Substation Power Quality Monitoring with Smart Relays

Technical Report

Substation Power Quality Monitoring with Smart Relays

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REPORT SUMMARY

Pressures to innovate efficiencies, compete in a deregulated electricity market, and improve customer satisfaction are increasing the demand for data on distribution feeder performance. Modern, microprocessor-based relays not only provide improved protection features, they also can be used by distribution (or “wires”) companies to monitor adherence to service-quality specifications. This report evaluates currently available relays that have data collection capabilities usable by utilities to monitor their power system performance.

Background

Deregulation of the electric utility industry in the United States and abroad is forcing utilities to operate their facilities more efficiently. Availability of system performance data is critical to improving system reliability while targeting scarce maintenance resources to those areas that will benefit the most. In the past, dedicated performance monitoring equipment, often in the form of power quality monitors, has been installed by utilities to collect this information. This report investigates another possible source of circuit performance data: the microprocessor-based feeder relay. Many distribution feeders in electric utilities are currently monitored by microprocessor-based relays. Using these relays to provide valuable power quality, and thus system performance, data will reduce data collection costs and provide information necessary to engineers as they try to allocate maintenance dollars.

Objectives

- To investigate power quality data collection, event reporting, and software interface capabilities of currently available feeder relays.
- To provide specifications for power quality data collection that could be included in future relays.

Approach

The project team surveyed product literature of relay manufacturers. These data were used to determine which relays had capabilities—namely, event waveform capture—that could be used for collecting power quality data. From this list of relays, two relays were tested using a test protocol defined in this report. a Schweitzer Engineering Laboratories (SEL) 351-7 feeder relay and a Basler 951 feeder relay. The SEL relay contains some limited capabilities for power quality monitoring, namely voltage sags, swells, and outages. The Basler is more typical of relays currently available. It also can capture voltage sags, swells, and outages data, but must do so by using “virtual” undervoltage and overvoltage relays to trigger oscillography data capture. The purpose of this testing was to evaluate the data capturing capabilities of the relays and to evaluate the software used for programming, data retrieval, and data analysis.

Results

An overview of the capabilities of various relays to collect power quality data is provided in this report. A proposed test protocol for verifying power quality data collection capabilities also is included. Testing of the Basler and SEL relays indicates that both performed as specified and could be used for collecting the most basic—and most common—power quality data: voltage sags, voltage swells, and interruptions. The software evaluation indicates that both Basler (BESTCOMS and BESTWAVE-32) and SEL (AcSELerator) provide adequate tools for programming their relays and viewing downloaded data. Programming a single relay at a time is not a big disadvantage because relay programs are seldom modified. However, manually downloading a single relay at a time creates problems as the number of relays increases. Both relays need a system that can automatically download new events.

EPRI Perspective

Many utilities are looking for alternative sources of performance data for power systems. This requirement is driven by a need to reduce costs and by increased reporting requirements of electric utility regulators. This report provides utilities with the data required to consider power system relays as a source of system performance data.

Keywords

Power quality monitoring
PQDIF
Relays

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1
INTRODUCTION

The deregulation of the electric utility industry in the United States and abroad is forcing utilities to become more efficient in the operation of their facilities. The availability of system performance data is critical to improving the reliability of the system while targeting scarce maintenance resources to those areas that will benefit the most. In the past, dedicated performance monitoring equipment, often in the form of power quality monitors, has been installed by utilities to collect this information. This report investigates another possible source of circuit performance data: the microprocessor-based feeder relay.

Many of the distribution feeders in electric utilities are currently monitored by microprocessor-based relays. The use of these relays to provide valuable power quality, and thus system performance, data will reduce the cost of data collection and provide information necessary to engineers as they try to allocate maintenance dollars. This report investigates the power quality data collection, event reporting, and software interface capabilities of currently available feeder relays. A limited number of relays were tested using a test protocol defined in this report. The report also provides power quality data collection specifications that could be included in future relays.

The Role of Deregulation

Pressures to innovate efficiencies, compete in a deregulated electricity market, and improve customer satisfaction are increasing the demand for data on the performance of distribution feeders. Modern, microprocessor-based relays not only provide improved protection features, they also can be used by distribution (or “wires”) companies to monitor adherence to service-quality specifications. In most models of a deregulated market, wires companies remain regulated. Most public utility commissions are including reliability requirements in the rate structure for the wires companies. Along with reliability requirements, some commissions include power quality requirements, mostly in the form of voltage-sag indices. Wires companies need some way to measure their performance because better performance means higher rates for electricity, and therefore higher profits. The reliability and power quality indices shown in Table 1-1 and Table 1-2 are ways to calculate performance from measured electrical parameters.

Table 1-1
Reliability Indices

Index	Full Name	Formula
SAIFI	System Average Interruption Frequency Index	number of customer interruptions / total customers in system
CAIFI	Customer Average Interruption Frequency Index	number of customer interruptions / # of customers with 1+ interruptions
SAIDI	System Average Interruption Duration Index	Σ of all customer interruption durations / total customers in system
MAIFI	Momentary Average Interruption Frequency Index	# of customer momentary interruptions / total customers in system
ASAIA	Average Service Availability Index	customer hours service availability / customer hours service demand

Table 1-2
Power Quality Indices

SARFI	System Average RMS (Variation) Frequency Index	$SARFI_x = \frac{\sum N_i}{N_T}$
SIARFI	System Instantaneous Average RMS (Variation) Frequency Index	$SIARFI_x = \frac{\sum NI_i}{N_T}$
STARFI	System Temporary Average RMS (Variation) Frequency Index	$STARFI_x = \frac{\sum NT_i}{N_T}$
SMARFI	System Momentary Average RMS (Variation) Frequency Index	$SMARFI_x = \frac{\sum NM_i}{N_T}$
ARDI	Average RMS (Variation) Duration Index	$ARDI_x = \frac{\sum N_i T_i}{\sum N_i}$

X = RMS voltage threshold, usually 70% of nominal.

N_i = Number of customers experiencing voltage deviations with magnitudes above *X%* for *X>100* or below *X%* for *X<100* because of measurement event *i.*

N_T = Number of customers served from the part of the system being assessed.

NI_i = Number of customers experiencing instantaneous voltage deviations with magnitudes above *X%* for *X>100* or below *X%* for *X<100* because of measurement event *i.*

NM_i = Number of customers experiencing momentary voltage deviations with magnitudes above *X%* for *X>100* or below *X%* for *X<100* because of measurement event *i.*

NT_i = Number of customers experiencing temporary voltage deviations with magnitudes above *X%* for *X>100* or below *X%* for *X<100* because of measurement event *i.*

T_i = Duration of measurement event *i.*

2
DEFINITIONS FOR POWER QUALITY EVENTS

An understanding of the types, and relative frequency of occurrence, of power quality events is required to evaluate the power quality monitoring capabilities of power system relays. What follows is a discussion of the accepted definitions of various power quality events as defined by the Institute of Electrical and Electronics Engineers (IEEE). Some discussion is also presented on the relative frequency at which some of the events occur.

Range of Power Quality Variations in Distribution Circuits

Proper application, and testing, of power quality monitoring equipment requires a good understanding of the electrical environment in which the monitoring device will be installed. This requires an understanding of the characteristics of the power quality events and the range of expected variation of these events in a typical distribution circuit. Understanding the electrical environment is critical not only to properly specify the performance requirement for monitoring devices, but also to ensure that such devices have the proper immunity to survive the electrical environment of the distribution system.

In this section, we review the definitions of power quality events as described in IEEE Std. 1159-1995, *Recommended Practice for Monitoring Electric Power Quality.* In addition, we review the range of expected values for power quality events based on the EPRI Distribution Power Quality (DPQ) Project. The material in this section has been compiled from several EPRI reports that have been published over the last decade and represent a vast body of knowledge regarding the range of power quality variations in distribution circuits. For a more detailed treatment of power quality variations, refer to the sources referenced in the bibliography.

Categories of Power Quality Variations

The recent proliferation of electronic equipment and microprocessor-based controls has caused electric utilities to redefine power quality in terms of the quality of voltage supply rather than availability of power. In this regard, IEEE Std. 1159-1995, *Recommended Practice for Monitoring Electric Power Quality,* has created categories of power quality disturbances based upon duration, magnitude, and spectral content. Table 2-1 shows the categories of power quality disturbances with spectral content, typical duration, and typical magnitude.

Table 2-1
Categories of Power Quality Variation – IEEE 1159-1995

Categories	Spectral Content	Typical Duration	Typical Magnitudes
1.0 Transients			
1.1 Impulsive			
1.1.1 Voltage	> 5 kHz	< 200 µs	
1.1.2 Current	> 5 kHz	< 200 µs	
1.2 Oscillatory			
1.2.1 Low Frequency	< 500 kHz	< 30 cycles	
1.2.2 Medium Frequency	300–2 kHz	< 3 cycles	
1.2.3 High Frequency	> 2 kHz	< 0.5 cycle	
2.0 Short-Duration Variations			
2.1 Sags			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.0 pu
2.1.2 Momentary		30–120 cycles	0.1–1.0 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.0 pu
2.2 Swells			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.8 pu
2.1.2 Momentary		30–120 cycles	0.1–1.8 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.8 pu
3.0 Long-Duration Variations			
3.1 Overvoltages		> 2 min	0.1–1.2 pu
3.2 Undervoltages		> 2 min	0.8–1.0 pu
4.0 Interruptions			
4.1 Momentary		< 2 sec	0
4.2 Temporary		2 sec–2 min	0
4.3 Long-Term		> 2 min	0
5.0 Waveform Distortion			
5.2 Voltage	0–100th Harmonic	steady-state	0–20%
5.3 Current	0–100th Harmonic	steady-state	0–100%
6.0 Waveform Notching	0–200 kHz	steady-state	
7.0 Flicker	< 30 Hz	intermittent	0.1–7%
8.0 Noise	0–200 kHz	intermittent	

Voltage Sags, Swells, and Interruptions

Figure 2-1 shows a typical voltage sag, voltage swell, and momentary interruption.

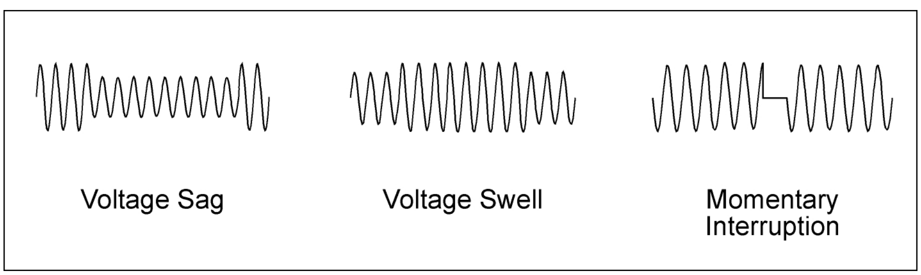

Figure 2-1
Typical, Short-Duration Variations in Root Mean Square Voltage

A *voltage sag* is a short-duration decrease of the root mean square (RMS) voltage value, lasting from 0.5 cycles to 120 seconds. Sags are caused by faults on the power system or by the starting of a relatively large motor or other large load. A voltage swell may accompany a voltage sag.

A *voltage swell* occurs when a single line-to-ground fault on the system results in a temporary voltage rise on the unfaulted phases. Removing a large load or adding a large capacitor bank can also cause voltage swells, but these events tend to cause longer-duration changes in the voltage magnitude and will usually be classified as long-duration variations.

A *voltage interruption* is the complete loss of voltage. A disconnection of electricity causes an interruption, usually by the opening of a circuit breaker, line recloser, or fuse. For example, if a tree comes into contact with an overhead electricity line, a circuit breaker will clear the fault (short circuit), and the customers who receive their power from the faulted line will experience an interruption.

System Faults

Customers located on a faulted feeder will experience one or more interruptions, depending on the type of fault and the reclosing practices of the utility. For a temporary fault, one or two reclosing operations may be required before normal power is restored. For a permanent fault, a number of reclosing operations (usually no more than three) will occur before the breaker “locks out.” In this case, the customers will experience a sustained interruption. Note that the interruptions associated with successive operations of the breaker may be of varying duration depending on relay characteristics. The multiple operations of the breaker give the fault multiple opportunities to clear. The multiple operations also give sectionalizers the opportunity to operate. Sectionalizers typically open during the dead time after counting a certain number of consecutive incidents of fault current within a short time period. The number of fault-current incidents is typically two, although it could be one if the sectionalizer is at the head of an underground cable where all faults are assumed to be permanent.

Reclosing practices vary from utility to utility and, perhaps, from circuit to circuit. Feeders that are mostly underground will typically not have any reclosing operations because most faults on underground feeders are permanent. Some utilities are experimenting with faster reclosing times (0.3 to 0.5 seconds) for the first reclosing operation to solve residential customer problems with momentary interruptions. Residential electronic equipment such as clock radios, VCRs, microwaves, and televisions can often ride through a 0.5-second interruption but cannot ride through longer-duration interruptions. At medium-voltage levels, it usually takes a minimum of 10 to 12 cycles of dead time to ensure that the ionized gases from faults are dispersed.

Customers located on parallel feeders (that is, feeders that are supplied from the same bus as the faulted feeder) will experience a voltage sag for as long as the fault remains on the line. On medium-voltage systems, nearly all faults are cleared within one second and can be cleared in as short as three cycles, depending on the magnitude of the fault current and the relay settings. This means that customers on parallel feeders will experience at least one voltage sag lasting from three cycles to approximately one second and, possibly, additional voltage sags if reclosing operations are required. Voltage sags are much less severe than interruptions, and the duration of interest is only the period of time that the fault is on the line.

If there are more than two feeders supplied from a common distribution bus, then voltage sags will occur more frequently than actual interruptions because a fault on any one feeder will cause voltage sags on all the other feeders.

Customers that are fed directly from the high-voltage, transmission system (typically large industrial customers) usually have more than one line supplying the facility. Therefore, interruptions should be extremely infrequent for these customers. However, these customers will experience voltage sags during fault conditions over a wide range of the transmission system. Voltage sags caused by faults in a high-voltage system generally have more consistent characteristics. The faults that originate in the medium- and low-voltage systems tend to have more variation.

Because voltage sags can be much more frequent than interruptions, it is important to consider the impacts and possible remedies for voltage sags separately from the required solutions for complete interruptions.

Overvoltages and Undervoltages

Long-duration voltage variations that are outside the normal magnitude limits are most often caused by unusual conditions on the power system, for example, out-of-service lines or transformers sometimes cause *undervoltages,* as shown in Figure 2-2. These types of RMS voltage variations are normally short-term, lasting less than one or two days. Voltage variations lasting for a longer period of time are normally corrected by adjusting the tap on a step-voltage regulating transformer.

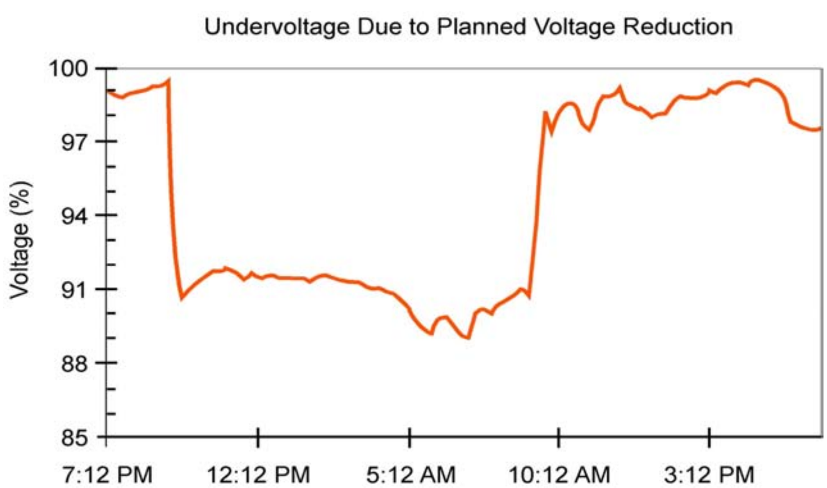

Figure 2-2
Example of Root Mean Square Measurement of Undervoltage

The root cause of most voltage-regulation problems is that there is too much impedance in the power system to properly supply the load. The load draws the current that gives a voltage drop across the system impedance. The resistive drop is in phase with the current, and the reactive drop is 90 degrees out of phase. Therefore, the load voltage drops low under heavy load. High voltages can occur when the source voltage has been boosted to overcome the impedance drop and the load suddenly diminishes.

Flicker

Flicker is an amplitude modulation of voltage at frequencies less than 25 Hz. The human eye can detect flicker as a variation in the light intensity of a lamp. Flicker as shown in Figure 2-3 is caused by an arcing condition on the power system. The arcing condition may be a normal part of a production process, such as a resistance welder or an electric arc furnace. Voltage step changes greater than 3%, usually caused by the starting of large motors, may also cause light flicker, but these events are better classified as sags. Flicker problems can be corrected with the installation of filters, static VAR systems, or distribution static compensators.

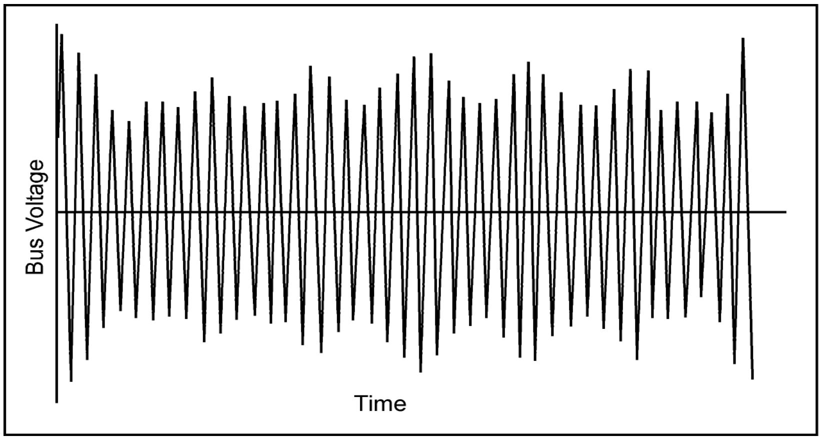

Figure 2-3
Example of Voltage Flicker Caused by an Arc Furnace

Harmonic Distortion

The phenomenon known as *harmonic distortion* is the presence of frequencies in the voltage that are integer multiples of the fundamental system frequency (60 Hz for the North American power system). Electronic loads and saturable devices generate harmonic distortion. Computers, lighting, and electronic office equipment generate harmonic distortion in commercial facilities. In industrial facilities, adjustable-speed drives and other power electronic loads can generate significant amounts of harmonics.

It is generally safe to assume that the sine wave voltage generated in central power stations is extremely good. In most areas, the voltage found on transmission systems typically has much less than 1 percent distortion. However, the distortion may reach 5 to 8 percent as we move closer to the load. At some loads, the current waveforms will barely resemble a sine wave. Figure 2-4, for example, shows a waveform with more than 17 percent harmonic distortion.

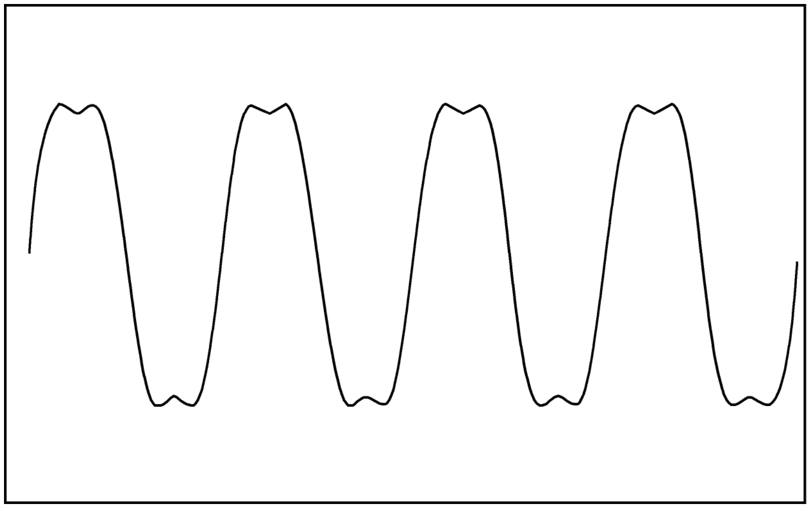

Figure 2-4
Example of Voltage Waveform with 3rd Order Harmonics and 17.42% Total Harmonic Distortion

Electronic power converters can chop the current into a variety of waveforms. Most distortion is periodic, or harmonic. That is, it repeats cycle after cycle, changing extremely slowly, if at all. The term “harmonics” has risen to widespread use to describe perturbations in the waveform. However, this term must be carefully qualified to make sense.

Solutions to problems caused by harmonic distortion include (1) installing active or passive filters at the load or bus and (2) taking advantage of transformer connections that enable cancellation of zero-sequence components.

Voltage Notching

Voltage notching is caused by the commutation of power electronic rectifiers. It is an effect that can cause concern over power quality in any installation where converter equipment, such as variable-speed drives, is connected. The effect is caused by the switching action of a drive’s input rectifier. When the DC-link current in a drive is commutated from one rectifier thyristor to the next, an instant exists during which a line-to-line short circuit occurs at the input terminals of the rectifier. The result is a phase voltage with four notches per cycle caused by a six-pulse electronic rectifier, as shown in Figure 2-5.

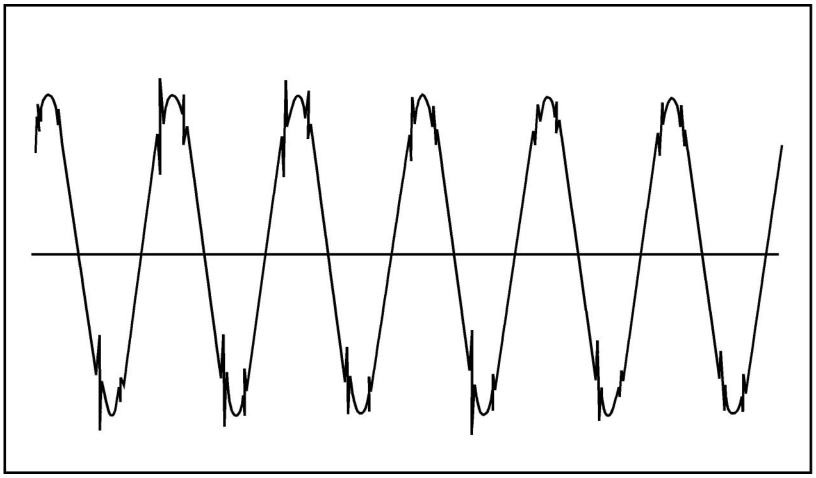

Figure 2-5
Example of Waveform with Notching

Transient Disturbances

Transient disturbances are caused by the injection of energy by switching or by lightning. The disturbance may either be *uni-directional* or *oscillatory*. Lightning, electrostatic discharge, load switching, or capacitor switching may cause a uni-directional transient, as shown in Figure 2-6, which is characterized by its peak value and rise time.

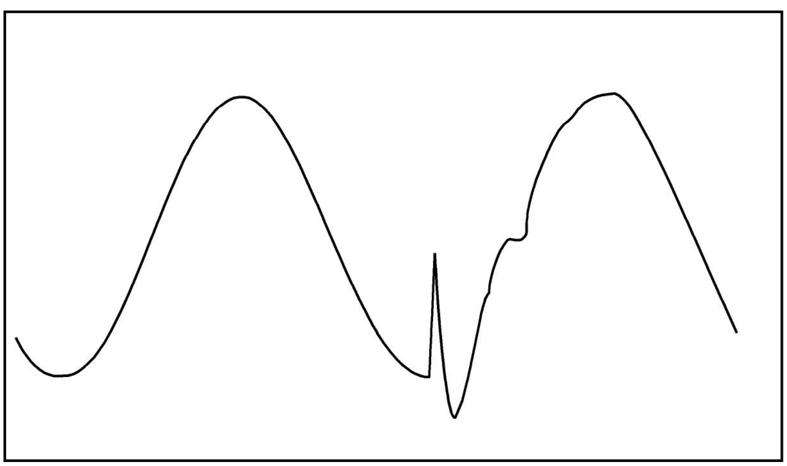

Figure 2-6
Impulsive, Transient Waveform

On the other hand, an oscillatory transient, as shown in Figure 2-7, is characterized by its frequency content. It can be caused by a switching operation such as energizing a capacitor bank, distribution line, or cable, or the opening of an inductive current. Low- and medium-frequency oscillations, with principle frequencies less than 2 kHz, are normally caused by power system switching. The switching of a load electrically close to the point of interest may cause high-frequency oscillations with principle frequencies greater than 2 kHz. Common solutions to problems caused by transients include the application of surge arresters, passive and active filters, and isolation transformers.

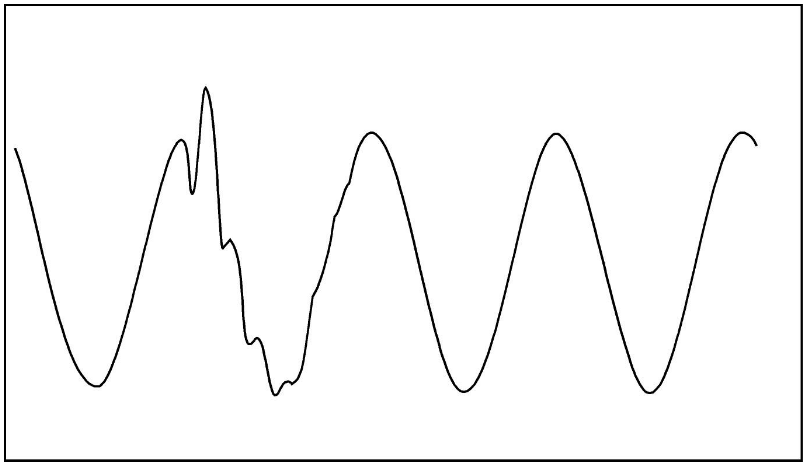

Figure 2-7
Oscillatory, Transient Waveform Caused by a Capacitor Energizing

Ranges of Power Quality Variations from the EPRI DPQ Project

EPRI Project RP3098 (commonly known as the EPRI Distribution System Power Quality Monitoring Project, or EPRI DPQ Project) consisted of a power quality monitoring survey of 277 measurement locations on the primary distribution feeders of 24 electric utilities across the continental United States. The data collected reflects a wide range of diversity in geography and operating practice. The result of the site-selection process was a set of 100 distribution feeders in the voltage range of 4 kV to 33 kV.

The monitoring sites were determined by using a systematic and controlled selection process to provide a wide diversity of distribution system conditions. The monitored feeders ranged in voltage level from 4.16 kV to 34.5 kV and in length from 1 km to 80 km. The 27 months of monitoring resulted in a staggering collection of data that was statistically summarized in a three-volume EPRI report[1]. The data collected during the measurement period provides a statistically valid sample of the range of power quality events in a distribution system, although not necessarily valid at any given site.

Figures 2-8 through 2-12 provide some results from the DPQ study to quantify the electrical environment based on the monitoring results. The data shows the sag and interruption rate, average magnitude and duration of sags and interruptions, oscillatory transient rate, average magnitude of oscillatory transients, voltage total harmonic distortion (THD), and individual harmonics from all monitoring sites.

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[1] *An Assessment of Distribution System Power Quality: Volumes 1-3*; TR-106294-V1, TR-106294-V2, TR106294-V3

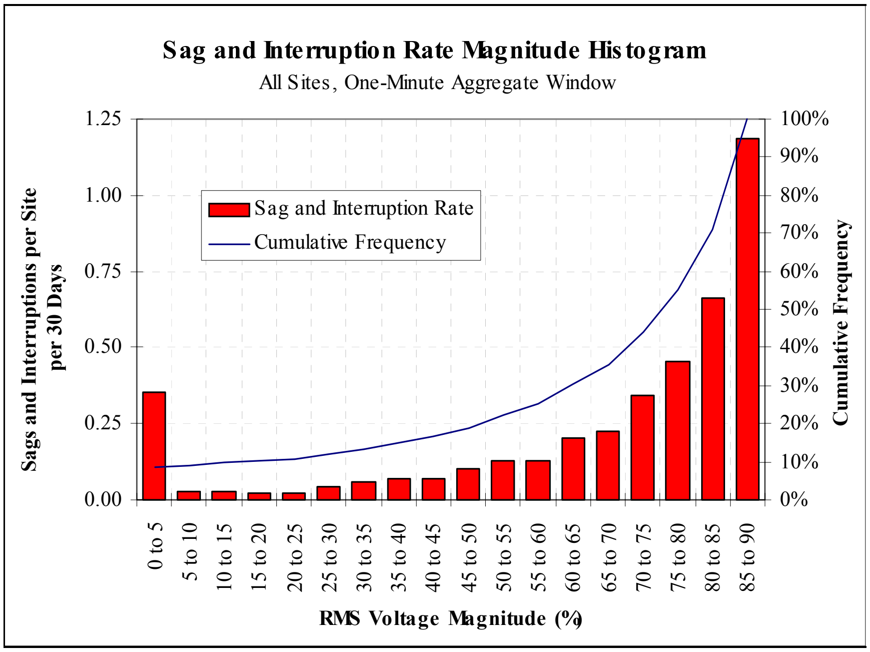

Figure 2-8
Sag and Interruption Rate – Magnitude Histogram, One-Minute Aggregation, 6/1/93 to 6/1/95, Treated by Sampling Weights, All Sites

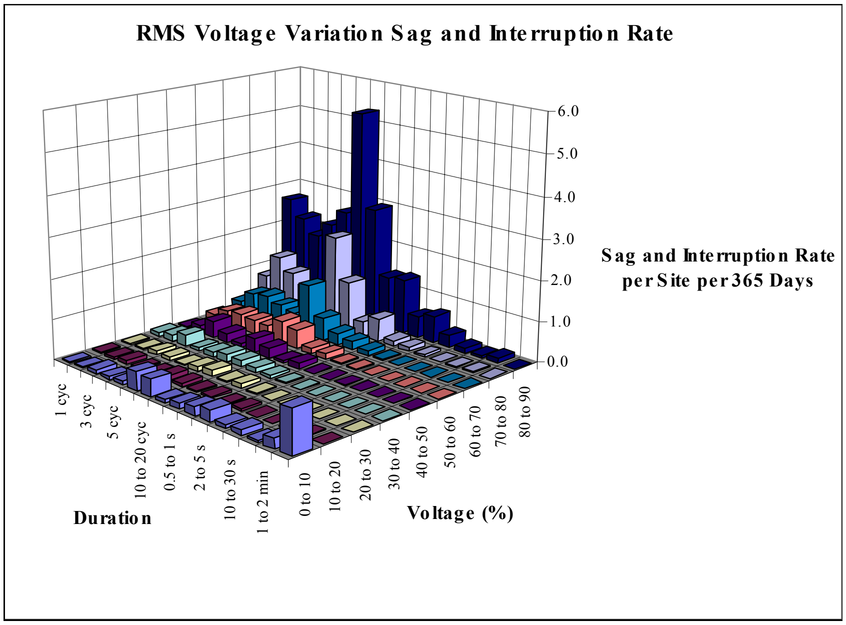

Figure 2-9
Sag and Interruption Rate – Magnitude Duration Histogram, One-Minute Aggregation, 6/1/93 to 6/1/95, Treated by Sampling Weights, All Sites

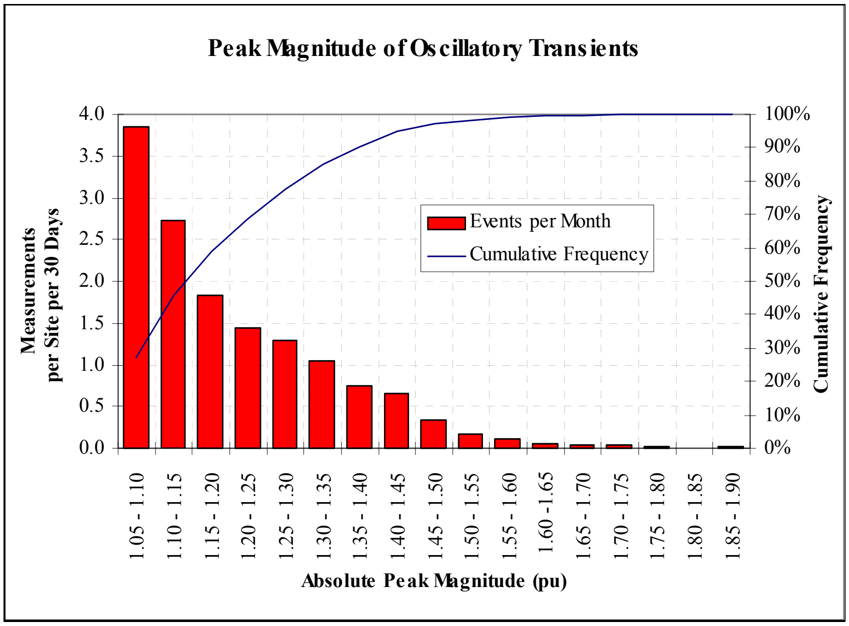

Figure 2-10
Histogram for Peak Magnitude of Oscillatory Transients Measurement Events, 3/1/95 to 9/1/95, Treated by Sampling Weights, All Sites

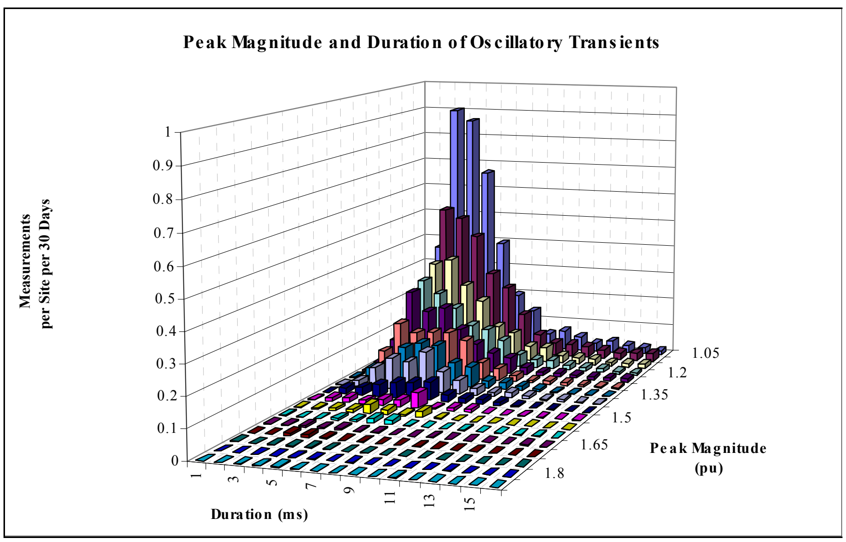

Figure 2-11
Peak Magnitude and Duration of Oscillatory Transients Measurement Events, 3/1/95 to 9/1/95, Treated by Sampling Weights, All Sites

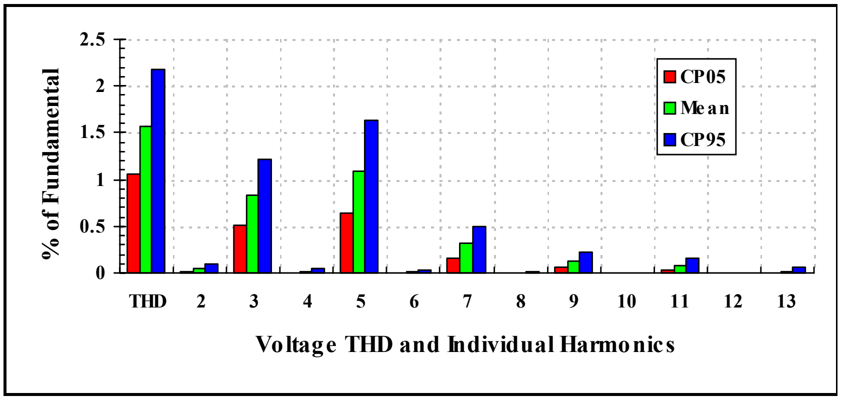

Figure 2-12
Voltage Total Harmonic Distortion (THD) and Individual Harmonics, 6/1/93 to 3/1/95, All Sites

The definitions of power quality events and their probable characteristics are important for both specifying monitoring equipment and for developing test procedures for evaluating the performance of the equipment. This data will be used in developing a test protocol to be used when evaluating the instrument's power quality monitoring capabilities.

3
REVIEW OF DATA AVAILABLE FROM MICROPROCESSOR-BASED RELAYS

Many relays that are currently available have some form of data capture that can be used for power quality investigations or evaluations. The current trend is toward microprocessor-based relays. The increase in available processing capabilities and the decrease in memory costs combine to allow relay manufacturers to offer greater functionality in their devices. The relay manufacturers also see power quality monitoring as a way to add value to their product line. Additional features, such as power quality monitoring, encourage customers to replace older relay technology with new equipment.

Relay Technology

Historically, relay functions have been performed by discrete devices. That is, a separate relay was required for each function, such as time-overcurrent protection. Therefore, a distribution feeder would require many independent, analog devices to provide for such functions as overcurrent protection, reclosing control, undervoltage protection, and overvoltage protection. Several years ago, manufacturers began replacing the older, electro-mechanical relays with electronic relays. However, the functions of the relays remained separate. It wasn't until the development of microprocessor-based (or digital) relays that the functions of more than one relay were combined in a single package. These relay functions are sometimes referred to as "virtual" relays because they have the function of an independent relay, but reside as software inside a common device.

Table 3-1 lists the common relay functions and the function number assigned to each. Many relay publications will refer to the function number rather than the name of the function. For example, a publication may refer to a 27 relay rather than using the term "undervoltage" relay. Many modern relays have the functionality of dozens of virtual relays. A single device may have six undervoltage relays that can be used simultaneously. This lowers the cost of ownership because fewer physical devices need to be installed and maintained.

Table 3-1
Function Numbers for Common Relay Functions[2]

Function (or Device) Description	Function Number
Distance Relay	21
Undervoltage Relay	27
Instantaneous Overcurrent Relay	50
AC Time Overcurrent Relay	51
Overvoltage Relay	59
AC Directional Overcurrent Relay	67
Frequency Relay	81
Differential Relay	87

Another advancement has been in the field of fault recording. The original fault recorders were oscillographs that recorded system faults on special paper that was developed using an ammonia bath, much like blueprint paper. Advancements in digital technology led to the development of digital fault recorders (DFRs). These recorders began as custom-built computers, but soon transformed into high-end personal computers with specialized data input modules. The increased processing power and data storage capabilities of modern relays have enabled the relay manufacturers to incorporate the functionality of the DFR into the relay. By combining the functionalities of the two devices, the manufacturer has further increased the value of the new microprocessor-based relays.

Data Monitoring and Power Quality

The development of relays with fault-recording capabilities makes them useful data sources for power quality engineers. Many of the currently available relays can store voltage and current waveforms when relaying events occur. This function is known as oscillography. The original use of this data was to verify that the relay had operated properly during system faults. Therefore, many relays will only record oscillography data when one of the virtual relays operates. With the standard settings used by a relay engineer to protect a feeder, for example, a relay would not capture voltage sags or swells. These are not events for which you want the breaker, or recloser, to open.

Voltage Sags, Swells, and Interruptions

It is still possible to use these relays to capture voltage sag and swell data. Assume you want to collect voltage sags. This can easily be done by setting a phase undervoltage relay (a 27 relay) to

[2] Terms Used by Power System Protection Engineers, IEEE, 1997.

the desired level, such as 0.9 per unit, or 90 percent of nominal. A 27 relay is one of the virtual relays in the device. Next, the output of this relay must be inhibited with respect to the trip equation. The trip equation contains a list of logical inputs (the outputs of virtual relays) that can indicate the need for the breaker to operate, or trip. A *trip equation* might look like Equation 3-1.

50 + 51 + 81 = TRIP **Equation 3-1**

In Equation 3-1, if any of the three virtual relays operates (changes state to a logic 1), the relay will send a trip signal to the breaker (note the logic "OR" represented by "+"). Trip equations are often much more complicated and can contain multiple levels of "And" and "OR" logic functions. Now the output of the virtual undervoltage relay (27) must be included in the event record equation. An *event record equation* might look like Equation 3-2:

50 + 51 + 81 + 27 = EVENT **Equation 3-2**

The event record equation (see Equation 3-2) controls when the relay records input signal waveforms. Usually the status of all virtual relays is recorded also. In Equation 3-2, any time the breaker trips or the undervoltage relay operates, an oscillography event will be triggered. Event record equations are often much more complicated, just like the trip equations. The same techniques can be used to capture voltage swells (using the overvoltage relays) and interruptions (using the undervoltage relays).

The oscillography events recorded by relays are usually limited in length. This length is often programmable, with longer lengths translating to fewer event captures fitting in memory. A common length is on the order of 30 cycles. Events longer than the event record length setting will be truncated. Many relays allow modifiers to the event record equation that cause the recording to begin on a rising or falling edge. For example, you might set the equation to begin recording on the rising edge of the undervoltage event. If you set the relay to record 30-cycle events, and include both the rising edge for undervoltage, and the falling edge for undervoltage, in the equation, you could record the beginning of a voltage sag and the end of the same sag, regardless of its length. For example, for a 120-cycle sag you would record the first 30 cycles and the last 30 cycles of the event.

Harmonics

The oscillography events recorded by relays are limited in bandwidth. The most common sampling rates are 16 and 32 samples per cycle. This limits the ability of the relays to measure higher-order harmonics. Harmonics measurement is not yet a common feature on relays. Currently available relays do not trigger on harmonic levels. Some can trend harmonics (THD and TDD) while others only provide the ability to perform harmonic analysis on captured waveforms. Traditionally, relays have filtered the harmonics on the input of the relay because it is desirable for the relay to operate only on fundamental (60 Hz in North America) values. This filtering is being modified to allow for some non-fundamental measurements. This modification becomes easier as sample rates increase. Digital sampling theory requires that you limit the frequency input of your sampling circuit to no more than ½ of the sampling frequency. As sampling frequencies increase, the input filter can be relaxed to allow higher frequencies to pass. The required filtering for relaying purposes can then be done digitally inside the relay.

Load Profile and Data Trending

Trending such quantities as voltage, current, and power factor (or var flow) can be extremely helpful to the power quality engineer. Many of the relays can now record power, energy, and analog input quantities at programmable rates. However, trending is often an option that must be specified at the time of purchase. Most of the available relays can trend any measured or calculated quantity. This data is stored in tabular format, usually with time and date stamps.

Overview of Relays with Some Form of Power Quality Data Capture

As stated before, many modern feeder relays contain some form of data capture that can be useful to power quality engineers. For this report, an attempt was made to identify all microprocessor-based feeder relays that provide data capture. A review of the associated product literature provides information regarding the relative capabilities of each relay. It is important to remember that the protective functions of these relays were not evaluated and no claim to the comparability of these functions is implied by this comparison. Table 3-2 contains information on all of the relays that were found to have some form of data capture. This list is not to be considered comprehensive. It is as complete as was possible at the time of this writing. New relays are being added to the marketplace regularly and the functionality of existing product lines are being upgraded also. The comparison is, however, a good starting point when considering the data capabilities of a relay.

Table 3-2
Comparison of the Abilities of Various Relays to Capture Power Quality Data

Brand	Model	Oscillography	Sample Rate	Voltage Sag	Voltage Swell	Outages	Harmonics (max order)	Load Profile
ABB	DPU 1500R	Y	32	Y[1]	Y[1]	Y[1]	Y[2] (11)	Y
ABB	DPU 2000R	Y	32	Y	Y	Y	Y[2] (11)	Y
Alstom	MiCOM P139	Y	20	Y[1]	Y[1]	Y[1]	N	N
Basler	BE1-951	Y	12	Y[1]	Y[1]	Y[1]	N	Y
Cooper	Edison Pro	Y	16	Y[1]	Y[1]	Y[1]	N	N
Cooper	iDP-210	Y	32	Y	Y	Y	Y (15)	Y
GE	750	Y	16	Y[1]	Y[1]	Y[1]	N	Y
GE	760	Y	16	Y[1]	Y[1]	Y[1]	N	Y
GE	F35	Y	64	Y[1]	N	Y[1]	N	Y
GE	F60	Y	64	Y[1]	Y[1]	Y[1]	Y (25)	Y
GE	SMOR-B	Y	16	Y[1][3]	Y[1]	Y[1]	N	Y
SEL	SEL-351	Y	16	Y	Y	Y	N	Y
VA Tech	Delta	Y	16	Y[1]	Y[1]	Y[1]	N	Y

1. Using undervoltage and overvoltage relays to trigger event capture
2. Harmonic analysis of captured waveforms
3. Three phase only

Communications

Communications options for the relays are extremely similar. Relay manufacturers generally provide equipment compatible with DNP3.0 and/or MODBUS. These are competing communication protocols. No clear winner has emerged, thus manufacturers have deemed it prudent to support both. A newer protocol, MMS/UCA, is beginning to show some promise. Its development has been supported by EPRI and several large electric utilities in North America. Only the GE line of relays listed the MMS/UCA protocol as an option. Table 3-3 shows the communication protocols supported by various relays.

Table 3-3
Communication Protocols Supported by Various Relays

Brand	Model	Modbus[3]	DNP 3.0[4]	MMS/UCA[5]	IEC 60870-5-103[6]
ABB	DPU 1500R	Y	Y	–	Y
ABB	DPU 2000R	Y	Y	–	Y
Alstom	MiCOM P139	Y	Y	–	Y
Basler	BE1-951	Y	Y	–	–
Cooper	Edison Pro	Y	–	–	–
Cooper	iDP-210	Y	Y	–	–
GE	750	Y	Y	Y	–
GE	760	Y	Y	Y	–
GE	F35	Y	Y	Y	–
GE	F60	Y	Y	Y	–
GE	SMOR-B	Y	–	–	–
SEL	SEL-351	Y[1]	Y[1]	–	–
VA Tech	Delta	–	–	–	Y

1. Through use of external communications processor: SEL-2030

The relays are available with various communications ports. Most manufacturers offer RS-232, RS-485, 10baseT Ethernet, and internal modem. While not evaluated in this report, communication of data to a central location can present the most difficulty in choosing to use power quality data from relays. Stations that contain Ethernet, the ideal communication option for the amount of data being transferred, are still relatively rare. It is not uncommon to find stations with no communications at all.

[3] www.modbus.org

[4] www.dnp.org

[5] IEEE-SA TR 1550, *IEEE-SA Technical Report on Utility Communications Architecture (UCATM).*

[6] IEC 60870-5-103 Ed. 1.0 b: 1997, *Tele-control equipment and systems - Part 5-103: Transmission protocols - Companion standard for the informative interface of protection equipment.*

Data Storage

The power quality monitoring is moving toward using PQDIF[7] (see Appendix A) as the data storage, or exchange, file format. The relay industry has standardized on COMTRADE[8] as the file format for data storage and exchange. All of the relays reviewed use the COMTRADE file format for storage of collected data.

Special Feature of Cooper Relays

Cooper relays have a special feature that is worth noting. They are able to detect the impending fault of medium-voltage, insulated cables. This is accomplished by recognizing a fault signature on the current signal. Some cable splices that are nearing failure will begin to have short-duration (¼ to ½ cycle) faults that are self-clearing. It is believed that the energy caused by the fault vaporizes the moisture in the fault area. This vaporization process creates a burst of steam that extinguishes the fault arc. The arc thus dries the moisture around the fault area, eliminating the fault path. Over time, the cable splice continues to degrade until a permanent fault occurs. Cooper has filed for a patent on this technology. This technology is known as incipient-cable-splice-failure (ICSF) detection. An example current waveform of an incipient cable splice failure is shown in Figure 3-1.

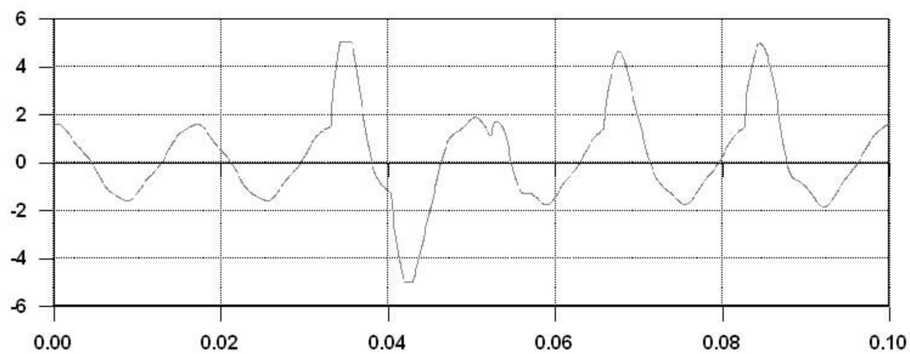

Figure 3-1
Fault Current During Incipient, Cable-Splice Failure Event

[7] IEEE Std. P1159.3, Recommended Practice for the Transfer of Power Quality Data (Draft 5).

[8] IEEE Std. C37.111-1999, IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems.

4

PROPOSED TEST PROTOCOL FOR EVALUATION OF THE POWER QUALITY MONITORING/REPORTING CAPABILITIES OF RELAYS

A defined test protocol is required when comparing the power quality monitoring capabilities of different relays. With a defined protocol, an “apples-to-apples” comparison can be made of the relays’ strengths and weaknesses. Much of the protocol was designed around the capabilities of a power quality monitoring test stand that was modified to also test the monitoring capabilities of relays.

Power Quality Monitor Test Stand

To facilitate the testing of power quality monitoring equipment under controlled situations, a power quality monitor test stand was designed and built. The stand was built with testing flexibility as a key design consideration. The test stand (see Figure 4-1) allows up to six power quality monitors to be tested at the same time using the same input signals. The test stand was modified to allow the testing of relays. Relays are mounted in the 19-inch rack on the right side of the test stand. Figure 4-2 illustrates the configuration of the test stand.

Figure 4-1
Power Quality Monitor Test Stand

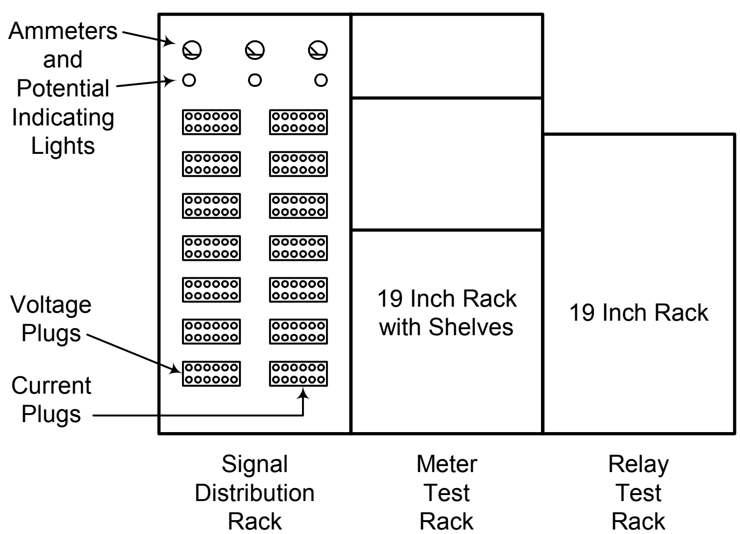

Figure 4-2
Layout for Power Quality Monitor Test Stand

The source of the voltage and current signals can be either the 120/208-V supply to EPRI PEAC's main building or from an arbitrary waveform generation rack with synchronized, but separately controllable, voltage and current sources as shown in Figure 4-3. Current transformers with a ratio of 250:5 amps were installed in the main 120/208 panel of the building. These signals are wired to two test plugs in the wall behind the test stand. The arbitrary waveform generation rack has been wired with similar plugs. The use of these plugs makes it possible to simply unplug the test stand from one source and plug it into the other.

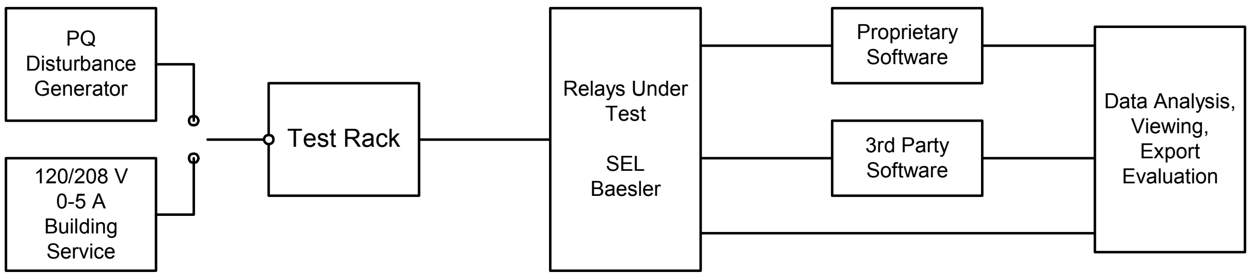

Figure 4-3
Block Diagram for Power Quality Monitor Testing

The test stand can accommodate instruments with direct-connected current channels (0 to 5 amps) and instruments that require the use of auxiliary current transformers (CTs). An instrument can be connected and disconnected from the test stand without affecting the other instruments. The current plugs are self shorting, eliminating the possibility of accidentally opening a CT circuit.

Test Protocol

The purpose of the test is not to perform any verification of absolute accuracy specifications, however, substantial variations in recorded values will be noted. Although most waveforms will be re-creations of actual recorded events, the magnitudes and durations of the re-created waveforms may be adjusted to challenge either instrument thresholds or over-range capability. In addition, the sequence of events and the intervals between events will be adjusted to determine the monitors' response to consecutive, related events. In instances where field recorded events lack high-frequency fidelity to similar known events (possibly because of potential transformer limitations), events will be staged with laboratory equipment and scaled to match nominal conditions.

The performance criteria for each test defined in this protocol is **not intended to be pass/fail**, but shall provide a consistent and repeatable mechanism for evaluation of the power quality monitoring capabilities of each relay. Because differences exist in feature capabilities among the relays that will be tested, the intent will be to report on the features and performance ability of each relay individually. While there is a natural tendency to want to compare one brand of relay to another, the emphasis in this test protocol is to compare the individual relay to the rationale behind the actual test and not to the other devices.

Relays with default threshold values will be initially set to those recommendations. In instances where the default values fail to cause an event trigger, EPRI PEAC will readjust the thresholds accordingly. Similar adjustments will be made if the nominal values are found too sensitive. Should problems arise, EPRI PEAC will communicate the findings with the manufacturer in an attempt to resolve the difficulty. Annotations will be recorded where the necessity to change thresholds, or induce current events, was required. Some tests listed in this protocol may be deemed unnecessary if the relay is not designed to respond to the given event type. The following procedures assume a single device is under test. However, the test stand is designed to test up to six different devices at the same time.

Voltage Sags

Rationale: Voltage sags are one of the most common power quality phenomena. Detecting, capturing, and recording these events accurately is essential to understanding susceptibility levels of load equipment.

Purpose: To characterize the relay's ability to capture and report voltage sags of varying magnitudes and durations.

Test Guidelines: Connect the relay and apply the following test sequence to the device under test.

Step 1. Connect the devices under test into the configuration shown in Figure 4-4 (single-phase connection).

Step 2. Set the relay thresholds for voltage sags to 90 percent of the applied input nominal voltage.

Step 3. Induce a voltage sag to 88 percent of Vnominal for one-half cycle and record the time that this event was induced. Record the response of the relays under test.

Step 4. Repeat Step 3 for durations of 1, 2, 6, 10, 20 and 30 cycles. Repeat Step 3 for durations of 1 second and 3 seconds.

Step 5. Repeat Steps 3 and 4 for voltage sags to 80, 70, 50, and zero percent of Vnominal.

Step 6. Obtain a hard copy of the relay information recorded during the test sequence (including plots and text data, if applicable) and attach to the recorded test results.

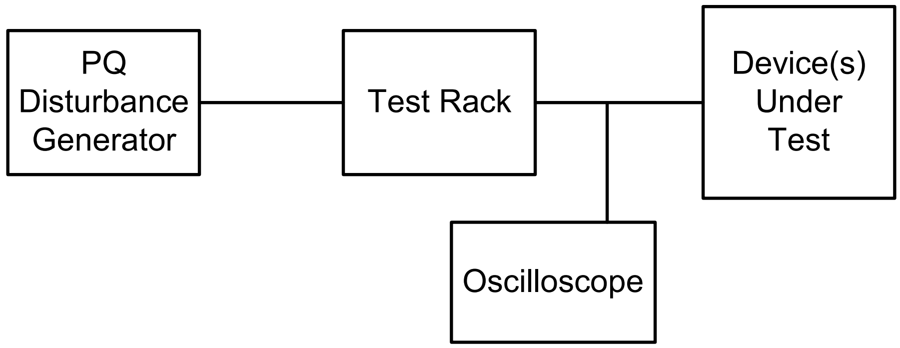

Figure 4-4
Test Setup for Power Quality Disturbance Testing

Voltage Swells

Rationale: Voltage swells occur on the power system occasionally and are observed at locations up to and including the location of load equipment. While most load equipment has inherent immunity to limited voltage swell conditions, it is important to accurately capture and report these events to understand equipment upsets and potential damage because of voltage swell events.

Purpose: To characterize the relay's ability to capture and report voltage swells of varying magnitudes and durations.

Test Guideline: Connect the relay and apply the following test sequence to the device under test.

Step 1. Connect the relay under test into the configuration shown in Figure 4-4.

Step 2. Set the relay to record voltage swells greater than 110 percent of the applied input nominal voltage.

Step 3. Induce a voltage swell to 112 percent of Vnominal for one-half cycle and record the time that this event was induced. Record the results of the test.

Step 4. Repeat Step 3 for durations of 1, 2, 6, 10, 20, and 30 cycles. Repeat Step 3 for durations of one second and three seconds.

Step 5. Repeat Steps 3 and 4 for voltage swells to 120, 140, and 180 percent of Vnominal.

Step 6. Obtain a hard copy of the relay information recorded during the test sequence (including plots and text data, if applicable) and attach to the results.

Temporary Voltage Interruptions

Rationale: Momentary voltage interruptions are common power quality phenomena occurring on average some ten to twenty times per year at the typical location. Detecting, capturing, and recording these events accurately is essential to understanding susceptibility levels of load equipment particularly because power conditioning solutions for momentary interruptions are distinctly different from those for momentary voltage sags. It is therefore extremely important that the relay be able to distinguish between the two events.

Purpose: To characterize the relay's ability to capture and report momentary voltage interruptions of varying magnitudes and durations.

Test Guidelines: Connect the power relay and apply the following test sequence to the device under test.

Step 1. Connect the device under test into the configuration shown in Figure 4-4.

Step 2. Set the relay to manufacturer's recommended levels for recording momentary voltage interruptions.

Step 3. Induce a momentary voltage interruption for one-half cycle and record the time that this event was induced. Record the response of the monitor.

Step 4. Repeat Step 3 for durations of 1, 2, 6, 10, 20, and 30 cycles. Repeat Step 3 for durations of one second and three seconds.

Step 5. Obtain a hard copy of the monitor information recorded during the test sequence (including plots and text data, if applicable) and attach to the recorded results.

Long-Duration Interruptions

Rationale: Long-duration interruptions occasionally occur. How a relay responds to these interruption events is of interest.

Purpose: To characterize the relay's ability to capture and report long-duration interruptions. Some power quality monitors contain built-in battery backup systems and should continue to function during power outages. Others do not have this feature and may shut down during interruptions. It is of interest to determine if the monitor can correctly record the time and duration of these events.

Test Guidelines: Connect the relay and apply the following test sequence to the devices under test.

Step 1. Connect the device under test into the configuration shown in Figure 4-4.

Step 2. Set the relay to record low root mean square (RMS) events less than 90 percent of the applied input nominal voltage.

Step 3. Induce a 5-minute interruption event. Note the time of the induced event and the monitor response

Step 4. Obtain a hard copy of the monitor information recorded during the test sequence (including plots and text data, if applicable) and attach to the recorded results.

Capacitor-Switching Transient

Rationale: Capacitor-switching transients are a known cause of upset for many industrial loads such as adjustable-speed drives, servo machines, and other devices with direct-current (DC) bus rails. It is important for the relay to be able to capture and identify capacitor-switching events that may be correlated to equipment upsets. Regardless of whether a relay has the ability to capture capacitor-switching events or not, it is of interest to understand how these events are captured and classified.

Purpose: To characterize the relay's ability to capture and report capacitor-switching transients and to understand the minimum bandwidth required by a monitoring device to accurately catch the event. Also to understand how the monitor must be set up to capture these events.

Test Guidelines: Connect the relay and apply the following test sequence to the devices under test.

Step 1. Connect the device under test into the configuration shown in Figure 4-4.

Step 2. Set up the relay according to the manufacturer's recommendations to capture capacitor-switching transients. If the device is not capable of capturing capacitor-switching transients, default settings for voltage thresholds will be used.

Step 3. Apply a capacitor-switching transient having a 2.0 per unit magnitude at the 90-degree peak of the voltage sine wave. Record the time of occurrence of this event and the response of the relay.

Step 4. Repeat the Step-3 procedure for events with magnitude 1.8, 1.6, 1.4, and 1.2 per unit. Then repeat the sequence at the 270-degree peak.

Step 5. If the monitor did not capture and record all of the applied events, and is specified to be able to record these types of events, determine what must be done to the monitor settings to achieve capture of all of the applied capacitor-switching transient. Record this information.

Step 6. Obtain a hard copy of the relay information recorded during the test sequence (including plots and text data if applicable) and attach to the recorded data.

ANSI C62.41, 100-kHz Ring Wave

Rationale: Ring waves are the most frequently observed transient events occurring in low-voltage power systems. Even a uni-directional, impulsive surge on overhead lines will induce oscillatory transients at a facility service entrance. The American National Standards Institute/Institute of Electrical and Electronics Engineers (ANSI/IEEE) Standard Ring Wave (represented by a 0.5-μs rise time and a 100-kHz frequency) has a shorter transition time than the

1.2/50µs-to-8/20µs combination wave. A short transition time means a fast dv/dt, which can fail or spuriously turn on semiconductors.

Purpose: To characterize the relay's ability to capture and report different amplitudes for the 100-kHz ring wave.

Test Guidelines: This test will not be performed in the power quality monitor test stand. Choose one relay and apply the following test sequence to the device under test.

Step 1. Connect the device under test into the configuration shown in Figure 4-5.

Step 2. Set up the relay to capture transient voltage events. If the monitor is not specified to capture such events, default settings for voltage thresholds will be used.

Step 3. Apply a positive-polarity (line-to-neutral) ring-wave surge with a 500-V peak amplitude at the 90-degree peak of the sine wave. Repeat the surge with the generator set for negative polarity.

Step 4. Obtain oscilloscope traces of the Step 3 events and attach them to a hard copy of the relay information captured during the applied transients.

Step 5. Repeat Steps 3 and 4 using peak amplitude levels of 1000, 2000, 3000, and 6000 Volts.

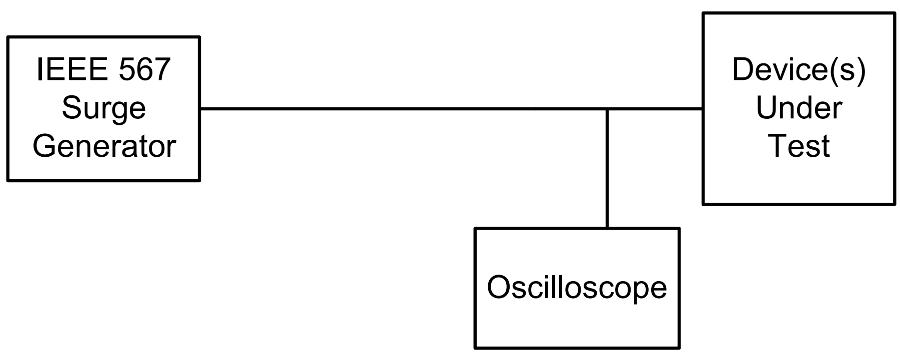

Figure 4-5
Test Setup for Surge Testing

ANSI C62.41, Combination Wave

Rationale: The 1.2/50-µs, open-circuit voltage component of the combination wave, described in ANSI/IEEE C62.41-1991, has long been used to represent lightning surges on overhead lines. A corresponding 8/20-µs, short-circuit, current waveform has also been defined with levels appropriate to the location within a building premises. These two waveforms have substantial energy deposition capability and provide representative stresses to the surge protectors and commercial electronics connected to the power system. A relay may be capable of capturing varying levels of this event.

Purpose: To characterize the relay's ability to capture, report, and survive a 6KV/3KA-combination wave.

Test Guidelines: This test will not be performed in the power quality monitor test stand. Choose one relay and apply the following test sequence to the device under test.

Step 1. Connect the device under test into the configuration shown in Figure 4-5.

Step 2. Set up the relay to capture transient voltage events. If the monitor is not specified to capture such events, default settings for voltage thresholds will be used.

Step 3. Apply a positive-polarity (line-to-neutral) combination wave surge with a 1000-V peak amplitude at the 90-degree peak of the sine wave. Repeat the surge with the generator set for negative polarity.

Step 4. Obtain oscilloscope traces of the Step 3 events and attach them to a hard copy of the relay information captured during the applied transients.

Step 5. Repeat Steps 3 and 4 with the surge generator set to deliver 6000 Volts at 3000 Amps.

Extraneous Zero Crossings

Rationale: Extraneous voltage zero crossings, while not common, have been reported by many utilities as the cause of fast clock operation, misfiring of silicon-controlled rectifier (SCR) control circuitry, and a variety of other equipment malfunctions. It is of interest to understand exactly what effect if any, a steady state, extraneous, zero-crossing event may have on different relays.

Purpose: To characterize the relay's ability to record accurate information in the presence of an unusual voltage waveform.

Test Guidelines: Connect the relay and apply the following test sequence to the device under test.

Step 1. Connect the device under test into the configuration shown in Figure 4-4.

Step 2. Set up the relay in the manufacturer's recommended configuration.

Step 3. Program the amplifier to deliver an output waveform similar to the one shown in Figure 4-6 and observe the monitor capture and reporting characteristics.

Step 4. Experiment with the relay's programmable settings until performance is observed that is not in either a standing trigger or some other unusual condition. Record all relay responses.

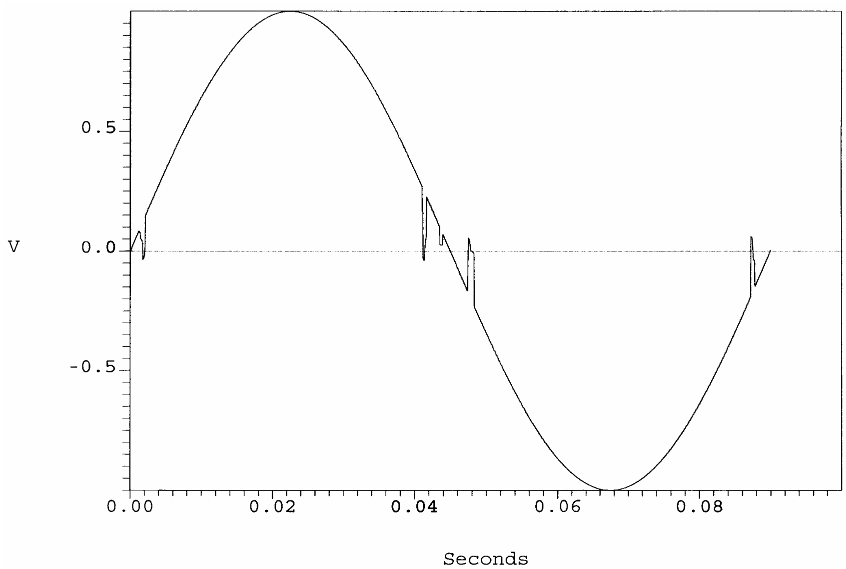

Figure 4-6
Waveform with Extraneous Zero Crossings

Harmonics

Rationale: Some relays have the ability to perform harmonic analysis of recorded voltage and current waveforms. Regardless of the specified claims of a given monitor regarding harmonic data capture, it is of interest to determine how accurately the monitor records data in the presence of harmonics.

Purpose: To characterize the relay's ability to record harmonic data, and/or record RMS voltage and current data, in the presence of different levels of harmonic distortion.

Test Guidelines: Connect the relay and apply the following test sequence to the device under test.

Step 1. Connect the device under test into the configuration shown in Figure 4-7.

Step 2. Set up the relay with the manufacturer's recommended harmonic voltage capture configuration. If the relay does not perform harmonic capture, set the device's other thresholds to default levels.

Step 3. Program the amplifier to deliver a steady state voltage waveform similar to the one shown in Figure 4-8.

Step 4. Obtain a voltage harmonic spectrum from the digital harmonics analyzer and attach them to a hard copy of the monitor information captured during the applied condition. Record the actual RMS voltage levels produced by the amplifier as well as the RMS voltage levels reported by the monitor.

Step 5. Repeat the above sequence with the amplifier programmed to deliver a steady state voltage wave shape similar to the one shown in Figure 4-9, Figure 4-10, and then Figure 4-11.

Step 6. Connect the non-linear test load, obtain a harmonic current spectrum from the digital harmonics analyzer, and attach it to a hard copy of the relay information captured during the applied condition. Record the actual RMS current values and those reported by the relay.

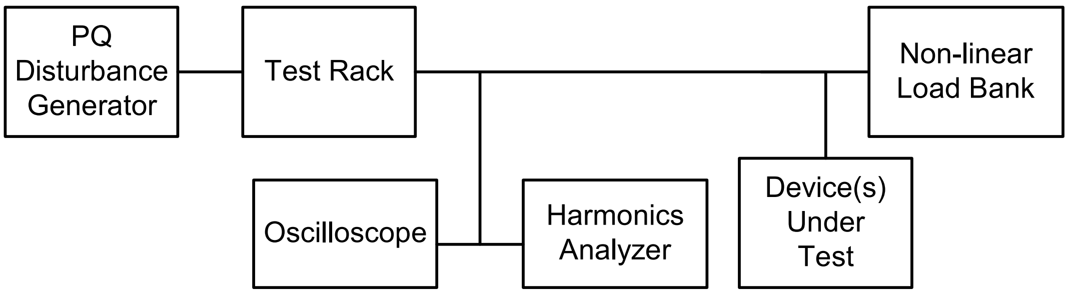

Figure 4-7
Test Setup for Voltage and Current Harmonics Test

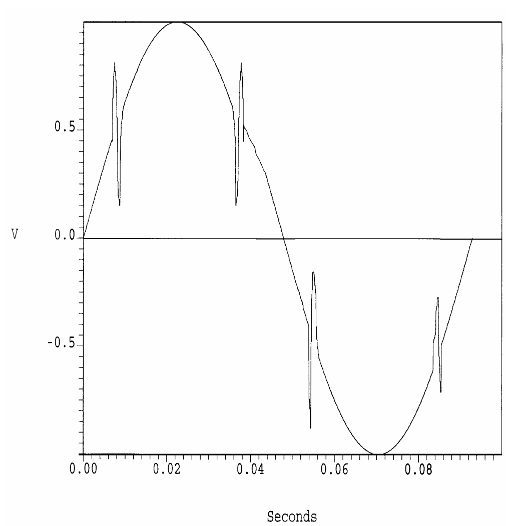

Figure 4-8
Harmonic Voltage Waveform

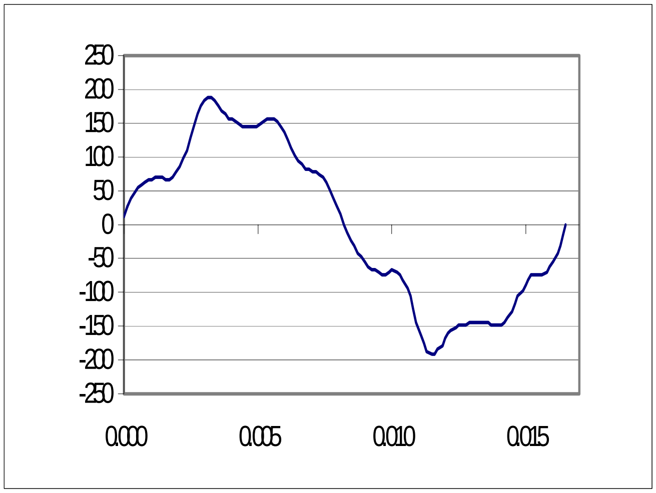

Figure 4-9
Harmonic Voltage Waveform

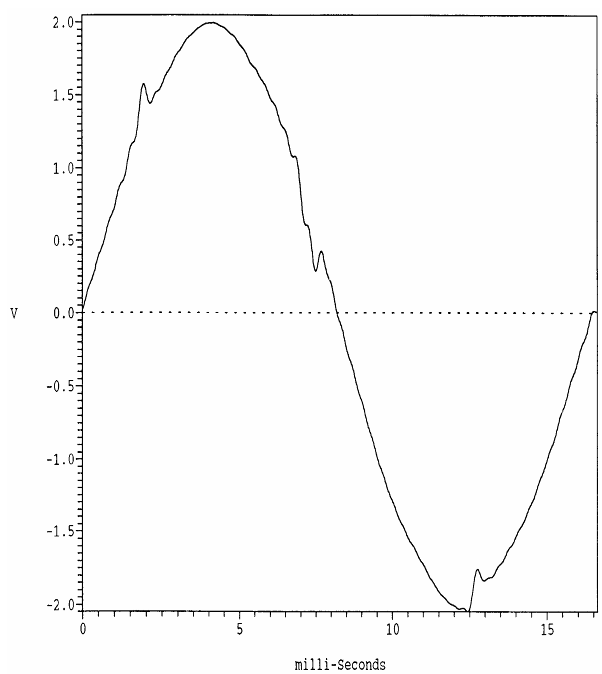

Figure 4-10
Harmonic Voltage Waveform

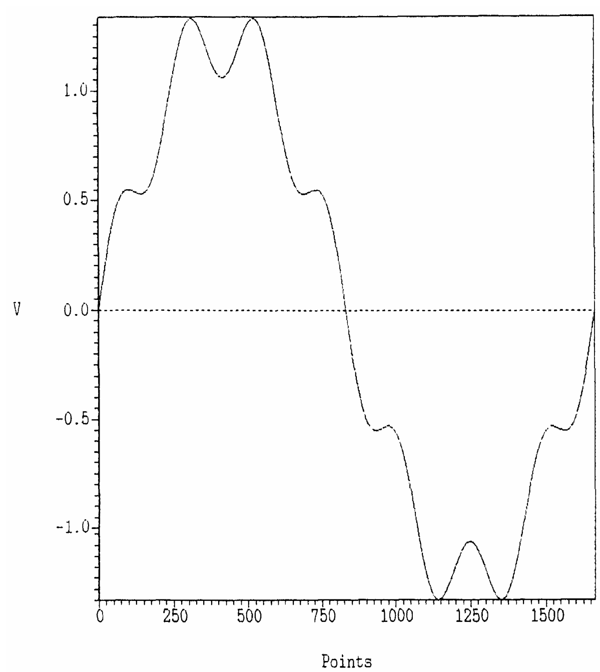

Figure 4-11
Harmonic Voltage Waveform

Conclusion

Many of the preceding tests will not apply to the relays that are currently available. Currently available relays do not have sophisticated power quality monitoring capabilities. The intent of this test protocol is to provide guidance for testing relays as additional features are added in the future. The next chapter discusses some preliminary testing of the monitoring capabilities of two relays. The testing emphasized voltage sags, the most common power quality event.

5

EVALUATION OF THE POWER QUALITY MONITORING AND REPORTING CAPABILITIES OF TWO FEEDER RELAYS

Two relays were acquired for project testing purposes: a Schweitzer Engineering Laboratories (SEL) 351-7 feeder relay and a Basler 951 feeder relay. The SEL relay contains some limited power quality monitoring capabilities, namely voltage sags, swells, and outages. The Basler is more typical of relays currently available. It also can capture voltage sags, swells, and outages, but must do so by using “virtual” undervoltage and overvoltage relays to trigger oscillography data capture. The purpose of this testing was to evaluate the data capturing capabilities of the relays and to evaluate the software used for programming, data retrieval, and data analysis.

Data Capture Testing

The relays were installed in the modified Power Quality Monitor Test Stand as shown in Figure 5-1. The testing concentrated on the response of the relays to voltage sags. Some testing was also performed for voltage swells and capacitor-switching transients. Both relays were tested at the same time as allowed by the test stand.

Figure 5-1
SEL 351 and Basler 951 Relays Installed in the Test Stand

Voltage Sag Testing

Voltage sags are the most common power quality event in electric utility distribution systems. Both relays have some capability for capturing voltage sags. For these reasons, most of the testing concentrated on voltage sags. The sags were created using a 30-amp, three-phase, portable sag generator built by EPRI PEAC. This device allows the creation of voltage sags of any magnitude (from 0 to 1 per unit) with any duration from ¼ cycle to 120 cycles, adjustable in ¼ cycle increments. This device was wired to the voltage input of the test stand.

While the SEL 351 has settings for voltage-sag trigger, the Basler must use a virtual undervoltage relay to trigger data capture. In the Basler, the duration required for triggering is adjustable down to 3 cycles. For this reason, the voltage sag test protocol from Chapter 4 was adjusted to test the relays at 1, 2, and 3 cycles. Both relays were programmed to respond to voltage sags below 0.9 per unit, or 108 volts.

The results of the testing are shown in Table 5-1. As can be seen, the SEL had some trouble detecting single-phase sags with durations of 1 cycle. It was, however, able to respond to all sags with durations longer than 1 cycle. As expected, the Basler was unable to respond to some sags with durations less than 3 cycles. This was expected because of the fact that time-delay setting on the undervoltage relay was set at 3 cycles, the minimum.

Table 5-1
Response of SEL 351 and Basler 951 Feeder Relays to Voltage Sags

Phase(s)	Cycles	Voltage	Response (Y/N)	
			SEL	BASLER
A	1	107.0	N	N
A	1	80.0	Y	Y
A	1	60.0	Y	Y
A	2	107.1	Y	N
A	3	107.0	Y	Y
A	15	80.1	Y	Y
B	1	107.0	N	N
B	1	80.0	N	Y
B	1	60.0	Y	Y
B	2	107.0	Y	Y
B	3	107.6	Y	Y
B	15	80.2	Y	Y

C	1	107.0	N	N
C	1	80.1	Y	N
C	1	60.0	Y	N
C	2	107.0	Y	N
C	3	107.0	Y	Y
C	15	80.1	Y	Y
AB	1	60.0	Y	N
AB	2	60.0	Y	Y
AB	3	60.0	Y	Y
ABC	15	60.0	Y	Y
ABC	120	60.0	Y	Y

Figure 5-2, Figure 5-3, Figure 5-4, and Figure 5-5 show the results of one of the voltage sag tests. In this case, the input voltage to the relays was lowered to 107 volts for 3 cycles. The undervoltage threshold on both relays was set at 108 volts. Figure 5-2 shows the output of the sag generator. This is the signal seen by both relays.

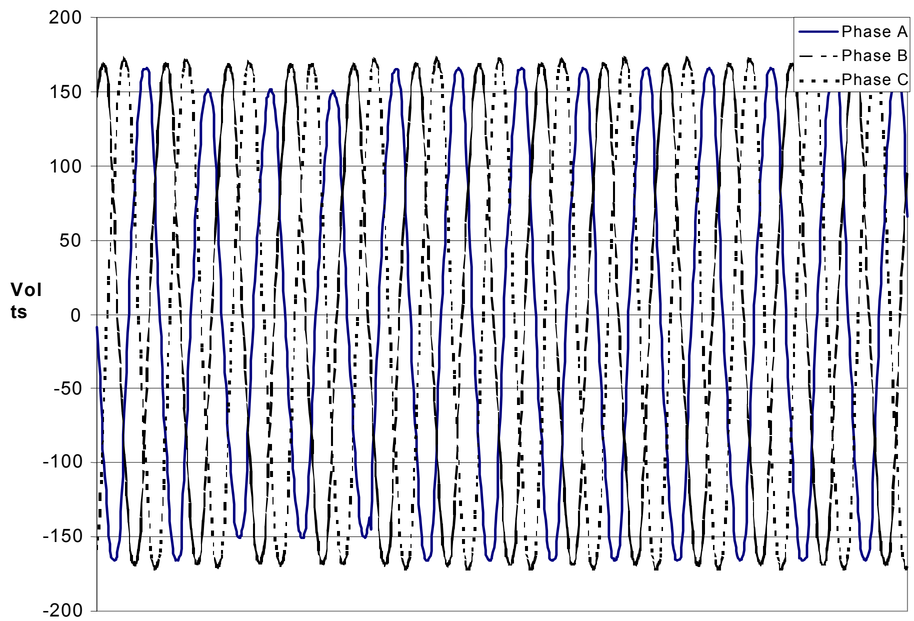

Figure 5-2
Voltage Sag to 107 Volts on Phase A: Output of Sag Generator

Figure 5-3 and Figure 5-4 are the data collected by the SEL relay during the voltage sag. The “Digitals” shown in Figure 5-3 are status indications for the virtual relays in the device. The text file is the sag, swell, and interruption (SSI) report. The SSI report provides RMS values for all analog inputs in ¼-cycle increments during SSI events.

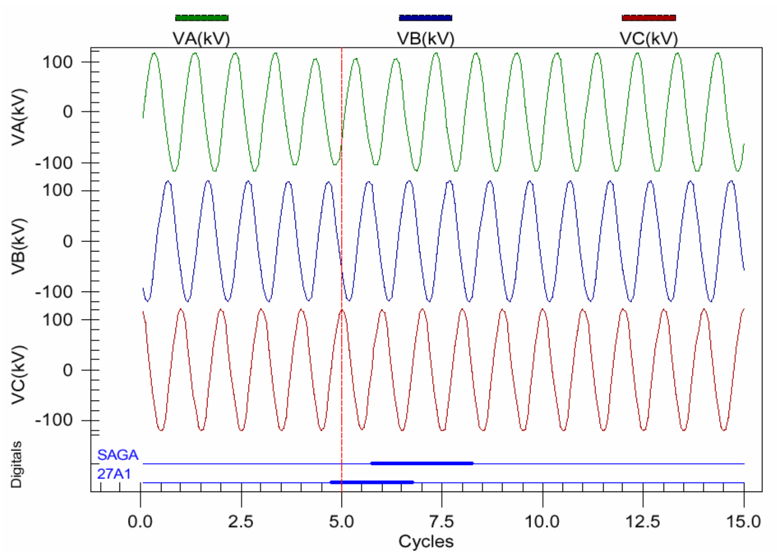

Figure 5-3
Voltage Sag to 107 Volts on Phase A: Graphic Data Collected by SEL Relay

FEEDER 1 Date: 11/13/01 Time: 12:40:15.230
STATION A

FID=SEL-351-7-R306-V0-Z003003-D20010307 CID=12D3

I nom. A B C G = 5 Amp N = 5 Amp

#	Date	Time	Current (% I nom.) Ia	Ib	Ic	Ig	In	Voltage (% Vbase) Va	Vb	Vc	Vs	Vbase (V)	Ph ABC	ST
30	11/13/01	12:29:28.102	27	30	28	1	0	98	99	99	0	122.09	...	E
29	11/13/01	12:29:28.106	27	30	28	1	0	97	99	99	0	122.09	...	E
28	11/13/01	12:36:40.271	28	22	17	6	0	98	98	100	0	122.13	...	P
27	11/13/01	12:36:40.275	28	22	17	6	0	98	98	100	0	122.13	...	P
26	11/13/01	12:36:40.279	27	22	17	6	0	98	98	100	0	122.13	...	P
25	11/13/01	12:36:40.284	27	22	18	6	0	97	98	100	0	122.13	...	P
24	11/13/01	12:36:40.288	28	22	18	6	0	95	98	100	0	122.13	...	P
24	11/13/01	12:36:40.288	28	22	18	6	0	95	98	100	0	122.13	...	P
22	11/13/01	12:36:40.296	27	22	17	6	0	90	98	100	0	122.13	...	P
21	11/13/01	12:36:40.300	27	22	17	6	0	90	98	99	0	122.13	...	P
20	11/13/01	12:36:40.304	28	22	17	6	0	87	98	99	0	122.13	...	P
19	11/13/01	12:36:40.309	28	22	17	7	0	87	98	98	0	122.13	...	P
18	11/13/01	12:36:40.313	28	22	17	6	0	87	98	98	0	122.13	...	P
17	11/13/01	12:36:40.317	28	22	17	6	0	87	98	98	0	122.13	...	P
16	11/13/01	12:36:40.321	28	22	17	6	0	87	98	98	0	122.13	U..	F
15	11/13/01	12:36:40.325	28	22	17	7	0	87	98	98	0	122.13	U..	F
14	11/13/01	12:36:40.329	28	22	17	6	0	87	98	98	0	122.13	U..	F
13	11/13/01	12:36:40.334	28	22	17	6	0	88	98	98	0	122.13	U..	F
12	11/13/01	12:36:40.338	28	22	17	6	0	90	98	98	0	122.13	U..	F
11	11/13/01	12:36:40.342	28	22	17	6	0	90	98	99	0	122.13	U..	F
10	11/13/01	12:36:40.346	28	22	17	6	0	95	98	99	0	122.13	U..	F
9	11/13/01	12:36:40.350	28	22	17	6	0	95	98	100	0	122.13	U..	F
8	11/13/01	12:36:40.354	28	22	17	6	0	97	98	100	0	122.13	U..	F
7	11/13/01	12:36:40.359	28	22	17	6	0	97	98	100	0	122.13	U..	F
6	11/13/01	12:36:40.363	28	22	17	6	0	97	98	100	0	122.13	...	E
5	11/13/01	12:36:40.367	28	22	17	6	0	97	98	100	0	122.13	...	E
4	11/13/01	12:36:40.371	28	22	17	6	0	97	98	100	0	122.13	...	E
3	11/13/01	12:36:40.375	28	22	17	6	0	97	98	100	0	122.13	...	E
2	11/13/01	12:36:40.379	28	22	17	6	0	97	98	100	0	122.13	...	E
1	11/13/01	12:36:40.384	28	22	17	6	0	97	98	100	0	122.13	...	E

Figure 5-4
Voltage Sag to 107 Volts on Phase A: Text Data Collected by SEL Relay

Figure 5-5 shows the data collected by the Basler relay during the voltage sag.

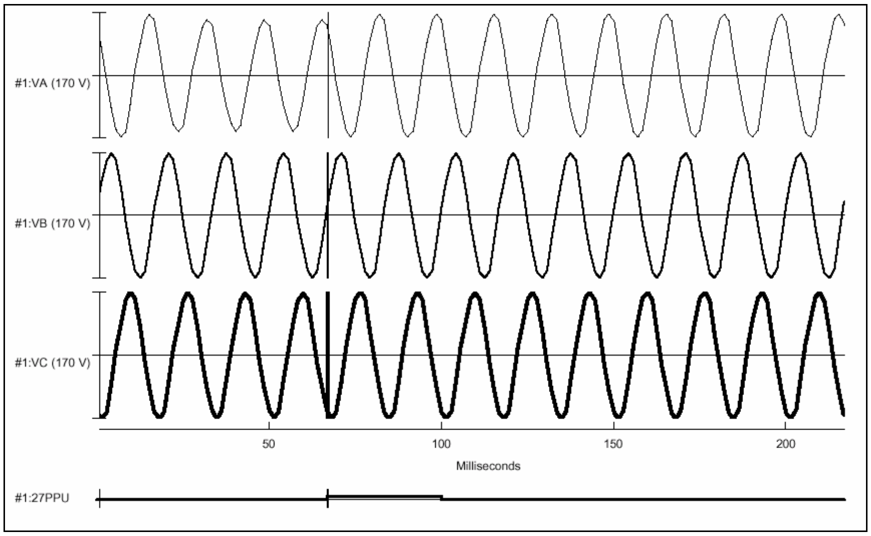

Figure 5-5
Voltage Sag to 107 Volts on Phase A: Data Collected by Basler Relay

As shown in Figure 5-6, the input voltage to the relays was reduced to 60 volts for 15 cycles.

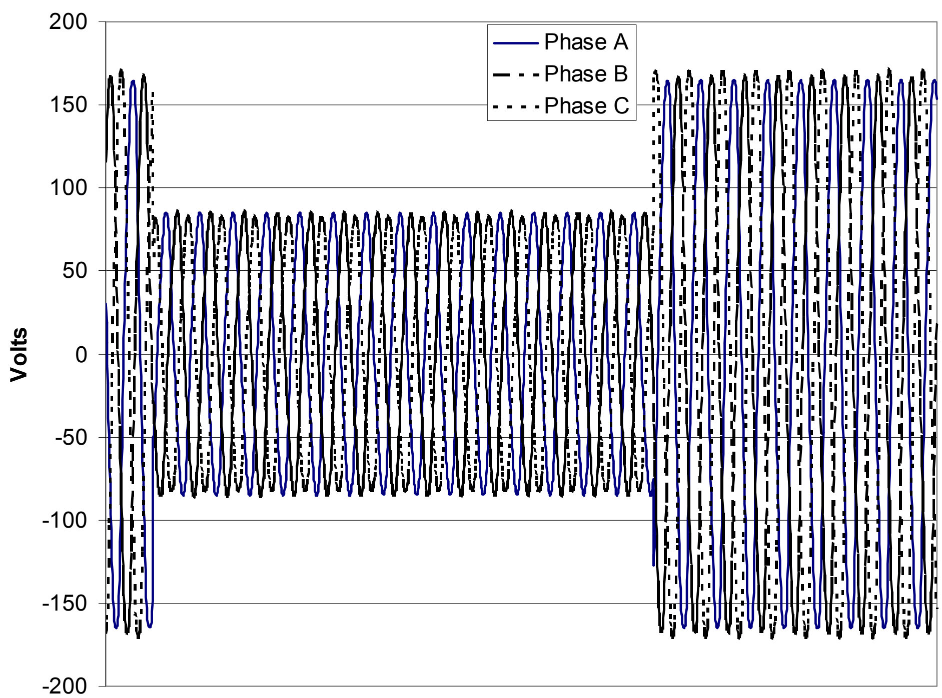

Figure 5-6
Three-Phase Voltage Sag to 60 Volts: Output of Sag Generator

Figure 5-7 shows the data collected by the SEL relay during the voltage sag.

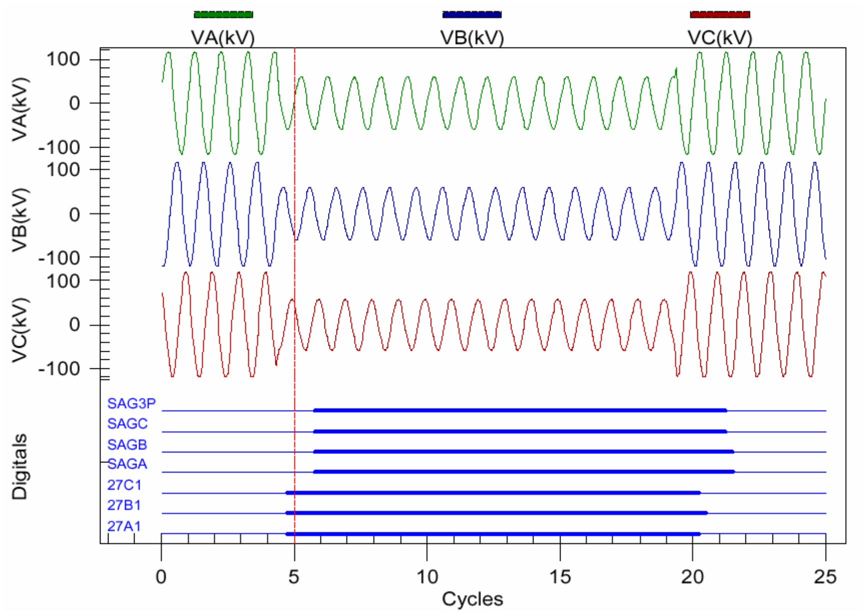

Figure 5-7
Three-Phase Voltage Sag to 60 Volts: Data Collected by SEL Relay

Figure 5-8 show the data for a three-phase voltage sag.

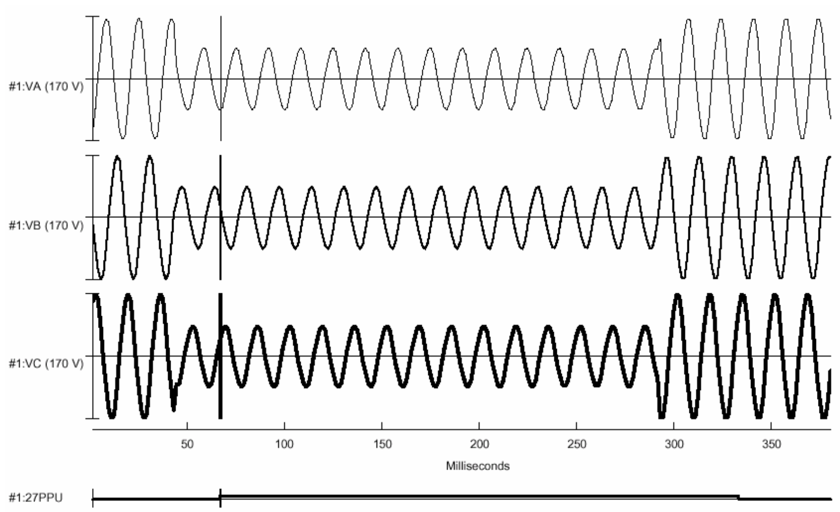

Figure 5-8
Three-Phase Voltage Sag to 60 Volts: Data Collected by Basler Relay

Both relays were able to accurately capture and record voltage sags within their stated accuracy. The undervoltage relay in the Basler has a minimum time to pickup of 3 cycles, so it was not unexpected that the relay would have trouble capturing sags with durations shorter than 3 cycles.

Voltage Swell Testing

Voltage swell testing was also performed on both relays. Fewer tests were performed. The performance of the relays was similar to the voltage sag performance. Both relays, and particularly the Basler, had trouble detecting single-cycle voltage swells with small magnitudes (just above the setpoint). Once the duration of the swell was increased to 3 cycles, neither relay had difficulty recording the events. Figure 5-9 and Figure 5-10 show the data collected by the relays for a three-phase voltage swell to 115% of nominal, or 138 volts with a duration of 5 cycles.

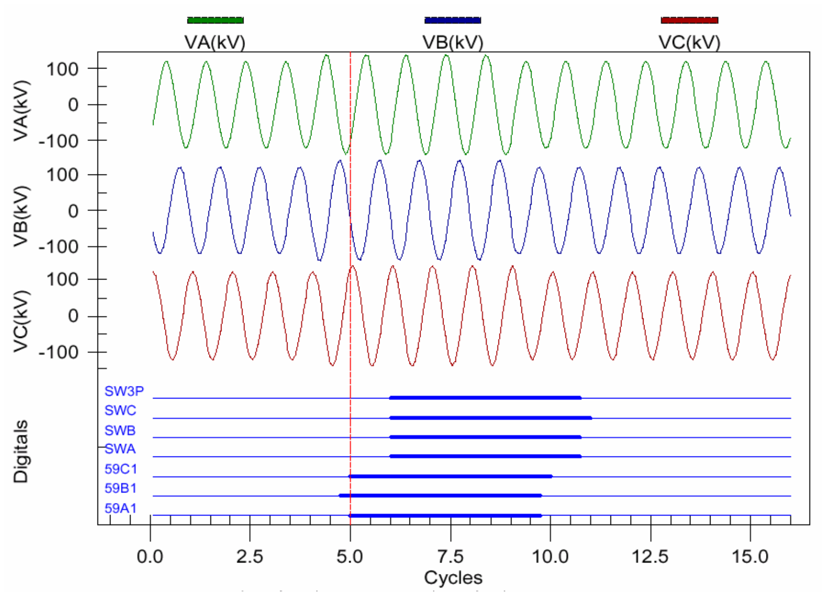

Figure 5-9
Three-Phase Voltage Swell to 138 Volts: Data Collected by SEL Relay

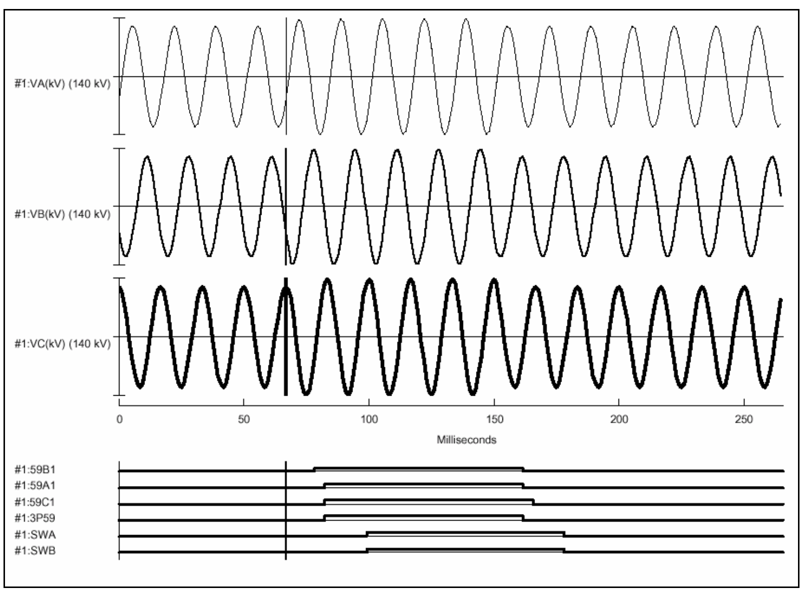

Figure 5-10
Three-Phase Voltage Swell to 138 Volts: Data Collected by Basler Relay

Capacitor-Switching Transient Testing

Neither device was rated to capture capacitor-switching transients. A capacitor-switching test was performed to determine the response, if any, of the relays to the event. Neither relay captured an event for the transient. Figure 5-11 shows the capacitor-switching transient used to test the response of the relays. This transient was created using an arbitrary waveform generator.

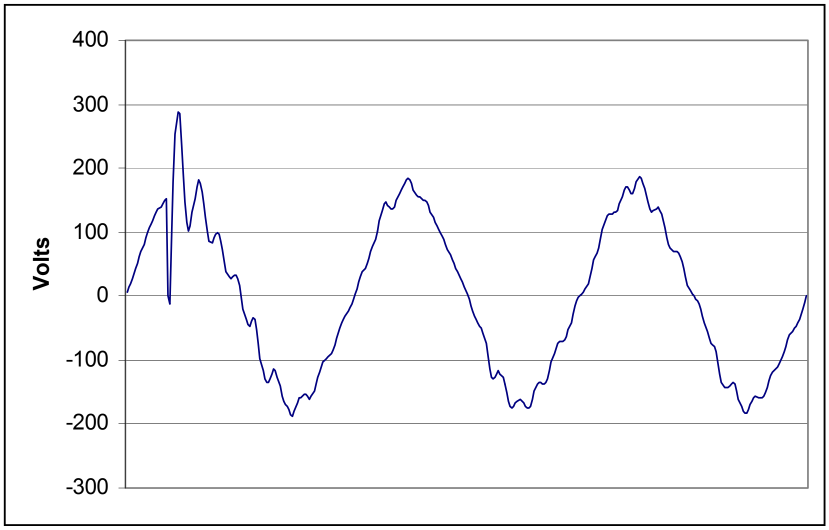

Figure 5-11
Capacitor-Switching Transient with Magnitude = 1.6 Per Unit

Software Evaluation

While the response of a relay, or any device, can be quantitatively measured, the evaluation of the associated software is a qualitative exercise. What follows is a brief description of how the associated software works with each relay along with any observations regarding the ease of use. Particular attention is given to the areas of programming the required settings and downloading captured event data.

Basler BESTCOMS and BESTWAVE-32

The Basler relay requires two pieces of software, one for programming and downloading data and a second application for data viewing. BESTCOMS is the application used to program the relay and download captured event data. Figure 5-12 shows the settings overview screen of BESTCOMS. From this screen, one can determine which virtual relays are programmed and active. The row of icons represents specific settings pages in the software.

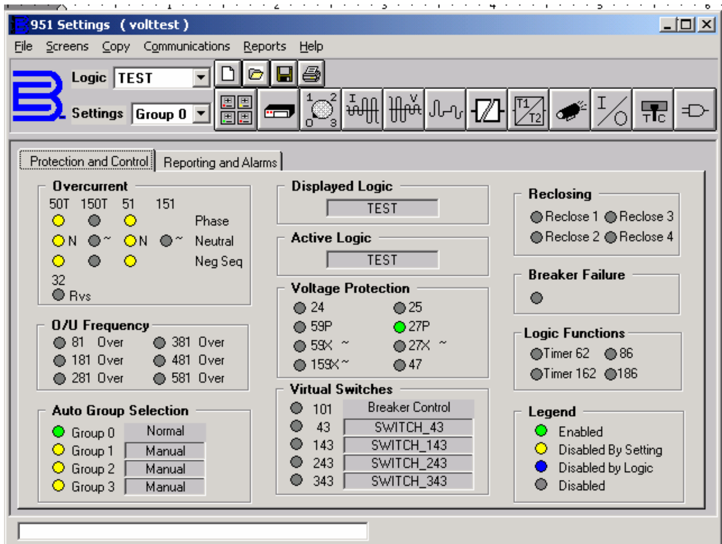

Figure 5-12
Relay Settings Overview Screen in Basler BESTCOMS Software

Selecting the icon with the waveform and a "V" will open the voltage relay settings page. This page has several tabs along the top, each representing a different type of voltage relay. Selecting the tab marked "27P" will open the settings page for phase-undervoltage relays as shown in Figure 5-13.

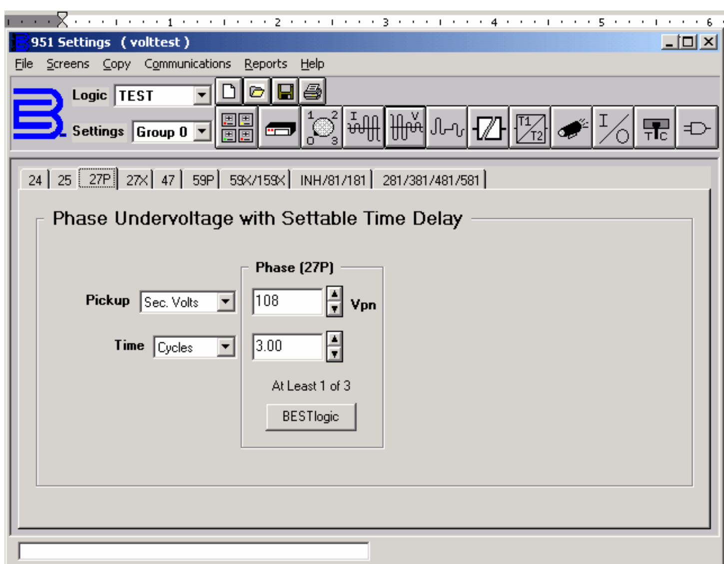

Figure 5-13
Undervoltage Relay Settings Screen in BESTCOMS Software

Selecting the icon that looks like a megaphone (4th icon from right) will open the alarms and reporting page. Selecting the fault-recording tab opens the page where fault-recording settings can be adjusted. This page is show in Figure 5-14.

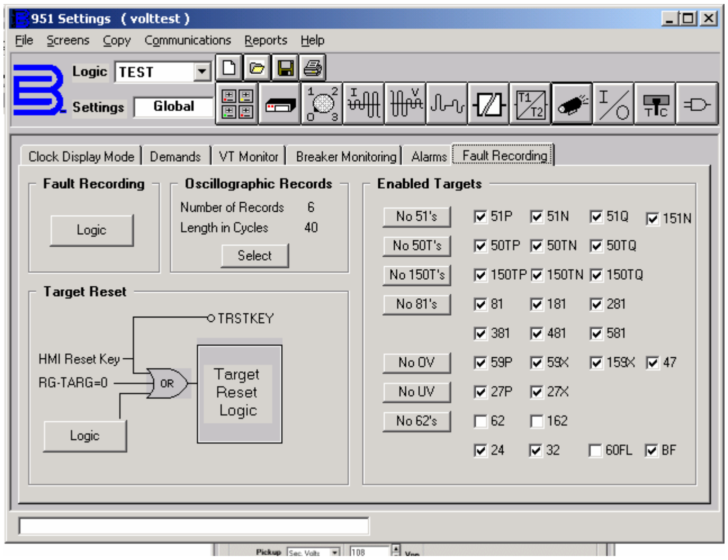

Figure 5-14
Fault-Recording Setup Screen in BESTCOMS Software

To download data, the Reports menu item is selected. After following the instructions, a list of existing events will appear. An event can then be highlighted and downloaded. During the testing, each event download took approximately two minutes. This process is manual with no provision for automation. The lack of automation is one of the current shortcomings of relay software. For the data from relays to be easily integrated into a power quality monitoring system, the data downloading must be automated.

Once the data was downloaded, it was stored as a COMTRADE file. The BESTWAVE-32 software is supplied to view the stored data. Any COMTRADE viewer should work. For this evaluation, the viewing tools supplied by each vendor were used to view the data. Figure 5-15 shows the way in which data is displayed by the BESTWAVE-32 software. The analog signals (voltages and currents) are shown on the upper portion of the screen while the digital signals (relay status) are shown on the lower portion. Selecting the “A” icon allows the selection of analog data to be displayed. In this example, only phase voltages are displayed. Selecting the “D” icon allows the selection of relay statuses to be displayed. The relay status changes from a logic 0 to a logic 1 when the relay detects an event outside of its setpoints.

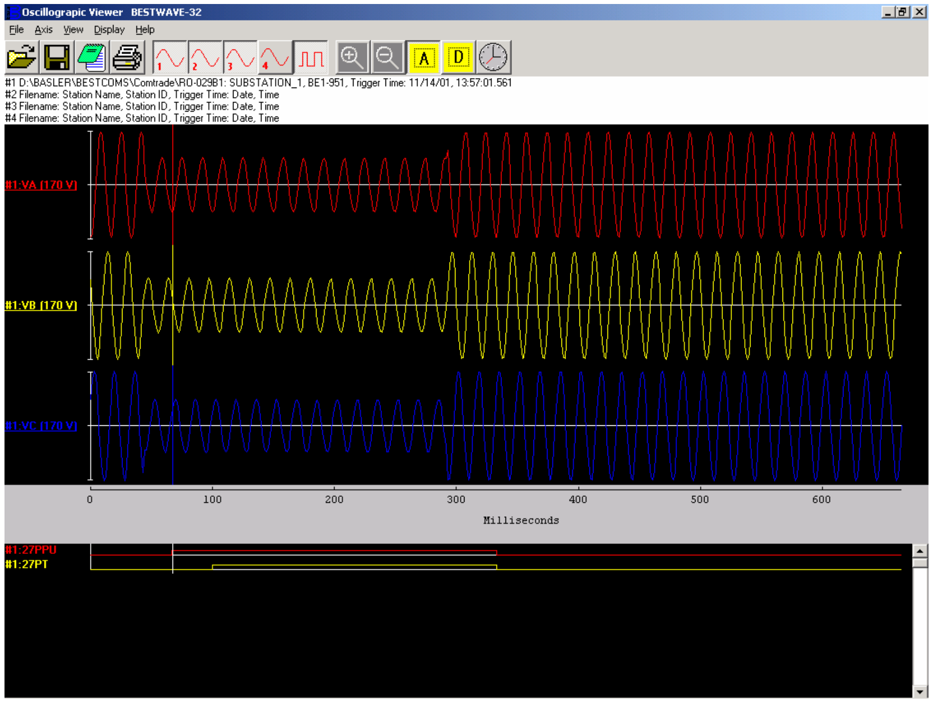

Figure 5-15
Oscillography Display in the BESTWAVE-32 Software

The BESTCOMS and BESTWAVE-32 software was not difficult to learn or use. Any difficulties experienced were more the result of learning the terminology of the relay industry. Being a relay, the Basler 951 is much different to program than the typical power quality instrument. However, it is likely that a power quality engineer would work with a relay engineer to make any changes necessary to capture power quality events. The event downloading capabilities could be improved. The BESTCOMS software is functional but not practical for a large number of devices being downloaded at regular intervals. This device does support Modbus and DNP3.0 communication protocols so development of automated downloading tools is a possibility.

The BESTWAVE-32 application is an acceptable viewing tool. However, it offers no data analysis tools such as those included in popular power quality analysis software, like EPRI's PQView. Any combination of analog and digital channels can be easily displayed. The software offers a zooming feature also. No support exists for copying a waveform to the clipboard for pasting into another Windows application such as a word processor. The Basler related figures in this chapter are either screen captures (in the software section) or graphics cut from Adobe Acrobat pdf files created by printing the waveforms to a pdf-creation application. Adding the ability to cut and past graphics would greatly increase the usefulness of the BESTWAVE-32 software.

SEL AcSELerator Software

A single software application, AcSELerator, provides for programming, data downloading, and data viewing for the SEL 351 relay. AcSELerator is a two-pane application, as shown in Figure

5-16. The left pane shows a menu tree of groups of settings while the right pane shows the settings for the selected group. In this specific case, the right pane shows the settings for the voltage elements.

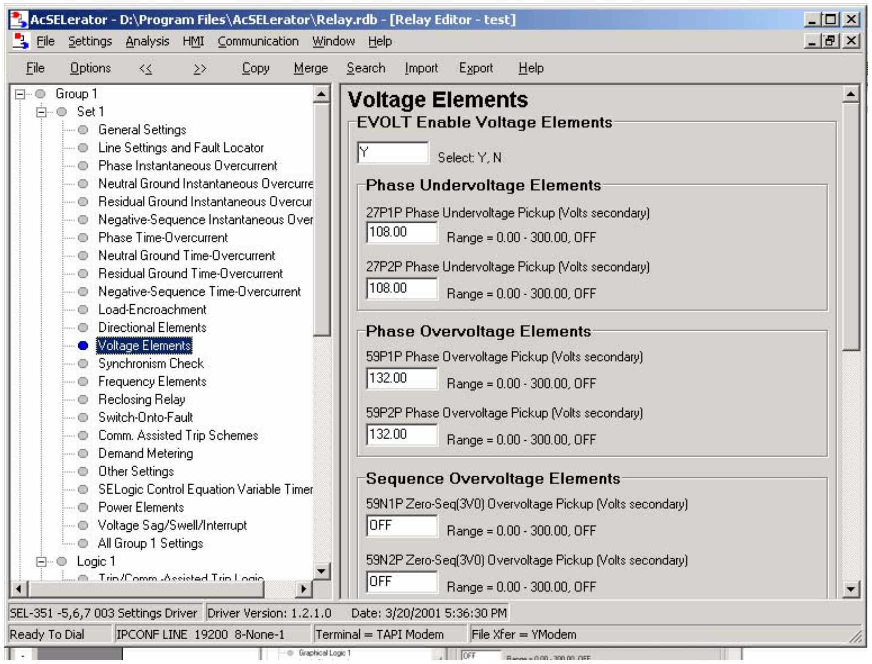

Figure 5-16
Voltage Elements Settings Screen for SEL AcSELerator Software

The unique feature of the SEL 351-7 relay is the inclusion of some power quality event thresholds. This feature is only available in the -7 firmware version of the relay. Figure 5-17 shows the settings screen for the power quality thresholds. These include settings for voltage sag, voltage swell, and interruption. Any voltage excursion outside of these settings will cause an SSI report to be stored. As previously mentioned, the relay will store the RMS values of all analog inputs for the duration of the event in predetermined time increments. The default increment is ¼ cycle. Also, the number of pre-fault and post-fault cycles can be set.

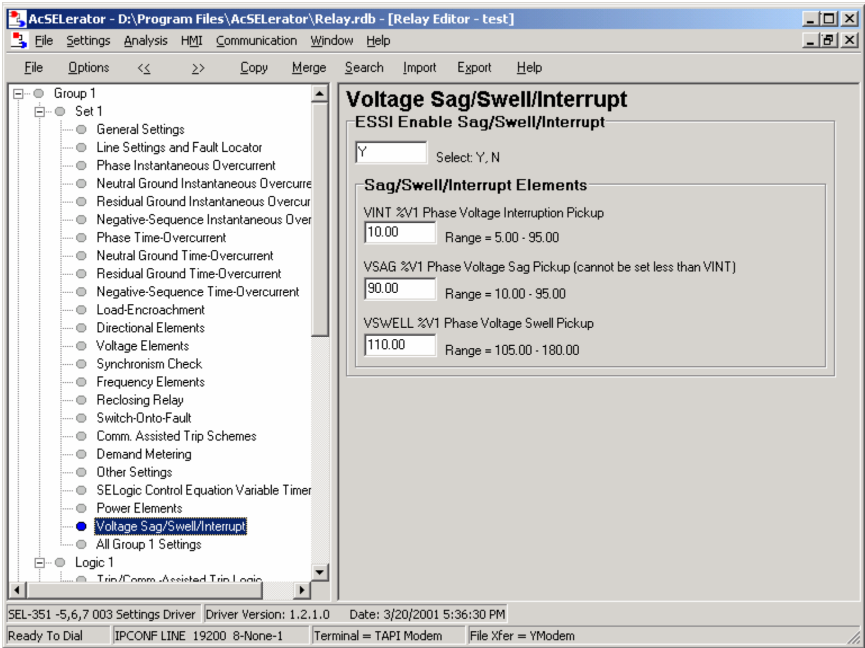

Figure 5-17
Voltage Sag, Swell, and Interrupt Settings Screen for AcSELerator Software

Figure 5-18 shows the screen used to program the event report equation, along with other equations.

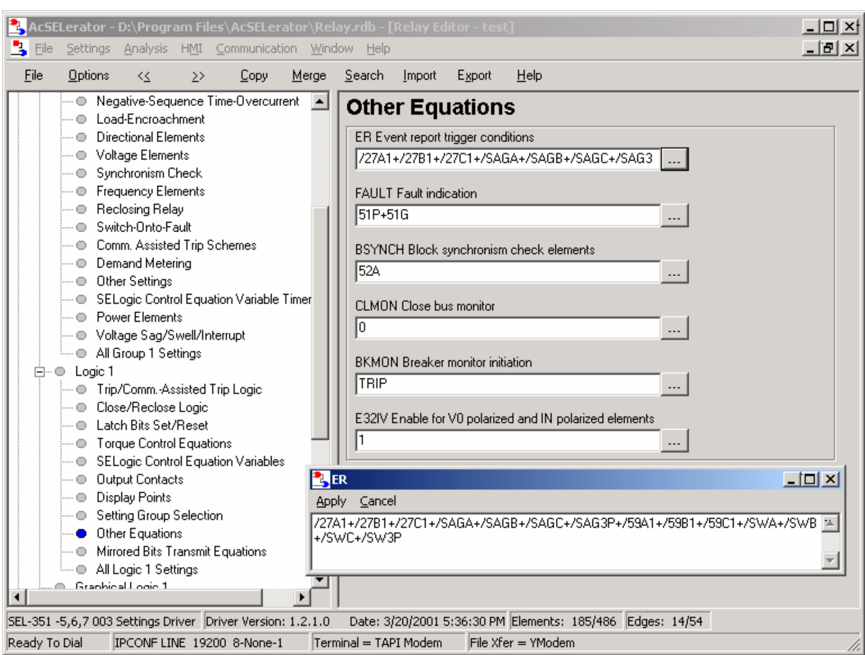

Figure 5-18
Event Report Setup Screen for AcSELerator Software

When the event report equation is selected, a window opens showing the entire equation. The equation can then be edited to include the relay outputs that should trigger an event report. This equation can also be created graphically using the built-in logic tool. Once you are familiar with the names of the relays that are used for triggering power quality event captures, it is much faster to edit the event report equation manually. In this example, the relay is programmed to collect an oscillography event when any (+ is an OR operator) of the virtual relays in Table 5-2 detects an event.

Table 5-2
Virtual Relays and Their Detection Events

Virtual Relays	Detection Event
27A1, 27B1, 27C1	Phase Undervoltage
SagA, SagB, SagC, Sag3P	Voltage Sag (phase A, B, C, or 3-phase)
59A1, 59B1, 59C1	Phase Overvoltage
SWA, SWB, SWC, SW3P	Voltage Swell (phase A, B, C, or 3-phase)

Captured event waveforms are downloaded by selecting the Analysis menu from the main menu bar. From this menu, Read History is chosen. This opens a window with a list of events stored in the relay. Events can be selected from this list for downloading. Each event takes approximately two to three minutes to download over a serial connection. Once the event is downloaded, it can be saved and then displayed within AcSELerator. AcSELerator does not offer an option for automated downloading. SEL does offer an external communications module, the SEL 2030, which communicates in Modbus or DNP3.0. The 2030 acts as a communication server for multiply SEL relays. Using a 2030 and Modbus, or DNP3.0, it should be possible to develop an automated download system.

Figure 5-19 shows the oscillography data display screen in AcSELerator. There is a window hidden behind the waveform window that contains the menus needed to select graphing options. The graph options are selected by first selecting the “Pref” button on the lower right of the screen. Selecting the “Pref” button opens the preferences window. From this window, the analog and digital channels can be selected for display. Such things as scale and plot length (in time) can be adjusted also. AcSELerator allows cutting and pasting of the displayed graphs.

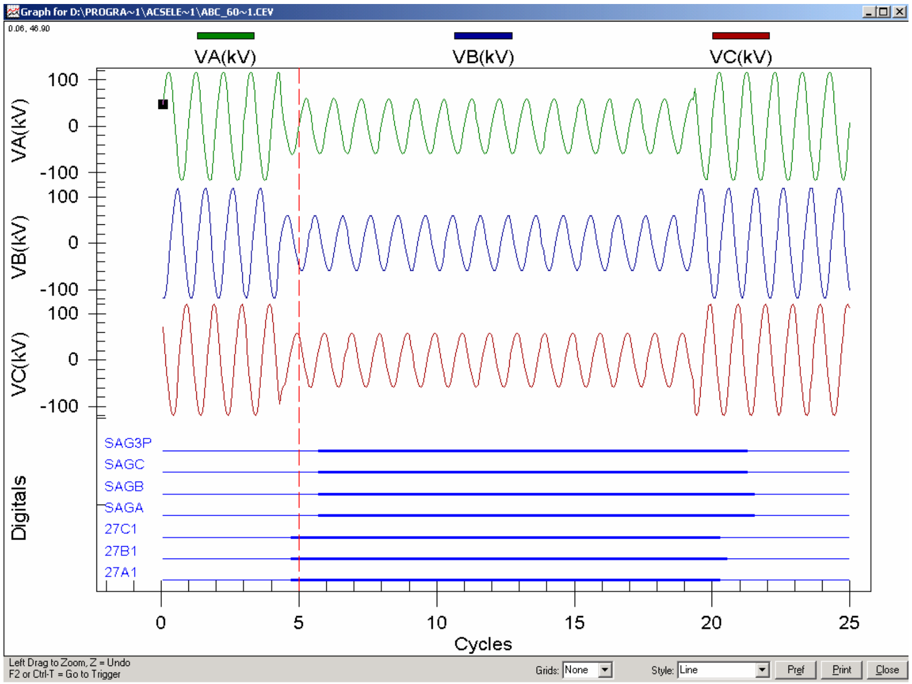

Figure 5-19
Oscillography Display in AcSELerator Software

Like BESTWAVE-32, AcSELerator does not offer any tools for analyzing power quality data. As a Viewer, AcSELerator is an acceptable tool. However, it does not have the types of tools, such as automated magnitude vs. duration scatter plots, desirable to power quality engineers.

AcSELerator is not difficult to use. Again, most of the learning curve involves getting familiar with the terminology used in the relay industry. As mentioned before, any programming of the relay settings is likely to be done in conjunction with a relay engineer. The collection of data in a centralized location is again a weakness. Some form of automated system is required if data is to be collected from a large number of relays.

Software Evaluation: Conclusion

Both Basler (BESTCOMS and BESTWAVE-32) and SEL (AcSELerator) provide adequate tools for programming their relays and viewing downloaded data. Programming a single relay at a time is not a big disadvantage because relay programs are seldom modified. However, manually downloading a single relay at a time creates problems as the number of relays increases. Both relays are in need of a system that can automatically download new events. The KJT OPEN System[9] is compatible with the SEL 2030 and SEL 351. It can provide automated downloading of SEL equipment. OPEN is a software package that collects data from monitoring instruments from diverse vendors and displays it in a common format.

[9] www.kjt.com

The data viewing capabilities of BESTWAVE and AcSELerator are acceptable—if viewing a single event at a time (with limited data analysis) does not limit your application. Any attempt at calculating reliability, and power quality, indices requires data segregation and analysis. Both applications store data in the COMTRADE format, a commonly used standard in the power system protection field. This file format is not supported by many applications in the power quality field. Power quality data interchange format (PQDIF) is the emerging standard for power quality data. The addition of PQDIF as a file option would improve the usefulness of both applications.

6

RECOMMENDED POWER QUALITY MONITORING SPECIFICATIONS FOR NEXT-GENERATION RELAYS

The technology improvements in digital signal processing fueled by the digital video and audio markets are working in favor of manufacturers of all kinds of power metering and monitoring hardware. The capabilities of today's digital signal processors (DSPs), along with the ever-decreasing prices, make it possible for a relay manufacturer to provide the functionality of many "virtual relays" in a single device. These improvements also make it possible for modern relays to collect and report power quality data.

Power Quality Monitoring

It is important to remember that a relay's primary function is to provide protection for the electric power system. After these functions have been ensured, any remaining processing power can be used for power quality, and quantity, monitoring. Knowing that the remaining processing power will be a finite quantity, it is important to prioritize the types of power quality, and quantity, data that are to be collected. A recent EPRI-sponsored project[10] surveyed utility engineers to determine the priority of certain functions for next generation revenue meters. The results of this survey are shown in Figure 6-1.

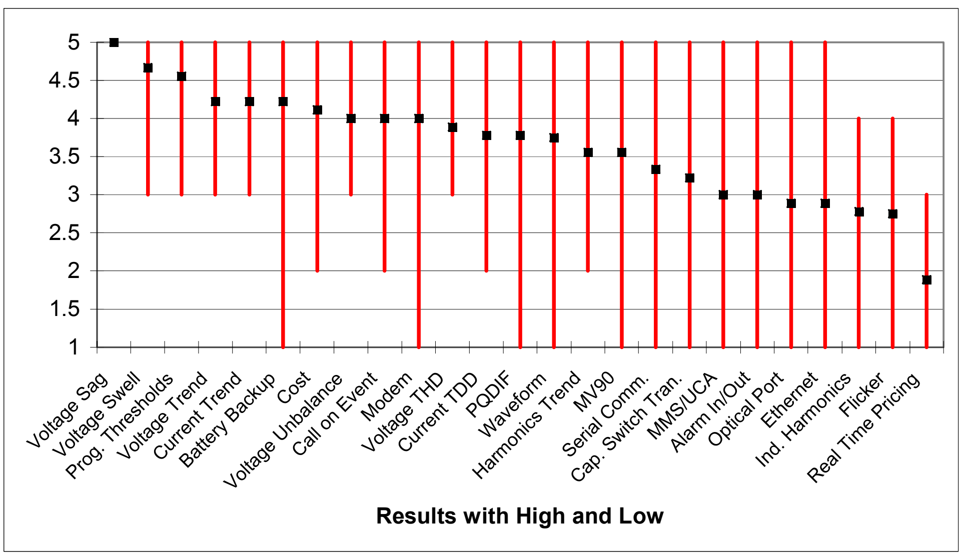

Figure 6-1
Ranking by Electric Utilities of the Importance of Features of a Next-Generation Revenue Meter[10]

[10] *Development of Meter Specifications*, EPRI, Palo Alto, CA: 2000. 1000372.

As can be seen, voltage sag and swell ranked first and second respectively. These two types of events, along with short-duration (or momentary) outages, are the most common types of power quality events in an electric power distribution system according to an EPRI-sponsored study of distribution power quality levels[11]. These three types of events (voltage sag, voltage swell, and momentary outages) are particularly disruptive to customer load—causing equipment and process shutdowns that result in lost or damaged product. Three other power quality events that can disrupt customers and are common on distribution systems include: voltage unbalance, harmonics, and capacitor-switching transients.

Data Storage and Communication

The current standard data format for feeder relays is COMTRADE (defined in IEEE Standard C37.111-1999[12]). This data format is not commonly used by power quality monitoring systems, or power quality evaluation software. The inherent limitations of this file format with respect to storing power quality data has led to the development of the power quality data interchange format (PQDIF). PQDIF is currently a proposed IEEE Standard[13]. PQDIF is covered in some detail in Appendix A, “PQDIF Overview,” of this report. Several power quality monitor vendors, as well as revenue meter vendors, currently support PQDIF as a data exchange file format. PQDIF is also supported by several power quality data analysis software packages, including PQView by EPRI and the Open System by Kreiss Johnson Technologies. To allow easy integration of the data from relays with the data from existing power quality monitoring systems, it is important that relay manufacturers provide a method of exporting PQDIF files.

Data is of little use to a utility if it resides on a device in the field, such as a relay in a station. Often the most difficult task in creating a power quality monitoring system in a utility is the communication of captured data back to a central location for processing. For this reason, the relay needs to be as flexible as possible with respect to communication options. While some utilities are working toward installing wide area networks (WANS) in their stations, most utilities are limited to using telephone modems for data transfer. Many utilities have communications available in their stations that move load and device status data back to a central dispatch center. In some cases, it may be possible to make use of the same data path for the power quality data if the relay can communicate using the required protocol. Three common communication protocols are MMS/UCA, DNP3, and MODBUS.

[11] An Assessment of Distribution System Power Quality: Volumes 1-3; TR-106294-V1, TR-106294-V2, TR106294-V3.

[12] IEEE Std. C37.111-1999, IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems.

[13] IEEE Std. P1159.3, Recommended Practice for the Transfer of Power Quality Data (Draft 5).

Functional Specifications for Power Quality Data Capture, Communication, and Exchange

The following specifications take into account the concerns discussed above. They are listed in order of importance within each category.

Power Quality Metering Functions

- Logging of voltage sags in table form (magnitude and duration with 0.5-cycle resolution, time stamp)
- Logging of voltage swells in table form (magnitude and duration with 0.5-cycle resolution, time stamp)
- Programmable thresholds for voltage limits
- Waveform capture on event (voltage and current at 128 samples per cycle)
- Voltage unbalance measurement
- Voltage trending (minimum, average, and maximum during a selectable interval)
- Current trending (minimum, average, and maximum during a selectable interval)
- Capture of capacitor-switching transients (300 to 900 Hz)
- Call home on event
- Logging of voltage total harmonic distortion (THD) events with programmable threshold
- PQDIF data export from the interface software (see Appendix A for more information on PQDIF)
- Logging of current total demand distortion (TDD) events with programmable threshold (TDD defined by IEEE Std. 519-1992)
- Harmonic trending (V_{THD} and I_{TDD})
- Individual harmonic trending

Communication Functions

- Serial communication
- Modem
- Ethernet communication
- Standard optical port
- MMS/UCA
- Modbus
- DNP3

Interface Software Specifications

- PQDIF data export option (see Appendix A for more information about PQDIF)
- Compliance with Open Database Connectivity (ODBC) (see Appendix G for more information on ODBC)
- Compatible with Windows 95/98, NT4.0, and 2000
- Automated polling of relays by telephone or Ethernet

7 CONCLUSION AND FUTURE WORK

Many of the distribution feeders in electric utilities are currently monitored by microprocessor-based relays. The use of these relays to provide valuable power quality, and thus system performance, data will reduce the cost of data collection and provide information necessary to engineers as they try to allocate maintenance dollars. This report investigates the power quality data collection, event reporting, and software interface capabilities of currently available feeder relays. A limited number of relays were tested using a test protocol defined in this report. The report also provides power quality data collection specifications that could be included in future relays.

The results of the investigation and testing are promising. Many relays are available that provide the ability to capture the most common power quality events: voltage sags, swells, and interruptions. The two relays that were tested preformed well within their specifications. The data collected was accurate and could be viewed in the vendor software packages with relative ease. These devices are not yet replacements for traditional power quality monitors, such as the Dranetz-BMI 8010. However, they do provide another source of data that should be considered.

Relay technology is constantly improving. Each new relay model adds monitoring capabilities that increase the usefulness of the device as a data-gathering tool. There are still improvements that must be made, particularly in the area of data retrieval and analysis. A common platform for the analysis and presentation of data is required if utilities are to make effective use of the data from various brands of relays. This platform needs to be vendor independent and must provide complex data analysis tools common in power quality analysis software packages.

The retrieval of the data must be automated. Manually collecting the data from each relay would be too time consuming to prove efficient. Consider that each station may contain multiple feeder relays and a utility may have many, even thousands, of stations. It is obvious that an automated system must be developed to perform the data retrieval. The data retrieval systems could be vendor specific as long as the data is stored in a common file format, such as PQDIF.

Future Work

Another possible source of power quality data is the new generation of electronic reclosers and recloser controls with embedded analog-to-digital (A/D) data acquisition systems. Many manufacturers are beginning to add data collection and analysis features to their lines of electronic reclosers that may make them suitable for providing both reliability and power quality data. These smart reclosers are often accompanied by reliable data communications infrastructures, thereby reducing the amount of additional effort required to collect the power quality data. A common data format in the form of IEEE COMTRADE makes the sharing of data with other application software easier than in the past.

There are areas that need to be investigated before this data is integrated into an existing, or planned, power quality monitoring system. Such things as accuracy, response to predetermined disturbances, and data presentation must be characterized so the data can be properly treated by power quality engineers or by software packages for automated power quality analysis. Possible communication media and protocols should also be investigated to ensure the reliability and accuracy of data transfer.

A
PQDIF OVERVIEW

Many utilities are monitoring the quality of the power they deliver to their customers, while some have plans to monitor the quality of power on every feeder in their system. Utility customers are also beginning to monitor the quality of the power delivered to them as well as the quality of power at key points inside their facilities. The many sources of power quality data rely primarily on proprietary data formats and analysis software. As the number of monitored points increases, the need for a universal software tool to analyze the data becomes critical, and a common data exchange format is therefore essential.

Overview

While utilities and their customers are increasingly monitoring the quality of the power they provide or use, the number of points that are monitored is driven by both need and cost. Often a utility or customer would like to monitor more points than they can justify financially. The proprietary nature of power quality monitors means that once a brand is selected, it must be used for all future expansions or the user is stuck with incompatible systems. This greatly increases the cost and difficulty of managing power quality monitoring.

Another concern is that, although some level of power quality data is available from nontraditional sources such as relays and revenue meters, these devices often have extremely limited tools for analyzing the data in a way useful to a power quality engineer. Protection relays and revenue meters are already required in the power system, so any power quality data they provide is inherently low cost. The development and use of a standard power quality data interchange format will make this data accessible for analysis, and the utility or customer can increase the number of monitored points without large capital outlays for equipment. The standard exchange format will also enable the user to change equipment vendors without concern about incompatibilities with existing equipment. Thus a power quality monitoring system originally commissioned with all brand-X equipment may subsequently be expanded using brand Y.

The power quality data interchange format (PQDIF) provides vendors with a common format for the export and import of data, allowing the end-user maximum flexibility in choice of tool and vendor. Power quality data is a broad category--many forms of data are collected, processed and stored, from basic information like raw voltage waveforms to highly processed statistical information on derived quantities such as total harmonic distortion (THD). Because of the wide range of data that may be measured or calculated, a highly flexible, standard method of data exchange is required. PQDIF was initially developed to allow for the transfer of *most* power quality data—measurements, simulation results, calculated index values, etc.—in a high-fidelity form and in a predictable, standardized way. The PQDIF file structure is therefore extremely open and flexible.

Several side effects exist from this level of flexibility, the most obvious of which is its complexity. PQDIF is indeed a fairly complex format when compared to the simple ASCII files of COMTRADE or other proprietary formats. Also, the flexibility of PQDIF leads to occasional ambiguities in modeling a particular type of data. Without the proper guidance, this flexibility can be confusing. For example, vendors may develop PQDIF files that appear to be structurally accurate with regard to allowable PQDIF element tags, but are not structured such that the data importer of the analysis tool can properly characterize the data.

Power Quality Data Interchange Format (PQDIF) Structure

There are two "layers" to the PQDIF file format: the *physical* layer and the *logical* layer. The physical layer describes the physical structure of the file without regard to what will actually be stored in it. It uses tags to identify particular elements of the file, similar in concept to the tagged image file format (TIFF) used for storing images. The logical layer uses the structure defined by the physical layer and specifies the tags to use when building up elements in the file.

The physical layer of the PQDIF file is based on the following:

- Specific "physical" data types (for example, INT1, INT2, INT4, REAL4, REAL8) for portability and a specific list of IDs for physical representation (for example, ID_SERIES_PHYS_TYPE_INTEGER1)
- Four-byte alignment for efficient processing
- Tags--using GUIDs (globally unique identifiers, or "tags")--for unique identification of elements. A GUID is a 16-byte integer that is defined by a standard algorithm. The length of the integer and the algorithm used to calculate it virtually guarantee that every tag created will be unique

At the highest level, the physical format of the PQDIF file is a series of linked records. Each record is made up of a header and a body as shown in Figure A-1.

- Record 1
    - Header
        - Signature
        - Record type tag
        - Size of the body
        - Link to next record
    - Body
        - Self-contained block of data
- Record 2

Figure A-1
Physical Format of Power Quality Data Interchange Format (PQDIF) File

The body of the record contains a set of elements that contain data. The three element types are:

- Scalar – represents a single data value
- Vector – represents an array of data values
- Collection – contains other elements

A scalar or a vector element can contain values of the following types:

- Signed integer (1, 2, or 4 bytes in length)
- Unsigned integer (1, 2, or 4 bytes in length)
- Complex (8-byte, single precision, or 16-byte, double precision)
- Boolean (1, 2, or 4 bytes in length)
- Real (4-byte, single precision, or 16-byte, double precision)
- Character (1-byte, ASCII or 2-byte, Unicode)
- Date stamp (12 bytes in length)
- GUID (16 bytes in length)

The logical layer of the PQDIF file is based on:

- Specific lists of tags to identify elements of a file
- A hierarchy of tags and expected physical types
- Extensibility using user-defined tags for private data
- Extensibility of the standard format using tags defined in the future

To keep things simple, many elements in the logical layer are based on an explicit list of enumerated identification codes, such as:

- Phase (for example, ID_PHASE_AN, ID_PHASE_BN)
- IEEE 1159 disturbance category (for example, ID_1159_TRANSIENT, ID_1159_SHORTDUR)
- High-level quantity type (for example, ID_QT_WAVEFORM, ID_QT_RMS)
- Series quantity units (for example, ID_QU_TIMESTAMP, ID_QU_VOLTS, ID_QU_AMPS)
- Series value type (for example, ID_SERIES_VALUE_TYPE_MIN, ID_SERIES_VALUE_TYPE_MAX)

A fragment of a PQDIF file is shown below in Figure A-2 to illustrate the hierarchy. This fragment was created using a PQDIF-to-ASCII tool available from the IEEE P1159.3 website at *http://grouper.ieee.org/groups/1159/3/index.html*.

```
+-Collection -- tag: tagOneChannelDefn (level 2)
| +-Vector -- tag: tagChannelName (type: CHAR1) [ 13 ]
| | value: 'Waveform VCA'
| +-Scalar -- tag: tagPhaseID (type: UNS_INTEGER4)
| | value: 7 - ID_PHASE_CA
| +-Scalar -- tag: tagQuantityMeasuredID (type: UNS_INTEGER4)
| | value: 1 - ID_QM_VOLTAGE
| +-Scalar -- tag: tagQuantityTypeID (type: GUID)
| | value: {67f6af80-f753-11cf-9d890080} - ID_QT_WAVEFORM
| +-Collection -- tag: tagSeriesDefns (level 3)
| | +-Collection -- tag: tagOneSeriesDefn (level 4)
| | | +-Scalar -- tag: tagQuantityUnitsID (type: UNS_INTEGER4)
| | | | value: 2 - ID_QU_SECONDS
| | | +-Scalar -- tag: tagQuantityCharacteristicID (type: GUID)
| | | | value: {a6b31ae5-b451-11d1-ae170060} - ID_QC_RMS
| | | +-Scalar -- tag: tagValueTypeID (type: GUID)
| | | | value: {c690e862-f755-11cf-9d890080} - ID_SERIES_VALUE_TYPE_TIME
| | | +-Scalar -- tag: tagStorageMethodID (type: UNS_INTEGER4)
| | | | value: 4 - ID_SERIES_METHOD_INCREMENT
| | | +-(End of collection)
| | +-Collection -- tag: tagOneSeriesDefn (level 4)
| | | +-Scalar -- tag: tagQuantityUnitsID (type: UNS_INTEGER4)
| | | | value: 6 - ID_QU_VOLTS
| | | +-Scalar -- tag: tagQuantityCharacteristicID (type: GUID)
| | | | value: {a6b31add-b451-11d1-ae170060} - ID_QC_INSTANTANEOUS
| | | +-Scalar -- tag: tagValueTypeID (type: GUID)
| | | | value: {67f6af97-f753-11cf-9d890080} - ID_SERIES_VALUE_TYPE_VAL
| | | +-Scalar -- tag: tagStorageMethodID (type: UNS_INTEGER4)
| | | | value: 3 - ID_SERIES_METHOD_VALUES | ID_SERIES_METHOD_SCALED
| | | +-Scalar -- tag: tagSeriesNominalQuantity (type: REAL8)
| | | | value: 48083.261121
| | | +-(End of collection)
| | +-(End of collection)
| +-(End of collection)
```

Figure A-2
Fragment of Power Quality Data Interchange Format (PQDIF) File

Other Recommended Reading

This chapter is not meant to be an in-depth coverage of PQDIF files, but rather an overview. Detailed information on the proposed PQDIF standard is available at *http://grouper.ieee.org/groups/1159/3/index.html.* The reader is referred to this document for more than a casual understanding of the requirements for a PQDIF file.

Target:
Power Quality for Transmission and Distribution

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