Power Quality

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Interruptions

Voltage Sag/Swell

Transients

Flicker

Frequency Variations

Harmonics

Voltage Regulation

Notching

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Power Quality Issues

Department of Electrical Engineering, College of Engineering Trivandrum
Impact of Sag/Swell

- Drive systems may trip on occurrence of sag/swell.
- Stored energy is not used or properly handled under such conditions
- *Ride through* methods are developed to manage these conditions

- **Duration:**
  - 0.5 to 30 Cycles
- **Voltage variation:**
  - 0.1 to 0.9 pu
Flicker

- Rapid on-off sensation of lamps as perceived by human eye
- Related to voltage fluctuations
- Caused by
  - Arc furnaces
  - Welding sets
  - Rapidly cycling loads
  - Adjustable speed drives with inadequate dc-link filters
Flicker Generation with VFD

50 Hz supply → 50 Hz Rectifier → DC Link → 60 Hz Drive
Notching

- Periodic voltage disturbance
- Caused by power electronic drives
  - Usually occurs when power is commutated from one phase to another
- Results in
  - Frequency detection errors
  - Zero crossing errors
Impact of Notching

- Multiple dc drives operating at different speeds complicating maloperation and potential failure issues resulting from notches
- Appropriate filters are to be installed to reduce the effect of notching
Harmonics

- Defined as sinusoidal voltages and currents at frequencies other than the fundamental frequency.
- Harmonic frequencies are integer multiples of the fundamental frequency.
- Caused by
  - Nonlinear components in system
  - Power electronic controllers

Mathematically:

\[ f(x) = a_0 + \sum_{n=0}^{\infty} [a_n \cos(nx) + b_n \sin(nx)] \]
Phasor-waveform relation

\[ f(x) = \frac{4}{\pi} \sin x + \frac{4}{3\pi} \sin 3x + \frac{4}{5\pi} \sin 5x + \frac{4}{7\pi} \sin 7x + \ldots \]
Sources of Harmonics

- DC power supplies including SMPS
- Transformer magnetisation nonlinearities
- Rotating machine harmonics
- Arcing devices
- Three phase adjustable speed drives
- Thyristor controlled reactors
- AC Regulators
How harmonics is generated in drives?

Input **current** is not pure sinewave

Output **voltage** is not pure sinewave
Harmonic Flows in Drive Systems

Converters generate harmonics in the supply line and also in the motor current.
Single Phase Power Quality Monitor
Three Phase Power Quality Monitor
Effects of Harmonics ....1

- Motor efficiency reduces with harmonics
- Transformer efficiency reduces with harmonics
- Harmonics may cause circulating current in delta side of transformers
- Harmonics results in de-rating of generator & transformer
- Harmonics may damage capacitors
- PF correction becomes ineffective with harmonics
Effects of Harmonics ...2

- Harmonics causes increased heat loss in conductors due to skin effect
- Harmonics may result in resonant conditions and result in excessive current and voltage in system
- Overloads the distribution system
- Overloads the neutral conductor
- De-rating of system
- Disturbance on communication networks
- Nuisance tripping of circuit breakers due to harmonics
Harmonics Created by Single phase rectifier

Third order harmonic is predominant
Rectifier with unsymmetrical current

Even order harmonics are also present
Three phase rectifier V and I
Harmonics Created by Three phase rectifier
THD and TDD

- Total Harmonic Distortion (Current)

\[ THD_I = \sqrt{\sum_{h=2}^{n} I_h^2} \]

- Total Demand Distortion

\[ TDD = \sqrt{\sum_{h=2}^{n} I_h^2} \]

Where \( I_{MD} \) is current corresponding to Max. Demand
Distortion Power

\[ U = U_1 \]

\[ I_5 \]

\[ W \]

0ms  10ms  20ms  30ms  40ms
Power factor under harmonic conditions

- Power equation takes into account a distortion power also
  \[ S^2 = P^2 + Q^2 + D^2 \]

- The effective power factor \( P/S \) decreases due to harmonics
## Standards Available

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 1433</td>
<td>Power Quality definitions</td>
</tr>
<tr>
<td>IEEE 519</td>
<td>Harmonic control</td>
</tr>
<tr>
<td>IEEE P 1453</td>
<td>Voltage flicker</td>
</tr>
<tr>
<td>IEEE 1409</td>
<td>Distribution and custom power</td>
</tr>
<tr>
<td>ANSI-IEEE C62</td>
<td>Guide for surge voltage</td>
</tr>
<tr>
<td>IEEE 1459</td>
<td>Definitions for the measurement of power quantities</td>
</tr>
<tr>
<td>IEC 61000</td>
<td>Power quality monitoring</td>
</tr>
<tr>
<td>EN 50160</td>
<td>Voltage characteristics of electricity supplied by public distribution systems</td>
</tr>
</tbody>
</table>
IEEE Std 519 -2014

- Sets limits for voltage and current harmonics in terms of Total Harmonic Distortion
- List out recommended practices for reduced level of harmonics

\[ THD_V = \sqrt{\sum_{n=2}^{N} V_n^2} \]

\[ THD_I = \sqrt{\sum_{n=2}^{N} I_n^2} \]

<table>
<thead>
<tr>
<th>Limits on Voltage THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upto 1 kV</td>
</tr>
<tr>
<td>1kV to 69 kV</td>
</tr>
<tr>
<td>69kV to 161 kV</td>
</tr>
<tr>
<td>Above 161 kV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limits on Current TDD</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{sc} / I_L )</td>
<td></td>
</tr>
<tr>
<td>Below 20</td>
<td>5 %</td>
</tr>
<tr>
<td>20 to 50</td>
<td>8 %</td>
</tr>
<tr>
<td>50 to 100</td>
<td>12 %</td>
</tr>
<tr>
<td>100 to 1000</td>
<td>15 %</td>
</tr>
<tr>
<td>Above 1000</td>
<td>20 %</td>
</tr>
</tbody>
</table>
Zero Sequence Harmonics

$H_3$
Negative Sequence Harmonics

$H_5$
Positive Sequence Harmonics
Neutral current in Y connection
Zero sequence harmonics cancel in line voltage

\[ V_{RY} = V_R - V_Y \]
Harmonic order classification

- Positive sequence: 1, 4, 7, 10, 13, …
- Negative sequence: 2, 5, 8, 11, 14, …
- Zero sequence: 3, 6, 9, 12, 15, … (called triplen)
K Factor

- Is an indication of possible heating up and de-rating of transformers due to harmonics

- Specified by the equation:

$$K = \frac{\sum I_h^2 \times h^2}{\sum I_h^2}$$

- Where $I_h$ is in PU

- K rated transformers have design modifications to meet the harmonic conditions
Resonance

(a) Parallel Resonance

(b) Series Resonance
**Interharmonics**

*Noninteger multiple* of the fundamental frequency is commonly known as an *interharmonic frequency*

Sum of Interharmonic frequencies does not necessarily result in a periodic waveform

It is possible to have interharmonics in variable speed drives and rapidly changing loads

Longer sampling interval is required to capture interharmonics. Sampling 10 cycles of 50 Hz result in a resolution of 5 Hz
Interharmonics Example

The diagram illustrates a 3-phase ac input of 60 Hz connected to a controlled rectifier. The output is then fed into a dc link, which connects to an inverter that produces a 1-phase ac output in the range of 150-300 Hz. The output is fed into a furnace coil.

The graph below shows the current as a function of frequency. The horizontal axis represents frequency in Hz, ranging from 0 to 1200 Hz, and the vertical axis represents current in A, ranging from 0 to 40 A. The graph highlights interharmonic frequencies at 2f₀ ± 60 Hz and 4f₀ ± 60 Hz, where f₀ is the fundamental frequency of 60 Hz.
Factors affecting impact of drives

- Pulse number of the front-end rectifier of the VSD
- Compensation circuits
- Magnitude of the power system (source) impedance at PCC
## Mitigation Methods for Harmonics

<table>
<thead>
<tr>
<th>Method</th>
<th>Schematic</th>
<th>THD Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>No mitigation</td>
<td><img src="image" alt="Schematic" /></td>
<td>THD &gt; 80%</td>
</tr>
<tr>
<td>DC Inductor</td>
<td><img src="image" alt="Schematic" /></td>
<td>THD &lt; 40%</td>
</tr>
<tr>
<td>AC Inductor</td>
<td><img src="image" alt="Schematic" /></td>
<td>THD &lt; 40%</td>
</tr>
<tr>
<td>Passive Filter</td>
<td><img src="image" alt="Schematic" /></td>
<td>THD &lt; 10%</td>
</tr>
</tbody>
</table>
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<tr>
<th>Method</th>
<th>Schematic</th>
<th>THD Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-pulse Rectifier</td>
<td><img src="image" alt="Multi-pulse Rectifier Schematic" /></td>
<td>THD &lt; 10%</td>
</tr>
<tr>
<td>Active Filter</td>
<td><img src="image" alt="Active Filter Schematic" /></td>
<td>THD &lt; 5%</td>
</tr>
</tbody>
</table>
Zigzag Transformers

- Phase Shifting in different angles possible
- Can selectively block certain harmonic order
6 Pulse converter

6 pulse inverter has considerable amount of waveform distortion in the input current
Phase Multiplication

12 pulse Series Connected Converter

Input harmonics in much less compared to 6 pulse converter
Converter Types and Harmonics

6 Pulse

12 Pulse

24 Pulse
Harmonics in input current

\[ h = n \cdot p \pm 1 \quad p = 1, 2, 3, \ldots \]

<table>
<thead>
<tr>
<th>( h )</th>
<th>Number of Rectifier Pulses, ( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>X</td>
</tr>
<tr>
<td>13</td>
<td>X</td>
</tr>
<tr>
<td>17</td>
<td>X</td>
</tr>
<tr>
<td>19</td>
<td>X</td>
</tr>
<tr>
<td>23</td>
<td>X</td>
</tr>
<tr>
<td>25</td>
<td>X</td>
</tr>
</tbody>
</table>
Remedies for Harmonic Problem

- Harmonic filters
  - Active, passive or hybrid
- Selection of nonpolluting equipment
- Good distribution network
- Stipulate power quality standards for consumer equipment
  - Already introduced in many countries
  - Implementation may be difficult
- Introduce a penalty/incentive scheme
- Good PQ monitoring System
Thank you