Comparison of Wide-bandgap Devices in 1 kV, 3 kW LLC Converters*

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Abstract: Emerging wide-bandgap (WBG) devices, such as silicon carbide (SiC) MOSFETs and gallium nitride (GaN) high-electron-mobility transistors (HEMTs) provide new opportunities to realize high efficiency, high power density, and high reliability in several kHz, 1 kV input, and several kW output applications. However, the performance comparison between SiC MOSFETs and GaN HEMTs in high-voltage, high-frequency, medium-high-power DC conversion applications have not yet been investigated thoroughly. Two 1 kV, 3 kW LLC prototypes with GaN and SiC devices are built to perform a careful comparison of the prototypes in terms of parameters, power density, zero voltage switch realization, and overall efficiency. This provides guidance for the appropriate evaluation of WBG devices in high-voltage, high-frequency, and medium-high-power applications.

Keywords: Wide-bandgap devices, application, high voltage, medium-high power

1 Introduction

With a tendency for higher voltage and increased power demands, traditional silicon (Si) devices can only meet the DC conversion requirements in applications used in, for example, ships, unmanned aerial vehicles (UAVs) and cars¹-².

The appearance of emerging wide-bandgap (WBG) devices, such as silicon carbide (SiC) MOSFETs and gallium nitride (GaN) high-electron-mobility transistors (HEMTs), provides new opportunities to address this problem ³-⁴. Compared with Si devices, SiC MOSFETs and GaN HEMTs possess a better figure of merit (FOM). Thus, they can realize higher withstanding voltage, lower loss, and higher frequency, which helps break down the technical barriers of efficiency, power density, and reliability in several kHz, 1 kV input, and several kW output applications ⁵.

However, the performance comparison between SiC MOSFETs and GaN HEMTs in such high-voltage, high-frequency, and medium-high-power DC conversion applications has not been thoroughly investigated. It needs to be mentioned that the LLC topology can realize the zero voltage switch (ZVS) of the switching devices on the primary side and the zero current switch (ZCS) of the rectifying devices on the secondary side ⁶. Thus, it becomes the competitive candidate in high-voltage, medium-high-power applications. In this study, two 1 kV, 3 kW LLC prototypes with SiC MOSFETs and GaN HEMTs are built to perform a careful comparison in terms of parameters, power density, ZVS realization, and overall efficiency, providing guidance for the appropriate evaluation of WBG devices.

2 Full-bridge LLC converter with SiC MOSFETs

2.1 Topology

Since the SiC MOSFET can withstand 1 700 V, the full-bridge structure is employed when considering the current stress on switching devices. The topology is shown in Fig. 1.

The matrix transformer can distribute the voltage stress on the primary side and the current stress on the secondary side, in which planar transformers with
lower height can be easily adopted. The thermal source is dispersed and the converter power density is increased. Thus, the matrix transformer can simplify the thermal and insulation design [7].

![Fig. 1 Full-bridge LLC topology with SiC MOSFETs](image)

The split resonant tank is adopted to restrain the current distortion in Ref. [8]. Since the input voltage rises and the device switches faster, larger dv/dt occurs on the inter-winding capacitor. When the planar magnetics are used, the inter-winding capacitor increases significantly, and the large displacement current is then induced, which causes the distortion of the resonant current. Because the LLC topology realized the ZVS with the help of resonant current, the distortion finally influenced the ZVS realization of the switching devices.

### 2.2 Operational mode

Following are the operational modes of the full-bridge LLC converter, as shown in Fig. 2. When $S_1$ and $S_4$ are on, the power flows from the primary side to the secondary side, and when $D_2$, $D_6$, $D_8$ are on, the load is supplied. When $S_2$ and $S_3$ are on, the resonant current changes direction, and $D_1$, $D_3$, $D_5$, $D_7$ are on.

Fig. 3 shows the main waveforms of the SiC full-bridge converter. Since the switching devices operate symmetrically, the waveform of the resonant current $i_{Lr}$ is symmetrical.

### 2.3 Prototype

To verify the feasibility of the topology, a 1 kV, 3 kW SiC LLC prototype is built, as shown in Fig. 4.

![Fig. 4 SiC full-bridge LLC prototype](image)

The auxiliary power supply powers the digital signal process (DSP) control system and the drive board. The DSP control system is responsible for the sampling of thermal, voltage, and current information,
along with calculation of the duty cycle and switching frequency. The drive board transforms the duty cycle and switching frequency to the driving signal of the primary switches.

Tab. 1 provides the parameters of the prototype. To make a compromise between the switching loss and the volume, 300 kHz is selected as the resonant frequency. Because four matrix transformers with center taps are adopted, the turn ratio is 8:1:1 for each transformer.

Tab. 1 Parameters of the SiC LLC prototype

| Parameter                      | Value             |
|--------------------------------|-------------------|
| Input voltage \(V_{in}\)/V     | 850-1150          |
| Output voltage \(V_{out}\)/V   | 32                |
| Output power \(P_{out}\)/W     | 3000              |
| Resonant frequency \(f_r\)/kHz | 300               |

Tab. 2 presents the power device selection of the prototype. Considering the reliability, high-voltage capacitors are used as input capacitors \(C_{in}\), and SiC MOSFET C2M1000170D that can handle 1700 V breakdown voltage is selected as the switching devices \(Q_1-Q_4\).

Tab. 2 Power device selection of the SiC LLC prototype

| Parameter                     | Description                     |
|-------------------------------|---------------------------------|
| Input capacitors \(C_{in}\)   | 2220Y1K50154KXTWS21.5 kV, 0.15 \(\mu\)F x 8 (Knowles) |
|                               | B32024A3224M000 1.5 kV, 0.22 \(\mu\)F x 2 (TDK)       |
| Output capacitors \(C_o\)     | KRM555WR71H336MH01L 50 V, 33 \(\mu\)F x 24 (Murata) |
|                               | GCM32DC72A475ME02L 50 V, 4.7 \(\mu\)F x 16 (Murata) |
| Resonant inductors \(L_{r1}, L_{r2}\) | PQ 20/16 DMR96 (DMEGC) |
| Transformers \(T_r\)          | PQI 35/23 DMR96 (DMEGC)         |
| Resonant capacitors \(C_{r1}, C_{r2}\) | F463AG102K2KOL 2 kV, 1 nF x 6 (KEMET) |
| Primary switches \(Q_1-Q_4\)  | C2M1000170D                  |

3 Stacked-bridge LLC converter with GaN devices

3.1 Topology

Three level topology features low-voltage stress. Thus, they are attractive for kV input applications\[^{[9-10]}\]. Because the maximum drain-to-source breakdown voltage of the commercial eGaN HEMTs is now 650 V, the stacked-bridge structure is employed, as shown in Fig. 5. The voltage stress of the primary switching devices is reduced by 1/2 compared to the full-bridge structure\[^{[11]}\].

Fig. 5 Stacked-bridge LLC topology with SiC devices

Similar to the SiC full-bridge LLC converter, a matrix transformer is used to distribute the voltage stress on the primary side and the current stress on the secondary side, and a split resonant tank is adopted to restrain the current distortion, which improves the ZVS condition of the switching devices.

3.2 Operational mode

Fig. 6 shows the operational modes of the stacked-bridge LLC converter. When \(S_1\) and \(S_4\) are on, the input voltage of the resonant tank is \(V_{in}\), the power
flows from the primary side to the secondary side, and when \( S_6, S_8, \) and \( S_{10} \) are on, the load is supplied. When \( S_2 \) and \( S_3 \) are on, the input voltage of the resonant tank is 0 V, the resonant current freewheels and then changes direction, and \( S_6, S_7, \) and \( S_9 \) are on.

Fig. 7 shows the main waveforms of the GaN stacked-bridge converter. The input voltage of the resonant tank \( V_{AB} \) is asymmetrical, the DC component of the resonant tank input voltage is totally applied on the capacitors \( C_{r1} \) and \( C_{r2} \), and the waveform of the resonant current \( i_{Lr} \) remains symmetrical.

**3.3 Prototype**

To verify the feasibility of the topology, a 1 kV, 3 kW GaN LLC prototype is built, as shown in Fig. 8. Similar to the SiC prototype, it contains the controlling, driving, and main power circuits.

Tab. 3 provides the parameters of the prototype. To take full advantage of the GaN HEMTs performance and provide a compromise between the switching loss and volume, 1 MHz is selected as the resonant frequency. The voltage ratio of the full-bridge topology is twice that of three-level topology. Thus, the turn ratio of transformer in the SiC prototype is twice that of the GaN prototype. As a result, the matrix transformer design of the two prototypes is different. Since three matrix transformers with center taps are adopted, the turn ratio is 6:1:1 for each transformer.

**4 Comparison of the two converters**

**4.1 Comparison of the device parameters**

From the comparison of the device parameters shown in Tab. 5, it is noted that the equivalent on resistance \( R_{on} \) of GaN HEMTs is smaller than that of the SiC MOSFET. As the rated current of SiC MOSFET C2M1000170D is significantly smaller than eGaN HEMT GS66508T, C3M0065100J is used to
make the comparison because the rated current is 22.5 A, which is similar to GS66508T. Meanwhile, the equivalent on resistance of eGaN HEMTs is smaller. Conversely, when considering the gate-source charge \( Q_{gs} \) and the gate-drain charge \( Q_{gd} \), eGaN HEMTs have better performance.

| Tab. 5 Device parameters         | \( V_{ds}/V \) | \( I_{ds}/A \) | \( R_{ds(on)}/m\Omega \) | \( Q_{gs}/nC \) | \( Q_{gd}/nC \) |
|---------------------------------|---------------|---------------|--------------------------|----------------|----------------|
| GS66508T (GaN)                  | 650           | 30.0          | 50                       | 2.2            | 1.8            |
| C3M0065100J (SiC)               | 1000          | 22.5          | 65                       | 9.0            | 16.0           |
| C2M1000170D (SiC)               | 1700          | 5.0           | 1000                     | 4.7            | 5.4            |

The conduction loss of the switching devices \( P_{con} \) is expressed as

\[
P_{con} = I_{ds\_rms}^2 R_{ds(on)}
\]

where \( I_{ds\_rms} \) is the drain-to-source RMS current; \( R_{ds(on)} \) is the drain-to-source on-state resistance.

Because the LLC topology can realize zero-voltage turn-on, the switching loss only includes the turn-off loss \( P_{turn\_off} \), which is expressed as

\[
P_{gate} = V_{gate}^2 C_{iss} f_{sw}
\]

\[
P_{turn\_off} = \frac{1}{2} V_{ds\_off} I_{ds\_off} \left( \frac{Q_{gs} + Q_{gd}}{I_{dr\_off}} \right) f_{sw}
\]

where \( C_{gs}, C_{gd}, C_{iss}, V_{gate}, V_{ds\_off}, I_{ds\_off}, I_{dr\_off} \) and \( f_{sw} \) are the gate-to-source capacitance, gate-to-drain capacitance, input capacitance, gate drive voltage, off-state drain-to-source voltage, turn-off instant drain-to-source current, sink current and switching frequency, respectively.

From these equations, although the eGaN HEMTs have a smaller drain-to-source break down voltage, they produce less conduction and reduce switching loss compared to the SiC MOSFETs.

4.2 Comparison of the power density

Since the two prototypes have the same output power, the smaller volume means higher power density. According to the previous section, eGaN HEMTs produce less switching loss and, thus, are more suitable for working at high frequency. However, higher frequency means smaller core and fewer winding turns, that is, smaller magnetics [12].

The comparison of the prototype dimensions are shown in Fig. 9. Evidently, with eGaN HEMTs, the converter becomes 18.06% smaller compared to the converter with SiC MOSFETs.

4.3 Comparison of the ZVS realization

Since the switching time of the SiC prototype is 140 ns, the \( dv/dt \) on the inter-winding capacitor is 11.8 kV/\( \mu \)s. High \( dv/dt \) will distort the resonant current waveform as the waveform of channel 2, as shown in Fig. 10a. Thus, it influences the ZVS realization of primary side switches as the waveforms of channels 2-4. With the help of the split resonant tank, the degree of resonant current distortion is restrained, as shown in Fig. 10b, and the ZVS is realized.

Similar to the SiC prototype, while the switching time of the GaN prototype is 30 ns, the \( dv/dt \) on the
Fig. 10  Waveforms of the SiC prototype

inter-winding capacitor is 33 kV/μs, the distortion of the resonant current is evenly severe, and the split resonant tank structure is necessary to realize the ZVS of the primary side switches, as shown in Fig. 11.

Fig. 11  Waveforms of the GaN prototype

4.4  Comparison of the loss and efficiency

The dominant power converter loss usually originates from switching devices and magnetics. Losses of switching devices have been discussed before, and the losses of magnetics are expressed as

\[ P_{\text{winding}} = I_{dc}^2 R_{dc} + \sum_{i} I_{\text{rms}, i}^2 R_{ac, i} \quad (6) \]

\[ P_{\text{core}} = P_v V_e \quad (7) \]

\[ P_i = C_m f^x B_m (C_0 - C_1 T + C_2 T^2) \quad (8) \]

where \( I_{dc}, R_{dc}, I_{\text{rms}, i}, R_{ac, i}, P_{\text{winding}}, P_v \) and \( V_e \) are the DC current, DC resistance, \( i \)-th RMS current, \( i \)-th AC resistance, winding loss, core loss per volume, and effective volume, respectively. Further, \( C_m, x, y, C_0, C_1 \) and \( C_2 \) are the coefficients of Steinmetz formula; \( f \) is the switching frequency; \( T \) is the temperature.

Since the AC resistance \( R_{ac} \) has a positive relationship with the switching frequency \( f_s \), it is observed that the winding loss and the core loss increase with the rise of the switching frequency.

Fig. 12 shows the comparison of the loss distribution. Replacing the SiC MOSFETs with the eGaN HEMTs as the switching devices, 27.3 W loss can be saved (67%). Since the loss of magnetics increases with the rise of the switching frequency, the resonant inductor loss in the GaN prototype rises 6.7 W, compared to the resonant inductor loss in the SiC prototype (which rises 137.77%). Because the SiC prototype uses four matrix transformers and the GaN prototype uses three matrix transformers, the transformer loss in the GaN prototype is only 2.8 W, different from the transformer loss in the SiC prototype (9%). However, when viewed in terms of individual transformer, the transformer loss in the GaN prototype is 1.65 W higher than the transformer loss in the SiC prototype (which is 21.2% higher).

Fig. 13 shows the comparison of the efficiency curve. As using the eGaN HEMTs as the switching device saves 67% loss because the diode forward recovery loss increases significantly at 1 MHz, the efficiency of the GaN prototype is 0.3% lower than the efficiency of the SiC prototype at a 3.3 kW load condition. However, with the help of the synchronous rectifier (SR) technology, the efficiency of the GaN prototype is 1.5% higher than the efficiency of the SiC prototype at a 3.3 kW load condition.

Fig. 14 shows a comparison of the thermal
images. Both prototypes use aluminum heat sinks with external fans for cooling. Fan volume is not included in the volume of prototypes. Consistent with the loss distribution analysis, the temperature of the SiC MOSFET is 44 °C higher than eGaN HEMTs (160% higher). The temperature of the transformer in the SiC prototype is close to the temperature of the transformer in the GaN prototype (only 1.2 °C difference). The temperature of the resonant inductor in the GaN prototype is 11.8 °C higher than the temperature of the resonant inductor in the SiC prototype (30% higher).

5 Conclusions

In this study, two 1 kV, 3 kW LLC prototypes are built with GaN and SiC devices. The advantages and the disadvantages of SiC and GaN devices are thoroughly compared based on the theoretical analysis and experimental results. The SiC MOSFETs are able to withstand higher voltage compared to the GaN devices, so it is suitable to use SiC devices in applications where the voltage is over 1 kV.

The commercial GaN HEMTs demonstrate more attractive performance when balancing the conduction and switching losses. They show high power density advantages under MHz-level frequency conditions. They may achieve similar efficiency as that of the SiC MOSFETs. However, the multi-level circuit increases the complexity and cost. In summary, the GaN HEMTs are more suitable for applications when high power density is the first priority and the voltage is less than 1.3 kV (so three level topology can handle the voltage stress). However, as the frequency increases, the magnetics loss will rise and the diode forward recovery loss cannot be ignored, so the design tradeoff needs to be made between the power density and the converter efficiency.

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