Power Quality 102

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Power Quality 102

- Transients
- IEEE 519 Harmonic Analysis
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads
PMI PQ Ruler

Key graphs, thresholds, and formulas from IEEE PQ standards on 6” ruler

White paper explaining all sections on ruler:
http://library.powermonitors.com/pmi-pq-ruler
Power Quality 102

- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads and PQ
- Further Reading
Voltage Quality Variations

Disturbances
- Occur at Random Intervals
- Transients
- Voltage Sags and Swells
- Voltage Fluctuations
- Momentary and Sustained Interruptions

Steady State Characteristics
- Quality of Normal Condition Voltage
- Voltage Regulation: Magnitude, Long Term Stability
- Voltage Unbalance
- Voltage Distortion – harmonics, notching, noise
Impulsive Transients

• IEEE 1159–1995, Recommended Practice for Monitoring Electric Power Quality: A sudden non-power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity.

• Rise time and duration can be in nS, µS, mS

• Damped quickly by circuit resistance

• Not conducted far from source (lightning, switching event, etc.)

• Can excite resonances and produce oscillatory transients

• Possible Solution: Surge Suppressors
Impulsive Transients

1 ms impulse transient capture with microsecond rise-time

Transient graphed with slower 60 Hz waveform
• Short duration, high frequency voltage impulses – local resonance ringing damped quickly
IEEE 1159–1995, Recommended Practice for Monitoring Electric Power Quality

- A sudden, non-power frequency change in the steady-state condition of voltage or current that includes both positive and negative polarity.

Possible Solutions:
- Series Surge Suppressors
- Line Reactors
Oscillatory Transient
Low Frequency < 5kHz

- Customer load current following voltage variations

Captured by a PMI Eagle® 440
Interpreting Captured Waveforms

Oscillatory Transient – Capacitor Energized

Voltage and Current Waveform Capture
Waveform Capture #3, Jan 23, 2008, 16:55-57, Cycle 51

- V notching
- Ringing damped by system R losses
- Ring wave approx 625Hz

Captured by a PMI Eagle® 440
Oscillatory Transient
Medium Frequency 5-500kHz

Possible Solutions: Pre-Insertion resistance or inductance
Oscillatory Transient
Medium Frequency 5-500kHz

• 5-500kHz: Med frequency ringing – System response to impulse transient
Voltage Sags

• IEEE 1159–1995, Recommended Practice for Monitoring Electric Power Quality

  A decrease in RMS voltage to between 0.1 and 0.9 pu at the power frequency for durations of 0.5 cycle to 1 min

Typical Causes:
• Power system faults
• Energizing loads that require large currents
• Motor starts

Possible Solutions:
• UPS
• Soft starts on motors
• Lower impedance
Sag with Interval Graphs

Interval Graph – V sag, 480V motor start

Captured by a PMI Revolution®
Voltage Sags

- Voltage Sags – can be caused by energizing large loads, starting large motors, loose connections, power system faults
- Can cause equipment trips, mis-operation
Voltage Sags
Customer Load Induced

\[ V_1 = I_1 \times Z_1 \]

Source Voltage

Customer Load
Motor

\[ V_{L1} = V_S - V_1 \]
Voltage Sags
Effects of Other Customer Loads

\[ V_1 = (I_1 + I_2) \times Z_1 \]

\[ V_L_1 = V_s - V_1 \]

\[ V_2 = I_2 \times Z_2 \]

\[ V_L_2 = V_L_1 - V_2 \]

Source Voltage

Customer 1 Motor Load

Customer 2 Other Customers
• Motor start inrush current – 7x running current

• Small momentary Vsag (1.5V) during inrush current
Voltage Sags

Interval Graph – V sags, utility supply or customer induced?

![RMS Voltage and Current graph](image)

- **1.** No Vag
- **2.** Vag, no current
- **3.** Matching Vags
- **3.** $I_{max}$ - result of Vags (motor)

Captured by a PMI iVS-2SX+
Voltage Sag – Utility Side

Captured by a PMI Eagle® 440
Voltage Sag – Load Induced

Captured by a PMI Eagle® 440
Voltage Sag with PV

Two power sources, with differing impedance

- Transformer + upstream impedance
- Inverter source impedance
- Service drop
- Building wiring

240VAC Utility Secondary
240VAC PV inverter
Motor Load
Voltage Sag with PV

Motor starts during day with PV, and also at night with no PV

- Voltage sags
- Current spikes
Voltage Sag with PV

150A inrush, 2.3V sag at night

106A inrush, 2.6V sag during day with PV support
Voltage Swell

Cause:

• Can be caused by SLG fault temporary V rise on unfaulted phases, switching events

• Can cause equipment trips, misoperation due to detection of overvoltage condition

Figure 8– Instantaneous voltage swell caused by SLG fault

Fault Voltage Swell


<table>
<thead>
<tr>
<th>System</th>
<th>Overvoltage Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ungrounded System</td>
<td>1.82</td>
</tr>
<tr>
<td>Four-Wire Multigrounded System (Spacer Cable)</td>
<td>1.5</td>
</tr>
<tr>
<td>Three- Or Four-Wire Unigrounded System (Open Wire)</td>
<td>1.4</td>
</tr>
<tr>
<td>Four-Wire Multigrounded System (Open Wire-Gapped Arrester)</td>
<td>1.25</td>
</tr>
<tr>
<td>Four-Wire Multigrounded System (Open-Wire Metal-Oxide Arrester)</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Cause:

- Fault pulls local ground away from substation ground potential, increasing ground-phase voltage on other phases
- Overvoltage factor depends on circuit grounding method
Recloser Voltage Swell

- Multiple recloses appear as single stripchart max voltage point
- Waveform captures give more timing detail

3 cycle reclose

30 cycle reclose
Voltage Unbalance

- Max deviation from ave, divided by ave.
- A, B, C = 124V, 119V, 112V
- Ave = (124+119+112)/3 = 118.3V
- dVmax = |112-118.3| = 6.3V
- Vu = 6.3/118.3 x 100% = 5.3%

ANSI C84 limit = 3% voltage unbalance, with no load

\[
dV_{max} = \max_{n=1,2,3} |V_n - V_{ave}|
\]

\[
V_u = \frac{dV_{max}}{V_{ave}} \times 100\%
\]
Delta Voltage Unbalance

- Voltage phase angle shifts can cause unbalance in delta circuit, not seen in wye!

\[ V_{AB} = V_{AN} - V_{BN} \]
\[ V_{BC} = V_{BN} - V_{CN} \]
\[ V_{CA} = V_{CN} - V_{AN} \]

\[ V_{AB} = |V_{AN}| \angle \theta_A - |V_{BN}| \angle \theta_B \]

Ex. 277/480V ideal system, 120 degrees

Add 5 degree phase B shift:

\[ |V_{AB}| = \sqrt{(277 \cos(0) - 277 \cos(125))^2 + (277 \sin(0) - 277 \sin(125))^2} \]
\[ = \sqrt{435.9^2 + (-226.9)^2} \]
\[ = \sqrt{241477.9} \]
\[ = 491.4 \text{ Volts} \]

11.6V shift = 2.4% change!
Delta Voltage Unbalance

- Be aware of delta voltage unbalance

- Utility limits are generally line-neutral, but most equipment is line-line connected

- Connect PQ recorder with same hookup type as sensitive equipment in some cases

- Unbalance may require phase angle fixes in addition or instead of voltage regulator adjustments

- Blown cap bank fuse in one phase

- Open deltas

- Neutral reactors and unbalanced feeders
Unbalance and AC Motors

- Motors are mostly unaffected by unbalance until 70% loaded or higher.
- Loaded motor’s current unbalance is ~ 6-10 times voltage unbalance.
- Lightly loaded motor’s current unbalance can be 20-30 times voltage unbalance – can false trip protection.
- Increased heating may damage motor, may have to derate.
- VFDs are often more sensitive.

[Graph showing temperature rise caused by unbalanced voltages and NEMA MG-1 derating curve]
Voltage Unbalance

- Causes unequal currents through 3-phase rectifiers
- Increased heating can lead to “thermal runaway”, causing the rectifier to fail
Voltage Unbalance

Unbalance ratio – Current unbalance / Voltage unbalance

- Typical VFD ratio is 10-20
- Ratio is over 30 below (1.18% voltage, 35% current) – indicates possibly failing VFD bridge input
Voltage Unbalance

Unbalance ratio – Current unbalance / Voltage unbalance

- Waveform analysis – high and runt current pulses – failing VFD rectifier
Case: Delta Voltage Unbalance

- Phase B: -117 degrees
- Phase C: 121 degrees
- 3.4% voltage unbalance
- Half is from phase shift
- Line reactor in substation combined with > 100A neutral current from unbalanced feeders

Check vector diagram for voltage phasors shifted from 120 degree marks
Power Quality 102

- Transients
- **IEEE 519 Harmonics**
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads
Harmonics - IEEE 519:2014

• Recommended practice for measuring and applying limits to voltage and current harmonics

• Applies at utility level – not an equipment spec

• Limits for utilities (voltage) and end-users (current)

Important to have a copy as the normative reference!

IEEE 519:1992 is also an excellent reference

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Sine waves

Sinusoid: \( V(t) = A \sin(2\pi Ft + \theta) \)

Sine properties:
- **A** = amplitude
- **F** = frequency
- **\( \theta \)** = phase angle
- Periodic
- Frequency unchanged by a linear system
- Orthogonal:
  \[ \int_{-\pi}^{\pi} \sin(Mt) \sin(Nt) = 0, \quad M \neq N \]

120 VAC = 167\( \sin(2\pi 60t) \) (167 = 120 \( \times \sqrt{2} \) )
Fourier theorem: Any periodic waveform may be uniquely decomposed into a summation of sine waves of amplitude $A_k$, phase $\theta_k$, and frequency $kF$

$$V(t) = \sum_k A_k \sin(2\pi kFt + \theta_k)$$

$kF =$ multiple of the base frequency $F$, or fundamental.
If $F=60 \text{ Hz}$, $kF = 2\times60$, $3\times60 = 120$, $180 \text{ Hz}$, etc.

$A_k =$ amplitude of the $k^{\text{th}}$ sine wave
$\theta_k =$ phase angle of the $k^{\text{th}}$ sine wave, relative to the fundamental
$k^{\text{th}}$ sine wave is the $k^{\text{th}}$ harmonic of the fundamental
Why use Harmonics?

Most waveform distortion is periodic, driven by the 60 Hz voltage waveform – these are nonlinear, but synchronous loads.

- Any complex, but periodic waveform shape has a unique harmonic representation.
- Harmonic breakdown is parsimonious – most real-world waveforms are described by a few large harmonics.
- Harmonics may be filtered by circuits tuned to specific frequencies – cf. linear system theory.
Harmonics are Steady State

Distortion repeated every cycle - harmonics

Vs

Oscillatory transient – NOT harmonics
What Causes Current Distortion?

- Nonlinear circuit elements dynamically change impedance at different points on the voltage waveform.
- Most modern loads convert 60 Hz AC into DC with rectifiers.
- Nonlinearity is memoryless – repeats every 60 Hz cycle.
What Causes Voltage Distortion?

- Harmonic load current flowing through system impedance causes nonlinear voltage drop.
- Harmonic voltage drop combines with and reduces supply voltage resulting in a distorted voltage applied to the load.
- Resulting voltage harmonics depend on system impedance and harmonic load current.
Don’t throw away the 1992 edition! Removed in 2014:

- Harmonic Generation
- System Response Characteristics
- Effects of Harmonics
- Reactive Power Compensation and Harmonic Control
- Analysis Methods

IEEE 519:1992: 101 pages
IEEE 519:2014: 29 pages

1992 edition contained background discussion, examples – still great info
2014 edition is tightly focused on just the limits and statistical analysis
Limiting distortion is a “shared responsibility” – utility and end users

- Utility – keep system impedance low to minimize voltage distortion with “acceptable” harmonic currents
- Users – keep load harmonics “acceptable” to allow a utility to operate with reasonable impedances

Harmonic voltage distortion limits are provided to reduce the potential negative effects on user and system equipment. Maintaining harmonic voltages below these levels necessitates that

- All users limit their harmonic current emissions to reasonable values determined in an equitable manner based on the inherent ownership stake each user has in the supply system and
- Each system owner or operator takes action to decrease voltage distortion levels by modifying the supply system impedance characteristics as necessary.
IEEE 519:2014 Definitions

Point of Common Coupling – “Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation.”

- Often at the revenue meter/service entrance
- Can be at transformer primary for industrial customers

Tricky cases:
- Single customer on a dedicated feeder – at substation, or transformer?
- Large industrial customer with a small 2nd customer tapped off one phase

Voltage harmonics are worse on transformer secondary, so when in doubt, use that to be conservative.
Max demand load current - sum of the currents at PCC, corresponding to the max demand during each of the 12 previous months, divided by 12

- Difficult to measure, must often be estimated
- For planning/design stages, cannot be measured!
- One approach is to use worst case full load current of all nonlinear loads
- I THD may be better at full load, but total harmonic contribution is usually highest at full load
IEEE 519:2014 Definitions

Total Harmonic Distortion, Total Demand Distortion (THD, TDD) –

Harmonic subgroups used in calculations

\[ X_{THD} = \frac{\sqrt{X_2^2 + X_3^2 + \cdots + X_{50}^2}}{X_1} \times 100\% \]

\( X_k \) is the \( k^{th} \) voltage or current harmonic

Excludes interharmonics, but allows for harmonic modulation

THD is only synchronous distortion – no interharmonic (non-synchronous) effects

Voltage THD not relative to a nominal system voltage

\[ I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + \cdots + I_{50}^2}}{I_L} \times 100\% \]

\( I_k \) is the \( k^{th} \) current harmonic
\( I_L \) is the max demand current
Very Short Time = 3 seconds

- Aggregation of 15 consecutive harmonic measurements $F_n$ for harmonic $n$
- 12 cycles/measurement = 0.2 seconds $\times$ 15 = 3 seconds
- $F_{n,vs}$ = very short time harmonic $n$
- RMS addition
- 3 seconds is the smallest time interval used for limiting
- Harmonics are a steady-state problem—hence 3 seconds = “very short”

$$F_{n,vs} = \sqrt{\frac{1}{15} \sum_{i=1}^{15} F^2_{n,i}}$$
Short Time = 10 minutes

- Aggregation of 200 consecutive very short time measurements $F_{n,vs}$ for harmonic $n$
- 3 seconds x 200 = 10 minutes
- $F_{n,sh}$ = short time harmonic $n$
- 10 minutes is the largest time interval used for limiting
- If you have a recording at 3 second intervals, can compute 10 minute short time values from that – don’t need to record both

\[
F_{n,sh} = \sqrt{\frac{1}{200} \sum_{i=1}^{200} F_{(n,vs)}^2}
\]
IEEE 519:2014 Voltage Limits

Table 1—Voltage distortion limits

<table>
<thead>
<tr>
<th>Bus voltage $V$ at PCC</th>
<th>Individual harmonic (%)</th>
<th>Total harmonic distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V \leq 1.0$ kV</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>$1$ kV $&lt; V \leq 69$ kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>$69$ kV $&lt; V \leq 161$ kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$161$ kV $&lt; V$</td>
<td>1.0</td>
<td>1.5$^a$</td>
</tr>
</tbody>
</table>

- Line-to-neutral voltage limits at PCC
- Daily 99th percentile very short time (3 sec) values should be less than 1.5 times Table 1
- Weekly 95th percentile short time (10 min) values should be less than Table 1

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IEEE 519:2014 Current Limits

Table 2—Current distortion limits for systems rated 120 V through 69 kV

<table>
<thead>
<tr>
<th>Individual harmonic order (odd harmonics)</th>
<th>$I_{SC}/I_L$</th>
<th>$3 \leq h &lt; 11$</th>
<th>$11 \leq h &lt; 17$</th>
<th>$17 \leq h &lt; 23$</th>
<th>$23 \leq h &lt; 35$</th>
<th>$35 \leq h \leq 50$</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 20^c$</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>$20 &lt; 50$</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>$50 &lt; 100$</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>$100 &lt; 1000$</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>$&gt; 1000$</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Even harmonics are limited to 25% of the odd harmonic limits above.

$^b$Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

$^c$All power generation equipment is limited to these values of current distortion, regardless of actual $I_{SC}/I_L$.

where

$I_{SC}$ = maximum short-circuit current at PCC

$I_L$ = maximum demand load current (fundamental frequency component)

at the PCC under normal load operating conditions

- Current limits at PCC
- Daily 99th percentile very short time (3 sec) values should be less than 2.0 times Table 2
- Weekly 99th percentile short time (10 min) values should be less than 1.5 times Table 2
- Weekly 95th percentile short time (10 min) values should be less than Table 2
### IEEE 519:2014 Current Limits

**Table 3—Current distortion limits for systems rated above 69 kV through 161 kV**

<table>
<thead>
<tr>
<th>Individual harmonic order (odd harmonics)</th>
<th>$I_{sc}/I_L$</th>
<th>$3 \leq h &lt; 11$</th>
<th>$11 \leq h &lt; 17$</th>
<th>$17 \leq h &lt; 23$</th>
<th>$23 \leq h &lt; 35$</th>
<th>$35 \leq h \leq 50$</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 20^c$</td>
<td>2.0</td>
<td>1.0</td>
<td>0.75</td>
<td>0.3</td>
<td>0.15</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>$20 &lt; 50$</td>
<td>3.5</td>
<td>1.75</td>
<td>1.25</td>
<td>0.5</td>
<td>0.25</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>$50 &lt; 100$</td>
<td>5.0</td>
<td>2.25</td>
<td>2.0</td>
<td>0.75</td>
<td>0.35</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>$100 &lt; 1000$</td>
<td>6.0</td>
<td>2.75</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>$&gt; 1000$</td>
<td>7.5</td>
<td>3.5</td>
<td>3.0</td>
<td>1.25</td>
<td>0.7</td>
<td>10.0</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Even harmonics are limited to 25% of the odd harmonic limits above.

$^b$Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

$^c$All power generation equipment is limited to these values of current distortion, regardless of actual $I_{sc}/I_L$

where

$I_{sc}$ = maximum short-circuit current at PCC

$I_L$ = maximum demand load current (fundamental frequency component)

at the PCC under normal load operating conditions

- Current limits at PCC
- Daily 99th percentile very short time (3 sec) values should be less than 2.0 times Table 3
- Weekly 99th percentile short time (10 min) values should be less than 1.5 times Table 3
- Weekly 95th percentile short time (10 min) values should be less than Table 3
IEEE 519:2014 Current Limits

Table 4—Current distortion limits for systems rated > 161 kV

<table>
<thead>
<tr>
<th>Individual harmonic order (odd harmonics)(a, b)</th>
<th>(\frac{I_{sc}}{I_L})</th>
<th>(3 \leq h &lt; 11)</th>
<th>(11 \leq h &lt; 17)</th>
<th>(17 \leq h &lt; 23)</th>
<th>(23 \leq h &lt; 35)</th>
<th>(35 \leq h \leq 50)</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; 25)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.38</td>
<td>0.15</td>
<td>0.1</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>(25 &lt; 50)</td>
<td>2.0</td>
<td>1.0</td>
<td>0.75</td>
<td>0.3</td>
<td>0.15</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>(\geq 50)</td>
<td>3.0</td>
<td>1.5</td>
<td>1.15</td>
<td>0.45</td>
<td>0.22</td>
<td>3.75</td>
<td></td>
</tr>
</tbody>
</table>

\(a\) Even harmonics are limited to 25% of the odd harmonic limits above.

\(b\) Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

\(c\) All power generation equipment is limited to these values of current distortion, regardless of actual \(\frac{I_{sc}}{I_L}\).

where

\[
I_{sc} = \text{maximum short-circuit current at PCC}
\]

\[
I_L = \text{maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions}
\]

- Current limits at PCC
- Daily 99\textsuperscript{th} percentile very short time (3 sec) values should be less than 2.0 times Table 4
- Weekly 99\textsuperscript{th} percentile short time (10 min) values should be less than 1.5 times Table 4
- Weekly 95\textsuperscript{th} percentile short time (10 min) values should be less than Table 4
IEEE 519:2014 PQ Ruler Limits

- Voltage Limits complete on ruler
- Current limits given for 120V-69kV

### IEEE 519 Voltage Harmonic Limits

<table>
<thead>
<tr>
<th>Bus V at PCC</th>
<th>Ind. Harm%</th>
<th>THD%</th>
</tr>
</thead>
<tbody>
<tr>
<td>V ≤ 1.0 kV</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>1 kV &lt; V ≤ 69 kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69 kV &lt; V ≤ 161 kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>161 kV &lt; V</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

- daily 99th pct. 3-sec = 1.5x table
- weekly 95th pct. 10-min = table

### IEEE 519 Harmonic Current % Limits, 120V-69kV

<table>
<thead>
<tr>
<th>lsc/I_L</th>
<th>3≤h&lt;11</th>
<th>11≤h&lt;17</th>
<th>17≤h&lt;23</th>
<th>23≤h&lt;35</th>
<th>35≤h&lt;50</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20 ≤ 50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50 ≤ 100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100 ≤ 1000</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>

- Evens limited to 25% of odd limits
- lsc = max short circuit current at PCC
- I_L = max demand current under normal load

- weekly 99th pct. 10-min = 1.5x table
- weekly 95th pct. 10-min = table
- daily 99th pct. 3-sec = 2x table
A. Determine Point of Common Coupling

B. Record data
   1. Voltage, current individual harmonic subgroups, 1-50
   2. Voltage, current harmonic subgroup THDs
   3. RMS voltage, current highly recommended
   4. Use 3 second recording interval
   5. Record for at least one normal week

C. Determine parameters
   1. max demand current $I_L$ – estimate, use historical data
   2. Find short circuit current $I_{SC}$

D. Compute statistics
   1. Compute TDD
   2. Compute percentiles of all 3 second data
   3. Compute 10 minute short time harmonic values
   4. Compute 10 minute percentiles

E. Apply limits
   1. Determine correct voltage, current tables from bus voltage and $I_{SC}/I_L$
   2. Compute table multipliers for each percentile
   3. Apply limits to each harmonic, THD, TDD

F. Declare pass or fail

Helpful Excel functions:

- SUMPRODUCT
- PERCENTILE
- SQRT
A. Record for 1 week with Revolution IEEE 519 config
B. Enter $I_L$, $I_{sc}$, bus voltage category (stored with recording)
C. Run 519 compliance report – ProVision computes:
   • TDD
   • 3 second, 10 minute percentiles
   • Voltage, current limits from 519 tables
   • Pass/fail for each harmonic, and overall
In many cases, harmonics are low enough to enable a simplified approach.

Given three observations:

1. THD is always ≥ than any single harmonic – true for 3 sec and 10 min. readings.

2. 3 sec values are always ≥ 10 minute values.

3. A percentile is always ≤ the max value. The max value is the 100\(^{th}\) percentile.

\[ \text{THD}_{\text{vs}} \geq \max F_{n,\text{vs}} \]
\[ \max F_{n,\text{vs}} \geq \max F_{n,\text{sh}} \]

Nth percentile ≤ 100\(^{th}\) percentile = max value

If the “largest” measurement type (3 second THD/TDD) is lower than the strictest threshold (10 minute THD/TDD), then all harmonics are under their thresholds.

If not, still some possible simplifications ….
Follow flowchart to check for immediate compliance in 1 week recording

If max 3 second THD < 5% - voltage is OK

Else if max 3 second THD < 8% AND max 3 second harmonic is < 7.5%, voltage is OK

Else if 3 sec THD > 12% for less than 10 minutes AND > 8% for less than 50 minutes AND max 3 sec harmonic > 7.5% for under 10 minutes, AND > 5% for less than 50 minutes, voltage is OK

Else – must do full analysis

In many cases, voltage THD is under 5% everywhere – automatically in compliance – no need to check harmonics!

### Table 1—Voltage distortion limits

<table>
<thead>
<tr>
<th>Bus voltage $V$ at PCC</th>
<th>Individual harmonic (%)</th>
<th>Total harmonic distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V \leq 1.0$ kV</td>
<td>5.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

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IEEE 519:2014 Voltage Notching

- A periodic distortion that’s best analyzed in the time domain due to special shape
- Limit is based on area of missing voltage waveform
- Not an event-based limit – only for sustained notching in every cycle
- Commonly seen with commutation problems in VFDs and other active 3 phase rectifiers

IEEE Std. 519-2014 - Reprinted with permission from IEEE - Copyright 2014, by IEEE. Copying, cutting and pasting, and/or redistributing electronically or otherwise of this graph is strictly prohibited.
IEEE 519:2014 Voltage Notching

• Since notching is a periodic distortion, it could be analyzed with harmonics
• Notching shows broadband harmonics – mitigation is difficult with filtering
• Harmonic breakdown is more complex than time-domain volts x seconds notch analysis
Harmonic Guidelines

Just because utility voltage is under limits doesn’t mean you shouldn’t monitor and limit current!

- Out-of-compliance customers should still be mitigated – could cause problems later when feeder is more loaded
- Underloaded feeder doesn’t give high harmonic customers a pass …
- More difficult to enforce limits later if high harmonic customers start affecting others later, but nothing on their load changed

This means proactive current monitoring – don’t let a customer be the first to tell you there are problems
Harmonic Guidelines

Just because customers are under limits doesn’t mean there isn’t a problem lurking

- With normal system impedance, all customers under limits -> utility voltage is under limits
- Resonance condition with PFCs and specific harmonic can cause localized elevated voltage THD and peak voltage
- Useful to measure voltage THD with and without PFCs
- Resonance frequency can change with load
- Good background in IEEE 519:1992, and PMI whitepapers Feeder Resonance and PFCs and Resonances
Guidelines

PCC issues

• Not always clear where the PCC actually is
• May be difficult to record on primary side

If in doubt, advantages to customer transformer secondary or metering cabinet:

• Voltage harmonics are higher due to transformer impedance – conservative choice
• Allows for easy isolation of customer current

Ask about any customer PFCs
Finding Source of Harmonics

- Harmonic Current Flow - “follow the current”
- Harmonic Power Sign (negative W) - beware of “IF’s”
- Relative Magnitudes approach
- Common sense approach - evaluate likely sources, customers
- Correlation of voltage distortion (VTHD) with customer load characteristics, time variations
- Resonance clues
Finding Source of Harmonics

Harmonic Current Flow

Without capacitors, normal harmonic current flow is back to substation (lowest impedance)
Finding Source of Harmonics
Harmonic Current Flow With Capacitors

Majority of harmonic current flow can be toward series resonance (low Z) formed by capacitor and feeder impedance. Can cause blown capacitor fuses.
Harmonic Power Sign

- Negative power of significant magnitude can indicate that load is source of harmonic current injection
- Phase angle between $V_h$ and $I_h$ greater than $\pm 90$ degrees = negative harmonic power, flow from load to source - opposite direction of 60Hz power flow
- Requires proper CT polarity
Finding Source of Harmonics

Common Sense Approach

Evaluate likely sources: Larger industrial, commercial customers – *look for nonlinear loads, not just large loads*

On customer side of transformer:

• Look for significant harmonic currents
• Elevated VTHD (greater than 5%) usually indicates resonance condition
• Check capacitor currents
• Correlation of VTHD with customer RMS and harmonic currents
Finding Source of Harmonics
Evaluate Customer Loads

Correlation of voltage distortion with customer load

- VTHD interval graph - does VTHD vary with customer shift changes, breaks, etc. – commercial/industrial customers

- Correlate VTHD patterns with customer load characteristics - equipment types, use patterns - VTHD vs RMS and harmonic load currents
Finding Source of Harmonics

Compare VTHD to customer load

VTHD unrelated with load current

VTHD unrelated to current

RMS Current
Finding Source of Harmonics

Correlation - Compare VTHD to customer load

VTHD Correlated with load current
Resonance Clues

• Resonance induced problem typically has one dominant harmonic

• Where harmonic problems exist, measure current in capacitors – single, large harmonic current nearly always indicates capacitor is in resonance with system impedance

• High voltage THD – usually a combination of excessive harmonic current injection and system response that magnifies harmonic currents, VTHD
Single Resonance

- 11\textsuperscript{th} harmonic dominant on voltage – sign of a resonance near 660 Hz
- Most of the 3\% voltage THD is from this single harmonic
Single Resonance

Oscillatory period measurement gives 1.41 ms, or ~710 Hz resonance

“Harmonic” graph shows mostly 11th, some 13th energy: 660 – 780 Hz range
Multiple Resonances

Each combination of C’s and L’s forms a resonance

174 MVAR short circuit current at substation
Cap bank 1: 1200 KVAR
Cap bank 2 (1.5 miles away): 600 KVAR

$$H = \sqrt{\frac{\text{MVA}_{SC}}{\text{MVAR}_{CAP}}}$$

$$H_1 = \sqrt{\frac{174}{1.2}} = 12 \text{ (722Hz)}$$

$$H_2 = \sqrt{\frac{174}{0.6}} = 17 \text{ (1022Hz)}$$

$$H_3 = \sqrt{\frac{174}{1.8}} = 9.8 \text{ (590Hz)}$$

Measured resonances ~10\text{th}, 13\text{th}, 18\text{th} harmonics (600, 780, 1080 Hz)
Power Quality 102

- Transients
- IEEE 519 Harmonics
- **CBEMA/ITIC**
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads and PQ
Computer Business Equipment Manufacturers Association, ~1970s

Guideline for computer manufacturers – a power supply design guide, not a PQ standard

Continuous curve and lack of detail created problems for PQ monitor recording
ITIC Curve

- Replaces CBEMA curve
- Applies to common 120V computer equipment
- Withstand capability – ride-through of loads to voltage variations
- Percent voltage vs duration of disturbance
Incompatible Standard - ITIC

Reclosers cause brief, deep voltage sags, outside ITIC cure

Cannot be met with normal utility infrastructure!
Interpreting Interval Graphs
Plotting a Disturbance on the ITIC curve

ITIC Curve – Point Location for 1 sec. duration = 89%, 1 sec duration. % = 107.3/120.5 = 89%; Duration was 1 cycle, = 16.67ms
Power Quality 102

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What is Flicker?

- Visible fluctuation in light intensity from changes in RMS voltage – more common for incandescent vs. fluorescent

- Human susceptibility to varying light intensity varies with
  - Magnitude of light intensity modulation
  - Frequency of occurrence (number of dips, time period)

- Humans more tolerant of larger light variations if less frequent, less tolerant of smaller variations if they occur more often

- Can cause headaches, complaints from all customers
What Causes Light Flicker?

- Fast or periodic load changes produce a in voltage drop across system impedance - causes variation in voltage applied to lighting equipment
- Only small voltage changes cause problems – under 5%
- Large industrial loads – arc furnaces, welders, starting of large induction motors
- Residential – heat pumps, hair dryers, fans, tankless water heaters, ovens, small welders, air conditioners
- Loose connections – majority of flicker problems?
How is Flicker Evaluated?
IEEE 141 Flicker Curve

- Frequency based on number of voltage “dips”, not number of changes.
- 1925 – “GE Flicker Curve” developed from 1921 research into human response
- Tests used square-wave step changes in line voltage at a constant frequency
- $\% \text{ V dip} = \frac{\Delta V}{V}$
- Threshold of perceptibility
- Threshold of irritability
Special amplitude modulation analyzer, based on human light-eye-brain response

Simulation of Lamp-eye-brain Response
Flicker Modulation – 60 Hz Waveform

Event Number 126  Channel A  Setup 1  12/26/94  03:04:55:95

Horizontal 50 milliseconds/division
Vrms: Prev=98.38, Min=98.80, Max=111.8

Vertical 50 Volts/division
Worst Imp= 8Vpk, 0deg
IFL - Instantaneous Flicker Level Signal: Based on the IEEE 1453 standard. IFL quantifies voltage fluctuation at a given instant. Voltage sags will immediately cause a change in the IFL data. IFL calculations include the eye-brain sensitivity curve for different modulating frequencies, but not the statistical aspect of how often such fluctuations occur.

Pst - Perceptibility Short Term: A parameter used to measure the severity of flicker. It is calculated using the "time at level" values of the IFL over 10 minute periods in the statistical classifier.

Pst of 1.0 = threshold of irritability
Pst of 0.35 = threshold of visibility
• Useful for determining combined effect of several randomly operating loads (welders, motors)

• Also considers effects of flicker sources with long/variable duty cycles (arc furnaces)

• Typically evaluated over 12 Pst intervals – 12 x 10 min. = 2 hours

\[
P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{sti}^3}{N}}
\]
IEEE 1453 recommended flicker limits to avoid complaints

<table>
<thead>
<tr>
<th>Compatibility Levels</th>
<th>Planning Levels</th>
<th>High V - EHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low, Med. V, &lt; 35KV, &gt;35 KV &lt; 230 KV</td>
<td>Med. V, 1 KV - 35 KV</td>
<td>.8</td>
</tr>
<tr>
<td>Pst 1.0</td>
<td>.9</td>
<td></td>
</tr>
<tr>
<td>Plt 0.8</td>
<td>.7</td>
<td>.6</td>
</tr>
</tbody>
</table>

**IEEE 1453 Flicker Levels**

<table>
<thead>
<tr>
<th>Compatibility Levels</th>
<th>Planning Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV-MV</td>
<td>MV</td>
</tr>
<tr>
<td>Pst</td>
<td>1.0</td>
</tr>
<tr>
<td>Plt</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Planning levels are 99% percentile over 1 week
Compatibility levels are 95% percentile
Pst = 10 minute interval  Plt = 12 Pst intervals
Resolving Flicker Problems

1. Increase transformer size
2. Increase size of service drop conductors
3. Tighten/remake all connections and splices
4. Install soft starts on large motor loads
5. Check for open or loose neutral connections
Advantages of 1453 Flicker Method

• IFL can be useful for locating source of flicker - shows fast time variations in voltage magnitude

• $P_{st}$ used for determining flicker severity – is there a problem?

• $P_{lt}$ - useful for determining combined effect of several randomly operating loads, and effects of flicker sources with long/variable duty cycles
Reasons to use older 141 Method

- Need to compare new readings with historical data recorded to IEEE Std. 141

- Utility had adopted “house flicker curve” – Std. 141 curve is adjustable, 1453 method is not

- Need to eliminate a single known flicker source – possible to customize the curve around a known flicker generator pattern

- Easier to estimate expected Std. 141 flicker levels by hand for a single large offender
IFL vs. Load Current - Stripchart Graph

IFL useful for locating source of flicker
Pst used for determining flicker severity

Captured by a PMI Eagle® 440
Pst vs Voltage Fluctuations

Time Trend Plot

Vmin data points – single cycle worst case values – frequency of occurrence?
Duration? Pst indicates human perception of flicker severity
Case Study 1: Tankless Electric Water Heater

Residential customer
25 kVA transformer

Customer installs 28 kW water heater:
EEMax EX280T2T
Case Study 1: Tankless Electric Water Heater

Water heater cycles elements for intermediate flow rates
Case Study 1: Tankless Electric Water Heater

Continuous 60-80A current swings!

25 kVA xfmr replaced with 50 kVA to reduce flicker – reduces impedance, therefore reduces voltage drop
Case Study 2: Amish Heater

Appears to be simple space heater – ideal resistive load

Uses power semiconductors to cycle heating element at sub-second speeds

*Produces huge amount of flicker*
Amish Heater

Continuous 12A load swings
6V voltage fluctuations

Residential recording with plugin PQ monitor

Flicker well beyond threshold of irritability
Amish Heater

- 40ms on, 20ms off – 17Hz rep rate
- Pure resistive load
- Switching asynchronous with 60 Hz

Cycle stripchart reveals duty cycle changes based on heat demand
Power Quality 102

- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern loads and PQ
Loose Neutrals

Very common residential problem
Can be very dangerous!

Open or high impedance neutral connection forms voltage divider with secondary loads

L1, L2 voltage sum to 240V, but can swing wildly depending on loads

Fluctuating light levels, especially increasing in brightness – can be confused with flicker

LED lights can hide symptoms

PQ monitor must be downstream of the neutral break to see symptoms
Loose Neutrals

Look for matching high/low swings with opposite legs
Loose Neutrals

Look for matching high/low swings with opposite legs
Loose Neutrals

Motor start currents on CH1 (Vsags), causes Vswells on CH2

Captured by a PMI Revolution®
Loose Neutrals

Waveform pattern is a bit different, since it’s instantaneous, not RMS (no negative RMS values)
Loose Neutrals

Waveform pattern is a bit different, since it’s instantaneous, not RMS (no negative RMS values)
• Transients
• IEEE 519 Harmonics
• CBEMA/ITIC
• Flicker
• Loose Neutral
• **Impact Loading**
• Variable Frequency Drives
• Modern Loads and PQ
Impact Loading

Impact Loads: frequent very high current surges, usually greater than the nameplate rating of the transformer

- Usually caused from high motor inrush currents with frequent motor starts
- Appears to transformer as repeated near-short circuit condition

- High currents cause large mechanical stress on internal windings and core
- Repeated stress causes early failure
- More commonly seen on “unit transformers” dedicated to a single load, sized specifically for the steady state load current

Transformer may need to be de-rated with impact loads – loads with very high peak to average RMS current, and frequent peaks
Impact Loading

Transformer de-rating chart

- X-axis: per-unit “pulse swing”
- Y-axis: current pulses/hour

“pulse swing” \( K = \frac{kVA_P}{kVA_T} \)

- \( kVA_P \) = inrush pulse
- \( kVA_T \) = transformer KVA rating

\[ 1 \text{hp} \approx 1 \text{kVA} \]
Case Study: Poultry Plant

Poultry Processing Plant
1 MVA transformer failed after 6 months. Peak 15 minute load ~1.1 MVA
2 minute stripchart interval, many 1500A current spikes
Poultry Plant

- Poultry plant used many directly connected AC motors
- Motors synchronized in a conveyor system
- Very frequent starts and stops
- No soft start or VFD drives
Poultry Plant

Flicker is high during periods where max current is spiking continuously (more than once per 2 minute interval)
Poultry Plant

Repeated impact loads of 2.5 MVA (840 KVA / phase)
Pulse swing = 2.5 /1 = 2.5, rate of 30/hour
New 1.5 MVA transformer installed
Giant Cranes at Shipyard

- 34.5 kV primary metered customer
- 12 cranes moving 50 ton containers, start approx. every 90 seconds
- 150-200A inrush every 7 seconds = ~7MVA inrush pulse

3.2% voltage swings every few seconds

Customer needs to triple the number of cranes!

Expansion needs to account for impact derating
Power Quality 102

- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- **Variable Frequency Drives**
- Modern Loads and PQ
Variable Frequency Drive

- Electronic equipment used to control motor speed, voltage and torque
- Composed of diodes, transistors, thyristors, MOSFETs, IGBTs, capacitors etc.
1. Rectifier: typically uses diodes to change AC to DC
2. DC Link: includes a choke and capacitor to filter out ripple; ensures the desired voltage or current is supplied to the inverter; monitored for protection from surges
3. Controls: inputs are operator settings including start, stop, motor speed upper and lower limits and system feedback; controls switching of input and output devices, monitors and reports malfunctions, shuts down VFD if needed
4. Inverter: typically uses thyristors or transistors to change DC to a variable frequency AC to control motor speed and torque
PWM Drive Characteristics

• VFD DC Link voltage is constant
• Pulse amplitude is constant over entire frequency range
• Lower resultant current is created by more and narrower pulses
• Higher resultant current is created by fewer and wider pulses
• Motor inductance smooths voltage pulses into smooth current flow

Optional line reactors
6 current pulses per cycle, 2 in each phase-phase pair

Simplest configuration, but highest harmonic content
12 pulse VFD

1 primary transformer, 2 secondaries (wye and delta)
2 6-pulse rectifiers

Transformer phase shift results in 12 pulses

Lower harmonics than 6 pulse, but much larger

Can be extended to 18 pulse

Armstrong, whitepaper on 6 pulse vs. 12 and 18 pulse harmonics effect reduction
Benefits of Using a VFD

- Can transform single phase input to 3-phase motor drive
- Lowers Motor Starting Current
- Isolates the system from motor switching transients
- Reduces Thermal and Mechanical Stresses on Motors and Belts During Starts
- Improves Power Factor
- Reduces KVA
- Lowers Cost Compared to a DC Motor
- Regeneration Possibilities
- Permits unlimited number of starts per hour
- Extends Equipment Life and Reduces Maintenance
Problems Produced by VFDs

• VFDs are often a significant source of excessive harmonic distortion.

• Harmonic distortion can result in misoperation of utility and customer relays and controls, capacitor failures and increased power system losses.

• Harmonics originate from both the supply input and motor sides of the drive

• Notching and Transients resulting from switching and commutation in power electronics can cause VFD component failures.
Other Problems Related to Use of VFDs

- Nuisance tripping caused by sags, transients, and momentary interruptions can cause protection circuits to shut down VFDs and production lines.

- Audible noise caused by high frequencies used in inverters can be annoying to employees.

- Overvoltages produced by long lead length between the VFD and motor can cause excessive Peak Inverse Voltages causing damage to semiconductor devices.

- Unbalance in 3 Phase Supply- can cause excessive current in one or more phases damaging VFD components.
PQ Problem Produced by VFDs: Harmonics

- Harmonics are created in both the converter and inverter sections of a VFD.

Distorted input current waveform causes distorted voltage drop across source impedance.

Output motor current waveform

Output voltage applied to motor
PQ Problems Produced by VFDs: Harmonics

A VFD is a very nonlinear load. A spectrum of the input voltage and current is shown in the figure below. THD in the current is 63%, in the voltage is 1.7

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th</td>
<td>63.4% THD-F</td>
</tr>
<tr>
<td>7th</td>
<td></td>
</tr>
</tbody>
</table>
Voltage Unbalance

- Causes unequal currents through 3-phase rectifiers
- Increased heating can lead to “thermal runaway”, causing the rectifier to fail
Voltage Unbalance

Unbalance ratio – Current unbalance / Voltage unbalance

- Typical VFD ratio is 10-20
- Ratio is over 30 below (1.18% voltage, 35% current) – indicates possibly failing VFD bridge input
Voltage Unbalance

Unbalance ratio – Current unbalance / Voltage unbalance

- Waveform analysis – high and runt current pulses – failing VFD rectifier
Solutions for Harmonic Problems

Resolving Harmonic Problems

Install Line Reactors
Solutions for Other Problems

Resolving Harmonic Problems

Install Drive Isolation Transformer

Drive isolation transformers reduce harmonic distortion effect of VFDs
Resolving Transient/Notching Problems

- Solid state switching devices cannot switch instantaneously.
- This causes commutation overlap where two diodes conduct briefly at the same time.
- Commutation causes transients and can excite system resonances.
- Transients can result in latent (gradual) degradation of semiconductors and conductor insulation.

Voltage waveform displaying notching

Use of drive isolation transformers to mitigate source voltage notching
Other VFD Characteristics:
Input Current Waveform and Harmonic Spectrum Comparisons

Voltage Source Inverter has Capacitor in DC Link

Current Source Inverter has Choke in DC Link

Formulas for characteristic harmonics where $n = 1, 2, 3 \ldots$  

$$6n \pm 1$$

Current Source Inverter has fewer and lower level of harmonics.
Power Quality 102

- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads and PQ
Incandescent Bulb - Design

Modern design stabilized in the 1950s

Very simple electrical design

Physics of operation simple and repeatable
Incandescent Bulb – Consumer Perspective

State of the art – colored bulbs in the 1950s

“Advanced” = 3 way bulb with multiple filaments

Dimming requires external hardware

Improvements focused on cost reductions, lifetime

1958

$1.16 = $10.26 today
Incandescent Bulb – Utility Perspective

Pure resistive load – ideal for utilities

2002: incandescent = 98.1% of all residential lighting
13% of total energy usage

Light Flicker from RMS voltage variations well known, predictable, and repeatable -> well developed IEEE standards for PQ

Modern LED “Bulb” – Design

Complex electrical design w/ multiple subsystems
Multiple power supplies
Incoming AC voltage rectified and re-regulated – not used directly
Nonlinear logic, microprocessor operation, complex state
Advanced features such as WiFi, audio in/out
Connected to other equipment

WiFi bulb – 802.11 b/g/n
32 bit ARM, 1MB Flash
14 dBm at 2.4 GHz
150 Mbit/sec – enough throughput for a mid-sized town in the 1950s
Adds ~$3 to production cost
Modern LED “Bulb” – Design

• Immediate AC->DC rectification

• DC hold-up time depends on high quality capacitor selection

• Dimmer sensing relies on analog waveform detection of SCR dimmer pattern

• Component selection determines sensitivity to AC power quality, esp. over time – could be good, or poor

http://www.ti.com/solution/lighting_bulb_replacement
LED “Bulb” – Consumer Perspective

• Advanced features – any color, any brightness, timers, remote control
• Long life – will become obsolete before it fails
• Low power – so low, power can be ignored
• Part of a larger networked system – smart home, phone
• Complex state – different modes, timers, etc.
• Same equivalent cost as 1950’s colored bulb

So advanced, it’s assumed it will outperform incandescent bulbs in every way

Hue lights
These smart and energy-efficient LED lights come in a wide variety of shapes, sizes, and models to suit your space.

Hue Bridge
The heart of your Philips Hue system, the Bridge acts as a smart hub, connecting your devices to your smart lights. You can add up to 50 Philips Hue lights and accessories to one Bridge.

Hue app
Control your smart lights quickly and conveniently with the Philips Hue app.

REMOTE CONTROL

- Dim up/Speed up
- Dim down/Speed down
- On/Off
- Smooth
- Red/Orange/Yellow/Blue/Cyan/Indigo/Violet/White
- Daily Lighting
- Color Plate
- Press one of color buttons and hold in clockwise or anti-clockwise.

Sunnest 120 Colors LED Light Bulb, Dimmable E26 LED Light Bulb, 10W RGBW Color Changing Light Bulb with Remote Control, Decorative Lights, Mood Light Bulb, Great for Home Decor, Stage, Party and More

by SUNNEST

3.9 out of 5 stars
385 customer reviews
64 answered questions

Amazon's Choice
for “color led light bulbs”

Price: $11.99 Prime
Your cost could be $1.99. Eligible customers get a $10 bonus when refilling $100.

Color: Rgbw
LED “Bulb” – Utility Perspective

- High current distortion
- Momentary “blinks” may reset complex light state
- Unpredictable relationship between RMS voltage and LED light output
- LED controller sensitive to power line carrier AMI systems, AC feeder events from upstream

Modern load characteristic – load behavior is only indirectly related to AC voltage – difficult to characterize or predict
Modern Power Load Example – Variable Frequency Drive

Conversion of AC to DC breaks direct link between utility AC and load – motor never sees utility voltage. VFD Controller is in charge, determining motor operation and judging incoming PQ.

VFD benefits:
- No motor-inrush current – eliminates voltage sags
- High efficiency
- Very fine-grained control of motor operation

VFD problems:
- High current harmonic distortion
- Voltage notching, transients from overlapped switching
- Complex VFD threshold programming – can be overly sensitive to AC power
Modern Load Characteristics

Disconnect between utility voltage and load performance
• Actual load doesn’t directly utility incoming AC voltage to do work
• Load driven by synthesized AC/DC from controller
• Relationship between utility voltage and load performance much blurrier

Increased/different sensitivity to upstream PQ events
• Smart load microcontroller the judge of PQ problems, not the load
• PQ sensitivity driven by load internal power supply design, not the actual load itself
• Extra layer of PQ sensitivity – controller thresholds

Higher proportion of harmonic loads
• switching power supplies are inherently nonlinear, drawing harmonic current
• plummeting cost of high power supplies turning even simple resistive loads into switched loads

Increased load complexity
• Complex power supply
• Complex controller
• Complex load state
Utility Challenges – PQ Standards

Traditional PQ standards out of date, not as useful for predicting equipment compatibility

Example: modern lights

Incandescent:
- Light flicker well determined based on physics of glowing filament
- IEEE 141 and 1453 provide voltage variation limits based on perceptible light flicker

LED:
- Light output based on internal power supply output, not utility voltage
- Operation in presence of voltage sags depends on power supply design – internal energy storage, etc.
- No standardized LED driver response to AC voltage changes
- LED bulb response often nonlinear

Voltage sag causes LED bulb to reset from purple to white – is that light flicker?
Utility Challenges – Increased Sensitivity

Example: UPS-based traffic signal controller
Utility Challenges – Increased Sensitivity

Nonlinear or “smart” operation can magnify PQ events

UPS-based traffic signal controller
Benign powerline carrier meter-read signal causes traffic signal UPS to operate
A member on our system is having problems with flickering LED lights on one circuit in their home though our monitor does not show any issues. They have indicated that the problem is only on one leg in the home. We switch our leads in the meter can and after switching the leads and checking all upstream connections the problem still persists. I've attached some of our monitor data and a video of one of the flickering lights along with the PMI version below. Any input would be helpful.

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When we first changed the leads in the meter can the owner told us the same lights were still flickering, but we have not heard anything since then. As far as we know it is still the same. The voltage readings that have shown up in the event report were all able to be traced back to an outage or temporary fault on the feeder. Most of the days look fine and the voltage levels stay within the acceptable range of 114-126 V. Even within this range the LEDs will flicker.

There are a few dimmable LED fixtures that are flickering, but not all of the fixtures having this problem are dimmable. They have all LEDs in their home but not all of the LEDs are having this issue. We took over some of our own LED bulbs and they did the same thing. We do not have a PMI monitor on the location at this time, but Joe is sending us a demo wall plugin recorder to see if we can identify the problem that way.

We've checked the neutral and connections, all upline devices and connections as well as replaced the transformer.
Power Quality 102

- Transients
- IEEE 519 Harmonics
- CBEMA/ITIC
- Flicker
- Loose Neutral
- Impact Loading
- Variable Frequency Drives
- Modern Loads and PQ
- Further Reading
Power Quality Standards
Partial List


IEEE 1453D2 (1453.1): Recommended Practice for Measurement and Limits Of Voltage Fluctuations and Associated Light Flicker on AC Power Systems

IEEE 1159, 2009: Recommended Practice for Measuring Electric Power Quality

IEEE C62.41: Recommended Practice on Surge Voltages in Low Voltage AC Power Circuits
IEEE 1159 *Recommended Practice for Monitoring Electric Power Quality*

- Provides guidelines for power quality monitoring
- Standard definitions for short term and long term power quality disturbances, distortions
- Provides common language for identifying and describing power quality events
- PQ monitoring objectives: effects on equipment settings
- Types of monitoring: predictive, diagnostic
- Disturbance effects on customer equipment
- Recommended practices, techniques
- Selecting monitoring location
IEEE 1250: Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances

- Describes momentary voltage disturbances, distortions, and causes in AC power distribution systems
- Effects on sensitive equipment
- Describes types of sensitive loads, ride-through capability
- Tolerance of computers to voltage magnitude, duration variations – CBEMA/ITIC curves
- Solutions to problems caused by voltage disturbances
Further Reading

- IEEE 519:1992 – good background
- IEEE Std C57.110-1986 – IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Current
- IEEE Std. 1159-2009 – IEEE Recommended Practice for Monitoring Electric Power Quality
- IEC 61000-4-7 – General Guide on Harmonics and Interharmonics Measurement
- IEC 61000-4-30 – Power Quality Measurement Methods
- IEEE Std. 1453 – IEEE Flickermeter Specification
- PMI whitepapers: [https://library.powermonitors.com/](https://library.powermonitors.com/)
Thank you for attending!