Power Quality & Harmonic Mitigating Solutions

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The ideal voltage supply does not exist

- 3-phase balanced
- Power Factor
- Harmonics
- Phase unbalanced
- Sags/swells
- Overvoltage
- Notches
- Spikes
- Flicker
The ideal voltage supply does not exist

3-phase balanced

Power Factor

Harmonics

Phase unbalanced

Sags/swells
Overvoltage

Notches

Spikes

Flicker
Energy Efficiency with PFC

Power Factor Correction benefits:

• Reduces Utility Bills
• Reduces loading on transformers
• Reduces I2R losses in Distribution Equipment
• Reduces Carbon Emission
• Reduces voltage drop
Power Factor is the ratio of Active Power to Total Power:

\[
\text{Power Factor} = \frac{\text{Active (Real) Power}}{\text{Total Power}} = \frac{kW}{kVA} = \cos(\theta)
\]

- Power Factor is a measure of efficiency (Output/Input)

Inductive loads that cause low PF:
- Induction motors
- Welders
- DC drives
- Transformers
- …
How to correct Power Factor?

Power Factor \[=\] \[
\frac{\text{Active (Real) Power}}{\text{Apparent Power}}\]

\[=\] \[
\frac{100 \text{ kW}}{125 \text{ kVA}}\]

\[=\] \[
\text{Cosine (}\theta\text{)} = 0.80\]

\[\text{Apparent Power} = 105 \text{ kVA}\]

\[\text{Active Power} = 100 \text{ kW}\]

\[\text{Reactive Power, Inductive} = 0.95 \text{ pf}\]

\[\text{KVAR} = \text{KW} \times (\text{Tan} \cos^{-1}(\text{Present PF}) - \text{Tan} \cos^{-1}(\text{Desired PF}))\]

Add 42 KVARc corrects PF to 95% lag
Power flow in MV and LV network without compensation

**Power Flow:**
- Real Power supplied by HV, MV & LV network
- Reactive Power supplied by HV, MV & LV network

**Impact:**
- PF penalty possible
- No voltage regulation
- No $I^2R$ losses or CO$_2$ reduction
- No LV or MV network off loading
Power flow in MV and LV network with MV compensation

**Power Flow:**
- Real Power supplied by HV, MV & LV network
- Reactive Power supplied by MV PFC and some by HV network
- Full Reactive Power still flow through the LV network

**Impact:**
- PF penalty eliminated
- No LV voltage regulation
- Some $I^2R$ & CO$_2$ reduction
- MV network off loading, no LV network off loading
Power flow in MV and LV network with LV compensation

Power Flow:
- Real Power supplied by HV, MV & LV network
- Reactive Power supplied by LV PFC & AccuSine. Small amount supplied by the network

Impact:
- PF penalty eliminated
- Voltage regulation
- Optimum I²R & CO² reduction
- LV & MV network off loading
- Harmonic reduction by De-Tuned LV PFC and AccuSine PLUS
Fixed Reactive Power Compensation

Application:

- Fixed capacitor can be used in network with low harmonic distortion level.
- When installed on the main bus, keep fixed capacitor kVAR value below 15% of transformer kVA rating in order to avoid over voltage condition.
- When installed on motors only apply on DOL starter.
- VFD’s not allowed on the same bus.
- When reduced voltage starter are present, only energized the Fixed capacitor when motor has reached full speed.
- Back to back capacitor switching issue possible when multiple fixed capacitor are present on the same bus.
Power Factor Correction for Linear Loads

Linear loads

• The electrical equipment draws current in a “linear” fashion

  • Current (i) & Voltage (v) are both “Sinusoidal”
Automatic Capacitor Systems

Automatic Capacitor Systems:

- **Contains:**
  - PFC Controller
  - Stage over current protection, Fuses or Circuit Breaker
  - Contactors
  - Capacitors

- **Usually at Main Switch Gear**

- **Controller Measures**
  P.F. & switches banks in & out of service to maintain user defined target P.F.
LV Automatic Capacitor Bank for Industries

Automatic capacitor bank NEMA 1, Indoor

- Standard Voltage, 208, 240, 480 & 600 V, 50-60 Hz
- Free Standing, Main Lugs or Main Breaker incoming
- Up to 500 KVAR @ 480 or 600 V in each section, 1000 KVAR max in two sections
- Section dim: 30” W x 36” D x 90” H
- PFC relay, Advanced Microprocessor controller
- Stage Circuit Breaker used for overload and over current protection
- cCSAul Approved, Optimized air flow & dead front construction
- Contactors equipped with soft charge resistors
- Heavy Duty LV capacitor, certified as per UL810
LV Automatic Capacitor Bank for commercial buildings and small industries

**Automatic capacitor bank NEMA 1, Indoor**

- **Standard Voltage**, 480 & 600 V, 50-60 Hz
- **Wall Mounted**, Main Lugs or Main Breaker incoming
- **Up to 300 KVAR @ 480 and 250 kVAR at 600 V**
- **Small enclosure**: 31.5” W x 16”D x 33.5” H
- **Large Enclosure**: 39.4” W x 16”D x 47” H
- **PFC relay**, Advanced Microprocessor controller
- **Stage Circuit Breaker** used for overload and over current protection
- **cCSAul Approved**, Optimized air flow & dead front construction
- **Contactors** equipped with soft charge resistors
- **Heavy Duty LV capacitor**, certified as per **UL810**
Introduction to Harmonics and PF correction in harmonic rich network
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:

\[ f(x) = \sin(x) + \frac{\sin(5x)}{5} \]
What produces “Non-linear” Current?

• Computers
• Copiers
• AC or DC drives
• Electronic Ballasts
Harmonics: Fundamentals

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

- **Voltage:** flat topping of waveform
- **Current:** high TDD between 90-100%

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Basic PWM VSD

![Diagram of Basic PWM VSD](image)
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)

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Frequency</th>
<th>Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60Hz</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>120Hz</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>180Hz</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>240Hz</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>300Hz</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>360Hz</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>420Hz</td>
<td>+</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>19</td>
<td>1140Hz</td>
<td>+</td>
</tr>
</tbody>
</table>
Multi-pulse converter

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></td>
</tr>
<tr>
<td>11</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
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<tr>
<td>15</td>
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<td>41</td>
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<td>43</td>
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<td>45</td>
<td></td>
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<tr>
<td>47</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td></td>
</tr>
</tbody>
</table>

Hc = np +/- 1

Hc = 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
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
Harmonics: Fundamentals

3 Phase Series Controller

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 Standards

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

Harmonic Standards

%THDv limits on suppliers

%TDD limits on users

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 Standards

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 Standards

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; $V$ ≤ 69 kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69 kV &lt; $V$ ≤ 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>

$^a$ New voltage class
IEEE 519-2014
USER standard for TDD limits
Same as 519-1992

Harmonic Standards

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

<table>
<thead>
<tr>
<th>Individual harmonic order (odd harmonics)</th>
<th>3 ≤ h &lt; 11</th>
<th>11 ≤ h &lt; 17</th>
<th>17 ≤ h &lt; 23</th>
<th>23 ≤ h &lt; 35</th>
<th>35 ≤ h ≤ 50</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{se}/I_L</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>&lt; 20°</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>20 &lt; 50</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>50 &lt; 100</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>100 &lt; 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>
<tr>
<td>&gt; 1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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

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

where

\[ I_{se} = \text{maximum short-circuit current at PCC} \]

\[ I_L = \text{maximum demand load current (fundamental frequency component)} \]

at the PCC under normal load operating conditions.
## TDD versus THD(I)

• **TDD and THD(I) are not the same except at 100% load**

### Example: with AccuSine PCS+ operating

<table>
<thead>
<tr>
<th>Measured</th>
<th>Total I, rms</th>
<th>Fund I, rms</th>
<th>Harm I, rms</th>
<th>THD(I)</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load</td>
<td>936.68</td>
<td>936.00</td>
<td>35.57</td>
<td>3.8%</td>
<td>3.8%</td>
</tr>
<tr>
<td></td>
<td>836.70</td>
<td>836.00</td>
<td>34.28</td>
<td>4.1%</td>
<td>3.7%</td>
</tr>
<tr>
<td></td>
<td>767.68</td>
<td>767.00</td>
<td>32.21</td>
<td>4.2%</td>
<td>3.4%</td>
</tr>
<tr>
<td></td>
<td>592.63</td>
<td>592.00</td>
<td>27.23</td>
<td>4.6%</td>
<td>2.9%</td>
</tr>
<tr>
<td></td>
<td>424.53</td>
<td>424.00</td>
<td>21.20</td>
<td>5.0%</td>
<td>2.3%</td>
</tr>
<tr>
<td></td>
<td>246.58</td>
<td>246.00</td>
<td>16.97</td>
<td>6.9%</td>
<td>1.8%</td>
</tr>
<tr>
<td></td>
<td>111.80</td>
<td>111.00</td>
<td>13.32</td>
<td>12.0%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

As load decreases, TDD decreases while THD(I) increases.
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:

\[ X_L = 2 \pi f l \]

\[ X_C = \frac{1}{2 \pi f c} \]

Where: \( f \) is the frequency, \( l \) is the length of the inductor, \( c \) is the capacitance, \( X_L \) is the inductive reactance, and \( X_C \) is the capacitive reactance.
How Harmonics Affect Capacitors:

How Capacitors “Tune” a circuit:

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

e.g. 1500 kVA 225 kVAR 5.5% Iz

\[
fr = 60 \times \sqrt{\frac{1500}{225} \times 100 \times \frac{5.5}{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)

4.2 Harmonic Tuning

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.
Power Factor Correction With Harmonics:

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
Low Voltage De-Tuned Automatic Capacitor Bank for Industries

Automatic capacitor bank NEMA 1, Indoor

- Standard Voltage, 208,240, 480 & 600 V, 50-60 Hz
- Free Standing, Main Lugs or Main Breaker incoming
- Up to 400 KVAR @ 480 or 600 V in each section, 1200 KVAR max in three sections
- Section dim: 30” W x 36”D x 90” H
- PFC relay, Advanced Microprocessor controller
- Stage Circuit Breaker used for overload and over current protection
- cCSAuL Approved, Optimized air flow & dead front construction
- Contactors rated for capacitor switching
- Heavy Duty LV capacitor, certified as per UL810
- De-Tuning Reactors tuned to 252 Hz
LV De-Tuned Automatic Capacitor Bank for commercial buildings and small industries

- **Automatic capacitor bank NEMA 1, Indoor**
  - Standard Voltage, 480 & 600 V, 50-60 Hz
  - Floor or Wall Mount, Main Lugs or Main Breaker incoming
  - Up to 200 KVAR @ 480 or 600 V
  - Enclosure size: 31.5” W x 16”D x 33.5” H
  - PFC relay, Advanced Microprocessor controller
  - Stage Circuit Breaker used for overload and over current protection
  - cCSAul Approved, Optimized air flow & dead front construction
  - Contactors rated for capacitor switching
  - VarPLus Can Heavy Duty LV capacitor, certified as per UL810
  - De-Tuning Reactors tuned to 252 Hz
For sensitive networks
Similar to De-Tuned Capacitor Bank except it’s equipped with solid state switching
Transient Free switching
Reactor tuned to 4.2 to 4.7
Response time of less than 5 sec
Up to 450kVAR per section
Expandable up to 1350kVAR without split incoming
Larger systems available with split incoming
Additional cubicles can be field installed if required
cCSAul Approved
Solid State Electronic Switch

- CB or Fuses
- SCR-Diode
- De-tuned Inductor

Diagram showing connections between L1, L2, and L3.
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.
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)
Harmonics: Fundamentals

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)

\[
V_h = I_h \times (Z_{sh} + Z_{ch})
\]

\( V_h \) = Harmonic voltage
\( I_h \) = Harmonic current
\( Z_{sh} \) = Source impedance for harmonic current
\( Z_{ch} \) = Cable impedance for harmonic current
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 \(5^{th}\)
  - 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, 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%

AC Source

LCL Filter

 IGCT Converter

VFD DC Bus

IGBT Inverter

AC Motor
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 ≥ 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
- Blackout
- Sags/swells
- Overvoltage
- Notches
- Spikes
- Flicker
Harmonic Mitigation with AHF

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<td>49</td>
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% THD(I) OFF: 35.28%  ON: 2.67%

AccuSine injection

At VFD Terminals

Source current
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
"Evolution" of Power Factors
With linear vs. nonlinear loads

Electrical system with ONLY linear loads

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

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

Electrical system with Nonlinear loads

\[
S = kVA \quad \text{(Apparent Power)}
\]

\[
P = kW \quad \text{(Real Power)}
\]

\[
D = kVA_h \quad \text{(Distortion Power)}
\]

\[
Q = kVAR \quad \text{(Reactive Power)}
\]

\[
\theta_{TPF} \quad \text{(True/Total Power Factor)}
\]

\[
\theta_{dispPF} \quad \text{(Displacement Power Factor)}
\]

\[
\theta_{distPF} \quad \text{(Distortion Power Factor)}
\]

True/Total Power Factor:
\[
\cos \theta_{TPF} = \cos \theta_{dispPF} \cdot \cos \theta_{distPF}
\]

Displacement Power Factor (Fundamental Components):
\[
\cos \theta_{dispPF} = \frac{kW}{kVA_{\text{fundamental}}}
\]

Distortion Power Factor (Harmonic Components):
\[
\cos \theta_{distPF} = \frac{1}{\sqrt{1 + THD^2}} \quad \sqrt{1 + THD^2}
\]
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>
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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
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.
Example of Active Harmonic Filter ratings & performance

**AHF ratings:**

- Dynamic Harmonic mitigation form the 2\textsuperscript{nd} to the 51\textsuperscript{st} 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 \(\frac{1}{4}\) of a cycle for reactive power injection
- cULus and CE certified
- And much more…
Technical Structure of Active Harmonic Filter, based on Schneider design
Technical Structure of Active Harmonic Filter, based on Schneider design

Customer Connections
- Modbus RTU Port*
- Parallel COM Ports*
- I/O dry terminals
- CT connections
- Modbus TCP/IP Port*

*Ports are RJ45 type
The ideal voltage supply does not exist

- 3-phase balanced
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- Flicker
Introduction to Hybrid Var Compensator (HVC)

HVC is a solution for flicker compensation
Flicker Producing Loads

Ball Mill
(Rock Crushers)

- Large motors starting
- Hoist
- Rubber batch mixer
- Linear Induction Motor
- ...

Spot welder

Steel Shredder

Results in equipment faulting
Results in flicker (medical issues)
Hybrid Var Compensator (HVC)

Real Time VAR injection for voltage regulation and flicker control.

- Available in Low and Medium Voltage
- High Speed Response, 5 milli seconds response time
- Infinite Variability
- Full Duration
- Can maintain Unity Power Factor
HVC Approach

Use fix or automatic capacitor bank for inrush support
- Always on line
- Instant response

Use AccuSine PFV+ for fine tuning
- Injects leading or lagging VARs
- Cancels fix caps leading VARs at no load
- Adds leading VARs as loads increase
- 5 ms response time

HVC in one enclosure or in a stand alone cubicle. Designed for the customer’s site requirement.
HVC Concept
LV HVC case study
spot welding sub station
Futaba welding sub, HVC SLD
Futaba welding sub, HVC OFF

Schneider/ Sq 'D' Power Quality
MAINS - HVC OFF (4 X 300 A Accusine + 900 kVAr Reactor)

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<td>3000</td>
<td>4000</td>
<td>0</td>
<td>500</td>
<td>2000</td>
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Time [MM:SS]:
The ideal voltage supply does not exist

- 3-phase balanced
- Power Factor
- Harmonics
- Phase unbalanced

Sags/swells
Overvoltage
Notches
Spikes
Flicker
Voltage Problems – Basics

### Chronic Voltage Regulation issues
Voltage outside ±10% for > 60 seconds

### Voltage Sag
Voltage < 90% for ½ cycle to 1 minute

### Interruption
Voltage < 10% for >3 cycles

95% of Voltage Quality Problems
Chronic Voltage Problems

Brownout – intentional reduction in grid voltage

External: Line Drops & Brownouts
Solid State tap switching voltage regulator

- Microprocessor controlled tap-switching
- Input voltage range: +10 to -25%
- Output regulation: ±3%
- Response time: 1 cycle typical
- Overload capacity: 1000% for 1 second
- No load or power factor limitations
- Independently regulated, shielded, isolated output
- Fan-free and maintenance-free
- Single or three phase
- 5 to 2,000 kVA
- 50 or 60 Hz
- Any input or output voltages up to 600v
Voltage Problems – Basics

**Chronic Voltage Problems**
Voltage outside ±10% for > 60 seconds

**Voltage Sag**
Voltage < 90% for ½ cycle to 1 minute

** Interruption**
Voltage < 10% for >3 cycles

95% of Voltage Quality Problems
Sag Mitigation Device

- Inverter-based, voltage injection design
- Corrects voltage sags back to >95% nominal voltage
- For sags down to **30% remaining voltage for 1 or 2 phase sags**
- For sags down to **60% remaining voltage for 3 phase sags**
- 2ms response time
- Provides SEMI-F47 compliant protection
- Correction independent of load or load pf, sag depth or duration
- Corrects phase shifting during sag event
- 3 phases, 20 to 2500 kVA, 50 or 60 Hz, up to 600 V.
Sag Mitigation Device operation

- Transformer “un-shorted”
- DC bus powered - inverters are ON
- Energy transfer phase-to-phase
- Non-sagging → sagging phases
- All in 2 ms

Input Voltage Sag – Correction Mode
Electronic Sag Fighter Performance

**Input**

**Output**

![Input Waveform](image1)

![Output Waveform](image2)
Surge Suppression Device
aka SPD or TVSS
The ideal voltage supply does not exist

- 3-phase balanced
- Sags/swells
- Overvoltage
- Power Factor
- Notches
- Harmonics
- Spikes
- Phase unbalanced
- Flicker
What is a Transient Surge?

> A surge or transient is a voltage spike that only lasts a few millionths of a second (the “blink of an eye” is thousands of times longer than the typical surge).

> A surge can contain thousands of volts and thousands of amps.

1 cycle at 60 Hz = 16.6 milliseconds

Transient event (between red lines) approximately 500 microseconds
Where do Transient Surges Come From?

80% inside
- Elevators
- Pump Motors
- Air conditioners
- Air compressors
- Blower Motors
- Office Copiers

Oscillatory transients
Typical of Internal events
(Smaller, lower energy)

20% outside
- Lightning
- Electrical Accidents
- Switching Cap Banks
- Utility Grid Switching

Impulse transients
Typical of External events
(Larger, higher energy)
The Effects of Transients on Business

$80B

“Power related problems cost companies over $80 billion a year”
(Source: Lawrence Berkeley National Laboratory)

“Industry experts estimate that power surges cost businesses $26 billion annually in lost time and equipment repairs and replacements”
(Source: Insurance Institute for Business & Home Safety)

- High Facility Maintenance Costs
- Equipment Failure
- Long-term System Degradation
- Process disruptions
- Data Loss or Corruption
- Costly Downtime
- Safety to drinking water
How does an SPD work?

The purpose behind installing any SPD is to divert damaging voltage and currents away from down stream equipment.

**SPD Method of Operation**

1. The SPD is installed in a parallel path with respect to the load.
2. When a surge voltage does come down the line, the SPD will respond in nanoseconds creating a low impedance path through the components within the SPD.
3. Current will flow through the path of least resistance.
4. The SPD becomes the path of least resistance and shunts the damaging energy before it is forced through the down stream protected equipment.
5. NO SPD will shunt 100% of the initial surge energy away from the load.
6. There is always some voltage/current that will be pushed through the load.
7. But if the SPDs are installed correctly and in the proper location, this Surge Remnant is well below the damaging level of the protected equipment.
Cascading - Location

*Cascading (layering)* your protection throughout your facility insures proper protection for your equipment.

Remember - Majority of disturbances come from within a Facility (80%)
Recommended Protection Levels

kA ratings may be modified to correspond with the intensity and frequency of transients.

High lightning areas or areas with a high frequency of Utility grid switching surges, etc. may require an increased kA rating.

The higher the frequency of surges, the higher the kA rating should be.

The dollar value of sensitive electronic equipment which receives power from the Branch Panel needs to be considered.

**Service Entrance**  240 kA  
**Distribution**     120-160 kA  
**Branch**          100-120 kA

**Rule of Thumb:** The higher the kA rating on the product, the better its withstand capability and overall robustness.  *For each level of protection (cascading) cut the kA rating by half.*

**4 Mode:** 4 Mode will provide protection to all ten modes via the L-N and N-G MOV’s.

- This configuration is not used often because of the poor levels of protection but is sometimes used because of the costs.

**7 Mode:** The 7 Mode will provide protection to all ten modes via the L-N, L-G and N-G MOVs.

- This is the most popular configuration as it allows the components to properly be sized for the voltage levels they are intended to protect. Most Manufactures provide this type of surge protection, it is proven and works well.

**10 Mode:** 10 mode, All Mode and Discrete, are more Marketing driven via a Specification than performance driven.
Lead Lengths - Installation

- Minimal Lead Length
- Factory Assembled
- Assures CSA Compliance
- Minimal Space Required
- Maximizes Breaker Availability
- Single Source for Service

Avoid Installation Uncertainty
Specify Integral Hard Bus Connection

INTERNAL

EXTERNAL

Distribution Panel

TVSS

Connecting Cables

400 V

1000 V

2000 V

Typical Let-Through Voltage**
(208Y/120)

Lead Length in Feet

0% 50% 100%

* % Effectiveness refers to the ability to keep the let-through voltage at minimal levels for typical transients
** Approx 160V / ft
Transient Voltage Surge Suppressors

- Power Factor
- Harmonics
- Phase unbalance
- Blackout
- Sags/swells
- Overvoltage
- Notches
- Transient (Spike)
- Flicker
- Noise
Case Studies
Active Harmonic Filter, turnkey project

The existing situation
The hospital’s air conditioning system had recently been modernized with a fleet of Variable Speed Drives (VSDs). These VSDs were polluting the hospital’s electrical network and were regularly causing the new dialysis machines to malfunction. Diabetic patients were regularly sent home and asked to reschedule their treatment.

- The VSD caused high THD(V) and THD(I)

Other PQ issues:
- Switching from Utility to generator mode caused short duration voltage sags
- Utility Capacitor bank switching caused ringing transient and multiple Zero Crossing

Problem:
In late 2013 the hospital reported the malfunction of several dialysis machines which were significantly impacting the quality of patient care.

Audit:
Audit PME 7.2 (Power Monitoring Expert) was utilized, in conjunction with a fleet of PM800 Meters to gather the Power Quality Data.
Power Quality disturbances

- 1. Voltage Distortion (aka THDv or Vthd)
- 2. Voltage Sag
- 3. Multiple Zero crossings
Turnkey Solutions: Engineer, Supply, Install & Start up

High THD(V) & THD(I)
Supply:
- 2 x 94 Ampere AccuSine PLUS at 600 V
- 2 x 157 Ampere AccuSine PLUS at 600 V
- 24 x Current Transformer
- 78 x 3% linear reactors for the VSD’s

Voltage Sags
- Not coincidental with dialysis machines shut down, not considered to be a problem by the end user.

Ringing Transient and Multiple Zero Crossing
- Installation of 3 isolation transformers on branch circuits that are feeding sensitive equipment
Simplified hospital electrical system

**T-EF2/ T-EF1 Electrical System**

- 600 V Bus, 3P3W
- Other Loads
- 208/120 V Bus, 3P4W
- Generators
  - T-EF2
    - 600 kVA
    - 600/208/120V
    - Delta/Wye
    - %Z = 5.2
  - T-EF1
    - 600 kVA
    - 600/208/120V
    - Delta/Wye
    - %Z = 5.2

**Existing Dialysis Machines Circuit**

**Proposed Upgrade**

**Dialysis Electrical Room Panel**

**Other Loads**

**ATS**

**Normal**
Low Harmonic Emission Solution
2 ways to achieve ‘Low Harmonic’ system

● Main Goal
  ● Comply with harmonic standards and reach a THDi level below 5%

● 2 solutions

1. Active Harmonic Filters for multiple standard VSD
   ● Active Harmonic Filter (AccuSine PCS+ 60,120,200 or 300A):
     ● For groups of multiple ATV600 & ATV900, up to 630kW each
     ● Achieve a THDi below 5%
     ● AC or DC chokes are needed at VSDs level (3-5% Z) to meet 5% THDi
     ● Can also be used to compensate for harmonics from non-VSD loads on the same bus as well as to provide PFC for line connected motors

2. ‘Low Harmonic’ drives up to 630kW “ATV680 & ATV980”
   ● One enclosure with ATV680 & ATV980, complete with AFE module
   ● 380 to 480 V, 50/60Hz, IP23 & IP54, THDi < 5%
   ● Can achieve a PF of 100%
AFE VSD Harmonic Solution

AFE VSD main building blocks

A
C
S
o
u
r
C
h
C
A
G
T
B
u
C
h
C
a
H
o
m
i
c
S
o
l
u
t
i
o
n
LCL Filter
Converter
DC Bus
Inverter

AC Source

IGBT

IGBT

AC Motor
**AFE Drive advantages**

1. It’s normally more cost effective for application with one large drive in comparison to AHF.

2. It has a footprint advantage over the AHF for installation of one or two drives.

3. It will be compliant to IEEE 519 when operating as Low Harmonic Drive when transmitting full load power.

4. It has a high power factor, going as high as 99% lagging, for most application it will have a lower kVA demand than AHF combined with 6-pulse VSD.

5. It’s capable of re-injecting power into the grid during dynamic breaking, therefore yielding some operation expenses saving during these instances.
AHF PCS+ advantages when Combined with standard 6-pulse VSD

1. When the AHF is sized appropriately, compliance to IEEE 519-2014 is attained regardless of the VSD loading.

2. One AHF can correct for multiple 6-pulse VSD unlike an AFE VSD where you need one for each drive product, making AHF more cost effective for multiple drive application, especially when redundant pumps are present.

3. AHF have less losses compared to AFE Drive, therefore it reduces the installation operating cost over time.

4. AHF introduces less switching ripple than AFE because it uses a higher commuting frequency, therefore reducing the risk of interaction with other loads present in the network.

5. AHF can simultaneously correct PF and do load balancing while mitigating harmonic, therefore improving the overall power quality of the installation.
AHF PCS+ advantages when Combined with standard 6-pulse VSD

6. The AHF parallel installation makes it easy to retrofit an installation and it also increases the continuity of service, basically the drive can still operate even though the AHF is off line.

7. The AHF can easily be integrated in MCC or in switch gear which can optimize the installation footprint and reduce construction costs.

8. Generally speaking, 6-pulse VSD are more robust and less complex than AFE VSD, therefore reducing maintenance frequency and complexity when they are combined with AHF.

9. AFE VSD offer begins at 110 KW and increases with KW rating. AHF advantage is that it be applied to all KW ratings (from 0.75 KW to 900 KW).
ATV680 Versus ATV630/ATV660 combined with PCS PLUS 1 to 5 identical VSD ranging from 110 to 500 kW

Base of comparison:

- the cost of ownership,
- the lineup footprint,
- the lineup weight,
- the apparent power
- and the losses of each solution.

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<td>Blue color: advantage ATV630/ATV660 + AccuSine PCS+</td>
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<th>Cost of ownership</th>
<th>Lineup length</th>
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Both types of systems are effective at mitigating harmonic distortion and meeting the most stringent harmonic standard around the world.

An advantage can be given to AFE VSD when only one drive is involved in the project, especially when dynamic braking is required.

However, a definitive advantage can be given to AHF with standard 6-pulse VSD when multiple drives are operating on the same bus. The greatest benefits of a system solution are reflected in the cost of ownership and the operating cost reduction due to the efficiency optimization of a system approach.
Questions?