Power Quality – Harmonic Basics
Problems and solutions

828m high
160 floors in total

<table>
<thead>
<tr>
<th>Type</th>
<th>IP Protection</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQFS</td>
<td>IP30</td>
<td>60</td>
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<td>IP30</td>
<td>100</td>
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<tr>
<td>PQFM</td>
<td>IP21</td>
<td>150</td>
</tr>
<tr>
<td>PQFI</td>
<td>IP21</td>
<td>450</td>
</tr>
<tr>
<td>PQFI</td>
<td>IP21</td>
<td>250</td>
</tr>
<tr>
<td>PQFI</td>
<td>IP21</td>
<td>450</td>
</tr>
<tr>
<td>PQFI</td>
<td>9M+2S</td>
<td>250</td>
</tr>
</tbody>
</table>

Total 113 PQF in this tower, 12000A
Harmonic Basics

Outline

- Harmonic definition
- Harmonic sources
- Problems caused by harmonic
Harmonic analysis
What are harmonics

- Integer multiples of the fundamental frequency of any periodical waveform are called Harmonics e.g.
  - Acoustic waves
  - Electrical ‘waves’
- For power networks, 50 Hz (60 Hz) is the fundamental frequency and 150 Hz (180 Hz), 250 Hz (300 Hz) etc. are higher order harmonics viz. $3^{rd}$ & $5^{th}$
  - Odd Harmonics ($5^{th}$, $7^{th}$……)
  - Even Harmonics ($2^{nd}$, $4^{th}$ ….)
  - Triplen Harmonics ($3^{rd}$, $9^{th}$, $15^{th}$ ….)
- Non-integer multiples of the fundamental frequency of any periodical waveform are called Inter-harmonics e.g. $2.5^{th}$ $\Rightarrow$ 125 Hz at 50 Hz base

Harmonic analysis
Harmonics representation

Time domain

Frequency domain

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Harmonic analysis
Fourier analysis

MATHEMATICAL REPRESENTATION:
- Any periodical waveform can be decomposed into a series of sinewave forms at different frequencies.

ELECTRICAL REPRESENTATION:
- The distorted voltage or current waveform can be seen as an add-up of many different frequency voltage and current sinewave forms.

- Most non-linear loads have symmetrical waveform;
- Most drive are six pulse drives;
- Harmonics orders: $P^{k\pm 1}$, $P$ is number of pulse. $k$ is an integer.
Harmonic analysis
Fourier analysis

Total Harmonic Distortion (THD)

- Relative importance of harmonics regarding to fundamental

\[
THD = \sqrt{\sum_{k=2}^{n} \frac{C_k^2}{C_1}} \quad \text{(expressed in %)}
\]

- THD(U): meaningful
- THD(I): ??? what is the reference ???
Harmonic Basics

Outline

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- Solutions to harmonic problems

Where do the harmonics come from?

- Power electronics, converters, drives...
  - Rectifiers
  - Inverters
  - UPS
  - ...

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Where do the harmonics come from?

Fluorescent lighting systems

- Computers
- Printers
- Faxing machines
- ...

Small but critical if lots of such devices on same transformer
LED bulbs and harmonics
IEC 61000-3-2 harmonic emission limits

- Lamps with P ≤ 25W shall comply at least one of these requirements:
  - 3rd harmonic current ≤ 86% of fundamental and 5th harmonic current ≤ 61% of fundamental
  - Not exceeding the limits below

<table>
<thead>
<tr>
<th>Harmonics [n]</th>
<th>Maximum permissible harmonic current per watt [mA/W]</th>
<th>Maximum permissible harmonic current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3.4</td>
<td>2.30</td>
</tr>
<tr>
<td>5</td>
<td>1.9</td>
<td>1.14</td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
<td>0.77</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>0.40</td>
</tr>
<tr>
<td>11</td>
<td>0.35</td>
<td>0.33</td>
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</table>

13 ≤ n ≤ 39
(odd harmonics only)
Harmonic content
LEDs and CFLs with dimming mode

<table>
<thead>
<tr>
<th>Tested lamp</th>
<th>Dimming angle [°]</th>
<th>3rd</th>
<th>5th</th>
<th>7th</th>
<th>THDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osram 20W LED dim</td>
<td>0°</td>
<td>100</td>
<td>49.5</td>
<td>26.5</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>100</td>
<td>54.0</td>
<td>17.9</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>100</td>
<td>86.6</td>
<td>71.2</td>
<td>60.0</td>
</tr>
<tr>
<td></td>
<td>135°</td>
<td>100</td>
<td>99.9</td>
<td>98.0</td>
<td>98.0</td>
</tr>
<tr>
<td>Osram 20W CFL dim</td>
<td>0°</td>
<td>100</td>
<td>82.1</td>
<td>49.3</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>100</td>
<td>92.0</td>
<td>79.4</td>
<td>63.8</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>100</td>
<td>94.5</td>
<td>95.9</td>
<td>92.8</td>
</tr>
<tr>
<td></td>
<td>135°</td>
<td>100</td>
<td>98.2</td>
<td>95.3</td>
<td>94.1</td>
</tr>
</tbody>
</table>


Where to find harmonic loads?
Summarized

Harmonic (non-linear) loads are everywhere and in ever increasing number!

- Industrial loads (mainly 3-wire systems)
  - AC and DC drives, UPS-systems, …
    - Harmonics between phases, imbalance, sometimes reactive power
- Commercial loads (mainly 4-wire systems)
  - All office equipment such as computers, saving lamps, photo copiers, fax-machines, …
    - Harmonics in neutral and between phases, imbalance, sometimes reactive power
Harmonic Basics Outline

- Harmonic definition
- Harmonic sources
- Problems caused by harmonic
- Solutions to harmonic problems

LV installation power quality overview
Peak and RMS distortion

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Peak</th>
<th>RMS</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100% H_1$</td>
<td>100%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>$+33% H_3$</td>
<td>133%</td>
<td>105%</td>
<td>33%</td>
</tr>
<tr>
<td>$+20% H_5$</td>
<td>168%</td>
<td>108%</td>
<td>38.6%</td>
</tr>
<tr>
<td>$...+4% H_{25}$</td>
<td>204%</td>
<td>110%</td>
<td>44%</td>
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</table>
Problems created by harmonics

- Nuisance tripping of circuit breaker
  - Increase of RMS → Thermally
  - Increase of peak → Magnetically
- Blown fuses

Excessive heating of devices

Excessive heating of devices

- Distortion → Increase of RMS

\[ \text{Losses} \# R \cdot I_{\text{RMS}}^2 = R \cdot I_1^2 + R \cdot \sum I_h^2 \]

Extra heat brought by harmonics
Problems created by harmonics

- Excessive harmonic current may lead to overheating (or even burning) of network components

Harmonics classification

<table>
<thead>
<tr>
<th>Order</th>
<th>Group</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 1$</td>
<td>Fundamental</td>
<td>Active power</td>
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<tr>
<td>$n = 3k + 1$</td>
<td>+ sequence</td>
<td>Heating</td>
</tr>
<tr>
<td>$n = 3k - 1$</td>
<td>- Sequence</td>
<td>Heating &amp; motor problems</td>
</tr>
<tr>
<td>$n = 3n$</td>
<td>0 sequence</td>
<td>Heating &amp; neutral problems</td>
</tr>
</tbody>
</table>
Problems created by harmonics

- Motor problems
  - Additional losses in windings & iron (RMS increase & skin effect)
  - Perturbing torques on shaft (negative sequence harmonics)

- Damage to electronic sensitive equipments
- Electronic communications interferences

Electrocardiography (ECG) at a hospital:

[Graphs showing ECG waves with and without PQF]
Problems created by harmonics

- Excessive neutral current (mainly zero-sequence harmonics)
- ...

Capacitor problems

- Decrease of impedance with frequency
- Resonance problems

Due to its lower impedance, capacitors are even more susceptible to higher order harmonics. If not protected from harmonic stress, a capacitor may fail pretty soon.
LV installation power quality overview

Summary of harmonics problems

Heat effect (RMS current):
- Overloading of neutrals
- Overheating of cables, motors and transformers
- Interference to sensitive instrument/devices (neutral point shift)

Waveform distortion effect (form, crest factor):
- Nuisance tripping of circuit breakers (peak current)
- Zero crossing problems

Frequency effect (high frequency):
- Capacitor resonance
- Skin effect
- etc…