A 500 kHz Silicon Carbide (SiC) Single Switch Class-E Inverter

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***Abstract*—Increased demand for intelligence in high performance applications such as home appliance, transportation, renewable energy systems, medical equipment and utilities interfaces, while managing cost, efficiency and volume is a challenge for inverter topologies. In addition, increased efficiency and optimal operation require complex control schemes, which require a large processing budget and expensive sensors. Advances in power semiconductor technology has revolutionized the industry, where signal processing methods and analog electronic topologies are being employed to process power. A Class-E inverter is a topology borrowed from amplifiers for DC to AC conversion. Class-E inverters promise an upgrade solution, where a single switch may be used for full wave inversion. Using this resonant topology promises to mitigate the need for complex control schemes, as only one switch must be controlled. Previous attempts at building Class-E converters, have been limited to smaller power ratings, as the switch experience's high voltage and current stress. SiC power semiconductor devices have been commercially available for the past few years, and offer several key advantages such as: faster switching speeds, higher voltage and current surge withstand capabilities, smaller overall system footprint and simpler cooling systems. This paper describes a 500 kHz Silicon Carbide (SiC) Class-E Inverter.**

***Index Terms*—class-E inverter, DC-AC conversion, high frequency power electronics, single switch, resonant inverter, silicon carbide**

I. Introduction

Most modern industrial, commercial and medical applications require high-frequency, low cost, reliable power supplies. Examples of such applications are home appliance, transportation, renewable energy systems, medical equipment and utility interfaces [1]. Class-E inverters meet these requirements, but have been limited so far to lower power levels. They have high-efficiency, high power density, control simplicity, and low part count [2]-[5].

A Class-E inverter is a resonant type converter which can operate at high frequencies, with only one switch. The load is supplied through a sharply tuned series connected resonant circuit that results in a sinusoidal current, satisfying inversion criteria. The input inductor is large enough to assume dc current at steady state. If the circuit is switched at resonant frequency, then switch zero-voltage turn-off is achieved [6].

Due to the sharp tuned circuit, small variations on the switching frequency control the output voltage, allowing multiple analog or digital control strategies. One such method is using a voltage controlled oscillator (VCO), with feedback from the output voltage [7].

The major drawback of Class-E converters, is the high Q-factor required at resonant frequency, and the high voltage and current stress the switch experiences under normal operation [3], [4]. This has made wide implementation of this circuit limited, due to the high surge current requirements for the switch. This is a major issue, especially when coupled with high frequency operation.

The high frequency, high current ratings for the magnetic components has also been an issue. High power inductor current ratings greatly reduce with increase in frequency, as well as rating of capacitor at high power and high frequency. Advances in materials for capacitors and inductor cores, have made such high-frequency high-power magnetics available.

Silicon has been the traditional material for semiconductor devices for decades. It is still the dominate material used for low voltage and current electronics. But many compound semiconductor materials have been explored for power semiconductor device applications and silicon carbide (SiC) has proven to be a good candidate material for devices operating at high temperatures, high frequency, large power while operating under high voltage and current stress [8]-[9].

SiC is a wide Bandgap semiconductor material that has several key advantages over silicon when used in

Manuscript received March 24, 2018; revised June 25, 2018.

resonant circuits [10]-[14]. Though SiC devices have larger on state voltage drops, increasing on state losses, this is mitigated by the reduced switching losses and increased functionality offered by the other key advantages from using the material. Table I compares Si and 4H-SiC important physical properties.

The main properties of SiC that make it very attractive for use in Class-E inverters is the breakdown electric field, higher current density and band-gap. These properties result in high switching speed devices that can withstand high temperature operation and larger current and voltage spikes. SiC switches have been commercially available for the past several years, and have shown superb reliability. Devices available include: diodes, BJTs, IGBTs, Thyristors and MOSFETs.

Table II below is a summary of the key advantages due to the properties of SiC.

These key advantages enable the build of a high-frequency high-power Class-E converter, which may be used in congestion with small size high frequency transformers and smaller passives due to high frequency operation to reduce overall system volume. In addition, by reducing the size of the cooling system due to temperature characteristics of SiC switches, the system volume can be further reduced. This paper focuses on a SiC based Class-E inverter.

TABLE I: SI AND SIC PROPERTIES

Parameter	Si	4H-SiC
Energy Bandgap (eV)	1.12	3.26
Electric Field Breakdown (x 10^6V/cm @ 1kV operation)	0.25	2.2
Saturated Electron Drift (x10^7 cm/s @ E>2x10^5 V/cm)	1.0	2.0
Thermal Conductivity (W/m K @ Room Temperature)	150	400
Current Density (A/cm^2)	200 100 commonly used	1000 200 available and 800 reported

TABLE II: SUMMARY OF ADVANTAGES OF SIC

Performance Metric	Causal Property Affecting Metric	Advantage
Blocking Voltage	Electric Field Breakdown	Higher blocking voltages 10×
Current Density	Saturated Electron Drift	Higher current density 5×
Volumetric Reduction	Electric Field Breakdown	Power density 100×
Switching Speed	Electric Field Breakdown	Faster speeds 100×
Operating Temperature	Energy Bandgap, Thermal Conductivity	Higher operating temperature 4×

II. SIC CLASS-E INVERTER DESIGN

A schematic of a Class-E inverter is shown in Fig. 1 below. It consists of a series resonant circuit, a shunt capacitor, a choke inductor, switch and a load. The transistor is switched at 50% duty cycle at resonant frequency. The tight design of circuit parameters guarantees transistor resonance and optimum operation of the Class-E inverter.

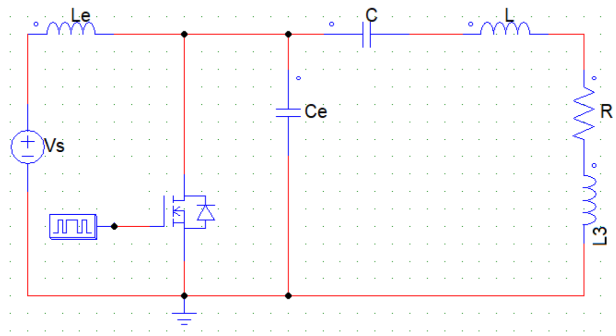

Figure 1. Class-E inverter schematic

The system is designed for 500 kHz switching frequency at 48 V DC input. A C2M0040120D SiC MOSFET from Cree/Wolfspeed was used as the main switching component.

During the switch off cycle, the switch current remains zero while the transistor voltage increases to peak. As the transistor voltage decreases to zero at the end of the off cycle where the switch is turned on and the transistor current increases to maximum. The transistor is switched off and the transistor current drops to zero before the switch voltage begins to rise again at the end of the on cycle. Ideally during on cycle, both transistor current and voltage have zero crossover which result in only conduction losses.

This is only valid at ideal conditions, at true resonance. Small switching losses occur if switching is not at true resonance. Class-E inverters efficiency can exceed 95% if precision components are used. This is a challenge as high frequency, high power, high tolerance magnetics are hard to find, especially at specific values to meet the high Q resonance requirements.

The design derivation is based on a switch-mode power amplifier's designs [15], but with some modifications for inverter considerations. The following equations and procedure are used to design the passive components:

For the input filter elements, (1) and (2) are used.

$$L_e = \frac{0.4004R}{2\pi f} \quad (1)$$

$$C_e = \frac{2.165}{2\pi fR} \quad (2)$$

where L and C are the resonant components, and may be calculated from derivation that satisfies the resonance equation as in

$$\omega_s L - \frac{1}{\omega_s C} = 0.3533R \quad (3)$$

where L may be calculated as following

$$L = \frac{QR}{2\pi f} \quad (4)$$

and therefore C may be calculated as following

$$C = \frac{1}{\omega_s\left(QR - 0.3533R\right)} \tag{5}$$

To ensure that the system is operating at resonance, the damping factor and the switching frequency may be verified according to (6) and (7)

$$\text{damping factor } (\delta) = \frac{R}{2}\sqrt{\frac{C}{L}} \tag{6}$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{7}$$

Table III below summarizes component design values, and commercially available devices chosen.

TABLE III: SIC CLASS-E PASSIVE COMPONENT DESIGN VALUES

Passive Component	Design Value		Available Value	
R	10	Ohm	10	Ohm
Le	1.28	μH	1.2	μH
Ce	68.9	nF	68	nF
L	22.3	μH	22	μH
C	4.79	nF	4.7	nF

III. SIC CLASS-E PROTOTYPE

The passive components were selected from commercially available values that are as close as possible to the design values. The values for magnetics where chosen such that they meet requirements at switching frequency.

The design was verified using the selected values in equations (6) and (7), and it was found that:

$$\delta = 0.073, \quad f = 495 \text{ kHz}$$

Fig. 2 is the constructed prototype. The PCB was carefully designed to reduce parasitics as much as possible, as they effect the passive component design values. This was accomplished by using planes instead of traces, in addition to reducing sharp corners as much as possible. Test points for voltage and current were also included.

The transistor was mounted on the bottom side of the PCB to a passive heat sink, while passive components on the top side of the board. This kept switch temperature at a distance from the capacitors and inductors, as their operating temperature is lower than that of the SiC switch.

Figure 2. SiC Class-E inverter prototype top-view.

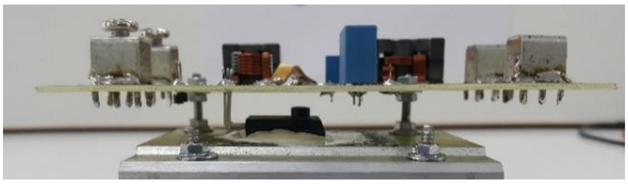

Figure 3. SiC Class-E inverter prototype side view.

Fig. 3 shows a side view of the prototype, showing the transistor mounting. A thermal insulating sheet was used to isolate the back side of the switch from the heat sink, as well as an insulating sleeve for the mounting screw. Thermal grease was used for a better thermal path from the switch to the heat sink.

IV. SIC CLASS-E INVERTER TESTING AND RESULTS

As the resonance frequency must be tightly controlled, it is important to test the resulting prototype frequency response. This is to actually use the appropriate frequency for operation. A Keysight E5061B network analyzer was used to test the devices response over frequency. The resulting resonance frequency was found to be 520 kHz as show in Fig. 4. This variation from design value is due to tolerances of the passive components in addition to parasitic in the PCB board, but still within acceptable limits.

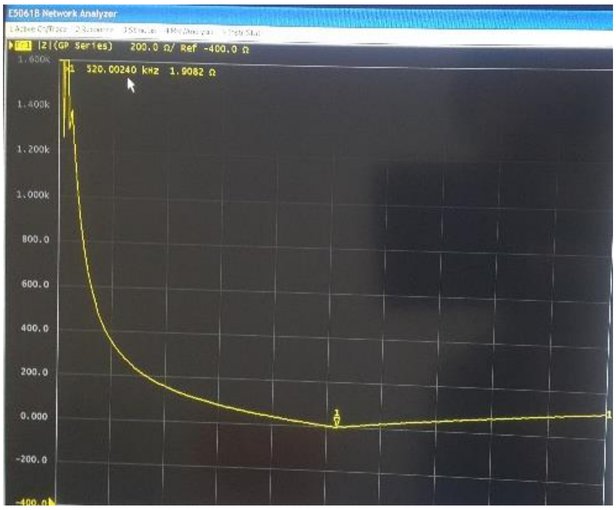

Figure 4. Frequency response of Class-E inverter prototype.

An open loop test was conducted to test the system. Fig. 5 shows the complete test setup. A programmable DC supply was used for the DC link, the supply was chosen to mimic a 48 V battery. A function generator provided the PWM control signal. As the signal was not efficient to drive the switch, an isolated gate driver was designed for proper drive and isolation. The gate driver was designed for voltage controlled devices such as IGBTs and MOSFETs. High power wire-wound resistors were used for the load, but it was found that the load inductance effected device operation. To decouple the load inductance from system operation, a full bridge rectifier was added before the load [16]. The rectifier was built using discrete SiC diodes as well.

Fig. 6 shows the output and switch voltage and current waveforms for a resistive load. The wire wound resistors show normal inductance behaviour, which led to the lagging current. As evident from the results, the switch does experience high current spikes, but within the SiC MOSFET rating, but this may be reduced with lower load parasitic inductance. The inverter was tested at approximately 100 W.

Fig. 7 shows the same waveforms but with a SiC full bridge rectifier between the inverter and load. By adding the rectifier, the inverter in not directly connected to the load, and hence the power factor correction and lower switch current spikes. Fig. 8 shows the load resistor current and voltage with the rectifier in place.

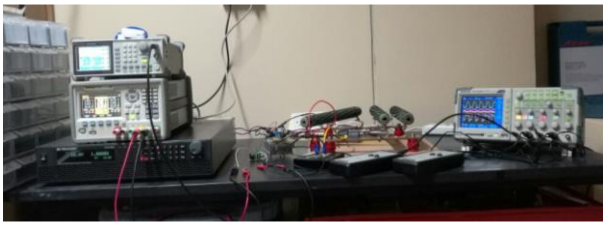

Figure 5. System test setup.

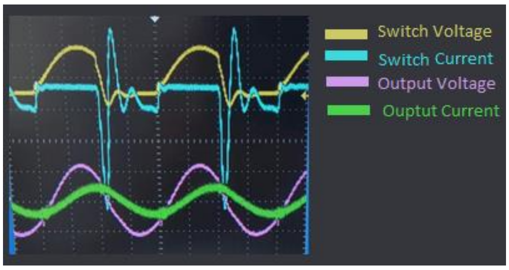

Figure 6. Output and switch voltage and current waveforms with resistive load.

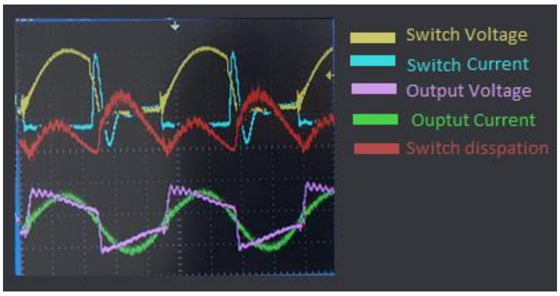

Figure 7. Output and switch voltage and current waveforms with rectifier load.

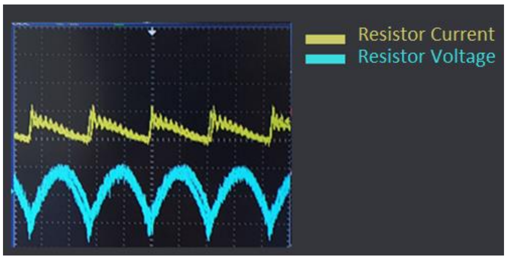

Figure 8. Load voltage and current waveforms with rectifier load.

V. CONCLUSION

A 500 kHz SiC Class-E inverter was successfully designed and built. A commercial SiC MOSFET was used to take advantage of SiC properties such as switching speed and high current stress withstanding capability. Testing of the system showed great results. This system is the first high-power high-frequency single switch SiC Class-E system. It will serve as a test vehicle for advances closed loop control algorithms.

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