Design and Optimization of a High-Performance LLC Converter
Design and Optimization of a High-Performance LLC Converter

Brent McDonald and Dave Freeman
Introduction

- Demanding efficiency requirements are driving engineers to the LLC resonant converter.

<table>
<thead>
<tr>
<th>80 PLUS Certification</th>
<th>115-V Internal Nonredundant</th>
<th>230-V Internal Redundant</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Rated Load</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>80 PLUS</td>
<td>–</td>
<td>80%</td>
</tr>
<tr>
<td>80 PLUS Bronze</td>
<td>–</td>
<td>82%</td>
</tr>
<tr>
<td>80 PLUS Silver</td>
<td>–</td>
<td>85%</td>
</tr>
<tr>
<td>80 PLUS Gold</td>
<td>–</td>
<td>87%</td>
</tr>
<tr>
<td>80 PLUS Platinum</td>
<td>–</td>
<td>90%</td>
</tr>
<tr>
<td>80 PLUS Titanium</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

- Significant challenges:
  - Fundamental operation can be confusing
  - Transformer behavior is complex
  - MOSFET control can be difficult:
    - Monotonic startup
    - Synchronous rectification
    - Overcurrent operation
    - Light load power savings

Discussion Outline

- Overview of the LLC converter
- Transformer
- MOSFET control methods
- Summary and conclusion
Primary MOSFET ZVS

1. VIN
2. VIN
3. VIN
4. VIN

Low-Side MOSFET V_DS

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Operation at Resonance

\[ f_s = \frac{1}{2\pi\sqrt{(L_R + L_K)C_R}} \]

\[ V_{IN} = 387.6 \text{ V} \]

LLC Resonant Tank Waveforms
Operation Below Resonance

\[ f_s < \frac{1}{2\pi\sqrt{(L_R + L_K)C_R}} \]

\[ V_{IN} = 370 \text{ V} \]

LLC Resonant Tank Waveforms

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**Operation Above Resonance**

\[ f_s > \frac{1}{2\pi \sqrt{(L_R + L_K)C_R}} \]

\[ V_{IN} = 410 \text{ V} \]

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Sinusoidal Approximation

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Equivalent Circuit – Power Balance

\[ R_E = \frac{8 R_0}{\pi^2} \]

\[ Q_E = \frac{1 N_S^2}{R_E N_P^2} \sqrt{\frac{L_R + L_K}{C_R}} \]
DC Operating Point

Sinusoidal Analysis

Frequency (Hz)

$V_{OUT}$

$I_{OUT} = 1$
$I_{OUT} = 5$
$I_{OUT} = 10$
$I_{OUT} = 25$

$2\pi \sqrt{(L_R + L_K + L_M) C_R}$

$2\pi \sqrt{(L_R + L_K) C_R}$

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Sinusoidal Approximation Summary

• Benefits:
  – Convenient closed form
  – Intuitive results
  – Good starting point for design or simulation

• Limitations:
  – Only valid near the resonant frequency
  – Only good for the DC operating point

• Time-domain simulation is required for improved accuracy:
  – PSpice
  – Simplis
  – MATLAB
  – Saber
Ideal Transformer + VL1 - VL2 - i2

\[ n = \sqrt{\frac{L_2}{L_1}} \]

\[ k = \frac{M}{\sqrt{L_2L_1}} \]

\[ L_K = (1 - k^2)L_1 \]

\[ L_M = k^2L_1 \]

\[ \nu_{L1} = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \]

\[ \nu_{L2} = M \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \]
Multiwinding Coupled Inductor Models

Cantilever Model

Cantilever Model with DCR
Resistance Characterization

- Use a conventional DMM to measure four resistances
- If the resistances are very small, a high-precision μΩ meter may be required
- AC loss terms are negligible for time-domain and frequency-response behavior

Resistance Characterization

\[
\begin{align*}
RT_1 &= \frac{1}{2} (RM_1 - RM_2 + RM_3) \\
RT_2 &= \frac{1}{2} (RM_1 + RM_2 - RM_3) \\
RT_3 &= \frac{1}{2} (-RM_1 + RM_2 + RM_3)
\end{align*}
\]
Direct Measurement Method

• Comments:
  – Simple calculation of model parameters
  – Works well if the short and current measurement impedance are similar to the PCB leakage impedance
  – Does not lend itself to the use of conventional impedance measurement tools
  – Difficult to measure $i_{ac}$ without adding a significant impedance

• Leakage measurements:

\[- l_{12} = \frac{v_{ac}(s) n_1}{i_{ac}(s) n_2 s}\]

\[- l_{13} = \frac{v_{ac}(s) n_1}{i_{ac}(s) n_3 s}\]

\[- l_{23} = \frac{v_{ac}(s) n_1^2}{i_{ac}(s) n_2 n_3 s}\]
Indirect Measurement Method

• Comments:
  – Complex calculations required to derive model parameters
  – Works well if the short and current measurement impedance are similar to the PCB leakage impedance
  – Very easy to implement with conventional impedance measurement tools
  – No additional measurement impedance added

• Leakage measurements:
  – $i_{12} = ...$
  – $i_{13} = ...$
  – $i_{23} = ...$

Details available in the paper
Complete Measurement Setup

Indirect Method

Direct Method

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Indirect Method Numerical Example

<table>
<thead>
<tr>
<th>LLC Extended Cantilever Model Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L_{11}</td>
<td>570 \mu H</td>
</tr>
<tr>
<td>n_1</td>
<td>32</td>
</tr>
<tr>
<td>n_2</td>
<td>2</td>
</tr>
<tr>
<td>n_3</td>
<td>2</td>
</tr>
<tr>
<td>RP_1</td>
<td>122.5 m\Omega</td>
</tr>
<tr>
<td>RT_1</td>
<td>2.6 m\Omega</td>
</tr>
<tr>
<td>RT_2</td>
<td>-415 \mu \Omega</td>
</tr>
<tr>
<td>RT_3</td>
<td>2.5 m\Omega</td>
</tr>
<tr>
<td>l_{12}</td>
<td>19.7 \mu H</td>
</tr>
<tr>
<td>l_{13}</td>
<td>16.8 \mu H</td>
</tr>
<tr>
<td>l_{23}</td>
<td>25.9 \mu H</td>
</tr>
</tbody>
</table>
Model Results vs. Measurement

Instrument impedance and transformer winding capacitance

Bode Plot

Impedance (Ω)

10^4

1000

100

10

1

0.1

1 10 100 1,000 10^4 10^5 10^6

Frequency (Hz)

Line: Model
Dot: Measurement

LP
LK1
LK2
LK3

Bode Plot

Gaine (dB)

-25

-30

-35

-40

-45

-50

-55

1 10 100 1,000 10^4 10^5 10^6

Frequency (Hz)

Line: Model
Dot: Measurement

VT2
VP1
VT3
VP1

Bode Plot

Phase (°)

180

135

90

45

0

-45

-90

-135

-180

1 10 100 1,000 10^4 10^5 10^6

Frequency (Hz)

Phase (°)

180

135

90

45

0

-45

-90

-135

-180

1 10 100 1,000 10^4 10^5 10^6

Frequency (Hz)
What Does This Mean to the LLC?

• Some primary to secondary leakage inductance is good
  – Inductance is required in order to regulate the output voltage
  – If the leakage is large enough it can even eliminate the external inductor

• Leakage between the tertiary windings can be problematic
  – Reduce the efficiency advantage of the topology
    • Driving the need for higher-voltage synchronous rectifiers
    • Increased RMS currents in the secondary windings and rectifiers
  – Lack of symmetry in the resonant states
    • Creating additional resonant frequencies
    • Generating larger output ripple voltage
    • Altering the steady-state and small-signal operating characteristics
Large Signal Simulation

Base Line

Amplitude (A)

Time (µs)

Base Line + 75 nH of Secondary Lk

Amplitude (A)

Time (µs)

ILM

ILR

\( \Delta I_{LR} = 68.305 \text{ mA} \quad 3.23178 \text{ A} \)

\( \Delta I_{LR} = 291.576 \text{ mA} \quad 3.33111 \text{ A} \)

\( \Delta V_{OUT} = 80.1128 \text{ mV} \quad 12.0552 \text{ V} \)

\( \Delta V_{OUT} = 88.5377 \text{ mV} \quad 12.0552 \text{ V} \)

10% Increase
Leakage Considerations

- $l_{23} = 0 \text{ H} – \text{best case:}$
  - No additional synchronous rectifier stress
  - Everything is symmetrical

- $(\infty \text{ H} > l_{23} > 0 \text{ H}) \land (l_{12} = l_{13})$
  - Synchronous rectifier voltage stresses can still be significant
  - Everything is symmetrical

- $l_{23} \rightarrow \infty \text{ H} – \text{worst case:}$
  - Maximum stress on the synchronous rectifiers
  - Ripple

  - $l_{12} = l_{13}, \text{ symmetrical}$
  - $l_{12} > l_{13}, \text{ asymmetrical}$
  - $l_{12} < l_{13}, \text{ asymmetrical}$
Piecewise Linear Transformer Model

- Equivalent values
  - \( l_{12e} = l_{12} \parallel (l_{13} + l_{23}) \)
  - \( l_{13e} = (l_{12} + l_{23}) \parallel l_{13} \)
  - \( R_{T1e} = R_{T1} + R_{T2} \)
  - \( R_{T2e} = R_{T2} + R_{T3} \)

- Each half cycle of the period has a different resonant frequency:
  - \( f_{r1} \approx \frac{1}{2 \pi \sqrt{(L_R + l_{12e})C_R}} \)
  - \( f_{r2} \approx \frac{1}{2 \pi \sqrt{(L_R + l_{13e})C_R}} \)
Transformer Winding Analysis

\[ F = \oint \vec{H} \cdot dl = I_{\text{Total}} \]
Transformer Winding Strategy

Minimize $L_{\text{LEAKAGE}}$ and $P_{\text{PROXIMITY}}$

Best  Worst

T1 Conducts

T2 Conducts

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Transformer Model Summary

• Accurate transformer model:
  – Is functional over a wide frequency range
  – Captures unique leakage inductances between all windings
  – Includes winding resistance impacts

• Practical characterization procedure:
  – Accurate results
  – Easy to perform

• Easy to use:
  – Works with almost any circuit simulator
  – Extendable to fast piecewise linear simulation methods
Transformer Model Summary

• Classic LLC converter requires high $f_s$
  – Low $I_{OUT}$
  – High $V_{IN}$
  – Low $V_{OUT}$
  – Constant power
  – Constant current
  – Short circuit

• Synchronous rectification

• Light load losses
• Both on time and period are varied.
• Duty cycle is always ~50%.
• Dead times are preserved at all operating points.
• Transition between modulation methods is seamless.
• Parameters should be configurable.
Problem No. 1: High $f_S$

- Steady state regulation:
  - Several operating points require high $f_S$
- Monotonic startup:
  - The beginning of the startup ramp always requires high $f_S$
- Constant current, constant power operation:
  - Reduced output voltage
  - Short circuit
- Solution:
  - Frequency modulation
  - Pulse-width modulation
  - Seamless mode switching

![Sinusoidal Analysis Diagram](image_url)
Pulse-Width Modulation

- Only on time is varied.
- Duty cycle is always less than 50%.
- Dead times are preserved at all operating points.
- Transition between modulation methods is seamless.
- Parameters should be configurable.
$V_{\text{OUT}}$ Performance

Channel 1: Output Voltage  
Channel 3: Resonant Tank Current
Constant Current, Constant Power

Output Voltage (V) vs. Load Current (A)

Graph showing the relationship between output voltage and load current for a constant current, constant power scenario.
Problem No. 2 – Zero Crossing

- Synchronous rectification
- Solution:
  - Frequency modulation
  - Pulse-width modulation
  - Synchronous rectifier clamp mode
  - Seamless mode switching
Synchronous Rectifier Clamp Mode

- Primary FETs operate the same as before.
- Sync FET’s period matches primary FET’s period.
- Sync FET’s pulse width is clamped to TSR.
Synchronous Rectification

Minimum body diode conduction time is preserved.
Synchronous Rectification

- Light load power dissipation
  - Clamping the frequency helps, but not enough
- Solution:
  - Burst mode
  - Seamless mode switching
Burst-Mode Algorithm

Load Current Threshold Adjustment

Burst Mode

Turn On Threshold
Compensator Control Effort
Turn Off Threshold

TON  TOFF

DPWM0A
High-Side Primary MOSFET

DPWM0B
Low-Side Primary MOSFET

DPWM1A
Synchronous Rectifier MOSFET No. 1

DPWM1B
Synchronous Rectifier MOSFET No. 2

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UCD3138 Evaluation Module

[Image of a circuit board]

[Graph showing efficiency (%) vs. load current (A)]

Efficiency (%) vs. Load Current (A)
Summary and Conclusions

- LLC converter overview:
  - ZVS and ZCS
  - DC operating point
  - Critical system waveforms

- Transformer model:
  - Accurate
  - Practical characterization procedure
  - Easy to use

- Advanced MOSFET control methods enable a wide variety of power-supply functions:
  - Monotonic startup
  - Synchronous rectification
  - Reduced light load dissipation
  - Constant power
  - Constant current
  - Short-circuit operation
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