Harmonics and mitigation techniques

Power & Energy Institute of Kentucky

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Digital Power B.U. - Schneider Electric
The ideal voltage supply does not exist

3-phase balanced

Power Factor

Harmonics

Phase unbalanced

Sags/swells
Overvoltage

Notches

Spikes

Flicker
Introduction to Harmonics
Harmonics in electrical systems increase business operating costs……

Increased system downtime
- Nuisance tripping of overloads and circuit breakers
- Bus failures
- Distortion of control signals

Increased maintenance
- Excessive heat places burden on electrical infrastructure from transformers to cables and bussing

Lower Quality and Efficiency
- Interrupt production causing downtime, rework and scrap

Reduced system capacity
- Requires costly equipment upgrades to support expansion

Harmonics are a circumstance of progress and they effect almost every business in today’s environment…
Harmonics: Fundamentals

Definition:
Harmonics are integer multiples of the fundamental frequency that, when added together, result in a distorted waveform.
Harmonics: Fundamentals

Sinewave of a specific frequency supplied by the utility (a “clean” sinewave):

\[ f(x) = \sin(x) \]

...plus a “5th” Harmonic Sinewave:

\[ f(x) = \frac{\sin(5x)}{5} \]

...results in a harmonic rich, non-linear wave shape:

\[ f(x) = \sin(x) + \frac{\sin(5x)}{5} \]
Harmonics: Fundamentals

What produces “Non-linear” Current?

- Computers
- Copiers
- AC or DC drives
- Electronic Ballasts

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>Typical Waveform</th>
<th>Current Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Phase Power Supply</td>
<td></td>
<td>80% (high 3rd)</td>
</tr>
<tr>
<td>Semiconverter</td>
<td></td>
<td>high 2nd, 3rd, 5th, or partial loads</td>
</tr>
<tr>
<td>6 Pulse Converter, capacitive smoothing, no series inductance</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td>6 Pulse Converter, capacitive smoothing with series inductance - 3%, or dc drive</td>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>6 Pulse Converter with large inductor for current smoothing</td>
<td></td>
<td>28%</td>
</tr>
<tr>
<td>12 Pulse Converter</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>ac Voltage Regulator</td>
<td></td>
<td>varies with firing angle</td>
</tr>
<tr>
<td>Fluorescent Lighting</td>
<td></td>
<td>20%</td>
</tr>
</tbody>
</table>
Harmonics: Fundamentals

Single phase full-bridge rectifier circuit

\[ h = np +/- 1 \]

Supply voltage (\(V\))

Supply current (\(i\))

DC bus voltage \(U\)

DC bus capacitor current (\(i_C\))

Supply voltage (\(V\))

\[ V = E - Zs \cdot i \]

<table>
<thead>
<tr>
<th>(n)</th>
<th>(h(-))</th>
<th>(h(+))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>5</td>
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<tr>
<td>2</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>13</td>
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<tr>
<td>4</td>
<td>15</td>
<td>17</td>
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<td>13</td>
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<tr>
<td>3</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>25</td>
</tr>
</tbody>
</table>

Requiring Neutral Compensation

NO need neutral compensation
Harmonics: Fundamentals

- **Nonlinear loads draw harmonic current from source**
  - Does no work

**Voltage:** flat topping of waveform

**Current:** high TDD between 90-100%

Basic three phase PWM VSD

Diagram of converter, DC bus, and inverter.
Harmonics: Fundamentals

- Characteristic harmonics are the **predominate harmonics** seen by the power distribution system

- Predicted by the following equation:

\[
H_c = np \pm 1
\]

- \( H_c \) = characteristic harmonics to be expected
- \( n \) = an integer from 1, 2, 3, 4, 5, etc.
- \( p \) = number of pulses or rectifiers in circuit

- Amplitude is inverse of harmonic order (perfect world)
Harmonics: Fundamentals

Harmonic signature

<table>
<thead>
<tr>
<th>Harmonics present by rectifier design</th>
<th>Type of rectifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hn</td>
<td>1 phase 4-pulse</td>
</tr>
<tr>
<td>----</td>
<td>-----------------</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>
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<tr>
<td>11</td>
<td>x</td>
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<td>13</td>
<td>x</td>
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<td>15</td>
<td>x</td>
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<td>17</td>
<td>x</td>
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<td>19</td>
<td>x</td>
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<td>21</td>
<td>x</td>
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<td>23</td>
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<td>25</td>
<td>x</td>
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<td>27</td>
<td>x</td>
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<td>29</td>
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<td>31</td>
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<td>33</td>
<td>x</td>
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<td>35</td>
<td>x</td>
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<td>37</td>
<td>x</td>
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<td>39</td>
<td>x</td>
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<tr>
<td>41</td>
<td>x</td>
</tr>
<tr>
<td>43</td>
<td>x</td>
</tr>
<tr>
<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>

\[ H_c = np \pm 1 \]

- \( H_c \) = characteristic harmonic order present
- \( n \) = an integer
- \( p \) = number of pulses

Multi-pulsing (ie: 12 & 18 pulses):

Elimination of lower order harmonic removes largest amplitude harmonics
Harmonic voltages (Vn):

- Develop as the harmonic current traverses the electrical system.
- Each harmonic order has its own system impedance (Zn) and thus develops its own harmonic voltage.
- The root-mean-square (rms) of all harmonic orders equals the total amplitude of harmonic current or voltage.
- Ohm’s Law applies: \( V_n = I_n \times Z_n \)
- To reduce \( V_h \): Reduce system impedance (Zsh & Zch) or reduce current (Ih)
Harmonics: Fundamentals

3 Phase thyristor rectifier (parallel, phase to phase)

Converts **AC** to controlled **DC**
Max harmonics at full load
Best PF at full load

**Harmful characteristic**

**Causes voltage notching (THDv)**

- Requires input line reactors (inductance) to reduce notch depth

Notch created by a momentary short circuit when SCR commute from one phase to the other
3 Phase controller (series)
Opposing (anti-parallel) thyristors per phase (not a rectifier)

AC to AC (variable volts)
No harmonics at full output
PF is load dependent
i.e. AC Motor

Solid State Starters (SSS)
Transition harmonics only
During acceleration and deceleration
• Transition lagging PF
  • At full voltage – AC motor characteristics apply
  • Thyristors are full ON or Bypass contactor used to bypass

No snubbers (R-C) on thyristors

Harmonics: Fundamentals

Transitions are short duration (2-3 seconds)
PF according to AC motor design
Resistive & Inductive Heaters

Same thyristor configuration as SSS
Different use as compared to SSS

- Designed to control current through resistor banks or inductive coils to control heating
- **High** harmonics - except at full load
- **Poor** PF – except at full load
Harmonic Standard

IEEE 519-2014

- Defines current distortion as **TDD (Total Demand Distortion)**
  - Largest amplitude of harmonic current occurs at maximum load of nonlinear device – if electrical system can handle this it can handle all lower levels of amplitudes
  - Always referenced to full load current
  - Effective meaning for current distortion
- Defines voltage distortion as **THD**
  - Total harmonic voltage distortion
- Does not use **THD(I)**
  - Total harmonic current distortion
  - Instrument measurement (instantaneous values)
  - Uses measured load current to calculate THD(I)
Harmonic Standard

IEEE 519-2014
IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Harmonic voltage distortion limits are provided to reduce the potential negative effects on user and system equipment. Maintaining harmonic voltages below these levels necessitates that:

- All users limit their harmonic current emissions to reasonable values determined in an equitable manner based on the inherent ownership stake each user has in the supply system and
- Each system owner or operator takes action to decrease voltage distortion levels by modifying the supply system impedance characteristics as necessary.
Harmonic Standard

IEEE 519-2014

Harmonic distortion terms used

**total demand distortion (TDD):** The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

**total harmonic distortion (THD):** The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included when necessary.

The recommended limits in this clause apply only at the point of common coupling and should not be applied to either individual pieces of equipment or at locations within a user’s facility. In most cases, harmonic voltages and currents at these locations could be found to be significantly greater than the limits recommended at the PCC due to the lack of diversity, cancellation, and other phenomena that tend to reduce the combined effects of multiple harmonic sources to levels below their algebraic summation.

Note: THDi is not used in IEEE 519-2014
Harmonic Standard

IEEE 519-2014
Supplier standard for THDv
New category for <1.0 kV (applies at 480 & 600 VAC)

Table 1—Voltage distortion limits

<table>
<thead>
<tr>
<th>Bus voltage $V$ at PCC</th>
<th>Individual harmonic (%)</th>
<th>Total harmonic distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V \leq 1.0$ kV</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>1 kV $&lt; V \leq 69$ kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69 kV $&lt; V \leq 161$ kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>161 kV $&lt; V$</td>
<td>1.0</td>
<td>1.5$^a$</td>
</tr>
</tbody>
</table>
Harmonic Standard

IEEE 519-2014
USER standard for TDD limits
Same as 519-1992

Table 2—Current distortion limits for systems rated 120 V through 69 kV

<table>
<thead>
<tr>
<th>$I_{sc}/I_L$</th>
<th>$3 \leq h &lt; 11$</th>
<th>$11 \leq h &lt; 17$</th>
<th>$17 \leq h &lt; 23$</th>
<th>$23 \leq h &lt; 35$</th>
<th>$35 \leq h \leq 50$</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 20\degree$</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>$20 &lt; 50$</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>$50 &lt; 100$</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>$100 &lt; 1000$</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>$&gt; 1000$</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>

*a Even harmonics are limited to 25% of the odd harmonic limits above.

*b Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*c All power generation equipment is limited to these values of current distortion, regardless of actual $I_{sc}/I_L$.

where

$I_{sc}$ = maximum short-circuit current at PCC
$I_L$ = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions
As load decreases, TDD decreases while THD(I) increases.

Example: with AccuSine PCS+ operating

<table>
<thead>
<tr>
<th>Measured</th>
<th>TDD</th>
<th>THD(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>111.80</td>
<td>3.8%</td>
<td>13.32</td>
</tr>
<tr>
<td>246.00</td>
<td>3.4%</td>
<td>2.9%</td>
</tr>
<tr>
<td>424.00</td>
<td>3.7%</td>
<td>2.3%</td>
</tr>
<tr>
<td>836.00</td>
<td>3.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>111.00</td>
<td>3.8%</td>
<td>3.8%</td>
</tr>
<tr>
<td>246.00</td>
<td>3.4%</td>
<td>2.9%</td>
</tr>
<tr>
<td>424.00</td>
<td>3.7%</td>
<td>2.3%</td>
</tr>
<tr>
<td>836.00</td>
<td>3.8%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

TDD and THD(I) are not the same except at 100% load.
Examples of grid code requirements
PQ Guidelines - What does Alliant Energy have to say?

CHAPTER 11

1100. SCOPE
This chapter covers the requirements for customer-owned equipment that may affect the quality of the service provided by Alliant Energy.

1101. SERVICE IMPAIRING EQUIPMENT
A. Service impairing equipment, because of its use, can lower the quality of power to other customers. Equipment that cannot be modified to prevent this shall be eliminated or controlled within permissible limits acquired by Alliant Energy. If the customer meets these limits but still causes issues, such as but not limited to: arcing, harmonic distortion, voltage fluctuation, the customer causing the issue shall install equipment that addresses the service impairment.

1. Certain types of service impairing equipment include: welders, arc furnaces, electric motors, generators, converters, plasma cutters, motors driven compressors, instantaneous water heaters, distributed generation, power factor correction equipment or other equipment having highly fluctuating or large instantaneous demands.

2. Other types of service impairing equipment include those with loads that cause harmonic distortion, such as data centers, inverters based equipment, electric vehicles, and variable frequency drives.

3. Equipment causing high-frequency current or harmonic distortion must comply with IEEE 519-2014.

B. The customer shall obtain pre-approval from Alliant Energy before installing equipment such as those listed in Section 1101A above.

C. In most circumstances, Alliant Energy’s electrical supply facilities are adequate to serve normal load additions. Customers installing service impairing equipment shall be billed the costs for additional facilities, metering and allowances specifically associated with preventing impairment of service to other customers caused by this service impairing equipment.

1102. PHASE BALANCE
The customer shall balance electrical loads on their service. Each phase conductor shall carry a minimum of 20% of the total kVA at maximum load conditions.
CHAPTER 25. SUBSTANTIVE RULES APPLICABLE TO ELECTRIC SERVICE PROVIDERS.

Subchapter C. QUALITY OF SERVICE.


(a) Voltage variation. (1) Standard nominal voltages to be adopted. In addition to the nominal voltages that each electric utility has already adopted, each nominal voltage adopted by an electric utility after approval of this rule shall be a voltage indicated by the version of the American National Standards Institute, Incorporating (ANSI) Standard C84.1, "Electrical Power Systems and Equipment-Voltage Ratings (60Hz)," or equivalent ANSI standard as later amended, in effect at the time of adoption of the nominal voltages. An electric utility may adopt different nominal voltages to serve specific customers if such action does not compromise present transmission and distribution system operation.

(2) Nominal voltage limitations. As far as technologically practicable, each electric utility shall maintain its standard distribution system nominal voltages within the limits specified in the current version of ANSI Standard C84.1, or equivalent ANSI standard as later amended. Each electric utility offering service at transmission voltages to customers who have their own transformation equipment shall maintain such voltages within a range of plus or minus 10% of its adopted nominal voltages. Variations in distribution system voltage in excess of the limits specified in ANSI C84.1 and transmission system voltage in excess of plus or minus 10% caused by action of the elements and intermittent and unavoidable fluctuations of short duration due to station or system operation shall not be considered violations of this subsection.

(b) Frequency variation. Each electric utility supplying alternating current shall adopt a standard frequency of 60 Hertz. This frequency shall be maintained within the limits stated in the current version of the North American Electric Reliability Council (NERC) operating manual, or succeeding NERC document that may subsequently replace the operating manual.

(c) Harmonics. In 60 Hertz electric power systems, a harmonic is a sinusoidal component of the 60 Hertz fundamental wave having a frequency that is an integral multiple of the fundamental frequency. "Excessive harmonics," as this subsection, shall mean levels of current or voltage distortion at the point of common coupling between the electric utility and the customer outside the levels recommended in the IEEE standard referenced in paragraph (1) of this section. Each electric utility shall notify every customer affected with problems caused by excessive harmonics and customers affected in exceptional cases as described in paragraph (1) of this section.

(1) Applicable standards. In addressing harmonics problems, the electric utility and the customer shall implement the extent reasonably practicable and in accordance with prudent operating the practices outlined in IEEE Standard 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, or any successor IEEE standard to the extent not inconsistent with law, including state and federal statutes, orders, regulations, and applicable municipal regulations.

5.5.5 POWER FACTOR

If the Power Factor of Retail Customer's load is found to be less than 95% lagging as measured at the Meter, Company may require Retail Customer to arrange for the installation of appropriate equipment on Retail Customer's side of the Meter necessary to correct Retail Customer's Power Factor between unity and 95% lagging as measured at Meter, or, if Retail Customer fails to correct its Power Factor consistent with this standard, the demand associated with Retail Customer's use of Delivery Service, as determined in the appropriate Rate Schedules in Section 6.1 RATE SCHEDULES, may be increased according to the following formulas:

(1) Calculation of Power Factor Adjusted NCP kW.
The NCP kW applicable under the Monthly Rate section shall be modified by the following formula:

Power Factor Adjusted Monthly NCP kW = (Actual Monthly NCP kW x 0.95) / Current Month Power Factor

(2) Calculation of Power Factor Adjusted 4-CP kW.
Each of the Retail Customer's monthly coincident peak kW Demands used to calculate the Retail Customer's average 4 CP kW Demand applicable under the Monthly Rate section shall be calculated using the following formula:


Request for Proposal
Sachem, Inc.,
Cleburne, Texas
PQ Guidelines - What does Rio Grande have to say?

Relationship between capacitors and harmonics
How Harmonics Affect Capacitors:

Capacitors are naturally a low impedance to high frequencies:

- Caps absorb harmonic in current

As capacitor absorbs harmonic in current, the capacitor heats up

- Reduced life expectancy

Voltage harmonics stress the capacitor dielectric

- Reduced life expectancy

Parallel combination of capacitors with motor or transformer can cause resonance.......
Capacitors Absorb Harmonic in current

The capacitor has lower impedance than the utility, therefore it absorbs the harmonics.

- Capacitor diverts flow of harmonics
- Harmonic current increases
- Capacitor absorbs harmonic current
- Capacitor overheats & can fail over time

or worse......
How Harmonics Affect Capacitors:

You use the principle of resonance every day!
How Harmonics Affect Capacitors:

A Radio uses Resonance to Capture a Radio Station:
How Harmonics Affect Capacitors (Resonance)

Resonance:

\[ X_L = 2 \pi f l \]

\[ X_C = \frac{1}{2 \pi f c} \]
How Capacitors “Tune” a circuit:

Standard Network:

Equivalent circuit:

\[ fr = 60 \times \sqrt{\frac{kVA}{kVAR} \times \frac{100}{Iz}} \]

e.g., 1500 kVA 225 kVAR 5.5% Iz

\[ \therefore fr = 60 \times \sqrt{\frac{1500}{225} \times \frac{100}{5.5}} = 660 \, \text{Hz} = h_{11} \]
Parallel Resonance and harmonic magnification

- **Resonance:**
  - Amplification of current between capacitor and transformer
  - Current distortion rises
  - Voltage distortion rises
  - Main transformer &/or capacitor fuses blow
  - Equipment damage
Parallel Resonance

Resonant Point likely to amplify dominant harmonic (typically 5th, 7th and 11th)

Magnification of Harmonic Current and Voltage when Standard Capacitor are Added to the Network
De-Tune to Avoid Resonance

Resonant Point where no Harmonic Content present (3.7th typical)

Effect on Harmonic Current and Voltage when De-Tuned Capacitor Bank is Applied (AV6000 & AT6000)
Low Voltage Automatic Capacitor Bank with De-tuning reactors

De-Tuned (DR) automatic capacitor bank:

- Same as automatic capacitor bank with c/w De-Tuning reactors.
- Works like a standard automatic capacitor bank
- Avoid resonance between the capacitors and the supply transformer.
De-tuning a network:

- “Force” the resonant point away from naturally occurring harmonics

4.2 Harmonic (252 Hz)

We control the impedance of these two elements
The ideal voltage supply does not exist, Active Harmonic Filters can correct 3 PQ problems.

- 3-phase balanced
- Power Factor
- Harmonics
- Phase unbalanced
- Blackout
- Sags/swells
- Overvoltage
- notches
- Spikes
- Flicker

The ideal voltage supply does not exist, Active Harmonic Filters can correct 3 PQ problems.
Harmonic mitigation methods
Various type of harmonic filtering solutions

**Applied per device**
- Inductance
- 5\textsuperscript{th} harmonic trap filters
- Broadband filters
- Multi-pulsing
- Active Front End converter

**Applied per system**
- Active harmonic filter (AHF)
Inductors/Transformers/DC Bus Chokes

**Description:**
Converter-applied inductors or isolation transformers.

**Pros:**
- Inexpensive & reliable
- Transient protection for loads
- 1st Z yields big TDD reduction (90% to 35% with 3% Z)
- Complimentary to active harmonic control

**Cons:**
- Limited reduction of TDD at equipment terminals after 1st Z
- Reduction dependent on source Z
5th Harmonic Filter (Trap Filter)

- Inductor (L_p) and Capacitor (C) provide low impedance source for a single frequency (5th)
  - 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 5th harmonics in system, that can result in overload.
  - If L_s not present, resonance with other tuned filters possible
- Injects leading reactive current (KVAR) at all times – may create leading PF and/or issues with back up generator
Broadband Filters

- Mitigates up to 13th order or higher
- 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)
    - When generators are present, re-tuning may be required
- Capacitor (C) designed to boost V at load to proper level (injects leading VARs)
  - Physically large
  - High heat losses (>5%)
  - Series device
Multi-Pulse Drives

**Description:** Drives/UPS 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
  - One required for each product
  - Cannot retrofit
Harmonic mitigation methods

VFD mitigation topologies

6-Pulse converter
- “C-less” or 3% reactance min (if included);
- small footprint, simplified cabling
- Current waveform distorted
  TDD 30% to 40% with 3% reactor
  (depending on network impedance)

12-Pulse converter
- Externally mounted 3 winding transformer;
  more wire and cabling; complicated
- Current slightly distorted
  TDD 8% to 15% (depending on network impedance)

18-Pulse converter
- Large footprint, more steel & copper (losses)
- Current waveform good
  TDD 5% to 7% (depending on network impedance)
Active Front End (AFE) Converters

Used in UPS and VFD
Replaces diode converter with IGBT converter

Pros
- Permits current smoothing on AC lines (< 5% TDD)
- Permits 4-quadrant operation of VFD
- Maintains unity TOTAL PF
- Meets all harmonics specs around the world

Input Filter Required to limit THDv to <5%
AFE Converters

American Bureau of Shipping (ABS) requires examination to 100th order when AFE applied.

Higher frequencies yield higher heating of current path & potential resonance with capacitors.

Significant harmonics above 50th order
AFE Converters

Cons

- Larger and more expensive than 6 pulse drives
  - Approximately twice the size & price
- 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 $\geq 40$ at PCC
- Switched mode power supplies prohibited
- Capacitors prohibited on mains
- IGBT & SCR rectifiers prohibited on same mains
  - No other nonlinear loads permitted
Active Harmonic Filter
The ideal voltage supply does not exist, some AHF can correct 3 PQ problems:

- **3-phase balanced**
- **Power Factor**
- **Harmonics**
- **Phase unbalanced**
- **Sags/swells Overvoltage**
- **notches**
- **Spikes**
- **Flicker**
- **Blackout**
Harmonic Mitigation with AHF

<table>
<thead>
<tr>
<th>Order</th>
<th>% I fund</th>
<th>% I fund</th>
<th>OFF</th>
<th>ON</th>
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<tr>
<td>Fund 100.000%</td>
<td>100.000%</td>
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<tr>
<td>3</td>
<td>0.038%</td>
<td>0.478%</td>
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<td>5</td>
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<td>7</td>
<td>11.480%</td>
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<td>9</td>
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<td>0.297%</td>
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<td>11</td>
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<td>13</td>
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<td>15</td>
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<td>0.052%</td>
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<td>3.438%</td>
<td>0.464%</td>
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<td>19</td>
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<td>0.639%</td>
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<td>21</td>
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<td>29</td>
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<td>0.325%</td>
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<tr>
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<td>0.279%</td>
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<tr>
<td>37</td>
<td>1.420%</td>
<td>0.815%</td>
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<tr>
<td>39</td>
<td>0.282%</td>
<td>0.240%</td>
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<tr>
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<td>0.588%</td>
<td>0.120%</td>
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<tr>
<td>43</td>
<td>1.281%</td>
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<td>0.769%</td>
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<tr>
<td>49</td>
<td>1.348%</td>
<td>0.590%</td>
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<tr>
<td>% THD(I)</td>
<td>35.28%</td>
<td>2.67%</td>
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AccuSine injection

Source current

At VFD Terminals
The ideal voltage supply does not exist, Active Harmonic Filters can correct 3 PQ problems

- 3-phase balanced
- Power Factor
- Harmonics
- Phase unbalanced
- Blackout
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Power Factor and Harmonics. What is "True " Power Factor?

With linear vs. nonlinear loads

Electrical system with ONLY linear loads (Displacement Power Factor)

\[ S(kVA) = \sqrt{P^2 + Q^2} = \sqrt{kW^2 + kVAR^2} \]

Power factor, \( \cos \phi = \frac{P}{S} = \frac{kW}{kVA} \)

\[ Q = kVAR \text{ (Reactive Power)} \]
\[ P = kW \text{ (Real Power)} \]
\[ S = kVA \text{ (Apparent Power)} \]
\[ D = kVA_{d} \text{ (Distortion Power)} \]

\[ TPF = (\text{DisplacementPF}) \times (\text{DistortionFactor}) \]

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

\[ DF = \cos \delta = \frac{1}{\sqrt{1 + (THDi)^2}} \]
Active Harmonic Filter

PF correction

When PF mode is activated

- Assign priority to Harmonic or PF (fundamental) modes.
- AccuSine injects fundamental current (60 Hz) to correct the Power Factor.

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

- \(I_{as}\) = rms output current of AccuSine PCS
- \(I_h\) = rms harmonic current
- \(I_f\) = rms fundamental current

<table>
<thead>
<tr>
<th>Examples</th>
<th>(I_{as})</th>
<th>(I_h)</th>
<th>(I_f)</th>
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<td>10.0</td>
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<td>40.0</td>
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<td>50.0</td>
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<td>100.0</td>
<td>60.0</td>
<td>80.0</td>
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<td><strong>100.0</strong></td>
<td><strong>70.0</strong></td>
<td><strong>71.4</strong></td>
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<td>80.0</td>
<td>60.0</td>
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<td>90.0</td>
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<tr>
<td>100.0</td>
<td>95.0</td>
<td>31.2</td>
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Load Balancing with some Active Harmonic Filter

**Principle of load balancing**

The principle of load current balancing is to inject a system of negative sequence current into the circuit \((i_{1n}, i_{2n}, i_{3n})\), so that only the system of positive sequence current \((i_{1p}, i_{2p}, i_{3p})\) has to be generated by the power supply.
Load Balancing with some Active Harmonic Filter

Voltage unbalance standards:
- ANSI C84.1: 3%
- PG & E: 2.5%
- NEMA MG-1-1998: 1%

Note: 1% voltage unbalance can cause 6% to 10% current unbalance. Some motor manufacturers tried to require less than 5% current unbalance for a valid warranty.

Example of unbalance voltage calculation on a 480 V electrical distribution system:

Average voltage (Ph to Ph): \((475 + 473 + 455) / 3 = 468\) V

Voltage deviation: \(468 - 455 = 13\) V

Voltage unbalance: \(100 \times (13 / 468) = 2.78\%\)
Example of Active Harmonic Filter ratings & performance

**AHF ratings:**

- Dynamic Harmonic mitigation form the 2nd to the 51st harmonic order
- Can meet a THD(I) of 3%, THD(V) and THD(I) target set point
- Standard Voltage, 208, 240, 480, 600 and 690 V, 50-60 Hz
- Wall Mount or Free Standing, Main Lugs or Main Breaker incoming
- 60, 120, 200 and 300 A @ 480 V or 47, 94, 157 and 235 A @ 600 V per cubicle
- Enclosure type: NEMA 1, NEMA 2 and NEMA 12
- 3 levels IGBT design with optimized losses
- Closed loop c/w FFT digital logic
- 2 cycle response time for harmonic correction and ¼ of a cycle for reactive power injection
- cULus and CE certified
- And much more…
Questions ?