12V/1200W High Frequency LLC Converter Design using GaN FETs

1. Introduction

Many people still debate whether global warming is real, and, if so, whether human behavior impacts it. Inarguably, 2018 was the fourth hottest year in history; July 2018 was California's hottest month on record [1]; and CO_2 emissions are known to affect climate change.

The Information and Communication Technology (ICT) sector generates over 2% of the global CO_2 emissions. Data centers are the fastest growing segment within ICT and account for 1.4% of global electricity consumption. That percentage is expected to increase at faster rates due partly to the rapidly growing use of cloud computing and Internet services [2].

High efficiency AC to DC and DC to DC power supplies using GaN can reduce energy loss by 50%, which would then reduce CO_2 emissions emitted by Data Centers. Soft-switching topologies capable of operating at high frequencies while reducing switching losses are optimal for such power supplies—with the more commonly preferred choice being the LLC resonant topology as it offers the following advantages:

- Zero-Voltage Switching (ZVS), which produces high efficiency and enables the transformer size to shrink due to high frequency use.
- Limited dv/dt and di/dt, which reduces ringing, spikes, and radiated EMI problems.

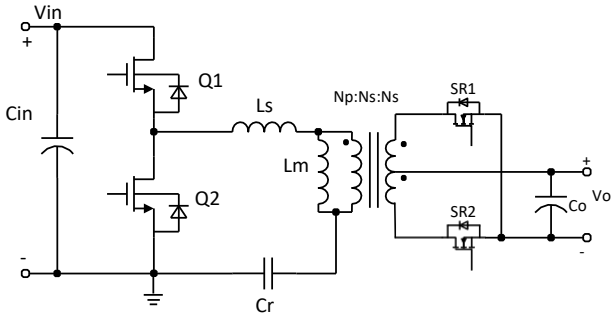


Figure 1. Schematic of half bridge LLC resonant converter.

2. LLC Converter Description

Figure 1 shows the half bridge LLC topology with a full wave synchronous rectified circuit, where Ls is the series resonant inductor, Lm is the magnetizing inductor, and Cr is the resonant capacitor. Q1 and Q2 are typically operating at a 50% duty cycle square waveform with variable switching frequency. It is similar to the series resonant converter (SRC) that both have resonant frequencies:

$$f_0 = \frac{1}{2\pi\sqrt{L_s C_r}} \quad (1)$$

To achieve ZVS at turn on, the current iL should lag the switching voltage (Vsw), i.e. the output impedance seen from the switching node should be inductive, as shown in Figure 2. Therefore, for an SRC converter, the switching frequency f_{sw} must be higher than the resonant frequency f_o. However, the drawbacks for SRC operating in $f_{sw} > f_o$ result in non-ZCS (zero current switching) on the secondary side (SR-MOSFETs) with <1 voltage gain. By paralleling an inductor with the transformer, the inductive current is obtained when $f_{sw} < f_o$, and this magnetizing current (iLm) will not show on the secondary side so ZCS can be achieved at the same time.

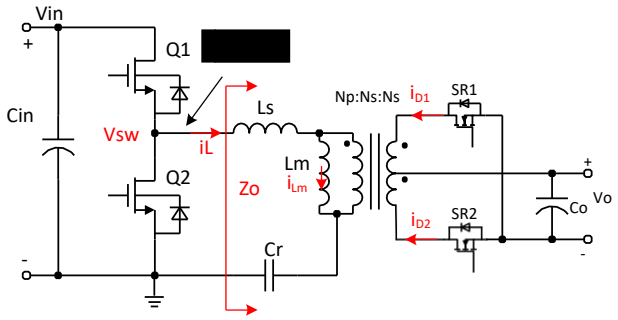


Figure 2. To achieve ZVS on the primary side and ZCS on secondary side, $f_{sw} < f_0$, and Zo should be inductive, so Lm is introduced

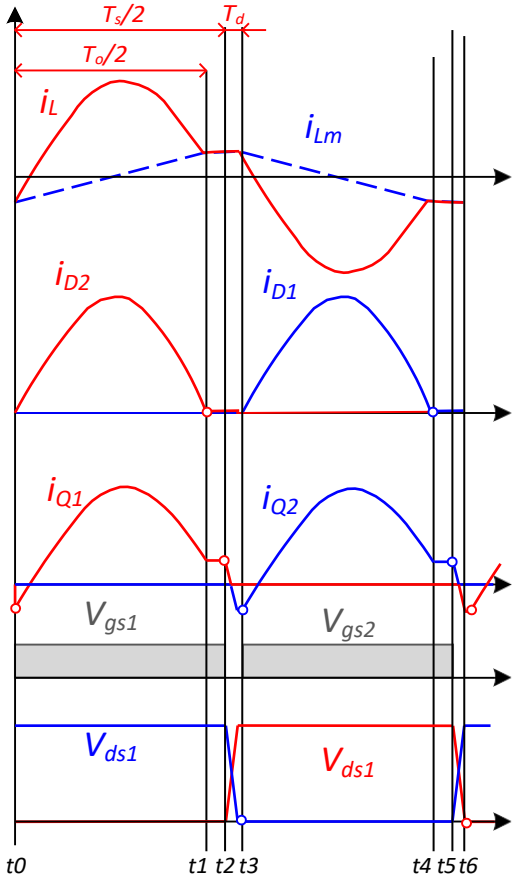


Figure 3. Typical waveform of half bridge LLC converter at $f_{sw} < f_0$

Figure 3 shows the typical waveforms of a half bridge LLC converter at $f_{sw} < f_o$. At t0, the current iL is negative so Q1 is freewheeling, and soft-switching at turn on. The voltage applies on the resonant tank and resonant current changes with the resonant frequency fo. On the other hand, the magnetizing inductor is charging. When the resonant current goes back to 0A at t1, the secondary side iD2 reduces to 0 as well to achieve ZCS. Since $f_{sw} < f_o$, when Q1 turns off, the magnetizing current flows through the body diode of Q2, so during the dead time its Coss can be discharged and Vds_Q2 reduces to 0 before it turns on. The relation between the magnetizing current and dead time will be discussed in the following section. The current iD2 resonances to 0 A before Q1 turns off, so zero current turn-off is achieved on the secondary side.

There is another resonant frequency determined by Lm, Ls and Cr:

$$f_{02} = \frac{1}{2\pi\sqrt{(Lm + Ls)Cr}} \quad (2)$$

When the load increases , the switching frequency will keep reducing to achieve higher gain, but the switching frequency f_{sw} should be higher than the resonant frequency f_{02} to avoid hard switching turn-on.

In this application note, a 12V/1200W LLC converter is designed, and the input/output specifications are as follows:

- Input: 380Vdc nominal (350V-400V)
- Output: 12Vdc at 100A;

Switching Frequency: 380kHz to 450 kHz

3. Parameters Design

3.1 Transformer Turns Ratio

For the LLC output, the input voltage varies in a small voltage range Vin ∈ [350V, 400V]. Since the LLC converter has the voltage boost function, the turns ratio can be selected according to the maximum input voltage, i.e. for a full waveform rectifier, N:/Ns=Vin_max/(2*Vo) = 16:1. To handle very high secondary side current, two transformers with the primary side connected in series and secondary side connected in parallel are applied. Each transformer consists of an EQ30/N49 planar transformer core and heavy copper PCB windings, with a turns ratio of Np:Ns = 8:1, as shown in Fig. 4. For each winding terminal on the secondary side, two 1.4 mΩ MOSFETs with an internal integrated Schottky diode in parallel are connected [note: additional output power (1200 W) can be achieved with 1 mΩ secondary side MOSFETs without affecting the overall performance of the converter].

3.2 LLC Converter Gain Calculation

As discussed in the design guide DG006 “600W DC to DC LLC Design Using GaN FETs” [3], the LLC transformer parameters can be designed. For a planar printed circuit board (PCB) transformer, the primary side PCB windings and secondary side PCB windings are constructed in sandwich mode, as shown in Fig. 4. The parameters for each transformer are Lp=34 µH, Ls=0.9 µH thus total Lp_total = 68 µH, Ls_total = 1.8 µH. An external 9.5 µH inductor consists of PQ20/16 3F36 core and 12nF 1kV/NP0 capacitors are selected as the resonance tank.

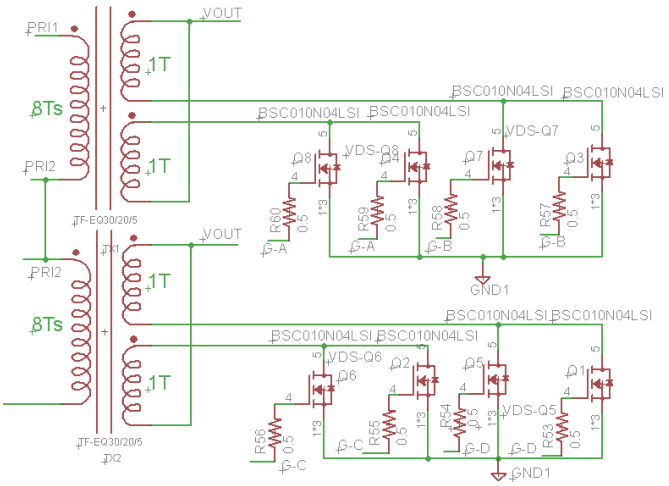


Fig. 4 LLC transformer using 2XEQ30 core transformer connected in parallel on the primary side, and connected in series on the secondary side

Three pieces using 4-layer 4Oz PCB boards are stacked with Pri-Sec-Pri sandwiched type shown in Fig. 5 so as to minimize the leakage inductance. There is only one winding turn on each layer for high current capability. The 8 winding turns are made by two pieces of 4-layer PCB windings connected in series, and PCB2 copper windings are used for secondary side windings, in which each single winding consists of two PCB layers connected in parallel.

3.3 Dead time calculation

For 1200W LLC converter using the 72 mΩ TP65H070LSG and TP65H070LDG GaN FETs are selected as high side and low side switches respectively. During the dead time between high side and low side devices, the turn-off current should be able to discharge the energy stored in the output capacitors and stray capacitor, and should meet:

$$I_{m(on)} \cdot T_d \geq V_{in}(2C_{o(tr)} + C_{stray}) \quad (3)$$

Where $I_{m(on)} = \frac{V_{iin}}{2L_m} \cdot \frac{T_o}{4}$, with the dead time to be calculated using:

$$T_d \geq \frac{8L_m(2C_{o(trr)}+C_{strray})}{T_o} > 103\text{ns} \quad (4)$$

The real dead time is set to 150 ns. The table I lists the required $I_{m(on)} \cdot T_d$ with different devices, which outperforms the best high voltage Si-MOSFETs.

3.4. Circuit design

The LLC circuit is shown on Page 6. A NCP1395B [4] LLC controller and NCP43045D [5] SR-MOSFET controller are selected for the control realization. Two 40V

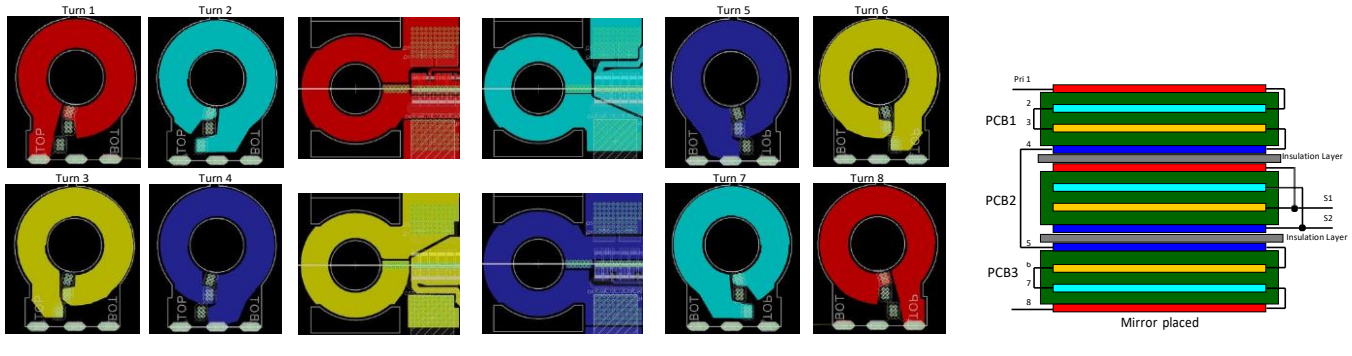


Fig. 5 PCB windings: (a) PCB1 layer1-4 as primary side 1st turn-4th turn; (b) PCB2 layer 1,3 as secondary side winding S1, 1 turn, layer 2, 4 as secondary side winding S2, 1 turn; (c) PCB3 layer1-4 as primary side 5th turn–8th turn. (d) PCB winding construction and connection

BSC014N04LSI in parallel from Infineon are selected as the SR-MOSFETs. X7R rating 10 µF MLCC are placed in the shortest high frequency current loop, and 1800 µF/16V high ripple current rating aluminum polymer capacitors are chosen to reduce the output voltage ripple.

Table I Required Charge for ZVS

Device	$R_{ds(on)}$	$C_{o(tr)}$	$I_{m(on)} \cdot T_d$
TP65H070 [6]	70 mΩ	220 pF	188 nC
TPH3208 [7]	110 mΩ	133 pF	118 nC
Si-MOS A	70 mΩ	990 pF	804 nC
Si-MOS B	99 mΩ	641 pF	525 nC
Si-MOS C	80 mΩ	643 pF	526 nC

4. Circuit Design Consideration for High Frequency High Current

For the low voltage high current LLC converter, the secondary side PCB layout is more critical. It is necessary to minimize the high frequency current loop, not only for reducing the terminal loss but also for reducing the high voltage induced by high di/dt. As shown in Fig. 6, the top layer winding is directly connected to the drain of the SR MOSFETs Q1 and Q5, with the other terminal connected to the ceramic capacitors for the shortest path. In the same way, the bottom layer winding is connected to the drain of the SR MOSFET. In addition, to handle high current, winding layer 3 is paralleled with winding layer 1 and the winding layer 2 is paralleled with winding layer 4 with vias.

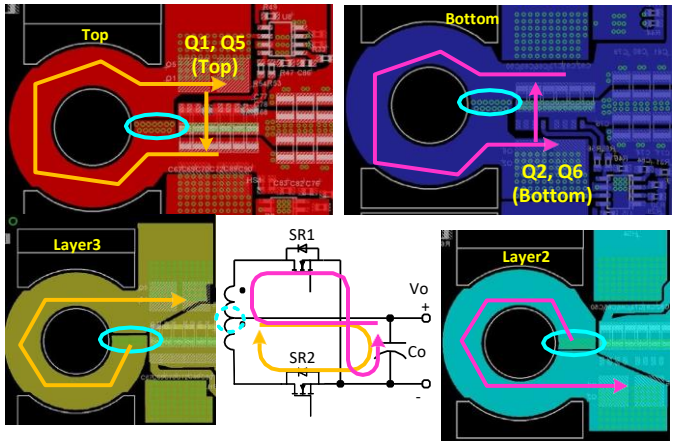


Fig. 6 Minimized secondary side circuit loop area

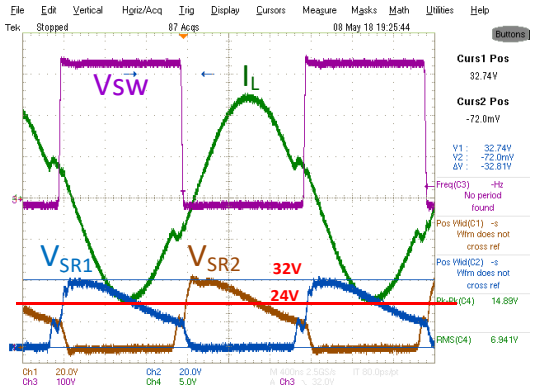
For the LLC converter, the resonant frequency of the secondary side winding current through the SR MOSFET is roughly:

$$i_{SR} = \sqrt{2} i_o \sin(\omega t) \quad (5)$$

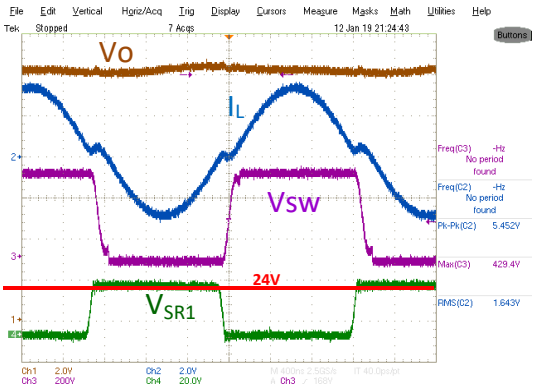
Where $\omega = \frac{2\pi}{T_s}$ The peak di/dt attime 0 can be achieved:

$$\frac{di_{SR}}{dt} \Big|_{max} = \frac{2\pi\sqrt{2} i_o}{T_s} \quad (6)$$

The di/dt at full load can be 0.3 A/ns. The PCB winding used in this planar transformer has the leakage inductance minimized to 0.95 µH, which is seen from primary side, and the leakage inductance on secondary side of less than 10nH for 8:1 turns ratio. For the traditional litz-wire wounded transformer using EER35 magnetics core (single 16:1:1) the resonance inductor is integrated having 10 µH of leakage inductance that is evenly shared by both sides of the windings, meaning around 20 nH inductance on secondary side. The calculated voltage induced by L*di/dt can be 2.78 V and 7 V. The SOA margin of SR MOSFETs is reduced due to the high voltage spike. As shown in Fig. 7, two LLC converters with different transformers were compared at 1 kW load condition. Figure 7 (a) waveform, an EER35 single core 17:1:1 transformer with Ls=9 µH was applied, and for Figure (b) two EQ35 8:1:1 PCB planar transformer with Ls=0.9uH was used. The voltage spike is 32 V and 24 V, respectively. In the ideal case, a 40 V rating MOSFETs is needed for case (a), though 30 V rated MOSFETs are safe for case (b). When the switching frequency goes beyond the resonant frequency, the SR MOSFET will lose ZCS condition, and the turn-off resulting in the voltage spike to increase.



(a)



(b)

Fig. 7 Voltage on SR MOSFET at 1kW load conditions: (a) resonance inductance integrated in the transformer; (b) leakage inductance is minimized in the transformer

5. Experimental Results

A 1200W LLC converter was designed, assembled and tested. The GaN FETs TP65H070LSG and TP65H070LDG are selected as the primary side low side and high side devices. With good thermal dissipation performance using 4-layer 4-Oz PCB, no heat sink is needed for the PQFN GaN devices. The hottest part of the converter is the SR-MOSFETs due to their high conduction losses. The SR driver controller turn on and off the MOSFETs by sensing their voltage drop. However, the driver will turn of the device before the current drops to zero to avoid shoot through, during this time the internal Schottky diode will take over the current so as to reduce the conduction loss. The efficiency is measured under the following conditions: the input voltage

Fig. 8 1.2kW 450kHz LLC Converter

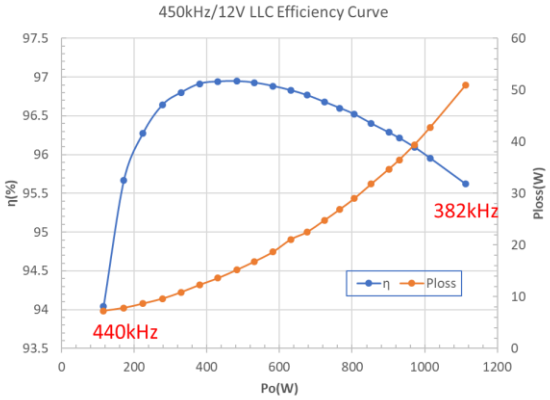


Fig. 9 Measured Efficiency Curve 385Vin-12Vo

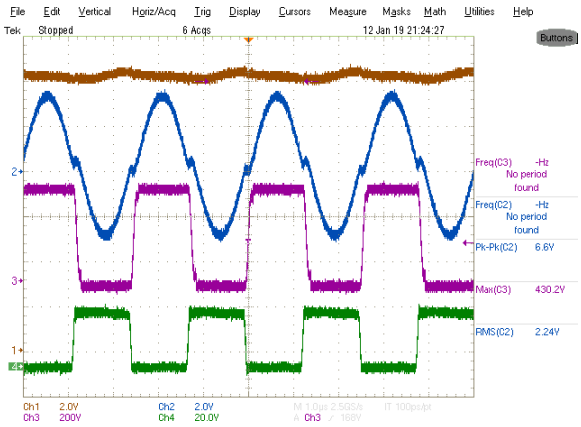
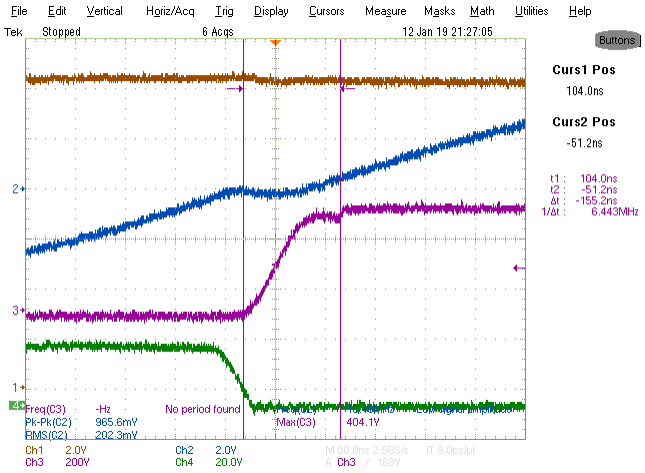


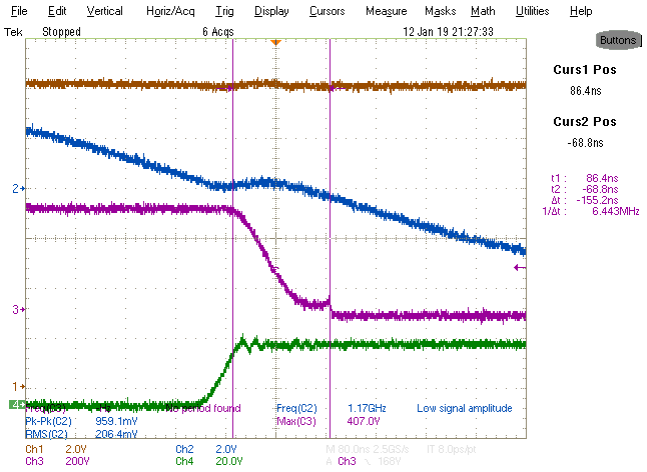
Fig. 10 Measured Efficiency Curve 385Vin-12Vo:
CH1: V_o, CH2: I_L, CH3: V_{sw}, CH4: V_{SR_MOS}

is 385 V with 120 Hz voltage ripple. The peak efficiency is over 96% from 200 W to 1000 W, as shown in Figure 9. Figure 10 shows the switching node voltage and transformer current waveform on the primary side. The primary side

devices are working in ZVS mode and the secondary side SR MOSFETs are working in ZCS mode. The switching frequency is 382 kHz at 1.1 kW load. The dead time is set to 155 ns and measured in Fig. 11.



(a)



(b)

Figure 11 Dead time waveforms at low side device turn-on and turn-off

6. Reference:

[1] Mindy Weisberger, “California Logged Its Hottest Month Ever, and Things Are Only Going to Get Worse”. https://www.livescience.com/63358-noaa-climate-report-and-predictions.html, On-line, August 2018

[2] M. Avgerinou, P. Bertoldi, L. CastellazziTrends in data centre energy consumption under the European code of conduct for data centre energy efficiency

Energies, 10 (2017), p. 1470

[3] “Desgin Guide: 600W DC to DC LLC Design Using GaN FETs”, on-line: https://www.Renesasusa.com/en/document/desig n-guide-600w-dc-to-dc-llc-design-using-gan-fets/

[4] Datasheet of NCP1395A/B, on-line: http://www.onsemi.com

[5] Datasheet of NCP4305A/D, on-line: http://www.onsemi.com

[6] Datasheet of TP65H070L, on-line: https://www.transphormusa.com/en/document/datasheet-tp65h070l-650v-gan-fet/

[7] Datasheet of TPH3208PS, on-line: https://www.Renesasusa.com/en/document/650v-cascode-gan-fet-tph3208ps/

7. Appendix:

1.2kW 450kHz LLC Schematic Diagram: