Power quality

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With equipment and energy costs rapidly rising, it's hard to stress enough the importance of power quality. Power quality issues can severely hamper production processes, damage costly equipment and lower productivity. A number of factors can cause power quality problems, including equipment problems, faulty lines, lightning and other severe weather conditions. These problems could be avoided through examining infrastructure requirements, protection, test and monitoring tools, and reviewing existing maintenance practices. A proactive approach to power quality issues will not only help businesses achieve cost savings and improve equipment performance but also improve network reliability and energy efficiency. This eBook features insightful articles on power quality challenges, managing and reporting problems, improving efficiencies and reducing costs. We hope it helps you make better business decisions, and improve productivity and network reliability.

Mansi Gandhi
Editor — *Electrical Solutions*

The power factor effect

How reactive and nonlinear load affect energy efficiency

Glenn Johnson, Editor, What's New in Process Technology

Technology such as variable speed drives allows us to save energy from motor applications, but electrical energy efficiency is not just about speed control. Non-unity power factor loads and harmonic distortion increase energy losses in the power distribution network and increase infrastructure costs.

The effect on power network infrastructure of non-unity power factor loads and harmonics has been increasing in recent years. Previously these loads were mostly linear (direct connected motors) and with minimal harmonic distortion, but the increase in the use of inverter drives in industry and other forms of commercial and domestic electronics in the form of fluorescent lighting and switchmode power supplies for electronic equipment such as computers has led to a sharp increase in harmonic distortion, and a decrease in energy efficiency.

This article is intended as a 'refresher' on non-unity power factor loads, both linear and nonlinear, and why they are detrimental to energy efficiency goals.

Power factor

In an AC electrical circuit, the power factor is defined as the ratio of the real power reaching the load to the apparent power in the circuit and is a dimensionless number between 0 and 1. Real power is the capacity of the circuit to perform work (for example, the capacity for the electrical energy to be converted to rotational motion in a motor), while apparent power is the simple product of the current and voltage in the circuit (simple Ohm's law).

The causes of the difference between real and apparent power are:

- the phase shift between current and voltage caused by a reactive (non-resistive) load;
- the non-fundamental harmonics (distortion) caused by non-linear loads such as rectifiers and inverters.

Both of these causes result in energy flowing in the circuit which is not used to do useful work at the load, but which is nevertheless consumed from the power supply grid. In other words, a load with a low power factor (closer to 0) draws more current from the supply than a load with a high power factor (close to or equal to 1) for the same amount of useful power transferred. The resulting higher current results in higher voltage drops in the circuit, and higher costs of delivery (such as larger cable), and usually results in larger electricity charges to the consumer.

Linear loads

In a purely resistive circuit (such as a simple filament lamp load), the current waveform is undistorted and in phase with the voltage supply (phase angle $\phi = 0°$ - see Figure 1). In this case the apparent power and real power are the same and all the energy is transferred to the load (with the exception of a small voltage drop and power loss in the cables delivering the current).

When reactive loads such as capacitors or inductors are present, energy stored in the load results in a phase shift between the current and voltage waveforms ($\phi \neq 0°$ - see Figure 2). The energy stored in the load is returned to the grid in each cycle after a delay. This stored energy is not producing useful work, and its flow is therefore referred to as reactive power.

In the case of a purely sinusoidal waveform as shown in Figures 1 and 2, the relationship between apparent power, real power and reactive power is a vector triangle such that:

$$S^2 = P^2 + Q^2$$

where: S = complex power ($|S|$ = apparent power) in volt-amperes (VA) P = real power in Watts (W) Q = reactive power in volt-amperes reactive (VAR)

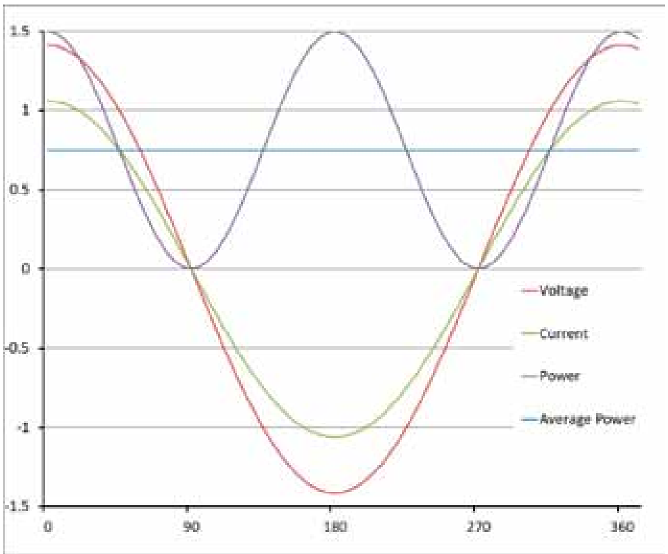

Figure 1: A purely resistive load (φ=0°) results in a unity power factor and all the power is delivered to the load.

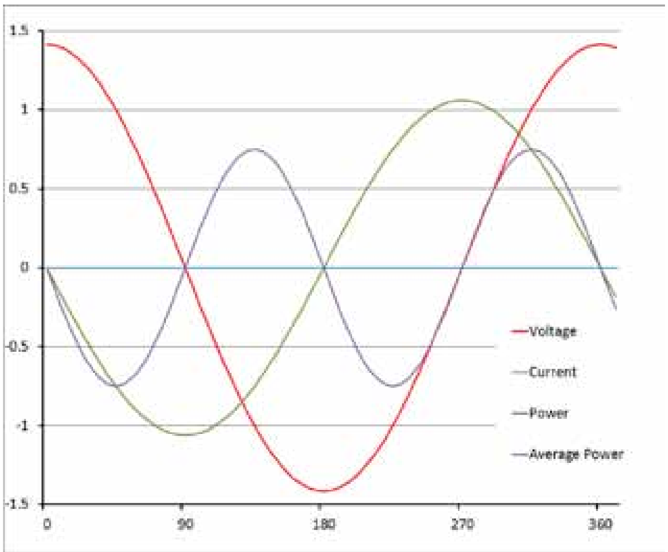

Figure 2: A purely reactive load (φ=90°) results in a zero power factor and no real power delivered to the load.

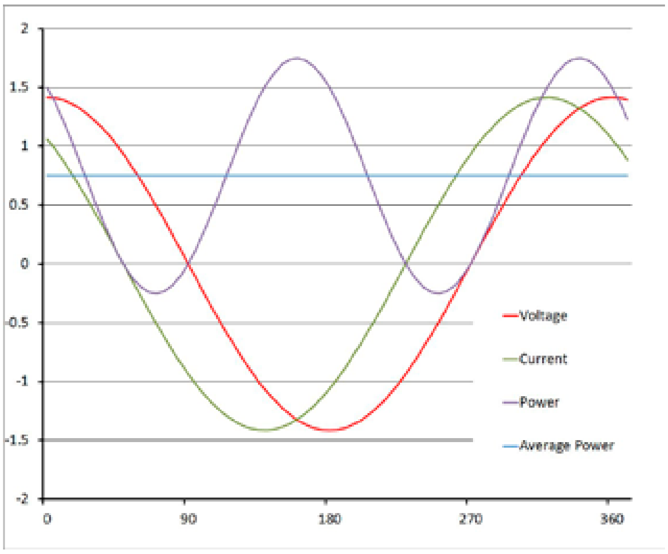

Figure 3: A real reactive load may typically result in a phase shift of φ=40° (PF ~ 0.8) and requires a larger peak current to deliver the same real power compared to the resistive load of Figure 1.

The power factor is the ratio of the real power to the apparent power, and since this is a vector triangle (phasor) relationship, the power factor is equal to the cosine of the phase shift between current and voltage, |*cos* ϕ|, and:

$$|P| = |S||\cos\varphi|$$

This type of linear power factor, arising only from the difference in phase between the current and voltage, is also known as ***displacement power factor***, to differentiate it from the power factor produced by nonlinear loads as described below.

Real-world loads consume both real and reactive power, but only the real power delivers work. For example, if a 1 kW load has an equally resistive and reactive component and results in a phase angle of 40° (Figure 3), then the power factor will be ***cos*** ϕ = 0.8 and the apparent power will be 1.41 kVA. The additional apparent power must be produced and delivered by the supply and results in larger distribution losses.

Linear power factor correction

The most common type of real loads in industry are inductive, usually motors or other types of electromagnetic actuator. Inductive loads, storing energy in a magnetic field, cause the current waveform to ***lag*** the voltage waveform. This can be offset by the use of a purely capacitive load in parallel with the inductive load, since the capacitor (storing energy in an electric field in its dielectric) causes the current waveform to ***lead*** the voltage waveform. Sizing the capacitive reactance to match the inductive reactance of the real load will cancel it out and reduce or eliminate the reactive power consumed by returning the power factor to 1.

All this is fine while the load is operating. If the motor is switched off, then the capacitors need to also be removed from the circuit so they do not consume reactive power themselves. In the case where power factor correction is applied across a system of loads (such as multiple motors), then the amount of correction needs to be switched/adjusted as the loads go on- and offline. Incorrect power factor correction in such a system can result in resonance in the electrical network and instability. In large sites, such as steel mills, other techniques are often used to provide dynamic power factor correction, such as ***synchronous condenser systems*** and ***static VAR compensators***, but these are beyond the scope of this article.

Nonlinear loads

Loads that involve frequent switching produce harmonics that are multiples of the power system frequency. Switchmode power supplies, fluorescent lighting, welding machines and arc furnaces commonly cause these kind of disturbances, but the most common source of these harmonics in industry today is variable speed drives. VSDs use a rectifier to switch the waveforms on each phase of the supply to produce a DC output for conversion to a variable frequency output via an inverter. VSDs are generally seen as beneficial from a power factor perspective, because they increase the displacement power factor that would normally be produced by a motor to almost unity (typically 0.95).

In a typical 3-phase rectifier, the diodes (or thyrsitors) switch on and pass current only when the voltage across them exceeds their switching threshold, and results in odd harmonics, the harmonics at 5, 7, 11 and 13 times the mains frequency being the most significant. These harmonics do not produce work in the end load being driven by the VSD, but still produce energy loss in the supply network.

Since the desired current is a pure sinusoid, the other harmonics present in the supply current go to make up what is known as harmonic distortion. Total harmonic distortion (THD) is defined as the ratio of the sum of the power in the non-fundamental harmonics to the power in the fundamental.

We can define then ***distortion power factor*** as the ratio of the fundamental current to the total phase current and is like displacement power factor, a number between 0 and 1. The total power factor can therefore be defined as the displacement PF multiplied by the distortion PF:

$$PF = \cos\varphi \frac{I_1}{I}$$

Passive harmonic correction

VSDs contain filtering capacitors after the rectifier and often line inductors before and/or after the rectifier, which have the effect of 'softening' the waveform of Figure 4 and reducing the harmonics of Figure 5, reducing the THD by as much as 50% on load. Even so, a typical 'passively filtered' VSD can still cause a THD of up to 50%.

Active harmonic correction

Many drive companies are now producing active harmonic filters (active PFC) to make the drive appear purely resistive and without harmonic distortion, as viewed by the supply grid. Active filters are wired in parallel (shunt) with the supply input of the drive system and actively change the waveshape of the supply current. They work by synthesising and injecting a current that negates the distortion, virtually eliminating the harmonics. The cost of doing this, of course, is much higher than with passive correction, and it should be noted that active correction must be provided in addition to passive correction, not instead of it.

Always seek expert advice

I hope this article has served as a basic reminder of how energy efficiency can be negatively affected by some of the very technologies (such as VSDs) that we apply to save energy. Of course, every application and situation will be unique, and if you are considering passive or active power factor correction or filtering, then you are best advised to seek the advice of your power system and drive vendor to decide on the appropriate technology for your PFC needs.

Improving power quality at mine sites

Ongoing discussion on the effect of variable speed drives (VSDs) on coal mining power systems has received some clarification with recently collected data.

A project within the CRCMining Power Management program based at the School of Electrical Engineering at the University of Newcastle has collected voltage and current information in an underground offshore coal mine at the substation (power centre) level into which the mine's continuous miners are connected. The work is part of an investigation into voltage stability and its effects on both production and maintenance. The data collection box, designed and built in Australia by the University of Newcastle, collected information well over the 100th harmonic in an attempt to capture transients associated with switched power factor correction capacitors and harmonics associated with variable speed AC drive units not fitted with active front end filters.

Modelling of a target mine in CRCMining's 'Statcom'-based voltage stabilisation project had indicated significant voltage transients would be found as a result of switched capacitors and this was proved to be both correct and accurate. However, the level of harmonic distortion was substantially higher than had been anticipated and is now the subject of further studies.

A quick analysis of the collected data indicates very high levels of 5th, 7th and 11th harmonics, which can considerably decrease the life of both power system components such as transformers and connected motors due to heating. Contributing components to these harmonics may include variable speed AC drives as well as core saturation of transformers in the system, which was previously not considered in the mix of potential issues. Overvoltage transients of 600 V were measured, associated with capacitor switching, and undervoltage issues associated with line impedances have been verified, validating the mine model developed by the university for the Statcom project. An interesting question raised by the results is whether a 'stiff supply bus' would have any effect on the data. While heavy dynamic loading of weak supplies will cause voltage fluctuations for equipment, the observed harmonic distortion could be generally unaffected by the stiffness of the connecting supply considering the line impedances between miners and their grid interconnect.

Electrical engineers in mining have welcomed the results, which they believe are very timely given the industry's rate of adoption of variable speed AC drives. It is believed increased nuisance tripping of conveyor belt drives and earth leakage detection failures are possible outcomes of not fully understanding the dynamics of the underground mining power distribution system as well as the obvious maintenance and life cycle issues of equipment.

Current work is focused on three main areas: developing a range of predictive condition monitoring tools (DC and AC motor duty meters and novel power quality measuring tools); identifying power supply and reticulation weakness to understand their effect on production and equipment, then providing voltage support and harmonic correction solutions; and, extending the interoperability capability of the CRCMining Power Management group by using mine precinct data to determine the key elements of mixed energy generation, with a view to optimising operational cost, power delivery capacity and power quality. Mine planners will be able to draw metrics for the development of power systems and researchers can focus on issues affecting operational capabilities to provide new and innovative solutions to optimise energy delivery and cost.

The second area aims to understand mine precinct power requirements driven by diurnal, shift, week/weekend, seasonal and product impacts, and matching this varied demand with grid supply options. This includes an assessment of interoperability between conventional, renewable and hybrid supply solutions.

CRCMining conducts projects within a number of key research, development and demonstration programs with its members. The programs currently span the areas of automation, power and equipment management, rock fragmentation and handling, and coal technology and fugitive emissions.

CRCMining members come from mining end users (Anglo American, AngloGold Ashanti, Barrick Gold Corporation, BHP Billiton, Newcrest Mining, Newmont Mining, Peabody Energy and Xstrata Coal), original equipment manufacturers and service providers (Caterpillar, CSC, Herrenknecht, Joy Global and Sandvik) and from the research providers at the Universities of Newcastle, Queensland, Western Australia and Curtin University. ■

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Quality management of power networks

Emissions from electricity production are one of the major contributors for global warming, being responsible for up to 40% of the carbon footprint in some developed countries. The demand for electrical energy will continue to grow and the question really becomes, what do we need to do to meet this demand without increasing the carbon footprint?

In this context, energy management is changing significantly in Australia and throughout the world. The smart grid concept came from the urgent need to enhance the current electric grid to use the energy we generate today in a smarter, more efficient way. In order to transform this concept in reality, two things are necessary: an automated metering infrastructure, allowing customers to have more control over their consumption, and an automated, modern and reliable transmission and distribution network, allowing utilities to operate with greater efficiency.

In order to improve reliability in transmission and distribution networks, a high level of automation is necessary in the electrical substations. This high level of automation is achieved using a wide range of electronic equipment, such as protection relays, programmable logic controllers and power meters. However, to make this wide range of devices work together and in coordination can be a real challenge.

Many attempts have been made over the years to address this challenge, but according to Daniel Brandao, Energy Management — Offer Manager, Schneider Electric, only recently we seem to have found a solution: the IEC61850 standard. “The main advantage of this standard is that it is vendor independent, which helps to address real needs from users and not only commercial interests from the manufacturers,” says Brandao. Apart from being vendor independent, the standard also provides a common dictionary of terms for all electronic devices that can be found inside of the substation, and it’s futureproof, as it doesn’t rely on underlying protocols.

Based in Canada, Brandao recently visited Sydney, where he presented a paper on energy management at the MMI Conference for metering professionals. His paper focused on power quality enhancements for IEC 61850. Brandao explains that the IEC 61850 protocol started out with a focus on high-voltage transmission substations but it’s now migrating to other areas of the power system, such as distribution substations, wind and hydro generation. Large-sized, energy-intensive businesses, from industry sectors such as manufacturing, oil and gas, and mining, are also interested in the standard and power quality is increasingly important with the uptake of these types of applications on the grid.

“Power quality is basically any problem manifested in the supplied power that can prevent electrical equipment from working properly, such as voltage drops, frequency deviations, harmonics and transients,” Brandao says. “It is deeply related to energy efficiency, since an appropriated level of the power quality improves the reliability and increases the availability of electrical networks.”

Power quality problems can be caused by loads (electronic equipment that distorts the waveform, unbalanced loads), environmental conditions (lightning, storms) or by the operation of substation equipment (switching, transformer tap changing). Utilities need to make sure consumers are not ‘polluting’ the network with their loads, and consumers want to make sure they are buying energy with good quality.

“If we have power quality issues on the network, the life of the important electric equipment, such as power transformers, can be shortened,” says Brandao. “Electric equipment must work within certain limits to ensure the total life span is achieved. Equipment working with adequate power is more energy efficient and requires less maintenance.”

Since IEC 61850 is so important in the smart grid concept, Schneider Electric is adopting the standard in its metering equipment and is also proposing additions to enhance the standard, specifically to address power quality-related aspects.

According to Brandao, Schneider Electric is calling for the power quality standards to be mapped into the IEC 61850. “It’s something new for metering devices,” he says. “We are aware that utilities are using the protocol very successfully for protection and automation devices but we want to include metering and power quality devices inside this whole concept.”

There are already important standards related to power quality (PQ), such as IEC 61000-4-30 (how meters should calculate PQ-related parameters) and EN50160 (defines a set of limits to PQ-related phenomena). Schneider Electric is proposing the adoption of these standards on the IEC 61850 (vendor neutrality, application relevance and global market presence) as well as some other additions, such as new logical nodes and improved time synchronisation.

“We believe the importance of power quality in the smart grid is being underestimated, and we want to influence the standards to bring real value to the users. After all, a reliable network is key to the successful implementation of the smart grid and therefore key to a sustainable use of electricity.” ■

Sourced from www.sustainabilitymatters.net.au

Improving distribution reliability

Lance A Irwin, Member, IEEE

Reliability has always been the central focus of network operators and, today, they must also focus on sustainability and efficiency. The increase in the use of intermittent renewable energy sources and the need to reconfigure the network based on efficiency seem to counter the quality of supply standards set forth by regulators. Both post- and the more recent pre-fault analysis techniques require the right combination of powerful hardware, good communications and software, and engineers must be skilled to interpret and use the data generated by a utility's power quality system. Jacksonville Electric Authority (JEA) describes how it has used new tools to generate and use its power quality data to meet its quality, reliability and efficiency targets.

Utilities have a range of reliability targets to meet, depending on the region of the world and the regulation in place, with penalties for exceeding this target, or they may set their own target, as a way to measure customer satisfaction. The most common methods of measuring electrical network reliability deal with the total number and duration of outages over a specified time.

Depending on regulatory or internal concerns, utilities may choose to implement more detailed measures at the customer level, on specific values, or segment outages into categories. The most common indices are System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). These indices deal in terms of the system level averages and are good benchmarking indices for the industry.

However, utilities have required more granular indices to assist with management of their networks and decisions for reliability-based capital expenditures, such as: Customer Average Interruption Duration Index (CAIDI), Momentary Average Interruption Frequency Index (MAIFI) and Customer Experiencing Multiple Sustained and Momentary Interruptions (CEMSMIn)[1].

All of the indices provide a performance baseline and give utilities a method for targeting improvements such as preventing faults from occurring (impacting SAIFI) or locating and repairing faults faster (targeting SAIDI).

Power quality information (PQ information) has historically been used for post-mortem analysis to determine root causes of problems and to mitigate future occurrences (targeting SAIFI).

In recent years, PQ information has been used to locate faults to help speed the restoration and improve SAIDI.

Now, new research and demonstrations are proving that PQ information can be used to detect the signatures of failing equipment and alarm the network operator in time to prevent a fault from occurring, improving not only SAIFI but other indices like MAIFI and CEMSMIn.

Post-fault analysis uses many methods, and much research has been done to try to detect and isolate faults to restore service more quickly. Protective relay schemes in substations, deployment of faulted circuit indicators along medium-voltage feeders and, more recently, Fault Location, Isolation and Service Restoration (FLISR) schemes, which automate the network switching, are all attempts, by network operators, to reduce SAIDI by deploying hardware, software and communications.

Using waveforms and symmetrical components analysis on hardware to locate faults is difficult and inaccurate on complex distribution networks and better location accuracy requires the addition of a communications network and software algorithms.

The Electric Power Research Institute in the US has worked with several utilities to study the capabilities of reactance-based location techniques and voltage drop techniques and has found that each method has merits and drawbacks but it is clear that combining hardware, software and communications to take power quality data and turn it into actionable information for reducing outage durations is possible[2].

Pre-fault analysis is also evolving. Distribution Fault Anticipation (DFA) projects are underway at universities and in field trials around the world. Work from the US and Korea[3,4] show cases of finding bad capacitor controllers, loose connections, failing transformers, misaligned switches and more, and demonstrates that using power quality data to locate problems, before they become outages, is possible, but requires powerful hardware, good communications and software.

Jacksonville Electric Authority (JEA) in Jacksonville, Florida, US, provides a real-world example of how new tools, to generate and use PQ data, have been used to meet quality, reliability and efficiency targets.

JEA operates generation, transmission and distribution assets to serve more than 360,000 customers and has adopted smart grid technologies, including advanced metering infrastructure, computer automated workforce management and active outage notification and management, to improve system performance and personnel response time in an effort to mitigate outage times and improve SAIDI and CAIDI.

JEA installed a wide area power quality monitoring solution to ensure it was delivering the clean power required for a twenty-first-century economy. Initially, the system was limited to monitoring equipment and data collection software, but manually pouring through thousands of records, generated by the power quality monitors, was not efficient and potentially useful information was being lost amidst the forest of waveforms and alarms.

JEA decided to enhance its PQ monitoring system by installing a reporting tool that could roll up data, based on known events, summarise wide area power quality monitoring system architecture statistics and provide a dashboard view for multiple users, based on a specific area of interest. An architecture for the system is shown in Figure 1.

System hardware consisted of IEC 61000-4-30 Class A compliant power quality monitors, located at interties between generation (17 monitors) and transmission, transmission and distribution (73 monitors) and on large industrial sites (92 monitors). The monitors are ION7650 or ION8600 devices, provided by Schneider Electric. Revenue data is also used for billing and SCADA purposes.

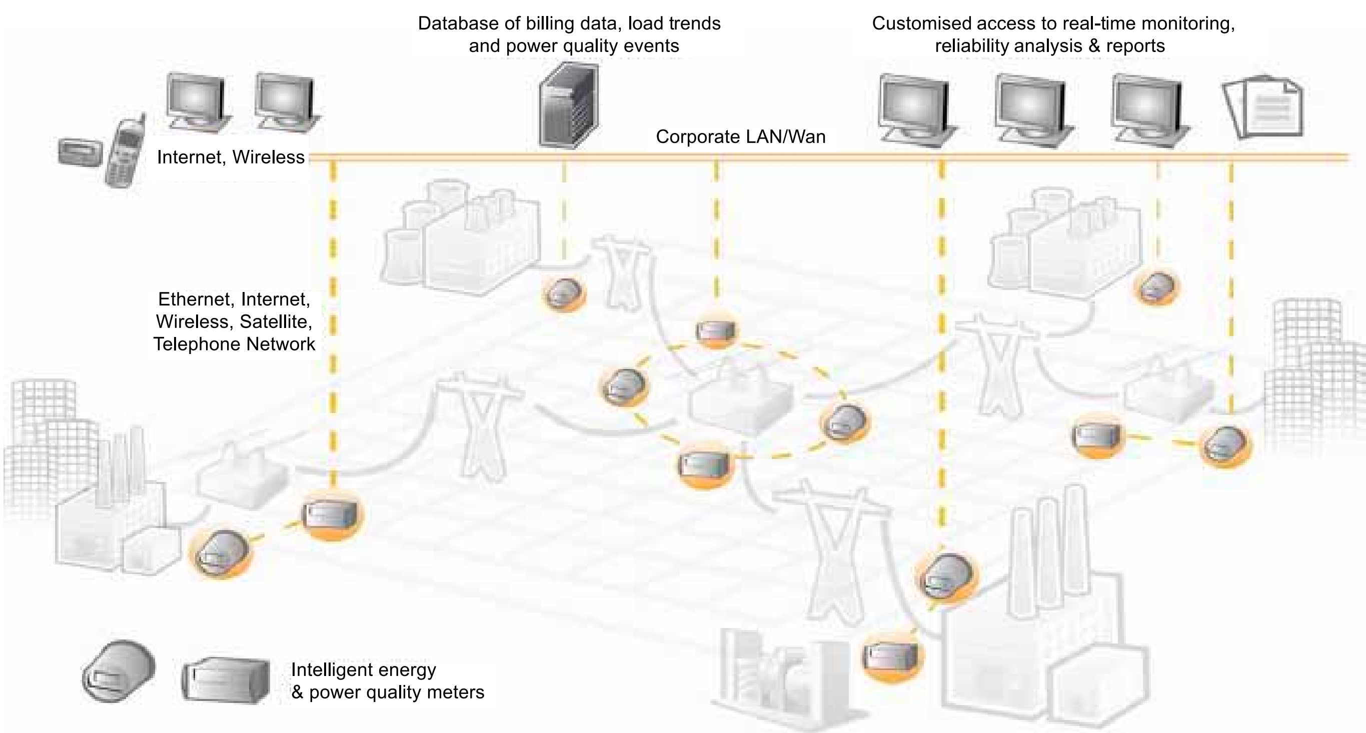

Figure 1. Wide area power quality monitoring system architecture.

As with most systems used by electric utilities, the PQ system has grown and will continue to grow, over time. However, the availability of communications infrastructure varies with location and time of installation. One requirement for the system was that it seamlessly handle multiple forms of communication, while allowing for easy upgrades, as new technologies were introduced.

Today, JEA has devices communicating with software with multiple protocols and through multiple media, simultaneously. For example, in the distribution substation, a device uses DNP3.0 over Ethernet to communicate with SCADA while allowing a modem connection to the billing software and a GPRS connection to the power quality analysis software, and also serves as a gateway for SCADA to master local devices over a serial connection.

Software initially consisted of data collection software that allowed viewing and analysis of waveforms and data. Reporting existed, but the system was dedicated to one vendor and use of the system was limited to compliance monitoring, for quality of supply, and post-mortem analysis of problems.

As the system grew, the ability of JEA reliability engineers to review all of the data and make decisions was restricted. Also, while the value of the system for customer service was meeting the intended ROI, JEA felt there were better uses for the data to make informed asset management decisions ***before*** there was a problem that caused an interruption.

Knowing that further growth of the system was certain, there was a requirement for the software to be easily scalable from the current size to many hundreds of devices more.

An 'open' platform was also required, as JEA wanted to bring data from multiple sources into the system and not be tied to one hardware vendor, one protocol or one communication media.

Understanding that different stakeholders in the utility needed to see the data in different ways, JEA required that the system allow configurable dashboard views, over the web, for improved decision making, and that these dashboards should include the ability to: see the data in a geographical view; run user-defined reports; classify event data; and perform analysis — as simply presenting data would not benefit JEA beyond the existing software they were using.

The final requirement for the software was to have the system present information based on algorithms used by JEA engineers. For instance, as the engineers classify events (tree, animal, lightning, etc) the engineers can see, over time, that more transients are being caused by trees and, perhaps, the line should be inspected. Another use is breaker timing analysis. The system monitors the number of cycles for a breaker operation and alarm, if the time is slowly increasing. Figure 2 shows the software architecture installed at JEA.

Transformer monitoring also realised substantial benefits. While reviewing individual records before implementing the new software system, JEA engineers found an anomaly that required further investigation. At the Northshore substation, the monitor on Transformer 1 was showing a loss of current on one phase for less than one cycle, several times a day. Figure 3 is an actual view of the waveform.

Further analysis showed that the duration of the zero current was increasing over the several days the engineer monitored the situation. A maintenance outage was scheduled, and when technicians inspected the load tap changer (LTC) on Transformer 1 they discovered a pin that was shearing and causing arcing during the travel of the LTC. Technicians believe the transformer would have been destroyed within two weeks if the arcing had not been detected and corrected.

After installing the new system, JEA configured the software to recognise and report if this signature was detected. Since then, three instances have been detected and alarmed automatically, leading to the prevention of the failure of three more large power transformers. JEA estimates the avoided cost of the transformer damage at four million US dollars.

Many methods are used to measure and verify system reliability and these lead to different approaches to reducing the amount and impact of outages. Technologies are available today to help utilities mitigate the impacts of outages and also to prevent the outages by monitoring their systems and evaluating the data.

From its experience, JEA concludes that a PQ system must be capable of progressive rollout and allow for open communication with multiple devices, over multiple media. Flexibility is also important; as communications networks, the technology in

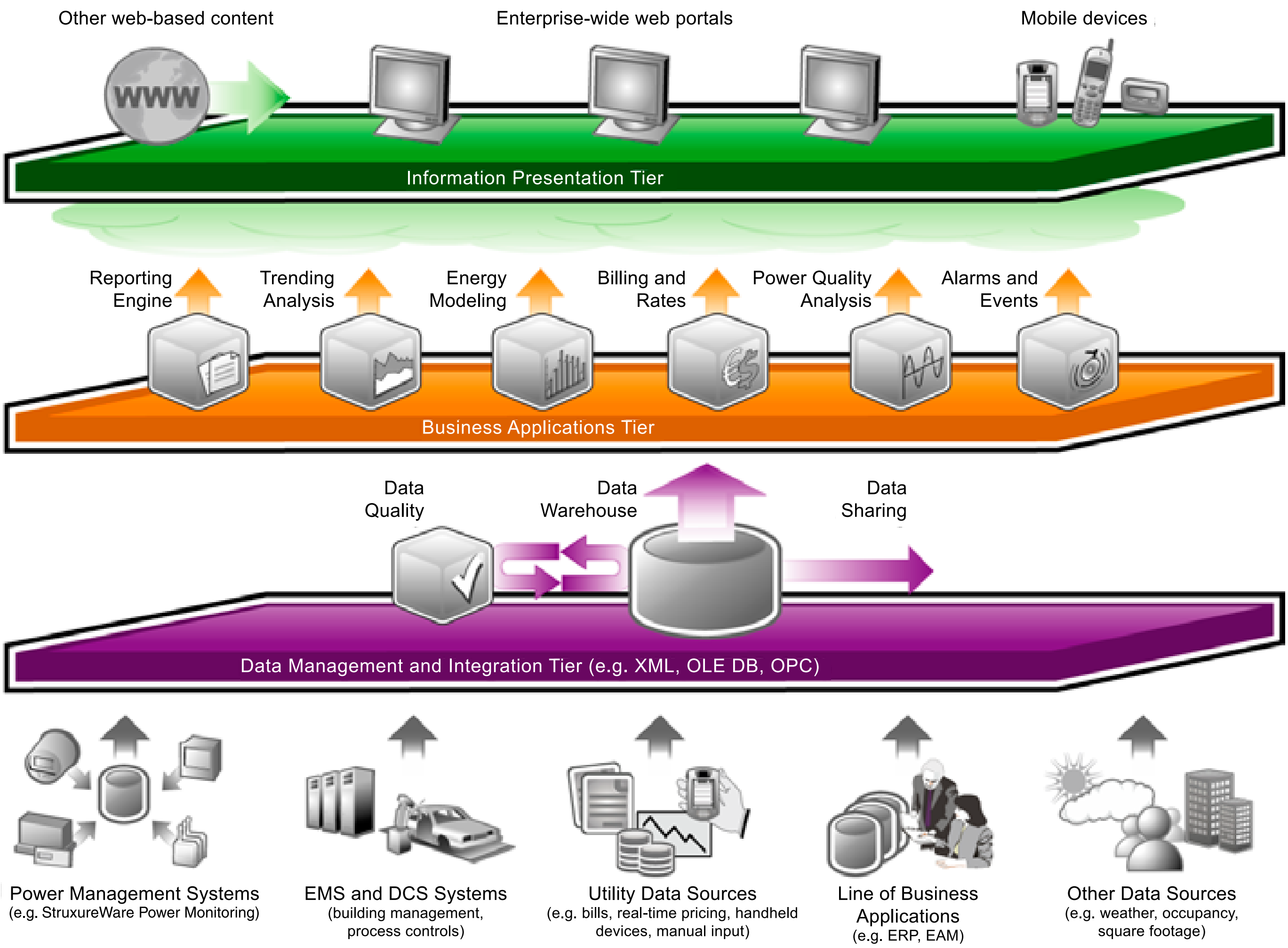

Figure 2. Software architecture of a wide area power quality monitoring system.

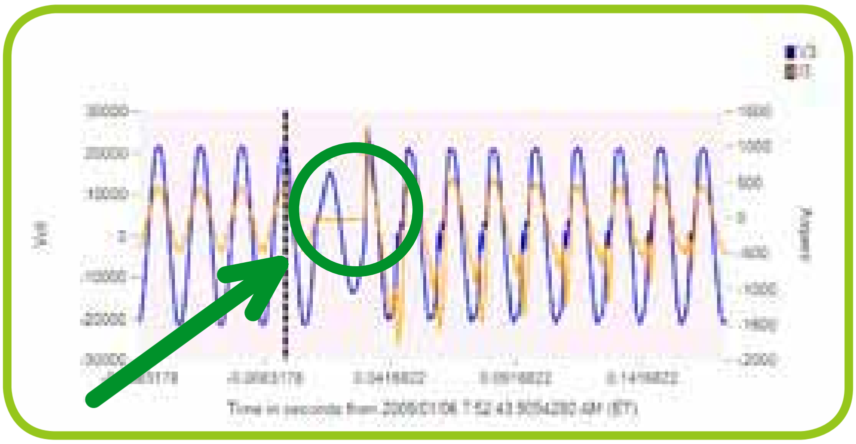

Figure 3. Captured disturbance waveform showing fault on Phase C (flat line) leading to discovery of melting metal in tap changer.

hardware and the algorithms in software are continually evolving.

The innovation and adaptability of engineers in using power quality information will be key to improving system reliability. ■

[1]IEEE Guide for Electric Power Distribution Reliability Indices, IEEE Standard 1366-2003, Dec. 2003. [2]M. Tremblay, M. Demers, G. Simard, M. McGranaghan, and J. Kim, 'Using waveshape analysis for fault location in distribution systems', Utility Automation, pp. 40-44, Aug. 2009. [3]C. Wallis, 'Distribution fault anticipation for distributed applications', presented at the EEI TD&M Conference, Savannah, Georgia, US, 2008. [4]I.K Moonjong Jang, H.J. Song, H.J. Lee, J.Y. Kim, 'Current practice and prospect of the distribution automation system of Korea', presented at the Gridwise Architecture Council Forum, Denver, Colorado, US, 2009.

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