

Typical DFR installations monitor analog voltage and currents of transmission and distribution lines, transformers and other system equipment. These inputs are used to determine fault type and duration. To facilitate fault analysis and review of system disturbances, lines, buses, transformers, and other circuits of interest within a station should be monitored. Monitoring of all three phase analog quantities is recommended, the exception being where the disturbance recorder is able to calculate input channels such as a residual current for a three-phase analog input.

Digital inputs to a DFR should be monitored to allow an engineer to assess the performance of protective relaying as compared to the analog inputs during a fault. Contact (event) inputs from the protection system and controlled apparatus are also typically connected to the recorder. These inputs include, but are not limited to, circuit breaker position, relay output contacts, auxiliary relays, and lockouts. Other transmission event inputs monitored may be pilot channel functions such as Carrier Start, Carrier Stop, Carrier Receive, and Transfer Trip. These analog and event inputs are used together to verify protection system performance and in misoperation investigation.

The input requirements for a generating station are different than a typical transmission substation. It is important to monitor turbine, generator, exciter, and regulator signals so they are all available on a common time base, to help determine if and how the turbine-generator-exciter system is responding to an external disturbance, generating a disturbance internally, or contributing to an external disturbance. This information can be extremely valuable in quickly determining whether the turbine generator system has incurred potential damage and can be safely returned to service following disturbances that result in a unit trip. For stations that have several generators, it can also help determine how the different generators are responding to the same event. Units can sometimes swing together, or apart, depending on the nature of the disturbance, the characteristics of the system, tuning of the voltage regulators and limiters, tuning of power system stabilizers, and other equipment within the plant.

Many times, the tripping of a generator is the result of several events that evolve into the actual tripping event. As such, the generator fault recording system may have the need for both short term and long term recording capability.

Record length requirements are different for distribution, transmission, and generation events. As pointed out in previous sections, records for transmission events tend to be cycles long, while distribution records may be seconds long. In addition, a recorder with system swing recording capabilities can be several minutes long. The record length and sampling frequency have a major impact on the recording capability of the device with regard to memory constraints, maximum duration of a record, number of records that can be recorded, etc. In the DFR, there is typically some form of memory management that allows for many records to be recorded or transferred to a storage disk. In the case of the IED relay, early devices may only allow for a single record to be stored, while newer devices may allow for several records before it either overwrites or stops recording. Philosophies with regard to reclosing and the capture and storage of this event may also affect the recording capabilities and memory requirements.



## 9. Data sources, processing and storage

There are three major categories of input sensors or transducers for these devices. Two of these are analog – current and voltage, and the other is digital, which reflects the status and change-of-state information for selected equipment operations.

### 9.1 Analog Inputs - Current and voltage transformers (CT & VT)

Recorder inputs (CT & VT) can be thought of as primary power system conditioners. They take the primary power system values and reduce their magnitude by a fixed transformation ratio appropriate for use by the secondary devices that provide protection, control, and monitoring functions.

#### 9.1.1 Current Transformers

Current transformers (CTs) have good frequency response and normally do not require any special attention when operated in their recommended range of one to twenty times rated current and at rated burden or less. Perhaps the only unanticipated degradation in the input signal will be due to the capacitance of the cables. This can introduce errors in magnitude at several kilohertz and errors in phase angle at several hundred Hertz.

When harmonics are to be measured, it is much easier to use current than it is to use voltage. Current circuits are low impedance paths that are less susceptible to induced signals or noise, whereas voltage circuits are high impedance paths that are more susceptible.

In medium and large area substations, the burden on CTs is mainly determined by the cable burden. The reduction of the relay burden with the use of digital relays is useful but usually the cable burden is the greater part of the total CT burden, with either digital or most electro-mechanical relays. However, some electromechanical relays such as sensitive ground overcurrent relays with settings on the order of 0.5 Amp will impose a significant burden to the CT circuits.

#### 9.1.2 Voltage Transformers

Voltage transformers do not have good frequency response, neither magnetic VTs nor coupling capacitor voltage transformers CCVTs. The capacitance of the cable between the voltage transformer and the relay will further degrade the input signal. But, depending on the frequency, this can be minimal compared to the errors due to the frequency response of the specific VT.

Select any auxiliary VTs with a ratio and classification sufficient to prevent any further degradation of the voltage circuit.

**1) Magnetic Voltage Transformers:** The errors are generally due to inter-winding capacitance and winding-to-ground capacitance. If the errors are to be limited to 10% (in magnitude or phase angle), then for harmonics or frequencies above 400-500 Hz. it is advisable to perform a frequency response test on the particular magnetic voltage transformer to be used for the measurements.

**2) Coupling Capacitor Voltage Transformers:** The coupling capacitor voltage transformer uses a series tuned circuit (tuned to the power system frequency) across a lower section of a capacitance divider to obtain a voltage proportional to the primary voltage. This voltage is transformed and compensated (for both magnitude and phase angle) to supply the specific attached burden. The output of the CCVT can vary by a factor of more than 10 for the same input frequencies other than the nominal frequency. It is certainly not recommended that a CCVT be used to measure harmonics, without first performing a frequency response test on the particular CCVT to be used for the measurements.

## 9.2 Digital Inputs

Digital inputs are usually added to the disturbance recorder data in addition to, or instead of, the sequence-of-events recorder data. These signals in the disturbance record may be from either external contacts or internal element status indications. Although this input can be a simple contact, it is deserving of considerable attention because of the importance it can assume in the analysis process. Some of the items to be considered are:

1) **Interposing Relays:** All interposing (auxiliary) relays introduce some time delay into the record. The amount can vary from relay to relay and can be in the range of less than 1 millisecond to 100 milliseconds depending on the design of the relay used. The amount of operate time is not as important as the fact that it exists. The pick-up time and drop-out time can be added to the data on the record, just as CT ratio and VT ratio are added.

2) **Open vs. Closed Contacts:** It is usually clearer to indicate deviation from normal (breaker trip, low air pressure, hot spot temperature, loss of station service, etc.). In analyzing the data, it is helpful to know that going from normal to abnormal is the same for all event inputs. Some manufacturers of recording equipment allow the user the option of selecting an open or a closed contact at the input but other manufacturers specify it.

3) **Wet vs. Dry Contacts:** This is the statement of who will supply the voltage to the event logic. The "wet" contact has voltage supplied from the user. The "dry" contact has voltage for the logic supplied from the recorder.

4) **Contact Sensitivity** (*current requirements*): With "dry" contact logic, the amount of current required for a closed contact multiplied by the number of logic circuits (worst case) determines the size of the recorder's power supply. Heat dissipation can also become a problem. For "wet" contacts, a ground on the battery (dc supply) should not cause a false indication. In the case of the substation battery being used, the requirements should include "battery on overcharge". Another consideration should be water saturated cables. The current required to operate the logic input should be greater than the current that will flow between the cables going to the switchyard

5) **Contact Bounce:** Contact bounce occurs whenever contacts close. It is the result of two contacts approaching each other, touching, and sliding (contact wipe) to their final location. From "contact first touch" to "contact at rest" may be a very short time, but the current flow may be interrupted "hundreds" of times. It is important that the contact bounce condition not be ignored as it will result in false triggering. Current should flow for a predetermined time period to be considered a closed contact. This contact bounce time interval (de-bounce time) must be coordinated with the event resolution time of the recorder.

Modern relays allow for recording of the status signals of dc inputs connected to the relay. However, as a rule, protective relays apply user-selectable or hard-coded de-bounce filtering. Typically, a relay records the input status after the de-bounce time. As such, the record reflects signals validated and used for protection and control, not signals as they actually appear across the input terminals of the relay. If the time duration of the de-bounce timers is known, an approximate timing correction can be applied to obtain the original signals occurrence before de-bouncing. Details of the de-bouncing algorithm must be known to accurately perform this correction.

6) **Event Resolution Time:** This is the time from event input to output. This time can include, or not include the de-bounce time.

## 10. Data Conditioning

The application of digital technology to oscillography requires the user to understand the implications of several areas of data conditioning. Filtering of the applied signals may be both analog and digital, and together with the sampling rate determines the frequency response of the recorded information. The use of measurement windows and associated measurement algorithms can have an impact on the data contained within the record. Triggering of the recording device may be dependent upon a calculated value for a specific parameter, or a magnitude of an input, or the position of an input contact, or a combination of these.

### 10.1 Analog filtering for ac signals

Any digital device, including relays and DFRs, must include an anti-aliasing feature, usually achieved using an analog filter. Anti-aliasing filtering eliminates higher frequencies that would otherwise overlap the lower portion of the spectrum due to the finite sampling rates of digital devices. According to the Nyquist sampling theorem, the cut-off frequency of the analog filter must be lower than or equal to half the sampling frequency.

DFRs traditionally sample at 64 to 356 samples/cycle and have their cut-off filters set well above 1 kHz, yielding comparatively good spectral coverage. Relays traditionally sample from 4-20 samples/cycle, but relays are now available that sample at 64 to 128 samples/cycle. However, protective relays, which use only filtered quantities for main protection and control functions, do not calculate harmonics, or apply comparatively low sampling rates, hence their analog filters are set comparatively low. As a result, the signal spectrum effectively recorded by these devices is limited to few hundred hertz.

Another aspect of analog filtering is the design of the filter itself. When high order filters are used, their response may not be ideally flat over the pass-band frequencies. This should be considered when a detailed harmonic analysis is performed using records produced by protective relays.

The analog filter of digital relays is typically a low-pass filter, allowing the sub-harmonics and dc components to pass through. However, the frequency response of the input magnetic modules at low frequencies may alter the low frequency components (at the level of a few Hz). This should be considered when analyzing sub-harmonics and decaying dc components. Not all recorders use magnetic input modules for isolation. Many have dc response capability.

### 10.2 Digital filtering for ac inputs

The primary purpose of the digital fault recorder is to record the applied signals within the spectral limitations of the equipment. The recorded data is to have a high level of accuracy in terms of representation of the input signal. The accuracy of this data is impacted by the performance of any digital filtering applied to the ac inputs. A DFR rarely applies digital filtering, as the DFR only captures data for later display and analysis. Protective relays do apply digital filtering, as relays process the sampled data to make appropriate protection function decisions. Proper analysis of recorded data requires understanding any digital filtering applied to the ac input signals.

Digital relays often perform digital pre-filtering prior to applying phasor estimation algorithms (such as the Fourier transform) to obtain input quantities for their protection and control algorithms. The primary objective of digital filtering is to filter out unwanted components of the

applied signals, the dc component in particular. To accomplish this, the filters must include a differentiating portion that ideally should match the L/R constant of the primary circuit.

Digital relays tend to record sampled data after digital filtering. Newer digital relays operate similar to DFRs and record raw samples prior to digital filtering. This not only widens the resulting frequency spectrum of the recorded waveforms, but also ensures that the stored information does not depend on any proprietary digital signal processing algorithms.

The recorded data from a digital relay can provide very good information, but the user will need to understand how the data is captured and any limitation in presenting the data. Limitations include slow sample rate, limited response to high frequency, dc filtering, and software filters, depending on the method used by the relay. For example, in some relays the voltage signals may use a special digital filter to cope with CCVT transients. For each type relay the user must review the relay specifications to determine type and amount of filtering is applied within the relay prior to the sample being recorded within the relay record.

Figure 5 illustrates the same event captured two ways from the relay and displayed by the vendor's display program. The first capture uses 4 samples/cycle of digitally filtered data and the second uses 16 samples/cycle of sampled data with no special filter. Note that the filtered data lags behind the sampled data (this time delay is the result of the filter) and does not show the dc offset. Another important observation is that the filtered value does not show the true waveform (e. g. peak current). This may be acceptable for a relay under certain conditions, but not acceptable for a recorder. Usually all the sampled ac signals immediately after the first analog to digital conversion are recorded even if the relay or recording device uses decimated samples for other functions which are desirable.

Other methods used on a limited basis include converting the sampled waveforms to RMS or other application specific values. In all cases, specific information is lost and it is important that the user understand what filtering or algorithms are used in order to properly analyze the data.

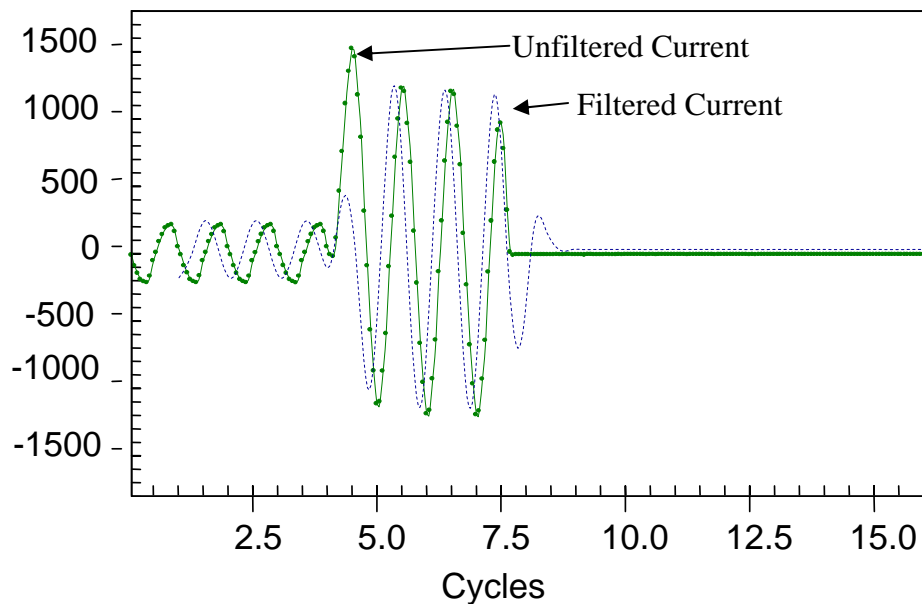


Figure 5 Unfiltered vs. Filtered Data

### 10.3 Sampling rate

The sampling rate of the recording device impacts the accuracy of the data captured for later analysis. The sampling rate also affects the performance of the analog and digital filters, and the input magnetics, of the recording device.

DFRs typically use a sampling rate of 64-128 samples/cycle, with some devices permitting sampling rates of up to 384 samples/cycle. Relays sample as low as 4 to 20 samples per cycle, to simplify analog to digital conversion and filtering. Some modern relays sampling in a range of 32 to 128 samples per cycle or more for recording purposes, providing good spectral coverage. Unlike a typical DFR, a typical relay may apply a variable sampling rate based on the system frequency.

The sampling rate, and sampling frequency, of a recording device is not necessarily fixed. DFRs generally use the same time interval between samples, without respect to the actual system frequency. In modern DFRs, different sampling rates may be used for different trigger conditions. In some DFRs, an adaptive sampling rate may be applied. In this case the sampling rate will increase when triggered internally. This allows the recorder to monitor the power system for changes from steady state, as well as increase its sample rate appropriately in the event of a system disturbance such as a power swing, or transmission line fault.

Protective relays generally used a fixed sampling rate that varies with the system frequency. To increase accuracy of digital measurements for protection, control and metering, microprocessor-based relays may track power system frequency to maintain a constant number of samples per cycle. This results in variable spacing between the recorded samples.

Some microprocessor-based relays sample and record at a constant rate, then re-sample the actual samples in software to maintain a constant number of samples per cycle for protection and metering functions. The constant sampling rate is obtained when the frequency tracking feature within the relay is disabled, or the effective tracking signal is not applied to the relay at a time of producing the record.

## 10.4 Measurement Windows

Some devices use a measurement window or the equivalent of a measurement window to capture transient waveform samples. This means that at minimum the first sampled value in the first window at the beginning of the record is not accurate (ramp up value). Likewise, the last sampled value in the last window of a transient waveform record is not accurate (ramp down value). Depending on the sample rate and window length, it is recommended that the first two (or more) samples at the beginning of the record be ignored and the last two (or more) samples at the end of the record be ignored for each analog input quantity. This makes slower sample rates less desirable because; 1) during analysis of all analog quantities, it is necessary to ignore the ramp up time of the quantity and the ramp down time of the quantity and 2) if data is analyzed from more than one device, it is necessary to keep up with the ramp up and ramp down times for the different devices and use the proper one with the proper device. The use of faster sample rates minimizes the ramp up and ramp down times, therefore making it no longer necessary to ignore these times in the analysis.

In other devices, a measurement window is associated with a group of samples over a period of time that is required by a measurement algorithm to calculate a value or series of values relative to the intended measurement. Examples of such measurement or calculation windows may be power at the fundamental frequency with all harmonic contributions excluded, rate of change of system frequency, the determination that a voltage sag exists, or the determination of which harmonics present on the monitored signal.

## 10.5 Triggering Methods

Triggers cause a disturbance recorder or microprocessor relay to capture waveforms for specific power system conditions. Recording events may be triggered by changes in measured analog values, calculated analog values, internal logic statements, operation of protection elements, or by the change in state of an external input. Triggers typically include both a threshold setting to indicate an operating condition to start a recording, and a time delay setting to ensure this event is truly a power system condition to record.

Analog triggers operate on the directly measured or calculated analog channels of the recording device. Each measured or calculated channel, depending on the device, can use any combination of these triggers to initiate a recording, and any one of these triggers can initiate any type of recording. Analog triggers include

- **Magnitude.** A magnitude trigger asserts when the value of the analog channel exceeds a set-point for a specified time delay (high magnitude) or is below a set-point for a specified time delay (low magnitude). A typical application of a magnitude trigger is a high magnitude trigger on a current channel. This trigger is set to assert with no intentional time delay when an overcurrent condition occurs, indicating a possible short circuit.
- **Rate-of-change.** A rate-of-change trigger asserts when the change in measured value exceeds (positive rate-of-change), or falls below (negative rate-of-change) a slope setting for some specified time delay. Rate-of-change triggers may calculate an instantaneous rate-of-change based on the derivative of the measured quantity, or they may simply compare the value of the measured quantity at the start and end of a specified time interval. A typical application of a rate-of-change trigger is to set positive and negative frequency rate-of-change triggers, with a short time delay, to initiate a long term recording to capture power system disturbances.

- **Harmonic.** A harmonic trigger asserts when the harmonic content of a measured or calculated channel exceeds a setting for a specified time delay. Harmonic triggers can typically be set to operate on a specific harmonic (2<sup>nd</sup> order, 3<sup>rd</sup> order, etc), or can be set to operate on total harmonic distortion. A typical application is to assert for the presence of 2<sup>nd</sup> or 3<sup>rd</sup> harmonics when located near a capacitor bank.
- **Sag and swell.** Sag and swell triggers are specific magnitude triggers, applied to voltage analog channels, designed to assert for power quality events, when the voltage drops below, or rises above, a certain setpoint. These triggers are set to assert with no intentional time delay, as the trigger is attempting to capture a short duration voltage event.
- **Protection function.** A protection function trigger is the operation of any protection function in a protective relay. The settings for these triggers are dependent on the needs of the protection function, and not that of system disturbances. Protection functions can typically be set to trigger a recording on protection function pickup, or on protection function operation.

In general, DFRs allow the use of any trigger on any measured or calculated analog channel, including current, voltage, voltage sags and swells, sequence components, measured impedance, real and reactive power, power factor, and system frequency. The type of trigger used, and the trigger criteria, is assigned for each individual channel. Modern numeric protective relays can trigger oscillographic data capture based on external inputs, programmable logic conditions, and internal protection function triggers, and the channels used with the protection function are fixed by the relay design.

External input triggers start recordings based on a binary signal, or on/off condition, of external power system equipment. Triggers may initiate a recording when an external input goes high or low. Typical uses for these types of triggers include trip signals from individual protective relays, communication-based schemes, and breaker position contacts.

In addition to filtering of the analog inputs, digital contacts can be filtered via de-bounce filters or internal time delays. Knowing when a system time tags the actual change-of-state with respect to a bouncing contact or the issuance of a command will impact how the data is interpreted. The common practice (but not always followed) for a de-bounce filter is to time tag the change-of-state at the rise time of the input, but only if it is still changed at the end of the filter time.

For internal alarms or commands in a relay, there can be a variable time between when the system issues the command, records the issuance of the command, the firmware initiating the control relay and finally the relay being energized. All these delays and the actual time reported needs to be understood for proper analysis. While most of these issues aren't related to filtering per se, they are critical to properly interpret the data.

The user typically has the option to define the triggering criteria for the recording, the pre-trigger and post-trigger intervals, and if extended recording should be available in cases of evolving faults or other changing system conditions.

Triggering may also be defined by a Boolean logic expression that defines a recording condition that may not be otherwise be seen by a single triggering element.

Recording devices may use edge triggers or duration triggers to initiate recordings. Fixed length recording, as illustrated in Figure 6, simply initiate a recording of pre-determined length, while duration triggers attempt to capture the length of an entire fault within one record. Edge triggering is the most common triggering mode in use.

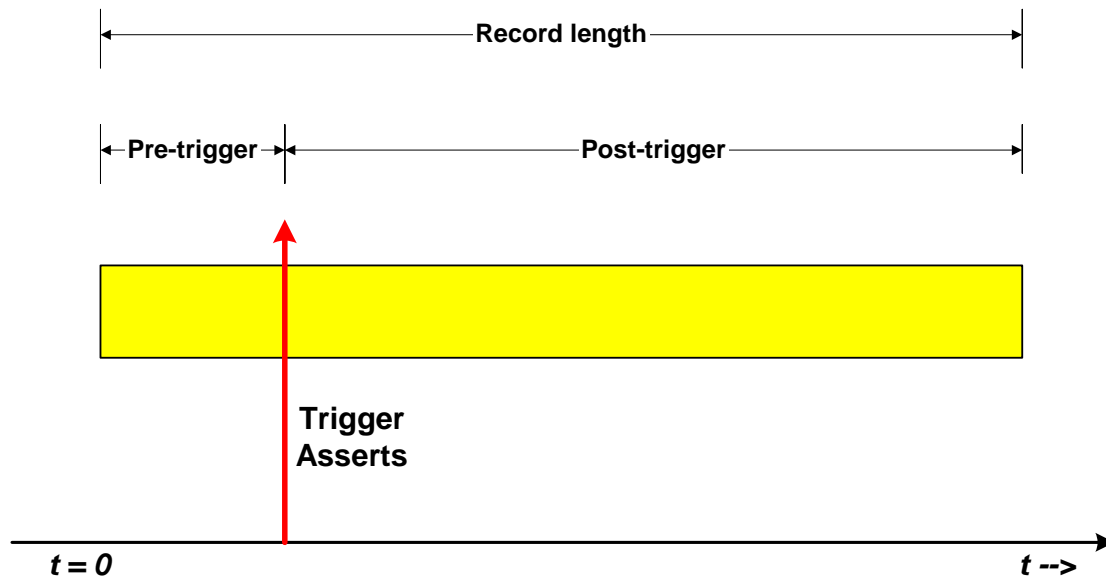


Figure 6: Edge triggering

A device using edge triggering initiates a recording on the rising edge of a trigger, and continues recording for a pre-determined length of time. The total record length is determined by the amount of pre-fault data, the length of the fault and the amount of post-fault data. The amount of pre-fault data is generally configurable in digital fault recorders, and may be a fixed or configurable value in protective relays. The amount of post-fault is either determined by an explicit setting for post-fault data, or by a setting for the normal record length. The amount of post-fault data is generally configurable in digital fault recorders, and may be fixed or configurable in protective relays.

A device using duration triggering, as shown in Figure 7, initiates a recording on the rising edge of a trigger, and attempts to keep recording as long as the trigger remains active. Once the trigger de-asserts, a device using duration triggering generally captures some amount of post-fault data.

The total record length is determined by the amount of pre-fault data, the duration of the event, the amount of post-fault data, and the maximum record length. The amount of pre-fault data and the amount of post-fault data for duration recording is generally configurable. The maximum record length may be configurable or a pre-fixed value. When the trigger duration exceeds the maximum record length, the recorder typically stops recording further data, resulting in possible unrecorded data.



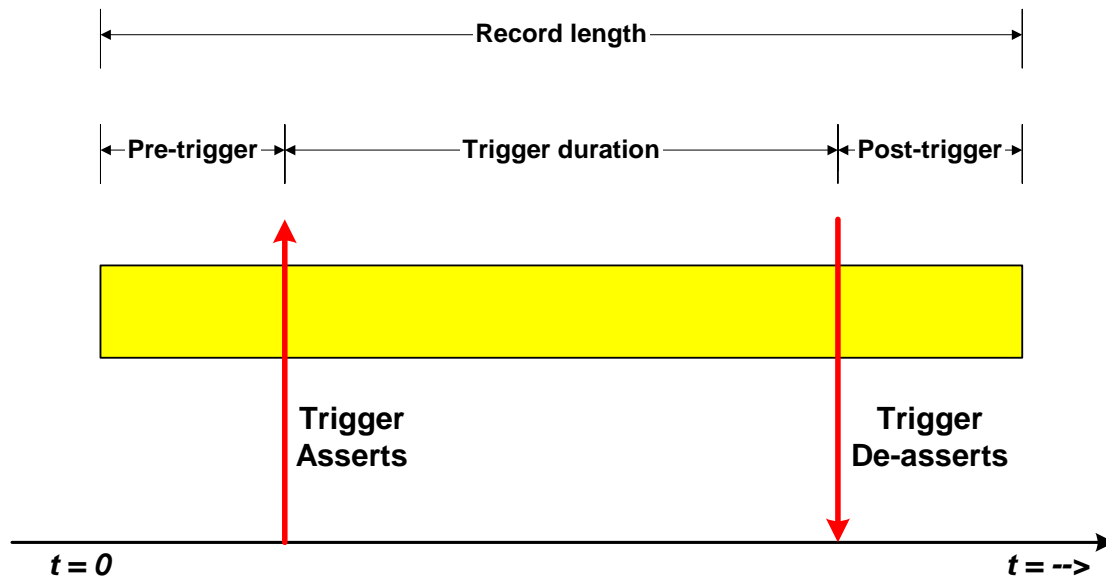


Figure 7: Duration triggering

Duration mode recording is one method to attempt to capture an entire power system event in one fault record. A second method that is available in some recording devices is automatic extension of fault records for multiple trigger conditions as shown in Figure 8. When a second trigger occurs while a prior recording is still active, the device extends the first recording to capture the appropriate amount of post-fault data for the second trigger. Similar to duration triggers, automatic extension is limited by a maximum record length setting, which is typically set far greater than the normal record length.

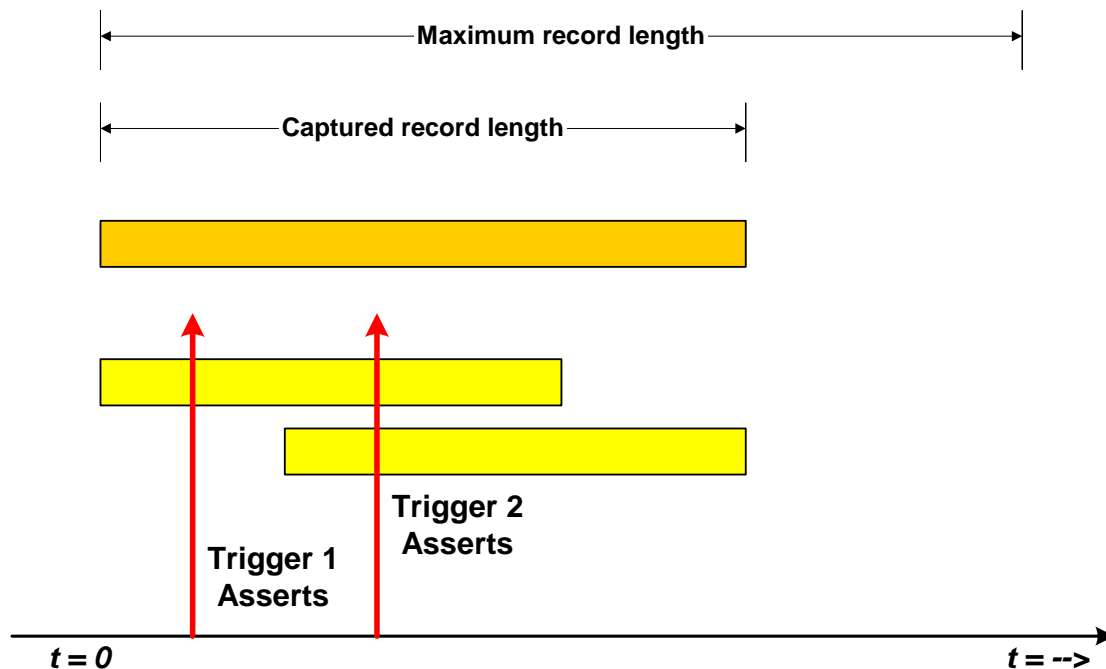


Figure 8: Automatic extension of records

## 11. Storage Methods

There are a variety of methods for storing data on recording devices, retrieving data from recording devices, and storing this data for the system. Consideration needs to be given to the type and size of memory at the recording device and at a central archiving location. The type of memory may impact the decision on the power supply for the recorder, and the size of the memory may dictate the retrieval method and timing.

Disturbance recorder memory is designed to store records on the recorder, to give users adequate time to retrieve the records. Users may need to store records on the recorder up to 60 days. Therefore, the memory size of a disturbance recorder must be large enough to store records to meet these requirements, based on the file size of a typical recording.

Writing records to memory uses one of two methods. One method is to use a first-in, first-out buffer. Once the memory is full, the recorder begins over-writing the oldest records as new triggers occur. The second method is to stop writing to memory, once the memory is full. This method requires the issuing of storage limit alarms, and requires users to manually remove stored records to permit the creation of records on new triggers. DFRs tend to allow user choice between methods, while protective relays typically use a first-in, first-out buffer.

Some microprocessor-based relays and DFRs allow user configuration of the oscillography records to be stored in memory. Configuration choices may include:

- **Triggering condition:** can be user-programmable to allow producing records from a number of conditions both internal and external to the recorder.
- **Recording rate:** the recording rate for many DFRs, and for some protective relays, can be configured. For some devices, this setting also changes the performance of the analog to digital converter, and the frequency response of any filters. Other devices use data decimation that mathematically eliminates samples recorded at the highest sampling rate of the device. For these devices, the spectral content of the recorded data will be lower, due to anti-aliasing of the device.
- **Content:** A number of user-programmable event and analog channels may be available. The analog channels may include signals measured and calculated in real time by the recording device, such as magnitudes and angles, positive-sequence quantities, power, differential currents, etc., or input signals other than ac currents and voltages (such as external transducer inputs). Event channels may include external contact inputs, internally created operands such as the pickup or operate flags for various protection elements, auxiliary flags of user programmable logic, etc.
- **Length of the pre- and post-trigger data** is often user-programmable.
- **Number or duration of records** is often user-programmable to maximize the recorded information based on available memory and anticipated duration of the power system events of interest.
- **Treatment of old records** is often user-programmable. The choices often are to automatically overwrite or forbid new records to protect the old ones.
- **Clearing the records** can be user-programmable, allowing for easy or automated clearance of old records.

- **Record Classification** - Some recorders have schemes for classifying records by a parameter such as trigger method. If the records are somehow classified automatically, it is possible to download only certain records.
- **Continuous Recording** - Some recording devices are capable of continuous recording, wherein the measured data is continuously streamed in near real time to a central location over a network connection. This feature requires only enough storage capacity to accommodate the speed of the communication medium. It also avoids the necessity of selecting appropriate trigger quantities.

### 11.1. Records Extraction

Data retrieval from recording devices can be performed locally, by directly communicating to the device while in the substation, or remotely, by using telecommunications access to the device from a central location. In either case, data retrieval is normally performed using proprietary software, from the manufacturer. Since this software typically only works with devices from one manufacturer, a user with many devices in the field needs to maintain several different host programs for file retrieval. This adds to the problems of analysis of a system disturbance.

With microprocessor based recording devices, the user often has the ability to select how the device will transmit the record for analysis. These units may be selected to operate in an auto-polling (central PC calling the recorders periodically) mode, auto-calling mode (recording device automatically initiates the call to transfer data) or a manual mode. Installation of a “mini-master” at the substation can also be set up to retrieve the records from individual recording devices with limited storage, alleviating the memory constraints at the recorder itself.

Recording devices from different vendors use different methods to name record files. For data analysis, it is necessary to identify records as for a certain event, and from a specific device. A method to standardize file names is very useful for this purpose. This report recommends using the recently developed Recommended Practice for Naming Time Sequence Data files (PC37.232) as the standard for record file names.

### 11.2. COMTRADE

COMTRADE defines a common format for the data files and exchange medium needed for the interchange of various types of fault, test, and simulation data. The rapid evolution and implementation of digital devices for fault and transient data recording and testing in the electric utility industry have generated the need for a standard format for the exchange of data. This data are used with various devices to enhance and automate the analysis, testing, evaluation, and simulation of power systems and related protection schemes during fault and disturbance conditions. Since each source of data may use a different proprietary format, a common data format is necessary to facilitate the exchange of such data between applications. This facilitates the use of proprietary data in diverse applications and allows users of one proprietary system to use digital data from other systems.

The COMTRADE standard C37.111 defines a format for files containing transient waveform and event data collected from power systems or power system models. Equipment manufacturers typically use a proprietary file format to manage several issues. The most important of these is the need to compress the file size to maximize storage capabilities of the device, and to reduce the transmission time when retrieving records from the device, and to ensure the reliable transmission of data. The COMTRADE format is intended to provide an easily interpretable form for use in

exchanging data. As such, it does not make use of the economies available from data encoding and compression that proprietary formats depend upon for competitive advantage. The standard is for files stored on physical media such as digital hard drives, compact disks, and diskettes. It is not a standard for transferring data files over communication networks.

All records – waveforms, disturbances or trends - should be saved in their native file format. This provides an original record of the data as recorded by the device and the starting point for later review should it become necessary.

## **12. Analysis of Disturbance Records for Power System Operations**

Historically disturbance records have been used to analyze a power system incident, the most common being to verify protection system performance. However, fault recorders are not the only tool available to the protection engineer. Sequence-of-Event (SER) data, and relay event data are also used regularly. In addition, due to incomplete monitoring restrictions for DFR or SER equipment, data from SCADA (Supervisory Control and Data Acquisition Equipment) is also used in the analysis. The protection engineer responsible for a fault investigation will typically use all of these resources in the analysis especially if a mis-operation of the protection system has occurred. All available information should be time-synchronized to the GPS system making it easier to align the information collected from multiple devices located in several different locations within the power system.

Before starting the analysis of a disturbance it is recommended that a backup copy of the original data be made in the event that the records being used for analysis become corrupt for any reason.

The manufacturer's of disturbance recording equipment and microprocessor relays provide software for display and analysis of the records captured with their equipment. There are third party software packages available that are able to read multiple manufactures original files and provide the tools to perform the analysis.

To date most post-fault analysis is done manually by the engineer, however, there work is on going by universities and some businesses to automate the analysis of fault records.

### **12.1 Fault Location**

Many microprocessor relays and some disturbance recorders produce a fault location output which is available as soon as the record is processed without any manual analysis. Some of these devices can send the fault location and fault type to the System Control Center via the SCADA/EMS system. Immediate access to the fault location allows power system dispatchers to make decisions about system restoration. However, the relay and recorder fault location information may be only an estimate due to infeed, mutual coupling, and nonhomogeneous line construction. The dispatcher using this information should be made aware of these inaccuracies or provided a means of compensating for them.

### **12.2 System Oscillations**

Power system disturbances, in some cases, initiate a period of oscillations which may continue for many seconds. There also have been occasions when system oscillations began without any apparent initiating event. The frequency of these system oscillations is often in the range of 0.2 to

1 Hz. These oscillations are of great interest to power system operators. DSRs can help determine some important answers to the following questions:

- Where is the oscillation magnitude highest?
- What are the natural frequencies in different areas?
- Under what system conditions are oscillations likely to occur?
- What is the relationship between system conditions and damping?

Note that DSRs must be located across the system to answer these questions.

## 12.3 System Conditions and Loading

Pre-event system conditions and particularly transmission loading are important in disturbance analysis. These parameters can be obtained from DSRs, provided that the DSRs trigger for the disturbance of interest.

## 12.4 Loss of Generation or Load

In power system operations or operations planning it is frequently necessary to determine the change in frequency, voltage, or MW flow that occurred on a contingency, such as loss of a generator tie. DSR records are frequently employed for such purposes. These evaluations are important for validation of contingency analysis studies and for calculating various system parameters. As an example, Figure 9 shows upon the loss of a large generator at UTZ 07:26:23 on 15 January 2006, the example record showed that the Eastern Interconnection frequency decline was 46mHz.

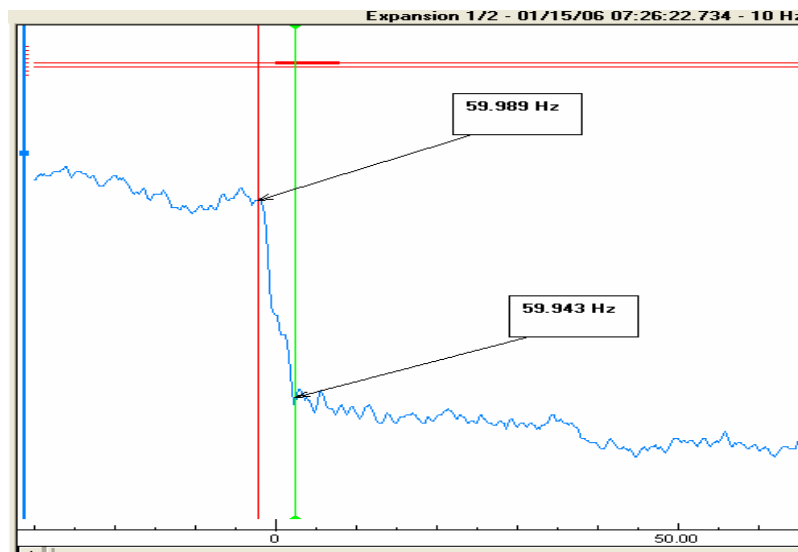


Figure 9 Change in Frequency Due to Loss of a 1300 MW Generating Unit

## 12.5 Real-Time Phasor Output

Some disturbance recorders provide a real-time voltage phasor output. This signal, when time stamped with microsecond accuracy can be coupled to a state estimator to provide an indication

of the power flow and stability of the system. In fact with PMUs, state estimation may be replaced with state measurement.

## 12.6 Wide Area Event

With an installed base of disturbance recording equipment that is time synchronized it is possible to analyze a wide area event. When considering the start of a wide area disturbance, it is usually caused by a short circuit fault, followed by protective relay operation and tripping of one or more system elements. For example a cross-country line fault that results in tripping of two transmission lines may lead to a more involved system disturbance.

The analysis will require the recordings of the current and voltage waveforms at different locations around the system, as well as accurate capturing of the change of state of breakers auxiliary contacts and the protection system's "Trip" outputs. These records need to include a time stamp, accurate to one millisecond, to chronologically align the records for analysis.

Experience gained from the analysis of the August 14, 2003 blackout demonstrates the need for accurate time synchronization and the ability to quickly collect and align records from a large number of locations throughout the affected system area. Over a thousand records from several utilities were submitted to the NERC task force for analysis. The use of the IEEE-PSRC file naming convention [2] was also mentioned as a very valuable method for quickly finding related files for the event analysis.

The records from a wide area can be used to identify the specific events that resulted in the deterioration of the situation that ended in the final several seconds of the blackout. Shutdown of generators, operation of under-frequency load shedding, tripping of transmission lines during faults or power swings can be analyzed using simulation of the system dynamics or directly replaying the records through protection test devices.

The analysis of the behavior of special protection systems or primary system elements during the next phase of a wide area disturbance imposes recording requirements that are quite different. Figure 10 illustrates the power system frequency as measured and collected by 99 sites for the August 14, 2003 event.

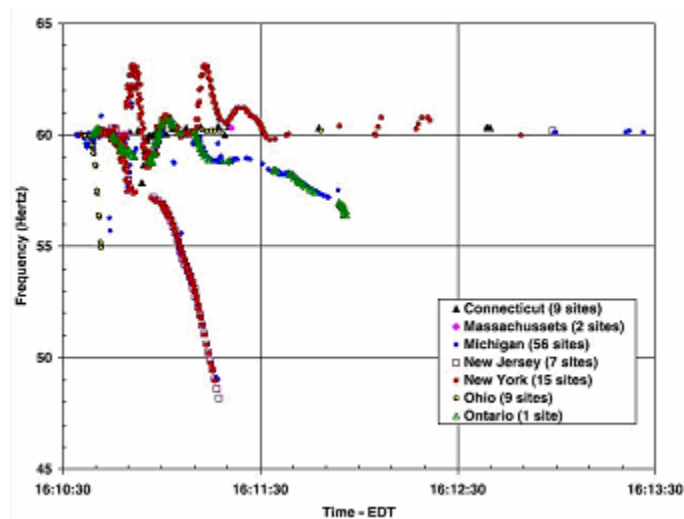


Figure 10 Frequency plot from NERC August 14, 2003 Blackout Report

Since the records can be used for different purposes, the user should be able to select the recording of the current sample of the monitored quantity, or to record and display the minimum, maximum, and average values that occurred during the previous interval recorded.

### 13. Conclusion

To analyze the performance of the power system after some event, it is necessary to use data from a variety of sources, including protective relay target data, SCADA data, oscillographic and event data, stand-alone sequence of event recorders, and power quality monitors. In general, disturbance recording devices are the first source for data used in analysis.

The event analysis may require data from more than one substation site to get the full picture of what happened if there is insufficient data available in the station of interest. Time stamping or time synchronizing of the individual recording devices becomes vital to comparing the data from multiple devices and being able to develop a composite “record” of what transpired.

Depending upon the parameters and characteristics that have been selected for each of the different type of recording devices, the user has to be cognizant that there will probably be differences between collected records when comparing the data or declaring absolute conditions referred back to the system parameters.

Twenty years ago, waiting days for data while someone went to the substation to retrieve paper or magnetic tape files was considered the norm. Today, this is no longer acceptable, when answers to the question of what happened are required within a relatively short period of time, usually the same day. The data must be accessed quickly so that analysis can be conducted in a timely manner. Automation of the retrieval of data has greatly improved the wait time.

Regulatory agencies are beginning to take more of an active part in prescribing data requirements in certain substation topologies. While more recorders will produce more data to be able to analyze what happened following a disturbance or event, it may also complicate matters by being inundated with so much data that it will be like “finding the needle in the haystack”. The PSRC working group report and continuing work by the working group related to the file naming convention of time sequence data [2] may assist in this effort. All of this data will not come free, as additional recorders will have to be installed, or the replacement of old electromechanical relays with digital protection relays with recording capability may be required. Perhaps data refining algorithms that can selectively transmit only the relative data to an event will evolve.

Future enhancements in fault recording technology will revolve not only around the hardware, but also through supplier and third party software programs to automatically gather and analyze some of the events. For example, certain types of events that take place more frequently than others might be able to be automatically analyzed with little or no input from a user if sufficient data and specifications are in the program. This will involve considerable “upfront” system parameter gathering and inputting to define what ultimately defines some form of “fault signature” data that can be used by the software. This may also have other benefits to the user as the software being able to automatically define “good” events from “bad” ones. Perhaps even to the extent of itemizing individual protection relays that if instrumented down to the needed level, require maintenance or adjustment. On the other hand, where data is missing, or the signature of the fault/event is indeterminate, then the user will still be required to gather and analyze all of the required data, and in some cases, construct missing data to arrive at sound conclusions.

Complete fault records can be used by simulation programs to analyze the performance of the protection and provide automated relay test set equipment with fault records that can be taken back to the substation sites and replayed into the protection relay system to help diagnose mis-operations and for end to end testing and verification of protection systems.



Long term disturbance records will continue to aid in the analysis of those events that spawn over a long period of time. For example, in a power plant, an initiating event that takes many hours or days to trend up to the point where a power system event finally takes place that can be analyzed when captured using the disturbance monitor functionality.

Regardless of the type of device, it is important to know what is actually being recorded. Triggering functions, frequency response, filtering, type of recording, recording algorithms, and record length are issues to be considered for each device applied to capture power system events.

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