High-Order Passive Filters for Grid-Connected Voltage-Source Converters: Topologies and Design Challenges

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Outline

• Introduction
• Passive Filters Description
• Design Challenges
• Optimum Passive Damping Method
• Conclusions
• Questions
• **Power Filters** are needed to link active converters with ideal power sources/loads

• A **high-order** filter is adopted usually due to size and cost considerations

• The aim is to **effectively** filter out the switching harmonics from the active converter and to ensure VSC operation
Passive Filters Description

Typical Power Filters

- **L filter**: 20 dB/decade attenuation
  
  \[
  \begin{array}{c}
  L_1 \\
  \end{array}
  \]

- **LC filter**: 40 dB/decade attenuation
  
  \[
  \begin{array}{c}
  \begin{array}{c}
  L_1 \\
  \end{array} \\
  C_f \\
  \end{array}
  \]

- **LCL filter**: 60 dB/decade attenuation
  
  \[
  \begin{array}{c}
  \begin{array}{c}
  L_1 \\
  \end{array} \\
  \begin{array}{c}
  L_2 \\
  \end{array} \\
  C_f \\
  \end{array}
  \]
Passive Damped Filters Topologies

✓ The key is to ensure high efficiency, low cost and size

✓ There should be no risk of harmonic amplification with the utility grid

Shunt passive damped filters topologies

*C-type filter used to damp the resonance and the high frequency ripple*

Passive Damped Filters Topologies

✓ “More effective” passive filter*

<table>
<thead>
<tr>
<th>Filter</th>
<th>Passive Device</th>
<th>Peak Rating</th>
<th>L/C/R</th>
<th>( L^2 ) (HA²)</th>
<th>Total Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCL + RC</td>
<td>L₁ 23 A</td>
<td>1.5 mH</td>
<td></td>
<td>1.06</td>
<td>513</td>
</tr>
<tr>
<td></td>
<td>L₂ 21 A</td>
<td>0.7 mH</td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Cᵣ, Cᵣ</td>
<td>330 V</td>
<td>4.7 µF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R₉ 17 W</td>
<td>17 Ω</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trap + RC</td>
<td>L₁ 23 A</td>
<td>1.5 mH</td>
<td></td>
<td>0.89</td>
<td>513</td>
</tr>
<tr>
<td></td>
<td>L₂ 21 A</td>
<td>0.3 mH</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Cᵣ, Cᵣ</td>
<td>330 V</td>
<td>4.7 µF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L₁ 3 A</td>
<td>0.05 mH</td>
<td></td>
<td></td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>R₉ 14 W</td>
<td>13 Ω</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2traps + RC</td>
<td>L₁ 25 A</td>
<td>0.8 mH</td>
<td></td>
<td>0.59</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>L₂ 21 A</td>
<td>0.2 mH</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Cᵣ, Cᵣ</td>
<td>330 V</td>
<td>4.7 µF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L₁ 5 A</td>
<td>0.05 mH</td>
<td></td>
<td></td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>Cᵣ 330 V</td>
<td>0.44</td>
<td></td>
<td></td>
<td>3.65</td>
</tr>
<tr>
<td></td>
<td>L₂ 2.5 A</td>
<td>0.14 mH</td>
<td></td>
<td></td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>R₉ 17 W</td>
<td>7.7 Ω</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\frac{L_{Total}}{C_{Total}} = 31
\]

\[
\frac{L_{Total}}{C_{Total}} = 27
\]

\[
\frac{L_{Total}}{C_{Total}} = 8.5
\]

Design Challenges of Passive Filters

Known challenges (physical design)

• Size optimized design/reduced filter cost result in low inductances (high capacitance) \( \rightarrow \) high ripple current in the filter \( \rightarrow \) increased power loss

• Loss optimized high-order filters results in increased size of the filter

• **Accurate models** to optimize the passive filter are not ready available

Additional challenges (system level)

• Attenuation of resonance harmonics or limitation of instabilities risks

• **Damping is more challenging** for size optimized filters due to increased capacitance

• Harmonics regulations not explicitly defined above 2 kHz (2-9 kHz specifications expected soon)
Design Challenges of Passive Filters

Power Loss in the VSC and Passive Filter

Results from literature

<table>
<thead>
<tr>
<th>Reference</th>
<th>Frequency range</th>
<th>VSC loss</th>
<th>Filter loss</th>
<th>Core loss calculation method</th>
<th>Verified</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>2~6 kHz</td>
<td>0.8~1.5 %</td>
<td>0.1~0.2 %</td>
<td>iGSE</td>
<td>–</td>
</tr>
<tr>
<td>[2]</td>
<td>2~12 kHz</td>
<td>0.5~1 %</td>
<td>0.3~0.5 %</td>
<td>NSE</td>
<td>–</td>
</tr>
<tr>
<td>[3]</td>
<td>3~12 kHz</td>
<td>0.5~1.2 %</td>
<td>1.2~2.2 %</td>
<td>i^2GSE+loss map</td>
<td>yes</td>
</tr>
</tbody>
</table>

- ~80% of filter loss occurs in the converter side inductance!

Power Loss in the Converter Side Inductance

Permeability dependence of the Fe-Si material simulated in time-domain

Example: 70% inductance decrease at rated current

- For a $m_i$ of 0.95, the maximum minor loop frequency is 20 fsw!
Power Loss in the Converter Side Inductance

- **Ferrite + Laminated sheets (H₀=0)**

  ![Graph showing power loss vs. ΔB for Ferrite and Amorphous materials with Fe-Si as a reference.](image)

- **Powder material (H₀=0)**

  ![Graph showing power loss vs. ΔB for various materials.](image)

**Core loss of Fe-Si 10 times higher in laminated sheets!**
Power Loss in the Converter Side Inductance

- Inductor loss characterization:
  - DC-bias influence at 10 kHz and \( \Delta B = 0.09 \text{T} \) for powder materials

- Core loss is not always increasing with dc bias!
- Combination of the core loss information and PWM modulation can result in more significant optimization of power loss in the filter!
# Current Harmonic Limits

Table I: Individual current harmonic limits at PCC
* the limits are referred to the low voltage side of the step-up transformer (400 V)

<table>
<thead>
<tr>
<th>Harmonic order $h$</th>
<th>VDE-AR-N 4105 (LV)</th>
<th>BDEW (MV)*</th>
<th>IEEE 519 (LV &amp; MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.08</td>
<td>2.06</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>1.39</td>
<td>2.84</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>0.69</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>0.55</td>
<td>1.32</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>0.42</td>
<td>0.76</td>
<td>1.5</td>
</tr>
<tr>
<td>19</td>
<td>0.35</td>
<td>0.62</td>
<td>1.5</td>
</tr>
<tr>
<td>23</td>
<td>0.28</td>
<td>0.42</td>
<td>0.6 (23≤h&lt;35)</td>
</tr>
<tr>
<td>25</td>
<td>0.21</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>25 &lt; h &lt; 40</td>
<td>5.2/h</td>
<td>8.67/h</td>
<td>0.3 (35≤h&lt;50)</td>
</tr>
<tr>
<td>40 &lt; h &lt; 180</td>
<td>6.24/h</td>
<td>6.24/h</td>
<td></td>
</tr>
</tbody>
</table>
Current Harmonic Limits

LCL filter design according to IEEE 1547 (series R damper)

- High difference between different harmonic regulations!
- Presence of low harmonics in the grid current needs compensation!
- Lack of damping can result in harmonics limits exceeded around the resonance!
- Alternative passive damping methods are needed to ensure low damping loss!
Optimum Passive Damping Method

✓ Optimum Damping Parameters

• Damping resistor – used to “limit” resonance instabilities in the utility grid. Low or high values of the resistor have equal impact.

• R.D. Middlebrook developed the “rules” for optimum damping design (1978)

• The damping parameters are dependent on the characteristic parameters of the filter and the ratio(s) between the reactive elements of the filter (capacitors or inductors)*

\[
R_0, f_0 = f \left( L_{eq}, C_{eq} \right) \quad a = \frac{L_d}{L_{eq}} \quad n = \frac{C_d}{C_{eq}}
\]


Resonance frequency can vary in a wide range!
Optimum Passive Damping Method

Damping current waveforms

- Series $R$ damper
- Shunt $RC$ damper
- Shunt $RLC$ damper
- Series $RLC$ damper
Optimum Passive Damping Method

Damping current waveforms

Half size!
IEEE 1547 regulations

- Passive damping loss are reasonable!
- Very high resonance attenuation requires RLC dampers to limit loss!

BDEW regulations
Optimum Passive Damping Method

IEEE 1547 regulations

- Design ratings are different depending on harmonic regulations, sensor position or damping topology

BDEW regulations
Summary

- Latest advancements in power filter topologies for grid connected VSC have been presented.
- The optimal design of the filter is related mainly to choice of the converter side inductance as function of the VSC topology and VSC specifications.
- The resonance damping and switching ripple attenuation can be ensured by shunt passive damped filters.
- An optimum design of the passive damped filters was proposed which can ensure also low damping loss and size.
- Further optimization can be performed by considering:
  - The grid impedance influence on damping and switching harmonics attenuation.
  - Harmonization between the PWM method and loss in the converter side inductor.
Thank You! Questions?

www.harmony.et.aau.dk