An Active Filter Approach to the Reduction of the DC Link Capacitor

Burak Ozpineci
Oak Ridge National Laboratory
May 21, 2009

Project ID: ape_01_ozpineci

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

Timeline
• Start date – Oct. 2007
• End date – Sep. 2009
• Percent complete – 50%

Budget
• Total project funding
  – DOE share: 100%
• Funding received in FY08: $158K
• Funding received in FY09: $294K
• Funding requested for FY10: $0K

Barriers
• Barriers
  – DC link capacitor problems: size (35% of the inverter volume), weight (23% of the inverter weight and cost (23% of the inverter)
  – High temperature capacitors
  – High active power filter device losses.

Vehicle Technology Program Targets
• DOE 2015 targets: 105°C Coolant
• DOE 2015 target: 12 kW/l

Partners
• UT (literature survey, modeling and simulation)
Objectives

- The objective of this project is to develop an active power filter (APF) to replace the bulky DC link capacitor.

- The APF is expected to
  - Imitate what a DC link capacitor does
  - Be much smaller size than the DC link capacitor
  - Be an enabler for higher temperature operation

- FY09: Develop new topologies and designs to reduce the efficiency problems associated with the high frequency switching and high inductor current the present APF designs require.
## Milestones

<table>
<thead>
<tr>
<th></th>
<th>FY08</th>
<th>FY09</th>
</tr>
</thead>
<tbody>
<tr>
<td>October to January</td>
<td>Establish the performance requirements for an active filter</td>
<td>October to February</td>
</tr>
<tr>
<td>February to July</td>
<td>Simulate an active filter that can replace a dc link capacitor in a traction inverter</td>
<td>March to June</td>
</tr>
<tr>
<td>August to September</td>
<td>Assess the simulation results, loss calculations, and comparisons against baseline technology</td>
<td>July to September</td>
</tr>
</tbody>
</table>
Approach

- An active filter with a much smaller capacitor (1/10th-1/20th of the Camry capacitor) and inductor can be used in the DC link together with semiconductor switches to replace the DC link capacitor.

- Impacts
  - Reduced size and cost
  - May provide more cost-effective solution for high temperature operation
Accomplishments

A Matlab/Simulink simulation model of a traction drive system was used to establish the performance requirements for an active power filter.
Simulated Operation Waveforms

Case 1 - w/ capacitor

Case 2 - w/ APF

DC Link Current

DC Link Voltage
## Comparison – APF vs Capacitor

<table>
<thead>
<tr>
<th></th>
<th>Case 1 (capacitor)</th>
<th>Case 2 (APF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Link Capacitor</td>
<td>2200μF</td>
<td>100μF</td>
</tr>
<tr>
<td>APF Inductor</td>
<td></td>
<td>25mH</td>
</tr>
<tr>
<td>APF Switching</td>
<td></td>
<td>130kHz*</td>
</tr>
<tr>
<td>frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extra Components</td>
<td></td>
<td>4 switches and 4 diodes (could be 4 reverse blocking IGBTs) + inductor</td>
</tr>
<tr>
<td>APF Inductor Current</td>
<td></td>
<td>100A* dc</td>
</tr>
<tr>
<td>Peak-to-peak voltage</td>
<td>2V (0.4% of DC voltage)</td>
<td>2V (0.4% of DC voltage)</td>
</tr>
<tr>
<td>ripple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak-to-peak current</td>
<td>10A (4.5% of the unfiltered ripple current)</td>
<td>10A (4.5% of the unfiltered ripple current)</td>
</tr>
<tr>
<td>ripple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC link voltage</td>
<td>500V</td>
<td>500V</td>
</tr>
<tr>
<td>Output Power</td>
<td>30kW</td>
<td>30kW</td>
</tr>
</tbody>
</table>

*At lower output power lower switching frequency and lower inductor current will be used.*
Parametric Study

- Switching frequency is inversely proportional with the smoothing capacitor size and the DC link voltage ripple hysteresis band limits

- The DC link voltage ripple hysteresis band limits are directly proportional with the amount of DC current ripple
Efficiency is a problem...

- A 100A - 5mH inductor has an internal resistance of $0.01\,\Omega^*$ and a 2.5mH inductor has half of that value.

- Typical losses in the inductor for 100A
  - 5mH inductor, 100W (0.33% for 30kW)
  - 2.5mH, 50W (0.17% for 30kW)

- The inductor current varies with the output power.

- Major losses occur in the devices (IGBTs 1427W – Diodes 460W)

*$www.hammondmfg.com$
Improved APF

• A new control method with
  – Reduced APF switching frequency – the APF can be switched at the inverter switching frequency
  – Reduced inductor current – half of what the original APF control needs
  – Slight increase in the DC-link capacitance

• Impact on APF losses compared to the original method
  – Reduction in switching losses to less than 20%
  – Reduction in conduction losses to less than 25%
## Comparison

<table>
<thead>
<tr>
<th></th>
<th>Active power filter (APF)</th>
<th>Improved APF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principle</strong></td>
<td>Increase the ripple frequency to reduce the smoothing capacitor</td>
<td>Compensate part of the ripple current</td>
</tr>
<tr>
<td><strong>Inductor current</strong></td>
<td>Higher than half the peak ripple (140A)</td>
<td>Higher than half the low-peak ripple (75A)</td>
</tr>
<tr>
<td><strong>Operating frequency</strong></td>
<td>10x inverter frequency</td>
<td>Inverter frequency</td>
</tr>
<tr>
<td><strong>Capacitor size</strong></td>
<td>Small (100μF)</td>
<td>Small (&gt;100μF, &lt;500μF)</td>
</tr>
</tbody>
</table>

![Diagram showing the comparison between Active power filter (APF) and Improved APF](chart.png)
Future Work

- Investigate topologies that will reduce the filter inductance requirements and improve the APF efficiency
- Demonstrate the improvements in the topology
- Demonstrate the successful operation of the APF replacing the DC link capacitor
- Develop a topology that is expected to
  - weigh half as much and
  - occupy less than half the space, when compared to the Camry DC link capacitor.
Summary

- The APF functions as expected but there are some practical barriers that need to be overcome.
  - Device losses can be reduced by
    - Using less switches and diodes or using a different topology
    - Reducing the inductor current
    - Reducing switching frequency
  - Inductance value and associated inductor size
    - Inductance value determines the stiffness of the dc current
      - Low inductance causes low frequency voltage ripple
    - An optimum inductance value is required
- A new APF control method has been developed that can reduce the losses on the APF and the size of the inductor with a slight increase in the capacitance.