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# Requirements of Power Quality Capabilities in Smart Revenue Meters

*Draft for Review*

**3002001345**

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EPRI Project Manager

T. Cooke

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# ABSTRACT

Revenue meter manufacturers have been designing smart revenue meters with a number of power quality measurement functions; however, EPRI testing in 2012 revealed that industry samples of these meters have several limits in PQ monitoring resolution and accuracy. This prompted EPRI to develop this requirements document to not only highlight existing industry power quality monitoring standards, but also give examples of down-scalable modifications of these standards that can help keep the price of these non-traditional PQ meters low.

This document is not intended to serve as a comprehensive design guide for power quality monitors. It is intended to give minimal requirements for each PQ phenomena by summarizing primary functions of each measurement at various tier levels. These tiers are designed to give meter manufactures some flexibility in choosing methods that may work with existing meter infrastructure or budget.  This document is currently in draft and to be reviewed by industry experts, electric service providers, and meter manufacturers.

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**Keywords**
Power quality monitoring, Power quality meter, Power quality measurement, Revenue meter, Smart meter

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# 1 INTRODUCTION

For electric utilities, one of the major gaps for continuous disturbance monitoring exists at the end of the distribution system. Power quality (PQ) monitors are available and can be installed to help collect these measurements, but the cost to effectively cover a distribution system can be significant. Recently revenue meter manufacturers have been designing smart revenue meters with a number of power quality measurement functions; however, EPRI testing in 2012 revealed that industry samples of these meters have several limits in PQ monitoring resolution and accuracy. This prompted EPRI to develop this requirements document to not only highlight existing industry power quality monitoring standards, but also give examples of down-scalable modifications of these standards that can help keep the price of these non-traditional PQ meters low.

## Application

This document is intended for electric service providers to provide revenue meter manufacturers with effective methods and requirements of incorporating PQ measurements in their revenue meters. This document is not intended to serve as a comprehensive design guide for power quality monitors. It is intended to give minimal requirements for each PQ phenomena by summarizing primary functions of each measurement at various tier levels.  These tiers are designed to give meter manufactures some flexibility in choosing methods that may work with existing meter infrastructure or budget.

*This document is currently in draft and intended for review by industry experts, electric service providers, and meter manufacturers.  Any comments and/or suggested edits can be forwarded to EPRI project manager, Tom Cooke, at tcooke@epri.com, or call 865-218-8010.*

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# PQ ELECTRICAL DISTURBANCES, MEASUREMENTS, AND REQUIREMENTS

IEEE standard 1159 characterizes typical power quality disturbances by the changes in a voltage or current waveform. As shown in Table 2-1, each signature is categorized based on the signature, amplitude, and duration of the event.

**Table 2-1**
**Summary of Common PQ Disturbances from IEEE Standard 1159**

| Categories | | | Typical Duration | Typical Spectral Content | Typical Voltage Magnitude | Method of Characterizing | Typical Causes | Example of Power Conditioning Solutions |
|---|---|---|---|---|---|---|---|---|
| Short Duration Variations | Sag | Instantaneous 0.5 cycles to 30 cycles | | | 0.1 to 0.9 pu | RMS vs. Time, Magnitude, Duration | Remote System Faults | Ferroresonant Transformers, Energy Storage Technologies, UPS |
| | Swell | Momentary 30 cycles to 3 seconds | | | 1.1 to 1.8 pu | | | |
| | Interruption | Temporary 3 seconds to 1 minute | | | < 0.1 pu | Duration | System Protection (Breakers, Fuses), Maintenance | Energy Storage Technologies, UPS, Backup Generators |
| Long Duration Variations | Undervoltages | | > 1 minute | | .08 to 0.9 pu | RMS vs. Time, Statistics | Motor Starting, Load Variations, Load Dropping | Voltage Regulators, Ferroresonant Transformers |
| | Overvoltages | | > 1 minute | | 1.1 to 1.2 pu | | | |
| Voltage Unbalance | | | steady state | | 0.5 to 2% | | | |
| Waveform Distortion | DC Offset | | steady state | | 0 to 0.1% | | | |
| | Harmonics | | steady state | 0 to 100th H | 0 to 20% | Harmonic Spectrum, Total Harm. Distortion, Statistics | Nonlinear Loads, System Resonance | Filters (active or passive), Transformers (cancellation or zero sequence components) |
| | Interharmonics | | steady state | 0 to 6 kHz | 0 to 2% | | | |
| | Notching | | steady state | | | | | |
| | Noise | | steady state | broad-band | 0 to 1% | | | |
| Voltage Fluctuations | | | Intermittent | < 25 Hz | 0.1 to 7% | | | |
| Power Frequency Variations | | | > 10 seconds | | | Variation Magnitude, Frequency of Occurrence, Mod. Frequency | Intermittent Loads, Motor Starting, Arc Furnaces | Static Var Systems |
| Transients | Impulsive | Nanosecond | > 50 nanoseconds | 5 ns rise | | Peak Magnitude, Rise Time, Duration | Lightning, Electro-Static Discharge, Load Switching, Capacitor Switching | Surge Arresters, Filters, Isolation Transformers |
| | | Microsecond | 50 nanoseconds to 1 millisecond | 1 μ rise | | | | |
| | | Millisecond | > 1 millisecond | 0.1 ms rise | | | | |
| | Oscillatory | Low Frequency | 0.3 milliseconds to 50 milliseconds | < 5 kHz | 0 to 4 pu | Waveforms, Peak Magnitude, Frequency Components | Line/Cable Switching, Capacitor Switching, Load Switching | Surge Arresters, Filters, Isolation Transformers |
| | | Medium Frequency | 20 microseconds | 5 to 500 kHz | 0 to 8 pu | | | |
| | | High Frequency | 5 microseconds | 0.5 to 5 MHz | 0 to 4 pu | | | |

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This section summarizes the characteristics, measurements, and standards of each power quality phenomena, and then is followed by requirements that present various tier levels of minimum measurement variables to be used for each PQ measurement.

## Voltage Interruptions, Sags, and Swells

Both voltage sags and swells are characterized by brief changes in voltage amplitude—sags decrease and swells increase. The amplitude of this event is given in percent of nominal voltage. So if the voltage drops by 20%, it is defined as an 80% voltage sag. These events are further broken down into instantaneous, momentary, and temporary categories based on the duration of the event. Of the six possible combinations, instantaneous sags are the most common event, with the majority of sags occurring between 60% to 90% and 2 to 10 cycles.

### *Measurement*

To characterize a voltage sag or swell, it's important to not only detect that a threshold has been crossed, but also measure and report the amplitude and duration of the event. This can be captured in an actual waveform recording, an RMS plot, or a simple log report stating the amplitude and duration. IEC 61000-4-30 specifies this measurement to be made with 0.5 cycle sampling. The most important factor is the capability to accurately, if not then precisely measure an event as short as one cycle.

### *Requirements*

- Tier 1
  - Voltage Waveform recording at the beginning and end of the event, with least 32 samples per cycle, and pre and post event recording of at least 3 cycles.
  - Voltage RMS plot with 0.5 cycle resolution during the whole duration of the event, with pre and post event recording of at least 1 second.
- Tier 2
  - Voltage RMS plot with 0.5 cycle resolution during the whole duration of the event, with pre and post event recording of at least 1 second.
  - RMS is calculated from a waveform sampling at least 16 points per cycle.
- Tier 3
  - Log report or tabular data with minimum, average, and maximum RMS voltage amplitude recordings during an event, as well as the duration of the event.
  - Statistical RMS recordings are derived from a 1 cycle RMS of a waveform sampled at least 16 points per cycle.
- Tier 4
  - Log report or tabular data with minimum, average, and maximum RMS voltage amplitude recordings during an event, as well as the duration of the event
  - Statistical RMS recordings are derived from a 12 cycle RMS of a waveform sampled at least 8 points per cycle

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## Voltage (or Current) Unbalance

This event can be considered a sub category of an under and over voltage, with the major characterization being the balance of voltage amplitude in a polyphase system.

### *Measurement*

IEEE standard 112 presents the method of calculating percent voltage unbalance as the maximum voltage deviation from the average voltage, divided by the average voltage. The sampling for this measurement can be collected at the same resolution as the under and over voltage; however, the unbalance calculation should be performed before reporting statistical values over a long period.

### *Requirements*

- Tier 1
  - Tabular trend data with at least 1 minute interval recordings of minimum, average, maximum Unbalance values, with values derived from 1 cycle RMS sampling.
- Tier 2
  - Tabular trend data with at least 1 minute interval recordings of minimum, average, maximum Unbalance values, with values derived from 12 cycle RMS sampling.
- Tier 3
  - Tabular trend data with at least 15 minute interval recordings of minimum, average, maximum Unbalance values, with values derived from 12 cycle RMS sampling.
- Tier4
  - Tabular trend data with at least 15 minute interval recordings of minimum, average, maximum Unbalance values, with values derived from 60 cycle RMS sampling.

## Voltage Fluctuations (Flicker)

This event can be characterized as a continuous or intermittent series of subtle voltage sags and swells. This event primarily effects the flickering of lights and can be an irritant to human beings at the point of perceptibility.

### *Measurement*

The method of calculating this perceptibility, which can be process intensive, is explained in IEC standard 61000-4-15. The typical measurement is perceptibility-short-term ($P_{st}$), with a long-term and instantaneous measurements given as well.

### *Requirements*

- Tier 1
  - Refer to IEC standard 61000-4-15.

## Waveform Distortion

The primary characteristic of this PQ phenomenon is the inclusion of other frequencies added to the fundamental (60 Hz) frequency, which can include zero hertz as a DC offset. If the

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frequencies are integer multiples of the fundamental (120, 180, 240, etc) it is identified as harmonics. If the frequencies are non-multiples they are identified as interharmonics.

### *Measurement*

The magnitude of these frequencies can be presented as actual values of voltage and current, or are typically reported as percent of fundamental. The sum of each can be presented as one number giving total harmonic distortion (THD), or total demand distortion (TDD). TDD measurement works well as a current distortion metric due to the impact load current has on creating voltage distortion. IEC 61000-4-7 standard defines these harmonic measurement calculations in two classes. Class I is intended for precise measurements that would be used in compliance for harmonic emission standards. Class II measurements are not as precise and are intended for general surveys to see if more precise measurements are needed.

### *Requirements*

- Tier 1
    - As defined by IEC 61000-4-7 up to 3 kHz
        - Interval recordings of individual voltage and current harmonics amplitude and angle, with at least 4 sets to select for trending.
        - Interval recordings of individual voltage and current interharmonics , with at least 4 values to select for trending
        - Interval recording of Voltage Total Harmonic Distortion (vTHD).
        - Interval recording of Total Demand Distortion (TDD).
        - Interval recording of Voltage Total Interharmonic Distortion (vTID).
    - Interval recording of Crest Factor derived from voltage and current Peak and RMS interval
    - 1 minute interval recordings of minimum, average, and maximum values
- Tier 2
    - As defined by IEC 61000-4-7 up to 900 Hz
        - Interval recordings of individual voltage and current harmonics amplitude and angle, with at least 4 sets to select for trending.
        - Interval recording of Voltage Total Harmonic Distortion (vTHD).
        - Interval recording of Total Demand Distortion (TDD).
    - Interval recording of Crest Factor derived from voltage and current Peak and RMS interval
    - 1 minute interval recordings of minimum, average, and maximum values
- Tier 3
    - As defined by IEC 61000-4-7 up to 900 Hz
        - Interval recording of Voltage Total Harmonic Distortion (vTHD).
        - Interval recording of Total Demand Distortion (TDD).
    - Interval recording of Crest Factor derived from voltage Peak and RMS interval

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    - 15 minute interval recordings of minimum, average, and maximum values.
- Tier 4
    - As defined by IEC 61000-4-7 up to 900 Hz
        - Interval recording of Voltage Total Harmonic Distortion (vTHD).
    - Interval recording of Crest Factor derived from voltage Peak and RMS interval
    - 15 minute interval recordings of minimum, average, and maximum values.

## Transients

Transients are sub-cycle deviations in the waveform of both voltage and/or current. These deviations can be characterized as impulsive or oscillatory depending on the waveform signature. As described in IEEE standard 1159, impulsive transients are generally one-shot impulses in one direction, while oscillatory measurements transition from one direction to the other as it decays.

### *Measurement*

The basic measurement of transients is the peak magnitude and the spectral content that may involve frequency or rise time. IEC 61000-4-30 gives several methods of capturing a transient, but does not standardize on a particular method.

### *Requirements*

- Tier 1
    - Voltage and current waveform recording of the transient event, with at least 256 samples per cycle, and pre and post event recording of at least 3 cycles.
- Tier 2
    - Voltage Waveform recording of the transient event, with at least 128 samples per cycle, and pre and post event recording of at least 3 cycles.
- Tier 3
    - Text log report with peak voltage amplitude recorded during the event, and the frequency or rise time of the transient.

## Requirements Summary

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Table 2-2 summarizes the requirement discussed for each PQ measurement type. As each tier decreases so does the required performance. Each tier set does not have to be bound to other sets, even though some may be presented that way. For example, a given meter may use tier 3 for voltage sags and swells, but use tier 1 for voltage unbalance.

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**Table 2-2**
**Summary of Requirements for PQ Capabilities in Smart Revenue Meters**

| | | METER | | | | |
|---|---|---|---|---|---|---|
| | Test and Measurement Standards | Typical PQ Monitor | Tier 1 | Tier 2 | Tier 3 | Tier 4 |
| **EVENT RECORDINGS** | | | | | | |
| Interruptions/Sags/Swells | IEC 4-30<br>IEEE 1159 | * 128 SPC wave w/ pre & post<br>* 0.5 cyc RMS w/ variable sec pre & post | * 32 SPC wave w/ 3 cyc pre & post<br>* 0.5 cyc RMS w/ 1 sec pre & post | * 0.5 cyc RMS w/ 1 sec pre & post | Text based stats. Of 1cyc RMS from 16 SPC | Text based stats. Of 12cyc RMS from 8 SPC |
| Transients | IEEE 1159<br>IEC 4-30 | => 512 SPC wave w/ pre & post | 256 SPC wave w/ 3 cyc pre & post | 128 SPC wave w/ 3 cyc pre & post | Text based w/ peak amp. & freq/rise-time | NA |
| **STEADY-STATE PARAMETERS** | | | | | | |
| Min/Max/Avg Interval | IEC 4-30 | = < 1 Minute | = < 1 Minute | = < 1 Minute | = < 15 Minute | = < 15 Minute |
| Voltage & Current RMS | IEC 4-30 | 1 Cyc | 1 cyc | 12 cyc | 12 cyc | 60 cyc |
| Unbalance | IEEE 112 | Same as V&I | Same as V&I | Same as V&I | Same as V&I | Same as V&I |
| Crest Factor | = Peak / RMS | Same as V&I | Same as V&I | Same as V&I | Same as V&I | Same as V&I |
| THD | IEC 4-7<br>IEEE 519 | Up to 3 kHz | Up to 1.5 kHz | Up to 0.9 kHz | Up to 0.9 kHz | Up to 0.9 kHz |
| TDD | IEC 4-7<br>IEEE 519 | Up to 3 kHz | Up to 1.5 kHz | Up to 0.9 kHz | Up to 0.9 kHz | NA |
| Indiv. Harmonic Quantities | IEC 4-7<br>IEEE 519 | Up to 3 kHz<br>> 4 Quantities | Up to 1.5 kHz<br>4 Quantities | Up to 0.9 kHz<br>4 Quantities | NA | NA |
| Harmonic Phase Angle | IEC 4-7 | Up to 3 kHz | Up to 1.5 kHz | Up to 0.9 kHz | NA | NA |
| Interharmonics | IEC 4-7 | Up to 3 kHz | Up to 1.5 kHz | NA | NA | NA |
| Flicker | IEC 4-15 | ✓ | ✓ | NA | NA | NA |
| Real (kW) | - | ✓ | Same as V&I | Same as V&I | Same as V&I | Same as V&I |
| Reactive (kVAR) | - | ✓ | Same as V&I | Same as V&I | Same as V&I | Same as V&I |
| Apparent (kVA) | - | ✓ | Same as V&I | Same as V&I | Same as V&I | Same as V&I |
| Displacement Pwr Factor | - | ✓ | Same as V&I | Same as V&I | Same as V&I | Same as V&I |
| Total Power Factor | - | ✓ | Same as V&I | Same as V&I | Same as V&I | NA |
| Frequency | IEC 4-30 | ✓ | Same as V&I | Same as V&I | Same as V&I | Same as V&I |
| Thresh. Limits (Parmaters) | - | ✓ | ✓ | ✓ | ✓ | NA |
| Waveform Snapshots (for Post Process Par.) | - | => 128 SPC | => 64 SPC | => 32 SPC | => 16 SPC | NA |

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# 3
# SELECTING PQ MEASUREMENT CAPABILITIES

Some PQ metering parameters or functions can be more taxing than others, which can cause significant increase in production cost. Table 3-1 highlights the choice of PQ capabilities that can be reduced in order to possibly meet present meter performance capabilities or minimize the production cost. Additionally it shows rankings collected from an EPRI survey on desired PQ functions from a revenue meter. Pairing this information can help determine which PQ capabilities to pursue.

**Table 3-1**
**Summary of Utility Needs and Performance Curtailment of PQ Capabilities in Smart Revenue Meters**

| | Test and Measurement Standards | Typical PQ Monitor | Utility Survey Ranking | Reduce Sampling Needs | Reduce Processing Needs | Reduce Memory Needs |
|---|---|---|---|---|---|---|
| **EVENT RECORDINGS** | | | | | | |
| Interruptions | IEC 4-30, IEEE 1159 | ✓ | 1 | ✓ | ✓ | ✓ |
| Sags/Swells | IEC 4-30, IEEE 1159 | ✓ | 2 | ✓ | ✓ | ✓ |
| Transients | IEEE 1159, IEC 4-30 | ✓ | 13 | | | |
| Waveshape Deviation | - | ✓ | - | ✓ | | |
| Thresh. Limits (Parmaters) | - | ✓ | 3 | ✓ | ✓ | ✓ |
| **Capture Method** | | | | | | |
| Text Based | - | ✓ | 1&2 | ✓ | | ✓+ |
| Fast RMS | IEC 4-30 | 0.5 Cyc | 1&2 | 0.5 Cyc | 1 Cyc | 1 Cyc |
| Waveform | IEEE 1159, PRC-002-1 | 1024+ SPC | 12 | 32 SPC | SNAPSHOTS | |
| **Functions** | | | | | | |
| Push Alerts | - | ✓ | 8 | ✓ | | ✓ |
| Battery Backup | - | ✓ | 6 | ✓ | ✓ | ✓ |
| Export to PQDIF | IEEE 1159.3 | ✓ | 11 | ✓ | ✓ | ✓ |
| **STEADY-STATE PARAMETERS** | | | | | | |
| Voltage RMS | IEC 4-30 | 1 Cyc | 4 | 1 Cyc | 12 Cyc | 1 Cyc |
| Current RMS | IEC 4-30 | 1 Cyc | 5 | 1 Cyc | 12 Cyc | 1 Cyc |
| Real (kW) | - | ✓ | - | ✓ | ✓ | ✓ |
| Reactive (kVAR) | - | ✓ | - | ✓ | ✓ | ✓ |
| Apparent (kVA) | - | ✓ | - | ✓ | ✓ | ✓ |
| Displacement Pwr Factor | - | ✓ | - | ✓ | ✓ | ✓ |
| Total Power Factor | - | ✓ | - | ✓- | | ✓ |
| Frequency | IEC 4-30 | ✓ | - | ✓ | ✓ | ✓ |
| Phasors | - | ✓ | - | ✓ | ✓- | ✓ |
| THD | IEC 4-7, IEEE 519 | ✓ | 9 | ✓- | ✓- | ✓+ |
| TDD | IEC 4-7, IEEE 519 | ✓ | 10 | ✓- | ✓- | ✓+ |
| Ind. Harmonic Quantities | IEC 4-7, IEEE 519 | Up to 50th | 14 | Up to 15 | | |
| Interharmonics | IEC 4-7 | Up to 50th | 14 | Up to 15 | | |
| Harmonic Phase Angle | IEC 4-7 | Up to 50th | 14 | Up to 15 | | |
| Crest Factor | - | ✓ | - | ✓ | ✓ | ✓+ |
| Flicker | IEC 4-15 | ✓ | 15 | ✓ | | ✓ |
| Unbalance | IEEE 112 | ✓ | 7 | ✓ | ✓- | ✓ |
| **DEMAND** | | | | | | |
| Real (kW) | - | ✓ | - | ✓ | ✓ | ✓ |
| Reactive (kVAR) | - | ✓ | - | ✓ | ✓ | ✓- |
| Apparent (kVA) | - | ✓ | - | ✓ | ✓ | ✓ |
| **ENERGY** | | | | | | |
| Watt-hours | - | ✓ | - | ✓ | ✓ | ✓+ |
| Var-hours | - | ✓ | - | ✓ | ✓- | ✓+ |
| VA- hours | - | ✓ | - | ✓ | ✓- | ✓+ |
| **CONTINUOUS TRENDING / DEMAND INTERVALS** | | | | | | |
| Minimum Interval (Min) | - | 1 | - | 1 | 15 | 60 |
| Statistical Quantities | - | ✓ | - | ✓ | ✓- | ✓+ |

| | |
|---|---|
| (red) | = No Performance |
| ✓- | = Reduced Performance / Need |
| ✓ | = Typical Performance / Need |
| ✓+ | = Increased Performance / Need |

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## Survey of Electric Utilities

From EPRI report 1000372, “Development of Meter Specifications”, a survey was given to electric utilities that was designed to determine which power quality functions in utilities value from revenue meters. Standard meter functions, such as kWh, kVA demand, and kVAR, were assumed functions. As was shown in Table 3-1, voltage interruptions, sags, and swells were the higher requirement of utilities, while flicker, individual harmonics, and transients were some of the least.

## Performance Curtailment

The following are highlights from Table 3-1 that show reduction or elimination of advanced features that can help curtail performance needs; therefore, reduce manufactures production cost. Note that some are shown to increase performance. For example, when reducing processing needs one could make up for eliminating harmonic measurements by collecting a waveform snapshot and post processing the harmonic data on another system. And conversely, when reducing memory needs one could make up for eliminating waveform capture by increasing calculated parameters that describe the waveform.

- Sampling Speed
  - Eliminate transient capture
  - Reduce higher frequencies / harmonics
  - Reduce sampling rate for waveform capture
- Processing Power
  - Eliminate/Reduce
    - Eliminate flicker, interharmonics, and individual Harmonics
    - Reduce higher frequencies in sampling for THD/TDD and Total Power Factor calculations
    - Eliminate advanced processing for pushing alerts and interpretation of events (waveform deviations, transients, text-based interpretations of the event).
    - Reduce the interval of statistical quantities of parameters.
  - Increase
    - Waveform snapshots for post processing in absence of harmonics and parameters
- Memory
  - Eliminate/Reduce
    - Reduce or eliminate event waveform storage
    - Reduce event RMS storage
    - Reduce Interval for Parameters
  - Increase
    - In absence of waveform storage, processing of parameters and alerts that describe the waveform or event.
    - Going beyond min/max/average statistics with cumulative percentile samples helps reduce the time interval for parameter storage.

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- Integral power measurements (energy) can be favored over power parameters.

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# 4
# CLOSING

When making a final decision on the type of PQ capabilities needed in a smart revenue meter, give consideration that these types of meters and their placement are to play a supportive role in a wide-area monitoring system. PQ monitors, fault recorders, and portable monitors are still available to fill in the gaps for advanced functions, so not every PQ measurement feature and standard accuracy has to be represented by this revenue meter. However, if the meter is going to perform a specific PQ measurement function, it has to be executed in a method that leads to effective and interpretable results. This can be achieved by understanding the characteristics of PQ events, the measurements standards, and following the requirements offered in this document.

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# 5
# STANDARDS FOR REFERENCE

- IEC Standard 61000-4-7, “Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto”
- IEC Standard 61000-4-15, “Testing and measurement techniques – Flicker meter – Functional and design specifications”
- IEC Standard 61000-4-30, “Testing and measurement techniques – Power quality measurement methods
- IEEE Standard 112, “Standard Test Procedure for Polyphase Induction Motors and Generators”
- IEEE Standard 519, “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”
- IEEE Standard 1159, “IEEE Recommended Practices for Monitoring Electric Power Quality”
- IEEE Standard 1159.3, “IEEE Recommended Practice for the Transfer of Power Quality Data”
- NERC Standard PRC-002-1, “Define Regional Disturbance Monitoring and Reporting Requirements”

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