Design Considerations for a GaN-Based High Frequency LLC Resonant Converter

This article evaluates the performance of Gallium Nitride (GaN) power transistors in comparison to Silicon Superjunction MOSFETs (Si SJMOS) and Silicon Carbide MOSFETs (SiC MOS) for the high frequency LLC resonant topology.

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Introduction

With the clear trends towards higher power, smaller size, and higher efficiency, a high frequency LLC resonant converter is an attractive solution for an isolated DC/DC topology in the industry, such as a laptop adapter (>75W), 1KW-3KW datacenter Power Supply Unit (PSU), and a multi-kilowatt On Board Charger (OBC) for electric vehicles. Figure 1 shows a topology for a half bridge LLC resonant converter with switching frequency at 100KHz and 500KHz. At the higher frequency, it is obvious that the size of the passive resonant tank (e.g. transformer, resonant inductor, and resonant capacitor) are dramatically reduced, thus the power density is improved. Additionally, the selection of the power transistors (Q1 and Q2) need to be considered to trade off the efficiency and power density. GaN power transistors have established themselves in the market as a proven transistor technology, but are often not considered in soft switching applications. While using GaN in hard switching applications shows a significant improvement in efficiency, improvements on efficiency and frequency in soft-switching converters (such as LLC) can also be equally dramatic.

In this article, the benefits of commercial GaN power transistors in comparison to Si SJMOS and SiC MOS transistors are discussed for a soft-switching LLC resonant converter. The analytical approach for the transistor selection and comparison are conducted. The transistor parameters such as time related output effective capacitance ($C_{o(tr)}$) and turn-off energy (E_{off}), etc., are taken into consideration, which influence the high performance achievements of an LLC converter. A 3KW 48V output LLC converter, based on GaN, Si, and SiC MOS, is also analyzed for efficiency and power density comparison.

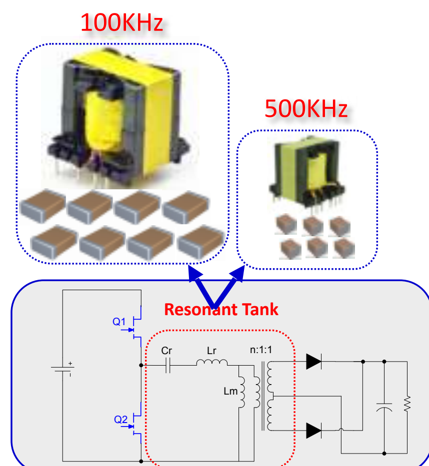


Figure 1: The Half bridge LLC resonant converter at 100KHz and 500KHz

Primary Transistor Selection

The LLC has several benefits due to its full resonant behavior allowing soft switching turn-on over the entire range which intrinsically helps to minimize losses in both power transistors and magnetic components. In Figure 2, the LLC primary side current, I_{Lr} , consists of a superposition of the secondary side current, divided by the transformer turns ratio n, and the magnetizing current I_{Lm}. The magnetizing current does not transfer to the output but is required to discharge the parasitic output capacitance of the transistors as well as a combination of the transformer intra-winding and inter-winding capacitance, hence to achieve Zero Voltage Switching (ZVS) for transistor turn-on without switching turn-on loss. On the one hand, in order to achieve the ZVS for turn-on, the parasitic output capacitance of the transistor should be fully discharged by using this magnetizing current during each dead time. On the other hand, the magnetizing current will contribute an additional circulating loss on the primary during the dead time. Minimizing magnetizing current is thus a goal for improving an LLC converter.

The minimum dead time $t_{deadmin}$ for a half bridge LLC's ZVS achievement condition can be derived from equation (1). Here, L_m is the magnetizing inductance of the main transformer and f_s is the switching frequency. From equation (1), The transistor parameter $C_{o(tr)}$, which describes the output capacitance needed to transition the drain to source voltage passively, is a key parameter for high efficiency and high density LLC converters. The lower the value of the effective $C_{o(tr)}$, the less magnetizing current is required for a given drain to source transition time, and this allows a higher value of magnetizing inductance for the transformer and a shorter dead time, which in turn lowers the circulating losses on the primary side. Meanwhile, for a given L_m and t_{dead}, the lower value of effective $C_{o(tr)}$, the higher switching frequency f_s can be used with ZVS condition to make a higher density.

$$t_{deadmin}=16\cdot C_{o(tr)}\cdot L_m\cdot f_s$$

This effective capacitance $C_{o(tr)}$ can be derived from the output capacitance C_{oss} through output charge Q_{oss}, which has the relation equations of $Q_{OSS} = \int_0^{Vds} Coss(v)dv$ and $C_{o(tr)}= C_{o(tr)}/V$. Figure 3 plots the Q_{oss} with the voltage of V_{ds}. For a V_{ds} voltage transition from 400V to 0V, Si SJMOS has typically 10 times higher $C_{o(tr)}$ than GaN, and SiC has 50% higher $C_{o(tr)}$ than GaN.

Another important transistor parameter for LLC is Q_{gd}, which describes the charge required for gate to drain switching and the switching turn-off time t_{off}. These two parameters give an indication of turn-off capability and losses, and thus the maximum operating frequency and efficiency. The turn-off time t_{off} is normally not shown in a transistor datasheet, but can be estimated according to the reference book [1] with the given switching voltage and current conditions.

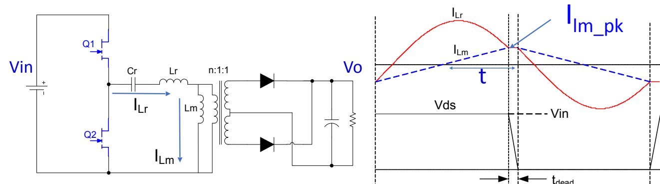


Figure 2: The primary current and voltage waveform for the half bridge LLC resonant converter

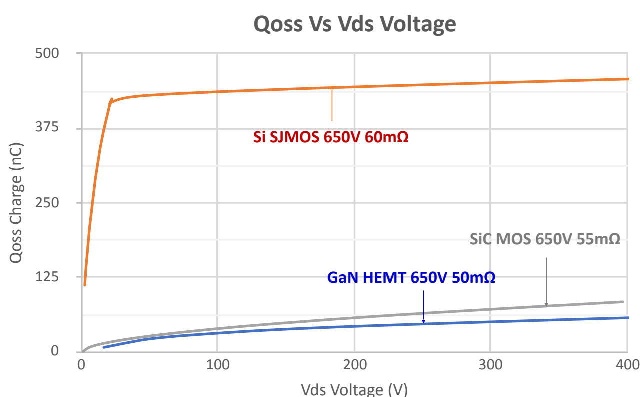


Figure 3: Q_{oss} Vs V_{ds} curves with different transistors (GaN, Si, and SiC)

One of the challenges for Si and SiC MOSFETs is incomplete body diode reverse recovery. With the exception of the capacitive load results from overload or during the startup, there is a potential system reliability issue caused by the incomplete body diode reverse recovery of the power MOSFET for the LLC [2]. The existing reverse recovery charge Qrr of the body diode will generate high dv/dt and a large shoot-through current will flow through the bridged transistors, which may result in a MOSFET breakdown. So, the Q_{rr} parameter is a key parameter to verify the risk for the hard commutation failure mode, and therefore the lower Q_{rr}, the better, to avoid the failure.

Table 1 summarizes three transistor type parameters with the physical material of GaN, Si, and SiC. For Si SJ MOS, the most recent Si-based MOSFET with an intrinsic fast body diode was chosen. GaN and SiC are the latest generation wide bandgap transistors which are more suitable for high efficiency and high density power conversions. As shown in the table, compared to Si and SiC, GaN power transistors with the similar $R_{DS(on)}$ have great benefits for the LLC key parameters. The lower values of $C_{o(tr)}$, Q_{gd}, toff, and Q_g, the better performance of the LLC converter designed for efficiency and power density. Additionally, GaN power transistors have a lateral two-dimensional electron gas (2DEG) channel formed on an AlGaN/GaN heterojunction which has no intrinsic bipolar body diode. No body diode means no Q_{rr}, which means no hard avalanche operation as mentioned above due to the existence of the body diode for MOSFET.

Operation and Loss Analysis

Figure 4 gives a steady state cycle for a half bridge LLC resonant converter. The following are the main five states, each with its accompanying loss analysis:

1. At state 1, when the high side driving signal V_{GSH} goes low, the primary side magnetizing current I_{LM} begins to discharge the output capacitance of the low-side transistor during the dead time.
2. At state 2, the parasitic output capacitance is completely discharged and the GaN power transistor is operating at its 3rd quadrant operation through the 2DEG channel from source to drain. As for the Si and SiC MOSFETs, there is an intrinsic bipolar body diode; the body diode will conduct the current from source to drain with the gate's channel turning off. At this state, there is a circulating reverse conduction loss on the primary side due to the existing of magnetizing current. This reverse conduction loss highly depends on the value of $C_{o(tr)}$. Lower $C_{o(tr)}$ results in shorter dead time and the lower magnetizing current results in lower reverse conduction loss.
3. At state 3, when the driving signal V_{GSL} is high, the ZVS is achieved for the transistor and there is no switching turn-on loss.
4. At state 4, the transistor is turned on with a forward current from drain to source. There is a conduction loss during this state which is related to the on-state resistance $R_{DS(on)}$ of the transistor.
5. At state 5, the driving signal V_{GSL} goes low and the channel of the transistor is turned off with hard switching. Due to a peak magnetizing current I_{m_pk}, there is a current and voltage crossover switching loss. This loss depends on the transistor's characteristic for gate to drain charge Q_{gd} and turn off time t_{off}.

Another loss not mentioned above in Figure 4 is gate drive loss, which is relative to the transistor's gate charge Q_g. Lower Q_g results in lower gate drive loss, especially for high switching frequency. This gate drive loss may not be ignored.

Parameters		GS66508B (GaN)	Superjunction MOSFET (Si)	SiC MOSFET (SiC)	GaN's value
Blocking voltage	V_{ds}; V	650	600	650	
On resistance	$R_{DS(on)}$,typ; mΩ	50	48	55	Almost same typical $R_{DS(on)}$
Time related effective output capacitance	$C_{o(tr)}$; pF	**142**	1171	210	Shorter dead time for LLC, low circulating loss
Gate to drain charge	Q_{gd}; nC	**1.8**	28	27	Lower switching turn-off loss
Turn-off time @5A 400V	t_{off}; ns	**2.52**	15.1	11.0	Lower switching turn-off loss
Total gate charge	Q_g; nC	**5.8**	79	73	Lower switching and gate drive loss
Reverse Recovery charge	Q_{rr}; nC	**0**	720	85	No hard commutation failure

Table 1: Key primary side transitor's parameters for LLC resonant converter

A 3KW LLC Resonant Converter

According to the above loss analysis, comparisons can be done with different primary transistors and different switching frequencies to evaluate the performance of efficiency and power density. A 3KW half bridge LLC resonant converter with 48V output are designed, comparing the performance with two comparable scenarios: the first one is all three transistor types are operating at 500KHz resonant frequency and the second one is 500KHz GaN-based LLC versus 100KHz Si-based LLC. The primary transistors are GaN, Si, or SiC. Each switch on the primary implements two transistor devices in parallel from table 1.

Figure 5 illustrates the efficiency and loss data for a 3KW Half bridge LLC with all transistors at 500KHz. With 500KHz, the loss breakdown for other components such as transformer, inductor, and SR transistors are supposed to the same, the key loss differences are from the primary side transistors. Although the LLC converter can achieve ZVS for turn-on, the switching turn-off loss still exists with magnetizing current on the primary, especially when the switching frequency is increased to 500KHz. These turn-off losses cannot be neglected. Compared to GaN, the most dominate losses for Si and SiC are the switching turn-off losses, and Si has six times higher switching turn-off loss than GaN, while SiC has four times higher switching turn-off loss than GaN. Also, the GaN-based LLC has much smaller drive loss compared to Si and SiC. The overall results show that the GaN-based LLC has around 20% lower total losses than SiC and 37% lower total losses than Si. Ultimately, high efficiency is achieved with GaN-based LLC, and this improvement in efficiency provides the incremental performance desired to meet or exceed the latest industrial system requirements, for example, 80Plus titanium for a telecom AC/DC PSU.

Figure 6 shows the other 3KW comparison between 500kHz GaN-based LLC and 100kHz Si-based LLC. In this example, efficiency was held constant with 97.9% to investigate the impact on power density.As shown in Figure 6, with GaN-based LLC at 500KHz, the volume of the resonant tank can be relatively reduced by 64% comparing to a Si-based LLC at 100KHz. Overall, the GaN-based solution with 500kHz can achieve 2.2 times smaller volume than Si-based for the 3KW LLC converter.

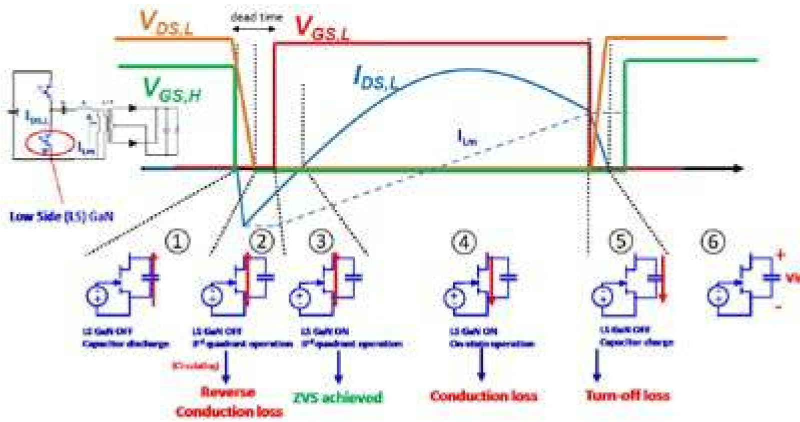


Figure 4: The LLC resonant converter's operation and loss breakdown for a steady state cycle

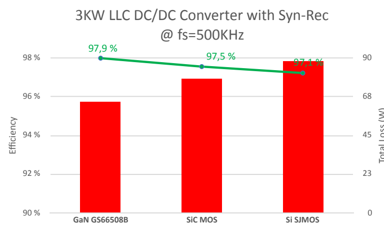
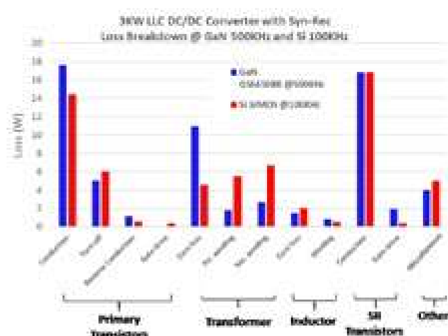


Figure 5:
The loss and efficiency of a 3KW 500kHz LLC resonant converter with GaN versus Si and SiC



Parameters	GaN @500KHz	Si @100Hz
Peak Efficiency	97.9%	97.9%
Resonant tank parameters	Lm=10uH, Lr=2uH, Cr=50nF	Lm=50uH, Lr=9uH, Cr=280nF
Transformer; Tr Size	PQ3535 17300mm³	PQ5050 37200mm³
Inductor; Lr Size	PQ2016 8T 2310mm³	PQ3535 12T 17300mm³
Capacitor; Cr Size	9x5.6nF 32mm³	6x47nF 82mm³
Total volume	19642mm³	54582mm³
Normalized total resonant tank volume	1x	3x
Normalized DC/DC power density	2.2x	1x

Figure 6:
The 3KW loss and efficiency of a 500kHz GaN-based LLC and a 100KHz Si-based LLC

Conclusion

This case study of the LLC resonant converter shows a clear performance advantage with GaN power transistors. From the viewpoint of efficiency and power density, GaN power transistors, with the lowest $Co_{(tr)}$, Q_{gd}, t_{off} and Q_g, are the best selection for LLC topology. Furthermore, the absence of the body diode with GaN and zero Q_{rr} makes the system more reliable, avoiding hard commutation failure damage. In summary, GaN provides much higher value in both efficiency and power density compared to Si and SiC transistors for LLC topology applications.

Reference

[1] B. Jayant Baliga's, the book "Fundamentals of Power Semiconductor Devices", on page 440~442.

[2] Clark Person, the Master Thesis of the Virginia Polytechnic Institute and State University "Selection of Primary Side Devices for LLC Resonant Converters", April 2008.

About the Author

Jimmy Liu is a technical marketing director at GaN Systems Inc. He holds PhD on power electronics and has deep experiences on wide bandgap devices' applications and renewable energy system designs.

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