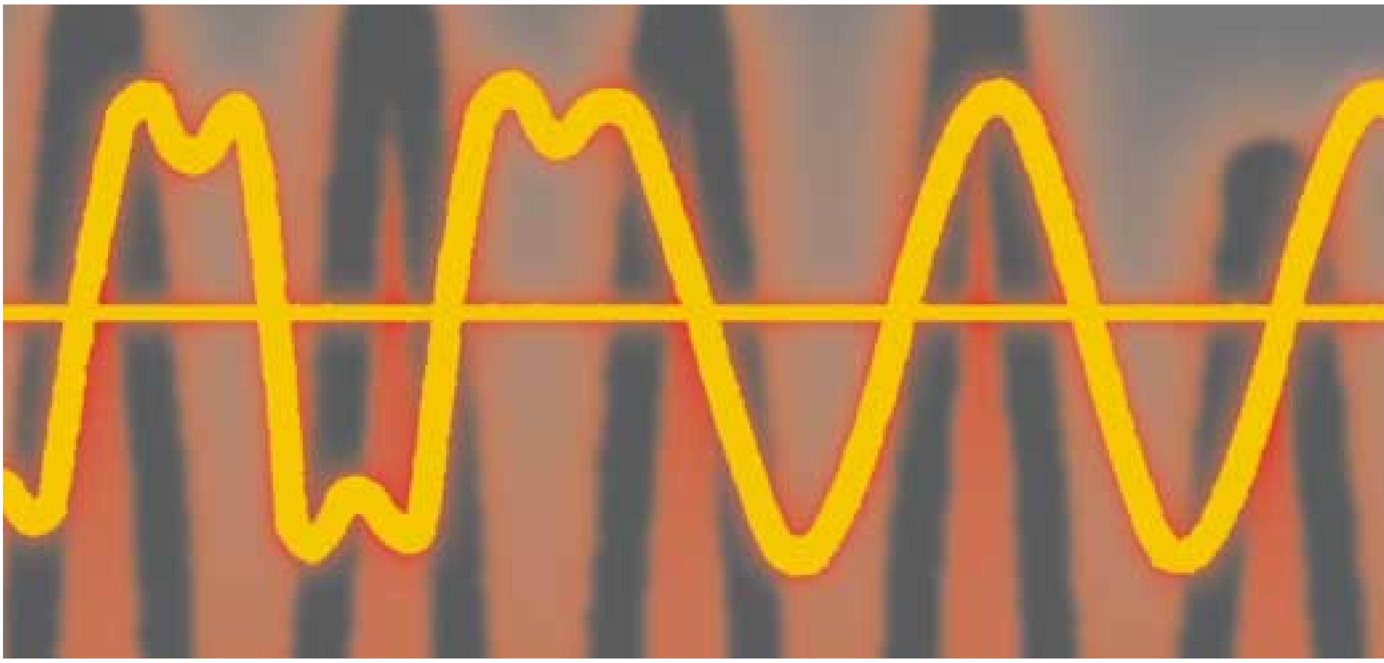

Improving power quality

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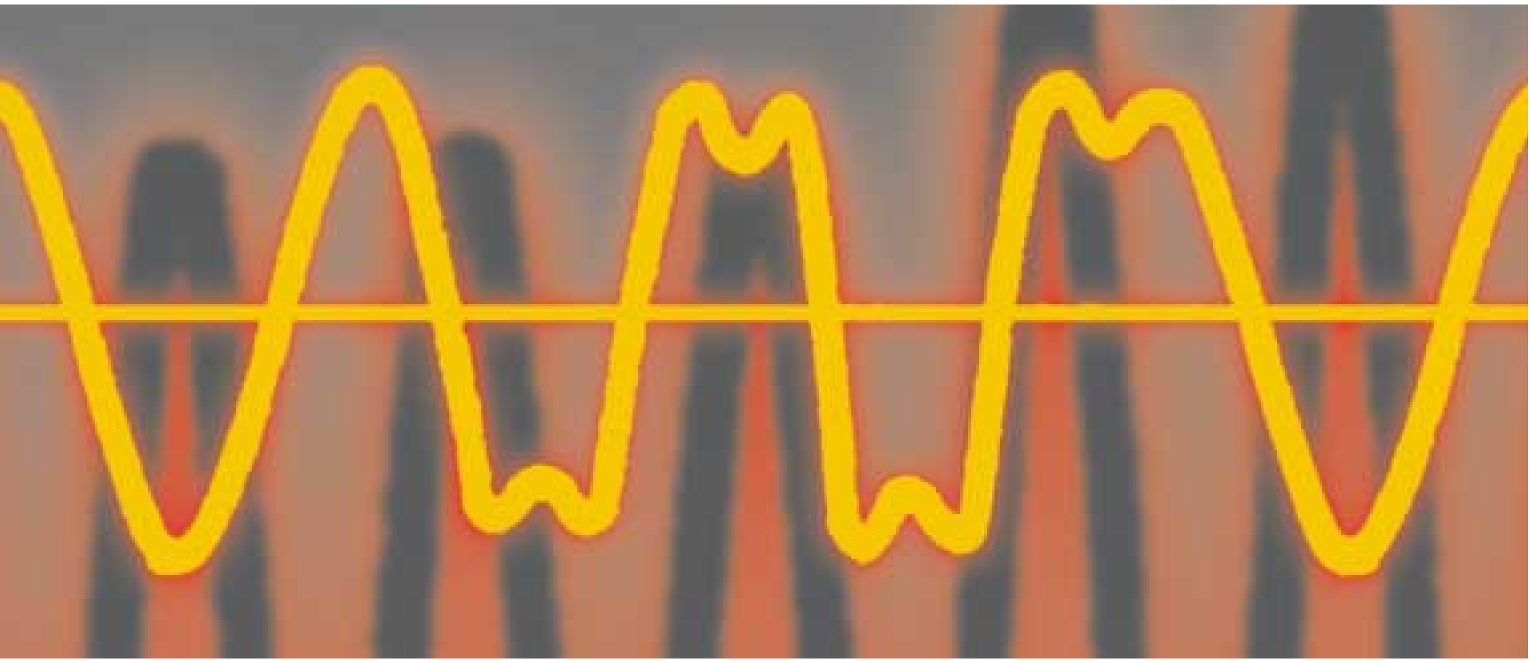
Since they are vital for power system operation, protective relays and distribution control equipment are deployed at every level in the grid – on every piece of major equipment and on every circuit-breaker. Liberalization of the energy market and increasing IT and microprocessor capability have now set the scene for new functionality to be integrated in these traditional devices. ABB has implemented advanced power quality monitoring functionality, such as load profiling, fault oscillographic waveform capture and metering, in its relays and distribution feeder equipment to empower customers to access PQ information at many points in the system, and so free them from having to rely on dedicated monitoring devices.

Protection relays and feeder control equipment are key to the operation of every power transmission and distribution system. Modern control and protection relays utilize microprocessors and digital signal processors (DSP) in order to implement more sophisticated protection algorithms and allow greater control and automation through digital communications networks. Thanks to advances in microprocessor and DSP technology, many relays now have more than just protection capability [1]. By giving them access to voltage and current measurements, they are able to meter, capture waveforms and monitor for power quality. Additional capability has been built into most modern relays to allow communication with other equipment, including Supervisory Control and Data Acquisition (SCADA) systems. Previously, power quality monitoring has been implemented in the ABB Alpha digital revenue meter with the help of microprocessor and DSP technology. The next logical step was to implement power quality monitoring in the upstream equipment. The medium-voltage SCD 2000 switch controller 1 and PCD 2000 recloser controller 2 utilize micropro-



monitoring for utilities

1 ABB DPU 2000R substation feeder breaker relay

2 PCD 2000 feeder recloser controller

3 SCD 2000 poletop switch controller

cessor technology for applications in ABB distribution feeders. The DPU 2000R feeder breaker relay 3 is utilized in substation applications.

What is power quality?

The answer to this question will obviously differ from engineer to engineer. Practically speaking, we refer to power quality as any electrical disturbance that could adversely affect a customer's load or power system equipment [2]. These types of events are typically monitored for post-event analysis. Since, in the industry, a fine line exists between power quality and reliability, and also the category into which the events may fall, we shall refer here to both power quality and power reliability (outages) as power quality.

The widespread interpretation of what constitutes power quality and a power quality event has led the IEEE to define power quality monitoring standards. There are several reasons for adopting the IEEE standards when implementing power quality monitoring; for example, it offers a published and widely accepted definition, clarifies the PQ terminology, and provides easy access to the standards

Table: Typical power quality event information that can be captured by protective relays

Duration	Category	Typical duration	Typical voltage variation
Short duration	*Instantaneous*		
	Voltage sag	0.5–30 cycles	0.1–0.9 pu
	Voltage swell	0.5–30 cycles	1.1–1.8 pu
	Momentary		
	Voltage interruption	0.5 cycles -3 s	<0.1 pu
	Voltage sag	30 cycles -3 s	0.1–0.9 pu
	Voltage swell	30 cycles -3 s	1.1–1.4 pu
	Temporary		
	Voltage interruption	3 s–1 min	<0.1 pu
	Voltage sag	3 s–1 min	0.1–0.9 pu
	Voltage swell	3 s–1 min	1.1–1.2 pu
Long duration	*Voltage interruption*		
	sustained	> 1 min	0.0 pu
	Undervoltage	> 1 min	0.8–0.9 pu
	Overvoltage	> 1 min	1.1–1.2 pu

documentation. The documents defining power quality monitoring are IEEE 1159 [3] and 519 [4]: IEEE 1159 includes voltage variations, high-frequency transients, short-duration effects (eg, sags and swells), long-duration effects (eg, overvoltages and undervoltages), interruptions, voltage imbalance, harmonics and frequency variations; harmonic disturbances are covered by IEEE 519.

Dedicated power quality monitoring devices are used frequently in medium- and high-voltage stations as well as at customers' sites to detect power quality events. When these devices are triggered by a power quality event, they often initiate a high-frequency oscillographic waveform capture based on current or voltage variations. The captured waveforms are stored in mass storage devices, such as a hard disk drive. Since, as a rule, many events are captured, the engineer has to sort through them and decide which of the data are critical. Protective relays do not typically have the memory storage that the high-end PQ monitors have. In addition, the typical relay minimum sampling rate starts at 8 samples per cycle. These limitations mean that the relays must filter PQ events to optimize storage and that relays cannot capture high-frequency events.

The IEEE definitions provide an ideal framework for the categorization of events. The *Table* shows typical PQ events based on duration and magnitude. High-frequency events caused by lightning surges and high harmonics will not be visible to a protective relay. However, the most critical information for utility account managers do not normally contain high-frequency data.

At 32 samples per cycle, protective relays can, in practice, only monitor up to the 9th harmonic due to the anti-aliasing filter and/or noise errors. This is sufficient to capture the majority of harmonics generated in power system operations. The important contribution of IEEE 519 to power quality monitoring is that it defines how harmonics should be measured for voltage and current waveforms. Total harmonic distortion (THD) is used as the measure of harmonic content of voltage waveforms. Total demand distortion (TDD) is used to measure the harmonic content of current waveforms.

Why use protective relays for power quality monitoring?

PQ monitoring in ABB protective relay or distribution control units is not intended to compete with the more sophisticated power quality monitors. It is, rather, to provide an economical means of deploying permanent monitoring points at multiple locations within the utility. If a power quality problem is detected, the more powerful monitoring systems can be deployed.

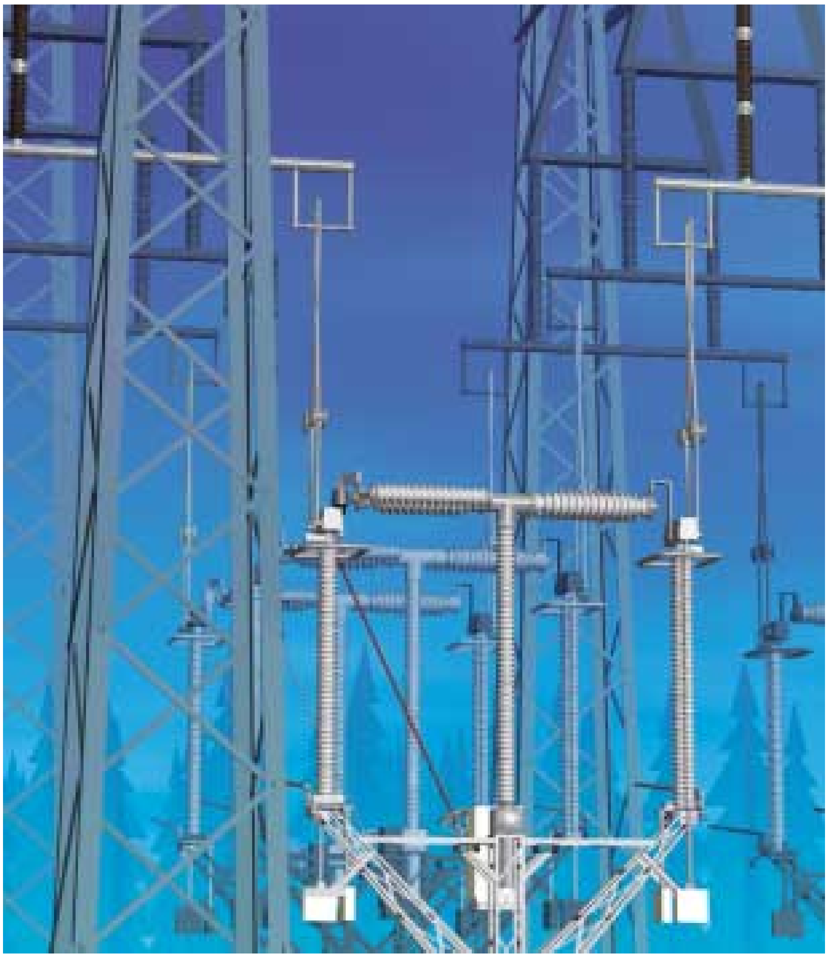
Relays and distribution control equipment are always attached to the power system, so they provide power quality information with only an incremental additional investment. And since they are connected to a battery back-up to provide protection during power failures, they can also record PQ events during system disturbances. Relays and distribution control equipment can and often are connected to a communications infrastructure, which now can be used to bring power quality information back to the central office. In addition to these benefits, the growth in microprocessor power provides scope for expanding relay and controller capability.

Using relays and distribution equipment controllers to collect PQ information

One of the major objectives of capturing data in a real-time intelligent electronic device, such as a protective relay, is to obtain concise information about the power quality events. PQ events should be intelligently filtered and recorded only if they have the potential to affect the system. For example, rather than use a simple magnitude trigger, a PQ event can be triggered using both time and magnitude settings. Each IEEE category is realized by a separate set of time and magnitude settings. This provides the protective relay with capability for pre-filtering and categorizing the events. Once the PQ event is triggered, the event data is captured in three ways: by the event record, the RMS trend of the event, and the oscillographic record.

Providing an event record gives the end-user an accurate summary of what has occurred in the system, and also enables the user to sort events by phase, type, duration, and deviation with ease. A typical event record will include a date and timestamp, the duration of the event, the phase the event occurred on, the minimum and maximum deviation from nominal, and pre-event loading. Using this format, several hundred PQ events can easily be recorded and quickly downloaded for off-line analysis.

Oscillographic data provides the most detailed information for engineering troubleshooting analysis. This data is most often three-phase to provide a complete snapshot of the system activity. However, oscillographic data occupies the most memory. For example, eight cycles of oscillographic data at 32 samples per cycle would require approximately 3.5 kbytes of memory (8 cycles x 32 samples/cycle x 7 channels x 2 bytes). Thus, 128 events would require just under half a megabyte of memory. Such memory capability is not present in a great number of protective relays, so oscillographic data may only be



Thanks to new power quality monitoring functionality implemented in ABB relays and distribution control equipment, customers can access PQ information at many points in the system and do not have to rely on dedicated power quality monitoring devices.

4 The DCD 2000 communications node

stored for the last several events. This provides data for recent events, while earlier events are still logged in event records for off-line analysis.

RMS trending offers a practical compromise for oscillographic data. Since RMS event data can be stored periodically, rather than per sample, the memory requirements are reduced. For example, with protective relay sampling at 32 times/cycle the RMS data can be stored four times per cycle, reducing the memory requirements by a factor of eight. If only the affected phase is stored for archival analysis, the memory requirements are reduced again by a factor of three. Thus, most of the critical information can be stored for the affected phase with potentially just 1/24th of the memory needed to store all the samples. RMS trending is therefore a much more practical option for storing a large number of events.

Power quality monitoring in ABB protection gear

PQ monitoring functionality has been implemented in two ABB protection products: the PCD 2000 poletop recloser control unit and the SCD 2000 switch control unit. A prototype implementation of the algorithm has been tested on the DPU 2000R (REF544) feeder protection unit. In addition to their normal protection, automation, and communications functions, these products have embedded software that monitors and classifies PQ events according to the IEEE definition, stamps an event record, provides an RMS trend, and captures oscillographic waveform data for voltage sags, swells and interruptions. In addition, the units can capture THD on the voltages and TDD on the currents for harmonics up to the 9th. The successful implementation of all these features in the mentioned products was due in large part to close cooperation between ABB Corporate Research, ABB Automation and ABB Distribution.

All of the functions are implemented on a per-phase basis. Thus, a disturbance on a single phase will generate one PQ event record, an RMS trend for just the affected phase, and an oscillographic record which includes data for all three phases. A three-phase event will generate three PQ event records, an RMS trend for each phase, but still a single oscillographic record (since all three phases are recorded in the waveform capture). At present, over 200 PQ event records with RMS trending can be stored. As a rule, only the last 8 three phase oscillographic waveform captures are stored.

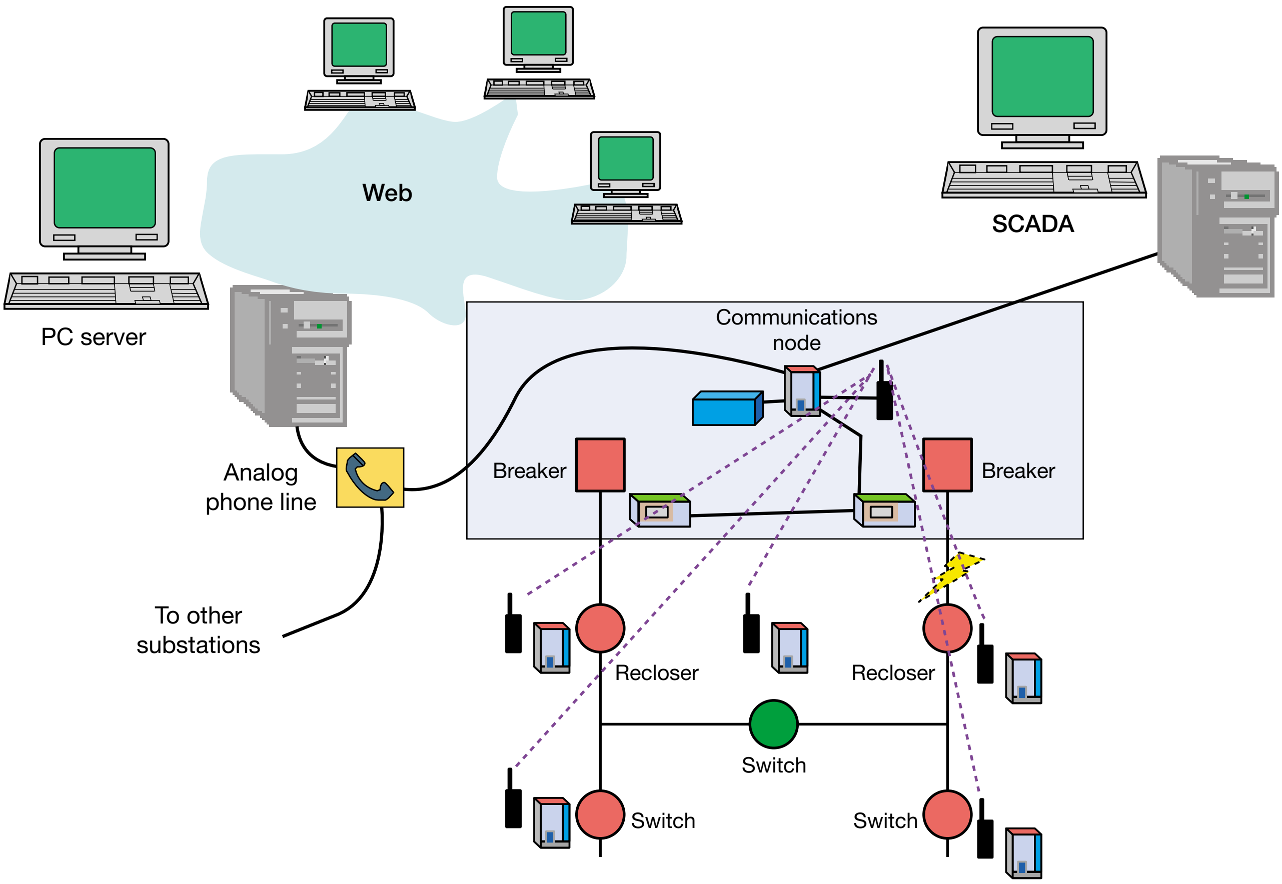
Obtaining PQ information from a protective relay

The power quality data collected by the protection devices needs to be made available to users in different departments. The information can be retrieved directly from the unit via a front panel interface featuring a menu system for guiding the user through the various power quality records. A personal computer with power quality application software can also be connected to a serial communications port. While these methods are effective for a stand-alone monitor that is easily accessible, an automated retrieval system will require a modem connected to the serial port or other type of network interface to retrieve the data.

To retrieve the power quality data from a substation, a communications node, such as the ABB DCD 2000 4, can be installed. This allows the remote terminal unit (RTU) to communicate uninterruptedly with the network of intelligent electronic devices while the remote user accesses the devices for PQ information on demand. The RTU is designed to provide upstream data to the SCADA system. The remote user application can access the power quality data through an auto-answer modem. With the DCD 2000 node, the same communications network is used to control and monitor the relays and feeder equipment and to retrieve PQ data. The advantage of allowing a PQ application to have access to the data without going through the RTU or SCADA system is that it minimizes the database point mapping required to obtain the PQ data.

A web-server application is used to demonstrate the new PQ monitoring capability. The motivation for designing the system as a server application, rather

5 Typical power quality monitoring installation with central server for PQ web application



than a stand-alone PC application, was two-fold:

- First, it simplifies the deployment and maintenance of the software package, as a server application only requires a single installation to make it work company-wide. Users then install a standard web browser on their machines.

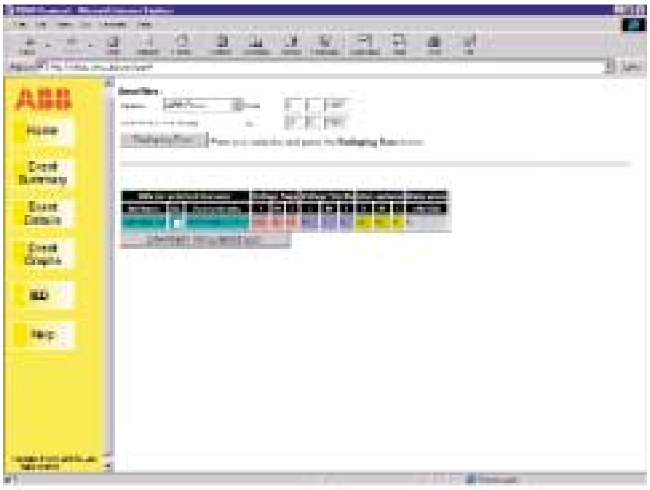
- Second, it gives a wide circle of clients in different areas controlled access to the information; a server-oriented system is better for distributing information and controlling access. The server also benefits from having a common database for all users and a single point of data collection from the field devices.

5 shows how the web-server application and ABB PQ monitoring equipment would be connected. A substation would typically have a communications node installed and connected to the relays and feeder equipment. When downloading PQ data, the central server would call the substations and download information from the connected ABB relays. The system may include several substations with multiple relays and feeders connected. For clarity, the figure shows only one substation and the associated feeder equipment.

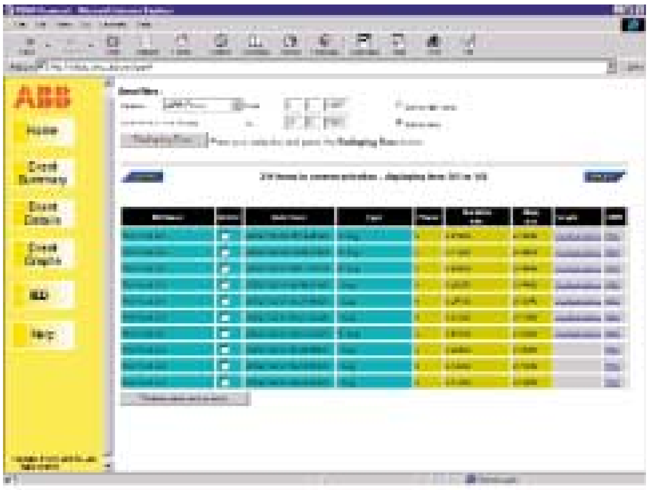
PQ monitoring in the field

An ABB PCD 2000 recloser controller protection unit with PQ functions implemented in it was installed in three industrial plants in different locations in the USA as part of a pilot project to demonstrate the system. The installations included a DCD 2000 communications node to provide modem access to the PCD 2000. The PCD 2000 samples

6 Web-based power quality application showing the event summary display with categorized data



7 Web-based event details screen, showing the PQ event date, time, classification, phase, duration, magnitude and graphics links



voltages and currents at 32 samples per cycle and has sufficient non-volatile RAM to store over 200 PQ event records with RMS trending. Oscillographic data are available for all channels for 8 cycles, but only for the last 8 events. RMS data were computed using 32 samples per cycle and are stored 4 times per cycle. The results presented here are for an industrial plant with a combination of overhead and underground feeders.

6 shows a web application displaying a summary of the power quality events as recorded by the PCD 2000. The table in the screenshot shows the number of observations for a given period of time, in the classifications specified by the IEEE 1159 definition.

The event summary provides the kind of concise information that a utility industrial account manager or other customer-relations person would find useful. It shows the name of the recording device, the date and time of the last download of information, and the count of the events in each of the IEEE classifications. The user can narrow the event filter parameters to see the last week or last day of events. This information is at a high enough level to provide quick access to the data to determine if a problem exists without being overly detailed.

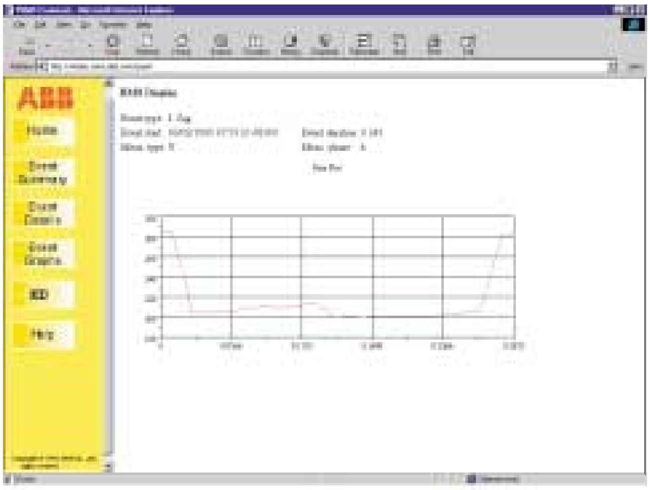
The next level of data can be found in the event details as shown in 7. This view shows the summary of each event recorded, the time of occurrence, the type as per the IEEE classifications, the phase, the duration and the magnitude. If an event of a specific duration or magnitude is the cause of a particular customer problem, then the account manager can pinpoint the event exactly. Two links allow the user to go to the RMS display or the oscillographic display when these are provided. Note that oscillographic data are only available for the first seven events displayed, while RMS graphs are available for all of the events.

RMS voltage profiles provide information for a more thorough analysis of the time-dependent characteristic of the voltage during an event. 8 shows the RMS voltage profile for the last PQ event in the event details list (the vertical axis shows the RMS line voltage, the horizontal axis the time in seconds from the event start time).

A detailed engineering analysis of the power quality event can be obtained by plotting the oscillographic record. The graph in 9 shows the phase waveform (pre-event and event condition) for the same event captured by the monitor. The vertical axis gives the voltage and the horizontal axis the clock time in seconds. Note that, in this example, the restrictions on device memory and the settings on the relay limit the size of the oscillographic waveform capture to eight cycles.

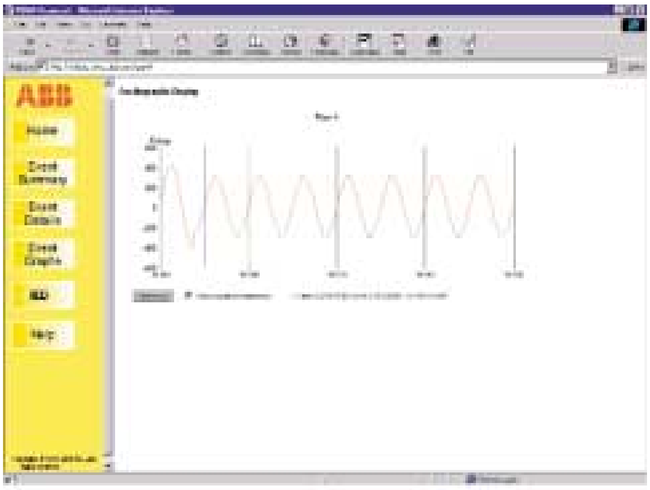
The field experience at these test sites over the past year testifies to the viability of using protective relays to measure power quality events ranging in time from sub-cycle to long-term plant outages, and demonstrates that the protective relay is

8 Web-based RMS voltage profile record



9 Web-based PQ event oscillographic display

In the figure, the oscillographic waveform begins at 07:54:38.967 and ends at 07:54:39.100 on March 2, 1999.



capable of capturing detailed information on these events. It was also shown that a majority of the power quality problems captured by the event monitors were voltage sags, and that these problems occurred more often in storm conditions.

Summing up

Advances in microprocessor technology allow extra functionality, such as PQ monitoring, to be integrated in digital protective relays and feeder equipment. These devices are commonly used throughout customers' systems, utilize familiar protocols, are hardened, and are already being maintained. The additional functionality lets utilities see power quality incidents in the system more clearly and respond more effectively to customers' needs. Benefits of integrating PQ monitoring with traditional protection and control equipment include:

- Additional or temporary PQ monitoring equipment is required less often.
- Utilization of existing assets can be optimized.
- Key account managers can access data at customers' sites with incremental additional investment.
- Utilities can respond more quickly to customer's problems.
- Trouble areas requiring in-depth PQ analysis or where maintenance is needed can be identified.
- Customers requiring utility PQ services can be identified.

References

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