A GUIDE TO DIGITAL FAULT RECORDING EVENT ANALYSIS

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Abstract

Proper interpretation of fault and disturbance data is critical for the reliability and continuous operation of the power system. A correct interpretation gives you valuable insight into the conditions and performance of various power system protective equipment. Analyzing records is not an intuitive process and requires system protection knowledge and experience. Having an understanding of the fundamental guidelines for the event analysis process is imperative for new power engineers to properly evaluate faults. As senior power engineers retire, knowledge of how to decipher fault records could be lost with them. This paper addresses aspects of power system fault analysis and provides the new event analyst with a basic foundation of the requirements and steps to analyze and interpret fault disturbances.

Introduction

The power system, a matrix composed of hundreds and thousands of electrical elements, is so massive that it can cover inter-continental territories and sometimes different countries. This colossal living matrix has to be properly synchronized, operated, and coordinated where power generation must equal power consumption. If sporadic interruptions are experienced inside of it, they must be isolated, investigated, and repaired until the cause of interruption has been resolved. Its advantage in size has it downsides since a failure in a small part of its structure can crumple the whole system. Fortunately, there are event analysts who investigate system failures and behavior of power system events, allowing them to continuously oversee proper and improper operation of the system. As a result, new discoveries are found on how to improve the design and proficiency of the power system. Being a good event analyst takes system protection knowledge, practice, and years of experience; good analysts are hard to replace. So how do we follow in their footsteps and train new people to have a great start? It is the purpose of this paper to provide a simple guide that will give the new event analyst a solid beginning to an exciting and rewarding career.

It is important to understand the meaning of fault analysis and recoding, and this guide offers the newcomer some practical explanations and applications. Digital fault recorders (DFRs) and microprocessor-based relays offer recording capabilities in the form of waveforms and sequences of events. However, these two differ in the sampling rate processing power, type of record they can capture, lengths of records, and the ability to record wide system response. Depending on the utility philosophy, one type of equipment might be preferred to the other. The important factor is to know the characteristics that both pieces of equipment offer and determine which one offers the best information for event analysis.

Sequence of event information is crucial for event analysis. It is widely known that a 52a contact operation can determine the status of a breaker operation. However, having trip surge coils can offer specific “trip coil energization time”, allowing analysts to determine whether or not a breaker is interrupting the current at an adequate time. Similar techniques can be applied to check transfer trip signals and operating times.

The basic concepts of symmetrical components and their respective sequences can be applied to decipher types of faults. In addition, phasor diagrams for current and voltages can greatly aid in the visualization of distinguishing fault behavior. This guide exhibits real time fault events where the concepts of phasor diagrams and symmetrical components are applied to decipher faults.

The analysis of power system events can be as exciting as it can be laborious. It can also be time-consuming since faults might happen in different parts of the system and may involve different utilities. Unique software features can definitely improve the analysis and investigation of system events.

Purpose of Fault Recording

Fault records are one of the most important pieces of evidence that event analysts can have during system event investigations. They can provide the reasons for premature equipment failure, supply waveforms and status of equipment behavior during an event, and give necessary information to perform post-fault event analysis. Proper use and interpretation of event records can lead to corrective action for a given system problem resulting in improved performance and reliability of any generation, transmission, and distribution system. Fault records are now captured by microprocessor relays but records are limited to sampling rate and record length. Some use digital filters that do not reflect the real captured waveform (10). Digital fault recorders offer specialized, specific, and dedicated microprocessor equipment with far superior sampling rates, record lengths, and unfiltered recording abilities. Utility engineers have to make balanced decisions as to what equipment is better to use for pre- and post-event analysis. Regardless of the equipment employed, both come at some economic cost. Nevertheless, as expected maximum use of their recording capabilities assures maximum return in their investment.

Fault recording has been used for decades now, and it is generally used for two main purposes:

- Recording of system events
- Monitoring of system protection performance

Recording of System Events

Recording of system events can be classified as fast transient recordings and slow swing recordings.

- Relays and recorders are capable of recording fast system events such as power system faults, lighting strikes, switching events, insulator flashing, etc. These types of transient events are usually short-lived and fast; therefore, they do not require long record lengths unless faults have cascaded into multiple system elements or a fault has remained in the system longer than normal. In these cases longer transient records are needed to capture the entire event. These types of records let the analyst know the current and voltage magnitudes, time, and duration that were observed during the course of the event. This information can then be analyzed and dissected to look for potential problems in the timing and current and voltage magnitudes. Analysts can detect abnormalities such as current transformer saturation, breaker restrikes, ferroresonance, CCVT transients, etc. Investigation of current magnitudes can also be used to determine the deviation of actual fault values vs. calculated values from software. Short circuit databases, due to their large composition, can contain errors that yield misleading fault values. Comparing actual and calculated values is a good practice to check for possible inconsistencies. Transient records can further improve the analysis of such events mentioned above by providing the symmetrical component quantities of the current and voltage during steady state and fault conditions. The positive, negative, and zero sequence components can be used to determine their individual magnitudes during the transient event. They can also be used to verify the type of fault. This process is further expanded in the section below about deciphering power system faults. Another type of system event is incipient faults such as early signs of insulator failure. Such conditions require longer record lengths to capture the early development of the event and are better handled by DFRs because of their record length capabilities.

- Slow swing recordings are designed to capture the power system's response in RMS values following a power swing or disturbance. These records can usually help to determine how well the system is designed. These types of records can capture the response of generators, power swings on transmission lines, load variations caused by voltage and frequency fluctuations, and transient phase angle changes (7). Since these records measure system response, swing recorders are required in specific spots and under different owners of an interconnected system. Swing records do not have the fast rise or sharp current changes that transient records have since they are sampled at very slow rates. Therefore, accurate time stamps are needed to analyze system event records from many pieces of recording equipment. The records themselves need to cover a much longer period than transient records. There are some microprocessor relays capable of swing recording data, but they are limited by record length. DFRs have swing recording as part of their design and can capture incredibly long records. It is recommended to use maximum record length.

Monitoring Power System Performance

Fault recording devices have proven to be invaluable assets in indentifying proper as well as improper behavior of system protection schemes and associated equipment. The ability to record protection system performance such as relays, circuit breakers, and control systems has resulted in design improvements and corrections of the power system. Consequently, companies have prevented future equipment damage and failure, generating economic savings and improving the overall performance of the power system.

Some practical applications of the fault recording devices include monitoring the "failure of a relay system to operate as intended, incorrect tripping of terminals for external fault zones, determination of the optimum line reclose delay, impending failure of fault interrupting devices and insulation systems (7). " Another application is to monitor trip coil energization. Monitoring of trip surges is far superior to monitoring breaker auxiliary contacts. Monitoring the coil energization tells precisely when the breaker command was received. The coil is de-energized by a 52a contact indicating the precise time when the contact motion began, which can sometimes be quite long. This can be combined with the line current information revealing when the last breaker interrupted the current, though not the first. Other record events that help to monitor the credibility of a protection system include: lockout relays, transfer trip keys, and receipts. The advantages of trip coil and transfer trip monitoring are expanded in the sequence of events section below.

Triggering of records should be sensitive enough to capture all local faults independent of relay response. Most importantly, the goal is to trigger for many events without resulting in local tripping so power system response can be reviewed. Secondly, it is important to capture a record of a local fault accompanied by a relay failure. Fault recorders have an advantage over recording relays in this regard.

Monitoring circulating zero sequence currents (Io) in autotransformers is very useful since they capture all local and most remote ground faults. Triggering for under-voltage conditions during voltage depressions is also advantageous. A wide variety of local and remote faults can be captured since faults will tend to depress or collapse the voltage. Also, complex line relaying schemes with weak feed provisions can mis-operate on these voltage depressions, so it is good to capture them. A combination of under-voltage and zero sequence current triggers will capture almost all faults near the recording equipment.

Sometimes initial triggering setup does not capture problems associated with mis-operating systems. This is particularly true when the protective scheme operates during non-fault events. Changing the sensitivity of the triggering and adding specific events such as high speed current relays or surge trip detectors can enable the identification of a particular cause or at least capture useful clues. Portable recording units can certainly be used as another tool to indentify incipient faults because of their flexibly and mobility.

Many people have questioned the value of digital fault recorders in an era of digital relays with recording capabilities. Nevertheless, digital fault recorders offer far advanced recording capabilities which results in better analysis of system problems and economic savings. Advantages of fault recorders include:

- They are independent of a failed or partially failed relay that a DFR maybe monitoring.
- They do not filter analog signals as many digital relays do.
- They offer more memory capacity, enabling longer records.
- They have faster sampling rates.
- They have broader frequency response.
- They are designed with more triggering options.
- They can monitor many power system components simultaneously.
- They can be used to monitor power quality issues, especially with connections with windfarms, FACTS, static VAR generators, arc furnaces, and variable frequency drives.
- They are useful in studying problems associated with current inrush where large autotransformers are applied in parallel combinations.
- They offer a wide spectrum of system responses during faults.

Oscillography and Components

The analysis of oscillographic data requires an excellent understanding of the recording equipment, protection system schemes, and behavior of power system elements. It is necessary for the event analyst to comprehend the characteristics and tools provided with recording equipment in order to maximize the equipment's use and to properly interpret the data. An understanding of the design, concepts, philosophies, and application of system protection is vital to decipher system events. Knowledge of the behavior and characteristics of power system elements, such as transformers, reactors, breakers, and capacitors, can aid the explanation and reasoning behind certain system events. Without a doubt, becoming proficient with system protection and power system element knowledge comes with years of experience and practice. For this reason, these two broad subjects cannot be covered fully in this paper. Nevertheless, understanding some of the recording equipment's oscillography characteristics can prove to be helpful when interpreting fault records. Concepts such pre-post triggering characteristics, time frames, fundamental RMS versus true RMS, sampling rates, and time synchronization are given below.

Pre-Post Initiation of Fault Data

The power system operates under steady state conditions when equal amounts of power are generated and consumed. This assumes that the system is working under its voltage, current, and element limits. We can also deduce that due to vast geographical exposure of the power system, this normal or steady state operation can be interrupted in certain parts of the system. No matter how well the system is designed, faults are going to occur for many reasons such as equipment failure, acts of nature, operator or technician errors, etc. The vital evidence that tells what happens during the fault is found in the pre trigger, event duration, and post fault information of the captured record. **Figure 1** exhibits these characteristics. There are other pieces of information such as SCADA logs that can also aid in the analysis of an event.

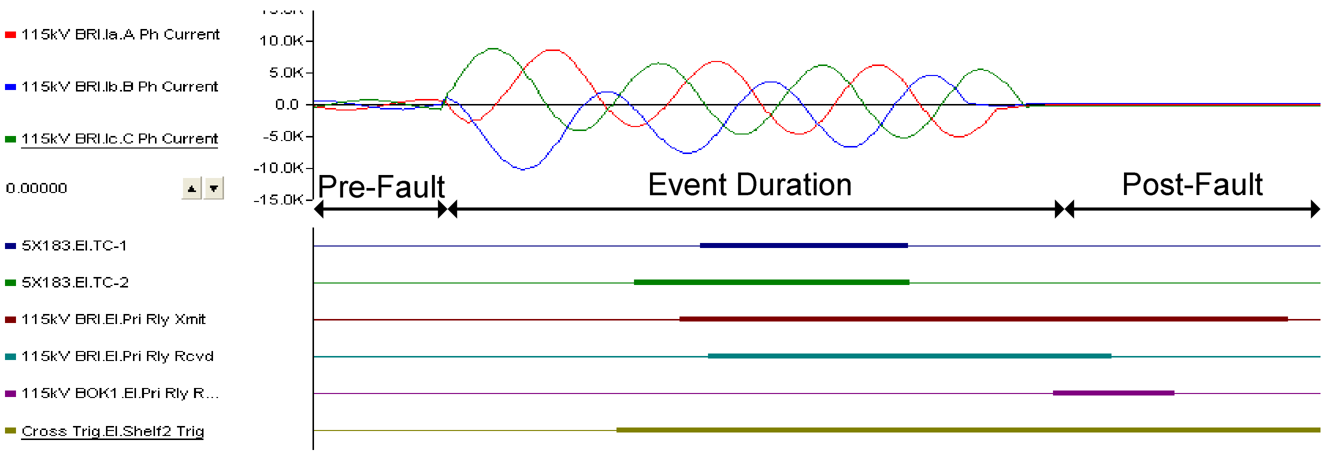


Figure 1. Characteristics of an Oscillographic Record.

Pre-triggering of the record's fault section is identified by all the voltages, currents, and sequence of events that existed during the steady state conditions before the inception of the fault. The system voltages and currents should reflect a balanced system except for normal unbalances caused by changes in load demand (14). The pre-trigger information is critical during analysis of an event since any loss of waveform data can delay event investigations. Therefore, it is recommended to use the recording equipment's maximum available pre-trigger settings.

Post-triggering indicates the beginning of the event duration. It is triggered immediately after an event detector such as over-current, under-voltage, or impedance, has indicated a fault inception (14). For proper fault analysis, the record should capture plenty of pre-fault data, total fault duration, clearing time of the fault, the magnitude of the fault voltages and currents, type of fault, and digital signals. For transmission line faults it is desired to capture the fault from its inception through its clearing time and reclosing for about 45 cycles. The duration characteristics of the pre-trigger, duration, and post-trigger of an event record depend on the type of record and application for the analysis. This could be classified into two different classes: transient and swing record lengths.

Transient records are designed to capture very fast events such as faults, lighting strikes, switching events, etc. Depending on the recording equipment, transient fault records can include several cycles of pre-trigger data to seconds of post-trigger data. Some micro-processor relays allow 10 cycles of pre-trigger data to 120 cycles of post-trigger data, sampled at 96 samples per cycle. As shown in **Figure 2**, long records in DFRs and microprocessor relays are advantageous to capture and check reclosing events.

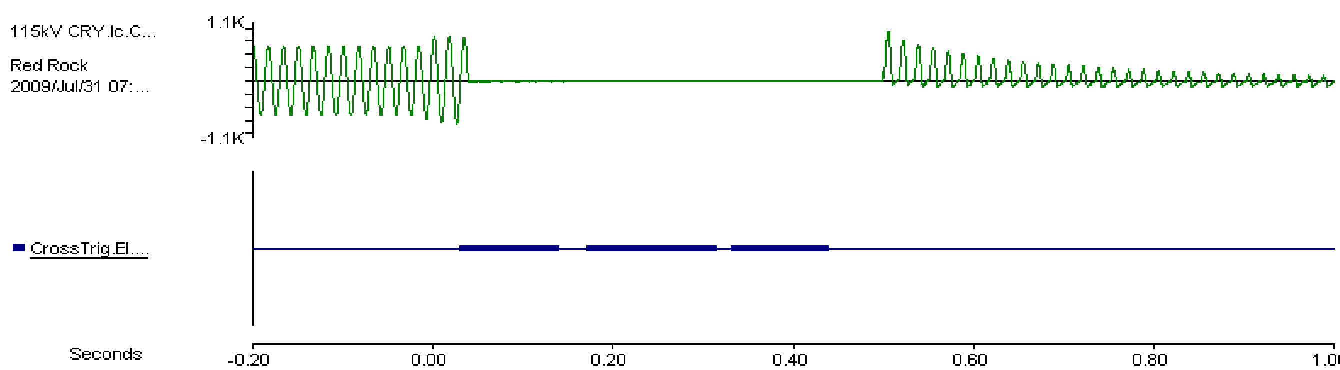


Figure 2. Reclosing Event.

For digital fault recorders, the pre-trigger data length for a transient record can last as long as 60 cycles (or 1 second) and post-trigger data can last as long as 30 seconds sampled at very fast rates of 384 samples per cycle. Long records become especially beneficial during multiple faults or triggering events, showing the event analyst the entire spectrum of the incidents during the fault. Sufficient data enables faster and better quality event investigations. **Table 1** summarizes the transient record lengths for microprocessor relays and DFRs.

Table 1. Pre and Post Trigger Transient Record Lengths for Relay and DFRs.

Transient Records	Pre-Trigger Time (Cycles)	Post-Trigger Time (Cycles)
Microprocessor Relays	10	120
Digital Fault Recorders	60	1800 (30 sec)

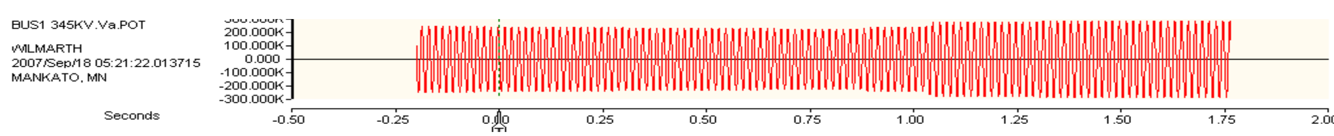
Swing records are designed to capture the dynamic response of the power system when the system has experienced a fault or a sudden change in load or generation (8). Typical swing record lengths can range from several seconds to minutes of pre-trigger and post-trigger data. Some advanced microprocessor relays have the ability to capture power swing events allowing 30 sec - 2 min of pre-post trigger of swing data, and some are sampled at 1 sample per cycle. When a DFR is not available, these limited microprocessor relay swing recording capabilities are invaluable. Digital fault recorders can capture swing record lengths from 1 min to 30 min of pre-post triggering of swing data. **Table 2** shows the swing recording capabilities of some advanced microprocessor relays and DFRs.

Table 2. Pre and Post Trigger Swing Record Lengths for Relay and DFRs.

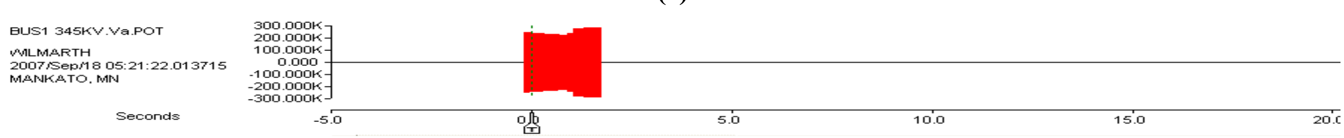
Transient Records	Pre-trigger Time (Seconds)	Post-Trigger Time (Seconds)
Microprocessor Relays	30	120
Digital Fault Recorders	60	1800 (30 min)

The advantage of such long records is to capture the system condition that initiated the swing event, which could be a fault activity or the switching of power system components. As mentioned earlier, such system events might happen at a neighboring utility or interconnected system, and accurate time stamps are necessary for proper analysis.

Figure 3 shows a voltage oscillation that lasts for approximately two seconds which was captured by a DFR as a transient and swing record. **Figure 3a** shows the transient record for Va Phase sample at very fast rates on a time scale of only 2.5 seconds. The next graph, **Figure 3b,** is the same voltage but on a larger time scale of 20 sec. Note that when viewed on the longer time scale which would be of interest for power system disturbances or oscillations, not much can be concluded from such a short transient recording. In order to analyze oscillations with system response, it is better to capture the RMS values of the oscillation as a swing record. **Figure 3c** illustrates the voltage and current RMS values sampled at 1 sample per cycle. Notice the behavior and response of the voltage and current on a wider time scale of 20 sec. The results of swing investigations could lead to improvements in coordination of relay systems that are affected by voltage and current oscillations.



(a)



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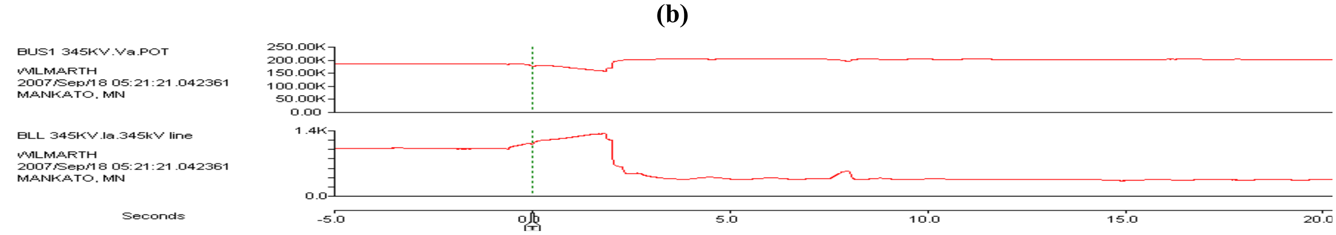

(c)

Figure 3. (a) Transient and Swing Record for Voltage Va and Current Ia.

The importance of having enough pre- and post-trigger data is observed during under-frequency events. The stability of a power system depends on how well the system reacts to a disturbance. For example, when the system is exposed to a sudden loss of generation, its ability to recover and remain stable will depend on the generation control system and load shedding schemes. Depending on the frequency relay settings, a 10 cycle delay might be implemented before operating. Then the second level of under-frequency relays will operate. If the frequency continuous to fall, then the next level of under-frequency relays will be executed until all levels have operated. At this point, the system might be unrecoverable in under just three seconds. Therefore, during an under-frequency event, it is desired to capture at least 3 seconds after the initiating event and perhaps as much as 30 seconds. Having plenty of information before and after the initiation, event permits the analyst to easily correlate data among other records (8).

Time Frames

Working with oscillographic information usually requires analyzing time frames that could be in the form of cycles, microseconds, milliseconds, seconds, minutes, or sometimes hours and days. Each time frame is used differently during an analysis and is usually a function of the application or purpose. **Table 3** gives the different time periods where a time unit is associated with a particular application.

Table 3. Time Frames.

Time Period	Event	Application
Microseconds	Switching Surges	Breaker Restrikes
Milliseconds	Harmonics	Variable Frequency Drives
Cycles	Faults	Relays
Seconds	Load Flow Changes	Governor, Exciter Response
Minutes	System Stability	Power Swings
Hours	Load Variations	Generation Schedules
Days	Continuous Data Recording CDR	NERC Requirements

During fault analysis, electrical cycles are the most common time frame used. They are very easy to distinguish, and most engineers and techs are already familiar with their concept. We say that the voltage or current has gone through a complete electrical cycle when it has traveled 360 time degrees. See **Figure 4**. Since most relay timers are set using milliseconds and resolution is important, familiarity with the milliseconds time frame is crucial. The transformation between cycles and seconds can be easily calculated using the following formula:

$$1\ Cycle = 360\,° \qquad 1\ \mathrm{sec} = 60\ cycles \qquad 1\ Cycle * \frac{1sec}{60Cycles} = 0.0166sec = 16.66\ ms$$

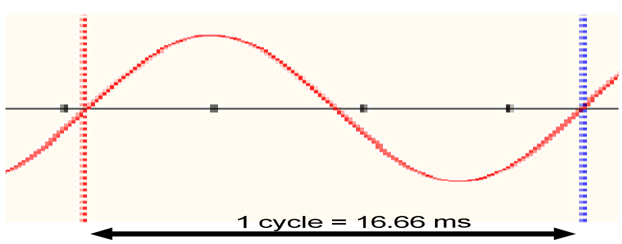

Figure 4. One Electrical Cycle.

Fundamental RMS vs. True RMS

The analysis of waveforms sometimes involves analyzing currents and voltages based on the true or fundamental RMS values. Understanding the concepts, differences, and applications of these two RMS quantities can help explain the behavior of protective relays.

True RMS. True RMS can be simply defined as the RMS measurement values of waveforms that contain all the harmonic components summed in the waveform (4). The number of harmonics available depends on the sampling rate of the relay or DFR. If each individual harmonic RMS value is available, the total true RMS value can be obtained using the following equation:

$$Irms = \sqrt{(I1rms)^2) + (I2rms)^2 + \ldots.(Inrms)^2}$$

The true RMS values become important when analyzing mis-operation from electromechanical relays since these relays are said to be true RMS responsive. It has been shown that true RMS responsive relays can mis-operate due to excessive harmonic content (16). **Figure 5** shows the current waveform that contains the true RMS value and each harmonic value as a percentage of the fundamental frequency. The true RMS values are very useful when analyzing harmonic content created by power electronic equipment such as variable frequency drives, soft starters, rectifiers, etc.

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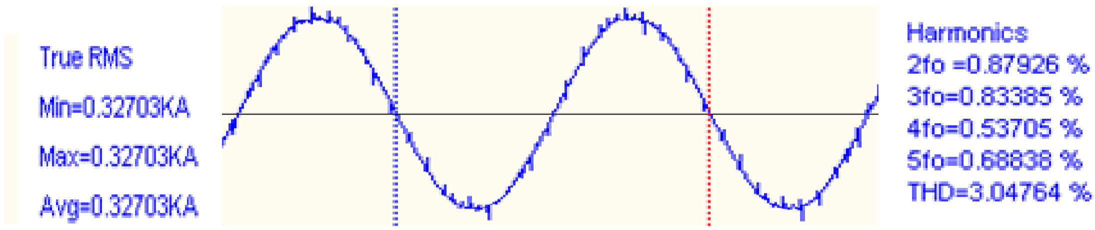

Figure 5. **True RMS Value of Waveform Including Harmonic Content.**

Fundamental RMS. Power system frequency is mostly composed of 60Hz since this is the frequency at which voltage and current are generated. However, due to the existence of non-linear loads, harmonics are injected into the power system. As a result, the voltage and current signals measured by protective and recording equipment include this harmonic content. With new microprocessor technology, it is possible to extract the fundamental frequency waveform by employing different filtering techniques such as the Discrete Fourier Transformer and attenuate all other harmonic signals (9). Consequently, the fundamental RMS waveform is based only on the fundamental frequency of 60 Hz or 50Hz. In contrast to electromechanical relays or solid state relays, which respond based on the true RMS or peak signal, microprocessor relays operate on the fundamental RMS waveform (16). The benefit of using the fundamental frequency of a fault voltage or current waveform is that the relay can be designed to only operate on the fundamental waveform and extract all other harmonic components (9). In consequence, microprocessor design enables avoidance of mis-operations seen in classical relays due to harmonics. **Figure 6** shows the fundamental RMS value for the same waveform above.

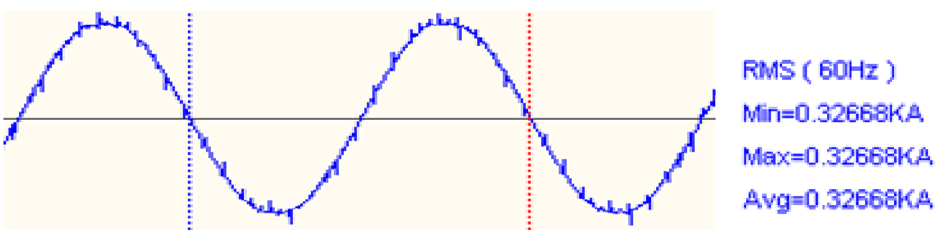

Figure 6. Fundamental RMS Value of Waveform with No Harmonic Content.

Transformer differential relays experience the benefit of working on the fundamental quantities during in-rush conditions. During energization, with the secondary side open, the in-rush current of the transformer will cause only the primary current transformers to provide current to the relay, resulting in a differential trip. Past experience and research have shown that the in-rush current contains significant amounts of the 2^{nd} harmonic. Using the filtering techniques mentioned earlier, differential relays can be set to recognize the 2^{nd} harmonic quantity and block the relay from operating. **Figure 7** shows the in-rush currents during energization and their respective harmonic content as a percentage of the fundamental. The circulating current in the tertiary winding of the transformer is shown in the graph below the in-rush currents.

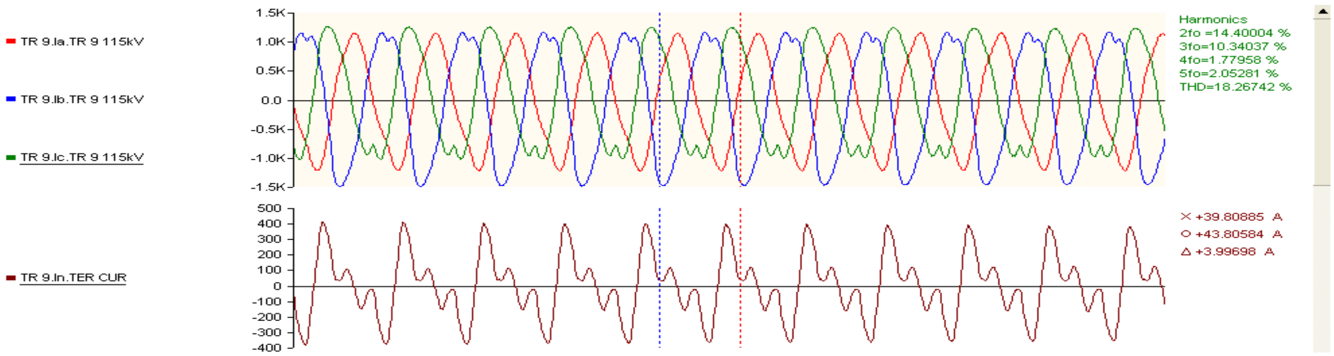

Figure 7. Currents Behavior during Transformer In-Rush.

The recording abilities of the true and fundamental RMS values from DFRs are an essential troubleshooting tool where the electromechanical or solid state relays are still in service.

Sampling Rates

Microprocessor relays and DFRs measure the continuous current and voltage signals from the power system and convert them into discrete time signals through a process called sampling. The sampling rate of the captured data impacts the accuracy of the waveform being replicated and the highest harmonic that can be obtained (9). **Table 4** shows the sampling rate, sample frequency ranges, and the highest harmonic for a typical DFR.

Table 4. Sampling Rate and Frequency Harmonic Range for a Typical DFR.

Sample per cycle	Sample Frequency (60 Hz)	Highest Harmonic
32	1920	8
64	3840	16
96	5760	25
128	7680	33
256	15360	66
384	23040	100

DFRs rarely apply digital filtering since their primary purpose is to capture the data and apply it only for investigative analysis. On the other hand, digital filtering is applied by microprocessor relays to filter out unwanted signals such as harmonics so that protective functions can be applied. In consequence, the recording is done after the digital filtering (10). Some digital relays can provide raw data that will allow reconstruction of the applied signals before digital filtering is applied. However, the user must specify that such data needs to be retrieved from the relay. **Figure 8** shows a good example of a filter versus unfiltered waveform taken from reference (9). It can be seen that the filtered waveform is not the actual presentation of the real system conditions. It is important for the analyst to understand the processes behind the sample data collection and filtering techniques that are employed to produce digital records. If proper analysis is to be conducted, the actual representation of the system behavior should be used.

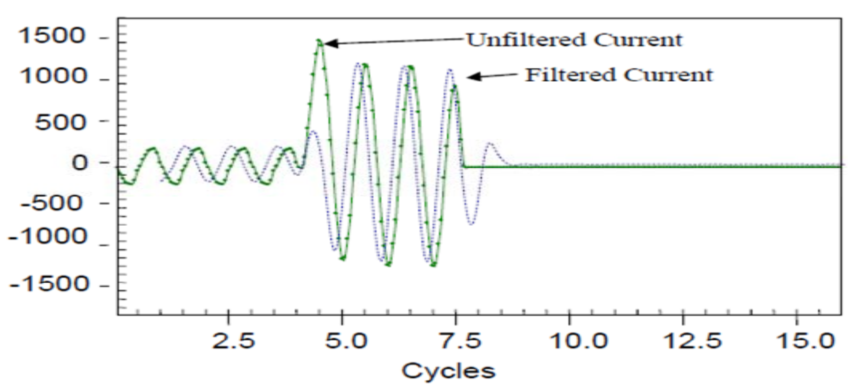

Figure 8. Unfiltered Versus Filter Waveforms.

Time Synchronization
A power system disturbance can happen at any time in various sections of an interconnected system, and it can involve multiple elements. Investigations of wide area disturbances can be time-consuming, laborious, and difficult to analyze. Investigations can be rationalized and simplified when records used to analyze events have been synchronized to the same time frame reference. The investigations and analysis of the August 2003 blackout was very difficult and time-consuming since disturbance recording equipment was not properly synchronized (11). Therefore, time synchronization of data becomes a critical factor in the analysis of power system events. The North American Electric Reliability Corporation (NERC) requires that internal clocks in disturbance monitoring equipment be synchronized to within 2 milliseconds or less of Universal Coordinated Time (UTC) Scale (12). Digital relays and records are equipped with IRIG-B communication ports that allow the records to be accurately time-stamped with the GPS system. A network synchronization method called precision time protocol (PTP) is being proposed that allows 1 μs timing accuracy for devices that are connected to a network such as Ethernet. This protocol is discussed in the IEEE 1588 standard (11).

Sequence of Events Monitoring

A sequence of events can be explained by considering the occurrences that happen before and after the fault. For example, a phase to ground fault could be caused by a lighting strike in the middle of a particular transmission line. The Zone 1 phase to ground instantaneous relays on both ends would detect the fault and issue a tripping signal, resulting in opening both line end breakers. After a few cycles, the relays would issue a reclosing signal, and the breakers would close. In the end, the fault would be cleared and reset, and power in the transmission line would be restored. As observed, a weather condition could interrupt the continuity of power and result in a sequence of protective equipment events that would start with the detection of a fault and end the restoration of the line after the lighting strike has passed. This is an example of an operation where the relays would carry out their job correctly. What would happen if a breaker never closes back or is late in reclosing? What if one relay never operates? The sequence of events recording becomes an indispensible tool to monitor and discover problems with system protection performance, and it should be used to its fullest.

Strategic selection of event points, or digital signals, is fundamental in using fault monitoring equipment to monitor the protection system. A minimum but usually sufficient number of event points associated with transmission line protection would include points that identify trip decisions, communication keys, communication receipts, and breaker status changes. There are many ways to obtain these points, and it is important to capture them in a manner that maximizes the value of the information while minimizing the impact on the protection system. This section will discuss some of the commonly used techniques and their relative advantages.

Breaker Status Change
The most straightforward method of monitoring changes in breaker status is to monitor a breaker auxiliary contact. Since the change of state of typical concern is from closed to open, a 52a contact that opens early in the breaker stroke is preferable to a 52b contact. Using a 52a contact is a low-cost, unobtrusive method of monitoring breaker status. When more than one breaker is tripped to clear a line fault, comparing the times of 52a contact opening can often identify marginally slow breakers before they result in breaker failure operation.

Using high speed current operated relays to sense the current surge in trip coils provides much more information than monitoring breaker auxiliary contacts. These devices typically operate in one millisecond. When placed in both trip coils, they provide very precise measurements of primary and secondary relay operating times. The two trip coils in any breaker are usually operated by different schemes, for example primary and secondary line relays. The onset of the coil energization can be used to determine the different operating speeds of the two schemes for a given fault. The interruption will typically happen at the same time, since that is a function of breaker auxiliary contacts. If a trip coil is energized for as long as 50ms, it probably indicates a breaker problem. It is valuable to catch and attend to these before they result in breaker failure operation or worse. **Figure 9** shows how the trip surge detector relay is used in series with the trip coil.

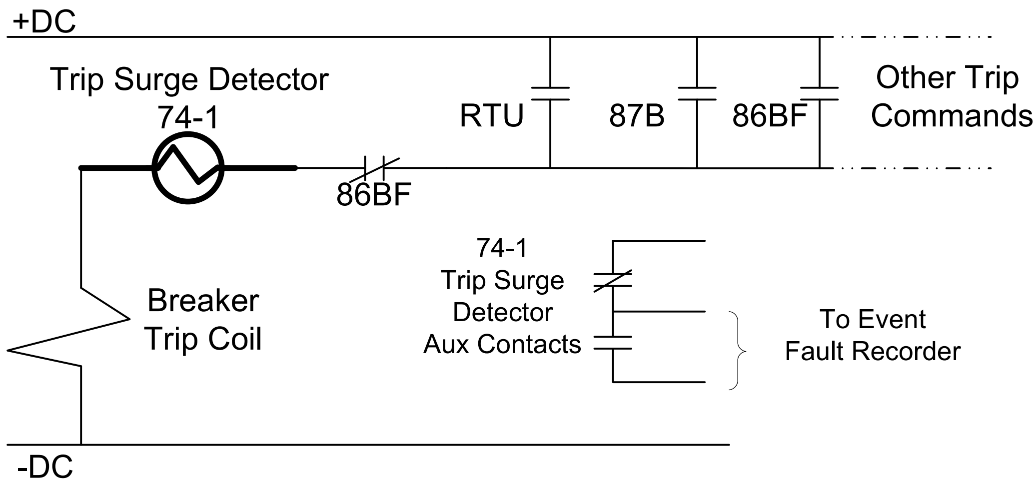

Figure 9. Trip Surge Detector in Series with Trip Coil.

Early acting 52a contacts are used to interrupt trip coil currents, and the fast drop out time of the current operated relay will give a very precise measurement of the time from trip command to the beginning of the breaker motion. In independent pole breakers, this will be the speed of the slowest pole, but that pole is usually the one of most interest. The current operated relay does add a series element to the trip path, but the relay is very robust. It is far more likely to identify a developing breaker failure than it is to cause one. **Figure 10** shows a three phase fault being cleared 2.5 cycles after trip coil energization. It can be observed that the trip surge detector TC2 is faster than TC1 in energization.

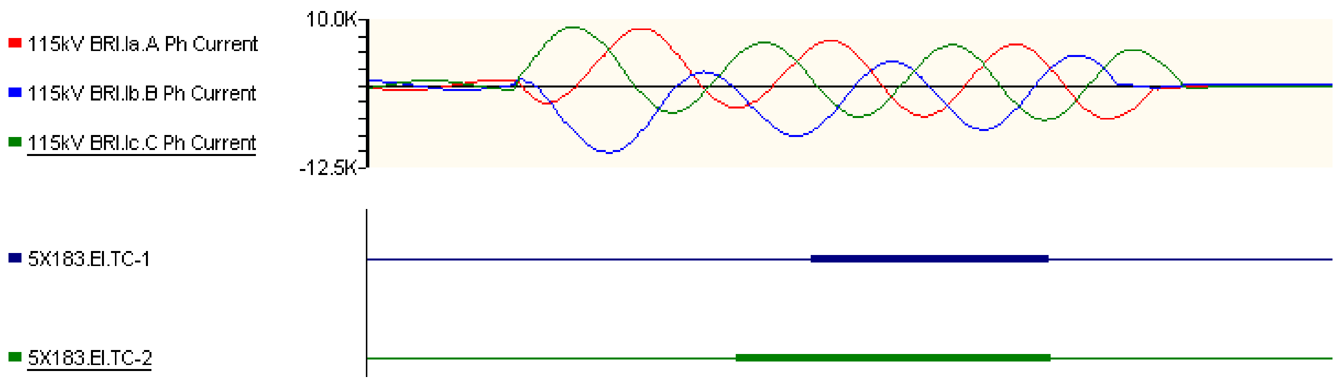

Figure 10. Trip Surge Detectors Operations.

Trip surge detector relays will operate within 1ms of any of the trip commands from devices wired into the trip circuit on the right side of **Figure 9**, but it will not indicate which device initiated the trip command. If unknown trips were being experienced on such breakers for some unknown reason, additional trip surge detectors can be installed in each of the individual tripping elements to trigger the recorder with them and reliably capture the source of the errant trips. This method can be used periodically to investigate these unexplained events, removing surge detectors once the offending device has been discovered.

Relay Pilot Signal Keying

The precise time of transmission of a relay signal is an important piece of information in analyzing protection system performance. For older carrier equipment, the transmitter is keyed by applying station battery voltage to an optically isolated keying input. Where this is the case, using a high speed optical coupler in parallel with the key is often an excellent method of bringing the information to the fault recording equipment. See **Figure 11.** Optical couplers can affect the performance of the protection system. This is especially true when they are used to monitor voltage outputs of older analog solid state relays. Care must be used to ensure that the couplers do not overload or introduce noise to these circuits. New relays and protection schemes have additional outputs that can be set to operate identically to keying outputs. While they do not monitor the transmitter key as directly as an optical coupler in the circuit, they do provide the time the transmitter should have been keyed, with no impact on system performance.

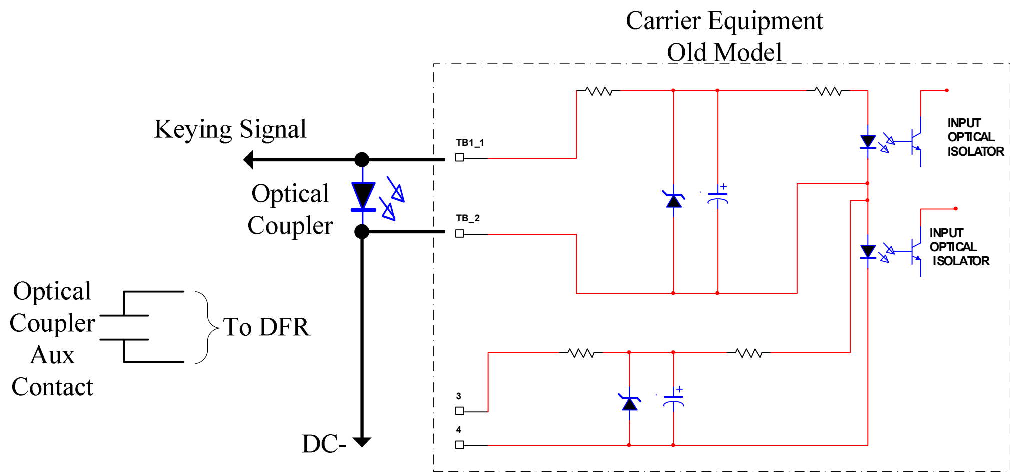

Figure 11. Use of Optical Coupler with Keying Signal.

Monitoring Signal Receipts

Methods similar to those used in monitoring transmitter keying can be used to monitor the receipt of signals. When precise keying and receiving times are available from both ends, any problems with channel delays or interruption can be observed. Monitoring transfer trip receipt and using it to trigger a record can be especially useful. Since these signals are unconditional trip commands, the record is always of value. Transfer trips sometimes occur under power system conditions that may not result in fault recorder triggering.

Other Event Points

Fault recorders are powerful tools in analyzing protection system performance. They can simultaneously monitor many different protection schemes and power apparatus. The few event points listed above are a subset of the events that can be used. Once a control problem is identified, voltage and current operated devices can be installed to capture information that can be used to diagnose and remove the causes of many problems. Often the most useful event points are ones not thought of at the time of installation. It is always a good idea to have many spare event points available in the recorder.

Deciphering Power System Faults

There are many different reasons for the existence of faults or short circuits in power systems. Some of these reasons could be equipment failure, design fallacies, forces of nature, operator errors, vandalism, etc. Each incident causes a different type of fault, and its type will depend on the phases involved. For example, a lighting strike produces excessive high voltage that can exceed the rating of the line, causing a flash over between the conductor and the tower. The current will then flow to ground resulting in a phase to ground fault. Power system faults can also be classified as symmetrical and unsymmetrical faults. During symmetrical or balance faults the current magnitudes in each phase are maintained during the fault and are seen only in three phase disturbances. On the other hand, during unsymmetrical faults the current magnitudes experience an unbalance. **Table 5** summarizes faults according to the type and symmetry.

Table 5. Types of Faults.

Type of Fault	Symbol	Type
Single Line-to-Ground	SLG	Unsymmetrical
Line-to-Line	LL	Unsymmetrical
Double Line-to-ground	LLG	Unsymmetrical
Three Phase	3P	Symmetrical

The quality of the analysis of unsymmetrical and symmetrical faults relies on how well the analyst understands the concepts of symmetrical components. Digital fault recorders and microprocessor relays are based on the symmetrical components method, which provides the foundation to understanding faults. The intention of this section of the paper is to outline what symmetrical components sequences to expect with different types of faults rather than to describe the theory behind them. However, this section does allow the future analyst to appreciate the practical use of such techniques. **Figure 12** shows the open and close system of phasors during balance conditions. The figure also shows the current and voltage vector behavior for different types of faults during unbalance conditions, which aids the visualization of faults.

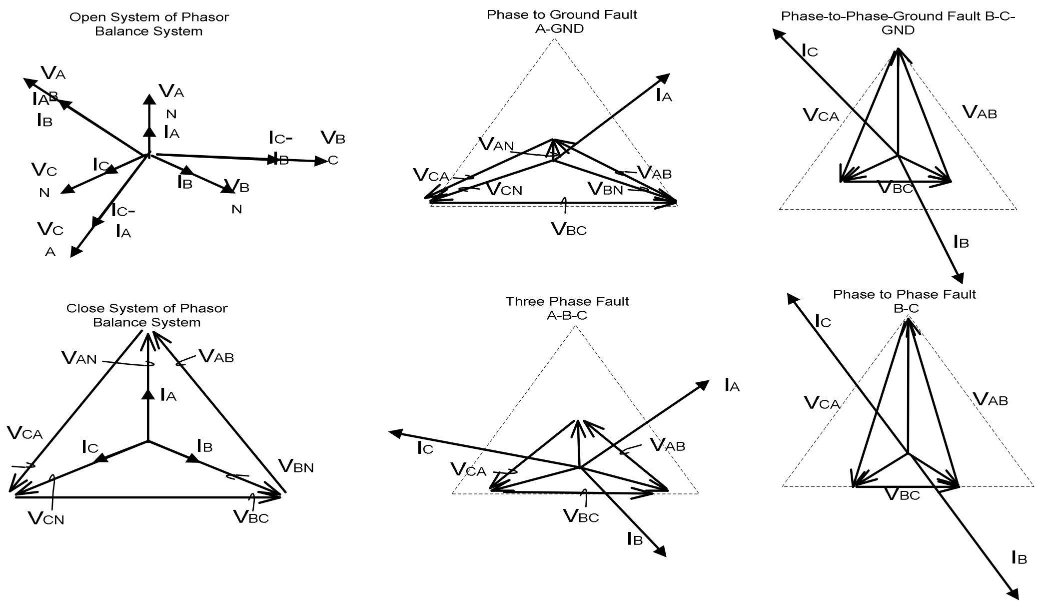

Figure 12. Phasor Representation of Power System Faults.

Line to Ground Fault

From symmetrical components, we know that for a line to ground fault we expect to see the positive, negative, and zero voltage and current components. We also expect to see a depression on the faulted phase voltage and a sharp increase in phase and residual current. These concepts are visualized in **Figure 13** for an A phase to ground fault. Notice the sharp increase in A phase current in the first phasor diagram taken from the second trace. The presence of all three sequence components for the three currents, are also shown in the other phasor diagrams as expected.

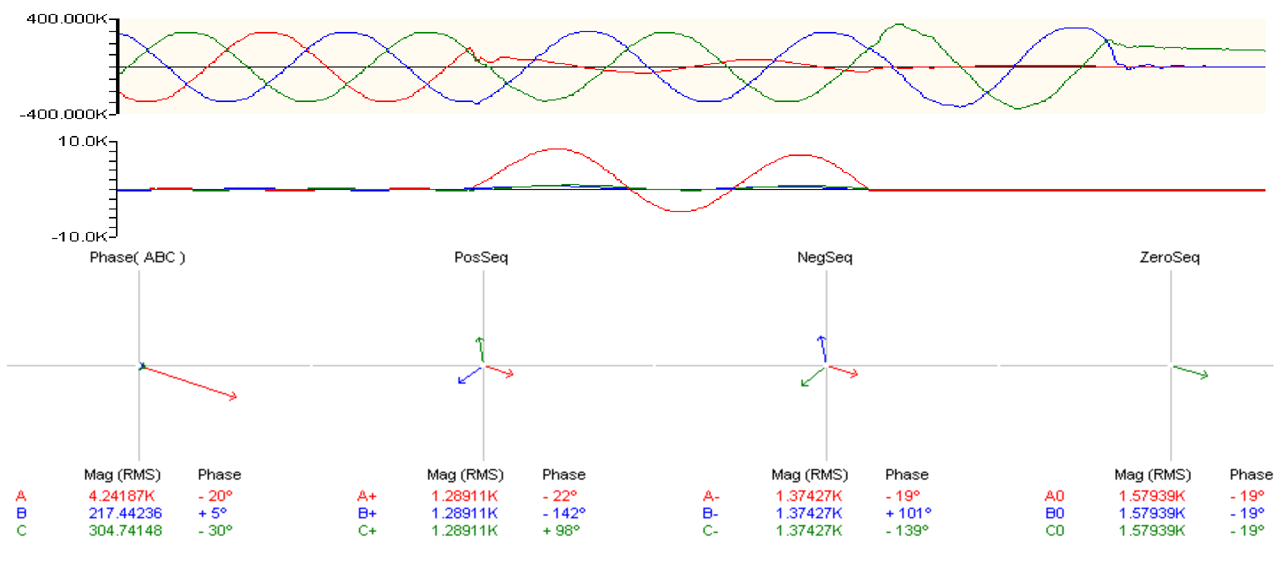

Figure 13. Phase A to Ground Fault.

Line-to-Line Fault

A line-to-line fault is another type of unsymmetrical fault in which only positive and negative sequence components should be anticipated. For the phases involved in a phase-to-phase fault, a rapid increase in current and a voltage depression on each phase should be observed. In addition, both currents should be 180 degrees apart. This principle is illustrated in **Figure 14** for an A-C fault.

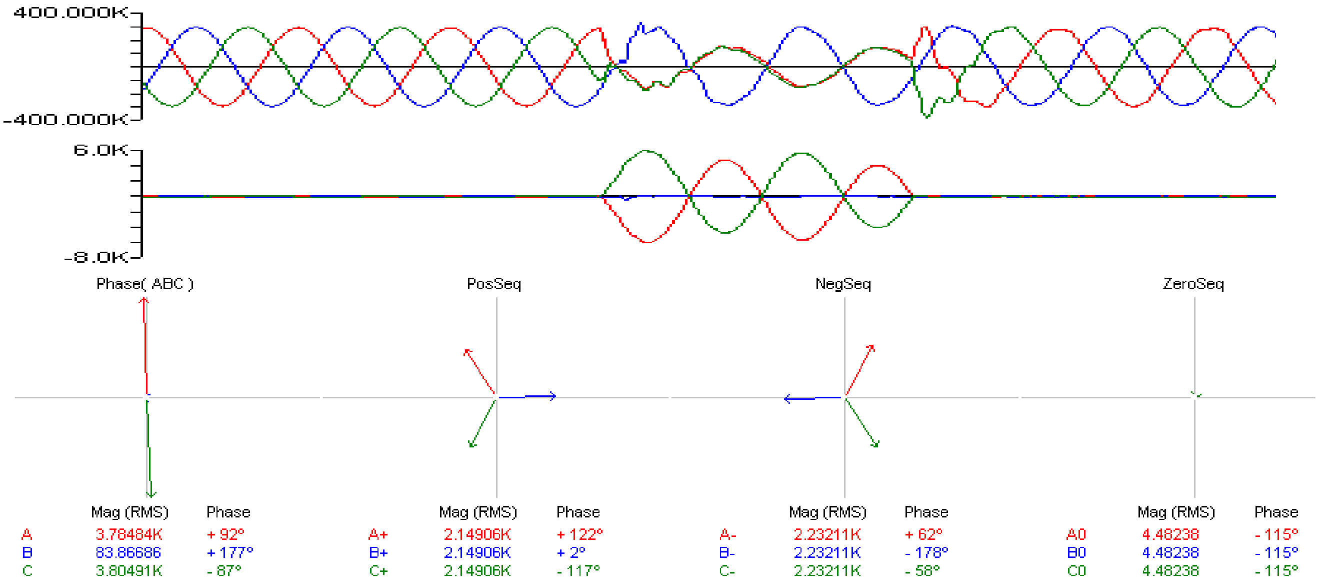

Figure 14. A-C Phase Fault.

Double-line to ground

A similar scenario occurs during a line-to-line-to-ground (or double-line) fault where the two involved phases will see an increase in current and a decrease in voltages. The difference is that a zero sequence component will be present. This can be appreciated in the phasor diagram in **Figure 15**.

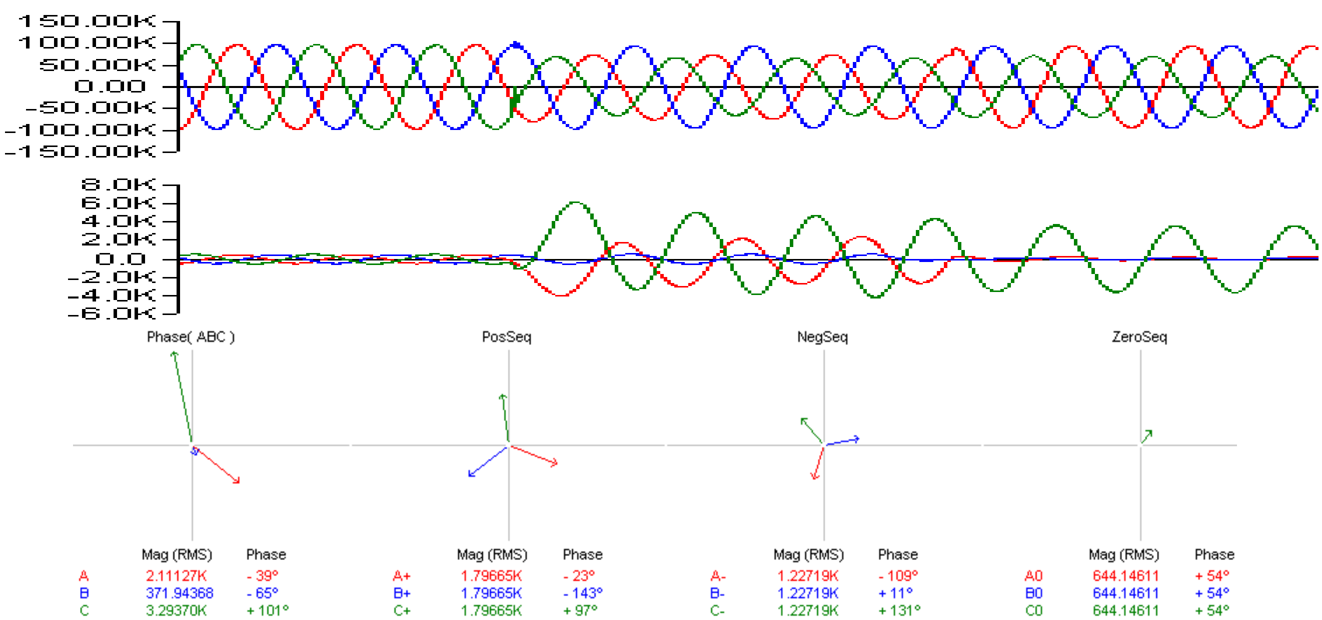

Figure 15. A-C-Ground Fault.

Three Phase Fault

A three phase fault will be reflected by a high, sharp increase in all three phase currents, and all three voltages should collapse. A three phase fault can be seen in **Figure 16**. Upon inspection, we notice the rapid increase in all three phase currents and a depression in all three voltages. Since three phase faults are considered symmetrical, there should be no presence, or very small values, of negative and zero sequence components as seen below in the phasor diagrams. In theory, the negative and zero sequence components should be zero; however, it could take some time for all three phases to become involved, and some zero and negative sequence quantities might be seen.

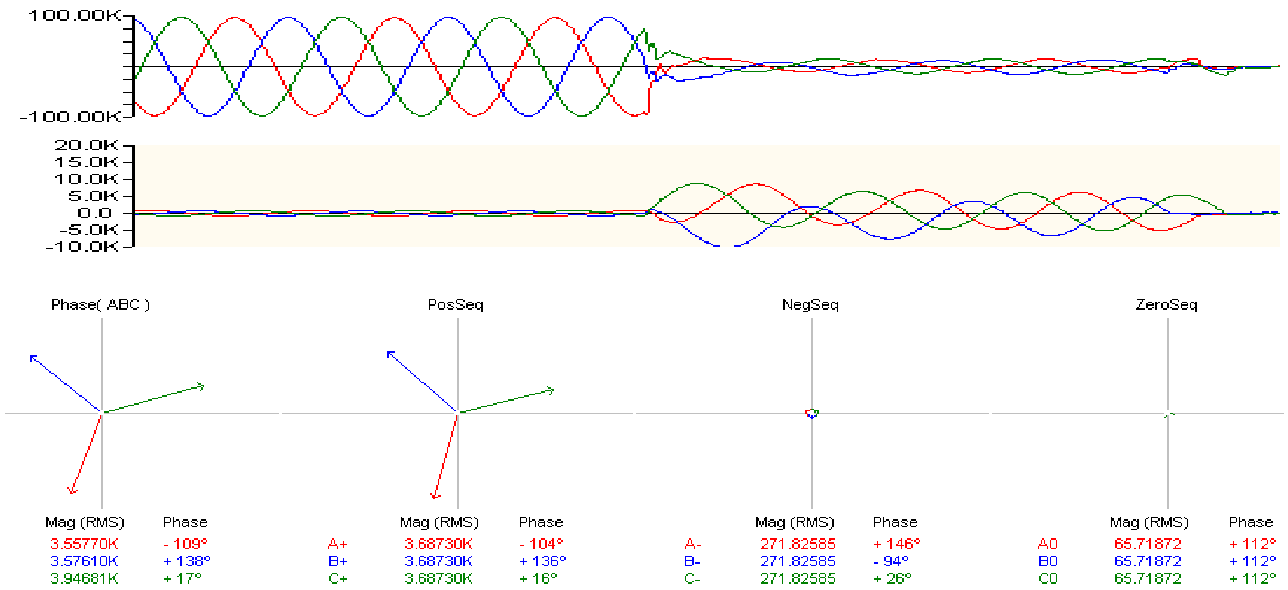

Figure 16. Three Phase Fault.

Improving Analysis Through Software

For a good size system, the number of events seen during certain periods of time can be quite large. Fault recording equipment provides the means to automatically pull records from field devices through a server centralized software. As a result, event analysts can access record information from any computer connected to their network. This type of implementation has been in place for several years and is common in recording equipment. Such features have certainly simplified the everyday tasks of event analysts. Other software features now offered with recording equipment facilitates the visualization of faults by plotting fault impedances during line faults and current differential behavior during a differential operation.

Plotting Line Impedance Faults

One of the most important tools that an event analyst or protection engineer can have is the impedance diagram. It allows the engineer to evaluate the performance and behavior of distance relays during power system disturbances. Generally, distance relays make decisions based on the voltages, currents, and angles measured at the relays. As a result, apparent impedances are derived from these measured quantities. These apparent impedances can be plotted in the R-X diagram to determine the behavior of relays during fault disturbances, normal loads, switching events, swings, and many more system operations. The distance relay operating characteristics such as a Mho circles for Z1, Z2, Z3, Z4, and blinders can be superimposed on the impedance diagram with any system performance. A graphical view of the measured load and short circuit impedances with the relay operating characteristics in the R-X diagram allow event analysts and protection engineers to clearly determine the relay's performance in the system. **Figure 17** shows the superposition of a line fault with the respective zones of protection.

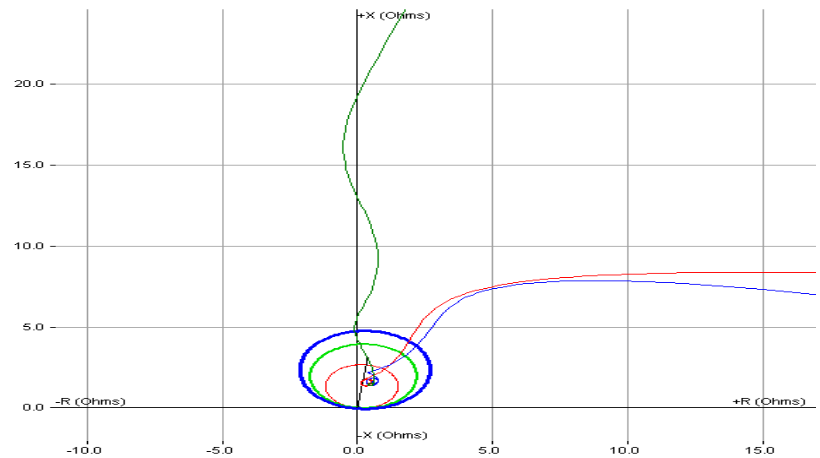

Figure 17. Fault Impedance Trajectory Superimposed With Zone Mho Circles.

Plotting Differential Views

In a similar fashion, differential views can be plotted to better visualize differential faults from transformer and bus differential relays. The differential view displays the variation in operating current, IO, and restraint current, IR. This can be appreciated in **Figure 18**.

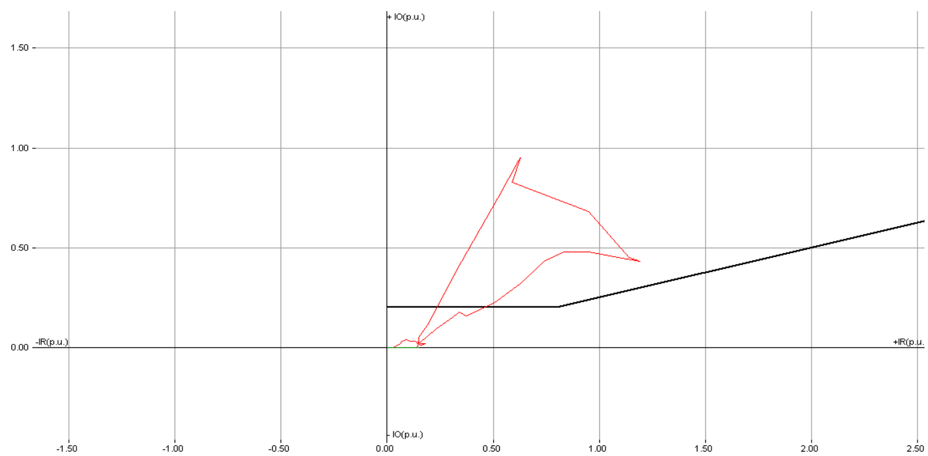

Figure 18. IO Versus IR Behavior During Differential Trip

Conclusion

The analysis of oscillograms has proven to be invaluable in improving the reliability of the power system. At the same time, it has resulted in great economic savings for utilities. When the proper people and recording equipment are used for system event investigations, the positive results can be immeasurable. Therefore, proper training of new engineers coming into the event analysis arena is an important factor for future event investigation success. The right knowledge supported by great recording tools leads to great event analysis.

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Biography

Joe Perez is a Sales Application Engineer for the relay and digital fault recorder products of ERLPhase Power Technologies, formerly NXTPhase T&D. He previously worked as a transmission engineer and a field application engineer, gaining experience in system protection projects and transmission system studies, including fault, power flow, and contingency analysis. Joe graduated from Texas A&M University in 2003 with a BSEE and resides in the Bryan/College Station, Texas area. He is an active member of IEEE and the Power System Relaying Committee.