Design of 200W LLC Resonant HB

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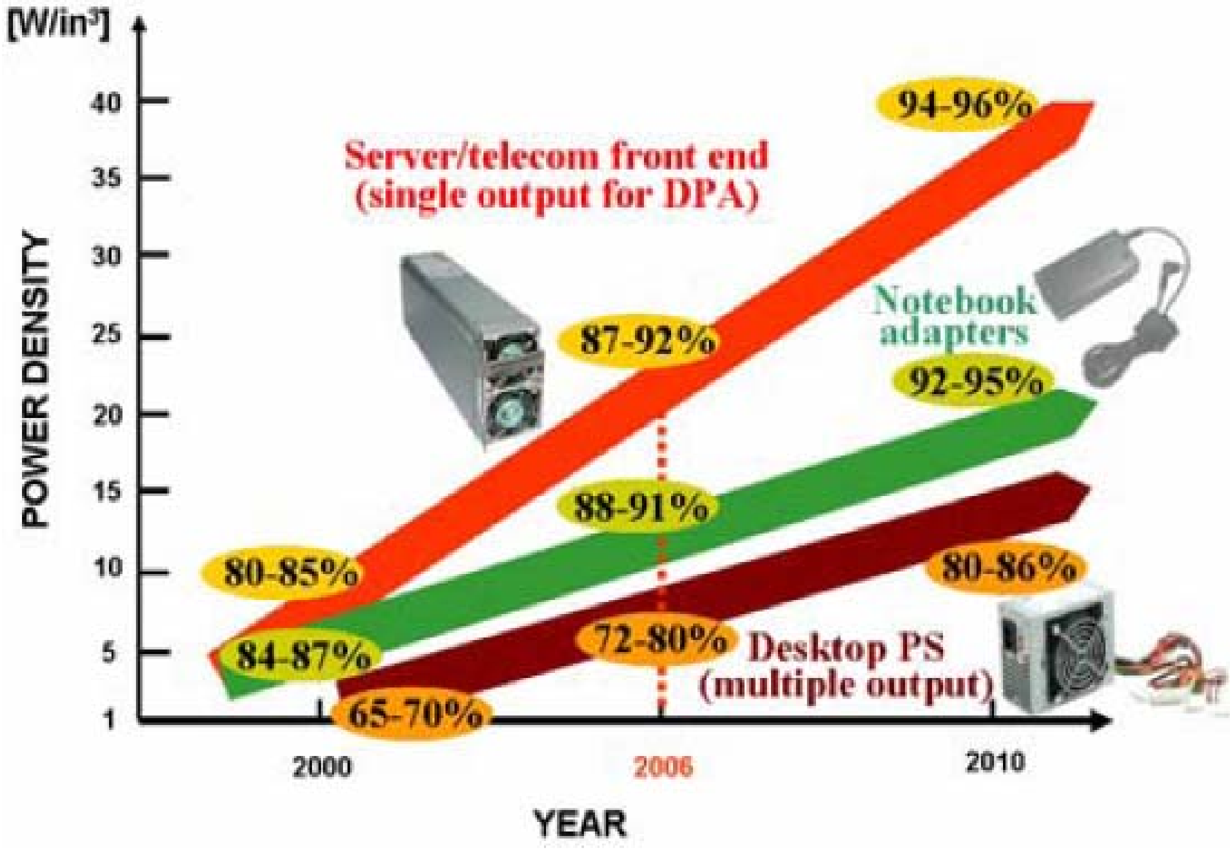
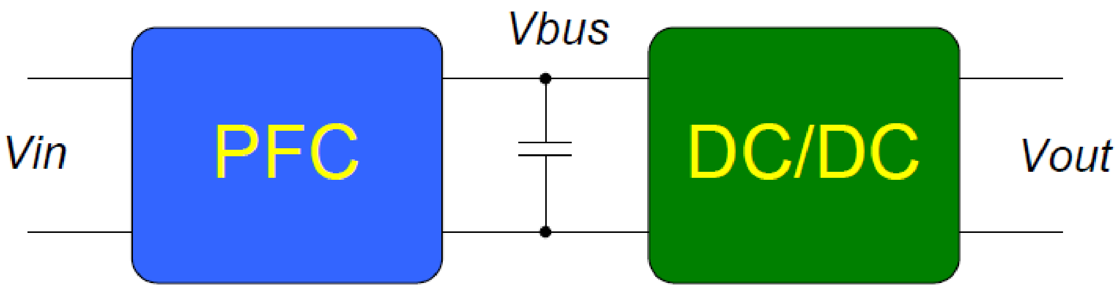
Dec 2009

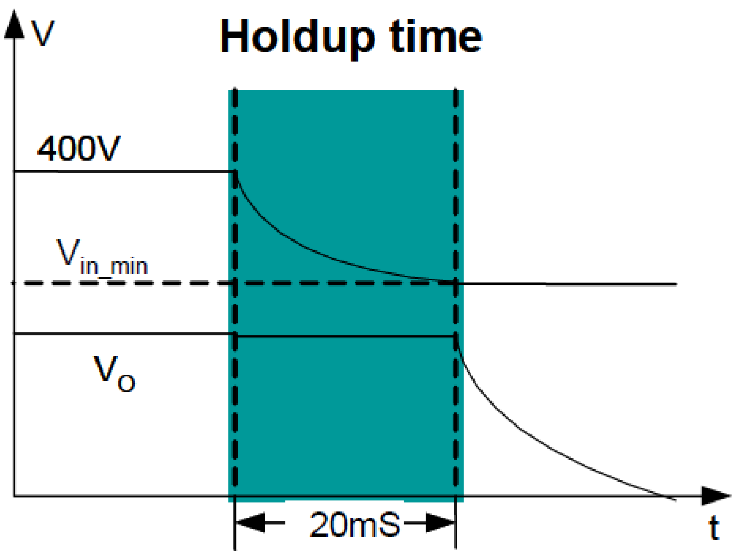
Technical Challenges of Front-End AC/DC Converter

Efficiency and Power Density



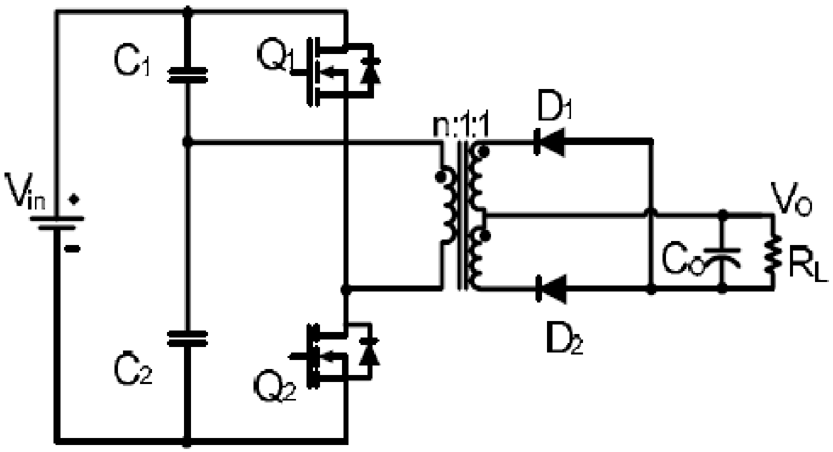
Hold-Up Time

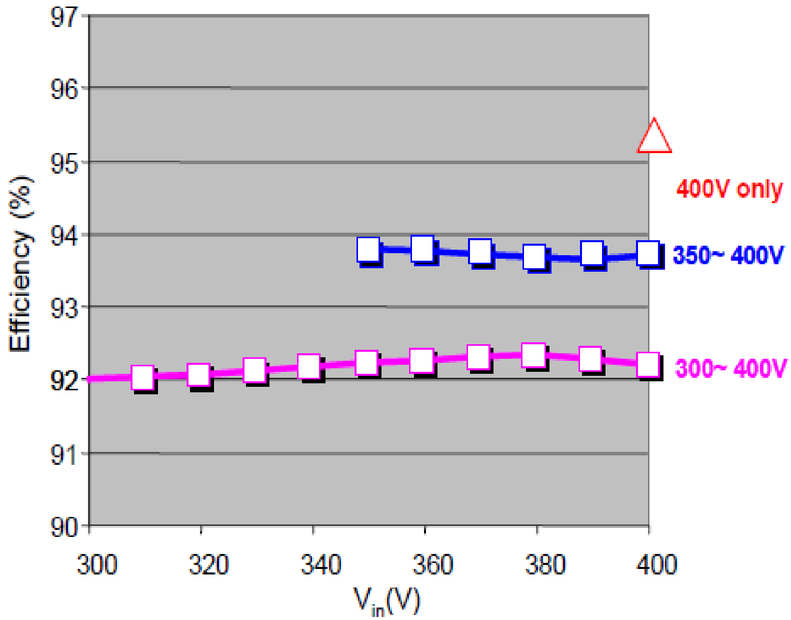




$$\frac{1}{2}C_h(V_{in}^{\ 2} - V_{in\_min}^{\ 2}) = P_{DC}T_h$$

Limitation of PWM Converter

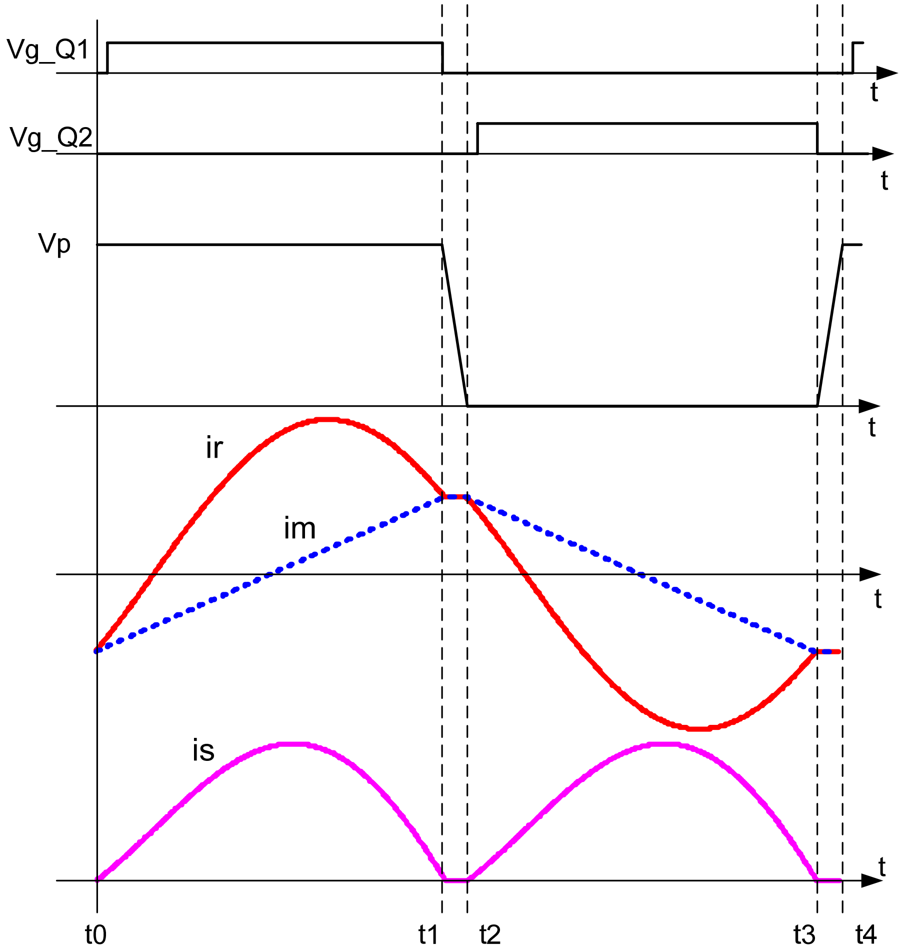


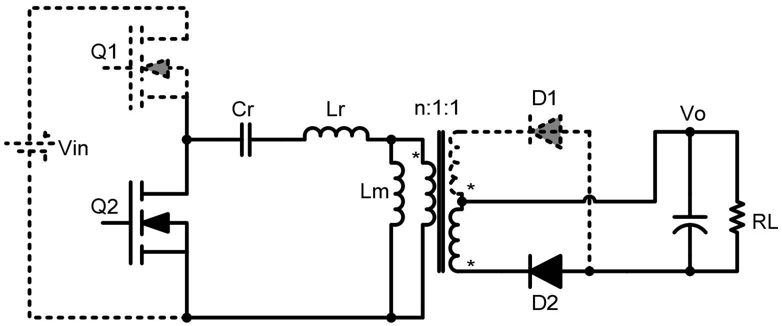


Test condition: Vo=48V Po=1000W

Operation of LLC Resonant HB

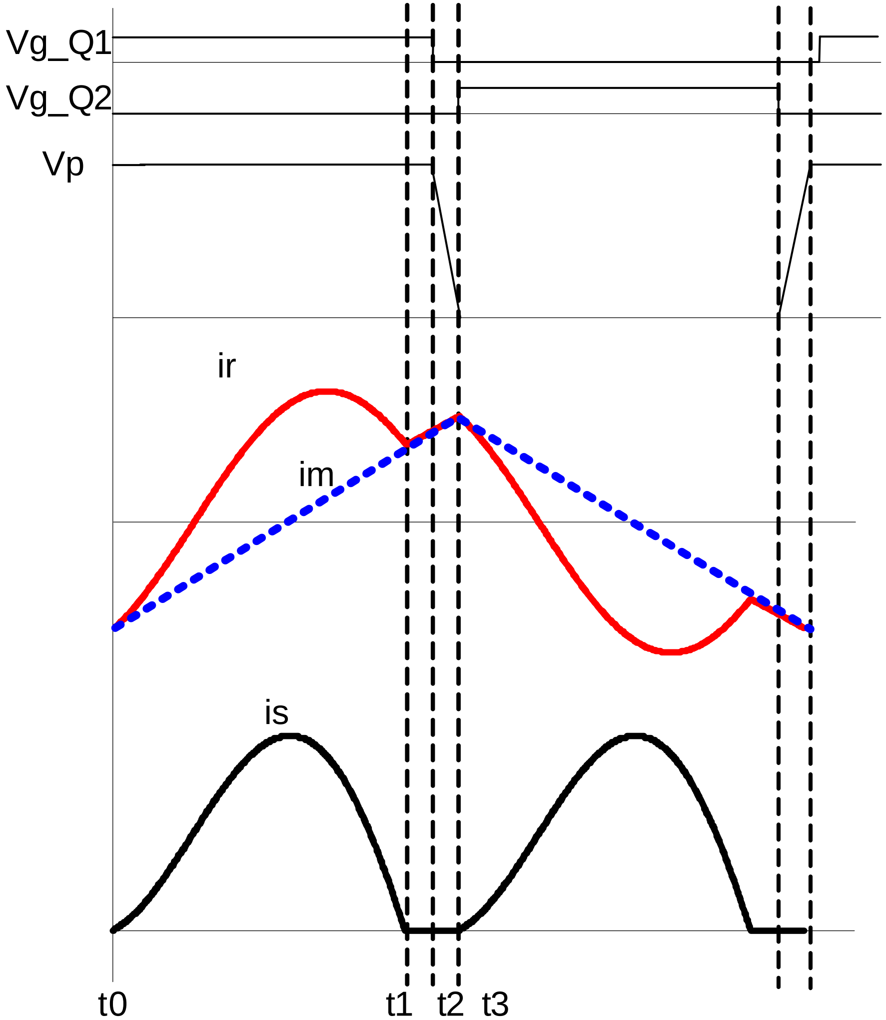
Operation Principles (fsw=fr)

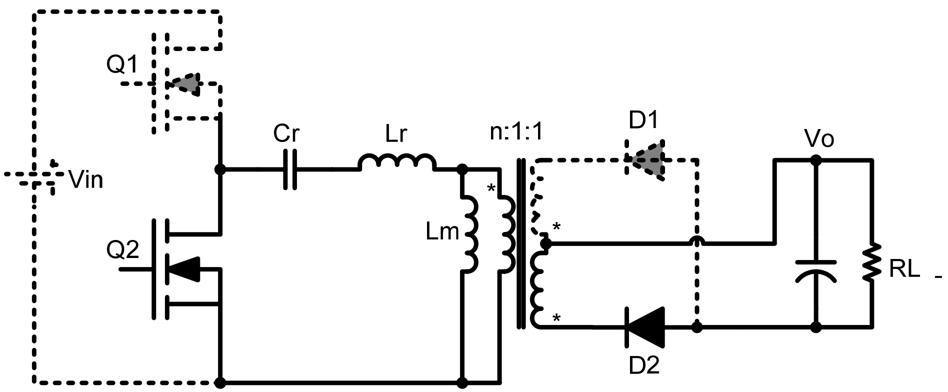




- At resonant frequency, maximum efficiency is expected

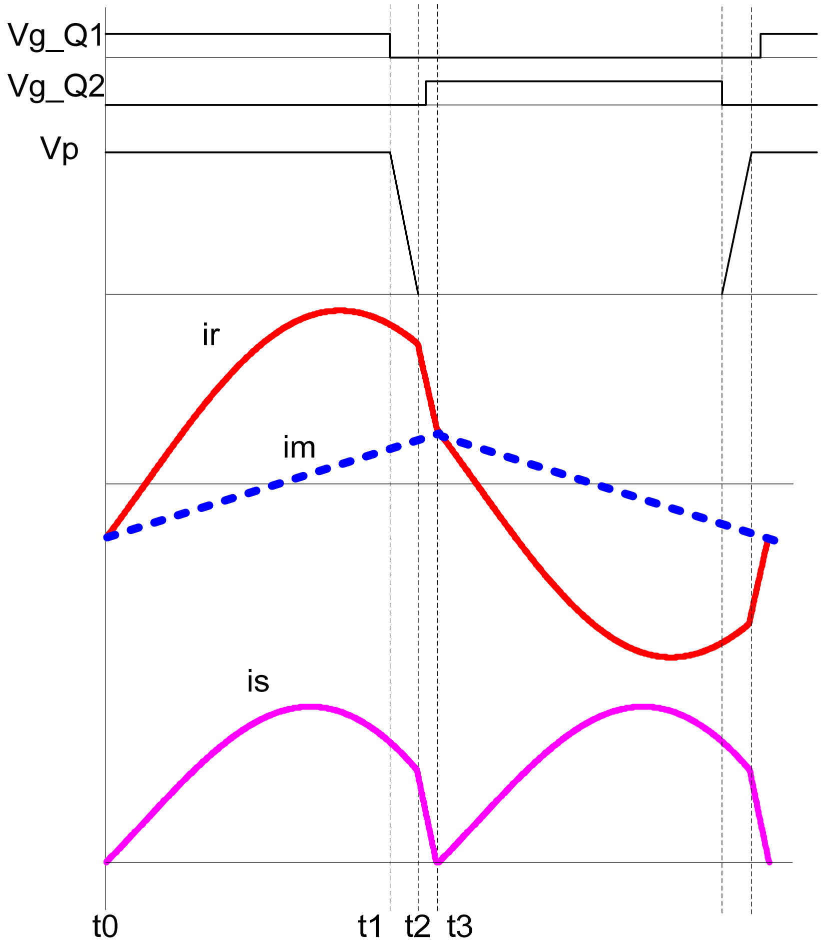
Operation Principles (fsw<fr)

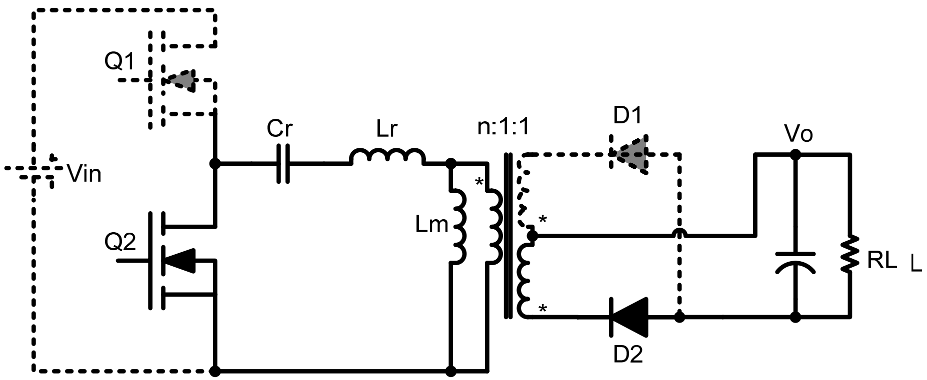




- ➢When switching frequency is below resonant frequency, magnetizing inductor begins to participate in resonant and increase voltage gain
- ➢Secondary diode becomes discontinuous

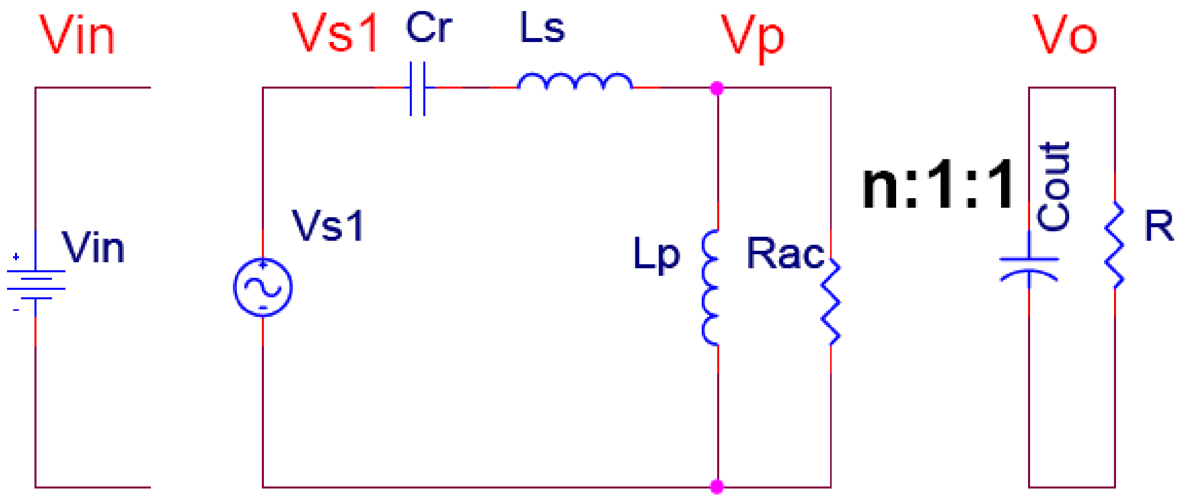
Operation Principles (fsw>fr)





- ➢When switching frequency is above resonant frequency, circuit behaves as SRC
- ➢Secondary current becomes CCM, reverse recovery loss increases

FHA of LLC Resonant HB



$$Vs1 = \frac{2}{\pi} Vin \Rightarrow Vin = \frac{\pi}{2} Vs1$$

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

$$|G| = \frac{nVo}{\frac{Vin}{2}} = \frac{n\frac{\pi}{4n}V_P}{\frac{\pi}{4}V_{S1}} = \frac{V_P}{V_{S1}}$$

$$= \frac{sLp\,//\,Rac}{1/sCr + sLr + (sLp\,//\,Rac)}$$

Voltage Gain Equation

$$M(f_n, L_n, Q) = \frac{nVo}{\frac{Vin}{2}} = \frac{n\frac{\pi}{4n}V_{Ro}^{F}}{\frac{\pi}{4}V_{d}^{F}} = \frac{V_{Ro}^{F}}{V_{d}^{F}}$$

$$= \left| \frac{(j\omega Lm) // Rac}{\frac{1}{j\omega Cr} + j\omega Lr + (j\omega Lm) // Rac} \right|$$

$$= \left| \frac{\frac{(j\omega Lm)Rac}{(j\omega Lm) + Rac}}{\frac{1}{j\omega Cr} + j\omega Lr + \frac{(j\omega Lm)Rac}{(j\omega Lm) + Rac}} \right|$$

$$= \left| \frac{j\omega LmRac}{\frac{Lm}{Cr} - \omega^2 LmLr + Rac(\frac{1-\omega^2 LrCr}{j\omega Cr}) + j\omega LmRac} \right|$$

$$= \left| \frac{\omega^2 LmCrRac}{[\omega^2(Lm + Lr)Cr - 1]Rac + j\omega \cdot Lm \cdot (\omega^2 LrCr - 1)} \right|$$

$$= \left| \frac{(\frac{\omega}{\omega_r})^2 \cdot \frac{Lm}{Lr}}{(\frac{\omega}{\omega_r})^2 \cdot \frac{Lm + Lr}{Lr} - 1 + j\frac{\omega}{\omega_r} \cdot [(\frac{\omega}{\omega_r})^2 - 1] \cdot \frac{Lm}{Lr} \cdot \sqrt{\frac{Lr}{Cr}} \cdot \frac{1}{Rac}} \right|$$

$$= \frac{1}{\sqrt{[1 + \frac{1}{L_n} \cdot (1 - \frac{1}{f_n^2})]^2 + Q^2 \cdot (f_n - \frac{1}{f_n})^2}}$$

$$L_n = \frac{Lm}{Lr}$$

$$f_n = \frac{f_{sw}}{f_r}$$

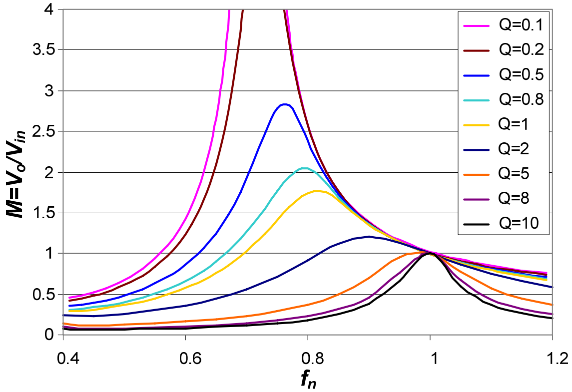
$$Q = \sqrt{\frac{Lr}{Cr}} \cdot \frac{1}{Rac}$$

$$Rac = \frac{8n^2}{\pi^2} \cdot \frac{V_{out}}{I_{out}}$$

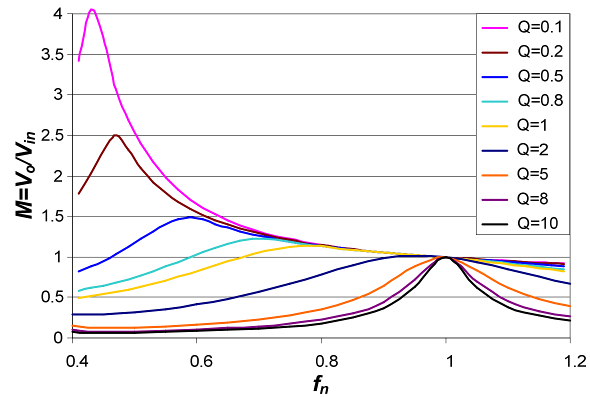
$$fr = \frac{1}{2\pi\sqrt{LrCr}}$$

$$fp = \frac{1}{2\pi\sqrt{(Lm + Lr)Cr}}$$

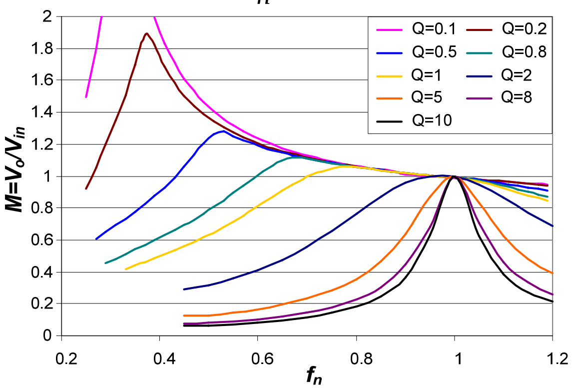
Voltage Gain of Different Ln



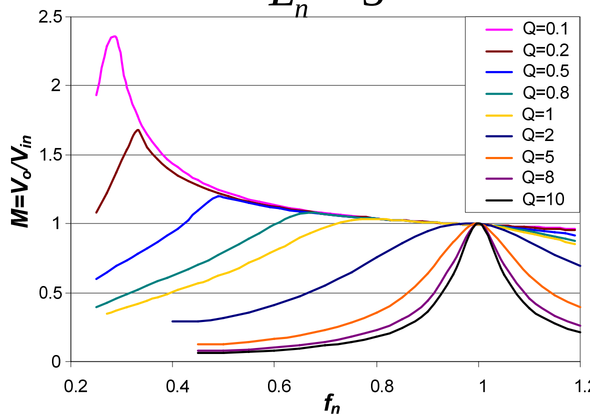
$L_n = 1$



$L_n = 5$



$L_n = 10$



$L_n = 15$

Ln ↑ → Traditional SRC → Enter into ZCS @ fsw<fr → lost gain monotony and MOSFET ZVS operation
→ much wider fsw range, not good hold-up time performance

Ln ↓ → if low inductance → Im ↑ → conducted and switched-off losses ↑
→ if high inductance, fixed resonant frequency → Cr ↓ → Vcr ↑

Start Up Current Consideration

$$Ip^* = \begin{cases} \dfrac{\pi^2}{4\cdot Q} & 1 < \Omega_S \le 2 \\ \dfrac{\pi^2}{4\cdot Q}\cdot\sin(\dfrac{\pi}{\Omega_S}) & \Omega_S > 2 \end{cases}$$

$$\Omega_S = \frac{f_{s-startup}}{f_0}$$

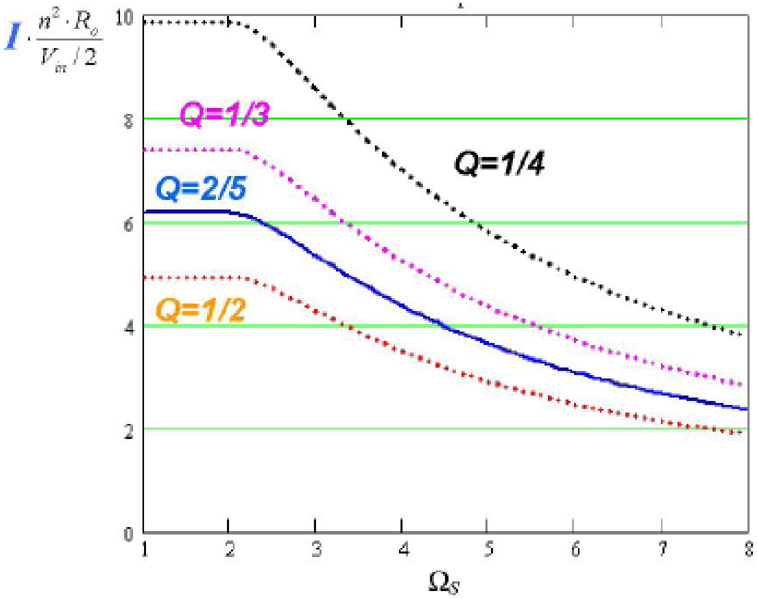


Fig.9 Normalized start-up first peak current

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

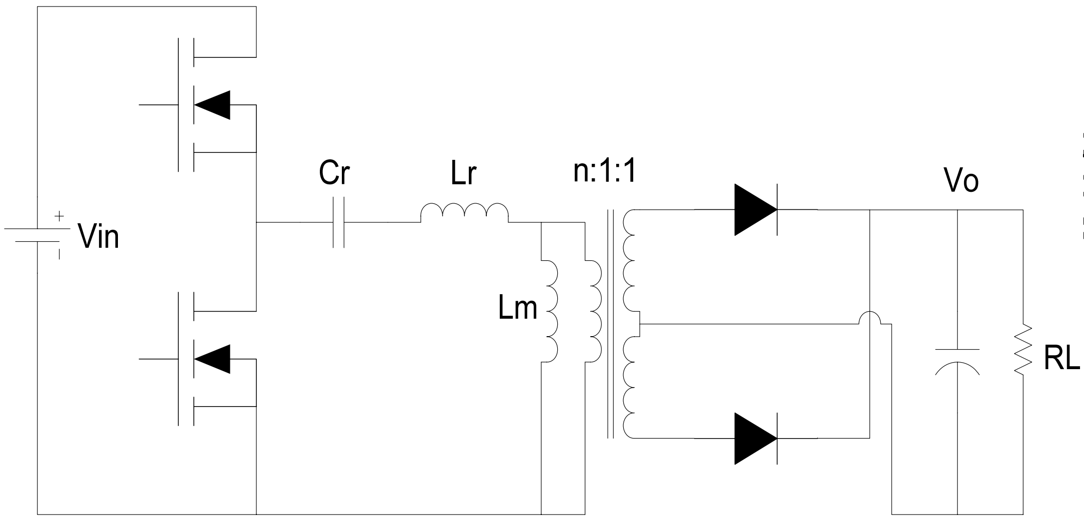
"A Novel Precise Design Method for LLC Series Resonant Converter", Teng liu, etc., INTELEC '06

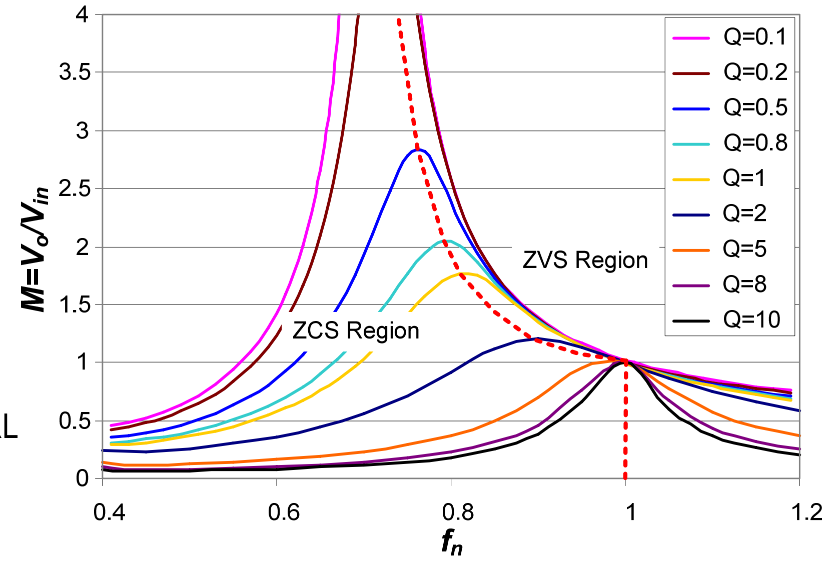
Advantages of LLC Resonant HB

- Primary ZVS can be achieved with wide load range
- Secondary ZCS can be achieved when fs<fr
- 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

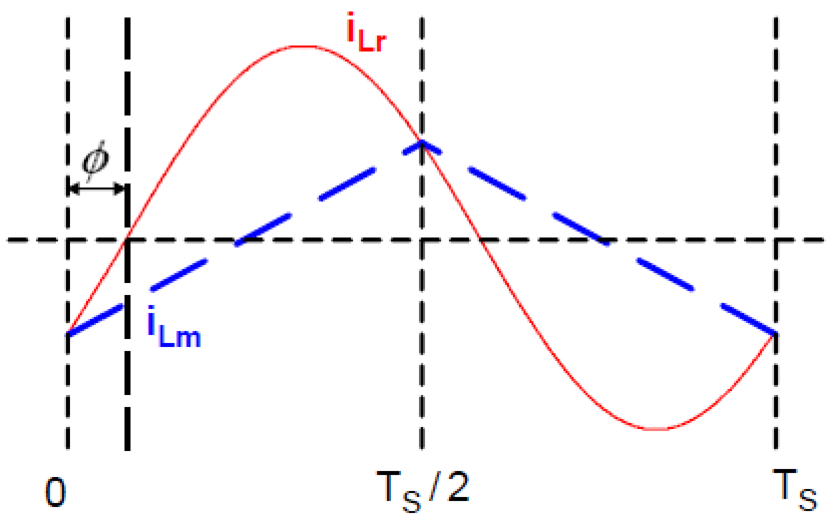
Design Targets





- Minimize RMS current under normal operation condition
- Ensure ZVS operation
- Ensure desired input voltage operation range

fsw=fr @ normal operation



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

$$\begin{cases} i_{Lm}(t)=-i_{Lm\_m}+\dfrac{nV_o}{Lm}t, t<\dfrac{Ts}{2} \\ i_{Lm}(t)=i_{Lm\_m}-\dfrac{nV_o}{Lm}(t-\dfrac{Ts}{2}), t>\dfrac{Ts}{2} \end{cases}$$

$$i_{Lr}(t0)=\sqrt{2}I_{RMS\_P}\sin(\Phi)=-\frac{nV_o}{Lm}\cdot\frac{Ts}{4}$$

$$i_{Lm}=\frac{nV_o}{Lm}\cdot\frac{Ts}{4}$$

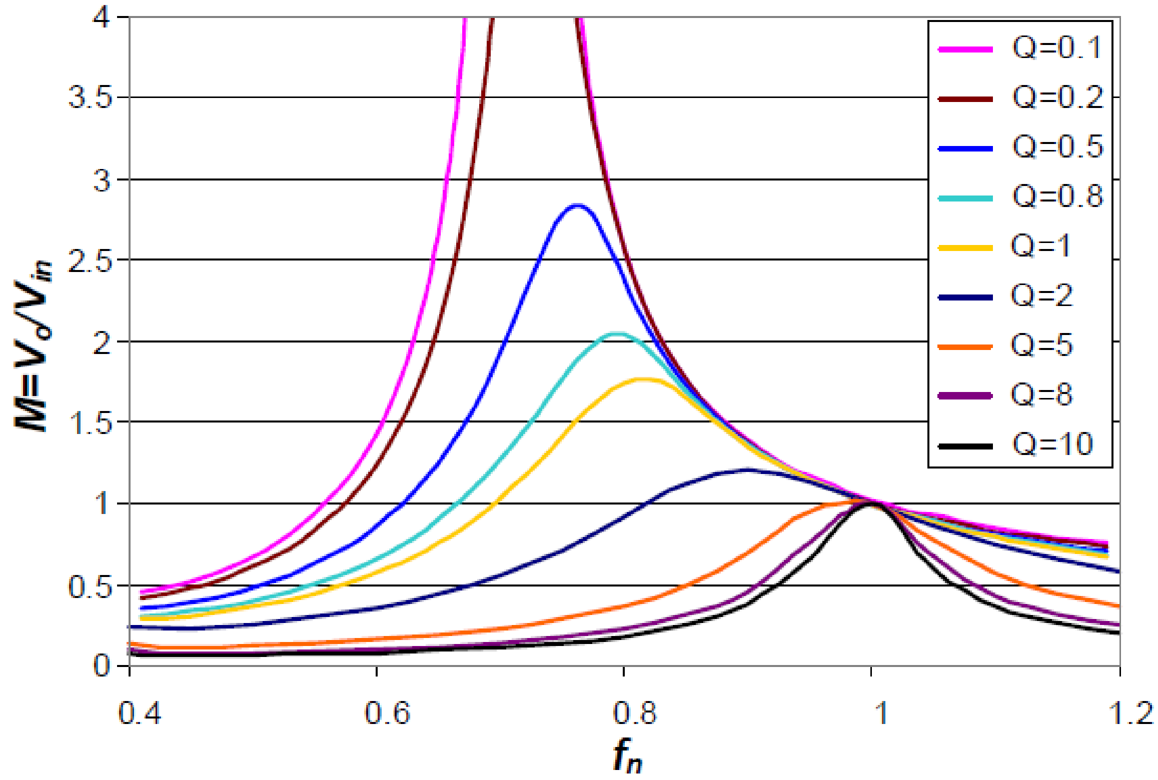
$$\frac{V_o}{nR_L}=\frac{\int_0^{\frac{Ts}{2}}[i_{Lr}(t)-i_{Lm}(t)]dt}{\frac{Ts}{2}}=\frac{\int_0^{\frac{Ts}{2}}[\sqrt{2}I_{RMS\_P}\sin(\omega_o t+\Phi)+\frac{nV_o}{Lm}\cdot\frac{Ts}{4}-\frac{nV_o}{Lm}t]dt}{\frac{Ts}{2}}$$

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

$$I_{RMS\_S}=\sqrt{\frac{\int_0^{\frac{Ts}{2}}[n\cdot i_{Lr}(t)-n\cdot i_{Lm}(t)]^2dt}{\frac{Ts}{2}}}$$

$$I_{RMS\_S}=\frac{\sqrt{3}}{24\pi}\frac{V_o}{R_L}\sqrt{\frac{(5\pi^2-48)n^4R_L^2T_S^2}{L_m^2}+12\pi^4}$$

fsw<fr @ hold-up time



Electrical Parameters

Nominal Vin	440V
Minimum Vin	360V
Maximum Vin	54V
Output Power	200W
Resonant Frequency	100kHz

1. Winding Turn Ratio of TX

fsw=fr at nominal condition，M=1，So

$$n = \frac{V_{PFC}}{2} \cdot \frac{1}{Vout + V_F}$$

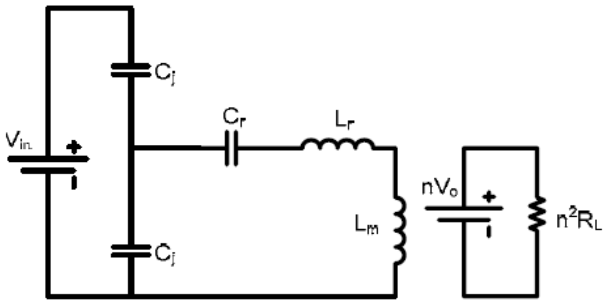
n=4

2. Magnetizing Inductance

The magnetizing inductance impacts conducted and switched losses，So

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

$$I_{RMS\_S} = \frac{\sqrt{3}}{24\pi} \frac{V_o}{R_L} \sqrt{\frac{(5\pi^2 - 48) n^4 R_L^2 T_S^2}{L_m^2} + 12\pi^4}$$



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

$$\begin{cases} I_{Lmp} > \dfrac{2V_{PFC} C_j}{td} \\ I_{Lmp} = \dfrac{nV_o}{Lm} \dfrac{Ts}{4} \\ V_{PFC} = 2nV_o \end{cases} \Rightarrow Lm < \frac{Ts \cdot td}{16C_j} \qquad Lm = \frac{Ts \cdot td}{16C_j} = \frac{td}{16 f_{sw} C_j}$$

td=175ns

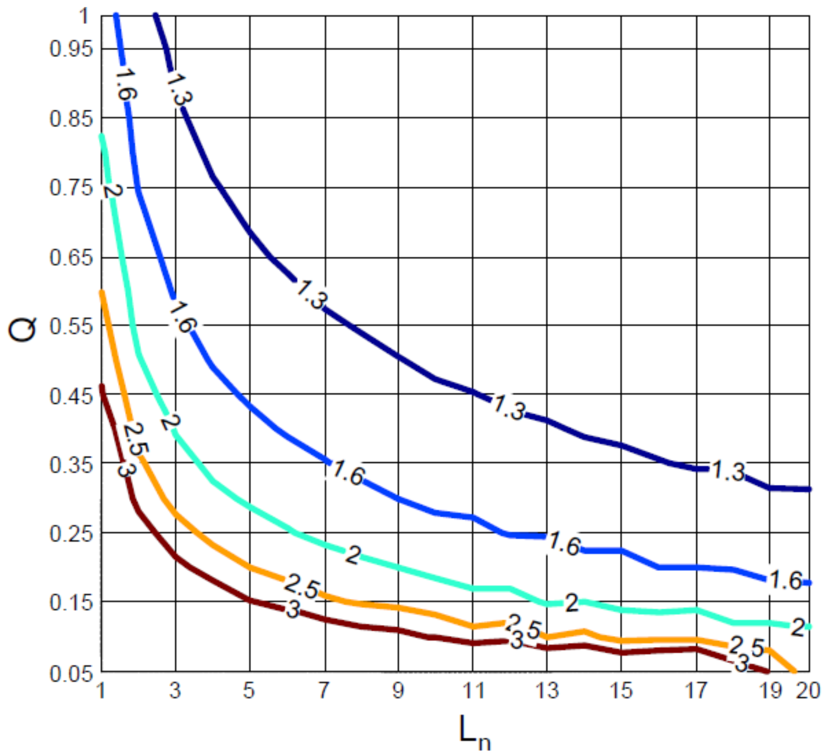
Cj=195pF, SPP20N60C3

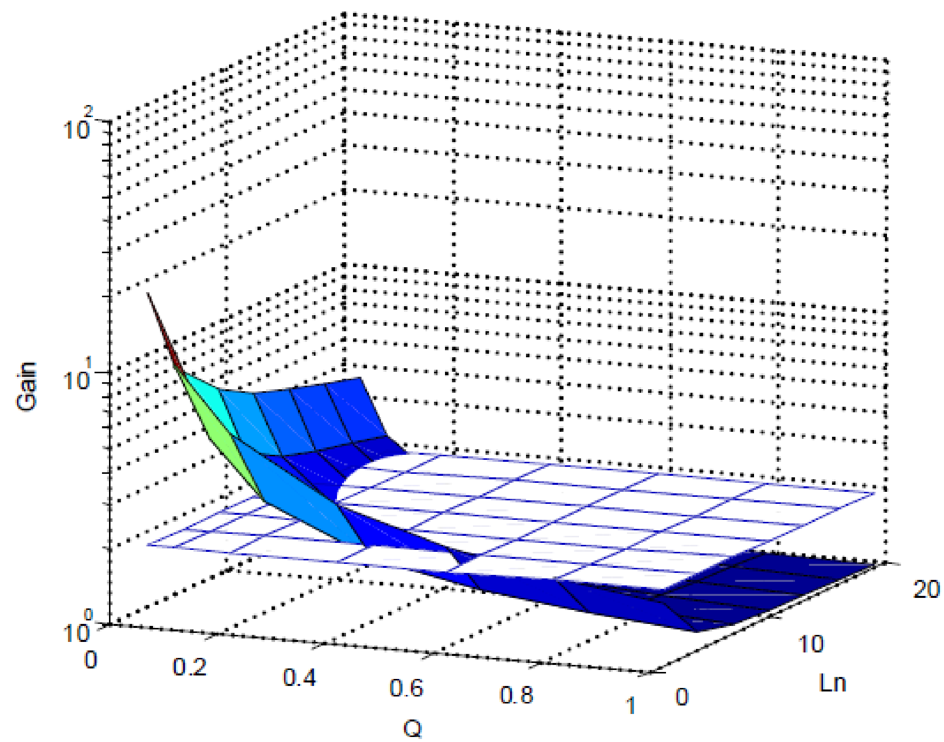
Lm=530

3. Maximum Peak Gain

$$G_{\max} = \frac{V_{PFC}}{V_{\min}}$$

Gmax=1.222





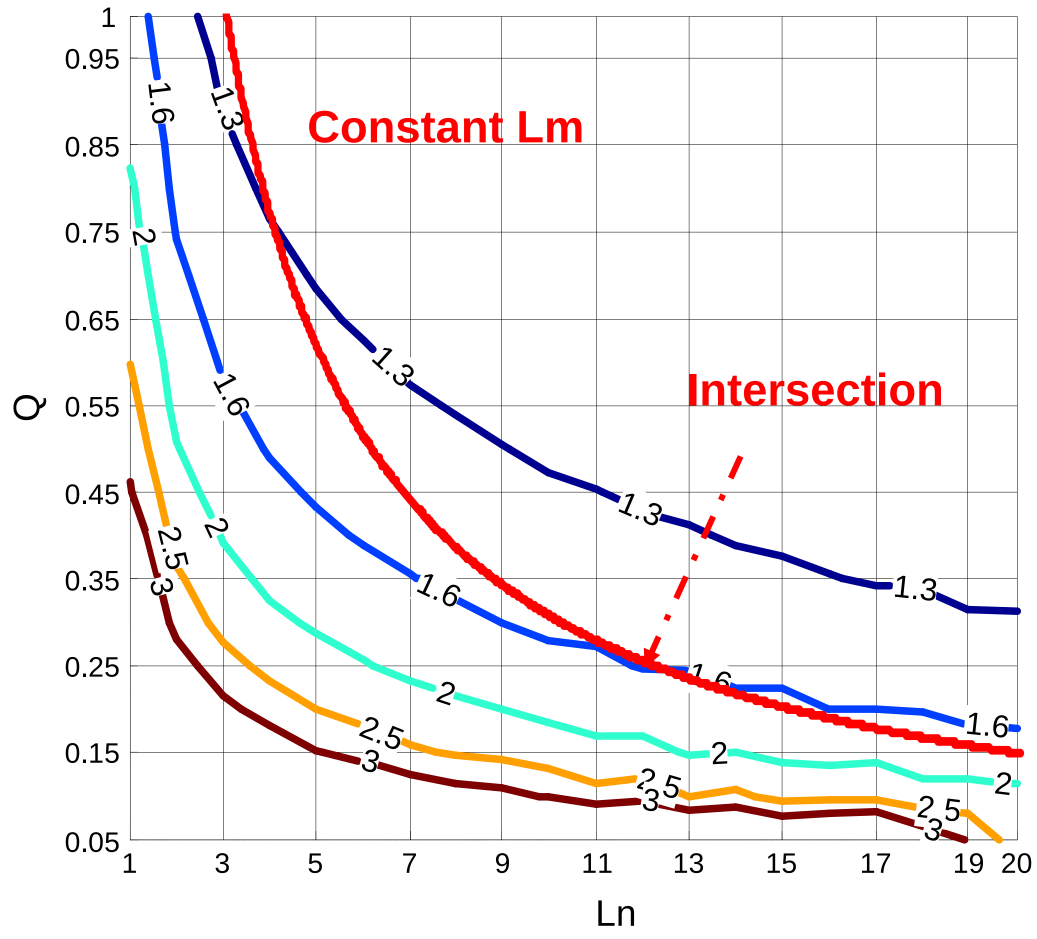
4. Decision Ln and Q

$$\begin{cases} Q = \dfrac{\sqrt{\dfrac{Lr}{Cr}}}{Rac} \Rightarrow L_n Q = \dfrac{2\pi f_o L_m}{\dfrac{8n^2}{\pi^2} \cdot R_L} \\ L_n = \dfrac{Lm}{Lr} \end{cases}$$

From the intersection of curves of LnQ and required maximum peak gain to get the appropriate Ln and Q.

Ln=6

Q=0.3



5. Calculation of Lr and Cr

$$Lr = \frac{Lm}{L_n}$$

$$Cr = \frac{1}{(2\pi f_o)^2 Lr}$$

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

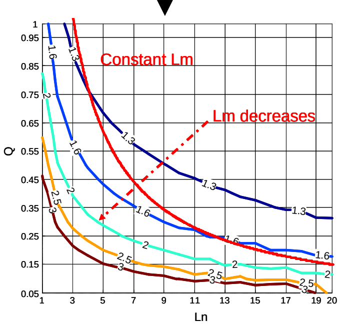
$$n = \frac{V_{in}}{2V_O}$$

Primary switching Device

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

Magnetizing inductor

$$L_n Q = \frac{2\pi f_0 L_m}{\frac{8n^2}{\pi^2} R_L}$$



Peak gain enough?

No — Reduce Lm

Yes

Choose cross section of required gain and constant Lm

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

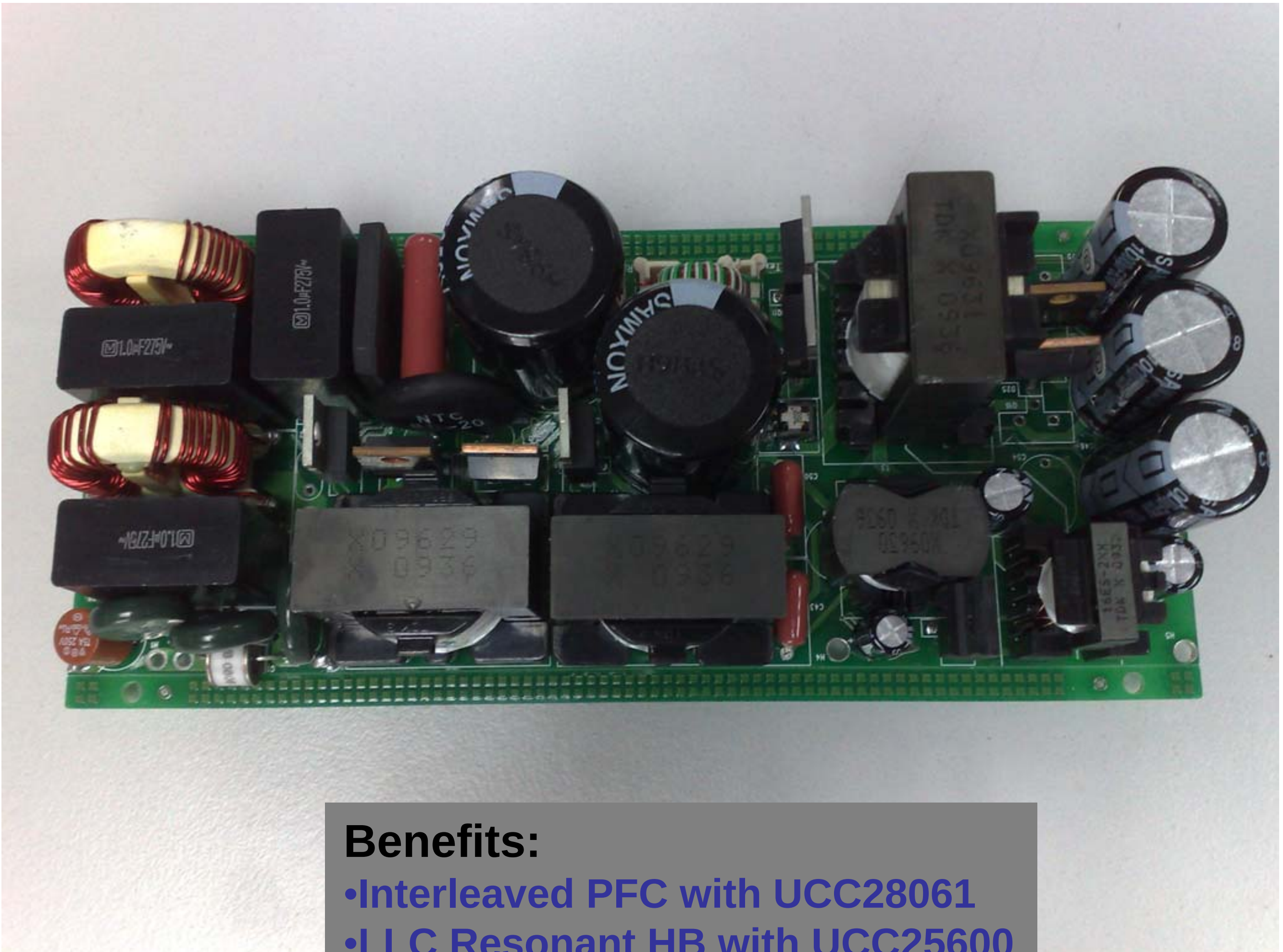
Resonant inductor

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

Resonant capacitor

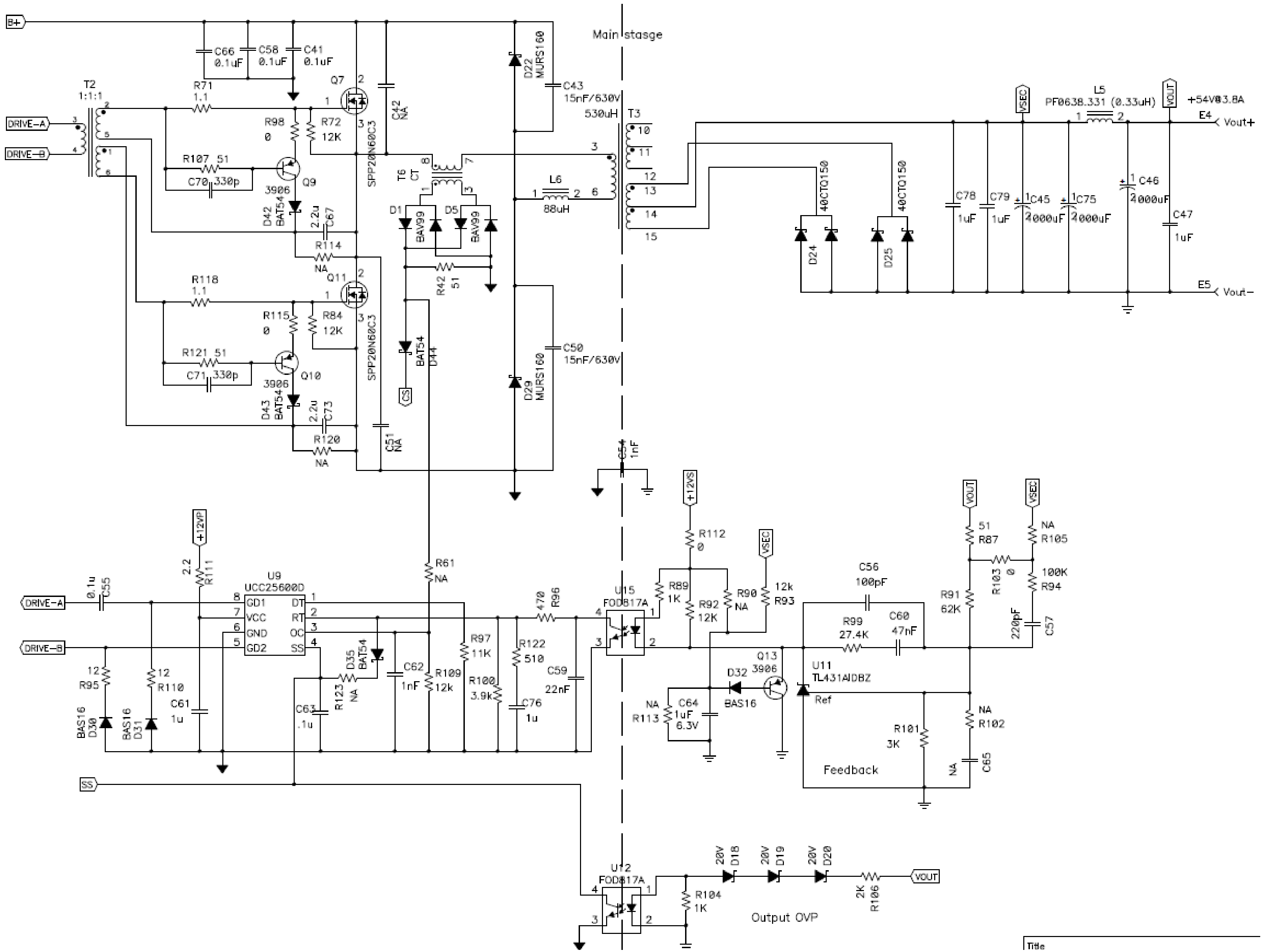
Check gain monotony, min and max fsw, Vcr etc.

Test of 200W LLC Resonant HB

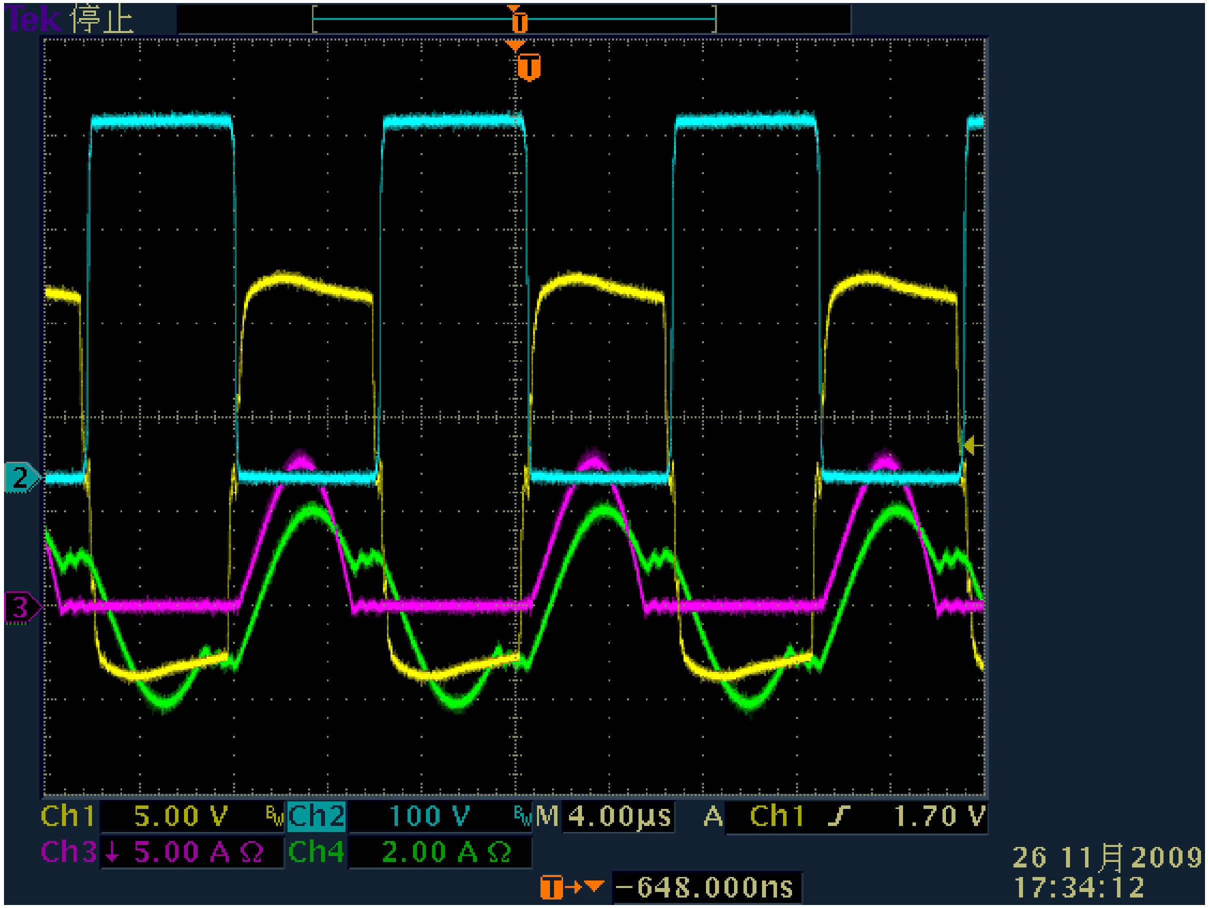


Benefits:

- Interleaved PFC with UCC28061
- LLC Resonant HB with UCC25600
- 93% Efficiency w/o Secondary SR



Main stasge
B+
C66 0.1uF
C58 0.1uF
C41 0.1uF
T2 1:1:1
DRIVE-A
DRIVE-B
R71 1.1
Q7
R98 0
R72 12K
C42 NA
R107 51
C70 330p
3906 Q9
D42 BAT54
2.2u C67
R114 NA
Q11
SPP20N60C3
R118 1.1
R115 0
R84 12K
R121 51
C71 330p
3906 Q10
D43 BAT54
2.2u C73
R120 NA
C51 NA
T6 CT
D1 BAV99
D5 BAV99
R42 51
BAT54 D44
CS
D22 MURS160
C43 15nF/630V
530uH T3
L6 88uH
C50 15nF/630V
D29 MURS160
C54 1nF
40CTQ150
D24
D25
C78 1uF
C79 1uF
C45 2000uF
C75 2000uF
VSEC
L5 PF0638.331 (0.33uH)
VOUT
+54V@3.8A
E4 Vout+
C46 2000uF
C47 1uF
E5 Vout-
+12VP
R111 2.2
U9 UCC25600D
GD1 VCC GND GD2 DT RT OC SS
0.1u C55
R95 12
R110 12
BAS16 D30
BAS16 D31
C61 1u
C63 .1u
R123 NA
D35 BAT54
C62 1nF
R109 12k
R61 NA
R97 11K
R100 3.9k
R122 510
C76 1u
470 R96
C59 22nF
SS
U15 FOD817A
+12VS
R112 0
R89 1K
R92 12K
R90 NA
12k R93
NA R113
C64 1uF 6.3V
D32 BAS16
Q13 3906
U11 TL431AIDBZ
Ref
C56 100pF
R99 27.4K
C60 47nF
R91 62K
51 R87
NA R105
R103 0
100K R94
220pF C57
R101 3K
NA R102
NA C65
Feedback
U12 FOD817A
R104 1K
20V D18
20V D19
20V D20
2K R106
Output OVP
Title

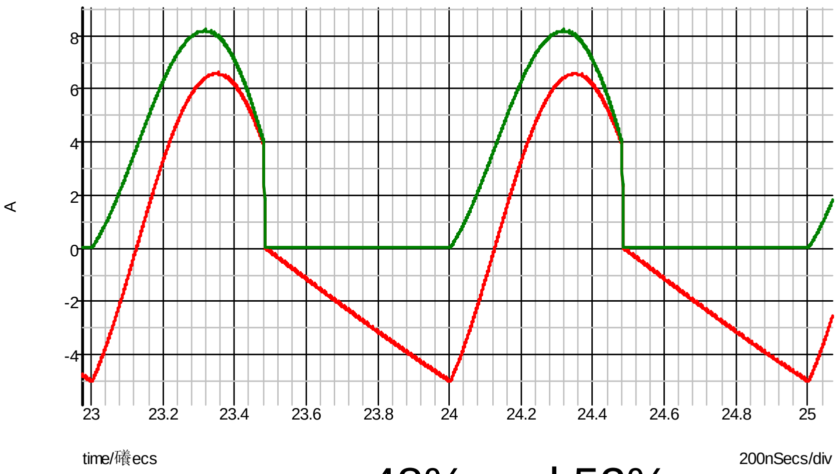


Tek 停止
Ch1 5.00 V
Ch2 100 V
M 4.00µs
A Ch1 1.70 V
Ch3 5.00 A Ω
Ch4 2.00 A Ω
-648.000ns
26 11月2009
17:34:12

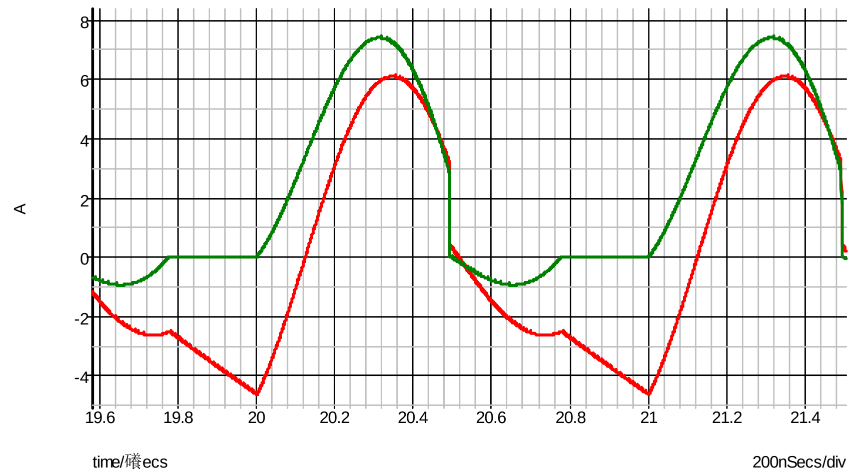
Eff=96.61%

Possible Technical Issues

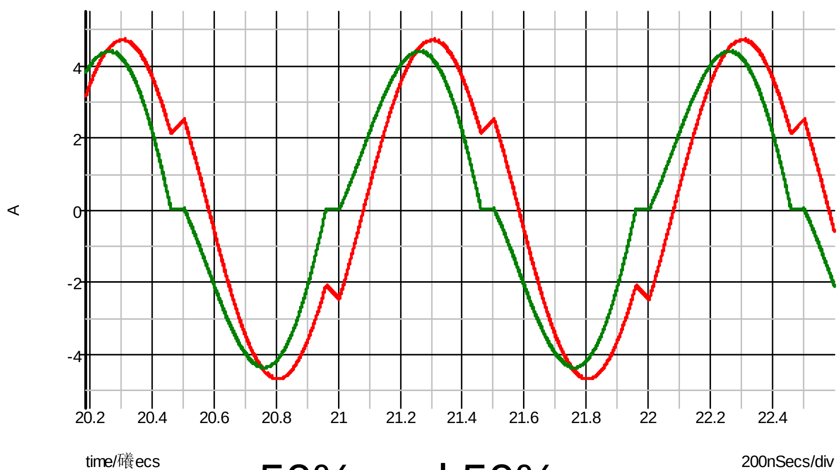
LLC Issue-Imbalance Current



48% and 52%



49% and 51%



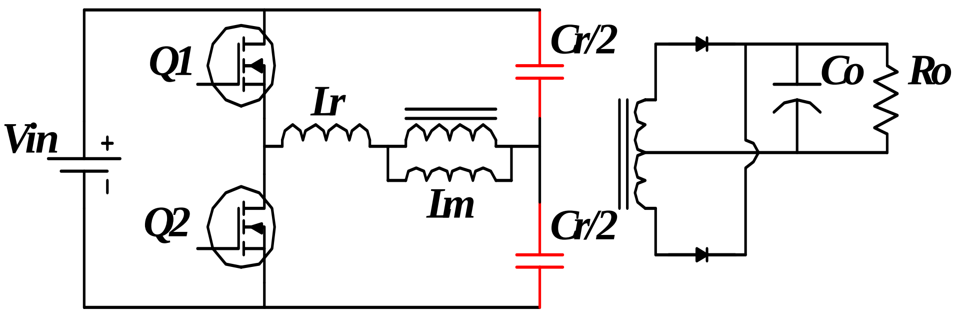
50% and 50%

- ➢Asymmetrical duty cycle makes resonant tank current unbalanced
- ➢Load current will be concentrated in one diode and increase conduction loss and switching loss

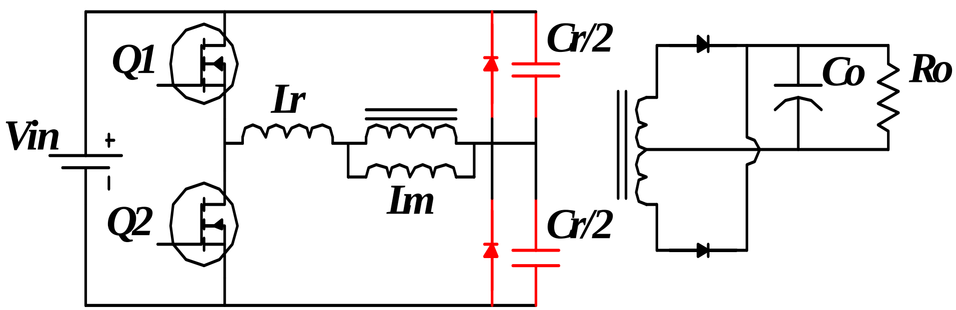
- Controller should provide well matched PWM signal

- Different secondary leakage inductance

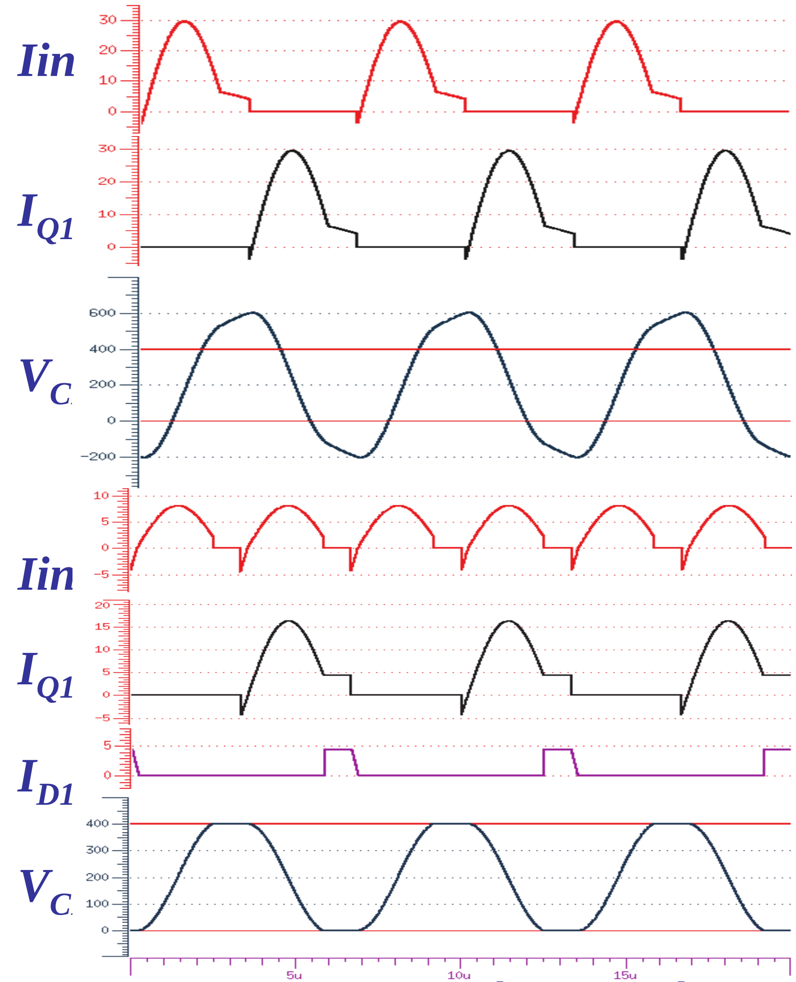
LLC Issue-Over Current



Add Clamping Diode

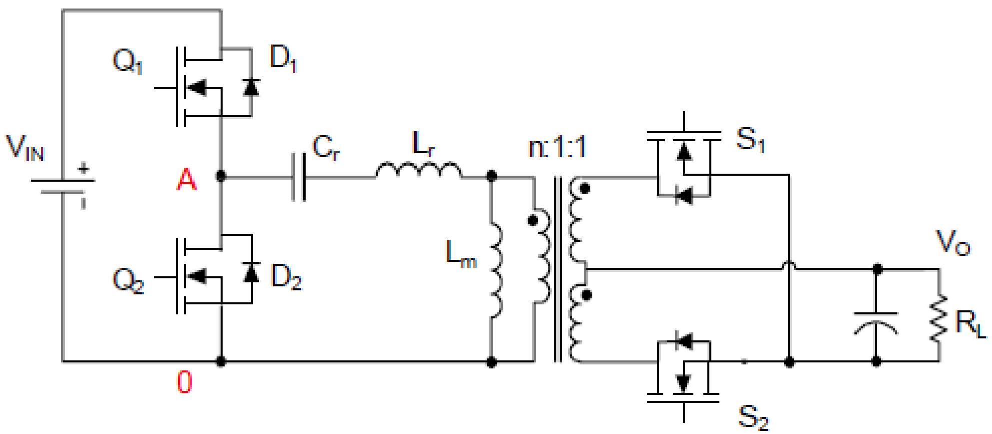


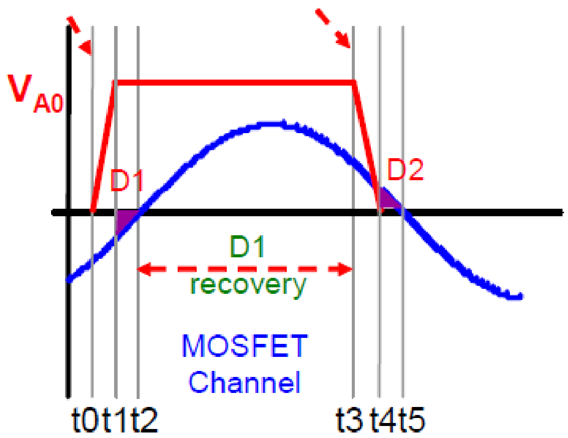
➢ Part of resonant tank energy could be feedback to source, which helps limit output current



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

- Bing Lu, "Investigation of High-density Integrated Solution for AC/DC Conversion of a Distributed Power System", Ph. D. dissertation, Virginia Tech, 2006

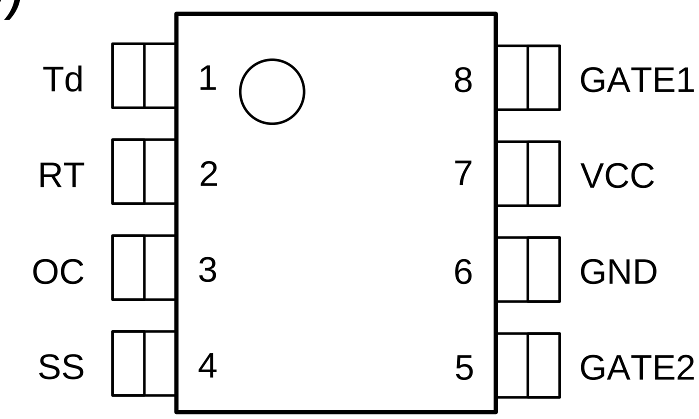
  http://scholar.lib.vt.edu/theses/available/etd-06262006-111218/
- Bo Yang, "Topology investigation of front end DC/DC converter for distributed power system " Ph. D. dissertation, Virginia Tech, 2003 http://scholar.lib.vt.edu/theses/available/etd-09152003-180228/

Back-up

TI UCC25600
8 Pin Resonant Half Bridge Controller

Features

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

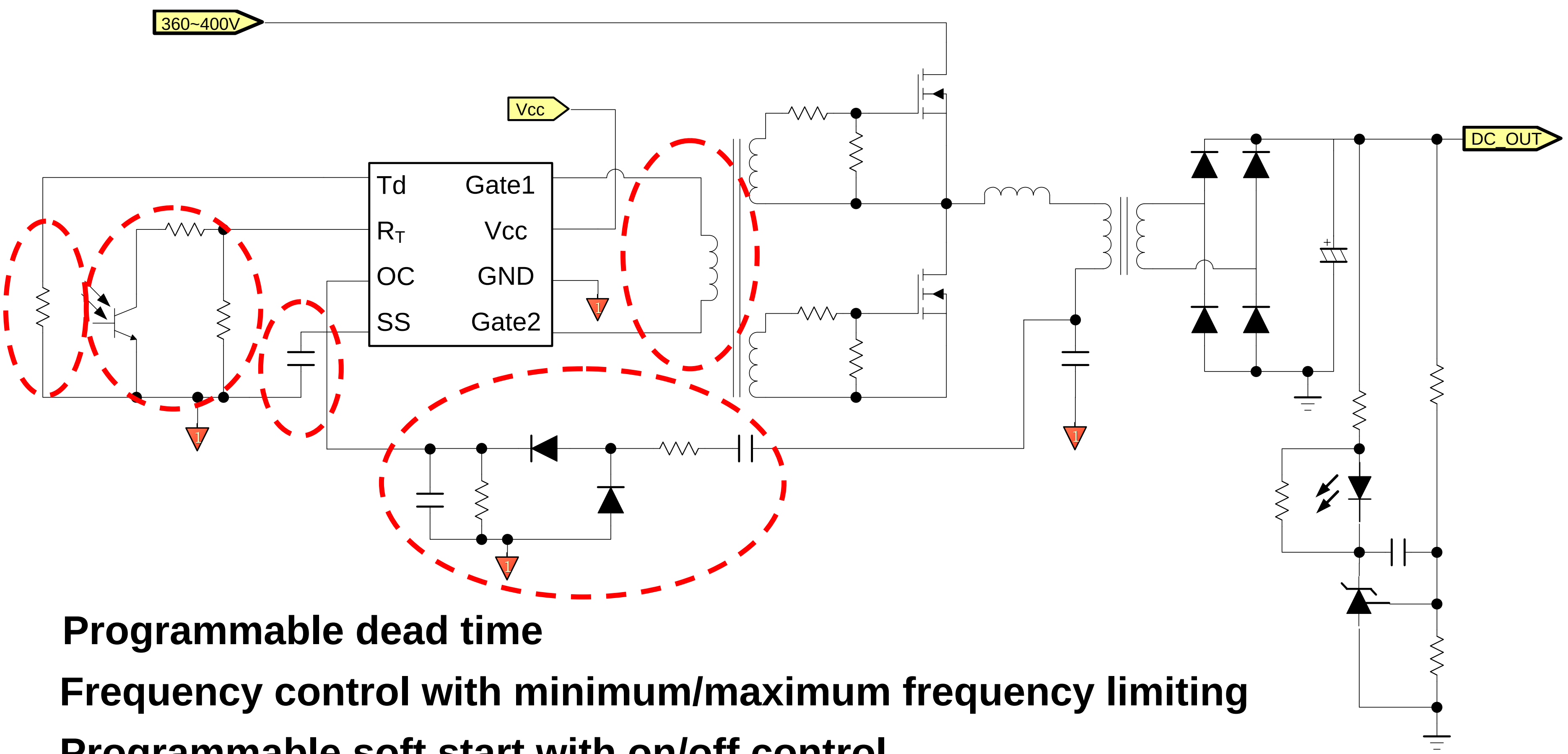


Protection functions

- 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

Application Circuit



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!