CONSIDERATIONS FOR A WIDE-AREA POWER QUALITY MONITORING SYSTEM

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ABSTRACT

Power quality monitoring has evolved from device-specific analysis of an event to system-wide benchmarking and reporting. Whether implementing power quality improvements for customer satisfaction or to comply with regulatory requirements, utilities need advanced software systems to reduce analysis time, ease reporting and demonstrate the return on investment. This paper describes the necessary components of a wide-area power quality analysis system including monitors, communication channels, data validation software, user interface needs and reporting features. Means of addressing potential pitfalls such as late- or missing-data, biasing statistical results due to planned outages and over-counting power quality events are presented. The system described allows for power quality benchmarking to industry standards such as EN50160 and trending of key performance indicators to show improvements over time.

THE NEED FOR IMPROVED AWARENESS

While the 2003 blackouts in Europe and America brought media attention to power quality and reliability, the need for increased awareness of the state of the grid has been growing for much longer and with much less dramatic symptoms. As new distorting loads are added, system total harmonic distortion (THD) increases, degrading the life of both industrial and consumer hardware and approaching fuse limits. Rapid voltage changes (Flicker) at the edge of human perception lead to eye strain and reduced worker productivity. And an immediate cost is borne by the economy, where the U.S. Department of Energy estimates that "power outages and power quality disturbances cost the economy from $25 to $180 billion annually. There are also operational problems in maintaining voltage levels."[1] In Europe, total cost of power quality has been estimated at over 150 B€ [2].

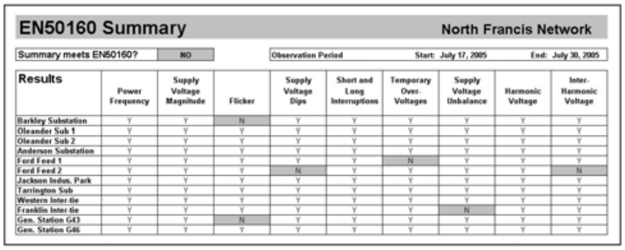
If this economic loss is to be reduced, we must first understand the state of the grid today. To gather the necessary intelligence, a *Wide-Area Power Quality analysis* (WAPQ) system uses power quality monitors distributed throughout the grid to monitor, record and in some cases alarm on power quality phenomena. While this level of monitoring is useful for a minute-to-minute operational view, system software is required to deal with the volume of data and convert it to actionable information.

In addition to the information obtained on overall grid status, a WAPQ system improves the ability of power quality departments to respond to customer complaints. Portable or temporarily installed power quality monitors have been used for this analysis in the past. When the problem observed by the customer was caused by a quasi-stationary and persistent condition, such as harmonics, or by periodic events, such as line-switching or motor start-up, installing a portable PQ monitor and evaluating its data would provide the necessary information to the customer. This approach, however, is not effective for spurious events which may not repeat after the installation of the portable device. Without information on these events, it is not possible to evaluate the source of a problem or the potential damage such an event may have caused to equipment.

WAPQ systems can be effectively used to address one or more of three main needs: Standards compliance, System reliability improvements, and Customer satisfaction.

1. Standards Compliance

Compliance reporting against an established standard allows for a simple view of system performance. For each PQ parameter, a Yes/No or Pass/Fail indication can be generated, making evaluation easy and efficient (Figure 1).



EN50160 Summary North Francis Network

Summary meets EN50160? NO

Observation Period Start: July 17, 2005 End: July 30, 2005

Results	Power Frequency	Supply Voltage Magnitude	Flicker	Supply Voltage Dips	Short and Long Interruptions	Temporary Over-Voltages	Supply Voltage Unbalance	Harmonic Voltage	Inter-Harmonic Voltage
Barkley Substation	Y	Y	N	Y	Y	Y	Y	Y	Y
Oleander Sub 1	Y	Y	Y	Y	Y	Y	Y	Y	Y
Oleander Sub 2	Y	Y	Y	Y	Y	Y	Y	Y	Y
Anderson Substation	Y	Y	Y	Y	Y	Y	Y	Y	Y
Ford Feed 1	Y	Y	Y	Y	Y	N	Y	Y	Y
Ford Feed 2	Y	Y	Y	N	Y	Y	Y	Y	N
Jackson Indus. Park	Y	Y	Y	Y	Y	Y	Y	Y	Y
Tarrington Sub	Y	Y	Y	Y	Y	Y	Y	Y	Y
Western Inter-tie	Y	Y	Y	Y	Y	Y	Y	Y	Y
Franklin Inter-tie	Y	Y	Y	Y	Y	Y	N	Y	Y
Gen. Station G43	Y	Y	N	Y	Y	Y	Y	Y	Y
Gen. Station G46	Y	Y	Y	Y	Y	Y	Y	Y	Y

Figure 1 Compliance reports quickly identify trouble spots

Some of the commonly used standards are:

EN50160 with IEC 61000-4-30

The EN50160 [3] standard provides a statistical model for evaluating power quality compliance against the following phenomena: supply voltage, frequency, flicker, sags, swells, long and short interruptions, harmonic distortion, interharmonic distortion and voltage unbalance. It is important to note that EN50160 does not define *how* the parameters themselves are measured. A standard such as IEC 61000-4-30 [4] should be used so that all parties involved can have confidence in the results, and so that all compliant monitors in the system will produce the same results when observing the same signal.

SARFI

The System Average RMS Frequency Index, or SARFI, can be used to count the number of times that system RMS voltage drops below or exceeds an established threshold, expressed as a percentage of nominal voltage.

Potential problems: Data Integrity – planning for late or lost data

A common misconception of permanently installed systems is that all data will be returned to the master software. However, communications may be interrupted by planned maintenance, damaged or disconnected media, interruptions in the 3rd party network (telco or WAN), or the removal from service of a PQ monitor.

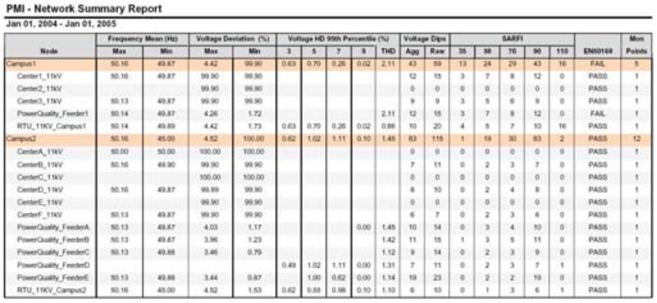
To deal with the reality of lost data, system indices (SARFI, etc) should be weighted to include the number of monitors reporting. For late data, ensure that the system is designed to poll the database immediately prior to running a scheduled report so that as much valid data as possible is included. For any system, communications diagnostics at the server level will both identify problems within the system and provide confidence in the data being reported.

2. System reliability improvements

For system reliability improvements, the pass/fail indications sufficient for compliance reporting will not provide information early enough to affect results. *System trending* of PQ parameters, *real-time alarming*, and *post-event analysis* may all be used to provide information and justification for reliability improvements.

System Trending

By recording and trending the underlying PQ values themselves, rather than merely the pass/fail indication, users may determine whether the system is static, improving or declining. If system trending is implemented, measures may be taken that can prevent future failures by delivering performance metrics that indicate increasing risk. Examples include high levels of electrical harmonics that can adversely effect normal equipment operation, or a load trend that shows the possibility of a circuit being overburdened if more equipment is added. A concise view of the grid can be obtained using a combination of compliance pass/fail information and trend data (Figure 2).



PMI - Network Summary Report

Jan 01, 2004 - Jan 01, 2005

Node	Frequency Mean (Hz)		Voltage Deviation (%)		Voltage HD 95th Percentile (%)					Voltage Dips		SARFI					EN50160	Mon
	Max	Min	Max	Min	3	5	7	9	THD	Agg	Raw	35	50	70	90	110		Points
Campus1	50.16	49.87	4.42	99.90	0.63	0.70	0.26	0.02	2.11	43	59	13	24	29	43	16	FAIL	5
Center1_11kV	50.16	49.87	99.90	99.90						12	15	3	7	8	12	0	PASS	1
Center2_11kV			99.90	99.90						0	0	0	0	0	0	0	PASS	1
Center3_11kV	50.13	49.87	99.90	99.90						9	9	3	5	6	9	0	PASS	1
PowerQuality_Feeder1	50.14	49.87	4.26	1.72					2.11	12	15	3	7	8	12	0	FAIL	1
RTU_11KV_Campus1	50.14	49.89	4.42	1.73	0.63	0.70	0.26	0.02	0.88	10	20	4	5	7	10	16	PASS	1
Campus2	50.16	45.00	4.52	100.00	0.62	1.02	1.11	0.10	1.45	83	116	1	19	30	83	2	PASS	12
CenterA_11kV	50.00	50.00	100.00	100.00						0	0	0	0	0	0	0	PASS	1
CenterB_11kV	50.16	49.90	99.90	99.90						7	11	0	2	3	7	0	PASS	1
CenterC_11kV			100.00	100.00						0	0	0	0	0	0	0	PASS	1
CenterD_11kV	50.16	49.87	99.89	99.90						8	10	0	2	4	8	0	PASS	1
CenterE_11kV			99.90	99.90						0	0	0	0	0	0	0	PASS	1
CenterF_11kV	50.13	49.87	99.90	99.90						6	7	0	2	3	6	0	PASS	1
PowerQuality_FeederA	50.13	49.87	4.03	1.17				0.00	1.45	10	14	0	3	4	10	0	PASS	1
PowerQuality_FeederB	50.13	49.87	3.96	1.23					1.42	11	15	1	3	5	11	0	PASS	1
PowerQuality_FeederC	50.13	49.88	3.46	0.79					1.12	9	14	0	2	3	9	0	PASS	1
PowerQuality_FeederD					0.49	1.02	1.11	0.00	1.31	7	11	0	2	3	7	1	PASS	1
PowerQuality_FeederE	50.13	49.88	3.44	0.87		1.00	0.62	0.00	1.14	19	23	0	2	2	19	0	PASS	1
RTU_11KV_Campus2	50.16	45.00	4.52	1.53	0.62	0.55	0.98	0.10	1.10	6	10	0	1	3	6	1	PASS	1

Figure 2 A network summary provides a concise view of system power quality

Potential problems: Data Integrity – biased results and double-counting

System trending provides an opportunity for preventative action but introduces an additional requirement for the system software. Unless designed into the system, planned outages will bias the statistical trend. A data aggregation algorithm must be developed so that these events are not overemphasized. If the values being obtained by the PQ monitors are not *flagged*, the trend will be biased by the worst values during an outage. For example, an outage will cause the 10-minute parameters such as voltages and harmonics to be significantly different from their normal steady state values, invalidating the statistically summarized data.

Therefore, a filtering mechanism is needed to exclude invalid 10-minute data from being considered for the statistical reduction process. The obvious solution is to adapt an approach similar to the IEC 61000-4-30 flagging concept whereby the value under consideration, for example flicker, should be excluded from evaluation against the flicker threshold if it was logged in an interval which experienced a voltage sag, swell or interruption (Figure 3).

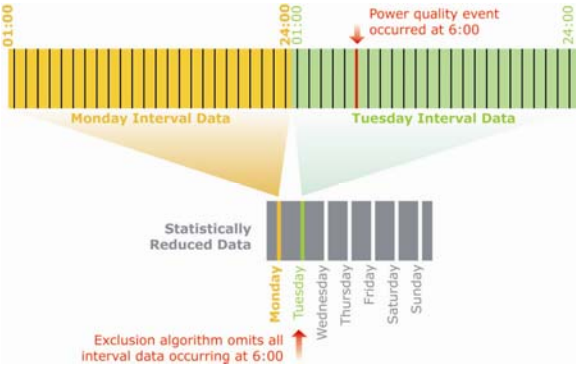


Figure 3 Using an exclusion algorithm to avoid double-counting

It is important to note that the 10-minute data should only be excluded from the statistical reduction process but not for historical trending. If a user were to trend the data, one should be able to observe the outage in such a trend.

Post-Event Analysis

Further improvements to system reliability may be obtained through detailed post-event analysis. This procedure is similar to that used with portable devices with two notable advantages: the system is always in place (so that all events are captured) and event aggregation intelligently reduces the number of data points to analyze.

Post-event analysis can be used to determine the root cause of the power quality event and to provide recommendations to avoid similar events in the future. An estimation of equipment damage and recommendations for upgrade or maintenance can also be obtained.

To obtain maximum benefit from post-event analysis, it is important to ensure that the system design includes monitors and software capable of recording and displaying both voltage and current waveform recordings. If both are available, the direction and often the cause of the event can be determined from the captured data.

Real-time Alarming

Implementing a Real-time alarming system helps utility staff easily keep on top of all active and passive distribution paths, simultaneously. It facilitates this through two complimentary methods of operational management:

Active. The system delivers a real-time "state of the grid" view at a glance. It provides comprehensive overview snapshots of the grid and detailed information at the substation and feeder levels. It can also "push" regular status updates to staff. Geographical views may also be used to observe the effects of PQ phenomena as they migrate throughout the system (Figure 4).

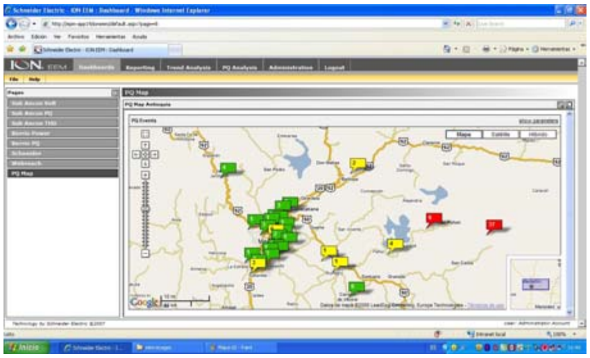


Figure 4 PQ system map showing geographical view of events

Reactive. The system delivers immediate notification of critical conditions to the right personnel, wherever they are. Staff can respond quickly and trigger recovery strategy processes when, for example, a circuit nears critical limits, excessive heat is sensed, or when equipment or circuits fail. Key data is logged to enable users to perform root cause and fault analysis, pinpoint the causes and effects of an anomaly, fix the problem and keep it from happening again.

Event Aggregation

Event aggregation is a necessary component of a WAPQ system in which large numbers of PQ monitors are being used. In these environments system events will be detected by multiple monitors, leading to an avalanche of data from which it is difficult to extract useful information. Event aggregation is an automated method that reduces the number of events requiring analysis by linking related events in the database and displaying only a single representative event.

The simplest method of event aggregation is temporal aggregation, where any event within a specified time of the first detected event is aggregated with that first event (Figure 5). The time window is typically 60 seconds, based on results from EPRI's Distribution Power Quality report. When aggregated, the most severe event is chosen for display.

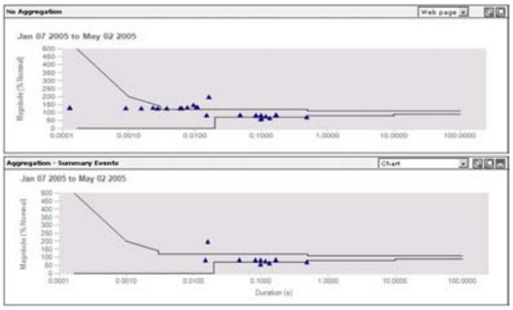


Figure 5 Temporal PQ event aggregation

The choice of which event is most severe is typically based on either the largest deviation from nominal voltage, or on the event representing the largest energy loss. However, this form of aggregation can miss important information.

Consider a voltage sag that is 75% of nominal. As loads are dropped during the sag, it is possible that a swell will immediately follow that rises to 115%. Temporal-only aggregation will link both events in the database but will display only the 70% sag, as it represents the higher deviation from nominal. In this case valuable information is missed, as the 115% swell may cause more severe equipment damage but is 'hidden' within the system, invisible to the operator.

If this is a concern, consider an aggregation method where temporal aggregation is used but where sags and swells may not be combined (Figure 6). This would result in two events within the system; a 25% sag event and a 15% swell event. Any additional sags or swells within the first 60s would be included in the two aggregated events.

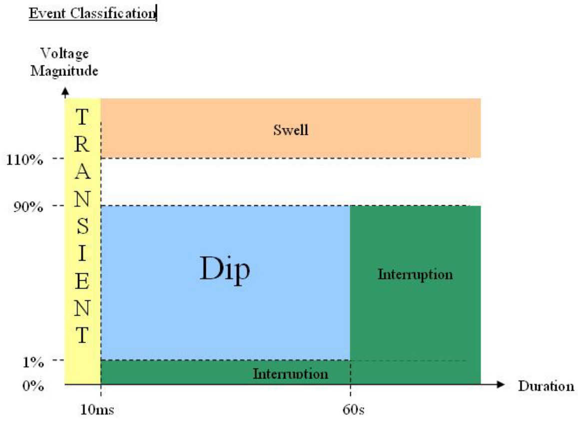


Figure 6: Temporal aggregation by event type

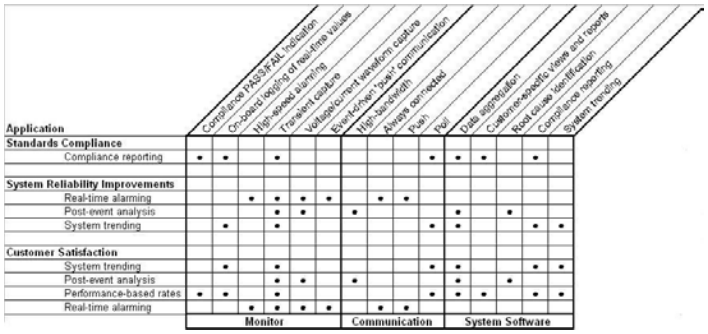
3. Customer satisfaction and competitive advantage

To improve customer satisfaction, and thereby gain competitive advantage, system trending, post-event analysis and real-time alarming as described above can all be provided as value-added services.

Additionally, a WAPQ system introduces the opportunity for establishing performance-based rates. Once a utility understands the capability of its transmission and distribution network, a performance guarantee may be established with the customer in return for a premium surcharge. Performance criteria can also be established on the customer's side, for example a requirement can be imposed on the customer to keep below certain limits of current harmonic distortion. The establishment of these rates allows both the utility and the customer to recoup costs associated with poor power quality.

SYSTEM DESIGN FOR MULTIPLE APPLICATIONS

Once the features for the initial requirement of the WAPQ system have been specified, complementary applications may be identified using a matrix similar to the one shown in Table 1. If the initial requirement is for PQ compliance monitoring, Table 1 shows that if event-driven "push" communications requirements are added to the monitor specifications and a long-term trending requirement is added to the software specifications, minimal added cost will put all of the necessary features for performance-based rates in place.



Application	Compliance PASS/FAIL indication	On-board logging of real-time values	High-speed alarming	Transient capture	Voltage/current waveform capture	Event-driven 'push' communication	High-bandwidth	Always connected	Push	Poll	Data aggregation	Customer-specific views and reports	Root cause identification	Compliance reporting	System trending
Standards Compliance															
Compliance reporting	•	•		•						•	•	•		•	
System Reliability Improvements															
Real-time alarming			•	•	•	•		•	•						
Post-event analysis				•	•		•				•		•		
System trending		•		•						•	•			•	•
Customer Satisfaction															
System trending		•		•						•	•			•	•
Post-event analysis				•	•		•				•		•		
Performance-based rates	•	•		•						•	•	•		•	•
Real-time alarming			•	•	•	•		•	•						
	Monitor						Communication				System Software				

Table 1 Requirements matrix by application

CONCLUSION

The first step in mitigating power quality problems is to understand regional system behavior through a permanently-installed, always-on wide-area power quality analysis system.

A wide-area power quality analysis system can provide valuable information to multiple departments within a utility. Whether the initial driver for implementation of such a system is compliance monitoring, system reliability or customer satisfaction, many of the infrastructure costs and information provided can be leveraged by a complementary application. For this reason it is prudent to examine all possible uses of the WAPQ system early in the design stage.

At this crucial point, a minimal increase in cost may result in a significant economic advantage. Identifying other stakeholders within the organization who could benefit from the information provided by the WAPQ system may provide a more comprehensive system with a higher return on investment.

REFERENCES

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[4] IEC 61000-4-30 Edition 2, 2008, "Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods"