Harmonics in Low Voltage Three-Phase Four-Wire Electric Distribution Systems and Filtering Solutions

Dr. Prasad Enjeti
Texas A&M University
Power Electronics and Power Quality Laboratory

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   - Passive Approach
   - Active Approach
5. Conclusions
Introduction
Typical Building Power Distribution Scheme

- Three Phase Supply From Utility Mains
- Three Phase Stepdown Transformer in Building Basement
- Delta/Wye Distribution Transformer For First Floor
- Power Feeder
- Branch Circuit
- Distribution Panel
- Load
- Floor
- Three Phase Bus
Harmonic Current Sources
Harmonic Producing Equipment in Office Buildings

<table>
<thead>
<tr>
<th>Copy machines</th>
<th>Recorders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric typewriters</td>
<td>Televisions</td>
</tr>
<tr>
<td>Light fixture ballasts</td>
<td>Video tape players</td>
</tr>
<tr>
<td>Personal computers</td>
<td>SCR drives for motors</td>
</tr>
<tr>
<td>Computer systems</td>
<td>SCR drives for elevators</td>
</tr>
<tr>
<td>Computer terminals</td>
<td>UPS systems</td>
</tr>
<tr>
<td>Audio visual equipment</td>
<td>Laboratory testing equipment</td>
</tr>
</tbody>
</table>
Harmonic Related Problems in Buildings

- Overheating and damage to neutral conductors
- Overheating and damage to panel board feeders
- Line voltage distortion
- Higher Common mode voltage
- Nuisance tripping of circuit breakers
- Overheating and premature failure of distribution transformers
Case Studies
Typical Current Waveforms of Appliances

- Microwave Oven Current Waveform #1
  - THD = 18.3%

- Weed Eater Current Waveform
  - THD = 16.8%

- Microwave Oven Current Waveform #2
  - THD = 26.4%

- Vacuum Cleaner Current Waveform
  - THD = 28.0%
Typical Current Waveforms of Appliances. Contd.
Typical Current Waveforms of Appliances. Contd.

Desktop Computer plus Laser Printer Current Waveform

THD = 140%

ASD Heat Pump Current Waveform #1

THD = 123%
Effect of Triplen Harmonics in Neutral Conductors

\[ I_{N,rms} = \sqrt{I_{a,rms}^2 + I_{b,rms}^2 + I_{c,rms}^2} \]

\[ I_{N,rms} = \sqrt{3} \times I_{\text{phase},rms} \]
Survey results, Building I

WITH THIRD HARMONIC

APPARENT POWER ≈ 48kVA
POWER FACTOR ≈ .73
CREST FACTOR ≈ 2.36
K RATING ≈ 5.8

WITHOUT THIRD HARMONIC

≈ 40kVA
≈ .89
≈ 5.34
Survey results, Building II

WITH THIRD HARMONIC

APPARENT POWER  ≈ 47.7 kVA
POWER FACTOR  ≈ .93
CREST FACTOR  ≈ 1.76
K RATING  ≈ 2.19

WITHOUT THIRD HARMONIC

≈ 46.4 kVA
≈ .97
≈ 2.09

Phase Current
Neutral Current

FFT of Phase Current
FFT of Neutral Current
<table>
<thead>
<tr>
<th>Phase Building</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>Neutral to Phase, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building I</td>
<td>66.8A</td>
<td>77.3A</td>
<td>72.5A</td>
<td>120.0A</td>
<td>170%</td>
</tr>
<tr>
<td>Building II</td>
<td>50.0A</td>
<td>65.6A</td>
<td>41.1A</td>
<td>53.7A</td>
<td>103%</td>
</tr>
<tr>
<td>Building III</td>
<td>12.8A</td>
<td>36.1A</td>
<td>24.5A</td>
<td>27.5A</td>
<td>80.9%</td>
</tr>
<tr>
<td>Building IV</td>
<td>80.6A</td>
<td>77.2A</td>
<td>90.0A</td>
<td>142.0A</td>
<td>171.3%</td>
</tr>
<tr>
<td>Building V</td>
<td>23.0A</td>
<td>17.4A</td>
<td>26.0A</td>
<td>12.7A</td>
<td>57.4%</td>
</tr>
<tr>
<td>Building VI</td>
<td>44.6A</td>
<td>41.2A</td>
<td>41.9A</td>
<td>60.7A</td>
<td>143%</td>
</tr>
</tbody>
</table>
OFFICE BUILDINGS

- 9 Buildings surveyed.
- Typical loads include computers and office equipment.
- Average neutral to phase ratio of 1.13
- Average crest factor of 2.12

MEDICAL FACILITIES

- 22 facilities surveyed.
- Typical loads include computers, office equipment, diagnostic and patient care equipment.
- Average crest factor of 2.02

INDUSTRIAL FACILITIES

- 14 sites surveyed.
- Typical loads include computers, laboratory equipment, telecommunication equipment.
- Average neutral to phase of 1.04
- Average crest factor of 2.12

**GOVERNMENT BUILDINGS**
- 6 sites surveyed.
- Typical loads include computers, data processing equipment, office equipment.
- Average neutral to phase of 0.77
- Average crest of 1.78

**AUDIO VISUAL STUDIOS**
- 8 studios surveyed.
- Average neutral to phase of 0.65
- Average crest of 1.74
Common Mode Noise, Building I

Common Mode Noise at Wall Receptacle In Building I

Frequency Spectrum of Common Mode Noise

Breakdown of Common Mode Noise Results
Line Voltage Distortion, Building I

Voltage at Wall Receptacle in Building I

THD of Line Voltage = 7.7%
Harmonic Effects on Transformers

**Transformer Losses Due to Triplen Harmonics**

- Losses in transformers are subdivided into core and winding losses.
- Core loss is of minor concern since it is due to flux generated in the core by the bus voltage.
- Winding losses are increased due to $I^2R$ and stray losses.

**Effects of Triplen Harmonics**

- Excessive stress due to heating
- Insulation breakdown
- Lower operating efficiency
- Short life span
- Acoustic noise
Solutions:
- Derating
- Passive Approach
- Active Approach
1. Derate transformers or use K-Factor Transformers.

2. Oversize all neutral components for 1.73 times rated full load amps.

3. Use separate neutral conductors for nonlinear loads and avoid shared neutral conductors where practical.

4. Use neutral over current sensors to trip phase conductors.

5. Use true rms. ammeters and instruments with sufficient bandwidth for measurement.
Transformer Derating Schemes

Derating is a means of determining the maximum load that may be safely placed on a transformer that supplies harmonic loads.

The most common derating method is the CBEMA approved "crest factor" method which provides a transformer harmonic derating factor, $THDF$.

\[
THDF = \frac{1.414(\text{True rms of the phase current})}{\text{peak of the phase current}}
\]
### Example of Transformer Derating. Building I

<table>
<thead>
<tr>
<th>Phase</th>
<th>True RMS Phase Current</th>
<th>Peak Value of Phase Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>70A</td>
<td>178A</td>
</tr>
<tr>
<td>B</td>
<td>76A</td>
<td>181A</td>
</tr>
<tr>
<td>C</td>
<td>73A</td>
<td>180A</td>
</tr>
</tbody>
</table>

\[
\text{AVG RMS} = \frac{(70 + 76 + 73)}{3} = 73A
\]

\[
\text{AVG PEAK} = \frac{(178 + 181 + 180)}{3} = 180A
\]

\[
\text{THDF} = \frac{1.414(73)}{180} = .57
\]

HENCE, THE TRANSFORMER SHOULD BE DERATED TO 57% OF ITS NAME PLATE RATING!!!
K Factor Rated Transformers

- K factor was developed by Underwriters Laboratory in UL 1561.
- K factor transformers are designed to supply nonsinusoidal loads.
- They contain enlarged primary windings to carry circulating triplen harmonic currents.
- The magnetic core has a lower flux density as it is designed with higher grades of iron.
- K factor transformers use smaller, insulated, secondary conductors in parallel to reduce skin effect.
- K factor transformers are more expensive than conventional transformers.
K factor is a means of rating a transformer with respect to the harmonic magnitude and frequency of the load.

\[ K = \sum_{h=1}^{\infty} \left( I_{h\text{pu}} \right)^2 h^2 \]

The K factor numbers do not linearly indicate transformer harmonic tolerance. For example, a K4 rated transformer has four times the eddy current tolerance as a K1 transformer. A K13 rated transformer has approximately twice the tolerance of a K4 and K30 has twice of a K13.
Example K Factor Calculation. Building I

TRUE RMS = $73.3\text{A} = 1\text{ pu}$

<table>
<thead>
<tr>
<th>h</th>
<th>$I_{RMS}$</th>
<th>$I_{P.U.}$</th>
<th>$I^2_{P.U.}$</th>
<th>$h^2$</th>
<th>$I^2_{P.U.} \cdot h^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.45A</td>
<td>.715</td>
<td>.511</td>
<td>1</td>
<td>0.511</td>
</tr>
<tr>
<td>3</td>
<td>42.27A</td>
<td>.577</td>
<td>.333</td>
<td>9</td>
<td>3.000</td>
</tr>
<tr>
<td>5</td>
<td>24.97A</td>
<td>.341</td>
<td>.116</td>
<td>25</td>
<td>2.900</td>
</tr>
<tr>
<td>7</td>
<td>9.44A</td>
<td>.129</td>
<td>.016</td>
<td>49</td>
<td>0.784</td>
</tr>
<tr>
<td>9</td>
<td>3.72A</td>
<td>.051</td>
<td>.003</td>
<td>81</td>
<td>0.243</td>
</tr>
<tr>
<td>11</td>
<td>5.51A</td>
<td>.075</td>
<td>.006</td>
<td>121</td>
<td>0.726</td>
</tr>
<tr>
<td>13</td>
<td>4.77A</td>
<td>.065</td>
<td>.004</td>
<td>169</td>
<td>0.676</td>
</tr>
</tbody>
</table>

$\Sigma = 1$

$k = 8.84$
Super Neutral Cable®

Super Neutral Cable is a metal-clad, Type MC Cable, manufactured with an oversized neutral conductor or one neutral per phase for three-phase/four-wire power supply systems to computers (with dc drive fan motors, tape and disk drives) office machines, programmable controllers, and similar electronic equipment where non-linear switching loads produce additive, odd order harmonic currents which may create overloaded neutral conductors.

The oversized neutral conductor(s) are sized 150% to 200% of the phase conductor ampacity to minimize the effects of harmonics generated by the non-linear loads. The neutral per phase (striped with color to match the phase conductor) accomplishes the same objective.

Super Neutral Cable can be used under computer room floors, raised floors, or overhead in the space above hung ceilings used for environmental air handling. It handles branch and feeder, plus power, lighting, signal, and control circuits in dry locations.
K-factor transformers:

Sola
Dongan
Disadvantages and Risks

Derating a transformer is a temporary fix and often translates into lower efficiency operation and increased heat for losses.

Derated transformers also run the risk of being perceived to be partially loaded and future load additions are possible.

While derating removes some stresses from the transformer, a typical dry type transformer is not designed to supply harmonic loads. Hence, it may be subject to a shorter life span and lower efficiency.

Oversizing of transformers, or selection of unnecessarily high K factor ratings of transformers, can increase the harmonic currents due to lower impedance.

Separate neutral conductors for computer loads is almost impossible to implement, due to a wide scattering of data processing equipment all over the building.
Solutions:
- Derating
- Passive Approach
- Active Approach
Circulates excessive triplen harmonics through the filter and back to the load.

Protects the distribution transformer and neutral conductor from excessive neutral currents.

Improves transformer power factor.
Zig-Zag Transformer for Neutral Current Reduction

VA Rating Calculation

\[
\text{VA rating} = \frac{3}{2} \left( \frac{V_{b1,o}}{\sqrt{3}} + \frac{V_{b2,b1}}{\sqrt{3}} \right) \frac{I_{FN}}{3}
\]

\[
\text{VA rating} = \frac{3}{2} \frac{2V_{ab}}{3} \left( \frac{I_{FN}}{3} \right) = 0.333 V_{ab} I_{FN}
\]
T-Connected Transformer for Neutral Current Reduction

VA Rating Calculation

\[ V_{an} = V_{bo} = \frac{V_{ab}}{2}, \quad V_{co} = \frac{\sqrt{3} V_{cb}}{2} \]

kVA rating is higher

\[ = 0.359 V_{ab} I_{FN} \]
Star-Delta Transformer for Neutral Current Reduction

Transformer kVA rating is higher.

Harmonic filtering is impedance sensitive.

VA Rating Calculation

Transformer VA rating = \(3 \frac{V_{ab}}{\sqrt{3}} \left( \frac{I_{FN}}{3} \right) = 0.577 V_{ab} I_{FN}\)
Zero sequence impedance of the Zig-Zag transformer must be low. This requires special design.

The effectiveness of the Zig-Zag transformer to divert 3rd. harmonic current is highly dependent on the distribution system impedance. In most cases only 50% reduction can be guaranteed.

Lower zero-sequence impedance increases the single-phase fault current level. Therefore, fusing and circuit breaker re-sizing may be necessary.

The specially designed low impedance Zig-Zag transformer becomes a low impedance path for zero sequence currents from other parts of the system.

Due to the reasons mentioned above the passive Zig-Zag transformer approach is larger in size and weight.
Acme's I-Trap™ Reduces Excessive Neutral Currents Caused by Harmonic Distortion

Acme has introduced a product that provides a cost effective solution to high neutral currents that result from zero sequence harmonics and unbalanced loads.

The I-TRAP™ units are designed for use on 208Y/120V three phase 60Hz systems. They provide electrical contractors, system designers and specifying engineers with an economical alternative to replacement of overheated system neutral conductors. The I-TRAP™ can be installed adjacent to distribution panels that will feed non-linear loads in plants, offices, hi-rises and other locations. This permits the use of smaller, less expensive neutral cable and provides protection to distribution transformers that may overheat due to harmonic loads.

The I-TRAP™ is for use on systems with maximum neutral currents of 100A, 150A, 300A and 450A. Each unit includes a built-in ammeter to provide constant reading of the neutral current.

Installation is accomplished by four simple terminal connections and the units can be floor or wall mounted and require minimal maintenance. All I-TRAP™ units are UL listed and CSA certified, rated for 115 deg. C temperature rise and 220 deg. C insulation class, and are covered under Acme's exclusive 10 year warranty. The I-TRAP™ and Acme's full line of dry type distribution transformers are available through a network of reps and electrical distributors in the United States and Canada.
Solutions:
- Derating
- Passive Approach
- Active Approach
Active Neutral Current Filtering Scheme

Circulates excessive triplen harmonics through the filter and back to the load.

Protects the distribution transformer and neutral conductor from excessive neutral currents.

Improves transformer power factor.

Single & Three-Phase Linear and Non-linear Distributed Loads

Harmonix™: Active Harmonic Cancellation System

I_n

I_ref = 0
Active Neutral Current Filtering Scheme

• Developed by Texas A&M University, College Station & Current Technology, Inc. Dallas, Texas.
• Design to Cancel Zero Sequence Harmonic Current from a 3-Phase 4-Wire Distribution System.
• Patented Technology.
Active Neutral Current Filtering Scheme
Active Neutral Current Filtering Scheme. Functional Block Diagram.
Active Neutral Current Filter
Active Neutral Current Filter. Features.

- High Cancellation Effectiveness: 90 - 95%.
- Performance independent of System Impedance.
- Cancels neutral current harmonics by measurement and close-loop control.
- No low-impedance path for Zero-Sequence 60 Hz.
- Built-in pulse-pulse current limit (No Overloading).
- Significant improvement in Voltage and Current THD’s.
- Fast-response characteristics.
Active Neutral Current Filter. Connection.
Active Neutral Current Filter.
Connection.
# Filter Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>120/208, 220/380, 277/480</td>
</tr>
<tr>
<td>Current</td>
<td>100 A rms per module</td>
</tr>
<tr>
<td>Frequency</td>
<td>50/60 Hz</td>
</tr>
<tr>
<td>Power Efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Cancellation Effectiveness</td>
<td>90-95%</td>
</tr>
<tr>
<td>Parallelability</td>
<td>Up to 4 filters can be connected in parallel</td>
</tr>
<tr>
<td>Topology</td>
<td>Parallel connection 3-Phase, 4-Wire</td>
</tr>
<tr>
<td>Protection</td>
<td>Pulse-Pulse current protection</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td></td>
<td>Thermal shutdown</td>
</tr>
<tr>
<td></td>
<td>Overcurrent protection</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Facility current</td>
</tr>
<tr>
<td></td>
<td>Filter current</td>
</tr>
<tr>
<td></td>
<td>Harmonics or total rms current</td>
</tr>
<tr>
<td>Status Indication</td>
<td>Indicator lights, Audible alarm,</td>
</tr>
<tr>
<td></td>
<td>Max current indicator,</td>
</tr>
<tr>
<td></td>
<td>Dry contacts</td>
</tr>
<tr>
<td>Enclosure</td>
<td>21H x 24W x13D</td>
</tr>
<tr>
<td></td>
<td>Floor mount stackable</td>
</tr>
<tr>
<td>Weight</td>
<td>200 lbs (approx.)</td>
</tr>
</tbody>
</table>
Active Neutral Current Filter. Test Results

120/208 Distribution Panel Boards

Load Center

PC

PG 2

PE

Harmonix™: Active Harmonic Cancellation System

Single-phase Linear & Non-Linear Loads

One-Line Diagram - Beta Site Electric Room 103
Active Neutral Current Filter. Test Results

Neutral Current without Active Harmonic Cancellation System

Neutral Current with Active Harmonic Cancellation System
## Active Neutral Current Filter. Test Results

<table>
<thead>
<tr>
<th>Variable</th>
<th>Without Filter</th>
<th>With Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral Current (A rms)</td>
<td>82.1</td>
<td>33.0</td>
</tr>
<tr>
<td>Zero-Sequence Harmonic Current in Neutral (A rms)</td>
<td>71.5</td>
<td>4.14</td>
</tr>
<tr>
<td>60 Hz Zero-Sequence Current in Neutral (A rms)</td>
<td>34.3</td>
<td>32.7</td>
</tr>
<tr>
<td>Voltage THD (% Fundamental)</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Current THD (% Fundamental)</td>
<td>67.2</td>
<td>33.3</td>
</tr>
<tr>
<td>Cancellation Effectiveness</td>
<td>-</td>
<td>94.2</td>
</tr>
</tbody>
</table>
Neutral Current Filtering Scheme
The active filter employs a conventional zig-zag transformer (not optimized for low zero sequence impedance) and cancels the neutral current harmonics by measurement and closed loop current control.

The performance of the active filter is independent of the system impedance, hence is not location sensitive.

The active filter compensates only for harmonic currents in the neutral and does not become a low impedance path to unbalanced 60Hz currents.

The active filter has an electronic built in current limit and does not overload.

The proposed active filter is rugged and stable in operation. Notice the power electronic components are not subjected to line disturbances such as over voltages, voltage spikes etc.

The kVA of the power electronic active current source in low as the voltage between the neutral of the zig-zag transformer and the system neutral is near zero.