HARMONICS - THE BASICS
Harmonic Basics

What are harmonics?

- Proliferated by power semiconductor devices
  - Converts power (AC to DC, DC to AC, etc.)
- A harmonic is a component of a periodic wave having a frequency that is an integer multiple of the fundamental power line frequency
  - Characteristic harmonics are the predominate harmonics seen by the power distribution system
- Predicted by the following equation:
  - \( h_C = np +/\!\!/- 1 \)

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Frequency Sequence</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>50Hz</td>
</tr>
<tr>
<td>2</td>
<td>100Hz</td>
</tr>
<tr>
<td>3</td>
<td>150Hz</td>
</tr>
<tr>
<td>4</td>
<td>200Hz</td>
</tr>
<tr>
<td>5</td>
<td>250Hz</td>
</tr>
<tr>
<td>6</td>
<td>300Hz</td>
</tr>
<tr>
<td>7</td>
<td>350Hz</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>950Hz</td>
</tr>
</tbody>
</table>
Multi-pulse Converters

Harmonic Orders Present

\[ H_n = NP \pm 1 \]

\[ H_n = \text{harmonic order present} \]

\[ N, n = \text{an integer} \]

\[ P = \text{number of pulses} \]

<table>
<thead>
<tr>
<th>Harmonics present by rectifier design</th>
<th>Type of rectifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_n )</td>
<td>1 phase 4-pulse</td>
</tr>
<tr>
<td></td>
<td>2 phase 4-pulse</td>
</tr>
<tr>
<td></td>
<td>3 phase 6-pulse</td>
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<tr>
<td></td>
<td>3 phase 12-pulse</td>
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<tr>
<td></td>
<td>3 phase 18-pulse</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
</tr>
<tr>
<td>9</td>
<td>x</td>
</tr>
<tr>
<td>11</td>
<td>x</td>
</tr>
<tr>
<td>13</td>
<td>x</td>
</tr>
<tr>
<td>15</td>
<td>x</td>
</tr>
<tr>
<td>17</td>
<td>x</td>
</tr>
<tr>
<td>19</td>
<td>x</td>
</tr>
<tr>
<td>21</td>
<td>x</td>
</tr>
<tr>
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<td>39</td>
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<td>41</td>
<td>x</td>
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<tr>
<td>43</td>
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<td>45</td>
<td>x</td>
</tr>
<tr>
<td>47</td>
<td>x</td>
</tr>
<tr>
<td>49</td>
<td>x</td>
</tr>
</tbody>
</table>
Harmonic Basics

- Nonlinear loads draw it
- Example: 6-Pulse VFD
Harmonic Basics

Why a concern?

- **Current distortion**
  - Added heating, reduced capacity in
    - Transformers
    - Conductors and cables
  - Nuisance tripping of electronic circuit breakers (thermal overload)
  - Blown fuses
  - Detrimental to generators
    - Heating of windings
  - Detrimental to UPS
    - UPS can’t supply the current

\[ V_h = I_h \times Z_h \]
HARMONIC BASICS

- **Voltage distortion**
  - Interference with other electronic loads
  - Faulting to destruction
  - Generator regulators can’t function
  - Shut downs

- **Not compatible with PF caps**
  - Potential resonance condition
  - Excessive voltage
  - Overheating of PF correction capacitors
  - Tripping of PF protection equipment
  - Shutdown / damage to electronic equipment

- **Encapsulated cables have stray capacitance**
  - Harmonics create resonance at generator
  - Critical to limit harmonics before the encapsulated cable power feeds
    - Especially on Ring Mains Systems
WHAT IS TOTAL POWER FACTOR?

TPF = (DPF) x (Distortion factor)

\[
DPF = \frac{KW}{KVA_f} = \cos \phi
\]

\[
\text{Distortion factor} = \frac{1}{\sqrt{1 + \text{THD}(I)^2}} = \cos \delta
\]

TPF = Total or true power factor

DPF = Displacement power factor

Distortion factor = Harmonic power factor
TOTAL POWER FACTOR EXAMPLE

- Variable frequency drive (PWM type)
- DPF = 0.95

- THD(I) = 35%
  - (with DC choke or input line reactor)

- Distortion Factor = 0.9438

- TPF = 0.95 x 0.9438 = 0.8966

\[
\frac{1}{\sqrt{1 + 0.35^2}} = 0.9438
\]
HARMONIC MITIGATION METHODS

- Typically applied per device
  - Line reactors/DC bus chokes
  - 5th harmonic filters
  - Broadband filters
  - Multi-pulsing
  - Active front end (AFE) converter
  - Low Harmonic Drives

- System solution
  - Active harmonic filter
**INDUCTORS/TRANSFORMERS**

- **Converter-applied inductors or isolation transformers. (Line Reactor less expensive than transformer)**

**Pros:**
- Inexpensive & reliable
- Transient protection for loads
- Suppresses voltage notch of SCR rectifier
- 1st Z yields big TDD reduction (90% to 35% w/3% Z)
- Complimentary to active harmonic control

**Cons:**
- Limited reduction of TDD at equipment terminals after 1st Z
- Reduction dependent on source Z
- Adds ~1% losses to individual system
5TH HARMONIC FILTER

- Inductor ($L_p$) and Capacitor ($C$) provide low impedance source for a single frequency ($5^{th}$)
  - Must add more tuned filters to filter more frequencies
- Inductor $L_s$ required to detune filter from electrical system and other filters
  - If $L_s$ not present, filter is sink for all $5^{th}$ harmonics in system
  - If $L_s$ not present, resonance with other tuned filters possible
- Injects leading reactive current (kVAR) at all times – may not need
- Losses of 1-2% typical
BROADBAND FILTERS

- Mitigates up to 13\textsuperscript{th} (19\textsuperscript{th}) order
- Each inductor (L) => 8\% impedance
  - V drops ~ 16\% at load
  - Trapezoidal voltage to load
  - Can only be used on diode converters
  - Prevents fast current changes (only good for centrifugal loads)
- Capacitor (C) designed to boost V at load to acceptable level (injects leading VARs)
  - Physically large
  - High heat losses (~5\%)
  - Series device
Multi-Pulse Drives

Rectifiers with two (12 pulse) or three (18 pulse) input bridges fed by a transformer with two or three phase shifted output windings.

Pros:
- Reduces TDD to 10% (12 pulse) & 5% (18 pulse) at loads
- Reliable

Cons:
- High installation cost with external transformer
- Large footprint (even w/autotransformer)
- Series solution with reduction in efficiency (1-2% losses)
- One required for each product
- Cannot retrofit
ACTIVE FRONT END CONVERTER

Input filter required to attain 5% THDv
AFE CONVERTERS

- PCC
- EMC Filter
- Mains Choke Reactance, 4%
- Mains Filter
- Mains Filter Reactance, 12%
- Mains Pulse Converter, IGBT
- DC Bus
- Motor Pulse Inverter, IGBT
- Motor
AFE CONVERTERS

- Disadvantages
  - Larger and more expensive than 6 pulse drives
    - Approximately twice the size & price
  - Larger & more expensive than 18-P VFD
  - Additional ~5% losses
  - Mains voltage must be free of imbalance and voltage harmonics
    - Generates more harmonics
  - Without mains filter, THD(V) can reach 40%
  - Requires short circuit ratio ≥ 40 at PCC
    - Transformers two times KVA of VFD
  - Switched mode power supplies prohibited
  - IGBT & SCR rectifiers prohibited on same mains
    - No other nonlinear loads permitted
  - Capacitors prohibited on mains
SYSTEM SOLUTION

ACTIVE HARMONIC FILTER

- Applied to one or many nonlinear loads
  - VFD, UPS, UV, DC drives, DC power supplies
- Provides DPF correction
  - Leading or lagging
- More cost effective for multiple loads
- Saves space
- Lower total heat losses
- Not critical to operation
ACTIVE HARMONIC FILTER

• Parallel connected

\[ I_s + I_a = I_1 \]

• \( I_a \) includes 2\textsuperscript{nd} to 25/50\textsuperscript{th} harmonic current

• \( I_s < 5\% \) TDD

Reduced THDv everywhere
ACTIVE HARMONIC FILTER

Pros:
- Load, bus, or PCC applied solution
- Easy sizing - not dependent upon system Z
- Scalable
- Dynamic - responds instantly
- Provides precise correction
- Parallel Installation
- Meets 5% TDD at equipment, bus, or PCC

Considerations:
- May Require additional impedance (eg 3%)
- Requires individual branch circuit protection
DUAL MODE OPERATION

MOST ACTIVE HARMONIC FILTERS CAN PROVIDE BOTH HARMONIC MITIGATION AND POWER FACTOR CORRECTION EITHER SEPERATELY OR AT THE SAME TIME – YOU CHOOSE

\[ I_{as} = \sqrt{I_h^2 + I_r^2} \]

- \( I_{as} \) = rms output current of AccuSine
- \( I_h \) = rms harmonic current
- \( I_r \) = rms reactive current

<table>
<thead>
<tr>
<th>Examples</th>
<th>( I_{as} )</th>
<th>( I_h )</th>
<th>( I_r )</th>
</tr>
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<tbody>
<tr>
<td>100.0</td>
<td>10.0</td>
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<td>90.0</td>
<td>43.6</td>
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<tr>
<td>100.0</td>
<td>95.0</td>
<td>31.2</td>
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ELECTRONIC POWER SOLUTIONS OFFER NUMEROUS HARMONIC MITIGATION SOLUTIONS

CONTACT ELECTRONIC POWER SOLUTIONS ABOUT YOUR HARMONIC MITIGATION SOLUTION