[Article 5 of 7]: ***Research on the Characteristics of a Smart Grid by the NETL Modern Grid Strategy Team***

Power Quality for the Digital Economy

Last month we presented the 4th Principal Characteristic of a Smart Grid, "**Optimizes Assets and Operates Efficiently.**" This month we present the 5th characteristic, "**Provides Power Quality for the Digital Economy.**" This 5th characteristic is intended to ensure that the quality of delivered power meets the diverse needs of society and that superior power quality will be treated as an available value-added product that, like most such products, comes at a higher price.

Summary

When consumers think of reliability, they think of power that is both free of interruption, and free of disturbance (i.e. "clean"). The focus of this paper is on the second attribute; *clean power*.

Clean power or power quality (PQ) deserves this special focus because of the importance of digital devices that have become the engines of most industries in today's economy. The level of delivered power quality can range from "standard" to "premium", depending on consumers' requirements. Not all commercial enterprises, and certainly not all residential customers, need the same quality of power. The Smart Grid will supply varying grades of power that are priced accordingly.

The grade of delivered power is largely determined by the design of the facilities serving a customer. Special attention can be devoted to minimizing the effect of such perturbations as lightning strokes, harmonic voltages and switching surges; the extra cost of these premium features can be included in the electric service contract.

The Smart Grid will mitigate PQ events that originate in the transmission and distribution levels of the electrical power system. Its advanced control and monitoring systems will enable rapid diagnosis and correction of PQ events. Advanced components will apply the latest in superconductivity, energy storage, and power electronics to improve power quality. Furthermore, the Smart Grid will help buffer the electrical system from irregularities caused by consumer electronic loads. Part of this will be achieved by monitoring and enforcing standards that limit the level of harmonics a consumer load is allowed to produce. Beyond this, the Smart Grid will employ appropriate measures to prevent harmonic pollution from feeding back into the grid.

Smart Grid technologies can be applied to the problem of power quality, but to do so will require the coordinated efforts of government, utilities, regulators, and standards bodies. It also requires widespread education of all the grid's stakeholders. The benefits of improved PQ will be tremendous, in both cost avoidance and in resulting productivity gains. Clean, reliable power can also create opportunities for economic growth in areas of the country previously denied the benefits of high-technology industry.

A Primer on Power Quality

Before delving into the issues of power quality, let us first review the things that disrupt it - harmonics, sags, spikes, and phase imbalances.

The power supplied by electric utilities starts out as a smooth sinusoidal waveform. This is the waveform (magnitude versus time) produced at the power plant by electrical generators. (See Figure 1.)

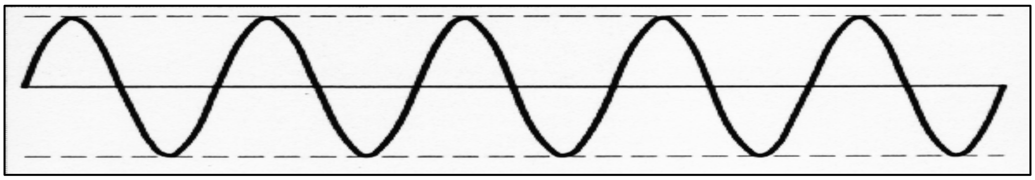


Figure 1: Normal power is supplied in smooth sinusoidal waveforms.

But as this power moves from the generator through the transmission and distribution systems and on to the customer's equipment, it can be affected by four kinds of perturbations that distort its pure (clean) sine wave envelope:

Sags (undervoltages) — Voltage sags are the most common power disturbance. They occur when very large loads start up, or as a result of a serious momentary overload or fault in the power system. At a typical industrial site, several severe sags per year are not unusual at the service entrance. Costs associated with sags can range widely, from almost nothing to several million dollars per event. (See Figure 2.)

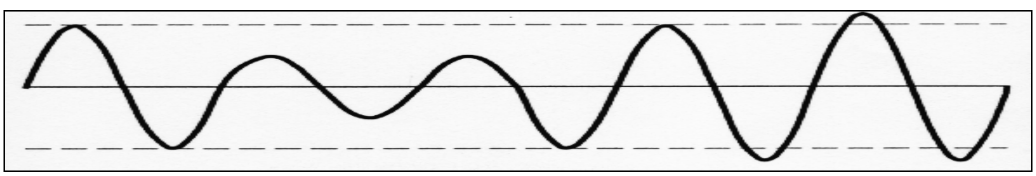


Figure 2: Voltage sags are the most common power disturbance, with associated costs ranging from zero to millions of dollars.

Harmonics — Harmonics are caused by "non-linear" loads, which include motor controls, computers, office equipment, compact fluorescent lamps, light dimmers, televisions and, in general, most electronic loads. High levels of harmonics increase line losses and decrease equipment lifetime. (See Figure 3.)

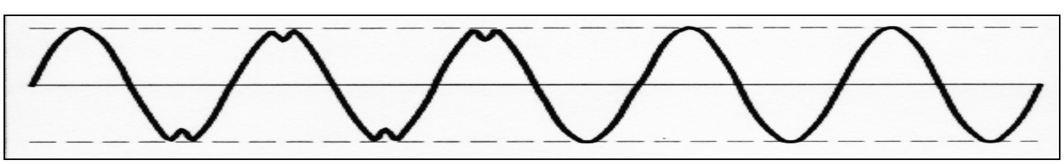


Figure 3: Non-linear loads create harmonic distortion, resulting in more line losses and reduced equipment life.

Spikes — Spikes are brief spurts of voltage (in the millisecond to microsecond range) that can be many times higher than normal. Spikes are caused by lightning and switching of large loads or sections of the power system network. They can disrupt the operation of data processing equipment and damage sensitive electronic equipment (See
Figure).

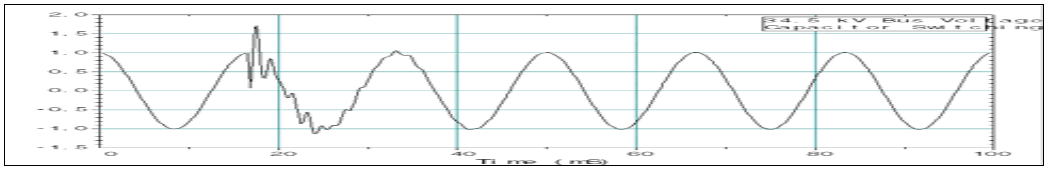


Figure 4: Spikes can damage sensitive electronic equipment.

Phase Imbalances — Imbalances are steady-state problems caused by such things as defective transformers or uneven loading of grid phase wires. They can gradually cause damage to equipment, especially electric motors, as well as increase system electrical losses.

Current State

Voltage sags represent the largest PQ issue. Several industry studies have provided insight regarding the number and type of voltage sags that may occur annually. They indicate that the vast majority of voltage sags last for less than 0.1 second and that, during this time, delivered voltage is 30 % or less of the rated value.These statistics may be compared to the Information Technology Industry Council's (ITIC) Semiconductor Equipment and Materials International (SEMI) F47 limits (Figure 5-shown below in green). While Figure 5 shows there is generally reasonable matching between what the utility supplies and what the customer designs to, there are also areas of non-compliance (points below the green line).These tiny power disturbances can wreak havoc with the increasingly complicated, computerized machinery found on today's assembly lines.

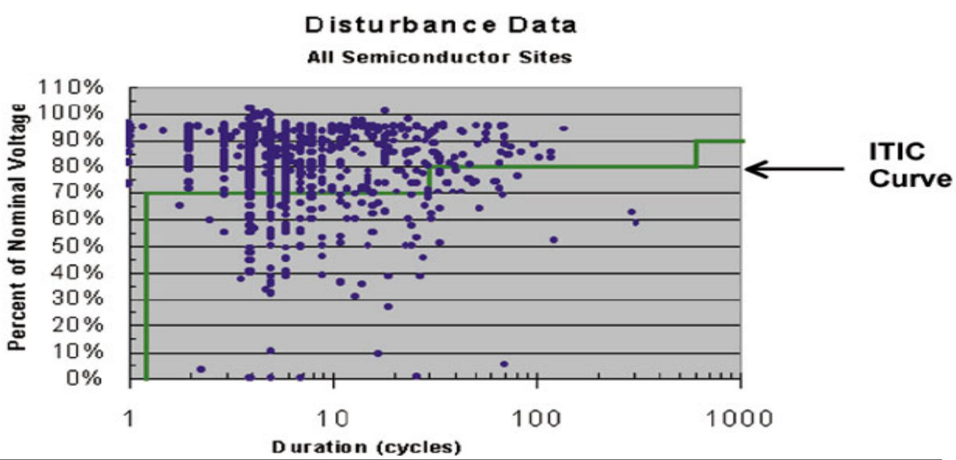


Figure 5: Sag Monitoring Data from 15 Semiconductor Sites
Source- EPRI Solutions

Applying advanced power electronics at each level of the grid is one key to solving PQ problems. Many of these devices fall under the broad heading of Flexible AC Transmission Systems (FACTS), even though some are actually deployed on the distribution system. FACTS and related technologies use power semiconductor switches applied to high speed voltage compensation devices. The costs are high, consequently deployments are scarce. As with any product life cycle, more economical designs will be developed when it becomes clear that a significant market exists

The PQ stakes are high. A momentary interruption due to a severe voltage sag (e.g. zero or near-zero voltage lasting for a fault clearing time of 32 milliseconds- i.e. two cycles) exceeds SEMI F47 allowable limits, potentially causing the costs shown in Table 1 below.

	Cost of Momentary Interruption ($/kW demand)	
Category	**Minimum**	**Maximum**
INDUSTRIAL		
Automobile manufacturing	$5.0	$7.5
Rubber and plastics	$3.0	$4.5
Textile	$2.0	$4.0
Paper	$1.5	$2.5
Printing (newspapers)	$1.0	$2.0
Petrochemical	$3.0	$5.0
Metal fabrication	$2.0	$4.0
Glass	$4.0	$6.0
Mining	$2.0	$4.0
Food processing	$3.0	$5.0
Pharmaceutical	$5.0	$50.0
Electronics	$8.0	$12.0
Semiconductor manufacturing	$20.0	$60.0
COMMERCIAL		
Communications, information processing	$1.0	$10.0
Hospitals, banks, civil services	$2.0	$3.0
Restaurants, bars, hotels	$0.5	$1.0
Commercial shops	$0.1	$0.5

Table 1 –Momentary Interruption Cost by Industry
(Source: McGranaghan, et al; EC&M article)

Today, most utilities have units that address power quality complaints, but these organizations may be more reactive than proactive. This is possibly a result of a continuing debate about who should bear the costs of PQ improvement; the utility or the consumer.

Not all customers want premium levels of power quality, or wish to pay for it. One solution, the development of new rate structures that offer premium quality, has not yet been broadly adopted or accepted. Regulators are well positioned to encourage such solutions that represent the lowest overall cost and provide a fair return to investors. For those customers who could suffer significant harm due to PQ events, a premium power product can be a good solution for both buyer and seller.

Regulators can also drive the development of standards that will make equipment less vulnerable. As an influential standards body, IEEE could create standards for categories of power quality from which consumers choose according to their needs

Future State

Advanced technologies deployed by the Smart Grid will both mitigate power quality events in the power delivery system and protect end users' sensitive electronic equipment. Twenty or more years ago, the power system's design was well suited to the type of loads that it supplied. But in the future, sensitive loads will grow to more than half of all loads. To accommodate this future, the Smart Grid will supply varying grades of power, with prices that vary accordingly. As Table 1 clearly shows, a premium power offering holds greater appeal to a semiconductor manufacturer than to a newspaper printer, although both benefit. Hence, customized premium power packages will be offered to meet these differing industry requirements.

The devices that mitigate PQ events will be spread among transmission and distribution levels of the Smart Grid, and also right at the sensitive load. Commonly, 40% of power quality issues relate to the delivery of power from the utility, and 60% relate to the use of power within an industrial facility. PQ problem identification will happen quickly because modern communicating meters will find and report it immediately. Another tool, the application of modern maintenance techniques, will reduce the system faults that cause many PQ events.

At the transmission level, voltage sags are frequently the result of faults (short circuits), which can exist for many milliseconds. High voltage static VAR compensators (a FACTS device) are fast enough to mitigate many of these events. As semiconductor component costs drop, these devices will be a common element of the Smart Grid. Also looking toward the future, affordable current-limiting devices will reduce the severity of voltage sags associated with faults. And eventually, lossless superconducting transmission lines will further reduce voltage sag concerns. More conventional techniques such as broader application of surge arresters, improved line shielding and grounding, and controlled switching angles will also be employed more aggressively to limit PQ disturbances.

At the distribution level, a variety of techniques will improve the quality of power delivered to the end customer. Since lightning is a major source of PQ problems, greater use of underground facilities can minimize this contribution. The creation of premium power parks, where sensitive load customers can locate, will be common. These parks will be directly connected by underground express feeders from distribution substations. They will be fed by redundant feeders via high-speed source transfer switches, so that when one feeder is perturbed the other can instantly take over.

The most direct way to deal with voltage sags is by providing adequate buffering right at the load. There are FACTs devices that do this. And for those customers who take advantage of the Smart Grid's distributed energy resources (DER), their locally produced power will be isolated from utility disturbances.

The power quality solution not only includes grid technologies that improve and maintain power quality, but also those that make customer loads more tolerant of PQ events. Within the customer's facility, advanced devices and techniques, including proper wiring and grounding practices, will offer solutions to PQ sensitivity. With regard to harmonics issues, customer-owned equipment is the most common source. Harmonics originating in customer equipment can also cause power quality problems for other utility customers, as well as to the power delivery system itself. Responsibility for controlling harmonics is twofold:

- The customer is responsible for limiting harmonic currents that interfere with the power system.
- The utility is responsible for maintaining the quality of the grid's voltage waveform.

Since these responsibilities are highly interrelated, guidelines will establish harmonic limits for each party.

Residential customers will also have varying power quality needs, depending on the sophistication of their home electronics. Here, much rests with the vendors of consumer products, which need to be designed to better tolerate common PQ events. And with so many small businesses now based at home, the economic impact of residential PQ should not be ignored.

Benefits of Clean and Reliable Power

Avoiding the productivity losses of poor quality power to commercial and industrial customers can shed billions of dollars of waste from the economy. A 2001 Primen study concluded that power quality disturbances alone cost the US economy between $15-24 billion annually. Voltage dips that last less than 100 milliseconds can have the same effect on an industrial process as an outage that lasts several minutes or more.

Improving PQ in the nation's power system will also offer opportunities to broaden and enrich the commercial bases of struggling communities and regions. Rural communities will be able to support clean, high-tech industries that demand high quality and reliable power. New jobs and higher tax bases will transform regions and communities that once depended solely on agriculture or single industries.

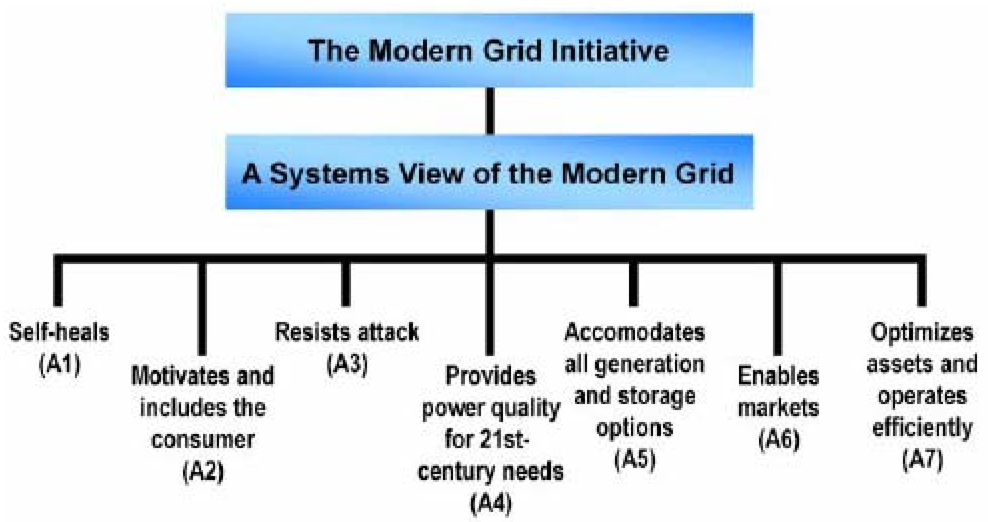
Several actions can be taken now to accelerate the realization of these benefits:

- Cost/benefit analyses should be conducted, taking into account the full range of benefits that improved PQ delivers. State utility commissioners, service providers and consumer representatives should work together to develop this crucial information. Those solutions with a favorable net value to society should be adopted broadly. When the energy delivery company is the best solution provider, electric rates should include the incremental cost to provide superior power.
- Government leadership is needed to hasten an answer to the question of who owns the PQ issue. Because PQ problems can originate anywhere along the electricity path, federal agencies and state regulators need to become more involved in determining how to allocate costs of PQ solutions.

- Programs to provide PQ education should be developed and broadly publicized. Customers need to be better educated about the PQ issue so their facilities can be designed to accommodate PQ imperfections. For future planning by consumers, the emerging solutions should be widely publicized.

For more information

For a high-level overview of the modern grid, see "A Systems View of the Modern Grid." MGI has also prepared seven papers that support and supplement these overviews by detailing more specifics on each of the seven principal characteristics.



Documents are available for free download from the Modern Grid Strategy website:

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