Pressing Power Quality Issues Worldwide with Special Comments on the Caribbean Region

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Abstract

In this paper, light treatments of several contemporary issues of electric power quality are encapsulated. Remarks are given for the most pressing areas. Some issues relating to developing countries are raised, and a section of the paper is devoted to topics of interest to the Caribbean region.

Index terms: Power quality; power quality indices; developing nations; the Caribbean region.

I. Power Quality Engineering

Power quality engineering has taken a focus within power engineering in the last 20 years. The reasons are complex including: deregulation issues; the advent of relatively high power electronic switches: the appearance of computer controlled loads (that are sensitive to momentary outages); and new interest in improving efficiency. Many of these areas relate to power utilization, and remarkable progress has been made in improving efficiency at the end use. The main focus areas within power engineering have been in two broad subjects: momentary events and repeating events. 'Momentary events' mainly refers to voltage sags that occur on a non-repeating schedule. 'Repeating events' mainly refers to harmonic signals in power systems. The 'front line' of both types of events is the primary distribution system. In the primary distribution system, low voltage events and high harmonic currents seem to appear in their most deleterious form, causing loss of production at industrial loads, active power losses, and interference. One may argue that the transmission system is also a region to be studied because the transmission system is very large (geographically), and in this high voltage system one may find the root causes of some power quality problem. Likewise, in the secondary distribution system and at the point of end use, one may find not only power quality problems, but also the effects of power quality degradation.

Issues of power quality are not relegated to huge power systems in highly developed countries. While it is true that losses of production at high-revenue industrial sites are more likely to occur in the developed nations of the world, and likewise large and highly interconnected transmission systems are mainly in the developed nations, one nonetheless finds power quality problems in developing nations. In developing nations, issues of low supply voltage (either in momentary events or in sustained events) are common. Computer controlled loads are also becoming common in developing nations. And the need for high reliability and high efficiency are pressing in developing nations as well as in developed nations.

The interest in the field of power quality is evidenced by several textbooks (e.g., [1-5]), and recent tutorials (e.g., [6-13]) supplementing the large research literature exemplified by papers in the IEEE Transactions on Power Delivery. Perhaps the most quoted IEEE standard relating to this field is IEEE 519 [15] that contains a set of definitions of periodic and repeating power quality events, a summary of issues relating to harmonics, limits of harmonic voltage and current in power systems, and some examples of calculations.

II. Measures of power quality

Measures of power quality are widely known and have been widely studied. Table (1) shows the main power quality indices. Useful classifications of power quality momentary events (i.e., non-repeating events) are shown in Table (2) [14].

Momentary events deserve special attention because they are no so easily studied in terms of an index. The (now defunct) Computer Business Equipment Manufacturers Association (CBEMA) developed a graphical means to classify momentary low voltage events as 'acceptable' or 'unacceptable'. The idea is that a voltage deviation $(\Delta |V|)$ is plotted versus the duration of the event. If the resultant point lies sufficiently in a region of small duration, and / or, the point occurs for small $\Delta |V|$, the event is classified as 'acceptable'. The graphic is shown in Figure (1) and is discussed at length in [16-18].

Table (1) Common power quality indices

Index	*Definition*	*Main applications*
Total harmonic distortion (THD)	$\left(\sqrt{\sum_{i=2}^{\infty} I_i}\right) / I_1$	General purpose; standards
Power factor (PF)	$P_{tot} / \lvert V_{rms} \rvert \lvert I_{rms} \rvert$	Revenue metering, mitigating losses
Telephone influence factor	$\left(\sqrt{\sum_{i=2}^{\infty} w_i^2 I_i}\right) / I_{rms}$	Audio circuit interference
C message index	$\left(\sqrt{\sum_{i=2}^{\infty} c_i^2 I_i}\right) / I_{rms}$	Communications interference
IT product	$\sqrt{\sum_{i=1}^{\infty} w_i^2 I_i^2}$	Audio circuit interference; shunt capacitor stress
VT product	$\sqrt{\sum_{i=1}^{\infty} w_i^2 V_i^2}$	Voltage distortion index
K factor	$\left(\sum_{h=1}^{\infty} h^2 I_h^2\right) / \sum_{h=1}^{\infty} I_h^2$	Transformer derating
Crest factor	V_{peak} / V_{rms}	Dielectric stress
Unbalance factor	$\lvert V_- \rvert / \lvert V_+ \rvert$	Three phase circuit balance
Flicker factor	$\Delta V / \lvert V \rvert$	Incandescent lamp operation; bus voltage regulation; sufficiency of short circuit capacity

Table (2) Duration of short-term voltage variations using IEEE 1159
(Durations shown in milliseconds for a 60 Hz system)

	Category of short duration variation		
Type of variation	Instantaneous	Momentary	Temporary
Interruption		8.33 – 3000	3000-60000
Sag	8.33 – 500	500 – 3000	3000-60000
Swell	8.33 – 500	500 – 3000	3000-60000

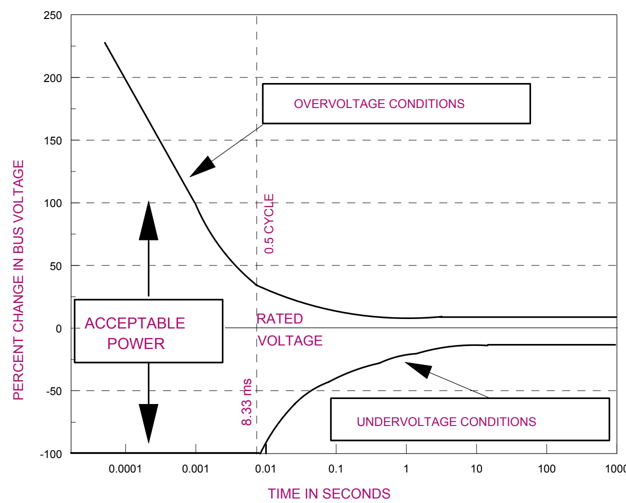

Figure (1) The CBEMA power acceptability curve

The foregoing has been a quick introduction of two types of power quality evaluation, the power quality index and the graphical acceptability curve. A third type is related to event counts: a popular method of evaluating service performance is through the simple count of 'events' such as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and the System Average RMS (Variation) Frequency Index Voltage Threshold (SARFI). These measures are defined as:

For sustained interruptions:

- SAIFI = (*Total number of interruptions*) / (*Total number of points of delivery monitored*)

For disturbances in general:

- SAIDI = (*Total duration of all interruptions*) / (*Total number of points of delivery monitored*)
- SARFI$_{\%V}$ = (*Summation of the number of customers experiencing rms < %V for variation* k (rms > $\%V$ for $\%V > 100$)) / (*Total number of customers*)

For the above indices, temporary interruptions only are to be counted. In order to quantify voltage sags, subsets of SARFI$_{\%V}$ are used, defining indices according to IEEE 1159:

- SIARFI$_{\%V}$ = (*Summation of the number of customers experiencing rms < %V for instantaneous variation* k (rms > $\%V$ for $\%V > 100$)) / (*Total number of customers*)
- SMARFI$_{\%V}$ = (*Summation of the number of customers experiencing rms < %V for momentary, i.e.*

30 cycles to 3 seconds, variation k (rms > %V for %V >100)) / (*Total number of customers*)

- STARFI$_{\%V}$ = (*Summation of the number of customers experiencing rms < %V for temporary, i.e. 3 to 60 seconds, variation k* (rms > %V for %V >100)) / (*Total number of customers*)

Event-count indices have the advantage of ease in instrumentation and convenient comparison. Some electric utility companies set power quality targets on the basis of event-count indices. However, event-count power quality indices can not be translated easily (or accurately) into loss of load data. The most elusive of questions, namely the cost of power quality, is poorly depicted by event-count indices. It seems that tailored CBEMA-like curves, generated for specific load types and specific load dynamics, have a potential of capturing load response and load survival. Cost of events, also, can be estimated albeit the estimates of cost are only as accurate as the data used for the cost of a typical power quality disturbance.

III. Power quality and reliability

Power quality appears to relate to the ability to use delivered electrical energy. If the energy can be used, the power quality is high. If the energy delivered can not be used easily, the power quality is low. Power system reliability also relates to energy use. Reliability, however, is often couched in terms of outages and failures. In many cases reliability may be analyzed as a progression of the system status from state to state in a Markov fashion. Figure (2) illustrates the point.

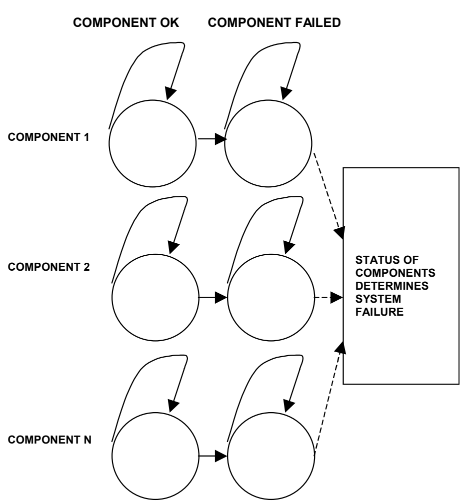

Figure (2) A Markov representation of system reliability

Reliability is related to power quality in the sense that:

- Momentary outages may be the results of component failure or misoperation
- Some momentary power quality events (as in IEEE 1159) are the results of degradation of reliability

Some methods of increasing system reliability have power quality consequences.

With respect to the use of alternate or distributed generation (DG) to improve power network reliability, note that a most appropriate use of DG is to access a truly independent source of electric power – that is independent of the electrical network. This raises the reliability considerably as compared with the use of double or triple service feeders. This is the case because service feeders are generally ultimately derived from the same energy source, and the multiple feeders are not truly independent sources. Table (3) list some DG sources. Note that in most of these cases, there is an electronic interface of the source and the AC distribution system. This electronic interface causes the appearance of harmonics and potential control issues.

Table (3) Alternatives for distributed generation

Type of distributed generation	*Interface with AC distribution system*
Fuel cells	DC / AC converter, fixed power control
Micro turbines	High frequency AC / line frequency AC converter
Photovoltaic sources	DC / AC converter, fixed voltage control
Wind turbines	AC/AC converter
Combustion turbines	Synchronous generator

IV. Power quality and the Caribbean region

Figure (3) shows a map of the Caribbean region. Selected regions are listed in Table (4) with certain primary distribution data [19]. It is reasonable to note that the standards of design in the region are mixed in type. The electrical needs at the residential and commercial level are mainly in heating ventilating and air conditioning (HVAC), lighting, and small rotating loads. At the industrial level, a full range of rotating loads are used in light to heavy manufacturing.

Figure (3) The Caribbean region

Table (4) Power distribution for selected islands in the Caribbean region

	Nominal frequency (Hz)	Residential / light commercial secondary distribution voltage (V)	Standards used
Cuba	60	110 and 220	Local
Puerto Rico	60	120	ANSI, IEEE
Dominican Republic	60	110	ANSI, IEEE
Haiti	60	110	Mixed
Jamaica	50	110	British National
Trinidad and Tobago	60	115	British National
US Virgin Islands	60	120	ANSI, IEEE
Bahamas	60	120	British National
Guadalupe and Martinique	50	230	IEC
St. Lucia	50	240	British National

For historical reasons, the region is tied to the outside world politically, culturally, and economically – but in diverse ways. For example, there are French islands in the region and these islands are departments (states) of France. Puerto Rico is a commonwealth within the United States. Many islands are part of the British Commonwealth. In fact, there are few islands in the Caribbean with a truly independent socio-econonomic and engineering system. However, the nature of the region does dictate some commonality. Fore example, most of these islands heavily rely on tourism as an economic engine. This industry entails heavy HVAC loads. Food processing is also a main element of the economy, and this industry relies heavily on computer controlled rotating loads. The region has a wide range of modernization from the archaic to the latest technology; but it is fair to say that from the point of view of power distribution, adjustable speed drives and computer controlled rotating loads are becoming very common (especially in Puerto Rico). Lighting loads are often of the electronic ballast fluorescent type. Table (5) shows some characteristics of electronic ballast fluorescent lighting.

Table (5) Electronic ballast fluorescent lighting

Energy consumption / efficiency	Low energy demand, common power for individual lamps in the 14 W range, high efficiency up to 10 times more efficient than incandescent
Load current	High harmonic distortion, up to 150% THD for first generation types, in the range of 30 – 100% for second generation, high third harmonic which ultimately appears in the primary distribution as zero sequence current
Life	Long life, in the 10,000 range, much better than incandescent. Even considering high initial cost, the long life and low energy consumption gives very short payback time for retrofits

HVAC loads in the region are generally of the conventional induction machine type. However, there has been a slow penetration of adjustable speed drives (ASD) into the HVAC market generally. In the Caribbean, investment funds are often in short supply, and the high cost of ASD heat pumps and HVAC equipment has made deployment of ASD technologies slow. In the neighboring United States, ASD heat pumps also have been slow in acceptance despite considerable savings of energy. Typical ASD heat pumps offer a relative coefficient of performance, COP_{rel}, of about 5. The COP_{rel} is given by

$$COP_{\mathrm{rel}} = \frac{(heat\ \ energy\ \ moved)/(electric\ \ energy\ \ used)|_{for\ \ ASD\ \ heat\ \ pump}}{(heat\ \ energy\ \ moved)/(electric\ \ energy\ \ used)|_{conventional\ \ heat\ \ pump}}$$

An interesting feature of several of the specialized load profile of the region is that there exists a number of electronic energy saving loads in place, and / or, the number of such electronic energy saving loads is increasing. This trend suggests that attention needs to be given to the potential for third harmonic currents in the three-phase primary distribution system. These high third harmonic currents can cause unsafe conditions for cases of undersized neutral conductors and transformer fittings.

A further observation is that industrial computer controls in the region may require special attention relating to momentary low voltage conditions. The use of DG as a measure to produce very high reliability is especially needed when the use of multiple feeder supplies is ineffective. In insular power systems, the majority of multiple feed designs are especially closely linked and therefore may warrant the application of DG. As an example, Figure 4 shows the effects of addition of service feeders to a load. In the figure, the vertical axis indicated the 'number of nines' of the reliability (e.g., 0.99 is two nines, 0.999 is three nines). Note that if the system reliability is p (and probability of failure is 1-p), then the 'number of nines' is N_9,

$$N_9 = -\log_{10}(1-p) = -\log_{10}(q)$$

In Figure 4, the factor d is the dependence of additionally supplied feeders on previous feeders (d is zero when there is total independence of feeders). In insular systems, it is expected that d would be high representing a high degree of dependence of supply feeder sources. There are several industries in which high and hyper reliability is required, such as in the financial services industry (e.g., in Puerto Rico and the Cayman Islands) and in certain process control industries (e.g., the rum distilling industry of many islands in the Caribbean).

V. Areas that deserve special attention

The review of electric power quality concludes with a conjecture on the identification of areas in power quality engineering that deserve special attention. These are offered as:

The cost of power quality: this is an issue of much debate. It is unclear whether establishing a cost of power quality will help in allocating funds for system design, but the present trends in deregulation seem to so indicate. The problem with this approach seems to lie in the inaccuracies and high variability in assigning costs of power quality degradation.

The impact of high power electronic converters of innovative design: although bridge rectifiers and inverters have been known for a long time, these devices are becoming less a choice even at high power levels. This is due to advances in innovative power electronic designs. For example, pulse width modulated converters seem to offer great advantages in control and low harmonic impact to loads. But the impact of these devices on the power supply has not been fully explored. The same remark applies to the simple integral cycle converter (see Figure 5). The integral cycle controller may have special interest to developing countries because of the simplicity of design.

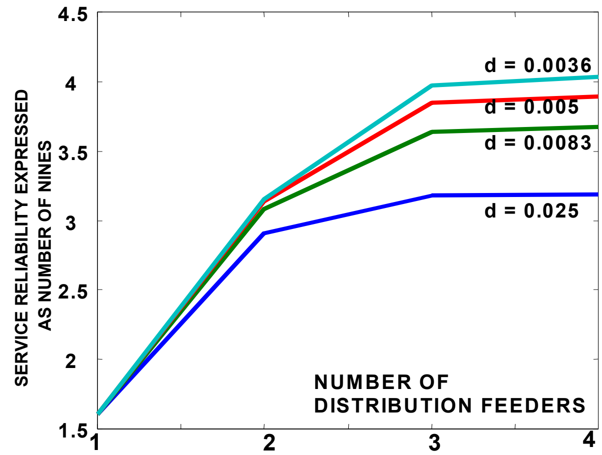

Figure 4 Reliability of a distribution service, expressed in number of nines (N_9), for the addition of primary feeders each having availability 0.975

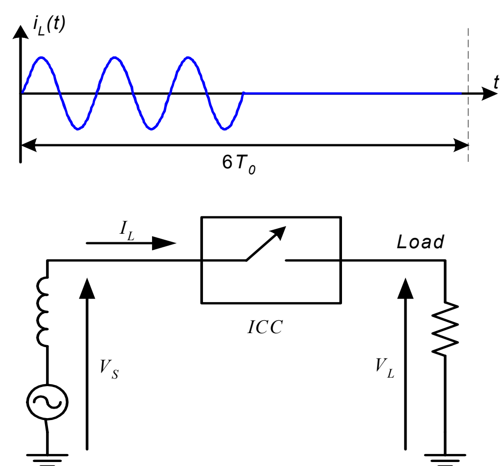

Figure 5 Integral cycle controller with three cycles 'on' and three cycles 'off'. T_o is one cycle length

High and hyper reliability: as indicated in this paper, high reliability and hyper reliability may require the use of DG. Many DG sources have attendant power quality implications.

End use designs with low vulnerability to power quality degradation: this is the inverse problem to power quality improvement. The concept is to harden end use designs to be less sensitive to power quality degradation.

VI. Conclusions

This paper is mainly a review of power quality issues. The topics highlighted are momentary events (mainly voltage sags), and harmonics in power systems. Certain special issues related to the Caribbean region have been identified as the utilization of high efficiency electronic switching at the end use, electronic lighting, and ASD heat pumps for HVAC. The areas that are projected as deserving special attention are:

- The cost of power quality
- The impact of high power electronic converters of innovative design
- High and hyper reliability
- End use designs with low vulnerability to power quality degradation.

Because Spanish and French are also widely spoken in the Caribbean region, the conclusions above are repeated in those languages.

Este artículo es una revisión sobre asuntos de actualidad en calidad de potencia eléctrica. Los problemas presentados son eventos momentáneos (principalmente depresión del voltaje), y armónicas en sistemas de potencia. Ciertos asuntos especiales relacionados con la región del Caribe se han identificado tales como la utilización de conmutadores electrónicos de alta eficiencia en las cargas, la iluminación electrónica, y los ASDs para HVAC. Los puntos principales que merecen atención especial son:

- El costo de la calidad de potencia
- El impacto de los convertidores electrónicos de la alta potencia de diseño innovador
- La confiabilidad alta o ultra-confiabilidad
- Diseños con vulnerabilidad baja a la degradación de la calidad de potencia.

Cet article est principalement un examen des issues de qualité de puissance. Considérés ici sont des événements momentanés (principalement fléchissements de tension), et des harmoniques dans des systèmes d'alimentation. Certains points spécifiques à la région des Caraïbes ont été identifiés: équipements électroniques de rendement élevé; éclairages électroniques; et climatiseurs électroniques. Les points qui sont projetés comme méritant une attention particulière sont:

- Le coût de la qualité de puissance
- L'impact des convertisseurs électroniques de puissance élevée de conception innovatrice
- Haute et hyper fiabilité pour l'utilisation finale
- Equipment d'utilisation finale a vulnerabilité faiable vis- à-vis de la qualité de puissance.

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