POWER QUALITY AND RELIABILITY

Case studies from operation of a nationwide PQ&R monitoring system

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INDUSTRIAL AND COMMERCIAL ELECTRICITY CONSUMERS are increasingly impacted by poor power quality and reliability (PQ&R). A utility distribution system fault, even hundreds of miles away, can cause widespread voltage sags that shut down susceptible process equipment [1]. Correlating process interruptions with voltage disturbances requires prompt notification of such PQ&R events. Effective communication with the utility company and assessment of mitigation equipment options are greatly facilitated when local historical PQ&R data are available, but only if the information is put in a form that the customer can act on.

A Web-based, near real-time PQ&R monitoring system is continuing to be put in place to provide such information, both locally and on a nationwide basis [2]. Low-cost monitors record PQ&R event characteristics and, using an internal modem, transmit event data via the Internet to a central database. The database servers are a component of the system, and no additional hardware or software is needed by the end user. The monitor system infrastructure, shared by all monitor owners, provides capabilities for data aggregation and display, e-mail and pager notification, site administration, and summary reporting of the data using a Web browser.

The system provides real-time notification of PQ&R events at single or multiple facilities and access to statistical information and trends related to PQ&R events as well as voltage regulation and imbalance. A principal goal is deployment of a vast network of monitors, which cannot be accomplished unless the monitors are affordable and the infrastructure is scalable.

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The monitor system architecture allows deployment of thousands of monitors at industrial, commercial, government, and utility sites at reasonable cost. In cooperation with the U.S. Department of Energy (DOE), utilities, and leading manufacturers, the deployment of system monitors is underway, with a target deployment of over 50,000 nodes across the United States and Canada.

This article briefly reviews the system architecture and presents selected case studies from the first year of system operation, focusing here on industrial sites.

CONSUMERS AND THE UTILITY COMPANIES THAT SERVE THEM NEED ACCESS TO RELEVANT AND TIMELY PQ&R INFORMATION.

Web-Based Monitor System Overview

The end-to-end system comprises the many deployed monitors, the public telephone system, the existing nationwide network of local Internet points of presence (POPs) that bridge the gap between the telephone lines and the Internet, the Internet itself, the monitor system servers and database, and finally, the end user's Web browser. The low-cost monitors function only as an integral part of the monitor system, in which much of the intelligence is placed on the system servers. This allows for advanced data analysis, display, and aggregation capabilities, while minimizing the cost per monitoring node.

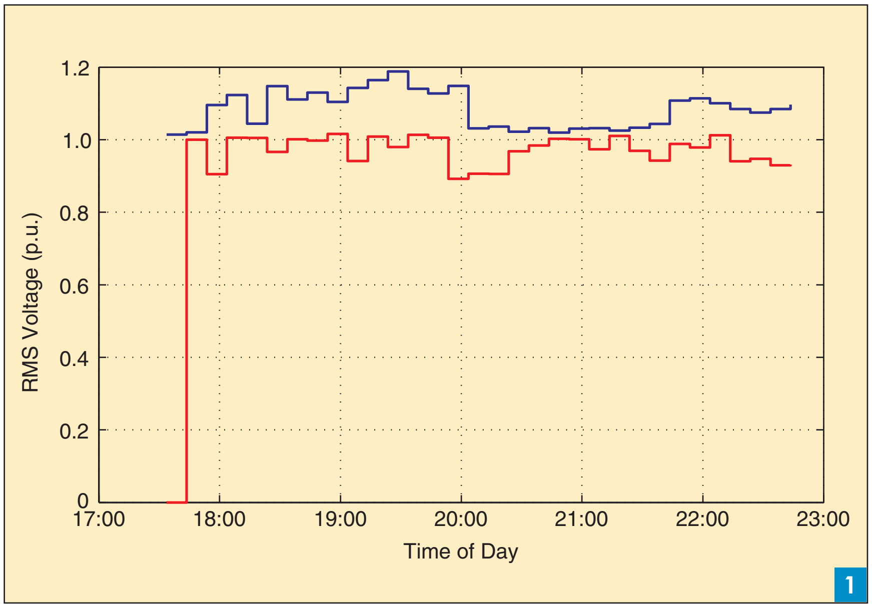
These monitors record both time stamped PQ&R event data and 10-min average rms voltages. An internal modem, together with a long-life rechargeable battery, allow the monitors to communicate data over the Internet with the central database servers, even during power interruptions. Immediately following data upload, the central servers e-mail event summary notifications to user-designated addresses. Commonly available "e-pager" services can forward these messages to alphanumeric pagers or text-capable mobile phones. The e-mail text includes a direct Web link (URL) to view detailed event waveforms on the system Web site. Both recent and historical data can be viewed at any time from any Internet-connected PC using popular Web browsers.

All system monitors are regularly synchronized with the central server, which is itself synchronized to NIST Coordinated Universal Time (UTC). Each monitor can record voltage sags and swells, brownouts, over voltages and sustained interruptions. It also has limited capability for transient monitoring. Available monitors can directly monitor single or three-phase voltages at 120, 120/208 or 480 V; 15-kV class (or higher) monitoring is accomplished using external potential transformers. Detailed system and monitor specifications were described in an earlier paper [2]. The monitor firmware is stored in flash memory and can be automatically upgraded as system improvements are developed. Nonvolatile event data memory is cleared after confirmation of successful data upload to the central database.

The end-to-end system is operational in the United States and Canada. A limited number of monitors in Singapore, Malaysia, Australia, and Brazil have verified the potential extension of this Web-based system to a worldwide monitoring network.

Monitoring System Case Studies

A prototype end-to-end PQ&R monitoring system began operating in February 2001, with approximately 30 monitoring nodes distributed around the United States. More than 10,000 event reports were transmitted to the alpha system database and Web server. The system monitors are now in normal production. More than 600 production monitors were shipped in 2002, and more than 1,100 units are now operating in 47 states. More than 30,000 PQ&R events were reported in 2002 alone; that total increased beyond 250,000 events by mid-2004.



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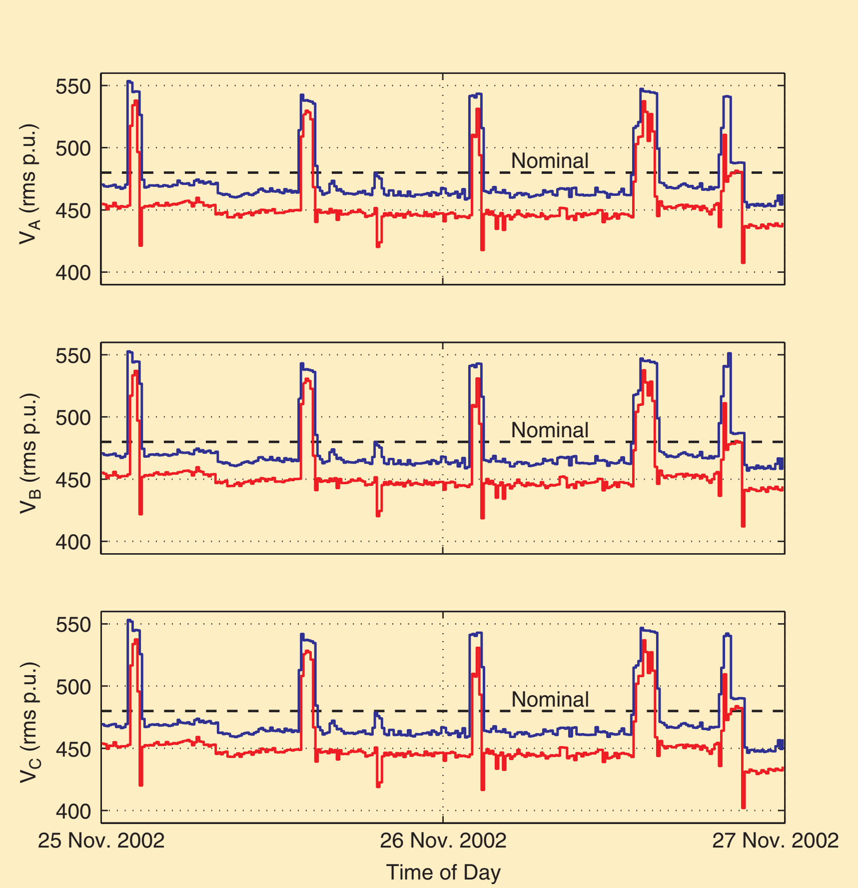
Single-phase monitor's 320-min periodic rms voltage report (June 2002): Maximum (top) and minimum (bottom) single-cycle rms voltage per 10-min period, immediately following installation.



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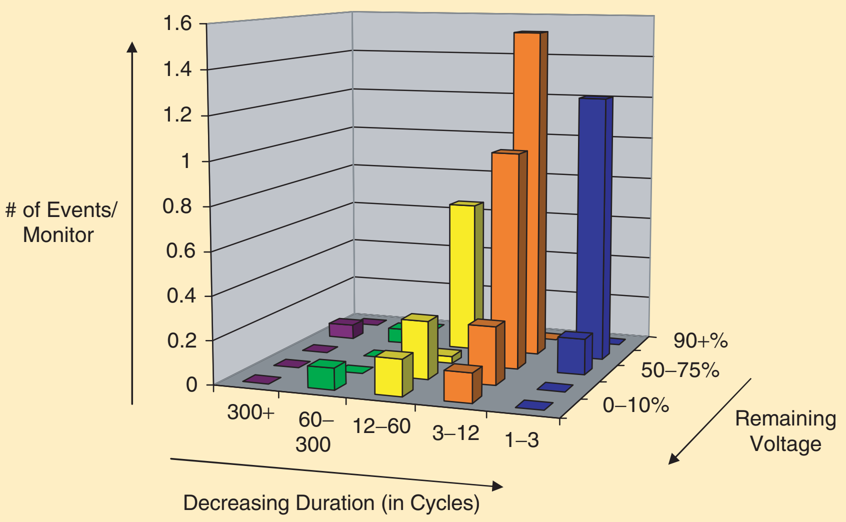
Three-phase monitor periodic rms voltage report: maximum (blue) and minimum (red) single-cycle rms voltage per 10-min period.



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Normalized PQ&R event severity density, for 32 large industrial plant monitors, over a two-month period of 2002.

Here, we discuss actual case studies from the production monitoring system. Precise dates and locations are omitted to assure monitor owners' anonymity. Voltage profile and waveform figures are identical to those on the system Web site, but are replotted here for improved resolution in print.

Tracing Facility PQ Problems

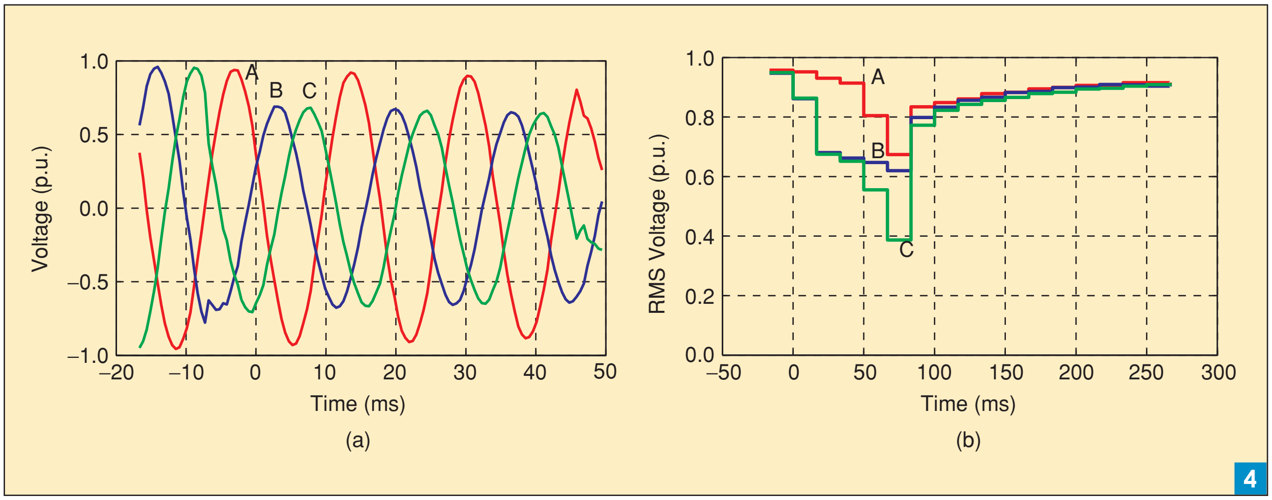
Facility Wiring Problem

PQ problems range from the occasional voltage sag to ongoing, yet intermittent, voltage variations. In one case, building tenants were experiencing continuing equipment failures on single-phase lines. In June 2002, the utility company installed a monitor at several locations throughout the building. Several voltage swell and voltage sag events were captured, yet the more telling information came from the periodic root-mean-square (rms) reports, which show the maximum and minimum rms voltages recorded in each 10-min period throughout the day. Figure 1 shows a periodic rms report over one five-hour period. Wide variation in voltage is evident.

From these reports, the utility engineer narrowed the cause to either a defective utility voltage regulator or a neutral bonding problem at the site. Subsequent investigation showed that a loose neutral wire connection at the site was the root cause of these voltage variations. A monitor system upgrade in October 2002 added 10-min average rms voltage measurements to the periodic rms records; these can be summarized to provide utility service voltage regulation and imbalance reports.

Utility Voltage Regulation Problem

A company running a seasonal 24/7 process installed monitors after experiencing repeated equipment shutdowns over several days. Periodic rms records, exemplified by Figure 2, showed that the utility supply voltage, nomi-



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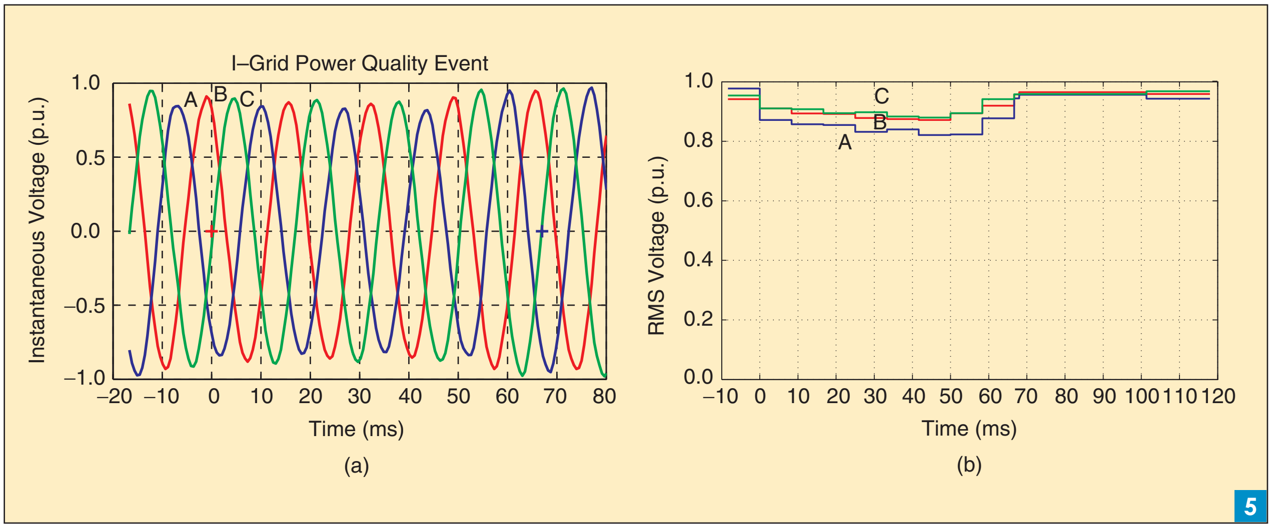
(a) Voltage waveform around event start (Summer 2002). (b) Cycle-by-cycle rms voltage profile during sag event.



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Event 1695 Detail (4 November 2002). (a) Voltage waveform. (b) RMS "voltage profile" or similar.

nally 480 V, varied from under 460 to over 530 V throughout a period of many days.

The facility engineer used this information to negotiate with the utility company, which subsequently rescheduled local substation maintenance to improve voltage regulation during the peak processing season.

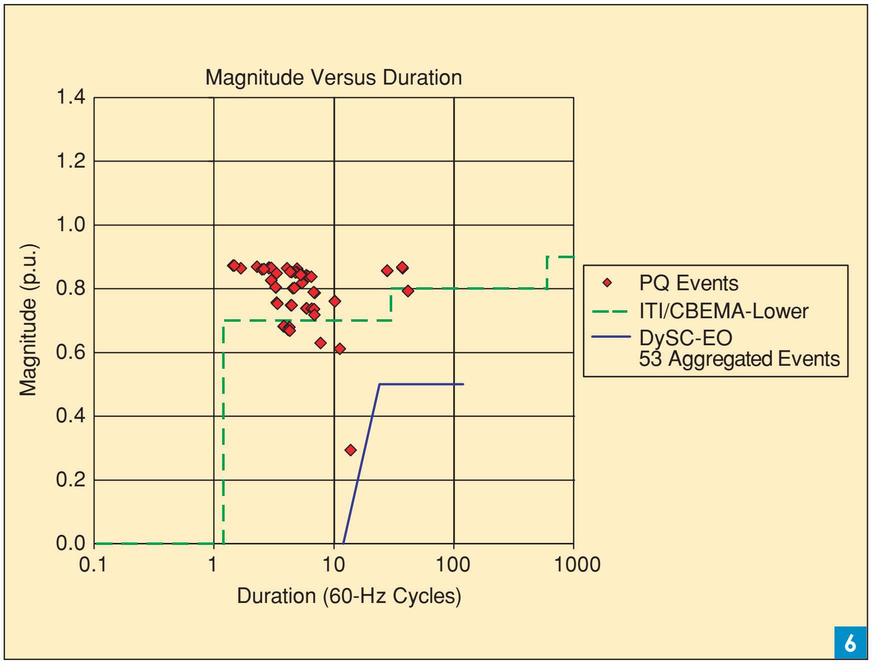
TABLE 1. VOLTAGE SAG EVENT SUMMARY DATA (SUMMER 2002).

Channel	*Min.*	*Worst Case RMS as % of Nominal*
1	72.8 V-rms	60.6%
2	74.2 V-rms	61.9%
3	35.3 V-rms	29.4%

Multiple-Facility PQ&R Statistics

Management of information on facility power systems status and history at multiple locations is simplified using a PQ&R reporting system with a central database and Internet-wide access. A number of companies with multiple facilities, many with dual feeds at transmission or subtransmission voltage, are using this monitor system. In those cases, a 120 V three-phase system monitor is connected to the preexisting service entrance potential transformers (PTs); the monitor presents less than 6 VA of load per channel to the PTs. A major manufacturer has installed over 100 monitors in this manner at its facilities across the United States and Canada, on its way to monitoring all of its North American facilities. Both local and corporate facility managers, as well as the local utility companies' account managers, receive pager notification when a PQ&R event occurs. The notification address list is distinct for each monitor site, and the notification criteria can be set separately for each address.

Data from 32 monitors at large U.S. industrial sites over a two-month period is normalized and plotted in



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MAG-DUR plot of all I-Grid events recorded over six months in 2002 at a major manufacturing location.

Figure 3 to demonstrate the relative density of the recorded voltage sag severities. It is evident that short duration shallow voltage sags are by far the most prevalent PQ&R events at these sites. This is in keeping with the basic results of the Electric Power Research Institute (EPRI) Distribution Power Quality (DPQ) Study [3] and the Canadian National Power Quality Survey [4]. Such site-specific statistics can help guide corporate investment in cost-optimal mitigation equipment, whether a backup generator, flywheel or battery UPS, or dynamic voltage sag correction device.

Individual Large Industrial Plant Monitoring

Information on a specific event from one multimegawatt manufacturing site is provided in Table 1. Figure 4(a) and (b) shows the voltage waveform at the start of the voltage sag event and the rms voltage profile throughout the event. The reported event duration is 13.8 cycles (230 ms). It is apparent from examination of Figure 4(b) that the utility system fault that caused this sag was cleared after four to five cycles (70–80 ms), yet restarting of large loads on the system kept the voltage suppressed for nine cycles (150 ms) more. The abrupt return to near-nominal voltage following a voltage sag is known to have damaging effects on motors and many power supplies [5].

Recorded waveform data spans four cycles around the event start time, one cycle before the detected start time and three cycles after, and another four cycles around the event end time, two cycles before and two cycles after. Events shorter than six cycles duration are

TABLE 2. EVENT LOG FOR WISCONSIN, 4 NOVEMBER 2002, AROUND TIME OF PLANE CRASH.

Monitor #	*Event ID*	*Local Time*	*Event Type*	*Duration*	*Worst Case RMS Voltage*	*Worst Case % of nominal*
1	111	11/4/2002 5:35:31 PM	Instantaneous Sag	5.8 Cycles	101.3	84%
2	1693	11/4/2002 5:35:32 PM	Instantaneous Sag	2.4 Cycles	417.6	87%
3	981	11/4/2002 5:35:32 PM	Instantaneous Sag	2.4 Cycles	98.9	82%
2	1694	11/4/2002 5:35:32 PM	Instantaneous Sag	2.5 Cycles	395.4	82%
4	2980	11/4/2002 5:35:32 PM	Instantaneous Sag	1 Cycles	104.4	87%
5	801	11/4/2002 5:35:32 PM	Instantaneous Sag	6.7 Cycles	99.3	83%
1	112	11/4/2002 5:35:33 PM	Instantaneous Sag	1.1 Cycles	104.9	87%
3	982	11/4/2002 5:35:33 PM	Instantaneous Sag	4.1 Cycles	96.3	80%
2	1695	11/4/2002 5:35:33 PM	Instantaneous Sag	4.1 Cycles	393.2	82%
4	2981	11/4/2002 5:35:33 PM	Instantaneous Sag	4 Cycles	100.9	84%
5	802	11/4/2002 5:35:33 PM	Instantaneous Sag	4.6 Cycles	98.4	82%
5	803	11/4/2002 5:35:36 PM	Instantaneous Sag	0.8 Cycles	107.1	89%
5	807	11/4/2002 5:42:46 PM	Instantaneous Sag	4 Cycles	102.2	85%
2	1699	11/4/2002 5:42:46 PM	Instantaneous Sag	3.8 Cycles	407.1	85%
4	2985	11/4/2002 5:42:46 PM	Instantaneous Sag	3.5 Cycles	101.4	85%

captured in their entirety. Figure 5(a) shows such a short event voltage waveform.

The ability to review historical data is critical for evaluating cost-effective solutions to PQ&R problems. Figure 6 shows a "MAG-DUR" scatter plot from the Web site, covering all events recorded in a six-month period at a major manufacturing plant. These data include the voltage sag event of Figure 4. For each recorded PQ&R event, one point is plotted for the worst-case phase voltage (the worst of the three phases). The total number of distinct three-phase events recorded over this period was 53, encompassing two monitors on site. The events from the two monitors are temporally aggregated, i.e., if both monitors reported an event in the same time window, only one point is plotted in Figure 6.

It is notable that no voltage swells or long interruptions occurred during this six-month period. Narrow voltage transients, less than 30- to 50-μs duration, are not captured by the monitors. The need for coordinated surge protection is well established, and many plants include this protection routinely. The need for sag protection is much more site dependent. For instance, this site, typical of many industrial locations, validates that a voltage sag correction device would have provided adequate process protection.

The Web site includes options for plotting the MAG-DUR data alongside standard industry voltage susceptibility curves, such as SEMI F47 [6] and ITI (CBEMA) [7].

Definite Grid Event Determination

On 4 November 2002, a single-engine aircraft struck 345-kV transmission lines near Fond du Lac, Wisconsin. Monitors located within the same transmission zone, as much as 50 miles distant, recorded resulting distribution system voltage sags. Of approximately 25 monitors deployed in Wisconsin at the time, five detected the related events as PQ events, i.e., with rms voltage falling below the voltage sag detection level, while other monitors recorded reduced minimum rms voltages in the periodic rms reports.

The system event log for Wisconsin during this period is listed in Table 2. Detail from one event, ID 1695, captured on a nominal 480 V three-phase line, is shown in Figure 5. In such a case of voltage sag on the EHV transmission system, all related 69-kV subtransmission lines will be affected as well.

Examination of event summary data from sites across a region can be used to identify "definite grid events," i.e., those PQ&R events that were definitely propagated on the utility grid, as opposed to "internal events" that are limited to a single facility. Furthermore, events with nearly simultaneous time stamps and known geographic proximity can be clustered and reported as single physical events. These powerful event clustering and data aggregation capabilities are only possible from a monitoring system with a central database. Knowledge of which events are definite grid events greatly aids in troubleshooting PQ&R problems.

Conclusions

Industrial and commercial electricity consumers and the utility companies that serve them need access to PQ&R information that is relevant and timely. From improving the utility-customer relationship to troubleshooting facility wiring problems and selecting PQ&R mitigation equipment, better and more complete information are vital to process reliability improvement efforts.

The PQ&R monitoring system described here provides the means to gain this information by removing previous cost barriers and moving system intelligence to a central computing server. The approach also allows for a monitor evaluation period to be immediately followed by scaling to company-wide deployment.

This article has presented several case studies from industry applications, providing a glimpse at the potential uses of corporate-wide PQ&R information gathering, aggregation, and reporting. The system has been independently tested by several industrial users, utilities, and EPRI-PEAC. Deployment of monitors continues through individual industrial and commercial sites, corporate and utility programs, and a cooperative program with the DOE.

System enhancements are under continual development and firmware upgrades can be automatically rolled out to all installed monitors. The system is expected to expand to cover all of North America and several overseas countries.

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