EPRI

PQ TechWatch

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Societal Costs of

Power Quality Disturbances

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Contents

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PQ-related problems can have societal costs related to them. For example, costs due to PQ events might be passed on to customers in some way. Most likely, such costs would reflect the added material and labor costs to a manufacturing process that has been interrupted by a PQ event. Some industries might be more affected by PQ disturbances than others. In addition, some industries might be so affected that they choose to move out of one service area's territory for another due to the repeated losses resulting from the PQ events in that area. In this case, the employees living in the previous service territory might suddenly find themselves in need of employment—a real problem should local industries be few in number. Other ways that private citizens might be affected is in noticing that their clocks must be reset after an outage. Perhaps they may even have to restart a washer or dryer cycle or have to throw out something baking in an oven that shut off and cooled before the food could be fully cooked.

However, PQ issues are more than annoyances for businesses in the United States—especially for those involving automated processes. Voltage sags might result in lost or scrapped product, lost labor, production delays, and possibly missed product delivery deadlines.

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THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

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PQ EVENTS OVER THE YEARS

The above-ground grid remains today just as susceptible to weather, animal, and other perturbations to power quality as it has been from its beginnings. Industrial customers bear the brunt of PQ effects—the voltage sag in particular—because of sensitive, interconnected automated processes.

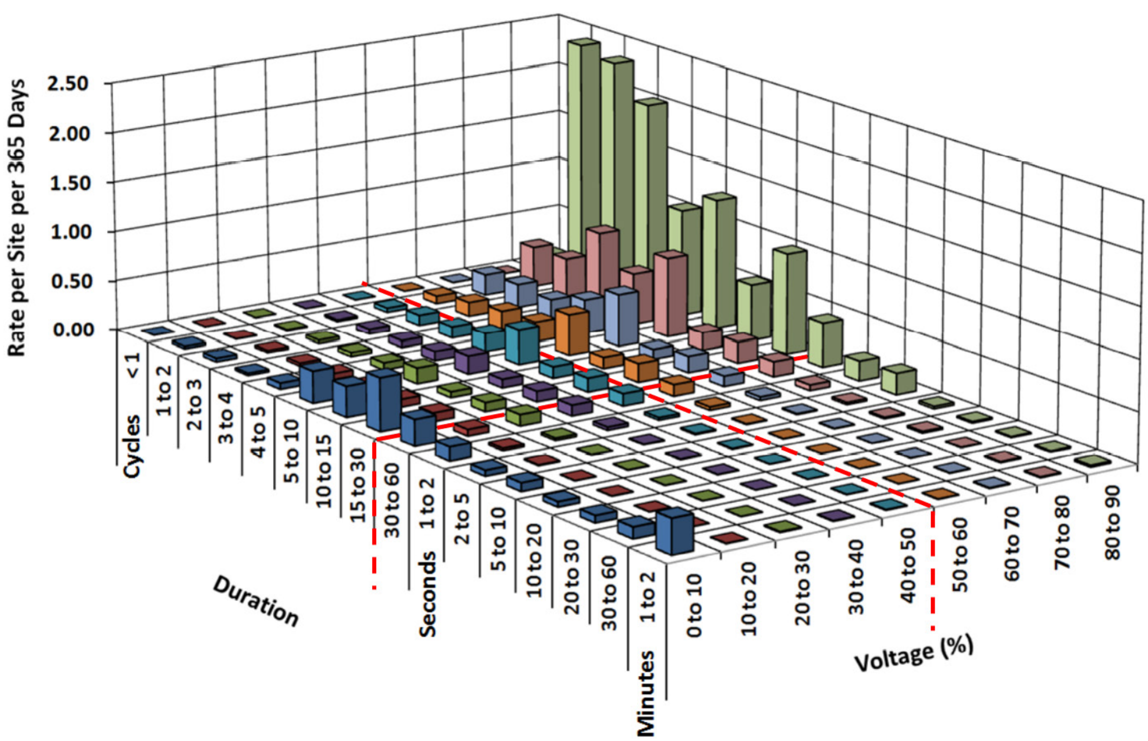
Voltage Sags

Early in the study of power quality, the most significant event affecting the commercial and industrial sectors was identified as the voltage sag, a momentary reduction in supply voltage. Several studies over the previous 25 years or so have established that most voltage sags (voltage events below 90% of nominal) have magnitudes at or above 50% of nominal voltage and durations of less than 0.5 seconds, as shown in the chart below (see dashed red lines).

The chart represents data from all systems or sites and came from the TPQ-DPQ III study—the third such examination of power quality in the electrical system of the United States. This study considered voltage levels of transmission, subtransmission, distribution, and low-voltage systems—singly and all together (all sites).

Harmonic Distortion

Electrical generation is shifting from steady fossil fuel–fired facilities to variable grid-connected distributed energy resources (DER), which may be expected to decrease grid "stiffness" and increase grid harmonics due to the power-electronic inverters connecting the DER to the grid. Indeed, new high-frequency harmonic resonance conditions have been observed on some areas—apparently due to the switching frequency of grid-connected inverters. Similar power electronics continue to appear, although at a lower power level, in consumer products that connect to the distribution



Source: All tables and figures are from EPRI, *Transmission–Distribution Power Quality Report (TPQ-DPQ III)* (Palo Alto, CA: 2014), 3002003905.

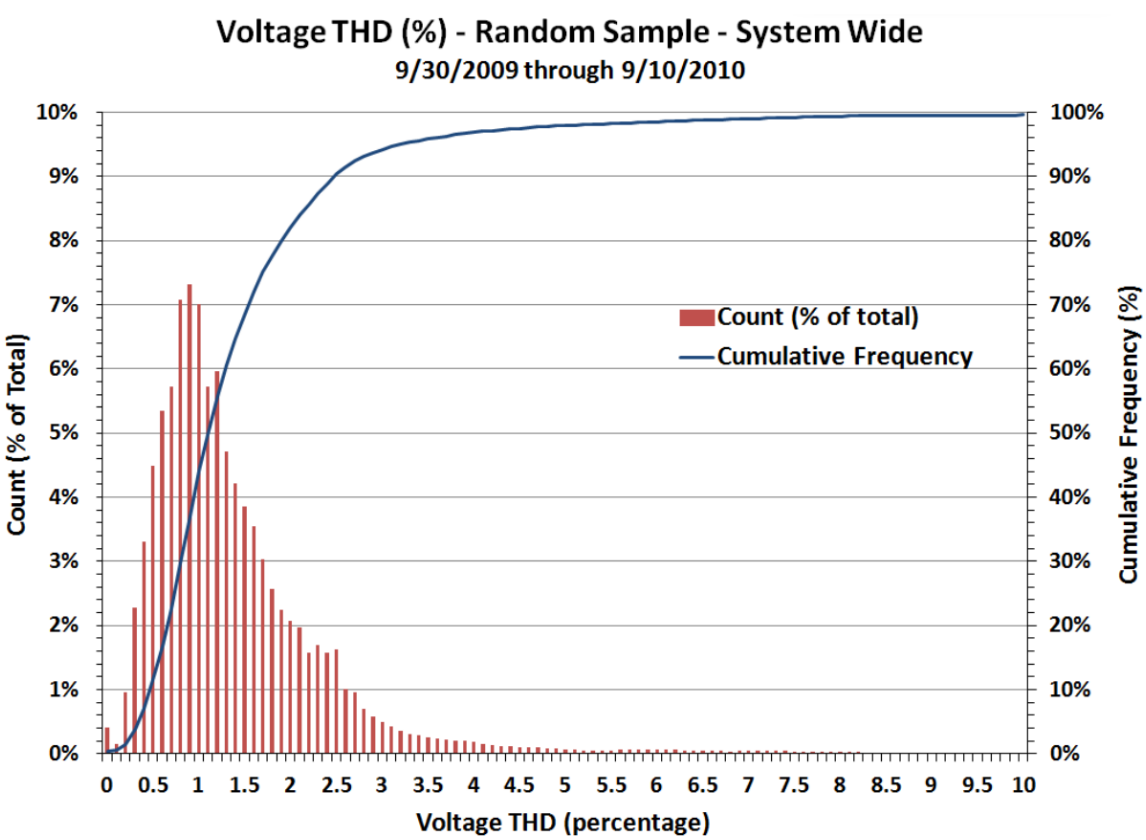
The TPQ-DPQ III study examined PQ data obtained from seven utilities spanning the continental United States between 2009 and 2012.

grid. In 2014, IEEE 519 was revised to increase the harmonic content of distribution systems from 5% to 8%.

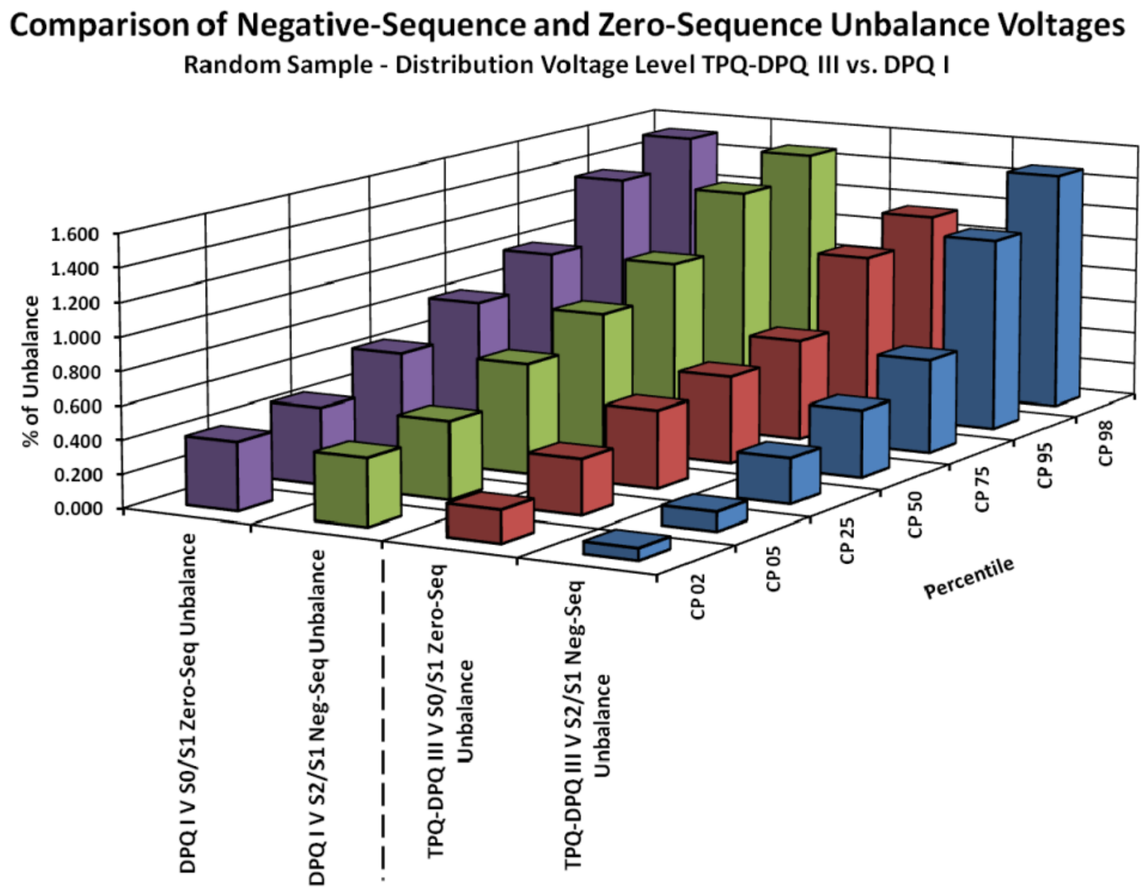
Also in 2014, EPRI published the TPQ-DPQ III study, which examined PQ data obtained from seven utilities spanning the continental United States between 2009 and 2012. This study included harmonic distortion (and other analyses) as shown below. At that time, voltage total harmonic distortion (THD) was found to be well below the pre-2014, 5% limit for these utilities. The high-frequency resonance conditions referenced above were not observed until several years after the study was published.

Voltage Unbalance

The 2014 TPQ-DPQ III study examined voltage unbalance (also called voltage imbalance) as shown in the figure at the top of the next page. This figure compared negative- and zero-sequence voltages for distribution voltage systems from the DPQ I and TPQ-DPQ III studies. Although generally similar, the DPQ I study may appear more uniform, perhaps due to the monitors used; the same type of PQ monitor using the same settings provided data for the DPQ I study, whereas all manner of monitors of unknown settings provided data for the TPQ-DPQ III study. The unbalance for the distribution voltage systems studied fell below 1.6%.



Source: TPQ-DPQ III.



Source: TPQ-DPQ III.

Reliability considerations are evaluated through SARFI values (system average RMS frequency index).

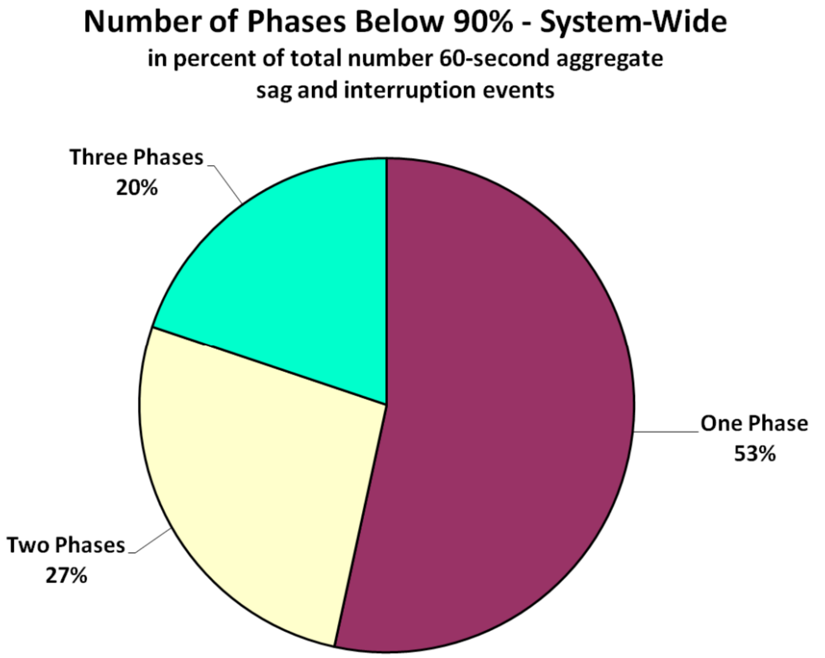
Reliability—SARFI$_x$

Reliability considerations resulted in the following comparisons between three successive PQ studies concerning various SARFI$_X$ values (system average RMS [variation] frequency index). Here the x subscript stood for the CBEMA, ITIC, and SEMI F47 performance curves along with percent of voltage remaining for PQ events. The data represented events from all sites averaged over 1 year or 365 days.

In each case, the number in the table represents the number of events below the indicated threshold (CBEMA, ITIC, etc.). For example, a critical process sensitive to 70% of nominal voltage (SARFI$_{70}$) may be expected to shut down for nearly 16 voltage sags per year, whereas a similar process conforming to the SEMI F47 standard (SARFI$_{SEMI}$) may be expected to shut down for nearly 12 events per year according to the TPQ-DPQ III study.

All Sites	SARFI$_{CBEMA}$	SARFI$_{ITIC}$	SARFI$_{SEMI}$	SARFI$_{90}$	SARFI$_{70}$	SARFI$_{50}$	SARFI$_{10}$
DPQ I	na	na	na	na	23.4	12.2	5.8
DPQ II	na	13.9	8.3	na	13.7	5.7	0.9
DPQ-TPQ III	22.4	17.0	11.7	48.5	15.7	8.7	3.4

Source: TPQ-DPQ III.



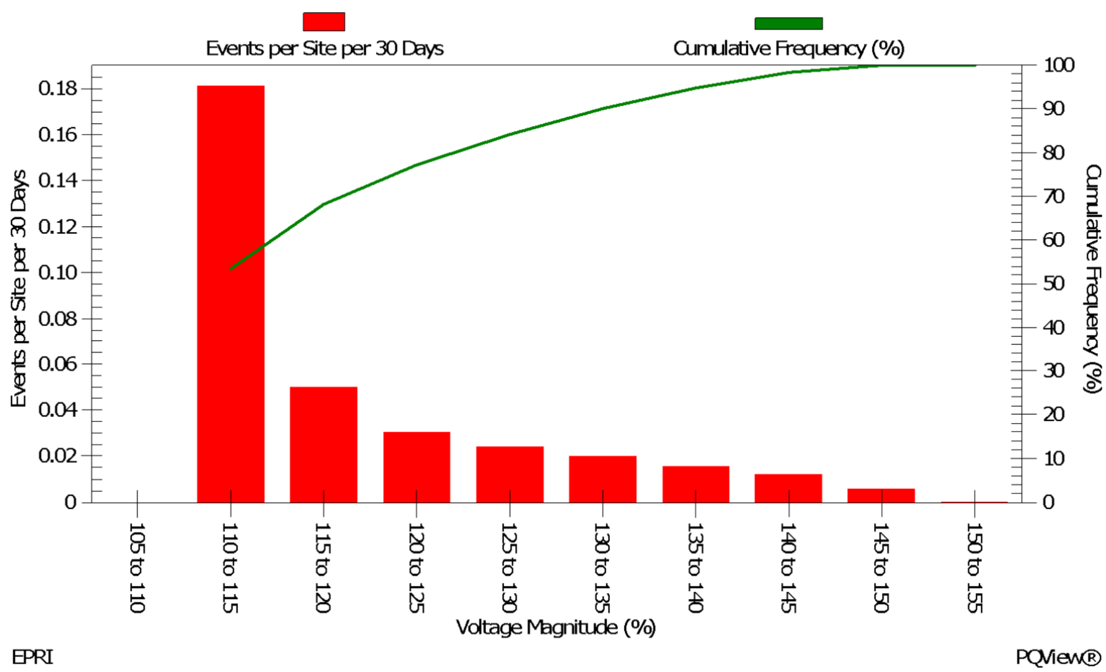
Source: TPQ-DPQ III.

Phases Affected by Voltage Sags

The pie chart at left illustrates that voltage sags most often affect a single phase (53%) of the three-phase electrical system in the United States, with two phases (27%) being affected slightly more often than three phases (20%). Mitigating for three-phase voltage sags proves to be more expensive than for single- and two-phase sags. Equipment that conforms to voltage sag standards such as SEMI F47 and IEEE Standard 1668 can have a more robust response to the voltage sag environment than equipment that does not meet those standards.

Voltage Swells

The graph below indicates that the most frequent overvoltage, between 110% to 115% of nominal voltage (1-minute aggregation, system-wide), occurred at 0.181 events per site per 30 days, which works out to 2.2 events per site per year. The next most frequent overvoltage event rate, 0.050 events



Voltage Magnitude (%)	105 to 110	110 to 115	115 to 120	120 to 125	125 to 130	130 to 135	135 to 140	140 to 145	145 to 150	150 to 155
Swell Rate per Site per 30 Days	0	0.181	0.050	0.031	0.024	0.020	0.016	0.012	0.006	0
Cumulative Frequency	0	53.3%	68.1%	77.1%	84.2%	90.1%	94.7%	98.3%	100.0%	100.0%

Source: TPQ-DPQ III.

Transient overvoltages are typically oscillatory and originate from capacitor banks switching onto the electrical system to boost voltage at that point on the system.

per site per 30 days for 115% to 120% of nominal voltage, might occur 0.6 times per site per year system-wide. The remaining voltage swell levels each may be expected to occur much less often than 1 event per year per site.

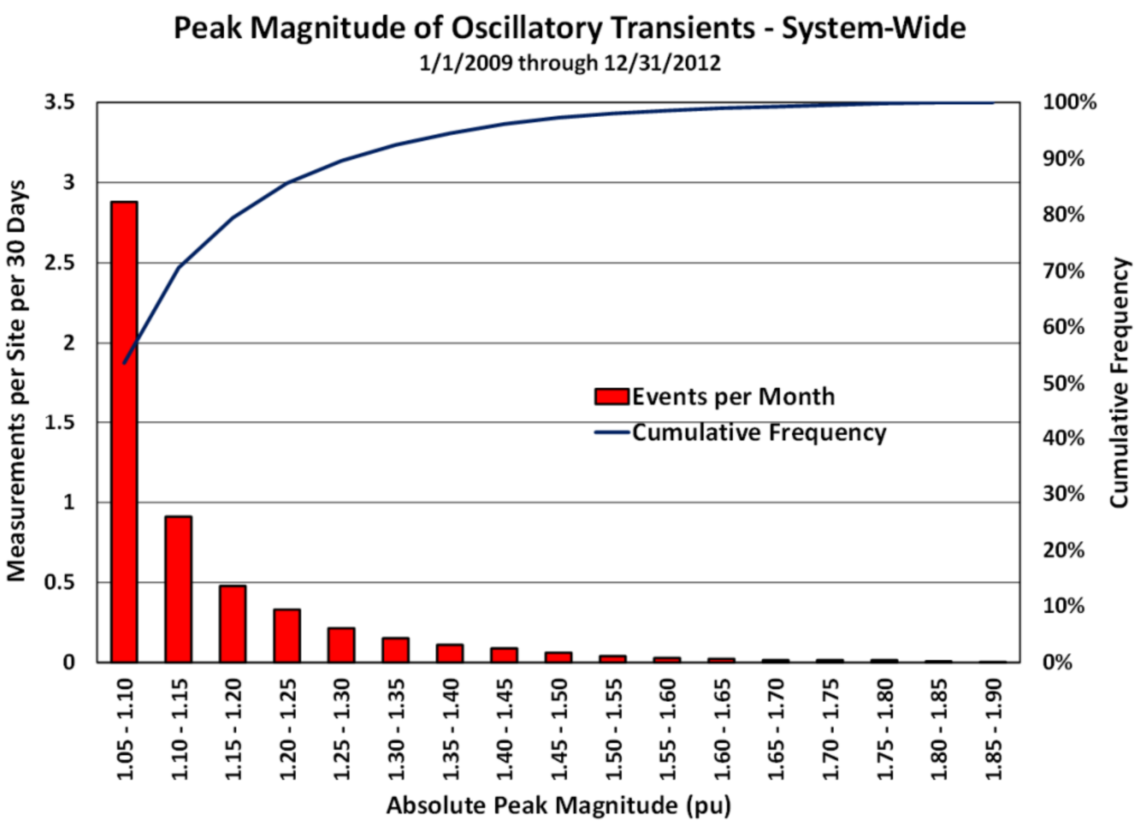
Transient Overvoltages

These events are typically oscillatory and originate from capacitor banks switching onto the electrical system to boost voltage at that point on the system. Voltage magnification may result when the transient from a large capacitor bank interacts with a smaller capacitor bank on the system (installed at a customer facility, for instance, to supply VAr to a large motor load). The resulting transient may be as high as 4.0 per unit and may damage unprotected electronics. Protection against these transients often involves metal oxide varistors (MOVs) that erode with each high transient and may eventually fail—leaving the sensitive electronics susceptible to the next transient and possible catastrophic damage. Fortunately, the higher values of oscillatory transients occur with much lower frequency.

Per the graph below, a transient magnitude of 1.05 to 1.10 per unit may occur fewer than 3 times per 30 days or about 35 times per year. The next level, 1.10 to 1.15 per unit, may occur fewer than 1 time per 30 days or 11 times per year, and so on.

Flicker

Flicker, a sudden fluctuation in system voltage, is a phenomenon made most evident by incandescent lighting. This phenomenon is usually caused by fluctuations in power demands of a large variable load such as an arc furnace. Flicker has two categories—short-term (P_{st}), based on a 10-minute observation period, and long-term (P_{lt}), calculated from 12 successive P_{st} values.

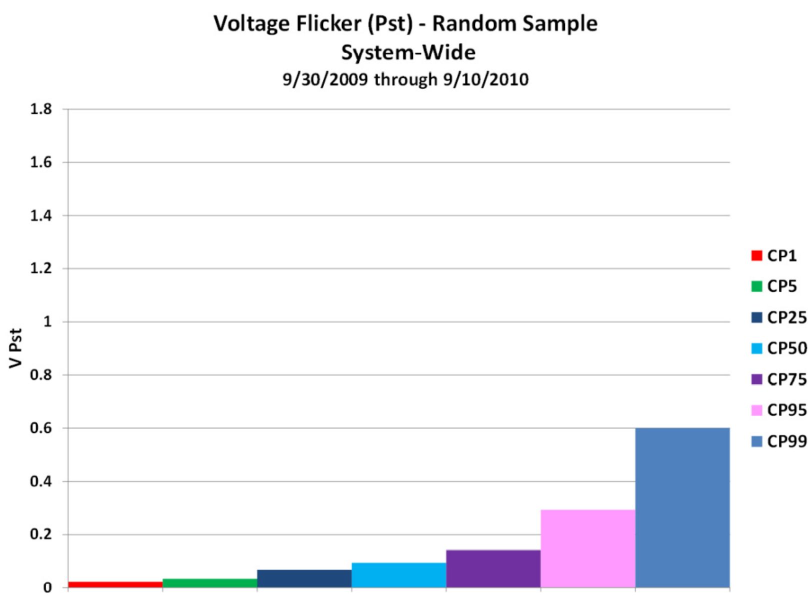


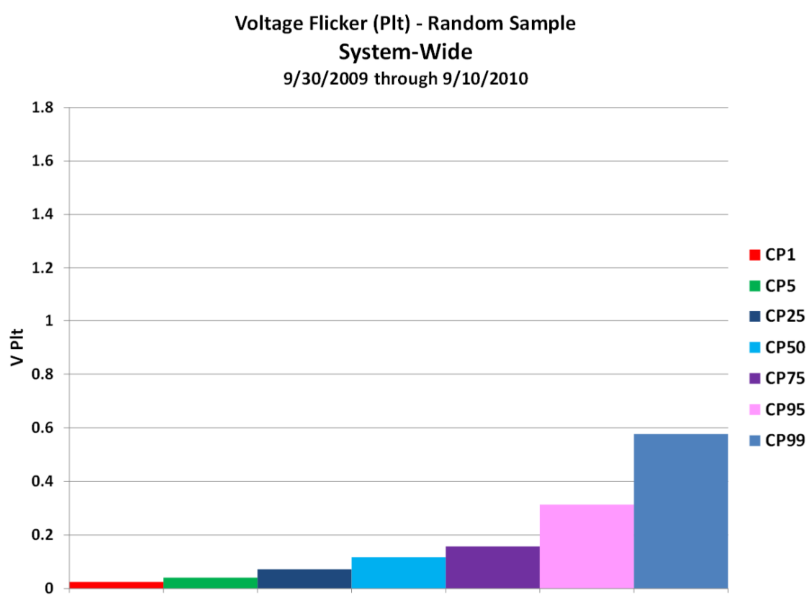
Source: TPQ-DPQ III.

The costs to industry from power quality estimated in a 2001 report have been updated for inflation in 2020.

P_{st} and P_{lt} should not exceed the planning levels more than 1% of the time (99% probability level), with a minimum assessment period of 1 week per IEEE 1453. For low-voltage systems, the compatibility planning level for P_{st} is 1.0, while that for P_{lt} is 0.8.

The randomly sampled values shown below obtained by the TPQ-DPQ III study for both P_{st} and P_{lt} are below 0.6 *system-wide*.





Source: TPQ-DPQ III.

MONETARY COSTS

The costs to industry have been estimated in a study that took place in the late 1990s and early 2000s. The Consortium for Electric Infrastructure to Support a Digital Society (CEIDS) report of 2001 represented a "snapshot" in time of what survey respondents thought was happening in their electrical systems and processes at that time. This report was updated for inflation in 2020 (EPRI, *Understanding the Cost to U.S. Business from Unmitigated Reliability and Power Quality Events* [Palo Alto, CA: 2020], 3002019395). Even today, businesses may not track these costs accurately or understand the effects of PQ on their processes.

INDUSTRIES MOST AFFECTED

Businesses involving automation (electronic or digitally controlled processes) can be greatly affected by PQ events—and might be more likely to act on mitigating the effects of PQ-related disturbances. The updated CEIDS study estimated the average annual losses for industries most affected at $40,350 per business in today's dollars. Being an average, some industries lost more while others lost less. Those most affected in the study might suffer annual losses as high as $78,000 to $93,000—although the maximum cost in the study, as reported by one of those surveyed, was just over $3,000,000. The total estimated annual costs today for all businesses *most affected* may be $59.92 billion.

The updated study (in year 2020 dollars) examined the monetary effects of PQ (the cost of "outages" and the cost of "PQ events") both separately and combined and ranked business sectors as those most affected and those least affected ("less sensitive"). Those most affected consistently included the following sectors:

- Lumber and Wood Products, Except Furniture
- Food and Kindred Products
- Chemical and Allied Products
- Primary Metals Industries

The average annual losses for industries most affected by voltage sags was estimated to be $40,350 per business in today's dollars.

- Paper and Allied Products
- Petroleum and Coal Products
- United States Postal Service

Often appearing with those most affected were *Systems Integration Services*, *Rubber and Misc. Plastics Products*, and *Textile Mill Products*.

Perhaps as an affirmation of PQ sensitivity, the EPRI PQ Team has had to visit sites in each of these sectors since the original CEIDS study.

INDUSTRIES LEAST AFFECTED

Those businesses considered less sensitive—and least likely to desire mitigation efforts—suffered annual losses estimated at $10,088 to $20,176 in 2020 dollars. However, because these businesses greatly outnumbered those involving manufacturing and automation, the total monetary losses for these sectors may range between $85.25 billion and $170.51 billion. These less-sensitive business sectors consistently included the following:

- Railroad Transportation
- Holding and Other Investments Offices
- Water Transportation
- Biological Research
- Chemical Manufacturing—Biological Products, Except Diagnostic
- Security and Commodity Brokers, Dealers, Exchanges, and Services
- Nursing and Personal Care Facilities
- Non-depository Credit Institutions

Often appearing with those considered less sensitive were *Local and Suburban Transit* and *Leather and Leather Products*.

Considering all industrial sectors in the United States, the estimated total annual cost of PQ events to all U.S. business establishments in today's dollars may be roughly $145.17 billion to $230.43 billion.

CONCLUSION

While the electric grid continues to evolve, both in electricity generation and electricity consumers, the voltage sag remains the most significant PQ event for the above-ground electrical system and its customers—especially industrial customers. The average annual losses for industries *most affected* was estimated to be $40,350 per business in today's dollars. Businesses most affected might suffer annual losses reported as high as $78,000 to $93,000, and the total estimated annual costs today for all businesses most affected might be $59.92 billion.

The estimated monetary losses due to PQ disturbances *for all businesses* in the United States (those least affected through those most affected) are between $145.17 billion and $230.43 billion.

About EPRI

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