Harmonic Filtering in 3-phase VSD Systems

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- 2002-2006 ETH Zürich, PhD in Power Electronics
- 2006-2007 Virginia Tech, Faculty ECE Dept.
- 2008-2011 Alstom, BU Turbogenerators
- 2011-2014 ABB, BU Power Conversion
- 2014- Schaffner, BU Power Quality

- IEEE Senior Member, Officer IEEE IES (Switzerland)
- European PhD School in Power Electronics, Co-Chairman (23-27 May 2016, 17th Edition)
Schaffner Group at a glance

- World leader in EMC filtering
- Serving markets and applications in the fields of power magnetics, power quality, and solutions for electromobility
- Corporate Headquarters in Luterbach, Switzerland
- Established in 1962
- Employees: 2'600 world-wide

- Worldwide application support with on-site R&D, supporting customers with local design, prototyping and sourcing, pre-sales and after sales services
- Manufacturing in five own plants around the globe (China, Germany, Hungary, Thailand, USA)
Market is served by divisions with strong position in their niches

**EMC division**
- Filters for electromagnetic compatibility
- Power Quality filters

**Power Magnetics division**
- Mission critical components for high power, high reliability electronics

**Automotive division**
- EMC filters for electric/hybrid cars
- Antennas for key-less entry systems

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Global footprint

Büren, Germany
117 employees
- PM R&D
- PM Manufacturing

Lüthenbach, Switzerland
HQ
110 employees
- Group Innovation Center

Kecskemét, Hungary
163 employees
- EMC, PM Manufacturing

Lamphun, Thailand
1’850 employees
- Product Development
- EMC, Automotive Manufacturing

Wytheville, USA
135 employees
- PM Manufacturing

Shanghai, China
520 employees
- Product Development
- EMC, PM Manufacturing

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Harmonic Filtering in 3-phase Variable Speed Drive Systems
Outlook

- Power electronics conversion in 3-phase VSD systems
- 3-phase diode bridge
- Requirements for rectifier
- Harmonics limits, standards & effects of harmonics
- Components of a conventional VSD power train
- Methods to reduce harmonics in a VSD
- Multi-pulse modular multilevel PWM converter
- SCR bridge-based cycloconverter drive topology
- Benchmark harmonic mitigation methods
- Conclusions
Power electronics supply of electrical 3-ph motors is typically realized in 2 stages (indirect): 3-phase mains to DC and DC to AC/motor stator terminals

Often one direction of power has to be provided, i.e. 1Q and 2Q operation

The inverter stage is typically a voltage source PWM 2- or 3-level forced commutated converter

3-ph diode bridge with capacitive smoothing of output voltage is the simplest and robust rectifier interface
3-ph diode bridge: case study

Measurements on a 3-ph diode bridge (eg. symmetric input voltage and load current kept constant)

THDi (IEC 61000-3-2)

\[
THD = \sqrt{\sum_{n=2}^{40} \left( \frac{I_n}{I_1} \right)^2}
\]

Overall evaluation and impression:

✓ pretty good rectifier!
3-ph diode bridge: pros & cons

- **Simple, robust, cheap**
  - No control
  - No sensors
  - No auxiliary supply
  - No EMI filtering
  - No acoustic noise
  - Reduced heat-sink
- **High RAMS**

- **Compact**
  - **Good symmetry** (mains balanced)
    - Works purely mains commutated
    - Very good DPF
    - Acceptable PF
  - Unregulated output voltage
  - Poor THDi (about 30%)

What are the methods to improve the THDi?
How is a good rectifier performance defined?
Requirements

- Sinusoidal input current, low effects on mains
  - THDi < 5% industrial requirement (IEEE519)
  - IEC 61000-3-2 (i ≤ 16A)
  - IEC 61000-3-12 (16A < i < 75A)
- Ohmic fundamental mains behavior, PFC (PF > .99)
- (Limited) capacity of reactive power compensation
- Unidirectional power flow (if load is a power sink)
- EMI requirements compliance
- Regulated output voltage
- Mastering of mains phase failure

Technology Clusters

- Harmonic reduction techniques
- PFC techniques
- Uni- or bi- directional rectifiers, indirect or direct conversion
- EMI filtering techniques
- Boost, buck topologies
- Active rectifiers

Passive Rectifiers
Hybrid Rectifiers
Active Rectifiers
EMI filters
LCL filters
dv/dt filters
Harmonic Frequencies – Limits & Standards

<table>
<thead>
<tr>
<th>Frequency Bandwidth</th>
<th>50, 60 Hz</th>
<th>2 kHz</th>
<th>9 kHz</th>
<th>150 kHz</th>
<th>30 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Grid harmonic frequencies”</td>
<td>“Switching frequencies”</td>
<td>EMC/EMI</td>
<td></td>
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</tbody>
</table>

Regulated, Partial regulated or non-regulated ranges

Standards on Grid Harmonics
- IEEE519-2014 (US, Asia)
- IEC 61000-3-12 (EU)
- EN 50160 (EU)
- Standard D.A.CH.CZ (EU)
- Standard G5/4 (UK, HK)

### Conducted RF range

<table>
<thead>
<tr>
<th>Harmonic order (odd harmonics)</th>
<th>IEEE 519-2014 current distortion limits [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31, 33, 35, 37</td>
<td>TDD</td>
</tr>
<tr>
<td>&lt;20</td>
<td>5.0</td>
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<tr>
<td>20&lt;50</td>
<td>8.0</td>
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<tr>
<td>50&lt;100</td>
<td>12.0</td>
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<tr>
<td>100&lt;1000</td>
<td>15.0</td>
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<tr>
<td>&gt;1000</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Maximum harmonic current distortion in percent of \(I_N\); even harmonics are limited to 25% of the odd harmonic limits above.
1. **EN 50160**, Voltage characteristics of electricity supplied by public distribution systems, 2011
3. **IEC 61000-3-2** Electromagnetic compatibility (EMC) - Part 3-2: Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)
4. **IEC 61000-3-12** ed. 2 Electromagnetic compatibility (EMC) - Part 3-12: Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤ 75 A per phase
5. **IEC 61000-4-30**, 2003: Power quality measurement methods
6. **IEC 61000-2-2**: Electromagnetic compatibility — part 2-2, environment compatibility levels for low-frequency conducted disturbances and signaling in public and low voltage
7. **Engineering Recommendation G5/4-2**
10. **IEC TR 61000-3-14**:2011. Electromagnetic compatibility (EMC) - Part 3-14: Assessment of emission limits for harmonics, interharmonics, etc in LV systems
11. **IEC TR 61000-3-15**:2011. Electromagnetic compatibility (EMC) - Part 3-15: Limits - Assessment of LF electromagnetic immunity etc (2-9 kHz)
12. **EN 12015:2014** Electromagnetic compatibility - Product family standard for lifts, escalators and moving walks - Emission; German version

<table>
<thead>
<tr>
<th>Requirement at installation level (PCC)</th>
<th>Requirement at equipment level</th>
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<tbody>
<tr>
<td>IEC 61800-3-14</td>
<td>IEC 61800-3-6</td>
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<td>ER G5/4-1</td>
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Effects of Harmonics

- Most electrical drives do **not have resistive mains behavior**
- **Non-linear loads as source** of harmonic currents and voltages
- **Short term effects**: equipment failures, shutdown, process restart costs, nuisance tripping
- **Long term effects**: thermal overload of cables and transformer, equipment lifetime reduction
- **Decreased system’s reliability and availability**
- **Lower power factor and efficiency decrease**: reduced utilization of system’s installed capacity
- **Additional costs in system operation and maintainance**
- **Violation international PQ and EMC Standards**
Components of a conventional VSD power train

- **Isolation transformer**
  - To match supply voltage supply, input protection

- **Harmonic filtering**
  - Filters to reduce specific harmonics

- **Line side filtering**
  - Type of filter depends on operating freq and system

- **PFC or rectifier**
  - PF and Q correction over all operating range

- **Power converter**
  - Passive, hybrid, active rectifiers

- **Motor filter**
  - To protect motor, suppress EMI disturbances

**Solutions addressed to match VSD voltage**

- To meet harmonic limits
- To meet medium and high freq limits
- To meet medium and high freq limits
For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

- DC-link choke
- AC line reactors
- Multipulse rectifiers
- Harmonic trap filters
- Broadband filters
- Active filters
- Multipulse distribution
Harmonic Mitigation Methods for VSDs

For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

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Integrated in drive
- Less voltage drop than equivalent line reactor
- Less input protection for semiconductors
- Not enough harmonic reduction
- Impedance fixed in design
- Often not available as option
For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

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<table>
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<th>Low cost</th>
<th>Moderate harmonic reduction</th>
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<tbody>
<tr>
<td></td>
<td>Increased input protection</td>
</tr>
</tbody>
</table>
- Separate mounting or larger drive enclosure
- Not enough harmonic reduction IEEE519
Harmonic Mitigation Methods for VSDs

For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

- DC-link choke
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- Multipulse rectifiers
- Harmonic trap filters
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<table>
<thead>
<tr>
<th>Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-link choke</td>
<td>Integrated in drive, less voltage drop than equivalent line reactor, less input protection for semiconductors</td>
<td>Not enough harmonic reduction, impedance fixed in design, often not available as option</td>
</tr>
<tr>
<td>AC line reactors</td>
<td>Low cost, moderate harmonic reduction, increased input protection</td>
<td>Separate mounting or larger drive enclosure, not enough harmonic reduction, IEEE519 limits not met</td>
</tr>
<tr>
<td>Multipulse rectifiers</td>
<td>Reasonable cost, substantial harmonic reduction (85%), increased input protection</td>
<td>Impedance matching with phase-shifted sources critical, large footprint, harmonic level still not below IEEE519 limits, cannot retrofit</td>
</tr>
<tr>
<td>Harmonic trap filters</td>
<td>Broadband filters</td>
<td></td>
</tr>
<tr>
<td>Active filters</td>
<td>Multipulse distribution</td>
<td></td>
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IEEE519
Harmonic Mitigation Methods for VSDs

For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

- DC-link choke
- AC line reactors
- Multipulse rectifiers
- Harmonic trap filters
- Broadband filters
- Active filters
- Multipulse distribution

- Allow better drive loading
- Increased input protection
- Meets IEEE519

- Care needed in filter design to avoid system resonances (de-tuned filters)
For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

- DC-link choke
- AC line reactors
- Multipulse rectifiers
- Harmonic trap filters
- Broadband filters
- Active filters
- Multipulse distribution

<table>
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<th>Allow better drive loading</th>
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<tbody>
<tr>
<td>Increased input protection</td>
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</tbody>
</table>

- May not meet IEEE519 limitations
- Require modification to match a drive internal line reactor
Harmonic Mitigation Methods for VSDs

For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

- DC-link choke
- AC line reactors
- Multipulse rectifiers
- Harmonic trap filters
- Broadband filters
- Active filters
- Multipulse distribution

- Compliance with IEEE519
- Harmonic cancellation from 2nd to 51st
- Easy installation
- Provide VAr currents, correct PF
  - Needed protection from line transients
Harmonic Mitigation Methods for VSDs

For the 3-phase diode rectifier front-end of a VSD, the following harmonic mitigation methods can be used:

- DC-link choke
- AC line reactors
- Multipulse rectifiers
- Harmonic trap filters
- Broadband filters
- Active filters
- Multipulse distribution

---

- Substantial reduction of current and voltage harmonics (50-80%)
- Increased input protection
  - Impedance and load matching of phase-shifted sources critical to performance
  - Separate mounting of transformers
  - Harmonic reduction not below IEEE519 limits
Example of 18-pulse 4160V Drive featuring 750V Power Cells

Source: Siemens
TDD reduction through reactors and multipulse systems

\[
\text{THD} = \sqrt{\frac{\text{sum of squares of amplitudes of all harmonics}}{\text{square of amplitude of fundamental}}} \times 100\%
\]

\[
\text{TDD} = \sqrt{\frac{\text{sum of squares of amplitudes of all harmonics}}{\text{square of maximum demand load current}}} \times 100\%
\]

Source: Schneider
SCR bridge based cycloconverter drive topology

SCR-bridge based six pulse cycloconverter drive topology [3]
A combination of harmonic filters need to be installed to filter out the different harmonics and interharmonics [3].
Mitigation methods depends on application type and on load:

<table>
<thead>
<tr>
<th>Mitigation Methods</th>
<th>Single Device (Drive)</th>
<th>Group of devices (Drives)</th>
<th>Complex mixed loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Line Reactors</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Passive Filters</td>
<td></td>
<td></td>
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<tr>
<td>Active Filters @ PCC</td>
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</tbody>
</table>

- Static load
- Variable load
- Dynamic load
- Highly dynamic load
Harmonics are inherent to non linear loads, in particular to diode-bridge, multipulse based rectifier topologies used in VSD applications.

Passive and hybrid rectifier topologies represent the most robust and cost effective front-end for 1Q and 2Q, LV and MV motor drive applications.

Harmonic mitigation, together with PFC and voltage control represents one of the key requirements of a rectifier system.

Current harmonics are regulated by standards.

Several methods are known to mitigate harmonics; not all of them are equivalent and have different impact in terms of installation effort, footprint, cost, efficiency, RAMS.

«The filtering of harmonics is an art, as well as a science, and due diligence shall be paid to the filtering cancellation techniques used in solving the harmonic problems in industrial systems.» [3]
Thank you for your attention
References

(1) H. Akagi, Modern active filters and traditional passive filters, Bullettin Polish Academy of Sciences, Vol 54, No. 3., 2006


(4) Guidance notes on control of harmonics in electrical power systems, ABS 2006

(5) P. Pejovic, “Low harmonic three-phase diode bridge rectifiers”, 2005
European PhD School

Power Electronics, Electrical Machines, Energy Control and Power Systems

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