Assessing Distribution System Transient Overvoltages due to Capacitor Switching

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Abstract - **Characterizing power quality levels on power systems has become extremely important with the increased sensitivity of customer load equipment to momentary interruptions, voltage sags, and transient voltages. EPRI has performed an extensive monitoring project that has resulted in a statistical database of power quality levels on distribution systems in the United States. This paper will present statistical analysis of the identified capacitor switching transient overvoltages, with particular focus on the peak magnitude of the transient, event duration, principal switching frequency, and hour of day of occurrence.**

Keywords: capacitor switching, power capacitors, power quality, power system monitoring, statistical databases.

I. INTRODUCTION

The application of utility capacitor banks has long been accepted as a necessary step in the efficient design of utility power systems. Capacitor switching is generally considered a normal operation for a utility system and the transients associated with these operations are generally not a problem for utility equipment. These low frequency transients, however, can be magnified in a customer facility (if the customer has low voltage power factor correction capacitors) or result in nuisance tripping of power electronic based devices, such as adjustable-speed drives (ASDs). Capacitor energizing is just one of the many switching events that can cause transients on a utility system. However, due to their regularity and impact on power system equipment, they often receive special consideration.

Transient overvoltages and overcurrents related to capacitor switching are frequently classified by peak magnitude, frequency, and duration. These parameters are useful quantities for evaluating potential impacts of these transients on power system equipment. The absolute peak voltage, which is dependent on the transient magnitude and the point on the fundamental frequency voltage waveform at which the event occurs, is important for dielectric breakdown evaluation. Some equipment and types of insulation, however, may also be sensitive to rates of change in voltage or current. The transient frequency, combined with the peak magnitude, can be used to estimate the rate of change.

There are a number of transient related concerns that are generally evaluated when transmission and distribution shunt capacitor banks are applied to the power system. These concerns include insulation withstand levels, switchgear ratings and capabilities, energy duties of protective devices, and system harmonic considerations. In addition, these considerations need to be extended to include customer facilities due to the increased use of power electronic based end-user equipment. Application concerns often evaluated include:

- overvoltages associated with capacitor energizing.
- open line/cable end transient overvoltages
- phase-to-phase transients at transformer terminations
- voltage magnification at lower voltage capacitor banks (including customer systems).
- arrester duties during restrike events
- current-limiting reactor requirements
- system frequency response and harmonic injection
- impact on sensitive customer power electronic loads
- ferroresonance and dynamic overvoltage conditions

Power quality symptoms related to utility capacitor switching include customer equipment damage or failure, nuisance tripping of adjustable-speed drives or other process equipment, transient voltage surge suppressors (TVSS) failure, and computer network problems.

II. CHARACTERISTICS OF CAPACITOR SWTICHING TRANSIENTS

Transient characteristics are dependent on the combination of the initiating mechanism and the electric circuit characteristics at the source of the transient. Circuit inductances and capacitances — either discrete components such as shunt capacitance of power factor correction banks or inductances in transformer windings, or stray inductance or capacitance because of proximity to other current carrying conductors or voltages — are responsible for the oscillatory nature of transients. Natural frequencies within the power system depend on the system voltage level, line lengths, cable lengths, system short circuit capacity, and the application of shunt capacitors.

Energizing a shunt capacitor bank from a predominantly inductive source results in an oscillatory transient that can approach twice the normal system peak voltage (V_{pk}). The characteristic frequency (f_s) of this transient is given in equation 1.

$$f = \frac{1}{2\pi\sqrt{L_s * C}} \approx f_{system} * \sqrt{\left(\frac{MVA_{sc}}{MVA_r}\right)} \qquad (1)$$

where:

f = characteristic frequency (Hz)

L_s = positive sequence source inductance (H)

C = capacitance of bank (F)

f_{system} = system frequency (50 or 60 Hz)

MVA_{sc} = three-phase short circuit capacity (MVA)

MVA_r = three-phase capacitor bank rating (MVAr)

Because capacitor voltage cannot change instantaneously (remembering that i(t)=Cdv/dt), energization of a capacitor bank results in an immediate drop in system voltage toward zero, followed by an oscillating transient voltage superimposed on the 60 Hz fundamental waveform. The peak voltage magnitude depends on the instantaneous system voltage at the instant of energization, and can reach 2.0 times the normal system voltage (V_{pk} – in per-unit) under worst-case conditions. The voltage surge is at the same frequency as the inrush current (I_{pk}) and rapidly decays to the system voltage.

For a practical capacitor energization without trapped charge, system losses, loads, and other system capacitances cause the transient magnitude to be less than the theoretical 2.0 pu. Typical magnitude levels range from 1.2 to 1.8 pu and typical transient frequencies generally fall in the range from 300 to 1000 Hz. Figure 1 illustrates an example (measured) distribution system capacitor energizing transient.

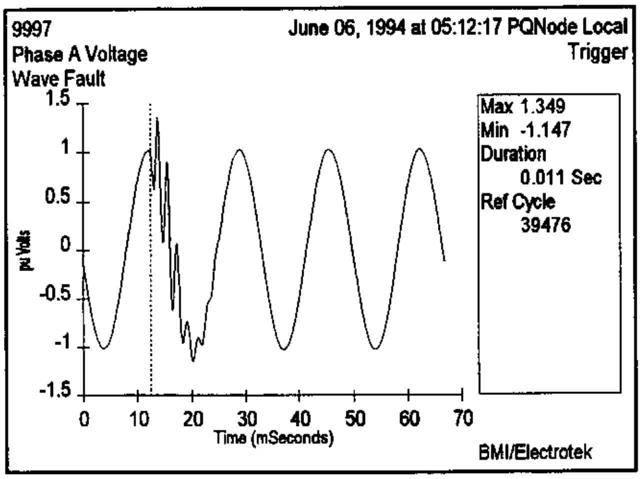


Fig. 1. Typical Distribution Bus Voltage during Capacitor Energizing

III. METHOD FOR DETECTING CAPACITOR SWTICHING TRANSIENTS

This paper presents statistical data based on the final results for a power quality monitoring survey of 277 three-phase measurement locations located on the primary distribution feeders of 24 electric utilities across the United States. The industry knows the project more commonly as the EPRI Distribution System Power Quality Monitoring Project, or the EPRI DPQ Project [4]. This project resulted in the recording of approximately six million steady-state samples and 500,000 triggered measurements. The data collection period was from Jun-01-1993 to Sep-01-1995. The waveforms recorded during the project were triggered by changes in either the rms voltage or the voltage wave shape measured by the power quality monitors. These changes were brought about by system disturbances such as system faults, load switching, lightning strikes, capacitor switching, fuse operations, etc.

A. Wave Shape Triggering Algorithm

The waveshape fault trigger employed a floating window to compare each sample point of the current cycle with the corresponding point of the previous cycle [2]. If a particular sampling point differs from its corresponding point in the previous cycle by 8%, then a counter within the monitoring instrument is incremented. A "waveshape fault" event is triggered when the counter reaches a value that is equivalent to 10% of the power cycle.

Since the power quality monitor for this project was sampling at a rate of 256 points per 60 Hz cycle, 25 points from a waveform needed to differ by 8% for a trigger. The counter will also decrement if the compared points are within an 8% band, but it will not drop below 0. This triggering algorithm resulted in the collection of approximately 320,000 measurements.

B. Wave Shape Fault Characterization

The next step in detecting the capacitor switching measurements required the waveforms to be characterized. Characteristics of each recorded waveform included peak magnitude, duration, and switching frequency. The duration of the disturbance was determined by applying a reversed floating window wave shape fault detection algorithm to the data to determine an end-of-trigger point in the data. The detection algorithm is applied in reverse chronological time to the waveform, starting at the end of the measurement. This characterization was carried out for each voltage phase independently without regard to which phase actually caused the original trigger in the monitor. The measurement's principal frequency was determined by performing an FFT on the first cycle of transient data following the trigger point. The principle frequency was the spectral component with the largest magnitude after the fundamental. Minimum and maximum values were determined by scanning the waveform for positive and negative peaks.

Table. 1. Database query filters used to isolate capacitor transient from the project's waveshape fault events

Database Filter	Criteria
Absolute Peak Magnitude	Between 1.05 and 1.9 pu
Principal Frequency	Between 220 Hz and 3 kHz
Event Duration	< 1 cycle
Date Range	From 3/1/95 to 6/1/95

C. Database Filtering

The final step in detecting transient waveforms that were caused by capacitor switching was to apply a set of database filters to the 330,000 wave shape fault triggered events. The filters applied are listed in Table 1. Only absolute peak magnitudes above 1.05 pu were analyzed to exclude rms voltage swells. No events with peak magnitudes above 1.9 pu were found during the data collection stage that were not proven to be spurious. Frequencies less than 220 Hz were excluded since they were not in the expected range for power capacitors. The 3 kHz cutoff frequency is the higher range to be expected of back-to-back capacitor switching events. Events longer than one cycle were not considered power capacitor switching, since system damping should end the transient within that time.

IV. STATISTICAL ANALYSIS

The statistics in this section are based upon the six months of monitoring during which the full-scale setting for the monitoring instruments was set to ±1000 V, which was from Mar-01-1995 to Sep-01-1995. During that time, 257 different instruments were on-line for a combined 41,674 monitor·days of monitoring. These sites collectively recorded 84,779 wave shape fault measurements, which averages to about two waveshape faults per site per day. Considering that there were three phases for each measurement, a total of 254,337 phase measurements needed to be analyzed. Each phase measurement contained four cycles of voltage data.

The application of the filters listed in Table 1 identified 15,803 wave shape fault measurements (or 47,409 phase measurements) which were recorded due to a voltage transient that resembled capacitor switching. This total includes both the triggered phase and other phases that may or may not have experienced a significant transient. Therefore, 19% of the wave shape fault measurements were determined to be due to capacitor switching. The statistics presented in Figures 2 to 8 are devoted to the analysis of phase measurement events. A phase measurement event is defined to be a single phase of a three-phase measurement. If a capacitor transient appeared on all three phases of a recording, then each is counted individually. These graphs offer statistical gauges on the characteristics of capacitor switching events. The data has been treated using sampling weighting factors described in [4].

A. Peak Magnitude of Capacitor Transients

Figure 2 illustrates the method of determining absolute peak magnitude from a phase measurement typical of those recorded during the EPRI DPQ Project. For each waveform, we can determine a peak magnitude, which can either be the absolute value of the positive or the negative peak depending upon which is larger. In the example provided, a peak of 1.34 pu is identified.

The statistical tool to analyze many of these measurements is a histogram; Figure 2 presents this histogram for the period from Mar-01-1995 to Sep-01-1995. The data represents all sites that were active in the project during that time. The height of each column represents the number of times that a particular peak magnitude was recorded, while the value along the vertical axis provides the peak value itself. The height has been normalized by the 1389.13 monitor·months registered during this monitoring period.

From Figure 3 it can be said that a peak magnitude due to capacitor switching between 1.30 and 1.35 pu (>1.30 and ≤ 1.35 pu) was recorded on average 1.047 times per 30 days per site. The height of all of the columns sums to 14.342 events per month. Additionally, the cumulative frequency can be used to tell us that a capacitor transient larger than 1.35 pu occurred on average 2.158 times per 30 days per site (100%-84.96%)•(14.342 events/month).

B. Duration of Capacitor Transients

Figure 4 illustrates the method of determining duration from a phase measurement typical of those recorded during the project. For each waveform, an ending point is determined by using the reverse wave shape detection method. The start point is determined by the monitoring instrument at trigger time and is stored in the resulting measurement record. In the example provided, a duration of 0.011 seconds is calculated.

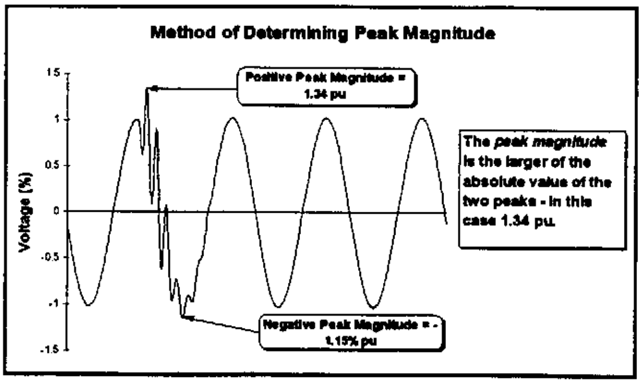


Fig. 2. Method of Determining Absolute Peak Magnitude

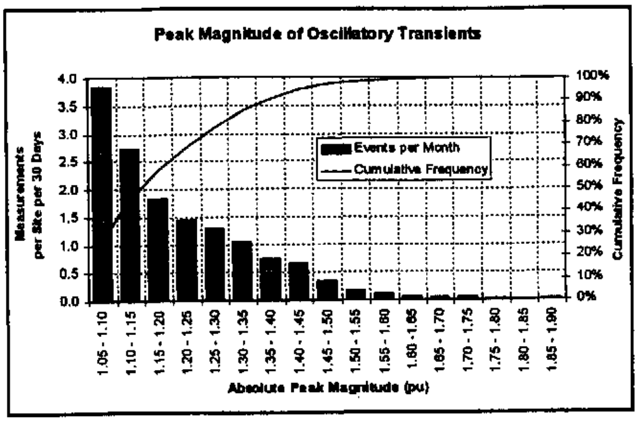
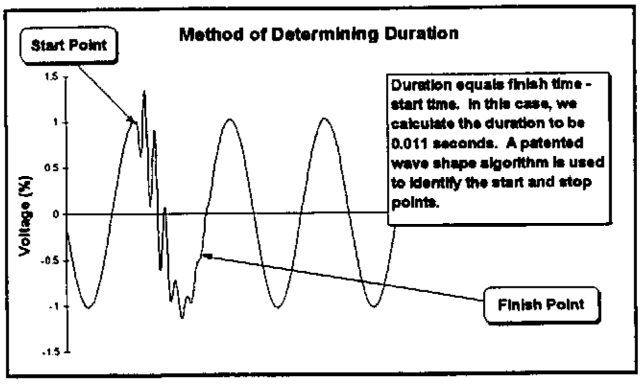


Fig. 3. Histogram for Magnitude of Oscillatory Transients, Phase Measurement Events, 3/1/95 to 9/1/95, Treated by Sampling Weights, All Sites



Duration equals finish time - start time. In this case, we calculate the duration to be 0.011 seconds. A patented wave shape algorithm is used to identify the start and stop points.

Fig. 4. Method of Determining Duration

Figure 5 presents the duration histogram for the period from Mar-01-1995 to Sep-01-1995. The data represents all sites that were active in the project during that time. The height of each column represents the number of times that a particular duration was recorded, while the value along the vertical axis provides the duration value itself. The height has been normalized by the 1389.13 monitor-months registered during this monitoring period.

From Figure 5 it can be said that a duration of a capacitor switching measurement between 7.0 and 8.0 ms (>7.0 and ≤ 8.0 ms) was recorded on average 1.226 times per 30 days per site. Additionally, the cumulative frequency can be used to tell us that a transient longer than 8.0 ms occurred on average 2.315 times per 30 days per site (100%-83.86%)•(14.32 events/month).

C. Principal Frequency of Capacitor Transients

Figure 6 illustrates the method of determining principal frequency from the measurement depicted in Figure 2. For each waveform, we perform an FFT upon the first cycle, resulting in a spectral series. The FFT groups the data in bins that are integer multiples of the fundamental (60 Hz) component. Then we search for the component that is largest in magnitude after the fundamental, assuming it to be the principal frequency of the capacitor transient oscillation. In Figure 6, the component that rises above all others is centered at 540 Hz.

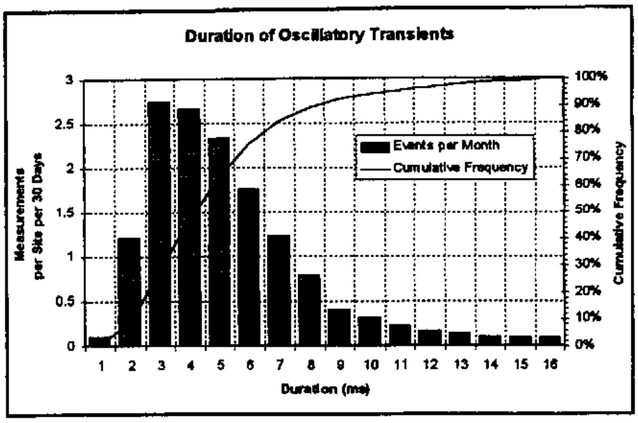
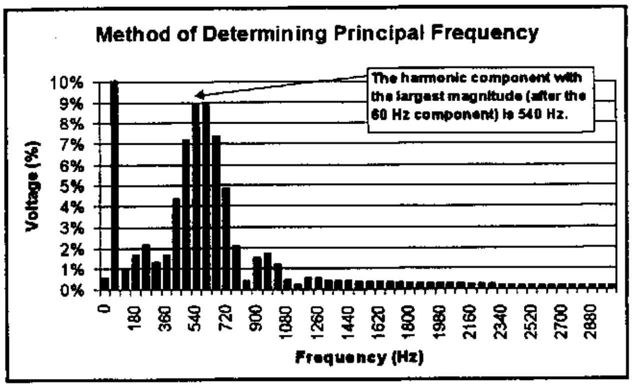


Fig. 5. Histogram for Duration of Oscillatory Transients, Phase Measurement Events, 3/1/95 to 9/1/95, Treated by Sampling Weights, All Sites



The harmonic component with the largest magnitude (after the 60 Hz component) is 540 Hz.

Fig. 6. FFT of Example Capacitor Switching Waveform

From Figure 7 it can be said that a principal frequency of a capacitor switching measurement centered at 420 Hz was recorded on average 1.682 times per 30 days per site. Additionally, the cumulative frequency can be used to tell us that a transient with a principal switching frequency less than 780 Hz occurred on average 11.681 times per 30 days per site.

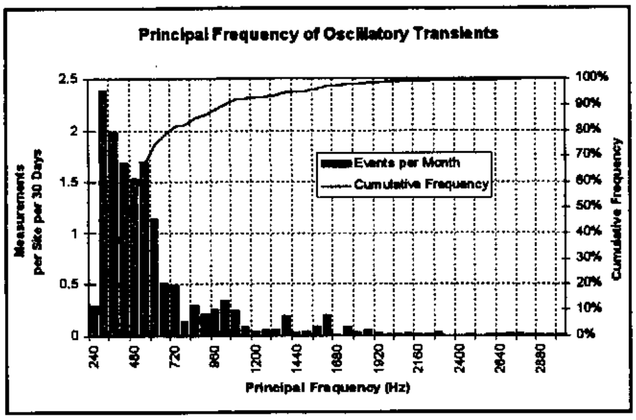


Fig. 7. Histogram for Frequency of Oscillatory Transients, Phase Measurement Events, 3/1/95 to 9/1/95, Treated by Sampling Weights, All Sites

D. Hour of Day of Capacitor Transients

The time of day that a capacitor bank energizes is interesting because many utilities use a clock to switch certain banks in and out of service at key points during the day. Frequently, a bank will be energized early in the morning to support voltage during the higher demand that begins at that time. These banks are usually switched out of service later in the afternoon or evening when they are no longer needed. We therefore have an interest in seeing the hour at which the capacitor switching events occur.

From Figure 8 it can be said that the hour at which the transient occurred between 6:00 to 8:00 AM (> 6:00:00 AM and ≤ 8:00:00 AM) was recorded on average 2.827 times per 30 days per site. Additionally, the cumulative frequency can be used to tell us that a transient occurred between 4:00 AM and 10:00 AM on average 9.723 times per 30 days per site.

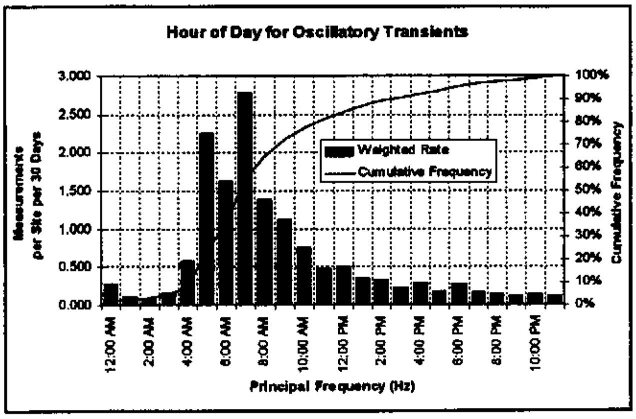


Fig. 8. Histogram for Time of Day of Oscillatory Transients, Phase Measurement Events, 3/1/95 to 9/1/95, Treated by Sampling Weights, All Sites

V. TRANSIENT PERFORMANCE INDEX

Just as with the voltage sag and interruption indices, it is pertinent to know the occurrence rate of transients exhibiting peak magnitudes greater than a specified value. For rms variation performance, these indices are referred to as frequency indices, such as $SARFI_x$ [6]. Principle frequency, however, is one of the characteristics that can be assessed for transient disturbances. Consequently, to avoid possible confusion, the transient frequency of occurrence indices are referred to as occurrence rate indices, i.e., *System Average Transient Magnitude Occurrence Rate IndexPeak* ($SATMORI_x$).

$SATMORI_x$ is a measure of the rate of occurrence of sub-cycle transients exhibiting overvoltage magnitudes greater than the specified threshold value, x. $SATMORI_x$ is defined by equation 2.

$$\mathrm{SATMORI}_x = \frac{\sum N_i}{N_T} \qquad (2)$$

where

x ≡ specified transient peak magnitude threshold; with typical values of 110%, 135%, 170% and 200%

N_i ≡ number of customers experiencing transient overvoltages having magnitudes greater than X % due to measurement event i

N_T ≡ number of customers served from the section of the system to be assessed

This index provides both the utility and end-users with a measure of how often transient overvoltages exceeding the specified peak magnitude occur. There are four defined threshold values for assessment – 110%, 135%, 170%, and 200%. These values are selected to allow for assessments of varying scope, including an assessment of both normal and abnormal capacitor switching transients. The 110% peak magnitude threshold coincides with the minimum transient magnitude as defined by IEEE Standard 1159. Consequently, $SATMORI_{110\%}$ allows for an assessment of all capacitor energization transients. The 135% and 170% threshold values are to be used for the assessment of capacitor switching transients having higher peak magnitudes.

Normal capacitor switching transient overvoltages exceeding 170% are less common, but do occur. Nonetheless, when calculated on a localized basis $SATMORI_{135\%}$ and $SATMORI_{170\%}$ are useful for assessing nuisance tripping concerns. Finally, $SATMORI_{200\%}$ allows for the assessment of abnormal capacitor energization transients. Under normal conditions, the theoretical maximum peak magnitude for a capacitor switching transient is 2.0 per unit. Due to system damping, however, peaks of this magnitude are not reached in practice. Under some abnormal circumstances, transients of this magnitude can occur. One such example is a switch restrike. These occurrences are quite rare, but are potentially very destructive when they do occur. $SATMORI_{200\%}$ allows for an assessment of these abnormal transients.

VI. CONCLUSIONS

It is important to note that the capacitor switching transients summarized in the previous section generally do not cause any problems for equipment on the electric utility distribution system. They are below levels that cause arresters to operate or dissipate any significant amount of energy, and they are well below the insulation withstand levels of distribution equipment. Therefore, measures to reduce capacitor switching transients are almost always associated with concerns with the sensitivity of customer end-use equipment to these transients or possibly with the concern for magnified transients within the customer's low voltage system. With this in mind, the problems can be resolved either by reducing the transients at the switched capacitor bank or changing the characteristics of the customer system that is sensitive to the transients.

Distribution and customer system power quality problems, caused by capacitor bank switching, can be controlled using a number of different methods. The first step is identifying the problem. Then the utility and customer need to work together to determine the best engineering and cost-effective solution possible. However, the criteria by which these solutions are evaluated are changing significantly. For example, design requirements often state that protection of utility equipment (i.e., transformers) is the primary factor. However, recent concern for customer systems has prompted a number of utilities to seek a "transient-free" solution. In addition to the overvoltage design limits, there are a number of other factors that have delayed the widespread application of mitigation technologies. One obvious obstacle is cost; however, an equally important reason has been reliability.

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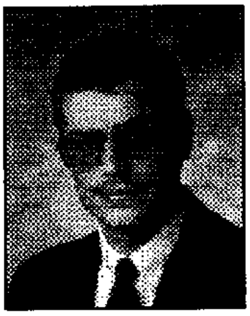
VIII. BIOGRAPHIES

D. Daniel Sabin is a project manager at Electrotek Concepts, Inc, in Knoxville, Tennessee. Dan was the principal engineer for the EPRI Distribution System Power Quality Monitoring Project (RP3098-01) during its data collection and analysis stages. In addition to developing the project's databases, he performed power quality event and statistical analysis for its monthly, quarterly, and final reports. Dan has a bachelor of science degree in electrical engineering from Worcester Polytechnic Institute of Worcester, Massachusetts, and a master of engineering degree in electric power from Rensselaer Polytechnic Institute in Troy, New York. He is the chair of the IEEE P1409 Distribution Custom Power Task Force and is registered as a Professional Engineer in the State of Tennessee.



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