Silicon Carbide MOSFET-Based Switching Power Amplifier for Precision Magnet Control

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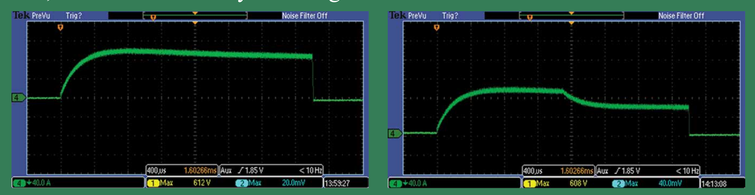
EAGLE HARBOR TECHNOLOGIES

Introduction

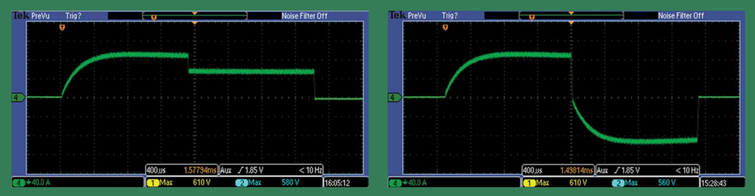
Eagle Harbor Technologies, Inc. (EHT) is using the latest in solid-state switching technologies to advance the state-of-the-art in magnet control for fusion science. Silicon carbide (SiC) MOSFETs offer advantages over IGBTs including lower drive energy requirements, lower conduction and switching losses, and higher switching frequency capabilities. When comparing SiC and traditional silicon-based MOSFETs, SiC MOSFETs provide higher current carrying capability allowing for smaller package weights and sizes and lower operating temperature. To validate the design, EHT has developed a low-power switching power amplifier (SPA), which has been used for precision control of magnetic fields, including rapidly changing the fields in coils. This design has been incorporated in to a high power SPA, which has been bench tested. This high power SPA will be tested at the Helicity Injected Torus (HIT) at the University of Washington. Following successful testing, EHT will produce enough SiC MOSFET-based SPAs to replace all of the units at HIT, which allows for higher frequency operation and an overall increase in pulsed current levels.

Low Power PWM Magnet Control

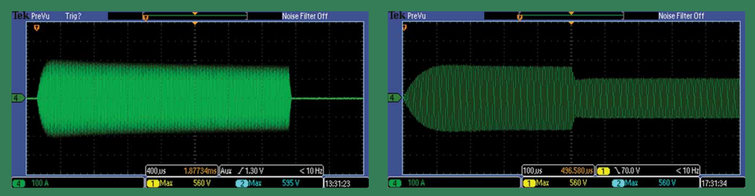
EHT developed a low power Switching Power Amplifier-2 (SPA-2) to test the board layout and components. The SPA-2 was tested for fast magnet driving. The pulser, operating at 250 kHz drove a magnet coil with an inductance of 85 µH. The pulse width was fixed during the initial current rise, but this could easily be changed for a faster rise.



All four waveforms produced at 500 V. Left: 2.15 ms pulse width at 250 kHz produced 100 A for 3 ms. Right: The pulse width started at 2.15 µs and was decreased to 2.09 µs to produce 100 A for 1.5 ms followed by 60 A for 1.5 ms.



Left: Same as above right with a single negative going pulse at the transition for 7.8 µs. Right: 2.15 µs pulse width for 100 A for 1.5 ms followed by -100 A for 1.5 ms.

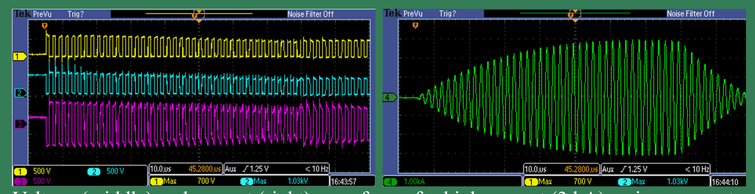


Resonant circuit: 85 µH, 5 nF, and 1.25 Ω Left: 200 A for 3 ms. Right: 500 µs at 200 A and 500 µs at 100 A. Both with 500 V drive.

High Power SPA

Using the lessons learned from the development of the SPA-2, EHT developed a high power version (SPA-16). This unit had cleaner switching waveforms than the first generation high power unit. The SPA-16 was tested into a range of resistive and inductive loads as well as series resonant circuits.

V_{Load} (purple), V_{S1} (yellow), V_{S3} (blue), and I_{Load} (green). Left: SPA-16 driving a 2.5-Ohm resistive load with 600 V at 200 kHz.



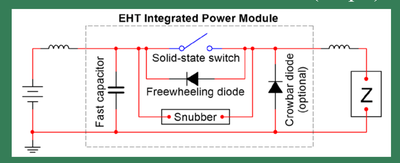
Voltage (middle) and current (right) waveforms for high current (3 kA) series resonant driving at 118 kHz. Drive voltage was 500 V

New Integrated Power Module

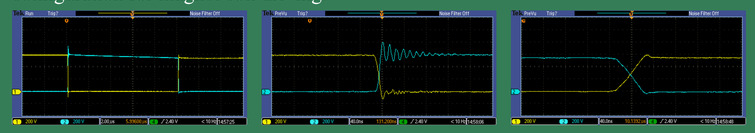
Originally designed to simplify precision magnetic control for the fusion science community, the EHT Integrated Power Module (IPM) is capable of hard switching high currents into resistive loads and driving crowbarred inductive loads. The EHT IPM includes fiber optically isolated gate drive, solid-state switches, freewheeling diodes, fast capacitors, snubbers (optional), and crowbar diodes (optional). This rack-mount unit is easily integrated with customer DC supplies, capacitors, and loads.

Below are sample specifications:

- Recommended maximum operating voltage: 800 V
- Single pulse current: 10 kA
- Magnet driver example: 2.5 kA at 100 kHz and 50% duty cycle for 10 ms
- Continuous current: 500 A at 30 kHz and 50% duty cycle (air cooled)
- Significant power increase with silicon carbide components and/or water cooling
- Control voltages produced from 120 VAC that is isolated to 5 kV (10 pF).



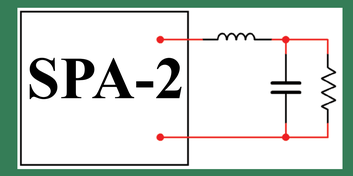
Left: New EHT Integrated Power Module. Right: Circuit diagram showing typical configuration for magnet coil driving.



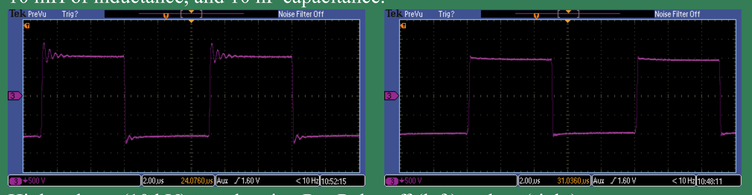
Left: V_{ce} (yellow) and V_{Load} (blue) hard switching 600 V into 1 Ω resistive load with 10 µs pulse width. Fast switch transitions: V_{ce} (yellow) and V_{Load} (blue) - 20 ns fall time (middle) and 40 ns rise time (right).

Pre-Pulse Technology

Many loads, even those generally considered pure resistive loads, have stray inductance and capacitance. These stray elements can cause ringing on the output waveform. EHT has developed a precision gate drive technique (patent pending) that can be used to significantly reduce or eliminate the ringing on the waveforms. EHT has tested this technique over a wide range of stray capacitance values (100 pF - 10 nF) and stray inductance values (100 nH - 100 mH).



Waveforms showing Pre-Pulse off (left) and on (right). Circuit parameters: 50 W load, 10 mH of inductance, and 10 nF capacitance.



High voltage (10 kV) test showing Pre-Pulse off (left) and on (right).

Conclusion

EHT has developed a SPA-2 for board layout and component testing. This board was used to demonstrate fast PWM magnet control and resonant circuit driving.

The testing results of the SPA-2 were used to design an SPA-16, which was capable of 3 kA into resonant loads at 118 kHz. This unit will be finalized and tested at HIT. Following successful testing, 30 units will be constructed and delivered to HIT to drive the helicity injectors.

EHT has also advanced the Integrated Power Module, including adding the heat sinking for CW operation. EHT has already sold 12 of these units.

EHT has developed Pre-Pulse Technology to reducing ringing on switching waveforms.

Acknowledgment

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