Power Quality Measurements: Bringing Order out of Chaos

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Significance
Part 6: Textbooks, tutorials, and reviews

The quality of the power supplied to sensitive electronic equipment is an issue that has been debated since the 1970s. This paper presents the perspective as of the mid-eighties, reporting on the progress toward developing power quality-related standards, giving emphasis to the technical aspects of the measurements, specifically field measurements of power quality.

After reviewing site surveys and their deficiencies or ambiguities, a plea is presented for improving the usefulness of such surveys by developing uniform procedures and instrumentation algorithms. This need was eventually fulfilled by the development of IEEE Std 1159 on Power Quality Measurements, and reaching the IEC with a standard on the same subject, IEC 61000-4-30:2003, “Testing and Measurement techniques - Power quality measurement methods.”

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POWER QUALITY MEASUREMENTS: BRINGING ORDER OUT OF CHAOS

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ABSTRACT - The quality of the power supplied to sensitive electronic equipment is an important issue. Quantifying this quality, however, is difficult under the present state of nonexistent or uncoordinated standards concerning two related questions: (1) what levels of power quality are required for what types of loads, and (2) what measurement techniques are required to determine reliably the level of disturbances that reduce quality. Development of standards by the consensus process and voluntary compliance, although a slow process, is a mechanism for reaching technically sound and cost-effective solutions. Several standards projects are in progress, but need an industry-wide support to become the generally accepted basis for valid and useful measurements of power quality.

INTRODUCTION

The issue of Power Quality has gained increased recognition as the result of two unrelated but parallel developments: (1) an increase in the sophistication of electronic systems, sometimes resulting in an unintentional increase in their sensitivity to power supply disturbances, and (2) an increase in the number and power rating of power conversion equipment, generally resulting in the distortion of the power system voltage. Improvements in the situation described as "poor power quality" can be achieved by reducing the sensitivity of equipment to power line disturbances, or by limiting the injection of disturbances -- or better yet, by reducing both in a coordinated approach. While these remedies might seem obvious in principle, their implementation (enforcement) appears more difficult. Voluntary standards provide a guide for such an implementation. To that end, three types of standards are necessary. The first concerns measurements, to obtain correct and universally acceptable data. The second concerns equipment performance, to define both its tolerance to disturbances and its limits on emission of disturbances. The third concerns acceptable disturbance levels on the utility supply, to promote compatibility of equipment with the utility supply. These standards are developed by reconciling purely technical objectives with economic reality. For a standard to be effective and acceptable, both aspects must have an accurate basis. This paper gives emphasis to the technical aspects of the measurements, specifically field measurements of power quality.

THE GOAL: MATCHING EQUIPMENT CAPABILITY WITH POWER QUALITY

To achieve a satisfactory operational environment regarding power quality, a coordinated approach is needed to match the characteristics of equipment with those of the power supply. The concept of matching is important: it implies actions on both sides of the issues, not unilateral demands for corrective action based on a posture that the other party is the offender. Three approaches will lead to this matching, separately or in combination:

1. Increasing equipment tolerance for disturbances,
2. Controlling the emission of disturbances by equipment, (utility equipment as well as end-user equipment)
3. Providing interface devices when necessary.

Each of these three approaches requires accurate information on power supply disturbances for any action to be effective. Action can be preventive, when a potential problem is identified before new equipment is installed. Action can be curative, when a problem arises after new equipment is installed. The problem can appear in two forms: (1) the new equipment is sensitive to disturbances already present in the system (the equipment is the *victim*); (2) the new equipment creates a disturbance that affects equipment already in service (the new equipment is the *offender*).

These two terms used to label the situation reveal the adversarial postures that can exist. In an ideal world, one would consider total system goals to optimize economical and technical solutions, rather than point fingers. In the real world, cooperation can lead to a mutually satisfactory solution between the *source* and the *receiver* of disturbances (note the neutral words) in contrast with the other labels.

The first step towards recognizing the need for improving the power quality situation is to determine the level of disturbances occurring in the system. The parameters characterizing a power supply are: frequency, voltage amplitude, waveform, and symmetry. Therefore, the nature of disturbances may be classified by their effect on these four parameters. The severity of disturbances is associated with their amplitude, their duration, and the probability of occurring at a given site over a time period.

The level of disturbances is determined by measurements conducted at the site of an existing installation or at a future installation of potentially sensitive equipment. These measurements are described as "site surveys." If the tolerance of the equipment for disturbances is defined (a need that is not always recognized) and the level of disturbances determined by the site survey is excessive, then the three matching actions mentioned above come into play. Any one of the three, or a combination, can be the most effective solution. Knowledge of the situation will point toward a solution, rather than reliance on a common misconception that providing a simple interface (line conditioning) will solve all problems. This misconception is nurtured by frequent observations that many problems have in fact been solved by simply inserting a line conditioner. However, one should not yield to the temptation of making a general rule from these isolated success stories, and ignore other, more effective or more economical approaches achieving inherent compatibility.

Because this additional line conditioning equipment may require significant capital investment, the choice of corrective measures is made by economic trade-off. However, if technical inputs to this trade-off are incorrect because erroneous conclusions result from a faulty site survey, the whole process is worthless or misleading. For this reason, a good understanding of the merits and limitations of site surveys is essential for reconciling expectations with reality before specifying expensive line conditioning equipment. In their review of power quality site surveys, Martzloff and Gruzs [1] discussed how one should deal, not with fiction or fallacies, but with facts.

In an attempt to clarify the issues, this paper first presents a review of the origins and definitions of disturbances. Next, the development of monitoring instruments during the last 25 years is described. Finally, an appeal is made for improving measurement methods to provide more consistent reporting of power disturbances recorded in future surveys.

CLASSIFICATION AND ORIGIN OF POWER LINE DISTURBANCES

The four power system parameters identified above -- frequency, amplitude, waveform, and symmetry -- can serve as frame of reference to classify the disturbances according to their impact on these four parameters.

Frequency disturbances are associated with power system faults. Interconnection of the utility grid ensures frequency stability, except when a fault occurs that isolates the local system from the grid, leaving local generation more sensitive to load variations. Transient frequency disturbances, just before an outage, occur in a system containing large rotating machines: should the system trip out, the machines will maintain some voltage, with decaying amplitude and frequency, while they coast to a final stop.

Amplitude variations can occur in several forms; their description is inextricably associated with their duration. They range from extremely brief durations to steady-state conditions, making the description and definition difficult, even controversial at times. Their causes and effects need close examination to understand the mechanisms and to define an appropriate solution.

Waveform variations occur when nonlinear loads draw a current which is not sinusoidal. One could also describe an amplitude variation as momentary waveform variation, but the intended meaning of the term is a steady variation of the waveform, or lasting at least over several cycles. This type of disturbance is also described as harmonic distortion because it is easy to analyze as the superposition of harmonics to the fundamental frequency of the power system.

Dissymmetry, also called unbalance, occurs when unequal single-phase loads are connected to a three-phase system and cause a loss of symmetry. This type of disturbance primarily concerns rotating machines, and as such is not receiving broad attention. It is important however, for machine designers and users. The percentage by which one phase voltage differs from the average of all three is the usual description of this type of disturbance.

The origin of disturbances can be described as external to the particular power system, or as internal. In a typical situation, the boundary of a power system is defined as the watthour meter, and reference is made to the utility side of the meter (external source), or to the user side of the meter (internal source). A different approach is to describe the origin in technical terms, such as lightning, load switching, power system fault, and nonlinear loads. Depending on local conditions, one can be more important than the others, but all need to be recognized. The mechanism involved in generating the disturbance also determines whether the occurrence will be random or permanent, unpredictable or easy to define.

Lightning surges are the result of direct strikes to the power system conductors as well as the result of indirect effects. Indirect effects include induction of overvoltages in loops formed by conductors and ground potential rises resulting from lightning current in the soil. A lightning strike to the power system can activate a surge arrester, producing a severe reduction or a complete loss of the power system voltage for one half-cycle. A flashover of line insulators can cause a breaker to trip, with reclosing delayed by several cycles, causing a momentary power outage. Thus, lightning can be the obvious cause of overvoltages near its point of impact, but also a less obvious cause of voltage loss at a considerable distance from its point of impact. Clearly, the occurrence of this type of disturbance is unpredictable at the microscopic level. At the macroscopic level, it is related to geography, seasons, and local system configuration.

Load switching is a major cause of disturbances. Switching large loads on or off can produce long-duration voltage changes beyond the immediate transient response of the circuit. Whether the switching is done by the utility or by the user is immaterial from the technical point of view, although the responsibility may be the subject of a contractual dispute. The occurrence of these disturbances is somewhat predictable, but not necessarily under controlled conditions. The introduction of power conversion equipment and voltage regulators operating by switching on and off at high frequency has created a new type of load switching disturbance. These disturbances occur steadily, although their amplitude and harmonic content will vary for a given regulator as the load conditions vary.

Power system faults occur on both sides of the meter, resulting from equipment failure or external causes (vehicle collisions, storms, human errors). These disturbances can range from a momentary voltage reduction to a complete loss of power lasting for minutes, hours, or days. Their accidental origin makes them unpredictable, although the configuration of a power system and its environment can make it more or less prone to this type of disturbance.

Nonlinear loads draw non-sinusoidal currents from the power system, even if the power system voltage is a perfect sine wave. These currents produce non-sinusoidal voltage drops in the system source impedance which distort the sine wave produced by the power plant generator. A typical nonlinear load is a dc power supply with capacitor-input filter, such as used in most computers, drawing current only at the peaks of the voltage sine wave.

Characterizing these four types of disturbances and disturbance mechanisms involves detection (measurement) of their occurrence and description of the results of these measurements. What might appear a simple process is in fact made difficult by deficiencies in defining disturbances observed when making site survey measurements.

DEFICIENCIES IN DEFINITIONS

One difficulty in coordinating efforts for improving power quality is that terms used to describe power disturbances are poorly defined. An effort is being made by standards writing organizations to resolve this problem, as described later in this paper, but consensus has yet to be reached. The following two examples of this lack of consensus illustrate the point; resolving them is beyond the scope of this paper.

What is a surge? The accepted meaning of surge, in the context of power systems, is a short-duration overvoltage, typically less than a few milliseconds. These surges are caused by lightning, power system switching, or faults. Protection against them is obtained by protective devices called *surge arresters* (formerly called lightning arresters) for utility systems, and *surge suppressors*, or spike suppressors for end-user systems. This first meaning of the word 'surge' is not that established by manufacturers and users of disturbance monitors and line conditioners. The unfortunate second meaning, a consequence of nonexistent standards on the subject, is a momentary overvoltage at the fundamental frequency, with a duration of typically a few cycles. What the designers and users of surge arresters or suppressors calls 'surge' is called 'impulse' or 'spike' by the monitoring instrument community. Figure 1 shows graphic descriptions of the confusion created by the dual meaning of the word 'surge.'

What is an outage? Most users agree that it means a loss of line voltage. The duration of this event, however, is quite different when 'outage' is cited by computer users (as short as one half-cycle), or by power engineers (seconds, perhaps minutes). Furthermore, some users and manufacturers of line conditioners do not make a clear distinction between complete loss of line voltage (zero voltage condition), severe undervoltages ('deep sags'), or the single-phasing of polyphase power systems. Part of the problem may be that the definition of 'outage' has regulatory implications for evaluating the performance of public utility companies.

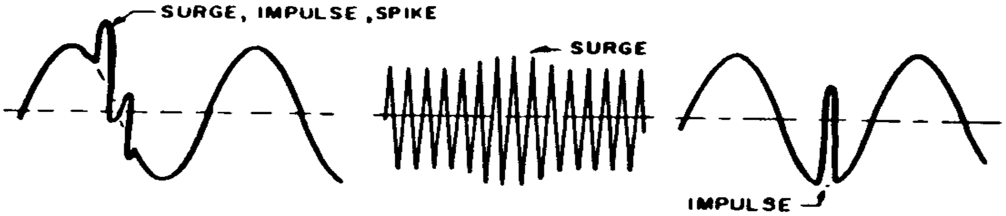

Figure 1 - Graphic illustration of different meaning of 'surges' and other disturbances

As another example of definitions deficiencies, standards dictionaries do not define the term 'sag'. It is accepted as meaning a momentary voltage reduction at the ac power frequency. However, there is no consensus on the details (threshold, duration, etc.) of what characterizes a sag.

With the present definition deficiencies, manufacturers and users of disturbance monitors are left without guidance and consequently define terms independently from each other, hence the confusion. In fact, the development and widespread use of disturbance monitors should motivate a more coordinated and rational approach toward resolving these deficiencies. Progress in technology of monitoring instruments during the last two decades is remarkable and worthy of a brief review.

DISTURBANCE MONITORS DEVELOPMENT HISTORY

Historically, the first (unintended) disturbance monitors were the actual load equipment. Only later, when confronted with unexplained failures or upsets, did the users start monitoring the quality of their power systems. Electric utilities have been monitoring the parameters of their systems, but the precise characterization of microsecond-duration surges in the early 1960s required special oscilloscopes. For the next 15 years, oscilloscopes or simple peak-detectors were the basic instruments for monitoring transient overvoltages. Starting in the 1970s, commercially-produced digitizers became available. Since then, technology has made continuing progress as experience has accumulated.

Early site surveys were limited to voltage measurements. This limited interest reflected concerns for damage to sensitive electronic components connected across the line. Ignoring the importance of the source impedance led to some performance standards [2] that do not specify the current-handling requirements for surge protective devices. With the introduction and widespread application of new clamping protective devices (silicon avalanche diodes or metal oxide varistors), the surge current diverted through these devices became a very important factor for proper device selection. Therefore, the need emerged for characterizing current surges as well as voltage surges, but few surveys to date have addressed this need. This need offers a challenge and an opportunity to designers of monitoring instruments.

This challenge has also produced attempts to measure 'energy' with an instrument which is actually only a voltmeter. By assigning parametric values to the source impedance of the surge and integrating the product (volts · seconds) of the surge, some knowledge of the energy involved would be obtained. Computing true energy, of course, requires the measurement of both voltage and current. However, the real question concerns the sharing of energy between the impedance of the source and the impedance of the load. A discussion of the *energy in the surge* versus *energy delivered to the protective device* is beyond the scope of this paper. The difference between the two must be recognized, however, to prevent further confusion as future monitoring instruments include an 'energy' parameter in their readouts.

With the present development of sophisticated multi-channel digitizing instruments, future surveys should monitor both voltage and current. Note, however, that the current of interest is that which the surge source would force through a surge protective device. The amplitude as well as the waveform of the surges needs to be characterized for the correct application of surge protective devices. Peak-reading monitors provide useful information on surge activity at a given site, but assessment of the surge severity level for the proper sizing of protective devices also requires waveform and source impedance information.

One difficulty facing users of monitoring instruments in this fast-paced technology is that manufacturers are steadily improving their instruments. These improved features respond to specific wishes of the users or result from their own product research and development, a desirable situation. On the negative side, however, data collected by different instruments become equipment-dependent. Comparison of survey results by third parties is then difficult in the absence of details on the instrument characteristics and methods of measurement.

TYPES OF MONITORS

The instruments used in past surveys reflect technology progress as well as logistics constraints, resulting in a diversity of approaches. Until recently, all monitoring instruments were just special voltmeters. Some of the monitors recorded a single parameter, such as the value of voltage peaks, or the occurrence of voltage peaks above a preset threshold. Other monitors combined time with voltage measurements, to characterize the voltage waveforms. The following list shows the evolution of simple surge monitors into complex disturbance monitors.

Threshold counters - The surge is applied to a calibrated voltage divider, triggering a counter each time it exceeds a preset threshold. The early types had analog circuitry; more recent types have digital conversion of signals.

Digital peak recorders - The surge is converted to a digital value and recorded in a buffer memory for later playback. In the early types of recorders, only the peak was recorded. In later types, the duration of the surge was also recorded, opening the way to the more complex digital waveform recorders now available.

Oscilloscope with camera - The surge triggers a single sweep on the cathode ray tube of the oscilloscope, and is recorded as it occurs by an automatic shutterless camera.

Screen storage oscilloscope - The surge is displayed and stored on the cathode ray tube, and a camera is used for permanent recording after the surge has occurred. The writing speed capability of these oscilloscopes was a limitation in the late 1960s.

Digital storage oscilloscope - The surge is digitized and stored in a shift register for subsequent playback and display whenever it exceeds a preset threshold. An important feature is the capability of displaying events occurring before the beginning of the surge.

Digital waveform recorder - With the advent of compact, portable instruments, a revolution has taken place in the field of disturbance recorders. The earlier surge waveform recorders were large and difficult to transport to field sites [3], [4]. New microprocessor-based instruments have introduced a portable storage and computing power which has made waveform analysis and graphic display possible. In these instruments, voltage and current signals are digitized and stored, allowing reports of many different parameters of the disturbance. The range of parameters which can be monitored is expanded, long trends can be detected, harmonic analysis can be performed, and the types of possible measurements are limited only by the creativity of the instrument designers and the curiosity of the users.

Although some site surveys might aim at high accuracy, the real world experiences an infinite variety of disturbances, making it difficult to fit them into simple, orderly categories. Any attempt to describe these disturbances in fine detail restricts general usefulness of the data and can lead to illusions on applicable accuracy. Some simple (and inexpensive) instruments are useful indicators of frequent disturbances. Other instruments, more complex (and more expensive), provide comprehensive data on disturbances. A general observation from many surveys conducted by different researchers is that results vary widely from site to site. Thus, there is a practical limit to the detail that a survey can yield, and unrealistic expectations of precise information should be avoided. What is really needed is a more uniform and compatible recording and reporting of the data.

COMPARISONS AMONG SITE SURVEY REPORTS

Relative occurrence of different types of disturbances. Two site surveys have been widely cited. One was performed in the early 1970s by Allen and Segall [5], the other in the late 1970s by Goldstein and Speranza [6]. Each of these surveys presented results by describing various kinds of disturbances (overvoltages, sags, etc.) and cited the percentages of each type of disturbance in the total of all the observed disturbances. The findings did not at first appear to agree, raising questions on the likelihood of a change in power systems between the first and second survey. However, a detailed comparison of these two surveys [1], revealed that the disagreement was rooted in a difference of the thresholds built into the monitors, rather than a change in the behavior of power systems.

Differences in surge amplitudes. Amplitudes of surges reported in several surveys vary over a wide range. Comparisons are difficult because the reports do not present the data in a uniform format. Attempting to get a quantitative comparison of the amplitudes reported seems a futile exercise, because of the following reasons:

1. Looking at the 'maximum values' cited in the reports, one finds that in some surveys this maximum is actually a value known only as being above the range of the instrument, while for others it is the measured value.

2. Because the threshold of the recorder varies among surveys, and the frequency of occurrences increases dramatically with a lower threshold, the labels of average, median, most frequent, typical, etc., are not meaningful for comparing amplitudes.

Differences in surge waveforms. What a 'typical' surge might be has been the subject of many discussions. Several surveys confirm the finding of ringing waves, as opposed to the traditional unidirectional impulses. However, wide differences still exist among the reports. The following examples illustrate this point.

Martzloff-Hahn [7] were among the first to report ring waves, recorded by 1960 vintage oscilloscopes. Their findings were incorporated into the data that resulted in the selection of a 100 kHz ring wave for the UL Standard *Ground Fault Circuit Interrupters* [8] and the IEEE *Guide on Surge Voltages* [9].

Odenberg and Braskich [10] used different instruments recording only two points of the waveform: (1) the peak amplitude and time to peak, and (2) the time to 50% of the peak amplitude. As such, this description is not a complete waveform. Furthermore, they reported that 90% of their 250,000 recordings show the 50% point occurred between 900 and 1100 microseconds. This finding is unique among all the surveys.

Wernstrom et al. [11] report ring waves of 500 kHz, bursts of fast transients lasting a few microseconds, and even some unidirectional isolated impulses.

Goedbloed [12] is more concerned with interference than damage; his report gives emphasis to amplitude, rate of rise, and 'energy', rather than to waveform.

With the advent of portable monitors capable of presenting the digitized data with graphic details as well as summaries, an explosion in the volume of data can expected. Just the detail and weight of the information being collected might swamp the researchers, unless data reduction procedures are implemented. However, whenever data reductions are performed by different persons, there is a high probability that criteria for reduction will be different, making comparisons difficult, even impossible. Thus, this increased sophistication of available instrumentation makes coordination even more imperative. The added availability of harmonic analysis by portable monitors will also lead to an expansion of data supporting standards on harmonic control [13].

Agreement and disagreement on rate of occurrence versus levels. Several survey authors have attempted to fit a classic statistical distribution or a simple relationship between the rate of occurrence of surges and their amplitude. The motivation for such a simplified presentation might be rooted in a belief that nature obeys simple mathematical laws. The reality, however, is that so many different mechanisms contribute to the generation of surges that a simple relationship is unlikely. Notwithstanding this rationale, a remarkable finding emerges from plotting the results of all the surveys on the same graph. Figure 2 shows the relative distributions of the findings, normalized for voltage level and frequency of occurrence for each survey report. The *slope* of the lines is what can be compared, not the absolute rate of occurrence. It is remarkable that slopes are similar among the surveys, although the absolute frequency of occurrence is site-dependent.

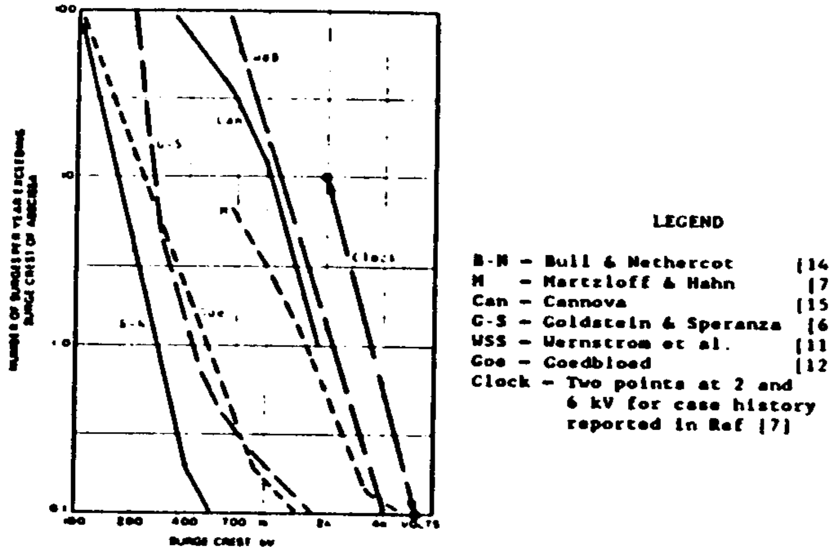

Figure 2 - Rate of surge occurrence as a function of peak voltage

WORKING TOWARD MORE CONSISTENT SURVEYS

The ambiguities plaguing the field of site surveys have become apparent to many interested researchers, resulting in the formation by IEEE of a new Working Group on Monitoring Electrical Quality. The scope of a Recommended Practice being prepared by this group reads:

> This Recommended Practice concerns the application of instruments used for monitoring electrical disturbances on power systems. The scope includes the definition of disturbance terms, the calibration and connection of the instruments, and the interpretation and reporting of the results. It does not include specific design aspects of the instruments.
>
> The disturbances of interest are those conducted on ac power lines for single or polyphase systems with direct operating voltage connections to the instruments not exceeding 1000 V RMS. Depending on the design of the instruments, the duration of the recorded disturbances may range from nanoseconds to many seconds, or more.
>
> While the prime interest is focused on monitoring low-voltage ac power systems (50, 60 or 400 Hz), suitable interfaces may allow monitoring systems of higher voltage; dc systems may also be monitored with these instruments. It is also recognized that available instruments may be capable of monitoring other parameters such as radiated EMI or environmental conditions; however, the scope of this document is limited to conducted electrical parameters (voltage, current, and derived parameters).

EXPECTATIONS VERSUS REALITY ON POWER QUALITY

Improved credibility of power quality data offers an opportunity to revisit existing standards or develop new standards dealing with power quality. Three areas would benefit from this review:

1. **More realistic definitions of the limits of system voltages.** The limits currently defined are relatively small percentages (5 to 15%) of nominal values. Many anecdotal stories have been told on momentary overvoltages exceeding the limits of the only standard addressing these limits, ANSI C84.1 [16]. Until well documented, these stories can only remain anecdotal. However, ignoring them can lead to misapplication of surge protective devices by attempting to suppress surges at a level too close to the momentary overvoltages that do occur.

2. **Improved consensus on the characteristics of surges.** The IEEE Guide on Surge Voltages [9], dating back to 1980, attempted to simplify the situation by describing the surge environment with only two waveforms and an upper practical limit. Unfortunately, this Guide was misconstrued by some users as a mandatory standard. A revision is underway, proposing two additional waveforms and presenting the information in a manner that should discourage the misguided use of the document as a performance standard.

3. **Improved Consensus on harmonic control.** Harmonic causes and effects have been the subject of many studies and technical papers, but no performance standard exists to settle potential disputes between sources and receivers of harmonic distortion. The prevailing document is a Guide [13]; significant improvements are expected from a revision currently being conducted.

CONCLUSIONS

Power quality measurements, typically performed by site surveys, have evolved from the simple monitoring of surge voltages to the sophisticated analysis of many criteria of power quality. There is still room for improvement in the procedures -- an improvement that can be guided by voluntary standards. Detailed observation of the issues lead to the following conclusions:

1. **Considerable progress** has been made in the recording capability of monitoring instruments as the result of progress in the hardware and software used in digitizing systems. Improvements include multi-channel synchronized recording of different parameters, fast data acquisition, automated data reduction, and improved resolution.

2. **Improvements in consistency** must be made, commensurate with the steady progress and expanded capability of instruments. This greater consistency is needed in the definitions of the disturbance parameters and the methods of application of the monitoring instruments.

3. **Site-to-site variations** in the occurrence of disturbances prevent making precise predictions for a specific site from an overall data base.

4. Differences among results indicated by a cursory comparison can be resolved by a closer examination of the conditions under which the surveys were conducted. However, some differences are less likely to be explained if raw data have been processed and the initial parameter measurements are no longer available for review.

5. A new IEEE Working Group on Monitoring Electrical Quality has been formed with a broad scope that encompasses this process of improving consistency in definitions and interpretation of power disturbances. In addition, the IEEE Working Group on Surge Characterization is also attempting to obtain a broader data base for the revision of the *Guide on Surge Voltages*.

6. Improved cooperation, promoted by the process of voluntary standards development and the exchange of ideas made possible by forums such as the Energy Technology Conference, will avoid some of the difficulties on sharing the data pool recited in this paper. This paper is presented in support of this effort and to promote greater participation among interested workers and users.

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