Design of 200W LLC Resonant HB

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Technical Challenges of Front-End AC/DC Converter
Efficiency and Power Density

- Server/telecom front end (single output for DPA): 94-96%
- Notebook adapters: 92-95%
- Desktop PS (multiple output): 80-86%
- Yearly improvements:
  - 2000: 80-85%
  - 2006: 84-87%
  - 2010: 88-91%

Power density vs. years chart.
Hold-Up Time

\[ \frac{1}{2} C_h (V_{in}^2 - V_{in_{\text{min}}}^2) = P_{dc}T_h \]
Limitation of PWM Converter

Test condition: Vo=48V, Po=1000W
Operation of LLC Resonant HB
Operation Principles (f\text{sw}=f\text{r})

At resonant frequency, maximum efficiency is expected
When switching frequency is below resonant frequency, magnetizing inductor begins to participate in resonant and increase voltage gain.

Secondary diode becomes discontinuous.
When switching frequency is above resonant frequency, circuit behaves as SRC
- Secondary current becomes CCM, reverse recovery loss increases
FHA of LLC Resonant HB

\[ V_{s1} = \frac{2}{\pi} V_{in} \Rightarrow V_{in} = \frac{\pi}{2} V_{s1} \]

\[ V_p = nV_{r1} = n \frac{4}{\pi} V_o \Rightarrow V_o = \frac{\pi}{4n} V_p \]

\[ |G| = \frac{nV_o}{V_{in}} = \frac{n}{4} \frac{\pi}{V_{s1}} = \frac{V_p}{V_{s1}} \]

\[ = \frac{sLp \parallel Rac}{1/sCr + sLr + (sLp \parallel Rac)} \]
Voltage Gain Equation

\[
M(f_n, L_n, Q) = \frac{nV_o}{V_{in}} = \frac{n}{4n} \frac{\pi \cdot V_{o}}{V_{i}} = \frac{V_{o}}{V_{i}}
\]

\[
= \left(\frac{j \omega L_m }{j \omega Cr} + j \omega L_r + \frac{(j \omega L_m )}{j \omega Cr} \right) \left(\frac{j \omega L_m }{j \omega L_m } + Rac\right)
\]

\[
= \frac{j \omega L_r \frac{L_m }{Cr} - \omega^2 L_m L_r + Rac \left(1 - \omega^2 \frac{L_r L_m }{j \omega Cr}\right) + j \omega L_m Rac}{j \omega Cr}
\]

\[
= \frac{\omega^2 \frac{L_m }{Cr} \frac{L_m Rac}{j \omega Cr} \frac{L_m }{L_r} \frac{L_m }{Cr} - 1]Rac + j \omega \cdot L_m \cdot (\omega^2 \frac{L_r L_m }{j \omega Cr} - 1)}{[\omega^2 (L_m + L_r)Cr - 1]Rac + j \omega \cdot L_m \cdot (\omega^2 \frac{L_r L_m }{j \omega Cr} - 1)}
\]

\[
= \frac{(\omega^2 \frac{L_m }{L_r}) \frac{(L_m + L_r)}{L_r} - 1 + j \omega \frac{L_m }{L_m} \left((\omega^2 \frac{L_m }{j \omega Cr}) - 1\right)}{(\omega^2 \frac{L_m }{L_r}) \frac{(L_m + L_r)}{L_r} - 1 + j \omega \frac{L_m }{L_m} \left((\omega^2 \frac{L_m }{j \omega Cr}) - 1\right)}
\]

\[
= \frac{1}{\sqrt{1 + \frac{1}{L_n} \cdot \left(1 - \frac{1}{f_n^2}\right)} + Q^2 \cdot (f_n - \frac{1}{f_n})^2}
\]
Voltage Gain of Different $L_n$

$L_n = 1$

$L_n = 10$

$L_n = 5$

$L_n = 15$

$\frac{M=V_{out}}{V_{in}}$ vs $f_n$

- $L_n \uparrow \rightarrow$ Traditional SRC $\rightarrow$ Enter into ZCS @$ f_{sw} < f_r$ $\rightarrow$ lost gain monotony and MOSFET ZVS operation
- $L_n \downarrow \rightarrow$ if low inductance $\rightarrow$ $I_m \uparrow \rightarrow$ conducted and switched-off losses $\uparrow$
- $\rightarrow$ if high inductance, fixed resonant frequency $\rightarrow$ $C_r \downarrow \rightarrow V_{cr} \uparrow$
Start Up Current Consideration

\[
I_p^* = \begin{cases} 
\frac{\pi^2}{4 \cdot Q} & 1 < \Omega_s \leq 2 \\
\frac{\pi^2}{4 \cdot Q} \cdot \sin\left(\frac{\pi}{\Omega_s}\right) & \Omega_s > 2 
\end{cases}
\]

\[
\Omega_s = \frac{f_{s\text{-startup}}}{f_0}
\]

Fig.9 Normalized start-up first peak current

➢ Larger Q value gives smaller start up current with less frequency range

“A Novel Precise Design Method for LLC Series Resonant Converter”, Teng Liu, etc., INTELEC ’06
Advantages of LLC Resonant HB

- Primary ZVS can be achieved with wide load range
- Secondary ZCS can be achieved when \( f_s < f_r \)
- Smaller switch-off loss due to small turn off current
- Capacitor filter w/o output inductor
- Less voltage stress on rectifiers
- >1 voltage gain during hold-up time
Step by Step Design of 200W LLC
Design Targets

- Minimize RMS current under normal operation condition
- Ensure ZVS operation
- Ensure desired input voltage operation range
fsw=fr @ normal operation

\[
i_{Lr}(t) = \sqrt{2} I_{RMS \_P} \sin(\omega_o t + \Phi)
\]

\[
i_{Lm}(t) = \begin{cases} 
  i_{Lm\_m} + \frac{nV_o}{Lm} \cdot t, & t < \frac{T_S}{2} \\
  i_{Lm\_m} - \frac{nV_o}{Lm} (t - \frac{T_S}{2}), & t > \frac{T_S}{2}
\end{cases}
\]

\[
i_{Lr}(t_0) = \sqrt{2} I_{RMS \_P} \sin(\Phi) = -\frac{nV_o}{4} \cdot \frac{T_S}{Lm}
\]

\[
i_{Lm} = \frac{nV_o}{8} \cdot \frac{T_S}{Lm}
\]

\[
V_o \cdot nR_L = \int_{0}^{T_S/2} [i_{Lr}(t) - i_{Lm}(t)] \, dt = \int_{0}^{T_S/2} [\sqrt{2} I_{RMS \_P} \sin(\omega_o t + \Phi) + \frac{nV_o}{Lm} \cdot \frac{T_S}{4} - \frac{nV_o}{Lm} \cdot t] \, dt
\]

\[
I_{RMS \_S} = \sqrt{\frac{1}{2} \int_{0}^{T_S/2} [n \cdot i_{Lr}(t) - n \cdot i_{Lm}(t)]^2 \, dt}
\]

\[
I_{RMS \_S} = \frac{1}{4 \sqrt{2}} \frac{V_o}{nR_L} \sqrt{\frac{n^4 R_L^2 T_S^2}{L_m}} + 4\pi^2
\]

\[
I_{RMS \_S} = \frac{\sqrt{3}}{24\pi} \frac{V_o}{R_L} \sqrt{\frac{(5\pi^2 - 48)n^4 R_L^2 T_S^2}{L_m}} + 12\pi^4
\]
fsw<fr @ hold-up time
## Electrical Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Vin</td>
<td>440V</td>
</tr>
<tr>
<td>Minimum Vin</td>
<td>360V</td>
</tr>
<tr>
<td>Maximum Vin</td>
<td>54V</td>
</tr>
<tr>
<td>Output Power</td>
<td>200W</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>100kHz</td>
</tr>
</tbody>
</table>
1. Winding Turn Ratio of TX

\[ f_{sw} = f_r \text{ at nominal condition, } M=1, \text{ So} \]

\[ n = \frac{V_{PFC}}{2} \cdot \frac{1}{V_{out} + V_F} \]

n=4
2. Magnetizing Inductance

The magnetizing inductance impacts conducted and switched losses. So

\[
I_{\text{RMS}_P} = \frac{1}{4\sqrt{2}} \frac{V_o}{n_R L} \sqrt{\frac{n^4 R_L^2 T_s^2}{L_m^2} + 4\pi^2}
\]

\[
I_{\text{RMS}_S} = \frac{\sqrt{3}}{24\pi R_L} \frac{V_o}{n_R L} \sqrt{\frac{(5\pi^2 - 48)n^4 R_L^2 T_s^2}{L_m^2} + 12\pi^4}
\]

On the other hand, the maximum magnetizing current also impacts ZVS operation.

\[
\begin{aligned}
I_{L_{\text{mp}}} &> \frac{2V_{\text{PFC}}C_j}{td} \\
I_{L_{\text{mp}}} &\leq \frac{nV_o T_s}{L_m 4} \Rightarrow Lm < \frac{T_s \cdot td}{16C_j} \\
V_{\text{PFC}} &= 2nV_o \\
Lm &= \frac{T_s \cdot td}{16 f_{sw} C_j} = \frac{td}{16 f_{sw} C_j}
\end{aligned}
\]

\[
\begin{aligned}
\text{td} &= 175\text{ns} \\
C_j &= 195\text{pF}, \text{ SPP20N60C3} \\
Lm &= 530
\end{aligned}
\]
3. Maximum Peak Gain

\[ G_{\text{max}} = \frac{V_{PFC}}{V_{\text{min}}} \]

\( G_{\text{max}} = 1.222 \)
4. Decision $L_n$ and $Q$

\[
\begin{align*}
Q &= \sqrt{\frac{L_r}{Cr}} \\
\Rightarrow L_nQ &= \frac{2\pi f_0 L_m}{8n^2 \cdot R_L} \\
L_n &= \frac{L_m}{L_r}
\end{align*}
\]

From the intersection of curves of $L_nQ$ and required maximum peak gain to get the appropriate $L_n$ and $Q$.

$L_n = 6$

$Q = 0.3$
5. Calculation of Lr and Cr

\[ L_r = \frac{L_m}{L_n} \]

\[ C_r = \frac{1}{(2\pi f_o)^2 L_r} \]

Lr=68uH, additional 20uH leakage inductor in main transformer

Cr=15nF*2, two capacitor structure to reduce input ripple current
Flow Chart of Optimal Design

Converter Specification

Primary switching Device

Magnetizing inductor

Check gain monotony, min and max fsw, Vcr etc.

Resonant capacitor

Resonant inductor

Choose cross section of required gain and constant Lm

$n = \frac{V_{in}}{2V_o}$

$L_m = \frac{T \cdot t_{dead}}{16C_j}$

$L_{nQ} = \frac{2\pi f_0 L_m}{8n^2 R_L}$

$f_0 = \frac{1}{2\pi \sqrt{L_r C_r}}$

$L_r = \frac{L_m}{L_n}$

Peak gain enough? Yes

Reduce Lm
Test of 200W LLC Resonant HB
Benefits:
• Interleaved PFC with UCC28061
• LLC Resonant HB with UCC25600
• 93% Efficiency w/o Secondary SR
Eff=96.61%
Possible Technical Issues
Asymmetrical duty cycle makes resonant tank current unbalanced
Load current will be concentrated in one diode and increase conduction loss and switching loss
- Controller should provide well matched PWM signal
- Different secondary leakage inductance
LLC Issue-Over Current

- Add Clamping Diode

- Part of resonant tank energy could be feedback to source, which helps limit output current

Over Load Operation
LLC Issue-MOSFET Failure @ Light Load

To achieve ZVS operation, the body diode of primary MOSFETs conducts first, and then the channel circulates the current. At light load, the reverse voltage between body diode is much small once the channel circulates the small current, such that the reverse recovery time in body diode is much long, resulting in primary MOSFETs shoot-through.
References

  http://scholar.lib.vt.edu/theses/available/etd-06262006-111218/
  http://scholar.lib.vt.edu/theses/available/etd-09152003-180228/
Back-up
TI UCC25600
8 Pin Resonant Half Bridge Controller

Features
- Adjustable Soft start (1ms to 500ms)
- Adjustable dead time
- Adjustable $F_{\text{swmax}}$ & $F_{\text{swmin}}$ (3% accuracy)
- $I_o = +1A / -1.5A$
- Enable (ON/OFF control)

Protection functions
- Two levels over current protection
  - auto recovery
  - latch
- Bias voltage UV and OV protection
- Over temperature protection
- Soft start after all fault conditions

SOT 8 pin package= Easy design and layout
Programmable dead time
Frequency control with minimum/maximum frequency limiting
Programmable soft start with on/off control
Two level over current protection, auto-recovery and latch up
Matching output with 50ns tolerance
Q & A

Thanks!