Phase I Development of Neutral Beam Injector Solid-State Power System

J.R. Prager; T. M. Ziemba*; K. E. Miller; I. Slobodov; S. Anderson
*prager@eagleharbortech.com

EAGLE HARBOR TECHNOLOGIES

Introduction

Neutral beam injection (NBI) is an important tool for plasma heating, current drive and a diagnostic at fusion science experiments around the United States, including tokamaks, validation platform experiments, and privately funded fusion concepts. Currently, there are no vendors in the United States for NBI power systems. Eagle Harbor Technologies (EHT), Inc. is developing a new power system for NBI that takes advantage of the latest developments in solid-state switching. EHT has developed a resonant converter that can be scaled to the power levels required for NBI at small-scale validation platform experiments like the Lithium Tokamak Experiment. EHT will present initial modeling used to design this system as well as experimental data showing operation at 15 kV and 40 A for 10 ms into a test load.

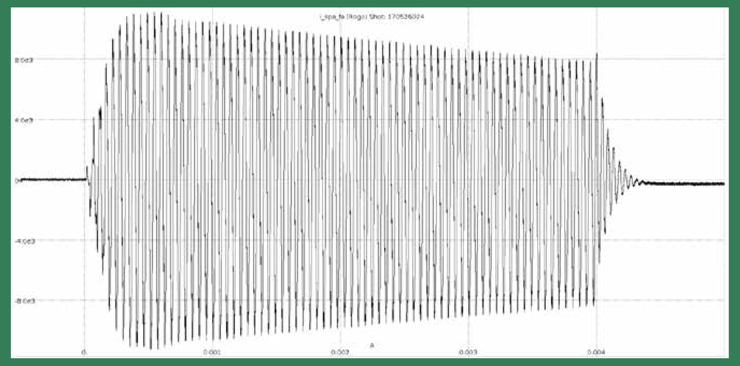
Neutral Beam Modulation

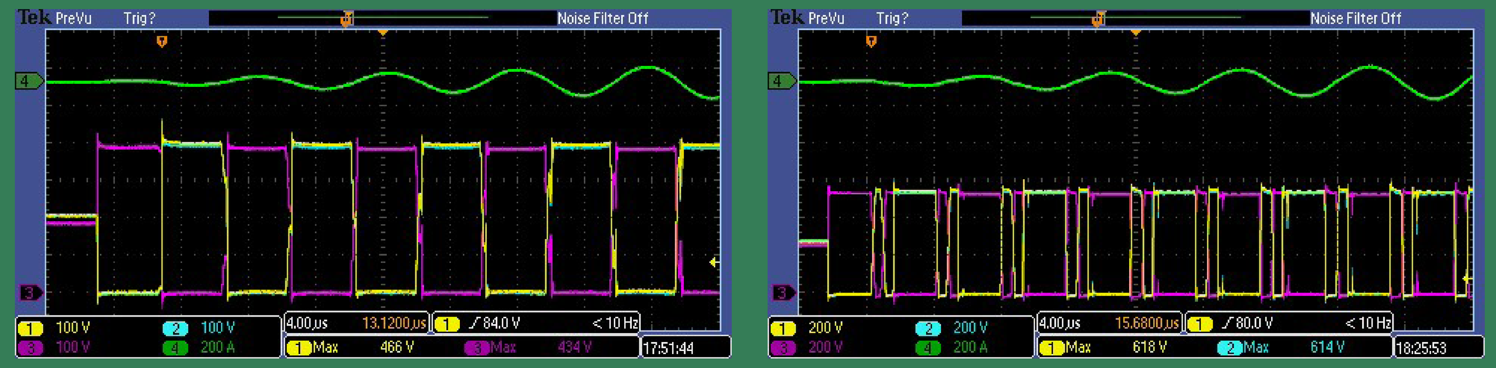
Neutral beam modulation experiments have been conducted at TEXTOR, MAST, and DIII-D. At TEXTOR, the NBI system apperature was modulated, while MAST modulated the current source. Recently, DIII-D published results modulating the grid voltage (slew 20 kV/s). The effects included beam torquing, instability supression, increased ion confinement time and improbed control of fast ion losses. This new EHT NBI power system can be used to modulate the NBI voltages on even faster timescales.

- Pace, et al. “Control of power, torque, and instability drive using in-shot variable neutral beam energy in tokamaks” Nucl. Fusion 57 (2017) 01400
- Pawley, et al. “Advanced control of neutral beam injected power in DIII-D,” Fusion Eng. Des. (2017)

SiC MOSFET Full Bridge

In a previous SBIR program, EHT developed a SiC MOSFET-based full-bridge to drive the helicity injectors at the HIT experiment at the University of Washington. Each full-bridge is capable of operation at 700 V and switching 16 kA at 100 kHz for 10 ms or lower current for CW operation. EHT extensively tested the full-bridges with the resonant voltage and flux circuits at HIT. EHT recently delivered six units to the HIT lab. This full-bridge will form the basis for the NBI grid power supply.

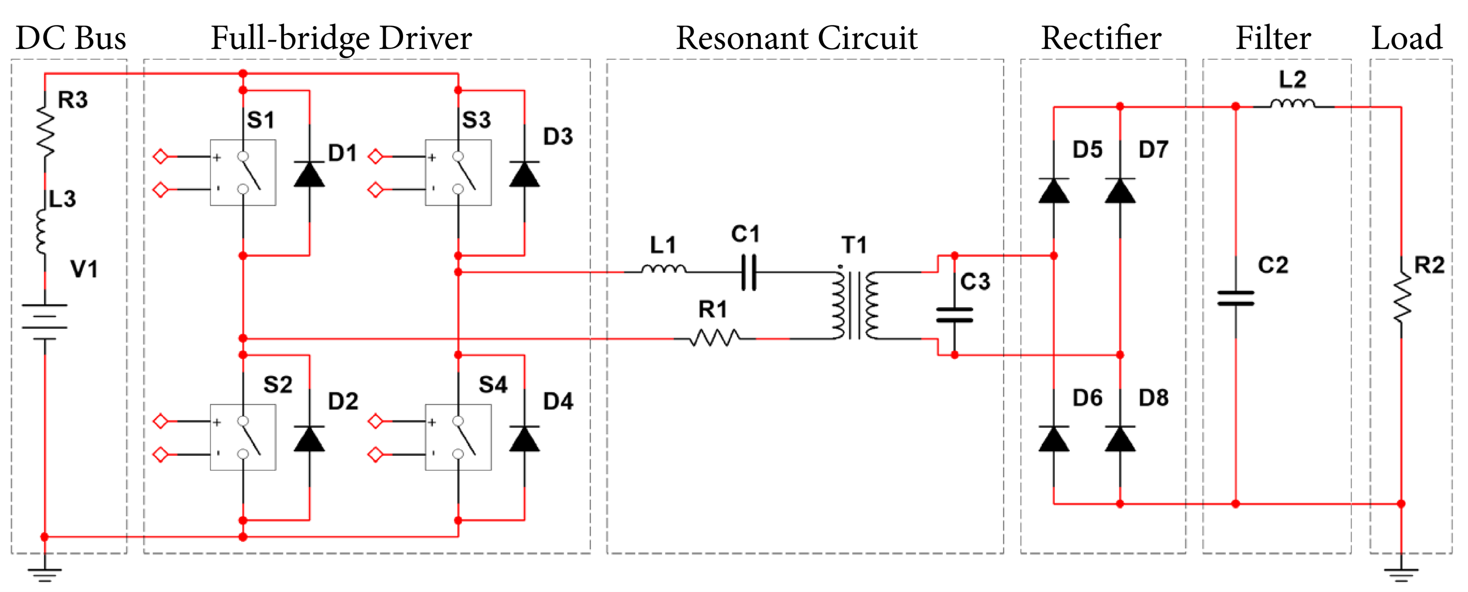




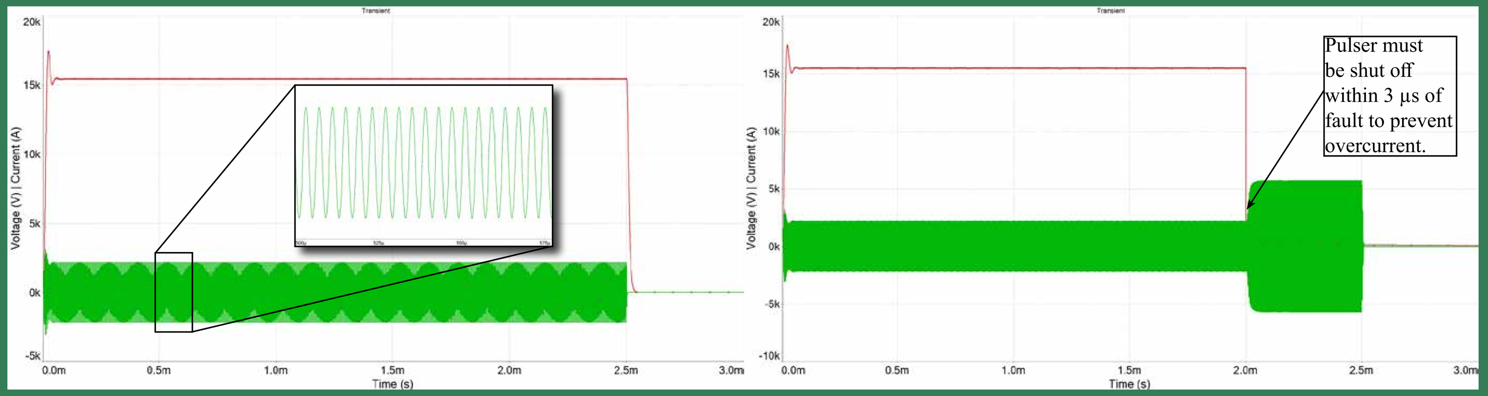
Upper right: 12 kA output waveform from HIT Rogowski. 4 ms duration. Lower Left: 100% duty cycle at V_{charge} = 400 V. Output current (green) and V_{ce} (magneta and yellow) Lower Right: 60% duty cycle V_{charge} = 550 V.

Circuit Modeling

EHT conducted initially circuit modeling using National Instruments Multisim to optimize the system efficiency, resonant components, switching frequency, and output stages. Additionally, modeling was used to identify potential fault conditions in the event that the grids short. The grid driver must be shut off within 3 µs of the grid fault to prevent an overcurrent condition. This loop time was easily achievable by the control system.



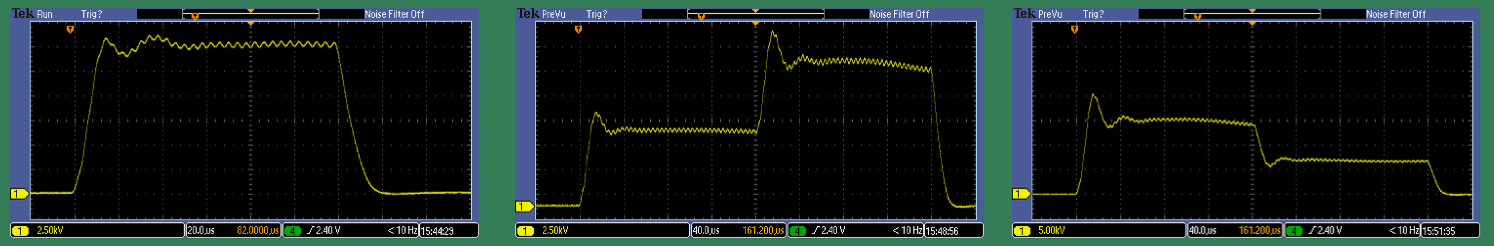
Simplified Multisim circuit model. Actual circuit model included stray components.



Left: Load voltage (red) and oscillating current (green) during normal operation. Initial voltage spike can be eliminated by lowering the switching duty cycle during startup. Right: Simulation of load fault at 2 ms. System must be shut down with 3 ms of fault to prevent overcurrent of solid-state switches in the full-bridge driver.

Initial Bench Testing

EHT conducted initial testing of the NBI grid supply into a 375 Ω resistive load. The initial pulse widths were kept short (few hundred microseconds) so that the energy storage capacitors could remain small to mitigate risk in the event of a failure. This initial testing focused on demonstrating the PWM control of the output voltage including changing the output voltage mid-shot. The results are shown below in the figures.



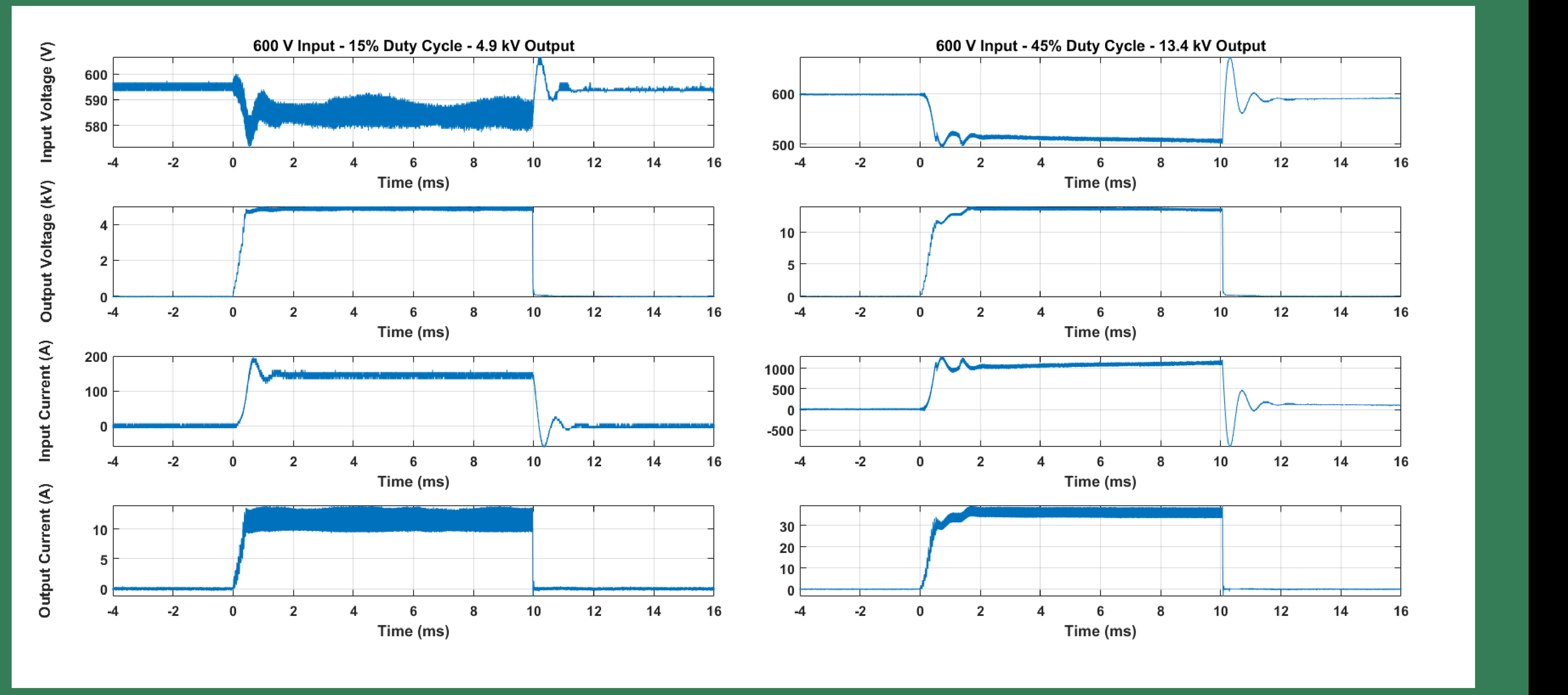
Left: 15 kV output for 120 µs into 375 Ω load. Middle: Increasing the voltage from 7.5 kV to 15 kV by increasing the duty cycle. Left: Decreasing the voltage from 15 kV to 7.5 kV by decreasing the duty cycle.

Acknowledgment

This work was funded by a DOE SBIR (DE-SC0017792).

Longer Pulse Dummy Load Testing

EHT tested the grid driver into a 375 Ω resistive load that can handle large dumps of energy. For 10 ms pulses, 13.4 kV was produced at the output with a 45% duty cycle. At 15% duty cycle, 4.9 kV was produced on the ouptut. The output voltage can be increased by raising the charge voltage. The energy storage for this test was a 1 MJ super capacitor bank. Future testing will include demonstration of slewing the voltage during the shot as well as fast shutdown during a simulated fault.



Plots of input and output voltage and input and output current with 600 V charge. Left: 15% duty cycle produced 4.9 kV into 357 Ω load. Right: 45% duty cycle produced 13.4 kV into 375 Ω load.

Conclusion

EHT has built an initial neutral beam grid power system with the following specs.

Charge Voltage: 0 – 700 V
Output Voltage: 0 – 15 kV
Output Current: 0 – 40 A

Switch Frequency: 125 kHz
Pulse Width: 8 µs – 100 ms
Shot Frequency: One per minute
Control: External Fiber
Short Tolerant: No (overcurrent requires shut down in 3 µs)

Weight: 126 lb (57 kg)
Size: 9U Rack Mount (15.75”x17”x28”)

Future work includes increasing the output voltage to over 20 kV, testing longer pulse widths, testing with real NBI grids, demonstrate fast shutdown, and measuring the efficiency.

For more information: http://www.eagleharbortech.com/