Harmonics in Grid-Connected Converters: challenges and cost-effective opportunities in ASD systems

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New Harmonic Reduction Techniques for Motor Drives (NHTD)

NHTD has two work-packages based on the harmonic mitigation techniques and solutions as follows:

1- Single Drive Systems
2- Multi Drive Systems

MAY 2014 ➔ APRIL 2017

NHTD Team

http://www.nhtd.et.aau.dk
Outline

- Introduction (three-phase diode front-end)
- Electronic Inductor (EI) Concept
- Proposed Selective Harmonic Mitigation
- Multi-Drive Systems
- Experimental Results
- Conclusion
Introduction

Three-Phase Diode Front-End System
Typical ASD System

Passive Filtering Solution

- AC or DC side passive filtering (inductor): simple and effective to some extent. But they are bulky, costly, causes resonance, worsen system dynamic, and etc.

- Active harmonic mitigation solutions have been introduced to improve the input current quality. But most of them are complex, costly and reduce system efficiency.
Typical ASD System

Three-Phase Diode Rectifier Passive Filtering Challenges

Performance of three-phase diode rectification using dc-side passive filtering: (a) effect of loading condition, (b) corresponding power factor $\lambda$ and input current THD at different power levels, (c) effect of dc-link inductor size.
Typical ASD System

- Three-Phase Diode Rectifier Passive Filtering Challenges

![Diagram of a typical ASD system showing a three-phase diode rectifier and an inverter with a dc-side filter.]

- Typical annual loading profile of adjustable speed drive applications: (a) water pump, (b) cooling tower.

(a) Water pump loading profile

(b) Cooling tower loading profile

Load power (%): 105, 80.9, 61.8, 46.8, 35.4, 28.7, 20.3, 15.8
Operating hours (%): 0, 10, 20, 30, 40

Load power (%): 80.5, 57.6, 40, 25.5, 16, 8.9
Operating hours (%): 0, 10, 20, 30, 40
Electronic Inductor Concept

Basic Idea
Electronic Inductor Technique

**Basic Concept**

- **λ ≈ 0.95**
- **THD_i ≈ 29%**

- Emulating the behavior of an ideal infinite inductor
- THD_i and Power Factor (λ) independent of the load profile.
- Controlling dc-link (u_{dc}).
Electronic Inductor Technique

- No major modification is imposed to the original system!
Electronic Inductor Concept

### Load Profile

**Independent performance**
(10% to 100% $P_o$)

![Diagram of electronic inductor (EI)]

- Circuit schematic of a boost dc-dc converter topology in a three-phase diode rectifier:
  - (a) Circuit schematic
  - (b) Corresponding input current waveform ($i_a$) at different power levels.

#### Implementation
- Simulation parameters: 
  - RMS line-to-line voltage $U_{g,LL,rms} = 400$ V
  - Grid frequency $f_g = 50$ Hz
  - Grid impedance $L_g = 0.18$ mH, $R_g = 0.1\Omega$
  - Rated power $P_{o,max} = 7.5$ kW
  - $U_{dc} = 700$ V
  - $f_{sw} = 40$ kHz
  - DC-link capacitance $C_{dc} = 470$ μF
  - DC-link inductance $L_{dc0} = 2$ mH

- THD
  - $i_a \approx 29\%$
  - $\lambda \approx 0.95$

- Assuring CCM operation:
  - $L_{dc} > \frac{D(1-D)U_{dc}^2}{2P_{o,min}f_{sw}}$
Experimental Setup

System Specifications

<table>
<thead>
<tr>
<th>$U_{g,LL,\text{rms}}$</th>
<th>$f_g$</th>
<th>$L_g, R_g$</th>
<th>$P_{\text{omax}}$ (100%)</th>
<th>$U_{dc}$</th>
<th>$f_{\text{sw}}$</th>
<th>$L_{dc0}$</th>
<th>$C_{dc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 V</td>
<td>50 Hz</td>
<td>0.18mH, 0.1 Ω</td>
<td>7.5 kW</td>
<td>700 Vdc</td>
<td>20 kHz</td>
<td>1 mH</td>
<td>470 μF</td>
</tr>
</tbody>
</table>

Employed components

<table>
<thead>
<tr>
<th>Module</th>
<th>Part-Number</th>
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<tr>
<td>Three-phase diode rectifier</td>
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<tr>
<td>Controller</td>
<td>TMS320F28335</td>
</tr>
</tbody>
</table>
Experimental Results

- **Original Drive (Passive Filter)**
  - $P_o = 5\,\text{kW}$  $U_{dc} = 534\,\text{V}$
  - $THD_i = 48.7\%, \lambda = 0.89$  $L = 2.5\,\text{mH}$

- **EI (flat current modulation)**
  - $P_o = 5\,\text{kW}$  $U_{dc} = 700\,\text{V}$
  - $THD_i = 28\%, \lambda = 0.95$  $L = 1\,\text{mH}$  $f_{sw} = 20\,\text{kHz}$

- **Original Drive (Passive Filter)**
  - $P_o = 3\,\text{kW}$  $U_{dc} = 534\,\text{V}$
  - $THD_i = 67.6\%, \lambda = 0.81$  $L = 2.5\,\text{mH}$

- **EI (flat current modulation)**
  - $P_o = 3\,\text{kW}$  $U_{dc} = 700\,\text{V}$
  - $THD_i = 28\%, \lambda = 0.94$  $L = 1\,\text{mH}$  $f_{sw} = 20\,\text{kHz}$
Improving Efficiency

Adjustable Switching Frequency Scheme
Proposed Solutions

■ Adjustable Switching Frequency

\[ f'_{sw} = \text{ceil} \left( \frac{f'_{sw,\text{max}} - f'_{sw,\text{min}}}{f'_{sw,\text{max}} - f'_{sw,\text{min}}} \left( f_{sw} - f'_{sw,\text{max}} \right) + f'_{sw,\text{max}} \right) \]

\[ HB' = k'_{\text{ripple}} I_L \quad \text{where} \quad k'_{\text{ripple}} = \frac{U_{dc} D(1-D)}{2L_{dc} f'_{sw} I_L} = \frac{k_{\text{ripple}}}{f_{sw}} \]

\[ f_{sw} = \frac{D(1-D)^2 U_{dc}^2 I_L}{L_{dc} P_0} \Delta I_{L,\text{pk}-pk} \]

\[ HB = k_{\text{ripple}} I_L, \quad HB = \frac{\Delta I_{L,\text{pk}-pk}}{2} \]

5 A/div, 2 ms/div

\[ P_o = 100\% \]
\[ P_o = 70\% \]
\[ P_o = 50\% \]
\[ P_o = 30\% \]
\[ P_o = 10\% \]

\[ \lambda \approx 0.95 \]

\[ \text{THD}_{i_a} \approx 29\% \]

## Proposed Solutions

### Adjustable Switching Frequency

Using ASFM strategy improves efficiency from 315W losses to 173W losses (95.8% vs 97.7%)

### System Specs:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>Grid phase voltage</td>
<td>$v_{abc}$</td>
<td>230 Vrms</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>$f_g$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Grid impedance</td>
<td>$L_g, R_g$</td>
<td>0.18 mH, 0.1 Ω</td>
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<td>DC-link inductor</td>
<td>$L_{dc-p}, L_{dc}$</td>
<td>2.5 mH, 2 mH</td>
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<td>DC-link capacitor</td>
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<td>470 µF</td>
</tr>
<tr>
<td>DC-link voltage</td>
<td>$U_{dc-p}, U_{dc}$</td>
<td>$\approx$ 534V, 700 V</td>
</tr>
<tr>
<td>Rate power</td>
<td>$P_{o,\text{max}}$ (100%)</td>
<td>7.5 kW</td>
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Using WBG Devices

Applying SiC power devices reduces the size of magnetic components and losses (131 W vs 173 W)

Passive filtering

Fixed switching - EI, IGBT with Xflux core @ 35 kHz

Proposed ASFS - EI, IGBT with Xflux core @ 10 kHz

Three-phase rectification with:
- Passive filtering
- Fixed switching - EI, IGBT with Xflux core @ 35 kHz
- Proposed ASFS - EI, IGBT with Xflux core @ 10 kHz

η : Efficiency
sw : Switching loss
D : Boost diode
gate : Gate-driver
cond : Conduction loss
T : Power switch (Transistor)
C,ESR : DC-Link Capacitor
Effective Series Resistor

\[ P_{loss, total}(W) \]

\[ P_{gate}(W) \]

\[ P_{bridge}(W) \]

\[ P_{T,cond}(W) \]

\[ P_{C,ESR}(W) \]

\[ P_{Ldc}(W) \]

\[ P_{T,sw}(W) \]

\[ P_{D,sw}(W) \]

\[ P_{D,cond}(W) \]

\[ k_{ripple}(\%) \]

\[ THD_i(\%) \]

\[ 1-\lambda \]

\[ L_{dc} = 2 \text{ mH} \]

\[ L_{dc} = 1 \text{ mH} \]
Proposed Solutions

- Pulse Pattern Modulation
Pulse Pattern Modulation

Pulse Pattern Modulation

\[ i_n = \frac{4}{n\pi} \left[ I_{dc1} \cos(n30) + I_{dc2} \cos(n\alpha_1) - I_{dc2} \cos(n\alpha_2) \right] \]

\[ 2\beta + \theta = 60 \]

\[ 30^\circ < \alpha_1 < 90^\circ, \alpha_2 = 120^\circ - \alpha_1 \]

Adding or subtracting phase-displaced current levels

\[ i_1 = \frac{4}{\pi} \left[ I_{dc1} \cos(30) + I_{dc2} \cos(\alpha_1) - I_{dc2} \cos(\alpha_2) \right] \]

\[ i_k = \frac{4}{k\pi} \left[ I_{dc1} \cos(k30) + I_{dc2} \cos(k\alpha_1) - I_{dc2} \cos(k\alpha_2) \right] = 0 \]

\[ i_m = \frac{4}{m\pi} \left[ I_{dc1} \cos(m30) + I_{dc2} \cos(m\alpha_1) - I_{dc2} \cos(m\alpha_2) \right] = 0 \]

Proposed Solutions

Pulse Pattern Modulation

Optimization

\[
\begin{align*}
\text{Obj}_1 &= M_a - |i_g(1)| \leq L_1 \\
\text{Obj}_n &= \frac{|i_g(n)|}{|i_g(1)|} \leq L_n
\end{align*}
\]

where \( n = 6k \pm 1 \) with \( k \) being 1, 2, 3, ....

\[
\alpha_0 < \alpha_1 < \alpha_2 < \cdots < \alpha_m < \alpha_0 + \frac{\pi}{3}
\]

Instead of fully nullifying the distortions, the harmonics could be reduced to acceptable levels by adding suitable constraints \((L_n)\).

Here, \( F_{obj} \) is formed based on a squared error with more flexibility by adding constant weight values \((w_n)\) to each squared error function.

Experimental Setup

Employed components

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</tr>
</tbody>
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Experimental Setup

- Synthesis of the modulation signal

\[ \alpha_1 < \alpha_{11} : \]
\[
\begin{align*}
  & \text{if } (|\sin(3\omega_0 t)| > \sin(3\beta)) \\
  & i_M = I_{dc1} + I_{dc2} \\
  & \text{else} \\
  & i_M = I_{dc1}
\end{align*}
\]

\[ \alpha_1 > \alpha_{11} : \]
\[
\begin{align*}
  & \text{if } (|\sin(3\omega_0 t)| > \sin(3\beta)) \\
  & i_M = I_{dc1} - I_{dc2} \\
  & \text{else} \\
  & i_M = I_{dc1}
\end{align*}
\]
Experimental Results

- **Harmonic Elimination [7\textsuperscript{th} and 13\textsuperscript{th}]**
  - THDI = 34\% \quad \lambda \approx 0.94 \quad 600\text{mA/div}
  - FFT of the grid current ($i_a$)

- **Harmonic Elimination [5\textsuperscript{th}, 13\textsuperscript{th}]**
  - THDI = 47.7\% \quad \lambda \approx 0.89 \quad 600\text{mA/div}
  - FFT of the grid current ($i_a$)

**Table:**

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<tr>
<th>Harmonic Mitigation Strategy</th>
<th>Harmonic Distribution and THD$_i$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$i_a(5)/i_a(1)$</td>
</tr>
<tr>
<td>7\textsuperscript{th} and 13\textsuperscript{th} harmonic cancellation</td>
<td>31.2</td>
</tr>
<tr>
<td>5\textsuperscript{th}, 13\textsuperscript{th} harmonic cancellation</td>
<td>4.7</td>
</tr>
<tr>
<td>Conventional method (square wave)</td>
<td>20</td>
</tr>
</tbody>
</table>

$P_0 = 5\text{ kW} \quad U_{dc} = 700\text{V}$

$Idc_1 = 1, \quad Idc_2 = 0.618, \quad \alpha_1 = 42^\circ$

$Idc_1 = 1, \quad Idc_2 = 0.653, \quad \alpha_1 = 70^\circ$
Proposed Solutions

Multi-drive

www.weg.net
Multi-Drive Configuration

Basic Concept

In many applications it is a common practice to employ parallel connected drive units. In this situation the application demand is met using multiple modestly sized motor units rather than one single large unit.

- Generating staircase total input current by proper combination
Multi-Drive Configuration

Phase-shifted Flat Current Control

The new current modulation technique is applied to each DC-DC converter in order to further improve the current quality. However, it requires PLL for synchronization purpose.


Multi-Drive Configuration

Pulse pattern current modulation ($\alpha_f \neq 0^\circ$)

\[
i_s(n) = \sqrt{(a_n + a'_n)^2 + (b_n + b'_n)^2}
\]

\[
a_n = \frac{2I_{dc}}{n\pi} \left[ -\sin(n\alpha_0) + \sin\left(n\alpha_0 + \frac{2\pi n}{3}\right) \right]
\]

\[
b_n = \frac{2I_{dc}}{n\pi} \left[ \cos(n\alpha_0) - \cos\left(n\alpha_0 + \frac{2\pi n}{3}\right) \right]
\]

\[
a'_n = \sum_{j=1}^{2} \frac{2I_{dc}}{n\pi} (-1)^{j+1} \left[ -\sin(n\alpha_j) + \sin\left(2n\alpha_0 - n\alpha_j + \frac{2\pi n}{3}\right) \right]
\]

\[
b'_n = \sum_{j=1}^{2} \frac{2I_{dc}}{n\pi} (-1)^{j+1} \left[ \cos(n\alpha_j) - \cos\left(2n\alpha_0 - n\alpha_j + \frac{2\pi n}{3}\right) \right]
\]
Multi-Drive Configuration

**Implemented Setup**

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<tr>
<th>Symbol</th>
<th>Parameter</th>
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<td>230 V&lt;sub&gt;rms&lt;/sub&gt;</td>
</tr>
<tr>
<td>$f_g$</td>
<td>Grid frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$Z_g$ (L&lt;sub&gt;g&lt;/sub&gt;, R&lt;sub&gt;g&lt;/sub&gt;)</td>
<td>Grid impedance</td>
<td>0.1 mH, 0.01 Ω</td>
</tr>
<tr>
<td>L&lt;sub&gt;dc&lt;/sub&gt;</td>
<td>DC link inductor</td>
<td>2 mH</td>
</tr>
<tr>
<td>C&lt;sub&gt;dc&lt;/sub&gt;</td>
<td>DC link capacitor</td>
<td>470 µF</td>
</tr>
<tr>
<td>V&lt;sub&gt;o&lt;/sub&gt;</td>
<td>Output voltage</td>
<td>700 V&lt;sub&gt;dc&lt;/sub&gt;</td>
</tr>
<tr>
<td>K&lt;sub&gt;p&lt;/sub&gt;, K&lt;sub&gt;i&lt;/sub&gt;</td>
<td>PI controller (Boost converter)</td>
<td>0.01, 0.1</td>
</tr>
<tr>
<td>K&lt;sub&gt;ff&lt;/sub&gt;, t&lt;sub&gt;s&lt;/sub&gt;, ξ</td>
<td>PLL parameters</td>
<td>0.8, 0.2 s, 1.41</td>
</tr>
<tr>
<td>HB</td>
<td>Hysteresis Band</td>
<td>2A</td>
</tr>
<tr>
<td>$P_{o_{total}}$</td>
<td>Total output power</td>
<td>≈6.5 kW</td>
</tr>
</tbody>
</table>
Multi-Drive Configuration

### Experimental Results (phase shift control)

THD$_i \approx 16\%$, $\lambda = 0.93$

THD$_{ig} = 16\%$

$\lambda \approx 0.93$

FFT of the grid current $i_g$

$P_{\text{SCR}} = 3 \text{ kW}$, $P_{\text{DR}} = 3.63 \text{ kW}$, $U_{dc} = 700 \text{ V}$

THD$_i \approx 15.8\%$, $\lambda = 0.95$

THD$_{ig} = 15.8\%$

$\lambda \approx 0.95$

FFT of the grid current $i_g$

$P_{\text{SCR}} = 3 \text{ kW}$, $P_{\text{DR}} = 3.36 \text{ kW}$, $U_{dc} = 700 \text{ V}$
Multi-Drive Configuration

### Experimental Results (current modulation)

**THD$_i$ ≈ 10%, $\lambda = 0.94$**

- $P_{SCR} = 3$ kW, $P_{DR} = 3.86$ kW, $U_{dc} = 700$ V

**THD$_i$ ≈ 8.6%, $\lambda = 0.94$**

- $P_{SCR} = 3$ kW, $P_{DR} = 3.65$ kW, $U_{dc} = 700$ V
Multi-Drive Configuration

- Extending number of the units (phase shift control)

- More flexibility in obtaining desired \( THD_i \) and PF

Five parallel units (\( n = 5 \))

\[
\text{THD}_{i,\min} \quad \lambda_{\text{max}}
\]

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Multi-Drive Configuration

- Extending number of the units (current modulation)

- Lower harmonic distortion can be obtained
Multi-Drive Configuration

Experimental Setup

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Conclusion

- The EI technique can significantly improve the THD$_i$, $\lambda$ and stable DC link
- The proposed pulse pattern modulation can eliminate low order harmonics
- With multi-drive configuration, the EI technique can further reduce the THD$_i$
- The EI technique can maintain the system performance under non-ideal operation conditions (e.g., unbalanced grid)
- The efficiency of EI technique can be significantly improved by employing WBG devices, alternative topologies and smart control techniques
Thank You

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http://www.nhtd.et.aau.dk