

An Investigation into the Tradespace of Advanced Wide-Band Gap Semiconductor Devices in a Full-Bridge DC-DC Converter

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ABSTRACT

In aerospace applications, it is important to have efficient, small, affordable, and reliable power conversion units with high power density to supply a wide range of loads. Use of wide-band gap devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) devices, in power electronic converters is expected to reduce the device losses and need for extensive thermal management systems in power converters, as well as facilitate high-frequency operation, thereby reducing the passive component sizes and increasing the power density. A performance comparison of state-of-the-art power devices in a 10 kW full-bridge dc-dc buck converter operating in continuous conduction mode (CCM) and at switching frequencies above 100 kHz will be presented in this manuscript. Power devices under consideration are silicon (Si) IGBT with Si antiparallel diodes, Si IGBT with SiC antiparallel diodes, Si MOSFETs, SiC MOSFETs, and enhancement-mode GaN transistors. A 10 kW full-bridge dc-dc converter operating in the buck mode will be designed and tested using the LTSpice circuit simulator. Steady-state and switching transition waveforms will be presented for each case to aid the performance evaluation. From the simulation results, while the use of IGBTs resulted in efficiencies > 95 %, the switching frequency of commercially available devices is limited to 70 kHz, resulting in larger passive components and higher transients. Converter using Si devices exhibited slightly lower efficiencies than the one using SiC devices. SiC devices, rated at 1200 V, exhibited better transient response as well as switching transitions. Use of GaN devices resulted in efficiencies > 98%, thus yielding performance much superior to the others. However, the commercially available GaN devices can only withstand maximum voltage stresses 650 V.

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INTRODUCTION

In aerospace applications, it is important to have efficient, small, affordable, and reliable power conversion units with high power density to supply a wide range of loads, including constant-current loads. Full-bridge dc-dc converters are very popular in medium and high-power applications. Figure 1 shows a full-bridge dc-dc converter circuit. Bridge A acts as a full-bridge network with controllable switches and Bridge B operates as a rectifier network. The transformer with the turns ratio $n:1$ provide galvanic isolation between the input dc bus and the load and if needed, provide a boost to the voltage conversion ratio. Inductor L and capacitor C form an output filter network. The efficiency and reliability of the converter is dependent on the semiconductor switch characteristics and resiliency. The size of the converter is mainly determined by the size of the passive components such as capacitors, inductors, and isolation transformers.

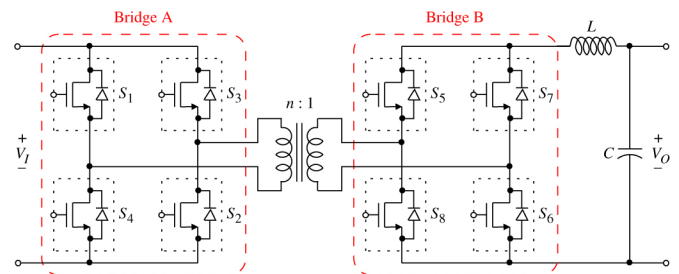


Figure 1. Full-bridge dc-dc buck converter circuit.

Silicon (Si) technology for power devices is well established and is near to its theoretical physical limitations. Because of their high gate capacitance and silicon's thermal properties, Si-based switches in dc-dc converters limit the switching frequency and high-temperature operation. By increasing the switching frequency, the size of passive components may be reduced. This reduction in size comes at the expense of increased switching losses in the switches. Soft-switching techniques may be used to reduce switching losses, but will increase the complexity and size of the converter. Snubber circuits may also need to be employed to improve the reverse recovery characteristics

of the antiparallel diodes. High-power operation results in high operating temperatures for the switches, requiring extensive thermal management systems for heat dissipation, which increases system complexity and size.

It has been proposed that wide-band gap (WBG) materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) might prove to be a better choice for power devices in high power, high voltage, and high temperature applications [1][2]. According to Lux Research, SiC is expected to displace Silicon (Si) in power converters as early as 2020 to better address the emerging needs of power electronic performance requirements in electric vehicles [4]. Table 1 shows a comparison of the electronic and physical characteristics of Si, SiC, and GaN. The wide-energy band gap allows SiC and GaN to operate at high-temperature, high-voltage, and high-power conditions. However, with the current device manufacturing technology, GaN devices can handle breakdown voltages up to 650 V, while SiC devices can handle up to 1200 V. SiC devices offer superior thermal performance due to their high thermal conductivity and GaN devices offer superior switching performance due to their high carrier mobility. High thermal conductivity of SiC indicates that it can dissipate heat easily, thereby reducing the need for excessive thermal management systems for high-power applications. Higher electric breakdown field results in thinner drift region and higher doping for a given voltage rating, reducing on-resistance of the devices and thus, increasing the system efficiency.

Table 1. Electronic and physical properties of Si, SiC, and GaN

Property	Si	4H-SiC	GaN
Band gap (eV)	1.12	3.26	3.45
Electron mobility (cm^2/Vs)	1200	800	1250
Hole mobility (cm^2/Vs)	450	140	850
Electron saturation velocity ($\times 10^7 \text{cm/s}$)	1.0	2.0	2.2
Critical breakdown electric field (MV/cm)	0.3	2.2	2.0
Thermal conductivity (W/cmK)	1.5	4.9	1.3
Dielectric constant ϵ_r	11.8	10.1	9
Commercial wafers (in)	12	4	2

Si IGBTs are very popular in high power applications due to their high power handling capabilities. Advantages of IGBT are ease in control and high input impedance as in a MOSFET and low conduction losses as in a BJT. However, due to current tailing in IGBTs, switching frequencies are limited to about 70 kHz. Antiparallel diodes connected to the IGBT improve its reverse current capability and the switching transitions. As SiC technology matured, it was evident that the use of SiC Schottky diodes, instead of the traditional Si diodes, as the antiparallel diodes for the IGBTs improve the switching transition performance by lowering the switching losses, although still limited by the switching frequency of the IGBT. An increase in switching frequency leads to smaller passive and magnetic components, which results in smaller power conversion

units. To this end, semiconductor devices such as MOSFETs should be considered due to its capability to handle higher switching frequencies. Si technology for MOSFETs is very well matured. WBG devices such as SiC MOSFETs and GaN transistors are gaining popularity in such applications due to their high power, high switching capabilities.

A 10 kW full-bridge dc-dc buck converter operating in continuous conduction mode (CCM) will be designed and a performance comparison of state-of-the art power devices in the designed converter operating at switching frequencies > 100 kHz will be presented in this manuscript. Power devices under consideration include:

1. Si IGBT with Si antiparallel diodes,
2. Si IGBT with SiC antiparallel diodes,
3. Si MOSFETs,
4. SiC MOSFETs, and
5. Enhancement-mode GaN transistors.

DESIGN

Input dc bus characteristics in military aircrafts, as specified in the DoD Interface Standards [5], are shown in Table 2. The constant current load specifications are shown in Table 3. In the tables, V_i is the input voltage, V_o is the output voltage, P_o is the output power, and I_o is the output current. Full-bridge dc-dc converters are popular in medium and high-power applications and provide galvanic isolation between the input dc bus and the constant-current load. Also, the effective frequency for the design of the inductor and capacitor is $2f_s$, where f_s is the switching frequency, which results in smaller components. The design procedure for a full-bridge dc-dc buck converter operating in CCM adopted from [6] is presented below.

Table 2. Characteristics of the input dc bus [5].

	270 V	± 270 V
During steady-state:		
$V_{R(\text{nom})}$	270 V	540 V
$V_{R(\text{min})}$	250 V	500 V
$V_{R(\text{max})}$	280 V	560 V
During transients:		
$V_{R(\text{min})}$	200 V	400 V for 10 ms
$V_{R(\text{max})}$	330 V	660 V for 20 ms

Table 3. Characteristics of the constant current load.

P_o	10 kW
I_o	66.5 A
$I_{O(\text{ripple})}$	$\leq 0.1 \text{ A}_{\text{p-p}}$
$I_{O(\text{regulation})}$	$\leq 0.5 \text{ A}$
$V_{O(\text{nominal})}$	$\approx 150 \text{ V}$

Assume the maximum duty cycle $D_{max} = 0.4$ and converter efficiency $\eta = 1$. The maximum turns ratio for the isolation transformer is

$$n = \frac{2\eta D_{max} V_{imin}}{V_o} \quad (1)$$

Choose $n = 1$. Therefore, the duty cycle required is

$$D = \frac{nV_o}{2\eta V_i} \quad (2)$$

Minimum inductance required to operate in CCM is given by

$$L_{min} = \frac{V_o(0.5-D_{min})}{2I_o f_s} \quad (3)$$

Choose $L > L_{min}$. Resultant maximum peak-to-peak inductor current ripple is given by

$$\Delta i_{Lmax} = \frac{V_o(0.5-D_{min})}{f_s L} \quad (4)$$

Maximum current through the primary winding is obtained as

$$I_{1max} = \frac{I_o + \Delta i_{Lmax}/2}{n} \quad (6)$$

Assume peak-to-peak ripple current through the magnetizing inductance L_m of the primary to be

$$\Delta i_{Lmmax} = 20 \% \text{ of } I_{1max} \quad (7)$$

Therefore, the minimum magnetizing inductance required is

$$L_{mmin} = \frac{D_{min} V_{1max}}{f_s \Delta i_{Lmmax}} \quad (8)$$

Choose $L_m > L_{mmin}$. If the allowed output voltage ripple is assumed to be 10 % of V_o , maximum capacitor equivalent series resistance (ESR) is obtained as

$$r_{Cmax} = \frac{V_r}{\Delta i_{Lmax}} \quad (9)$$

Choose $r_C < r_{Cmax}$. Thus, the minimum value of filter capacitance required is

$$C_{min} = \max\left(\frac{D_{max}}{2f_s r_C}, \frac{0.5-D_{min}}{2f_s r_C}\right) \quad (9)$$

Table 4. Design parameters and component stresses for full-bridge converter.

Parameter	Unit	$V_i = 540$ V using ± 270 V buses	
D_{min}		0.114	
D_{nom}		0.139	
D_{max}		0.188	
n		1	
f_s	kHz	30	200
L_{min}	μ H	14.52	2.18
Choose L	μ H	100	20
Δi_{Lmax}	A	19.32	14.49
L_{mmin}	μ H	164.13	25.43
Choose L_m	μ H	250	40
r_{Cmax}	m Ω	77.6	103.5
r_C	m Ω	50	50
C_{min}	μ F	128.8	19.32
Choose C	μ F	250	20
$V_{SM(primary)}$	V	660	660
$V_{SM(secondary)}$	V	660	660
$I_{SM(primary)}$	A	83.78	81.12
$I_{SM(secondary)}$	A	76.16	73.74

Choose $C > C_{min}$. The voltage stresses on the switches on the primary and secondary sides of the transformer are given by

$$V_{SM(primary)} = V_{1max} \quad (10)$$

and

$$V_{SM(secondary)} = \frac{V_{1max}}{n}, \quad (11)$$

respectively. The current stresses on the switches on the secondary and primary sides of the transformer are given by

$$I_{SM(secondary)} = I_o + \frac{\Delta i_{Lmax}}{2} \quad (12)$$

and

$$I_{SM(primary)} = \frac{I_{SM(secondary)}}{n} + \frac{\Delta i_{Lmmax}}{2}, \quad (13)$$

respectively. Table 4 shows the design parameters and component stresses obtained for the full-bridge converter operating at switching frequencies $f_s = 30$ kHz and 200 kHz. Based on the calculated component stresses, the following state-of-the art semiconductor switches were chosen: