COMPONENTS OF HEATING AND FUELING OF FUSION PLASMAS*

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Abstract

Diversified Technologies, Inc. (DTI) has bench-tested a table-top scale 'Buck Matrix' modulator with an efficiency of ~96% which uses a single set of IGBT switches for voltage regulation, arc protection, and pulse modulation.

INTRODUCTION

Next generation fusion facilities will require many megawatts of RF power from dozens of gyrotrons. Each gyrotron requires a power system that must deliver high-voltage power, modulate cathode voltage, and protect these expensive gyrotrons from arcing damage. It must be highly efficient to minimize both the power and cooling costs associated with operation and to ensure high facility availability.

Conventional DC power systems, built from WWII era components, have provided the typical approach to powering this class of high-power RF vacuum devices for the last 50 years. These systems, with their variacs, inductrols, spark gaps, ignitrons, and tetrodes, traditionally suffer from reliability and availability problems and are often only 50 – 70% efficient. Scaling conventional RF power electronics technology for next generation high power fusion facilities is not practical in either cost or reliability.

The technology for off-the-shelf, reliable solid-state modulators does exist, but currently requires two layers of solid-state switches – a voltage regulation step followed by a modulator / opening switch for arc protection. These two-step approaches are unnecessarily large and expensive, and an approved approach will be presented.

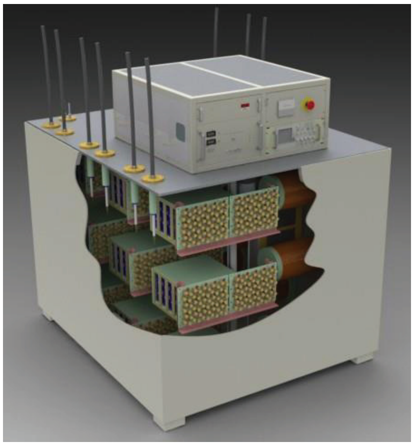

Figure 1: 75 kV, 45 A CW multi-phase buck-matrix regulator with low filter energy – serves dual purpose of regulating power and protecting a 1 - 1.5 MW gyrotron during arcs.

TECHNICAL APPROACH

Diversified Technologies, Inc. (DTI), under a DOE SBIR grant, has bench-tested a table-top scale 'Buck Matrix' modulator which uses a single set of IGBT switches for voltage regulation, arc protection, and pulse modulation.

DTI's Buck Matrix modulator (Figs. 1 and 2), with an efficiency of ~96%, cuts the size of the system in half, using a single layer of solid-state switches for both voltage regulation and arc protection/modulation. This cuts the total hardware costs by 30% or more, and eliminates the need for a separate opening switch or crowbar.

Although pulse step modulators also represent a one-step solution, their size and the complexity of their driving transformer make them more expensive than DTI's approach.

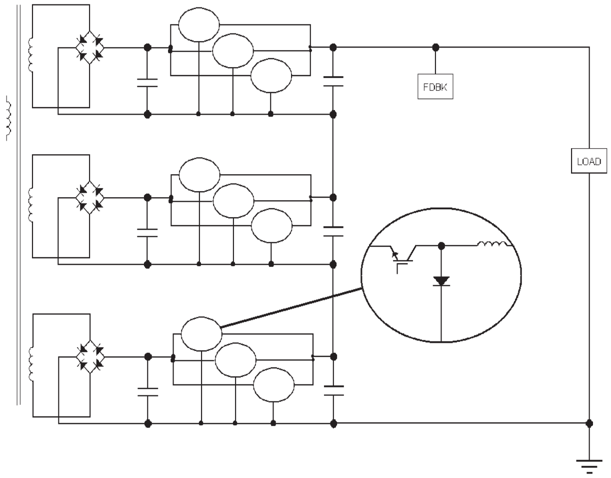

Figure 2: A series/parallel "Buck Matrix" topology combines superb ripple reduction and tube protection for minimum complexity and maximum efficiency. Transformer / Rectifier pairs are shown single-phase for simplicity.

OBJECTIVES

DTI focused on five primary objectives in developing the modulator. The first three focused on demonstrating the technical feasibility of the project: to assess any control system instabilities, to ensure the concept design would meet real gyrotron requirements, and to build and test a low voltage demonstration unit. The latter two tasks focused on the construction of a full-scale prototype. A high voltage electrical design for the full-scale system has been completed, as well as the ground work for the mechanical design, and the auxiliary systems have been

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defined, including the custom transformer-rectifier needed to power the Buck Matrix.

Design

Low stored energy is required in the Buck Matrix design to ensure that the tube is not damaged during arcs. This low stored energy is a major constraint of the design of the Buck Matrix; other key parameters are listed in Table 1.

Table 1: Key Specifications of the Prototype

Parameter	Full System	2x2 Demo	Units
Vin	95	2.5	kV
Vk	75	2.0	kV
Ik	45	2	A
Max Stored Energy	30	0.04	J
Max Voltage Ripple	1%	5%	

The principle behind the Buck Matrix converter is that very small output capacitors can be used, since the large out-of-phase ripple voltages will cancel each other out at the converter output. If we consider the case of a 2x2 Buck Matrix, the midpoint of the two sets of output stages sees significant ripple during the switching period.

Any ripple causes the current through each inductor to behave highly non-linearly. For example, a ground-side buck stage inductor will nominally see (Vi/2 - Vo/2) when its switch is turned on. If the ripple voltage at the midpoint swings 50% during a switch period, the voltage seen across the inductor would in reality vary from (Vi/2 - Vo/4) to (Vi/2 - 3Vo/4). The non-linear current waveform no longer has a predictable turn-off time, and the nominally stable operating point becomes marginally stable. Transient load or command changes have a nearly immediate effect on the output capacitor voltages, which can push the converter to a non-ideal operating point.

Simulation of the designed 2x2 Buck Matrix using fixed duty cycle control (open loop) showed a well-behaved circuit, with no output voltage overshoot and symmetric inductor waveforms.

A 3x3 system was later simulated (Figure 4). This system is harder to stabilize because of even smaller output capacitors and more component interactions in a 3x3 Buck Matrix. Simulations are not conclusive on whether fast peak-to-peak current regulation or slower voltage-mode feedback regulation result in a more stable system.

Experimentation

A low voltage 2x2 Buck Matrix was built to confirm the results of the simulation and analysis, and to demonstrate the feasibility of the Buck Matrix concept. Figure 3 shows the test setup.

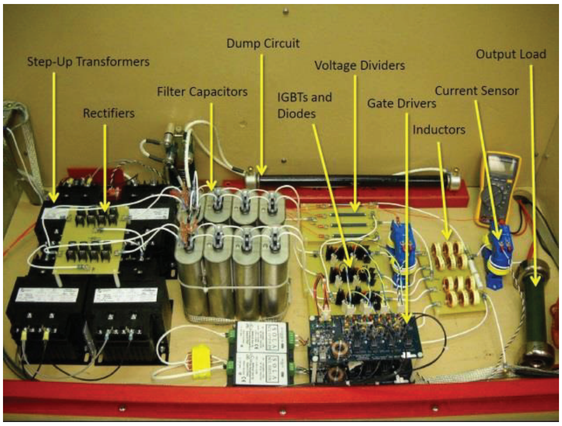

Figure 3: Components of the 2x2 experimental setup.

The 2x2 Buck Matrix performed as expected. Other than the inherent noise from the open hardware setup, the circuit waveforms nearly identically matched those from the simulations. The output ripples appropriately

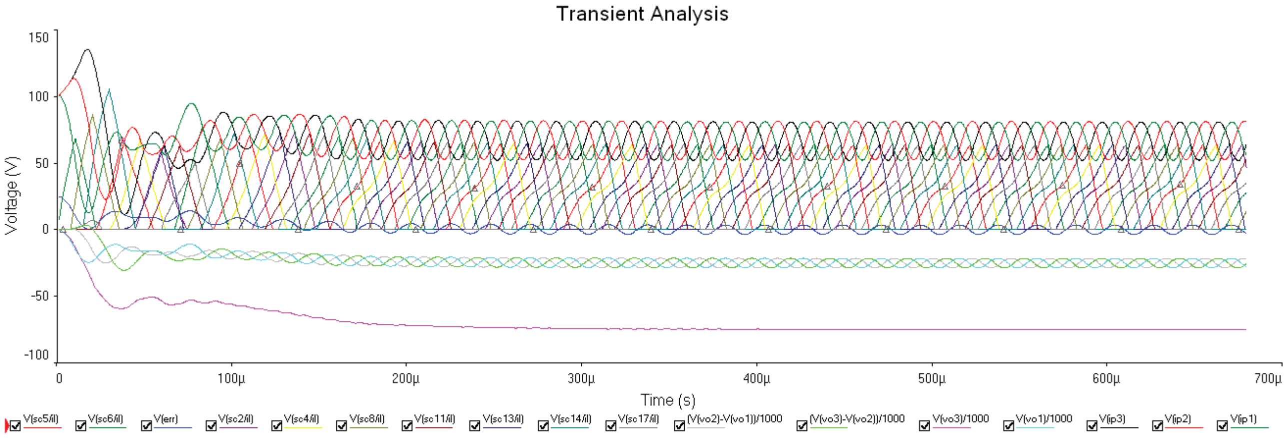

Figure 4: A 3x3 Buck Matrix under peak current mode control, with a fast PI voltage loop compensator. The response is fast, with symmetric inductor currents.

cancelled each other due to phase interleaving. The measured output ripple was approximately 7%; theoretical ripple was 5%. This discrepancy is due to small timing and component value differences. With slightly different inductor and capacitor values, and with slightly different IGBT and diode transition times, the individual component contributions are not perfectly symmetric, thus perfect cancellation is not possible.

Switch Resilience

To verify if standard silicon IGBTs or SiC JFETs could be run at the planned power levels and frequency, two DTI 10 kV switchplates (Figure 5) were manufactured: one with the SiC JFETs, and one with the silicon IGBTs. A test setup was constructed to verify full voltage and full current switching and conduction losses of these different switch plates (Figure 6). The result of this testing allows us to predict with confidence what the expected junction temperature of the transistor will be in the real buck matrix system.

Figure 5: Three DTI 10 kV solid-state switchplates.

Transistor Selection

Silicon Carbide (SiC) transistors have recently become commercially available at reasonable prices. SiC boasts extremely fast commutation, essentially eliminating switching losses in power converters. 85 milliohm and 45 milliohm SiC JFETs [normally-on devices which need to be operated in a cascode circuit and controlled with a low voltage (40 V), extremely low on-resistance and low switching-loss MOSFET] were evaluated.

Two of the tests related to the device physics performed were to examine the JFETs' ability to reverse-conduct (similarly to the internal body diode of many IGBTs), and to determine if the intrinsic over-voltage avalanche characteristics would simplify operation of these devices in series for high voltage applications.

Reverse Conduction

The JFETs do reverse-conduct, but testing revealed that the devices will break if operated with significant current in the reverse direction—similar current levels as the forward conduction current is enough to damage the devices. If reverse conduction is required, blocking and antiparallel diodes should be added

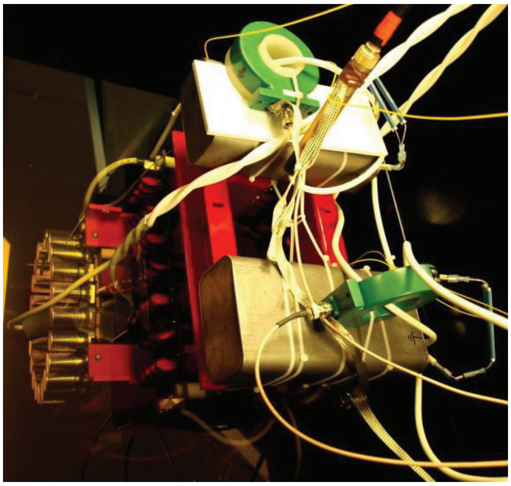

Figure 6: Switchplate test setup in dielectric oil. The assembly is vertically symmetric. A 20-stage switchplate with heatsinks is on the far left, at the bottom of the oil tank; above it is a high voltage diode assembly; on top are the two high voltage capacitors, and current sensors.

Avalanche

To test the avalanche characteristics, the JFETs were pulsed into an inductive load at very low pulsewidths (less than 1 microsecond) and low rep rate. When the JFET was turned off, the inductive voltage spike, which was a function of the input voltage and pulsewidth, would rise to above the device rating, and avalanche into the device. This worked as expected with very low avalanche energies, but damaged the device at higher avalanche energies.

Future Work

The huge reduction in ripple afforded by series/parallel multi-phasing allows the filters to become quite small, and it is precisely this reduction in stored energy in the filter – to below the threshold for arc damage – which enables the elimination of the second switch.

The results of this effort will eliminate half of this hardware, yielding approximately 30% savings, as well as improved system reliability and efficiency. The resulting design will be easily transferable to other voltage and current regimes, and is suitable for any CW or long pulse application – including future RF accelerators, light sources, and synchrotrons, and may also be applicable to other DOE programs, including the International Linear Collider (ILC). Other fusion power systems (e.g. ICRF, LHCD, neutral beam heating) may also make use of this technology with similar performance and cost advantages.