Metrology Challenges in the Brave New World of Electronics

Minnesota Power Systems Conference
Daniel E. Nordell, P.E.
d.nordell@ieee.org
November 7, 2018
What Used to Be

- Electricity metering measured total energy consumption and sometimes power factor.
- Metering was an elegant electromechanical device coming from the end of the 19th century and serving us well for 100 years.
What Is Now

- Electricity Meter is the “gatekeeper” (Point of Common Coupling) between the utility and the consumer
- Meter is now a complex electronic measurement device / computer
- Energy flow is often bi-directional – customer-owned generation
- Tariffs are much more complex
- Electricity almost always passes through power electronics on its way to the user
The Electronic Meter

[Diagram of an electronic meter with various components labeled, including Utility Source, Electrical Output, Disconnect, Voltage, Current, Meterology (Energy), Power Supply, Register (Display, Data), Communications (FAN), Communications (HAN), Antenna, and Customer Load.]
Present Day Challenges

- The meter is more fragile than it used to be and now has a reputation for either exploding or burning at inconvenient times.
- Complex tariffs require more intelligence and better communication.
- Power Electronic loads often create unusual waveforms.
Characteristics of Power Electronic Waveform Currents

- Harmonics
- Subharmonics
- Multiple zero crossings
- Pulses
Power Quality Phenomena

- Repetitive
- Non-repetitive
Power Disturbances:
Overvoltages: Spikes and surges

Causes:
- Lightning
- Power network switching
- Operation of customer loads

Duration:
- Spikes: from 0.5 to 200 $\mu$s
- Surges: up to 16.7 ms
Power Disturbances: Undervoltage (sags)

Causes:
- On-site customer load changes
- Faults on the power system
- Large load changes in the utility service area
- Utility equipment malfunction

Duration:
- From 67 ms to 1 second
Power Disturbances: Outage

Causes:
- Lightning
- Power network switching
- Operation of customer loads

Duration:
- From 2 to 60 seconds if correction is automatic.
- Unlimited if correction is manual
Power Disturbances: Harmonic Distortion

Causes:
- Discontinuous or nonlinear electronic control devices or loads
- Saturated transformers

Duration:
- Unlimited
The CBEMA Curve (1980’s)
Power Electronic Systems

Most systems (except for AC choppers and large horsepower cycloconverters) look like:

- AC Input
- Rectifier
- DC Link
- Other Converter(s)
- Output

May be controlled or uncontrolled
Diode Rectifier

Supply Voltage

Battery Voltage

Load Current
Thyristor Control
Characteristics of Power Electronics Waveforms

- Non-linear devices produce harmonic-rich current waveforms.
- Will also distort the voltage waveform through system impedance.
- Harmonics in power waveforms cause interesting problems......
Diode bridge waveforms are rich in third harmonics

Typical Full-wave rectifier current waveform

Very similar to fundamental plus 60% third harmonic

Fundamental & 3rd harmonic added together
Arc Characteristics

- Non-linear Voltage / current curve yields harmonic response.
- Voltage flicker, particularly from arc furnaces.
Transformer Saturation

- Hysteresis curve of transformer iron leads to non-linear exciting current

\[ v_1 = N_1 \frac{d\phi}{dt} \]
Qualification of new AMI meters

- Service disconnect switch – operation and reclose restraint
- Timekeeping
  - Disciplined Clock
- Load Profile recording – optical / AMI match?
- Power Factor measurement
  - Definition: \( \text{kW} / \text{kVA} = \frac{\text{kW}}{\text{kVA}} \)
  - Definition: \( \cos(\theta) \)
  - Equivalent only for sinusoidal waveforms
Whole Service Disconnect Backfeed Restraint Test

- Most meters fail restraint when Phases A & C in phase “Single Phase Backfeed”
Overvoltage Stress Test
2x nameplate up to 1000 volts
Random Load Pattern
Delivered / Received

Simulates residential with solar approx 2 kW
Meter Waveform Test Bay
4 Wire Wye – 50% Power Factor

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Freq (Hz)</th>
<th>Duty Cycle (%)</th>
<th>Phase Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase A:</th>
<th>Voltage:</th>
<th>Voltage Phase:</th>
<th>Current:</th>
<th>Current Phase:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod % or deg:</td>
<td>0.00</td>
<td>0.00</td>
<td>5.000</td>
<td>-60.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase B:</th>
<th>Voltage:</th>
<th>Voltage Phase:</th>
<th>Current:</th>
<th>Current Phase:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod % or deg:</td>
<td>0.00</td>
<td>0.00</td>
<td>5.000</td>
<td>180.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase C:</th>
<th>Voltage:</th>
<th>Voltage Phase:</th>
<th>Current:</th>
<th>Current Phase:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod % or deg:</td>
<td>0.00</td>
<td>240.00</td>
<td>5.000</td>
<td>300.00</td>
</tr>
</tbody>
</table>

I Phase Tweak: 0.0

Voltage Freq: 60.00
Current Freq: 60.00
4 Wire Wye Reverse Power Unity Power Factor
3 Wire Delta Unity Power Factor
120/240 Unity PF 50/50% Light Dimmer

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Pulse</th>
<th>Freq (Hz)</th>
<th>Duty Cycle (%)</th>
<th>Phase Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120.00</td>
<td>50.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Voltage Phase</th>
<th>Current</th>
<th>Current Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A: 120.000</td>
<td>0.000</td>
<td>5.000</td>
<td>0.000</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>-100.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Phase B: 0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>-120.000</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>-100.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Phase C: 120.000</td>
<td>-180.000</td>
<td>5.000</td>
<td>-180.000</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>-100.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>i Phase Tweak:</th>
<th>0.0</th>
</tr>
</thead>
</table>

| Voltage Freq: | 60.00 |
| Current Freq: | 60.00 |
120/208 4W Wye subharmonics 117 Hz
-100% pulse

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Freq (Hz)</th>
<th>Duty Cycle (%)</th>
<th>Phase Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse</td>
<td>117.00</td>
<td>50.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase A:</th>
<th>Voltage</th>
<th>Voltage Phase</th>
<th>Current</th>
<th>Current Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod % or deg:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-120.000</td>
<td>0.000</td>
<td>5.000</td>
<td>-120.000</td>
<td>0.000</td>
</tr>
<tr>
<td>-20.000</td>
<td>0.000</td>
<td>-100.000</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase B:</th>
<th>Voltage</th>
<th>Voltage Phase</th>
<th>Current</th>
<th>Current Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod % or deg:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-120.000</td>
<td>-120.000</td>
<td>5.000</td>
<td>-120.000</td>
<td>0.000</td>
</tr>
<tr>
<td>-20.000</td>
<td>0.000</td>
<td>-100.000</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase C:</th>
<th>Voltage</th>
<th>Voltage Phase</th>
<th>Current</th>
<th>Current Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod % or deg:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-120.000</td>
<td>-240.000</td>
<td>5.000</td>
<td>-240.000</td>
<td>0.000</td>
</tr>
<tr>
<td>-20.000</td>
<td>0.000</td>
<td>-100.000</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I Phase Tweak:</th>
<th>Voltage Freq:</th>
<th>Current Freq:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>60.00</td>
<td>60.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Freq:</th>
<th>60.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Freq:</td>
<td>60.00</td>
</tr>
</tbody>
</table>
120/240 2S/12S Unity PF 6th harmonic
Conclusions

- We have developed unique capabilities to stress-test AMI meters
- Found a few issues:
  - Timekeeping / load profile issues
  - Disconnect / reconnect restraint failures
  - Power Supply overvoltage failures / fire
  - Power Factor measurements
  - Harmonic / subharmonic waveforms - generally good with a few exceptions