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Research Article

Challenges and Trends in Analyses of Electric Power Quality Measurement Data

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Power quality monitoring has expanded from a means to investigate customer complaints to an integral part of power system performance assessments. Besides special purpose power quality monitors, power quality data are collected from many other monitoring devices on the system (intelligent relays, revenue meters, digital fault recorders, etc.). The result is a tremendous volume of measurement data that is being collected continuously and must be analyzed to determine if there are important conclusions that can be drawn from the data. It is a significant challenge due to the wide range of characteristics involved, ranging from very slow variations in the steady state voltage to microsecond transients and high frequency distortion. This paper describes some of the problems that can be evaluated with both offline and online analyses of power quality measurement data. These applications can dramatically increase the value of power quality monitoring systems and provide the basis for ongoing research into new analysis and characterization methods and signal processing techniques.

1. INTRODUCTION

Electric power quality problems encompass a wide range of different phenomena with time scales range from tens of nanoseconds to steady state. Each of these phenomena may have a variety of different causes and, thus, require different solutions that can be used to improve the power quality and equipment performance. Many power quality (PQ) problems arise from the incompatibility in the electrical environment between the utility supply system and the equipment it serves. There are also PQ problems arising from adverse interactions between the equipment and the supply system. For instance, nonlinear loads are known to produce harmonic currents that can excite the supply system into resonance [1].

The majority of power quality problems can be characterized through measurements of voltage and current. Since PQ disturbances are relatively infrequent and the times at which they occur are unscheduled, continuous measurement or monitoring over an extended period is often required. In addition to characterizing PQ problems, PQ monitoring has been widely used to evaluate system-wide performance (benchmarking). By understanding the normal power quality performance of a system, a utility can identify abnormal characteristics (may be an indication of equipment or system problems) and can offer information to customers to help them match their sensitive equipment characteristics with realistic power quality characteristics.

Since the time scales of PQ disturbances vary widely, power monitoring instruments should ideally have the capability of capturing events ranging in frequencies from DC to a few megahertz. Many commercial power quality monitoring instruments have sampling rates of 256 samples per cycle since the majority of PQ events have frequency contents below 5 kHz [1]. The availability of high-end instruments to capture infrequent very high frequency events is limited due to technical and economical hurdles.

As more and more PQ monitors are installed in the utility and customer facilities, end-users of PQ monitors are often inundated with voluminous data. It is not uncommon that end-users undergo a “drinking from the fire hose” experience especially at the time when the analysis results of the data are most needed [2, 3]. The true value of any power quality monitoring program lies in its ability to analyze and interpret voluminous raw data, and generate actionable information to prevent PQ problems or improve the overall power quality performance. To this end, signal processing techniques in conjunction with various artificial intelligence techniques are invaluable to meet this goal.

The objective of this paper is not to present signal processing or artificial intelligent techniques, but rather to describe challenges and potential applications of signal processing techniques in turning raw PQ measurement data to a much more valuable commodity—knowledge and information to improve PQ performance. Section 2 of the paper presents online and offline monitoring approaches, while Sections 3 and 4 provide descriptions on potential applications of signal processing methods to analyze raw PQ measurement data. The applications described provide the basis for research efforts (many of which are under way around the world) to identify new and improved methods for the data analysis and development of important conclusions from the measurement data.

2. ONLINE AND OFFLINE POWER QUALITY MONITORING

As utilities and industrial customers have expanded their power quality monitoring systems, the data management, analysis, and interpretation functions have become the most significant challenges in the overall power quality monitoring effort. The shift in the use of power quality monitoring system from a traditional data acquisition system to a fully automated intelligent analysis system would tremendously increase the value of power quality monitoring as proposed in [4].

There are two streams of power quality data analysis, that is, offline and online analyses. The offline power quality data analysis, as the term suggests, is performed offline at the central processing locations. On the other hand, the online data analysis is performed within the instrument itself or immediately upon collection of the information at a central processing location. Online analysis results are very helpful to support actions that must be taken (e.g., determination of fault location from voltage and current waveforms).

Offline analyses are suitable for system performance evaluation, problem characterization, and just-in-time maintenance where rapid analysis and dissemination of analysis results are not required. Typically offline analysis is better suited to analyze steady-state data. Examples of signal processing applications include the following.

(i) RMS variation analysis which includes tabulations of voltage sags and swells, magnitude-duration scatter plots based on CBEMA, ITIC, or user-specified magnitude-duration curves, and computations of a wide range of RMS indices such as SARFI. Signal processing techniques can be used to quantify voltage sag and swell performance. Furthermore, signal processing techniques in conjunction with the load equipment models can be used to predict voltage sag impacts on sensitive equipment [5, 6].

(ii) Steady state analysis which includes trends of RMS voltages, RMS currents, negative- and zero-sequence unbalances, real and reactive power, harmonic distortion levels and individual harmonic components, and so forth. In addition, many software systems provide statistical analysis of various minimum, average, maximum, standard deviation, count, cumulative probability levels. Statistics can be temporally aggregated and dynamically filtered. Figures 1 and 2 show the time trend of phase A RMS voltage along with its histogram representation. Using such steady-state data, statistical signal processing can be used to predict performance or the health condition of voltage regulators on distribution circuits [7].

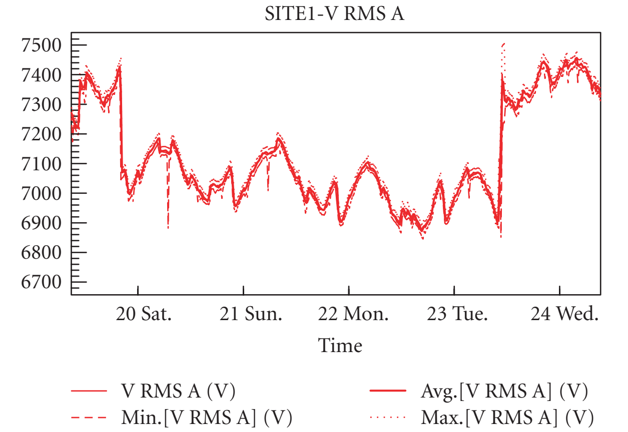


Figure 1: Time trend of an RMS voltage is a standard feature in many PQ analysis software packages.

(iii) Harmonic analysis where users can calculate voltage and current harmonic spectra, statistical analysis of various harmonic indices, and trending over time. Such analyses can be very useful to identify excessive harmonic distortion on power systems as a function of system characteristics (resonance conditions) and load characteristics.

(iv) Transient analysis which includes statistical analysis of maximum voltage, transient durations, and transient frequency. These analyses can indicate switching problems with equipment such as capacitor banks.

(v) Standardized power quality reports (e.g., daily reports, monthly reports, statistical performance reports, executive summaries, customer PQ summaries).

(vi) Analysis of protective device operation.

(vii) Analysis of energy use.

(viii) Correlation of power quality levels or energy use with important parameters (e.g., voltage sag performance versus lightning flash density).

(ix) Equipment performance as a function of power quality levels (equipment sensitivity reports).

Online power quality data assessment involves analysis of data as they are captured. The analysis results are available immediately for rapid dissemination. Complexity in software design requirement for online assessment is usually higher than that of offline. Most features available in offline analysis

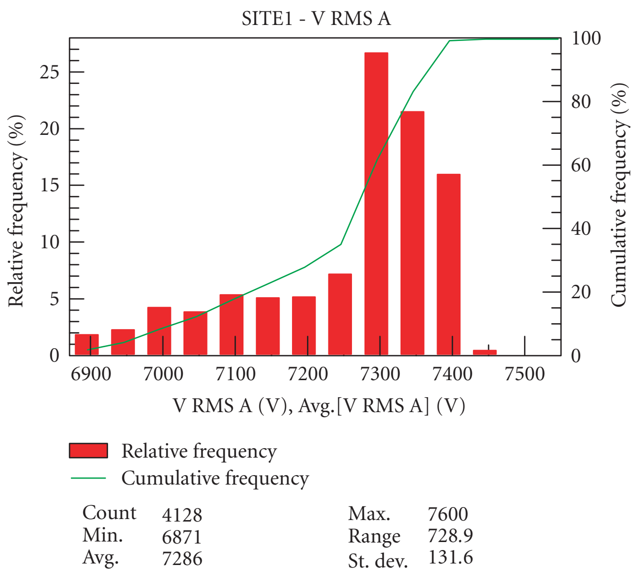


Figure 2: Histogram representation of RMS voltage indicates the statistical distribution of the RMS voltage magnitude.

software can also be made available in an online system. One of the primary advantages of online data analysis is that it can provide instant message delivery to notify users of specific events of interest. Users can then take immediate actions upon receiving the notifications. An excellent example of an online analysis is for locating a fault on a distribution circuit. Signal processing techniques would be used to extract and analyze voltage and current waveforms. The analysis would reveal the fault location and this information would be disseminated quickly to the line crew [8].

3. POTENTIAL FUTURE APPLICATIONS

Signal processing techniques would be very useful in developing various applications of power quality data analysis. Some of the more important applications are listed in this section. The examples described in the previous section are also included in this listing.

3.1. *Industrial power quality monitoring applications*

(i) Energy and demand profiling with identification of opportunities for energy savings and demand reduction.
(ii) Harmonics evaluations to identify transformer loading concerns, sources of harmonics, problems indicating misoperation of equipment (such as converters), and resonance concerns associated with power factor correction.
(iii) Unbalance voltage profiling to identify impacts on three phase motor heating and loss of life.
(iv) Voltage sag impacts evaluation to identify sensitive equipment and possible opportunities for process ride through improvement.
(v) Power factor correction evaluation to identify proper operation of capacitor banks, switching concerns, resonance concerns, and optimizing performance to minimize electric bills.
(vi) Motor starting evaluation to identify switching problems, inrush current concerns, and protection device operation.
(vii) Profiling of voltage variations (flicker) to identify load switching and load performance problems.
(viii) Short circuit protection evaluation to evaluate proper operation of protective devices based on short circuit current characteristics, time-current curves, and so forth.

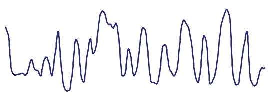
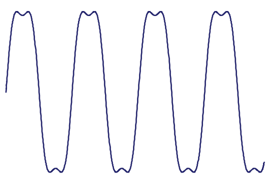
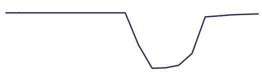
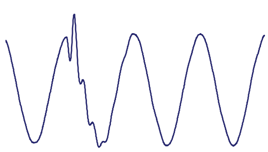
3.2. *Power system performance assessment and benchmarking*

(i) Trending and analysis of steady-state power quality parameters (voltage regulation, unbalance, flicker, harmonics) for performance trends, correlation with system conditions (capacitor banks, generation, loading, etc.), and identification of conditions that need attention.
(ii) Evaluation of steady state power quality with respect to national and international standards. Most of these standards involve specification of power quality performance requirements in terms of statistical power quality characteristics.
(iii) Voltage sag characterizing and assessment to identify the cause of the voltage sags (transmission or distribution) and to characterize the events for classification and analysis (including aggregation of multiple events and identification of subevents for analysis with respect to protective device operations).
(iv) Capacitor switching characterizing to identify the source of the transient (upline or downline), locate the capacitor bank, and characterize the events for database management and analysis.
(v) Performance indices calculation and reporting for system benchmarking purposes and for prioritizing of system maintenance and improvement investments.

3.3. *Applications for system maintenance/ operations/reliability*

(i) Locating faults. This is one of the most important benefits of the monitoring systems. It can improve response time for repairing circuits dramatically and also identify problem conditions related to multiple faults over time in the same location.
(ii) Capacitor bank performance assessment. Smart applications can identify fuse blowing, can failures, switch problems (restrikes, reignitions), and resonance concerns.
(iii) Voltage regulator performance assessment to identify unusual operations, arcing problems, regulation problems, and so forth. This can be accomplished with

Table 1: Summary of monitoring requirements for different types of power quality variations.

Type of power quality variation		Requirements for monitoring	Analysis and display requirements
Voltage regulation and unbalance		• 3 phase voltages • RMS magnitudes • Continuous monitoring with periodic max./min./avg. samples • Currents for response of equipment	• Trending • Statistical evaluation of voltage levels and unbalance levels
Harmonic distortion		• 3 phase voltages and currents • Waveform characteristics • 128 samples per cycle minimum • Synchronized sampling of all voltages and currents • Configurable sampling characteristics	• Individual waveforms and FFTs • Trends of harmonic levels (THD and individual harmonics) • Statistical characteristics of harmonic levels • Evaluation of neutral conductor loading issues • Evaluation with respect to standards (e.g., IEEE 519, EN 50160) • Evaluation of trends to indicate equipment problems
Voltage sags, swells, and short duration interruptions		• 3 phase voltages and currents for each event that is captured • Configurable thresholds for triggering events • Characteristics of events with actual voltage and current waveforms, as well as RMS versus time plots • RMS resolution of 1 cycle or better during the RMS versus time events and for triggering	• Waveform plots and RMS versus time plots with pre- and post-event information included • Evaluation of cause of each event (fault upline or downline from the monitoring). • Voltages and currents to evaluate load interaction issues • Magnitude duration plots superimposed with equipment ride through characteristics (e.g., ITIC curve or SEMI curve) • Statistical summary of performance (e.g., bar charts) for benchmarking • Evaluation of power conditioning equipment performance during events
Transients		• 3 phase voltages and currents with complete waveforms • Minimum of 128 samples per cycle for events from the power supply system (e.g., capacitor switching) • Configurable thresholds for triggering • Triggering based on waveform variations, not just peak voltage	• Waveform plots • Evaluation of event causes (e.g., capacitor switching upline or downline from monitor) • Correlation of events with switching operations • Statistical summaries of transient performance for benchmarking

trending and associated analysis of unbalance, voltage profiles, and voltage variations.

(iv) Distributed generator performance assessment. Smart systems should identify interconnection issues, such as protective device coordination problems, harmonic injection concerns, islanding problems, and so forth.

(v) Incipient fault identifier. Research has shown that cable faults and arrester faults are often preceded by current discharges that occur weeks before the actual failure. This is an ideal expert system application for the monitoring system.

(vi) Transformer loading assessment can evaluate transformer loss of life issues related to loading and can also include harmonic loading impacts in the calculations.

(vii) Feeder breaker performance assessment can identify coordination problems, proper operation for short circuit conditions, nuisance tripping, and so forth.

4. SUMMARY AND FUTURE DIRECTION

Power quality monitoring is fast becoming an integral part of a general distribution system monitoring, as well as an important customer service. Power producers are integrating power quality monitoring with monitoring for energy management, evaluation of protective device operation, and distribution automation functions. The power quality information should be available throughout the company via the intranet and should be made available to customers for evaluation of facility power conditioning requirements.

The power quality information should be analyzed and summarized in a form that can be used to prioritize system expenditures and to help customers understand the system performance. Therefore, power quality indices should be based on customer equipment sensitivity. The SARFI indices for voltage sags are excellent examples of this concept.

Power quality encompasses a wide range of conditions and disturbances. Therefore, the requirements for the monitoring system can be quite substantial, as described in this chapter. Table 1 summarizes the basic requirements as a function of the different types of power quality variations.

The information from power quality monitoring systems can help improve the efficiency of operating the system and the reliability of customer operations. These are benefits that cannot be ignored. The capabilities and applications for power quality monitors are continually evolving.

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