Multi-Constraint Optimization and Co-Design of a 2-MHz All-GaN based 1kW 96% Efficient LLC Converter

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Objective

• Minimizing the power losses in a 2MHz LLC resonant converter, a novel multi-variable multi-constraint design optimization algorithm as well as a control system is developed.
• Designing a GaN-based High-density Highly Efficient Power Converter for Data Centers applications.

Key Contributions of the Work

• Comprehensive frequency dependent loss characterization, minimization, and detailed design specific trade-off analysis by developing and solving a multi-variable multi-constraint optimization function
• Intricate quantification of gain gradients corresponding to achievable frequency resolution facilitating MHz level digital implementation
• Accurate parameterization of linearized small signal model using GHA based extended describing function
• Presentation of feasibility and fast transient response of proposed sliding mode control scheme

LLC Resonant Converter Topology

General Harmonic Approximation (GHA) based Modeling

![Equation](image)

Frequency-dependent active loss equation and constraint imposed by ZVS

\[ p_{\text{active}}(s, f_{\text{osc}}, \phi) = p_{\text{con}} + p_{\text{sw}} + p_{\text{core}} + p_{\text{wind}} + p_{\text{C+E}} \]

where, \( p_{\text{con}} = \frac{K_{\text{con}}}{s} \cdot (f - f_{\text{osc}})^2 \cdot \sin(\theta) \cdot \sin(\phi) \)
\( K_{\text{con}} = \frac{2\pi}{f_{\text{osc}}} \cdot \frac{2\pi}{f_{\text{osc}}} \cdot \sin(\theta) \cdot \sin(\phi) \)

GHA-based small signal modeling

\[ \dot{x} = f(x, u) \]

Sliding Mode Control Scheme

Sliding surface definition

\[ S = A_{\text{x}} \dot{x} + k_{\text{s}}(t) \]

Setting time constraint

\[ A_{\text{x}} \cdot \text{Int}(t) = k_{\text{s}}(t) \]

Overshoot/Undershoot constraint

\[ A_{\text{x}} \cdot \text{Err}(t) = k_{\text{s}}(t) \]

Controller response results

Experimental Verification and Benchmarking

Design Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power (P)</td>
<td>1kW</td>
</tr>
<tr>
<td>Primary input voltage (V_p)</td>
<td>380V</td>
</tr>
<tr>
<td>Secondary output voltage range (V_o)</td>
<td>12V</td>
</tr>
<tr>
<td>Transformer Turns Ratio (n)</td>
<td>2:1</td>
</tr>
<tr>
<td>Resonant Inductance (L)</td>
<td>11.27H</td>
</tr>
<tr>
<td>Magnetizing Inductance (L_m)</td>
<td>95.99H</td>
</tr>
<tr>
<td>Resonant Capacitance (C)</td>
<td>0.5647F</td>
</tr>
<tr>
<td>Resonant frequency (f)</td>
<td>2MHz</td>
</tr>
</tbody>
</table>

Experimental Waveforms

(90% to 10% and 10% to 90% load change)

Controller Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Efficiency (η)</td>
<td>99.99%</td>
</tr>
<tr>
<td>Power Density (W/cm³)</td>
<td>&gt;32W/cm³</td>
</tr>
</tbody>
</table>

Acknowledgement

This research has been supported by ASU, MORE program and Arizona New Economic Initiative, which are gratefully acknowledged. The research project was co-sponsored by W. L. Gore & Associates. Special thanks to Prof. Ayan Mallik (Mentor) for his expert guidance and support.