High Capacitor Bank Utilization with a Ćuk Converter

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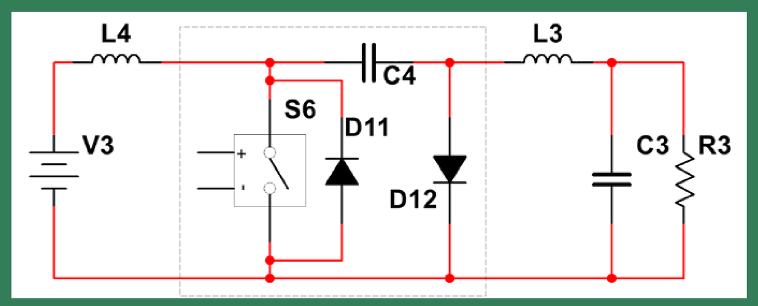
EAGLE HARBOR TECHNOLOGIES

Introduction

Eagle Harbor Technologies (EHT), Inc. is developing a Ćuk converter for local helicity injection and magnet driving and control for the Pegasus Toroidal Experiment at the University of Wisconsin – Madison. A Ćuk converter has low output ripple; high efficiency; voltage gain greater than one, allowing for deeper energy storage utilization; continuous power flow that lowers output EMI, reducing noise generation; continuous input and output current – energy flow from the series capacitor allows for greater control of the injector currents. Additionally, this configuration allows for series arrangements that isolate individual switch modules, so a failure does not potentially damage all solid-state switches. EHT has completed a Phase I program to design and build a high-frequency Ćuk converter, which was tested at Pegasus. EHT will present Phase I results showing increase capacitor bank utilization with a Ćuk converter. In a potential Phase II program, EHT will design, build, and test a bidirectional Ćuk converter that will reduce the heat load on electromagnet coils.

Motivation

Pegasus has recently investigated a new DC-DC converter design based on the Ćuk converter topology, which enables more precision injector and magnet current control on Pegasus over the present IGCT based system. The Ćuk converter can provide major benefits for fusion science applications, including:



Ćuk converter circuit diagram.

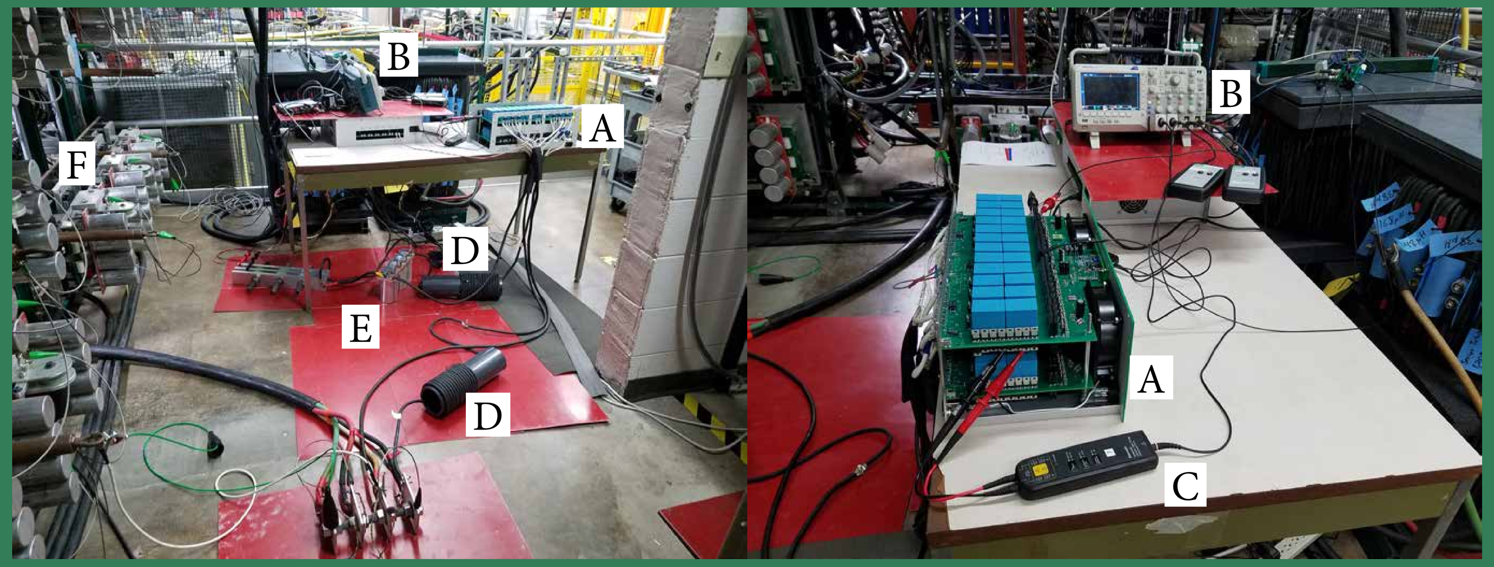
- Low output ripple
- Higher efficiency
- Voltage gain greater than one, which allows for deeper energy storage utilization
- Continuous power flow that lowers output EMI, reducing overall noise generation
- Continuous input and output current – energy flow from the series capacitor should allow for greater control of the injector currents
- Series arrangements can be utilized that effectively isolates individual switch modules so a failure does not damage all solid-state switches

The initial design from Pegasus was a single module switching at least several kiloamps and at a switching frequency of 4 kHz. If the switching frequency could be increased to 100 kHz, the value of the passive elements can be significantly reduced (see table). EHT has developed proprietary gate control of solid-state switches that allows for robust operation at high frequency. If EHT's switching technology can be applied to the Ćuk converter, this could reduce the system size while lowering component costs.

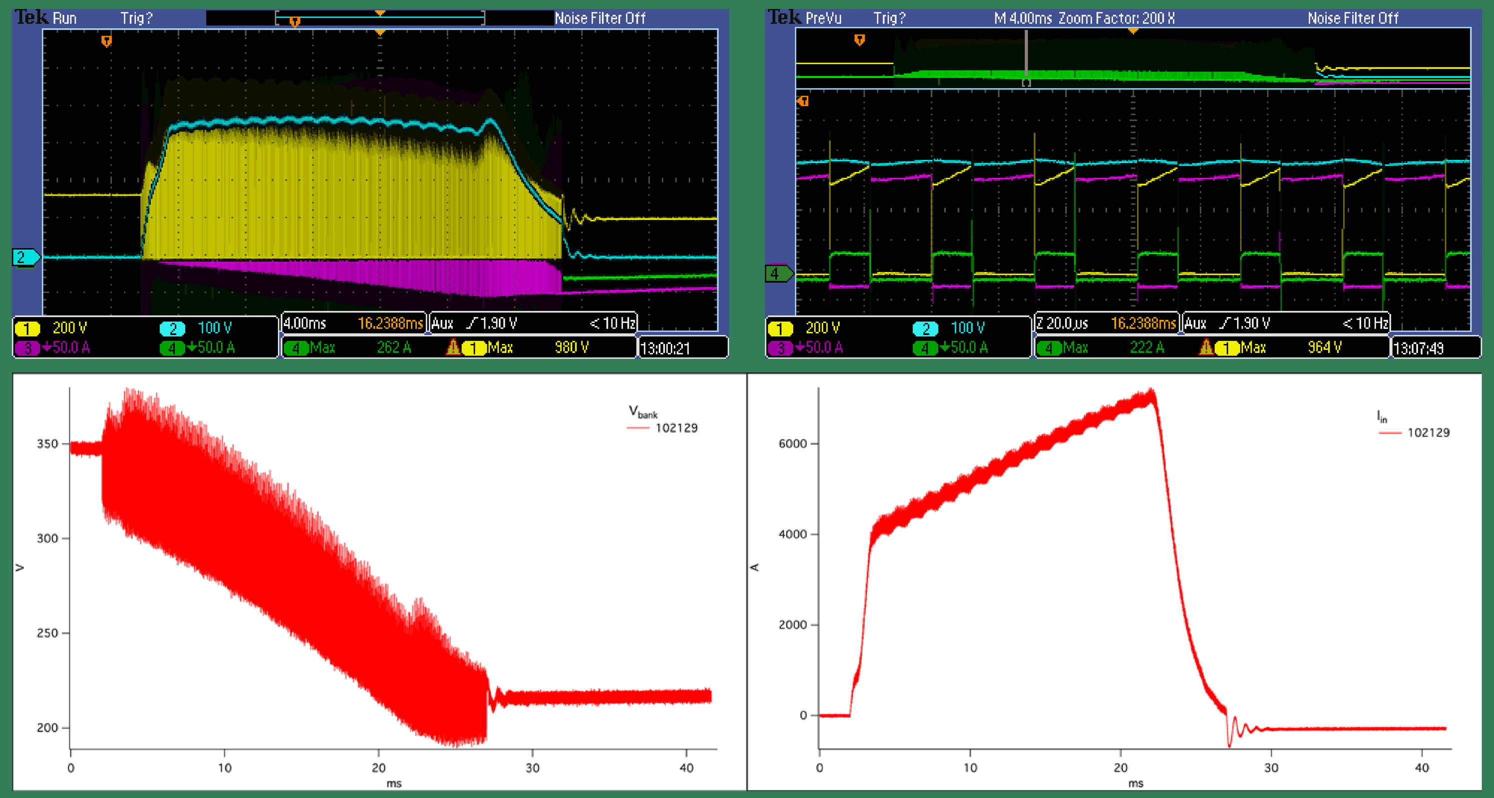
Frequency	L1	L2	C1	C2
4 kHz	36 µH	72 µH	1.6 mF	3.2 mF
30 kHz	12 µH	12 µH	500 µF	500 µF

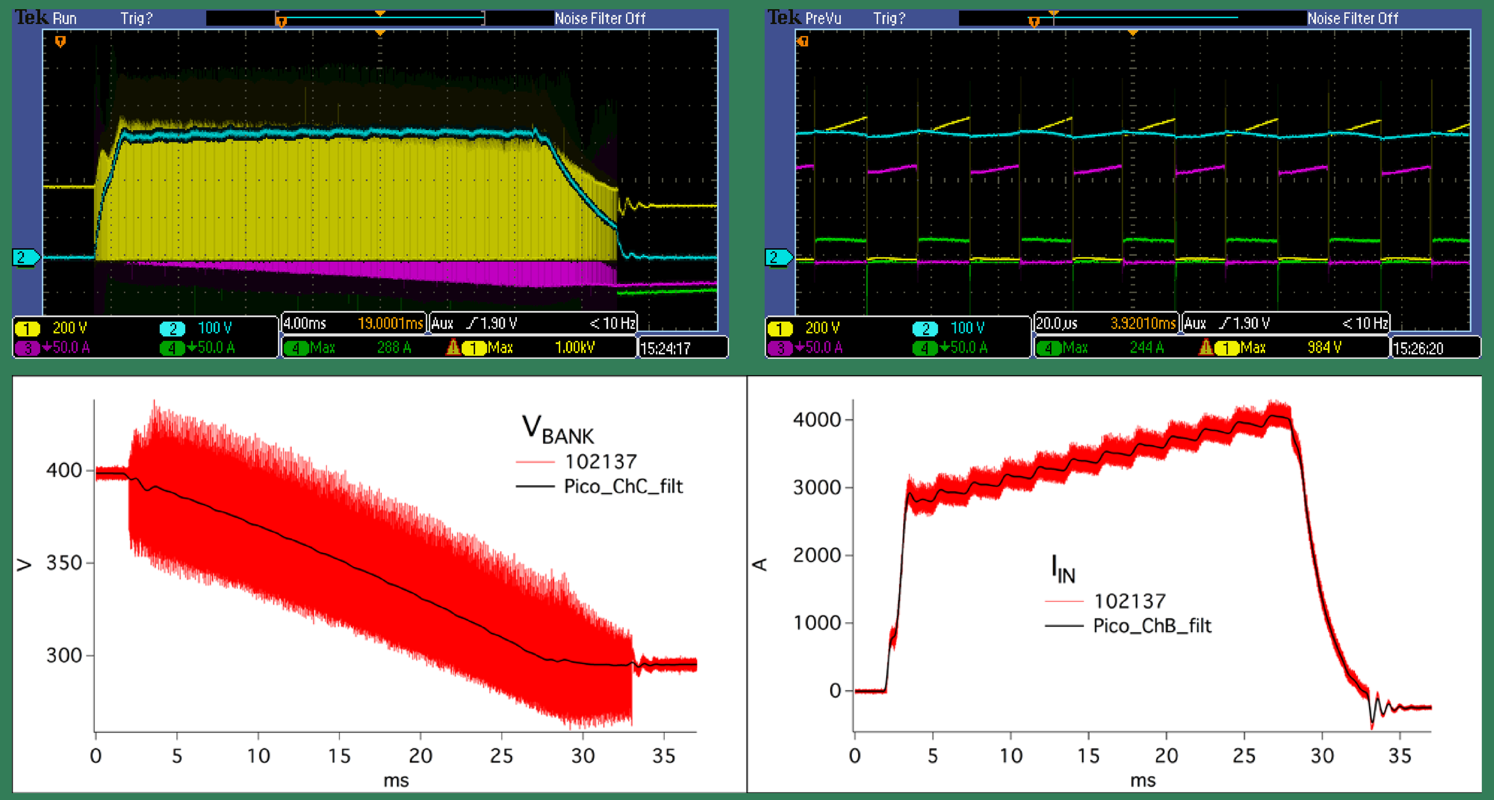
Testing at Pegasus

EHT solid-state switching units were brought to Pegasus and connected with inductors and capacitors to form a Ćuk converter. For energy storage, we used their existing 100 kJ (450 V) capacitor bank. We conducted experiments to demonstrate clean, high-current switching and efficient capacitor bank utilization.



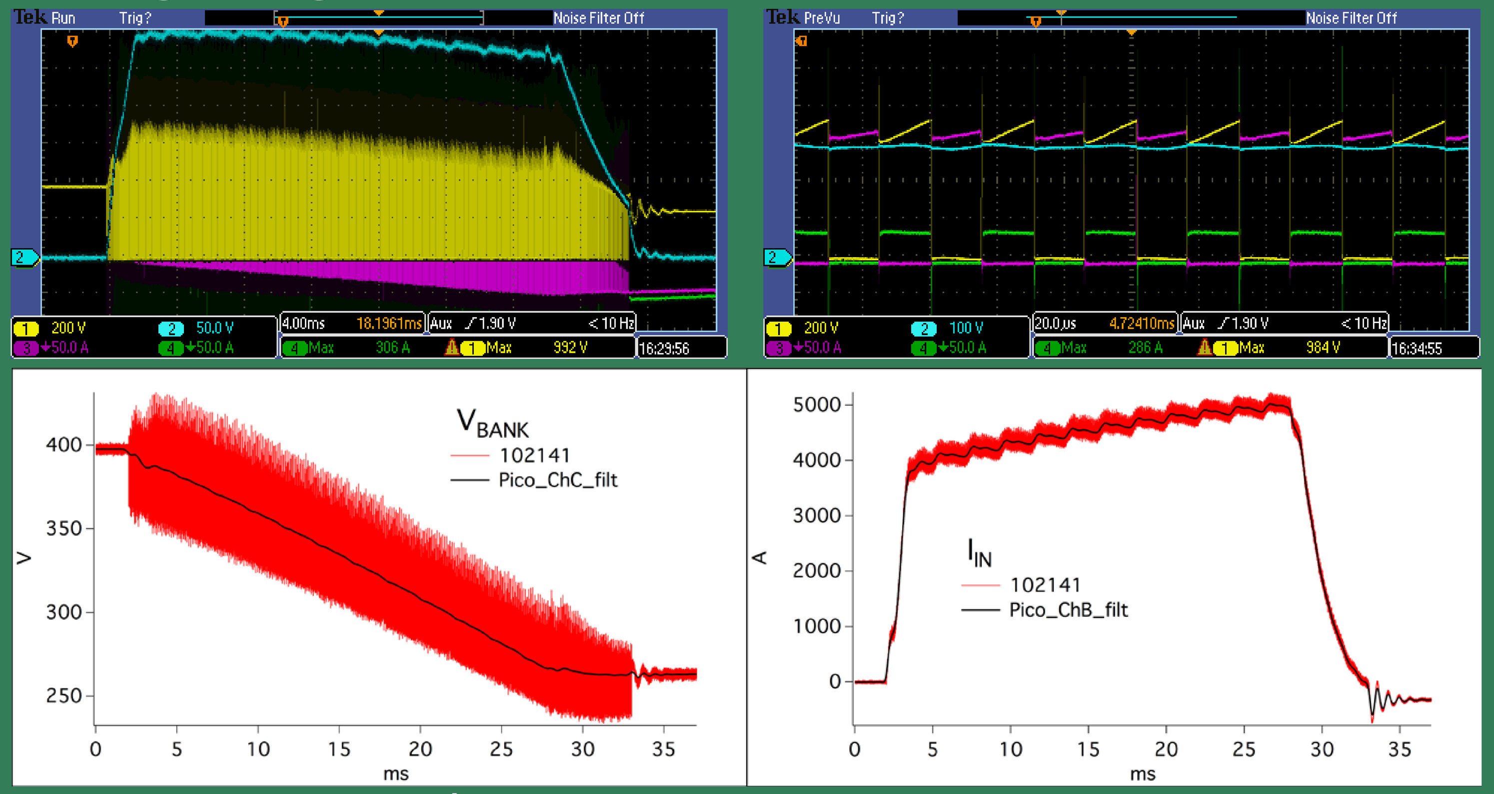
Experimental setup at Pegasus showing the EHT solid-state switch (A), oscilloscope (B), voltage probe (C), inductors (D), capacitors (E), and energy storage bank (F).


Upper: Measurements of Ćuk converter driving 100 mΩ load for 19 ms on two timescales. Input voltage is 350 V; output voltage is 350 V; output current is 3.5 kA; and output power is 1.2 MW. V_{ce} (yellow), V_{out} (blue), IGBT current (purple), and diode current (green). Lower: Energy bank voltage (60% utilization) and current from bank.



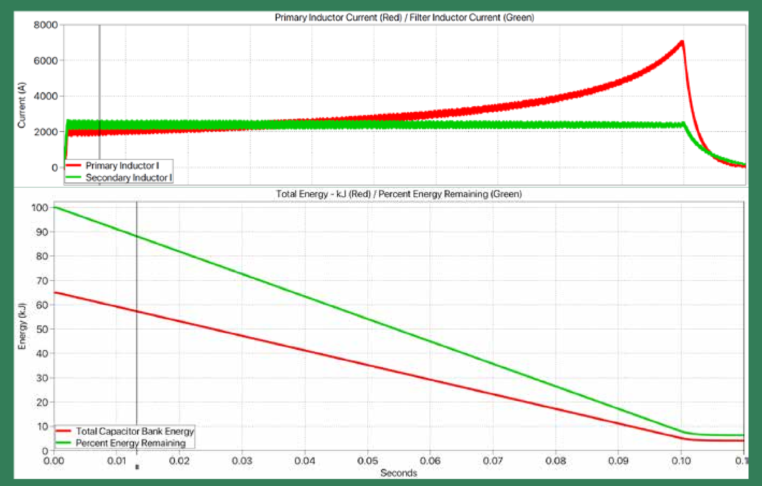
Upper: Measurements of Ćuk converter driving 100 mΩ load for 25 ms on two timescales. Input voltage is 400 V; output voltage is 325 V; output current is 3.25 kA; and output power is 1.0 MW. V_{ce} (yellow), V_{out} (blue), IGBT current (purple), and diode current (green). Lower: Energy bank voltage (45% utilization) and current from bank.

Testing at Pegasus (continued)



Upper: Measurements of Ćuk converter driving 72 mΩ load for 25 ms on two timescales. Input voltage is 400 V; output voltage is 305 V; output current is 4.2 kA; and output power is 1.3 MW. V_{ce} (yellow), V_{out} (blue), IGBT current (purple), and diode current (green). Lower: Energy bank voltage (55% utilization) and current from bank.

EHT conducted SPICE modeling to scale the solid-state switches and diodes. The switches must handle currents that are larger than the load current. This model demonstrate that the Ćuk converter can provide high current flattops over the timescales of interest at Pegasus with high capacitor bank energy utilization.


SPICE modeling results

Conclusion

We have used EHT solid-state switches to construct Ćuk converter that has been successfully tested at Pegasus. EHT solid-state switches allow higher frequency operation and therefore smaller components. The key results of this demonstration are:

- High current output (4 kA) for 25 ms
- Module power handling in excess of 1 MW
- Flattop ripple (< 4%) with PWM control
- High capacitor energy utilization (60%) with flattop output

Future work will incorporate the inductors and capacitor into a single module that can be stacked in series and parallel for fusion science applications. For more info: http://www.eagleharbortech.com/

Acknowledgment

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