• Introduction to power quality (PQ)
• Causes of poor PQ and impact of application
• PQ characteristics
• Tools for monitoring PQ
• Case studies
Poor PQ refers to changes in an electric power supply that can cause equipment to fail, misoperate, or degrade.
**What Is the Cost of Poor PQ?**

Equipment failures, misoperations, and degradation

<table>
<thead>
<tr>
<th>Condition</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power frequency</td>
<td>Pass</td>
</tr>
<tr>
<td>Supply voltage variations</td>
<td>Pass</td>
</tr>
<tr>
<td>Flicker</td>
<td>Pass</td>
</tr>
<tr>
<td>Supply voltage unbalance</td>
<td>Pass</td>
</tr>
<tr>
<td>Harmonics</td>
<td>Fail</td>
</tr>
<tr>
<td>Rapid voltage changes</td>
<td>Concern</td>
</tr>
<tr>
<td>Voltage dips and interruptions</td>
<td>Concern</td>
</tr>
<tr>
<td>Temporary overvoltages</td>
<td>Pass</td>
</tr>
</tbody>
</table>
PQ Problems Can Affect Metering Accuracy
ANSI C12.20-2015, Accuracy Class 0.1 Adds Tests

- **Test 39**: 90° Phase-Fired Waveform
- **Test 40**: Quadriform Waveform
- **Test 41**: Peaked Waveform
- **Test 42**: Pulse Waveform
- **Test 43**: Multiple Zero-Crossing
- **Test 44**: Multiple Zero-Crossing

![Graphs of waveforms for each test]
Several Factors Affect PQ

Nonlinear Loads

Large Load Changes

Faults
Nonlinear Loads Distort Waveforms
Incandescent Bulb With Dimmer

Voltage
169 V peak
120 V rms

Current
0.15 A peak
0.07 A rms
LED Lights Provide Energy Efficiency But Distort Waveforms

Incandescent Bulb With Dimmer
- Peak: 0.60 A
- RMS: 0.44 A

LED Light
- Peak: 0.11 A
- RMS: 0.04 A
High Sampling Rates Accurately Capture Waveform Content

LED Light Bulb Waveforms

8 kHz – 0% Error

1 kHz – 2.2% Error
Customer and Utility Share Responsibility

- Customer limits current distortion
- System owner or operator limits voltage distortion by modifying supply system impedance characteristics

IEEE 519-2014 applies to point of common coupling
EPRI 2001 Study of Typical PQ Phenomena

- Voltage Sags: 46%
- Voltage Swells: 10%
- Spikes, Transients: 10%
- Outages: 5%
- Line Noise: 5%
- Harmonics: 5%
- Frequency Variations: 5%
- Overvoltage: 7%
- Undervoltage: 7%
Voltage Sag, Swell, and Interruption (VSSI)

![Graph showing voltage sag, swell, and interruption over time](image)

- **Voltage (V)**
- **Time (seconds)**
- **Swell**
- **Sag**
- **Fault Interruption**
Analyze Sag Event Using Waveform or RMS Plots

- $V_A$ rms
- $V_B$ rms
- $V_C$ rms

Time (ms):
- 0
- 50 ms
- 1,000 ms
- 2,400 ms
VSSI Are Described by Depth and Duration

- Voltage (V)
- Sag Event Waveform

85 V Sag Peak
60 V rms

~3 cycles
Combined Waveform and RMS Plot

Voltage (V)

V rms
V inst
### Overvoltage and Undervoltage Are Long-Term Phenomena

<table>
<thead>
<tr>
<th>PQ Phenomenon</th>
<th>Amplitude Range</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sag</td>
<td>10–90%</td>
<td>0.5 cycles to 1 minute</td>
</tr>
<tr>
<td>Undervoltage</td>
<td>80–90%</td>
<td>&gt;1 minute</td>
</tr>
<tr>
<td>Swell</td>
<td>≥110%</td>
<td>0.5 cycles to 1 minute</td>
</tr>
<tr>
<td>Overvoltage</td>
<td>110–120%</td>
<td>&gt;1 minute</td>
</tr>
</tbody>
</table>
Lightning Strikes Cause Voltage Sags

Lightning Strikes Power Pole

- Insulators Flash Over and Fault Current Flows

- Instantaneous Voltage Drop Occurs

- Protective Relays Operate

- Circuit Breakers Open
Power System Faults Can Cause Voltage Sags

Voltage Profile of a Three-Phase Fault

Voltage disturbance effect is more at fault point and less away from it
Fault on Transmission Line Causes Sag and Interruption
Restoration Event Causes Damage to 3D Printer

Asymmetric waveform indicates presence of second harmonic
Motor Operation Can Cause Voltage Sags

Motor Starting Period

Steady-State Running Period

Motor Current

Motor

Mechanical Load
University Uses Voltage Sag Data to Continue Operations and Buy Planning Time

700 hp pump
Optimized Motor Shutdown Reduces Sag and Eliminates Problems

Before

After

Voltage

Current

Startup

Shutdown

Startup

Shutdown
Voltage Sag Ride-Through Characteristics

- **Electronic Drive**
- **Computer**
- **Contactor**

Voltage Sag Ride-Through Graph:
- Voltage (%) on the y-axis.
- Time (cycles) on the x-axis.
- Lines representing different systems.
Voltage Events Damage Motors and Sensitive Processing Equipment

$65,000

$1,300

$1,300

$65,000
Voltage Events Damage Motor Fan and Compressor and Degrade Power Supply

- **Swell Limit**: 280%
- **Sag Limit**: 40%
- **Duration (seconds)**: 40, 46, 21
- **Vrms = 110%**: 46 minutes
- **Vrms = 112.5%**: 41 minutes
- **Vrms = 113%**: 21 minutes
- **Safe Region**: Vrms < 110%
- **Prohibited Region**: Vrms > 113%
- **No-Damage Region**: 110% < Vrms < 113%

Voltage Events may lead to damage to the motor, fan, and compressor, and degrade the power supply.
VSSI Data Reveal Stuck Load Tap Changer

Graph showing Vbase (%) over time with a peak at 110% Vbase and a duration of 41 minutes.
IEC 61000-4-30 Standardizes PQ Measurements

Class A: For contractual applications and verifying compliance

Class S: For surveys and assessment

IEC 62586-2 specifies functional test requirements for IEC 61000-4-30
Voltage Unbalance Damages Motors

- Causes temperature rise
- Reduces life expectancy

Photo courtesy of Electrical Apparatus Service Association
Unbalance Occurs When $V_A + V_B + V_C \neq 0 \text{ V}$

Balanced Three-Phase Waveforms

![Diagram showing the relationship between $V_A$, $V_B$, and $V_C$ with a 120° phase difference and their corresponding magnitude (pu) waveforms.](image-url)
Unbalance Occurs When $V_A + V_B + V_C \neq 0 \text{ V}$

Unbalanced Three-Phase Waveforms

![Diagram showing unbalanced three-phase waveforms with vectors $V_A$, $V_B$, and $V_C$ and a graph plotting magnitude over cycles with labels A-Phase, B-Phase, C-Phase, and Unbalance.]
Typical Voltage Unbalance Levels in U.S. Three-Phase Power Delivered to Industrial Plants

- **<1% Unbalance**: Operates normally (66%)
- **1–3% Unbalance**: Causes overheating and premature aging (32%)
- **>3% Unbalance**: Can cause significant damage (2%)
Facilities Operator Uses Data to Balance Loads

I Unbalance = 11%

I Unbalance = 7%

Phase Currents (A)

June  | August  | October | December | February | April

Loads Balanced in December
Common Causes of Unbalance

- Faulty distribution equipment
- Random phase loading (arc furnaces)
- Unbalanced distribution feeders
Unbalanced Magnitude Phasor

---

**Magnitude (V)**

<table>
<thead>
<tr>
<th>150</th>
<th>100</th>
<th>50</th>
<th>0</th>
<th>–50</th>
<th>–100</th>
<th>–150</th>
</tr>
</thead>
</table>

- **A-Phase**
- **B-Phase**
- **C-Phase**
- **V₀**

---

**Time (cycles)**

- 0
- 0.33
- 0.67
- 1
- 1.33
- 1.67
- 2

---
Harmonics Occur as Multiples of 60 Hz

- Fundamental: 60 Hz
- Third harmonic: 60 • 3 = 180 Hz

Voltage (pu) vs. Time (s)

- Fundamental
- Third Harmonic
- Fundamental + Third Harmonic

Fundamental: 60 Hz
Third harmonic: 60 • 3 = 180 Hz
Harmonics Occur as Multiples of 60 Hz

Fundamental: 60 Hz
Fifth harmonic: $60 \cdot 5 = 300$ Hz

![Graph showing voltage (pu) vs time (s) for fundamental, third harmonic, fifth harmonic, and their combination.]
Harmonics Cause Humming in Transformers
Spectral Analysis Displays Harmonics, Subharmonics, and Interharmonics

- 60 Hz Fundamental Harmonic Component
- Subharmonic Components
- Second-Harmonic Component
- Interharmonics 65–115 Hz
Harmonics Described as Percent of Fundamental Frequency

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Frequency (Hz)</th>
<th>RMS Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental (1)</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>3rd</td>
<td>180</td>
<td>6</td>
</tr>
<tr>
<td>4th</td>
<td>240</td>
<td>4</td>
</tr>
<tr>
<td>5th</td>
<td>300</td>
<td>3</td>
</tr>
</tbody>
</table>

\[
THD = \sqrt{\frac{\text{Sum of squares of harmonics} \times 100}{\text{Amplitude of fundamental}}} = \sqrt{\frac{6^2 + 4^2 + 3^2 \times 100}{120}} = 6.5\%
\]
Total Harmonic Distortion (THD) Is High Under Low-Load Conditions Although Impact Can Be Low

Incandescent Bulb With Dimmer
Current THD: 20%
0.44 A rms

LED Light
Current THD: 45%
0.04 A rms
IEEE 519-2014 Uses Total Demand Distortion (TDD)

\[
\text{TDD} = \sqrt{\frac{\text{Sum of squares of harmonics}}{\text{Maximum demand load current}}} \cdot 100
\]
Third-Order, Odd Harmonics (Triplens) Align With A, B, and C Phases

Peaks align with fundamental peaks of other phases
Harmonic Currents Produce Heat and Cause Damage

Losses = $I^2R$

Use K-factor measurements from advanced meters to size transformers to serve distorting loads without overheating.
Rotate Angles to 5x Position

Fifth Harmonic Counters Torque

Normal (ABC)

Fifth Harmonic (ACB)
Harmonic Trending Pinpoints Cause of Lighting Ballast Failures
Electronic Ballasts Cause Fifth-Harmonic Disturbance

Current Harmonics (%)

5:30 a.m. 5:30 a.m. 5:30 a.m.

Day 1 Day 2 Day 3
Adjustable Speed Drives Cause Harmonics

Six-pole adjustable speed drive creates fifth and seventh harmonics
HVdc and Industrial Interties Cause Harmonic Issue for Georgia
Low Harmonics Are More Common in Power System

Third Order

Fifth Order

Fiftieth Order
High Crest Factor (CF) Indicates Reduced Lamp Life

- CF = peak / rms
- For ideal sine wave
  - RMS = peak / $\sqrt{2}$
  - CF = peak / rms = 1.414

$$y(t) = Y_m \cos(\omega t + \varphi)$$
$$\omega = 2\pi f$$

- $Y_m$ = peak
- $-Y_m$ = negative peak

- $t$ = time
- $\omega t$ = angular position
- $\varphi$ = phase shift

\[ \frac{2\pi}{\omega} = \text{period} \]
Higher-Order Harmonics Are Lower in Magnitude
Identify Sources of Harmonics

- Nonlinear loads
- HVdc interties
- Saturated transformers
- Arcing devices
- Renewable energy generators
- Electronic-ballast fluorescent lights
Turning on Water Results in Voltage Variation That Affects Lights

Variable-Frequency Drive (VFD) for Constant Water Pressure
VFD Not Running
512 Samples Per Cycle
VFD Running
512 Samples Per Cycle
Reduce Harmonic Disturbances

- Isolate voltage sources for sensitive devices from harmonic-generating devices
- Use K-rated transformer or derate transformer
- Install filters between drive and power system
Amplitude modulation of voltage when signal carries another signal
Nonlinear Loads Cause Unwanted Zero-Crossings That Affect Digital Clocks
• PQ issues are changes in electric power supply that can cause equipment to fail, misoperate, or degrade

• Common PQ phenomena are VSSI, harmonics, voltage unbalance, and transients

• PQ characteristics can be described by amplitude, duration, frequency, and wave shape
Troubleshooting Summary

• Look for patterns in disturbances by noting time of day, duration, and how often events occur
• Correlate PQ events with load changes, switching capacitor banks, and so on
• Remember that PQ events are typically worse near the source of the problem
• Note that high neutral current can indicate third harmonics
Questions?