

Development of a Steady Operating Pulsed Power System for FRC and Inductive Thrusters

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Abstract: A steady operating pulsed power system has been developed for advanced electromagnetic propulsion systems. This PPU has been developed for propulsion systems which use inductive loads to provided electromagnetic forces which accelerate a plasma. In this paper, the development of this PPU is described including circuit, thermal, and drive considerations. The operating range of the PPU from 500-5000 W will be described with a summary overview of the larger, 25 kW model. Finally, testing results from steady thermal, vacuum, and plasma operation will be given as have been applied to MSNW thrusters.

I. FRC and Electromagnetic Thruster Operational Requirements

A. Generic Thruster Requirements

The first consideration in a pulse power system for FRC propulsion systems is the empirically required electrical characteristics; specifically this paper will focus on MSNW developed thrusters. For low to medium powered inductive thruster systems less than 100 kW, the voltages have typically and historically been as high as 4 kV, peak currents of 10 kA, and 1 microsecond rise times. Clearly, these parameters highly vary between device scale, pulse energy, and repetition rate, but reasonably consistent as a maximum [1, 2, and 3] for less than 100 kW systems. These requirements are consistent with an RMF system except that the discharge current is oscillatory instead of a single pulse. Rotating Magnetic Field (RMF) systems are typically 300 kHz but can range well into the MHz [3 4]. The required waveform for an RMF discharge is shown in **Figure 1** for a 5 kilowatt class thruster. Shown is a single discharge with and without a plasma load. Recent experimental programs at MSNW have demonstrated multi-pulse [5] and steady operation of RMF-formed FRC thrusters [6]. Specific thruster operation (beyond PPU requirements) will not be given in this paper, as it has been detailed repeatedly and extensively elsewhere [7].

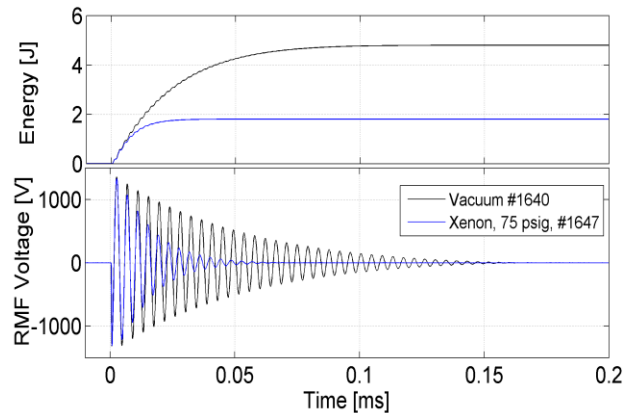


Figure 1. Time resolved plot of a typical Xenon FRC energy loading. Shown is the integrated energy deposited in the discharge coil for both vacuum and plasma discharges. The instantaneous capacitor voltage is shown as energy is deposited in the plasma.

II. PPU Design and Generic Component Description

B. Generic Architecture

The general circuit architecture uses a traditional design for FRC thrusters. Figure 2 shows the generalized circuit diagram which operates in the following manner: A high-Q capacitor is charged to 1200 - 1700 V. It is connected in series to a switch and high-Q inductor. In this case, the inductor is the thruster antenna. The semiconductor switch is closed, discharging the capacitor into the inductor. For RMF thrusters, a free-wheeling diode leads to a resonant oscillating current at 300 kHz. If that diode was replaced with a crowbar diode, it would yield an exponential decay with all circuit energy applied to the antenna inductive load or a Teflon-PPT style load. A waveform for this traditional circuit is shown in Figure 1. This single pulse generalized oscillating circuit is not unique and has been detailed with RMF thrusters in a variety of publications [7]. This architecture can then be extended to the requirements for a steady operating pulsed processing unit that is suitable for spacecraft operation.

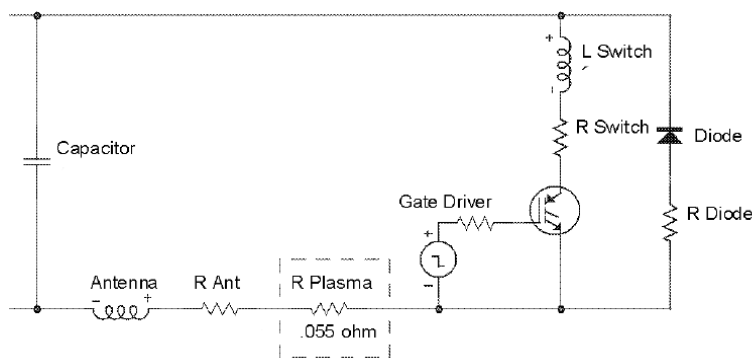


Figure 2. Generalized circuit architecture for a single pulse, oscillating RMF thruster discharge circuit.

C. Steady Operating Architecture

Shown in Figure 3 is a generalized operational architecture for a steady operating pulsed power system. Two parallel strings are shown corresponding to the two out-of-phase inductive antennas required for RMF operation. This power string consists of a DC low voltage power source, typically 100 - 300 VDC, traditionally, a current source such as a battery. It then goes through a mil-spec filter to isolate the battery and regulator system from the thruster. However, as shown in Figure 3, the current draw requirements of a pulsed power system are unique for spacecraft power systems and thus require a dedicated filter. This inductive capacitor filter can be made light-weight and high-efficiency if a specific thruster operating condition is known. This filter then imposes a steady current steady low amperage current draw on the spacecraft but with a fixed ripple.

Further in the string, a pulsed charging or matching network system is used to convert low-voltage DC to high-voltage which is suitable for pulsed electromagnetic thruster operation. This has been detailed in previous publications. Finally, the primary pulsed PPU architecture is the driver circuit itself as described in the previous section. The final critical component is the inlet power for the switch's gate. This inlet power is required to operate the switch and ideally is isolated from the primary gate drive circuit.

The key circuit requirements then become the drive requirements for the IGBT switches and thermal concern. The unique nature of a pulsed electromagnetic PPU is that it very simply allows a high degree of parallelization to limit resistance and thermal concerns. The primary electronic component limiter is the semiconductor switch which must be suitable for both moderate steady operation as well as high-intensity pulsed operation. Some of the key design requirements will now be described.

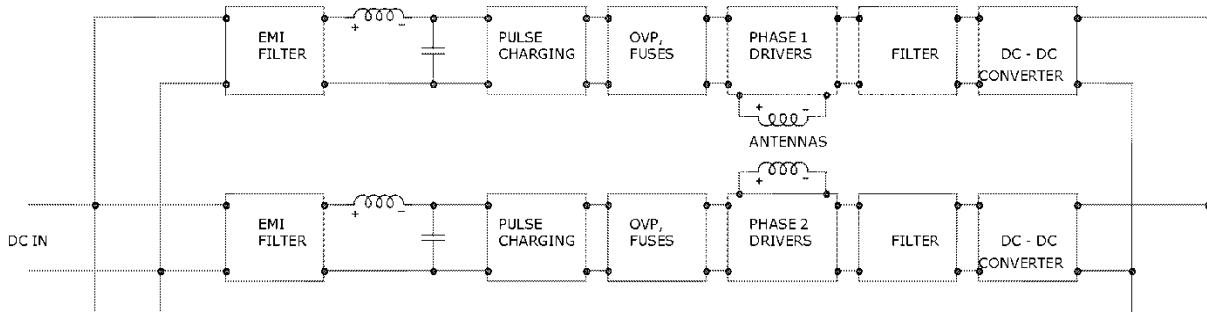


Figure 3. Generalized circuit architecture for two steady operating oscillating RMF thruster discharge circuits that are compatible with a typical space power system.

A steady operating thruster has a discharge waveform that is a series of pulsed, RF oscillations. A complete waveform set is shown in Figure 4. In Figure 4, the top trace is the capacitor voltage, which is charged between discharges and rings down at the RMF frequency. The third and fourth traces show the RMF current in a single antenna. This current clearly has a series of high intensity discharges spaced at 1.1 ms. One of the unique features of these systems is the locally (both temporally and spatially) high power density, with peak power on the order of 2 MW. However, because the duty cycle is so low, the average power is comparable with other electric propulsion systems, as well as the expected mass flow and current flow rates.

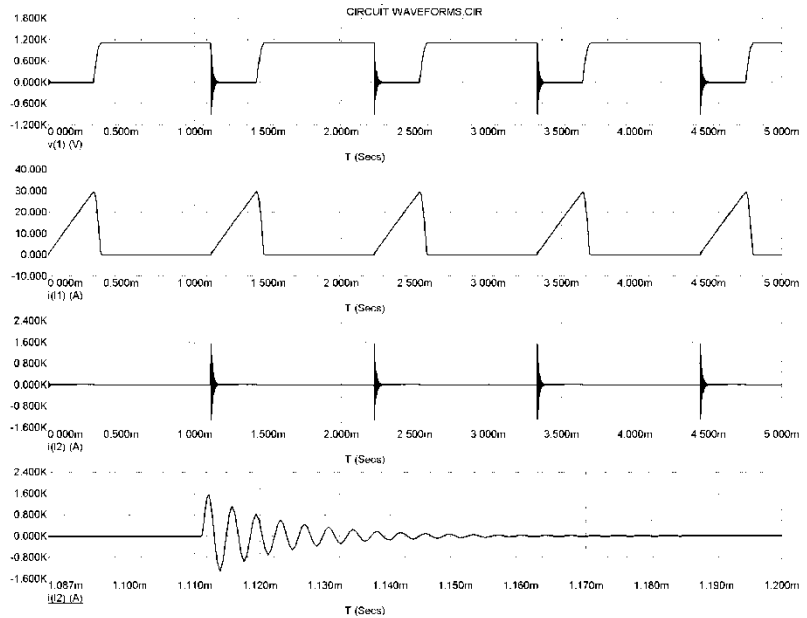


Figure 4. Circuit simulation for a 1 kW steady operating thruster. Shown is a 900Hz charge rate with a 300 kHz RMF frequency. The first trace is capacitor voltage, second is battery draw, third is antenna current, with the last trace showing an expanded view of the antenna current.

D. On Repetition Rate

As has been seen in other pulsed electromagnetic devices, one of the primary challenges is gas utilization. In particular, the time between pulses can be easily seen as one of the primary determiners of gas utilization efficiency. Simply, if the time between pulses is too long, then cold, slow gas is lost between discharges, and if it is too fast, then only a small axial fraction of the thruster is being used for acceleration. Therefore, several scenarios are apparent; either gas is injected transiently or steady. MSNW has done extensive investigation in design of high-speed puff valves, a wide range of designs have been built and empirically characterized including flying plastic poppet (as in a series 9 valve) metal flying poppet, metal seal, piezoelectric and electromagnetic diaphragm some of which are described in the following references [8, 9]. For the typical required flow, throughput and vacuum sealing requirements, the designs of such valves are quite challenging. They must be able to withstand a wide range of thermal variation, long lifetimes, fast opening times, and most challenging, short closing time. It has been found by MSNW and others [9, 10], that even the highest speed valve (and in this case the authors are referring to less than 100 microseconds opening time), the realities of a gas injection system and a thruster-like configuration yield many milliseconds of gas flow per puff within the thruster body. As such, MSNW thruster family has been designed to maximize gas utilization by incorporating discharge rates on the order of neutral flow times. This can be compared directly with single-puff thrusters that have been shown in numerous occasions to have extremely poor gas

utilization [1]. Transient gas utilization is still believed possible to enable power and thrust throttling; however, at MSNW, this is being implemented in a burst mode. An idealized burst mode configuration is shown in Figure 5. Where gas rise and valve opening is accomplished in 200-600 microseconds, a steady on period exists for 5 ms and a few ms turnoff time required for propellant to fully leave the flow system and thruster body. During the steady period, multiple thruster discharges can be performed at the neutral gas fill rate. In this example, high gas utilization is possible, though it is clear that the trailing edge gas is significant. It is important to reiterate that a 200 microsecond opening time on a puff valve with a <4 cm flow stem leads to a long decaying flow condition. Clearly increasing the length of the burst increases gas utilization for the thruster. A key variability in gas utilization is the propellant flow species, molecular weight, and bulk temperature; increasing gas sonic velocity increases the minimum required repetition rate for ideal gas usage. Figure 6 shows a chart of minimum repetition rate as a function of the size of a thruster and gas species. Thus it is clear that a well-performing thruster will require operational repetition rates from 1 to 5 kHz.

In addition to the total gas/propellant utilization before and after firing, the utilization of a gas during a single discharge is critical to proper and efficient operation. Gas utilization during a discharge has been looked at extensively in FRC thrusters and FRC-based fusion devices [11]. It has been found that the high plasma density and general inward radial plasma flow due to compressing fields and rotating magnetic fields lends FRC thrusters to possibly very high gas utilization efficiency. Current thruster testing work will validate the single-pulse empirical studies that have been done previously in a more traditional manner on a thrust stand with steady flowing gas. However, several key experiments involving the multi-pulse EMPT can be leveraged in order to form a robust conclusion of gas utilization in these high density plasma thrusters with only a single pulse. Several key gas utilization conclusions that separate FRC-based devices from other pulsed plasma thrusters include:

- With few exceptions, the downstream probe density measurements are within 50% of the expected plasma density from measured neutral gas flow and single-shot thrust measurements. This is well within the error range for a double Langmuir probe in a flowing, supersonic plasma.
- For the multi-pulse EMPT testing it was found that after the magnetic signature of the FRC had translated out of the device (from external probes) there was no evidence of diamagnetism or inductive loading. This suggests that there was little or no gas left in the device to form a plasma.
- In large-scale fusion DOE experiments, it is clear that FRC plasma sweep up all background gases and compress it. This has been shown in contamination studies [11].

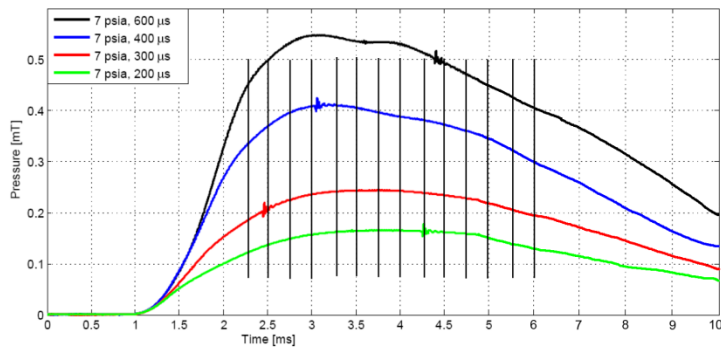


Figure 5. Idealized burst mode operation for superior gas utilization. Shown is fast ion gauge neutral density for several puff conditions. Also shown is notional operation at approximately 80% of peak gas fill. Leading to 15 discharges at 2 kHz in a 10 ms total gas flow condition (with 0.2 ms puff operation).

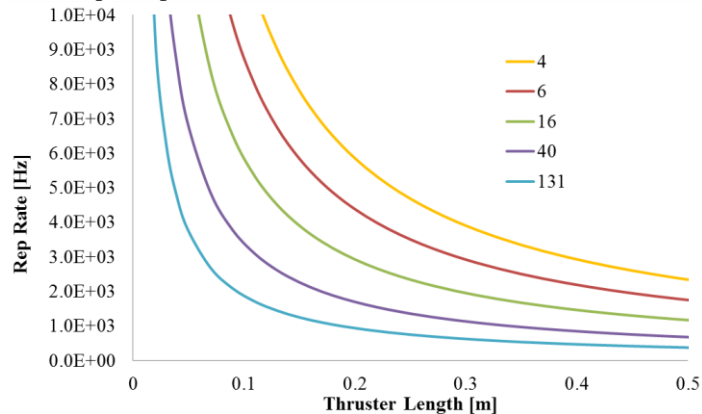


Figure 6. Minimum repetition rate as a function of size and gas species for several key gases. Assumed is 400 K inlet gas temperature.

- It is expected that an FRC would sweep up most of the propellant in the device. The ion-neutral collision mean free path is 3-10 mm, leading to significant interaction of the radially and axial plasma population with background neutrals.

E. Switch Efficiency and Speed

All semiconductor IGBT switches have a standard on-state resistance versus conducted current. This is typically represented as the voltage drop across the switch and is given in Figure 7. As can be seen by increasing the gate voltage, the resistance the on-state resistance of the switch is decreased for a steady current. While this trend is significant, less than 15 V the increase in performance for DC currents are minor. This on-state resistance is well understood and can be simply described as the energy and local available charge required to initiate switch conduction. With a higher voltage at the gate, a larger portion of the switch can enter conduction and tends to do so at a higher speed. This on-state resistance can also be described for an oscillatory circuit. It has been routinely found that as the switch is oscillating, it enters and exits conduction. During this process, the on-state resistance increases significantly near zero current. In practice, this tends to have a minor effect as long as the RMF current is large.

Therefore, for a 300 KHz oscillation of a 200 amp IGBT, the same switch shown in Figure 7, and equivalent resistance can be determined for the complete oscillatory behavior. This resistance is measured via equivalent exponential resistive decay of discharge current.

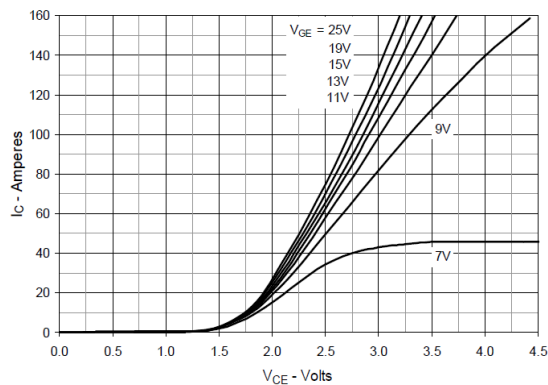


Figure 7. Individual IGBT switch on state voltage drop as a function of conduction current.

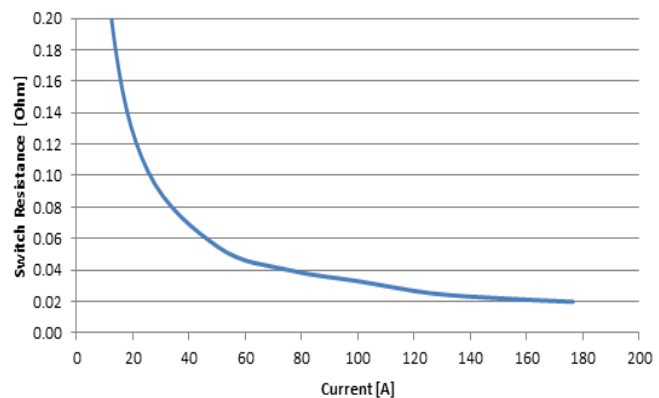


Figure 8. EMPT individual switch resistance as a function of peak collector current. Note, multiple switches are paralleled to reduce overall resistance.

Figure 8 shows the net composite resistance for this circuit. Clearly de-rating circuit components can significantly increase their on-state resistance and optimal de-rating must be very carefully analyzed. In the EMPT, the driver efficiency is the key efficiency in the system. Compared to the plasma resistance or inductance the circuit efficiency is a minor resistance or energy loss. However, the switching components are the most temperature sensitive components and are designed to operate at 125 C, while the thruster is easily capable of greater than 250 C. Therefore, any efficiency increase in the switching components results in less heating and therefore less thermal management mass in the PPU system. Therefore a complete investigation into the IGBT drivers developed at MSNW was undertaken and completed to optimize the circuitry. A range of IGBT gate drive voltages from 15-25 V were investigated. Figure 8 shows the effective switch resistance as a function of peak gate current. This was measured with a high-efficiency oscillating circuit at 300 kHz and measuring and compensating for all know circuit components. Their high-frequency impedance was determined and the resulting resistances must then be from the switching. This is as expected, that as the switch oscillates and spends more conducting period near zero current, its efficiency and resistance, and thus its heating, is increased. Figure 9 shows the results of IGBT driver testing. Each test required a circuit reconstruction and several critical power regulator and diode upgrades. It was expected that increasing driver voltage and decrease driver resistance would increase both the energy to the gate and thus the turn-on time of the switch, lowering its overall losses. However, it was found that at some maximum drive energy the switch would lock up and oscillate in and out of conduction, thereby dramatically increasing its overall resistance and most likely reducing its life. Therefore it was found that the optimal operation conditions was that which maximized turn-on with no deleterious oscillations. Further testing revealed that decreasing the inductance of the gate drive circuit increased the frequency of the oscillations, reducing switch turn off.

Drive V	TVS	R Gate	Q	Trise @ G	Tdly @ C	Tfall @ C	Rswitch
15	18	1 ohm	209	40nS	25nS	25nS	26mOhm
15	18	5 ohm	214	80nS	30nS	35nS	25mOhm
15	18	10 ohm	214	150nS	35nS	50nS	25mOhm
18	22	1 ohm	214	60nS	20nS	20nS	25mOhm
18	22	5 ohm	209	100nS	25nS	25nS	26mOhm
18	22	10 ohm	223	130nS	30nS	35nS	23mOhm
20	22	1 ohm	-				
20	22	10 ohm	223	330nS	25nS	55nS	23mOhm
20	22	15 ohm	214	350nS	30nS	35nS	
18	22	1 ohm	242	60nS	20nS	20nS	21mOhm
18	22	5 ohm	232	100nS	25nS	25nS	22mOhm

Figure 9. Results of EMPT switch driver testing. Shown are various drive voltages, resistances, and effective switch resistance. In orange, a low-inductance gate was implemented further increasing performance (20%). Italics shows the current design.

III. MSNW PPU Development

A. 1-5 kW PPU

A steady operating pulsed power system has been developed for advanced electromagnetic propulsion systems. This PPU has been developed for advanced electric propulsion systems which use inductive loads to provide electromagnetic forces which accelerate a plasma. Specifically, the Electromagnetic Plasmoid Thruster (EMPT) system operates from 1 to 5 kW with a 300-500 kHz Rotating Magnetic Field (RMF) Field Reversed Configuration (FRC) Plasma. The PPU consists of a fiber-optically driven driver circuit which triggers 2-6 switching modules. Each of these modules individual contains on board energy storage, in the form of high-Q ceramic COG capacitors, high current capability IGBT, and an MSNW developed driver circuit. The generalized circuit diagram is shown in Figure 10 and contains a capacitive energy storage, a high-Q inductor (RMF antenna), and a low loss switch. The PPU consists of a pulse charging circuit which uses an inductor to pulse charge a 100 VDC bus to 1600 V as described above. This in turn charges a high-Q capacitor. Connected in series with the thruster antenna, the resonant RLC circuit oscillates at high frequency with a vacuum Q factor of greater than 100. The high speed IGBT array is switched, discharging the circuit with a rise time of less than 400 ns (and a capability of 26 ns). When a neutral gas is present, two out of phase ringing RF circuits create a net Rotating Magnetic Field which fully ionizes and inductively 'loads' the antenna circuit. The net effective resistance and inductive coupling decreases the plasma Q to approximately 16 leading to greater than 95% energy coupling into the plasma. The rotating magnetic field induces a large current in the plasma, creating a field reverse configuration plasma. This plasma is then ejected from the thruster via Lorentz forces and is described in significant detail in other references [7]. A single module is shown in Figure 10 and when insulated is shown in Figure 11.

The driver circuitry has been designed specifically for fast response and high throughput. In addition to the basic pulsed inductive circuit described, a suite of MSNW-standard circuit techniques are also employed. Onboard, real-time over-voltage, over-current, and integrated switch health monitoring circuitry protect the PPU from any anticipated circuit, plasma, or spacecraft radiation fault modes. In addition, significant advances in high-speed, inductive switch gate drive, input filtering, and power regulation are be utilized to aid switch stability and increase efficiency. This PPU system has demonstrated greater than $1E9$ discharges and steady thermal operation in vacuum. Several of the protection measures will now be described.

1 kW Pulse Power Module

- 1700 V operation with <25 ns turn on
- 1 MW peak pulse power, 600 W steady power
- 100 hrs operation
- Integrated IGBT, freewheeler, fiber optic trigger, health monitoring, ceramic capacitors, and required thermal management for steady operation
- Health monitoring includes over voltage, over current, saturation initiation monitoring with switch disable, fusing, and fiber optic output

B. Over Voltage Capability

A pulsed electromagnetic thruster fundamentally has pulsed, high peak power discharges, with low average power and low average current. Typically, these peak powers can have reasonably high voltages. In EMPT the thruster may operate at up to 1.6 kV peak voltage. The thruster has been appropriately derated for robustness, including 1700 V switching, 3 kV capacitor, and 10 kV-capable insulation. However, it has been found that in pulse-charging circuits, arcing or thruster failures can lead to low-energy, but extremely high voltages applied to the 1700 volt switching, as high as 4 kV. Therefore, a fast overvoltage protection circuit has been designed that will remove the voltage from the switch in the case of overvoltage and the circuit shall remain protected until nominal circuit parameters are returned. This circuit uses a pair of high-speed Zener diodes to detect high voltage transients, and using a separate high speed IGBT switch, it dumps those transients into a resistive circuit. Subsequently, the circuit then prevents the power processing system from returning to its high energy and high voltage charge until such time as the arc or discharge that caused the high voltage incident has been mitigated. The Zener diode voltage limit must be carefully chosen for the specific application. As a diode turn on voltage can be soft, this specific limit must be

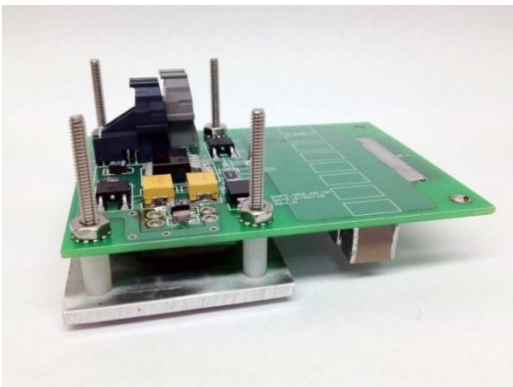


Figure 10. 600 W Module. Integrated driver,

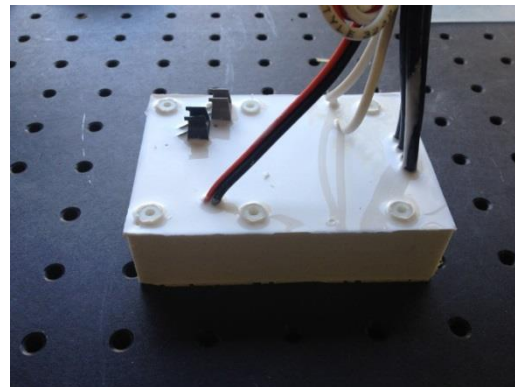


Figure 11. Potted 600 W module with fiber, coaxial power, and control power

chosen to be well within the limit of both the desired operation frequency and the switch limits.

C. 5 kW Complete System

A complete 5 kW system is then shown in Figure 12 and contains six independent capacitor, switch, and driver modules that are attached in parallel in a low loss system. Each of these modules is fiber optically triggered and has a fiber optic output that relays continuous health and status monitoring signals. Each module is charged and triggered independently, with parallel connections to the load. There are several key considerations which must be maintained in parallelizing pulsed RF modules. For independent gate operation it was found that significant inductive and radiated coupling between switch drive units can be developed. This must be mitigated as it will lead to switch operation and possibly failure. In these systems, the 1 kW modules were designed to have independent on board voltage regulation, per-channel filtering, and isolation at 4 kV. This isolation provides significant protection from deleterious coupling. Another key technique employed is independent triggering. By utilizing HFBR-style fiber optic triggering input timing and operation can be highly regulated.

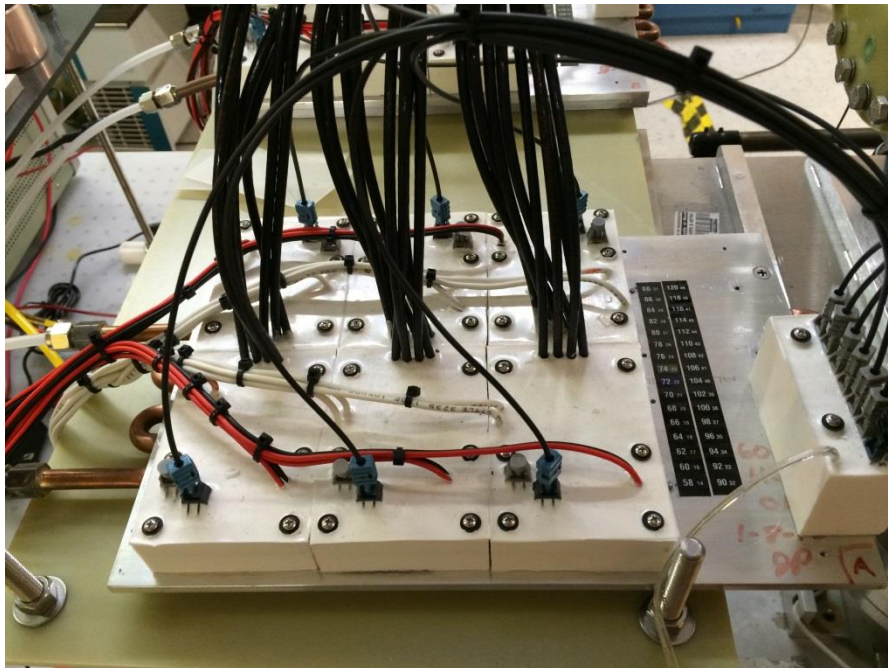


Figure 12. IGBT and MSNW Driver Electronics

Summary of 5 kW paralleled module operation

- 1700 V operation with <25 ns turn on
- 5 MW peak pulse power, 3000 W steady power
- Paralleled high power bank
- Isolated driver circuits capable of series operation 4 kV
- Key Considerations in Parallelization
 - Thermal, Rating
 - Isolated gate drive triggering
 - Isolated and filtered drive power

D. 15 kW PPU

The 30 kW ELF power processing unit (PPU) uses the standard MSNW RMF a pulse charging supply as described above. It was then extended to larger, higher power IGBT units from ABB. A proprietary IGBT driver by MSNW was developed specifically to operate these switches at high speed. Shown in Figure 14 is the driver which is based on the same architecture described in the previous sections, however with components cable of the voltage isolation and power throughput required for a high power system. Shown in Figure 15 is three independent IGBT arrayed in parallel with capacitive energy storage.

This PPU was operated with a bus voltage of 300 volts that is then inductively and at high efficiency pulse charges the onboard capacitors to 4000 volts. This inductive pulse charging used a 4 microhenry air-core inductor with a 1.2 microfarad high-Q capacitor [5]. The repetition rate was varied by fiberoptically triggering the IGBT switches at various average rates. The peak charging voltage could be varied by changing on time, charging time, and bus voltage.

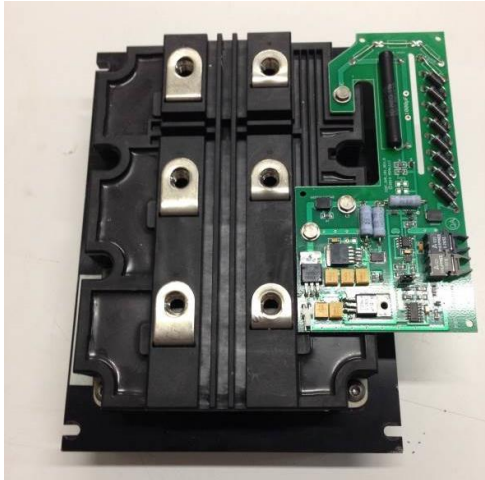


Figure 13. IGBT and MSNW Driver Electronics



Figure 14. Total system.

The MSNW high power driver is shown in Figure 13. This gate drive system provides 21 volts across the gate in less than 50 ns. It has a low inductance, low capacitance designed specifically for this fast-switching application. In addition, a current saturation detection has been included which, in the event of a fault in the capacitor will detect and shut down the switch. An overvoltage clamp consisting of a string of fast Zener diodes is designed to prevent transient voltages above 4300 volts. This can be adjusted for the switch of interest. The driver gate includes the standard MSNW packages including ultrahigh voltage isolation (in this case 10 kV), output and input fiberoptic triggering and health monitoring as well as, in this case, a jumper assembly to allow gate drive voltage increase from 21 volts to 28 volts for very limited duty, higher current operation. This switch has been tested in a steady operating mode with a water-cooled inductive load. Shown in Figure 15 is a picture of the entire experiment set including high-Q capacitors, driver circuitry, actively cooled switch baseplate, and copper load 'antenna'. Figure 16 shows a ringing wave forms of a 4 kV discharge operating at 1 kHz and maximum power as well as the gate voltage. It is believed that this PPU is ready to be insulated and tested under vacuum with a high-power thruster.

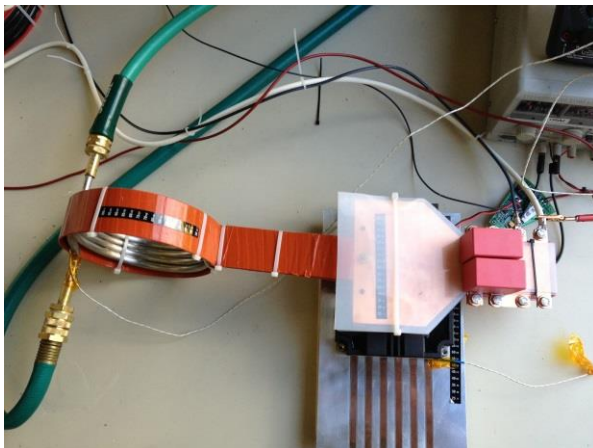


Figure 15. IGBT and MSNW Driver Electronics during thermal testing.

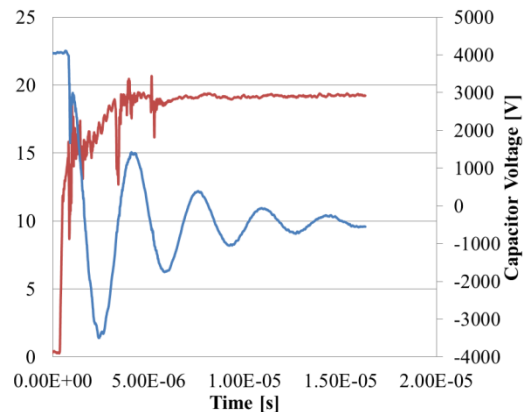


Figure 16. Discharge coil voltage and operational Gate voltage for 4.0 kV operation with a 20 V gate voltage. Turn on noise and coupling is apparent due to non-ideal inductive coupling to gate leads.

Summary of High Power Unit Operaiton

- 6000 V operation with <100 ns turn on
- 55 MW peak pulse power, 15 kW steady power
- Parallelized and tested up to 20 kA
- Isolated driver circuits capable of series operation up to 20 kV, full range of health and operational monitoring.

E. On Going Work

As has been shown, MSNW has developed a pulsed power PPU solution for RMF-formed FRC thrusters that can meet the demanding high instantaneous power and high average power density performance required for steady operating pulsed power thrusters. These PPU architectures have been proven with a variety of inductive and plasma loads and for well over 1E9 discharges. The primary development at MSNW is developing and qualifying the hardware and mechanical construction required to operate these power systems in space.

IV. Acknowledgments

The authors would like to thank DARPA and NASA for funding support for this program.

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