INTEGRATION AND TEST OF A DUAL PURPOSE PULSE FORMING NETWORK INTO THE P&E HWIL SIL

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ABSTRACT

A Dual Purpose Pulse Forming Network (DP-PFN) has been developed to power both the Electro-Thermal-Chemical (ETC)/Electro-Thermal-Ignition (ETI) lethality capability and the Electro-Magnetic Armor (EMA) survivability capability improvements envisioned for future hybrid-electric combat vehicles. The DP-PFN is capable of providing two types of energy pulses to accommodate gun and armor loads: extremely short pulse lengths for the EMA, or longer pulse lengths for the ETI/ETC Gun. This capability of the DP-PFN allows for emulation of three major hybrid-electric, lethality, and survivability functions of an electrically-driven ground combat vehicle.

Recently, an advanced first-generation DP-PFN for driving both ETI/ETC and EMA emulators has been integrated into the Power and Energy (P&E) Hardware-in-the-Loop (HWIL) System Integration laboratory (SIL) in San Jose, California. This paper describes the DP-PFN integration and testing in the SIL. In addition, this paper describes the design and the build plans underway for integrating a second-generation Variable Pulse Forming Network (VPFN) into the SIL. The VPFN will augment the SIL's capabilities for forming a wide variety of pulse waveforms while providing both enhanced high density energy storage and fast recharge capabilities.

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1. INTRODUCTION

A series of advanced Pulse Forming Networks (PFNs) are under development in the P&E HWIL SIL (Danielson[1] et al., 2002; Danielson[2] et al., 2003, Danielson[3] et al., 2003, Freeman et al, 1999) in San Jose, California to provide pulsed power for ETC, ETI, and EMA capability improvements envisioned for future hybrid-electric combat vehicles. ETI provides an enhanced hit probability of a round by reducing the ignition variability associated with launching conventional munitions. ETC provides enhanced lethality and range of munitions with higher muzzle velocities through the incorporation of temperature compensation methods. EMA reduces the depth of penetration from an offending shaped charge jet munition by using stored electric energy to disrupt it. A shorting circuit is formed between two parallel armor plates and through the jet upon the jet's impact into the armor. The voltage discharge results in ohmic heating and magneto-hydrodynamic effects that enhances the jet's instabilities and cause it to particulate and form "smoke rings". The residual armor penetration is thus drastically reduced.

The PFNs under development enable the SIL to emulate these lethality and survivability capability improvements. A dual purpose (DP) PFN has already been integrated in the SIL as a first generation solution for the two main lethality and survivability applications: firing an ETC gun, and activating EM armor respectively. The DP PFN is capable of providing either short energy pulses for armor loads, or longer pulses for gun loads. Extensive testing is now underway using the DP PFN for the emulations. Development has also begun on designing and implementing a Variable PFN (VPFN) that will have the capabilities for forming a wide variety of pulse waveforms while providing enhanced high density energy storage and a fast recharge capability.

2. FIRST-GENERATION PFN

2.1 DP-PFN Description

The first generation dual purpose DP-PFN (PFN) is an apparatus that provides the necessary electric power in intensity, duration, and waveform to power ETC guns and EMA loads. The ETC gun loads and the EMA loads have different power requirements from the PFN. The ETC gun requires relatively long duration and low current pulses of power on the order of ~1 ms and ~100 kA peak values respectively. The EMA load requires short duration and very high current pulses of power on the order of hundreds of microseconds and about 1 MA respectively. To accommodate these requirements, the PFN in the SIL is equipped with two subsystems that can provide 100kJ each, PFN1 and PFN2. Both subsystems fire for the EMA load, whereas only one subsystem fires for the ETC load.

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The two PFN subsystems are each composed of eight 250 µF, 10 kV, 12.5 kJ capacitors that are linked to the ETC and EMA loads. Each PFN has a high current switch for discharging from the capacitors to the EMA load. A specially designed bus links the PFN capacitors to the switches while minimizing undesired magnetic forces from the very high currents involved in the discharge. The connection to the EMA load includes four coaxial transmission lines, two per PFN, capable of passing peak currents of 400kA each. A motor operated contactor connects PFN 1 to the ETC load. A 10^{-9} torr triggered vacuum switch (TVS) is set up for firing the PFN into the ETC load. A PFN charger is connected to each PFN via relays, one for each PFN and charging resistor. A protective circuit is incorporated in the charging circuit to protect the charger in case of pre-firing. A dump circuit is incorporated for dumping the PFN energy under both normal operation and in the event of an emergency. Figure 1 shows a schematic of the PFN including its main features, components, and loads. Figure 2 shows a picture of the PFN set up in the SIL.

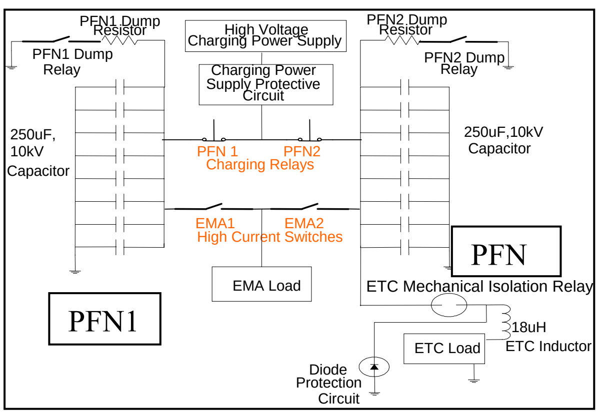

Figure 1. Generation 1 PFN schematic.

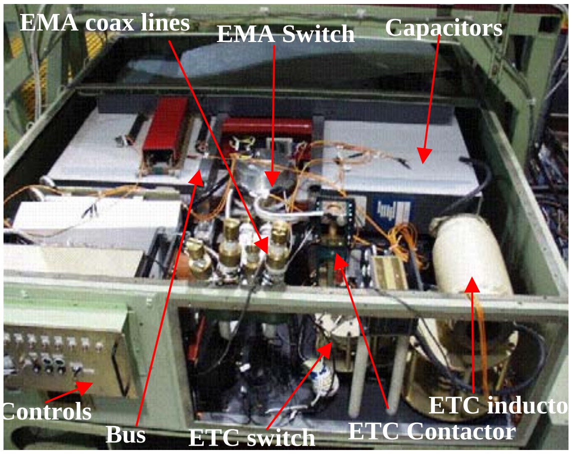

Figure 2. Generation 1 PFN integrated in the SIL

The major components of the PFN include:

- Capacitors
- Bus
- EMA vacuum high current switches
- High current transmission lines
- Charge/dump system
- ETC mechanical contactor
- ETC TVS switch
- ETC inductor
- ETC load
- EMA load
- Charger
- Control system

Capacitors

Figure 3 shows the present 12.5kJ capacitors used in the PFN. The capacitor specifications are:

- Aerovox ModelLM103EW250D21A
- Capacitance 250 µF
- Stores 12.5 KJ @10 KV
- Peak current 130 kA
- Fault current 180 kA
- ESR 3 mΩ
- Internal inductance <30 nH
- Life: 1500 discharges
- Dielectric, metallized polypropylene

Figure 3. PFN capacitors

PFN Bus

The PFN bus has a tri-plate structure (i.e. the hot is sandwiched between two grounds). The hot conductor is shaped in a winding fashion to increase the inductance to a desired level as required by the design. The inductance of the bus is 3 nH/ft and the bus is 8 feet long. Figure 4 shows a picture of the bus during its construction phase.

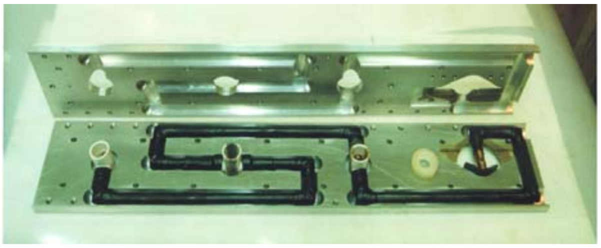

Figure 4. PFN Bus

EMA vacuum high current switches

The PFN incorporates two high current EMA switches, one for each PFN. These switches are capable of carrying 500kA peak currents for short current bursts. They are composed of two sintered tungsten-copper (Elconite) plate electrodes of about 5 inches in diameter. The body of the switch is made from alumina. The switch inductance is 20nH and the resistance is 200μΩ. The switch operates below 5 microns of pressure, has been successfully tested to 500kA, and has held voltages as high as 39kV without pre-firing. This switch is demountable (not sealed) and requires a roughing pump to keep the vacuum below 5 microns of pressure. Figure 5 shows the EMA switch.

Figure 5. EMA switch

High current transmission lines

The transmission lines are comprised of a center conductor (hot) made of a 0000 welding cable and a return conductor made of three layers of breaded wire. Several layers of different types of insulation separate the hot center cable from the return. The two conductors are wrapped together with a fiber reinforced tape to resist the magnetic pressure which develops between the two conductors during EMA shots.

Charge/ dump system

The charge system components include the two charge relays, the charging resistors, the surge protection circuit, and the cables connecting the charger to the PFN. The resistors are ceramic type resistors and the relays are Ross Engineering model E12-NO-12-1-0-BD. The charge relays are kept open for normal operation. The dump system is similar to the charging system except the dump relays are normally closed and lack the surge protection circuit. A ceramic resistor provides an automatic short to the PFN after every shot. The PFN energy can be dumped into the resistor in the event of an emergency.

ETC mechanical contactor

The ETC mechanical contactor is a high current mechanical relay operated by an electric motor upon commanded from the PFN controls. The ETC part of the PFN is isolated from the EMA part when the contactor is opened. When commanded to close by the control system, the contactor connects PFN1 to the ETC switch.

ETC TVS switch

The ETC switch is a triggered vacuum gap of a rod array type that operates at 10^{-9} torr pressure. The electrode structure is an interleaf design that minimizes the effects from the magnetic field of the current on the plasma (Goody et al, 1981).

ETC inductor

The ETC inductor is a 15 μH coil type inductor. The inductor is a replacement for a "jelly roll" type inductor that was originally incorporated in the PFN. The original inductor was replaced because it had failed during high energy testing.

ETC Load

The ETC load is an assembly designed to emulate the firing of a 60mm ETC gun when triggered. The emulated ETC gun can fire five shots consecutively in rapid mode in less than half a minute, a feat that exceeds all known ETC guns to date. The ignition element that handles this rate of fire is a Flash Large Area Radiation Element (FLARE) since it is also capable of use in several ETC ignition element concepts. The FLARE is made of a 4 mil thick copper foil adhered to a Mylar sheet. The copper foil is cut in columns of diamond shaped elements. The length and/or the number of columns of the FLARE can be changed to control the impedance of the element so it can be tailored to match that of the PFN for optimum energy and power transfer.

Each ETC cartridge contains two elements placed along the interior surface of an acrylic tube shown in Figure 6 (inside an aluminum cylinder with holes to provide visual access.) Two long leads on the top are connected to the hot bus of the PFN and a small one at the bottom is connected to the ground. When current is passed through the element, the copper from the diamond-cut foil is annihilated to form hot plasma that is injected radially inward toward the axis of the cartridge to ignite the propellant for the gun's projectile. Figure 6 shows the ETC cartridge fully assembled.

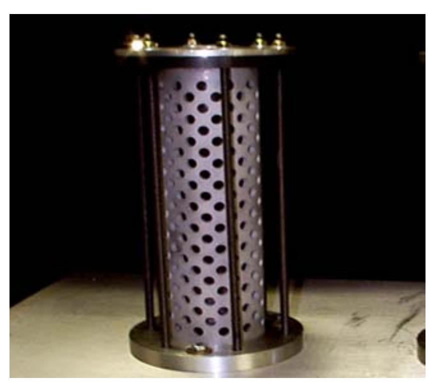

Figure 6. Fully Assembled ETC Cartridge

Five cartridges are included in the ETC load. Each cartridge is connected to the PFN with a vacuum contactor that is pneumatically actuated. When a contactor closes, the corresponding cartridge is connected to the PFN and fired. Figure 7 shows the ETC load in the SIL with the five cartridges mounted with their respective vacuum contactors on top of the housing.

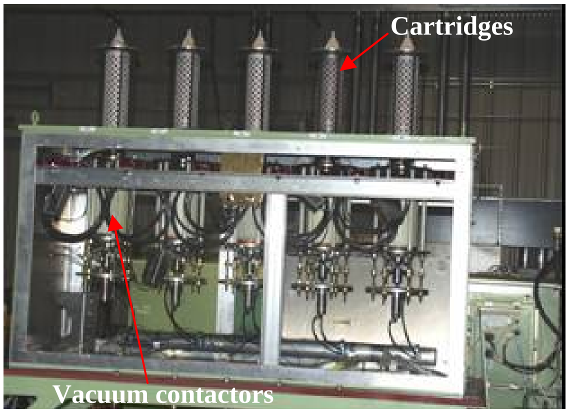

Figure 7. ETC load

The ETC load can emulate an ETC gun breech/autoloader system as well. For this, the cartridges are commanded to fire sequentially. The controls close the PFN charge relays and charge PFN1. After the charging is complete, the controls open the charge relay, close the first vacuum contactor of the load, and fire the first cartridge. The charge relay is then closed and the PFN1 is recharged. This is repeated to fire each consecutive shot of the ETC load. The process continues until all cartridges are fired or until the number defined by the operator has been reached. The operator can set between one and five (all) cartridges to be fired. When done, the control system shuts the system down and safes the PFN.

EMA load

The EMA load is designed to emulate the behavior of an EMA module. The EMA load includes two fuses, an arc gap, and a resistor. Figure 8 shows a circuit schematic of the EMA load connected to the PFN.

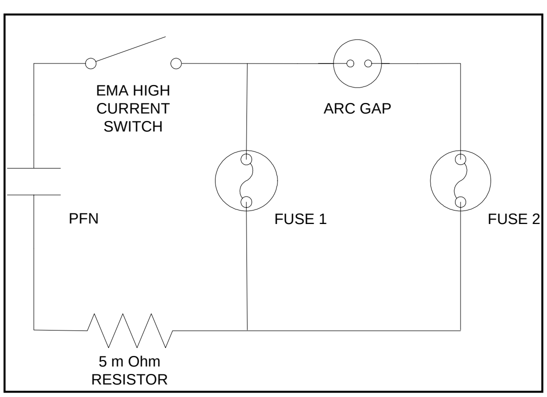

Figure 8. EMA load circuit

The EMA load is operated by using double fuse action to simulate EMA dynamic behavior. First, the EMA switch is closed to allow current to flow through fuse 1 shown in Figure 8. Action (integral of current squared) is deposited on the fuse while the current flows until a critical amount has been deposited. Once that amount is reached, the fuse explodes causing the impedance to increase at that part in the circuit. The current then decreases while the voltage across the arc gap increases. When the voltage reaches the breakdown voltage across the gap, the gap breaks down and current flows through the second fuse of the load. The 5 mΩ (can vary between 3 and 6 mΩ) resistor is included in the load to limit the current and to absorb part of the energy. Figure 9 shows a picture of the EMA load in the SIL.

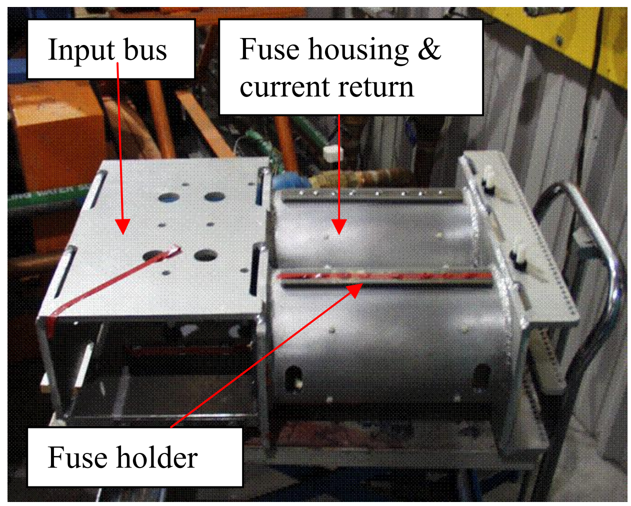

Figure 9. The EMA load in the SIL.

The left side of the load (square part) is the input bus of the load. The two cylindrical conductors serve as the fuse housings and the current return. Two parallel brackets with a series of holes drilled in them are attached to the conductors. The resistive elements of the load are bolted onto these brackets. Each cylindrical conductor has a slot at the top through which the fuse is inserted. Figure 10 shows an EMA fuse as it is inserted into the housing. The two holes at the side of the fuse housing provide access to the bolts that attach the fuse to the load bus. Before the load is fired, the fuse housings are filled with sand or salt to provide a means of absorbing part of the PFN energy and also to protect the insulating parts of the load from metallization.

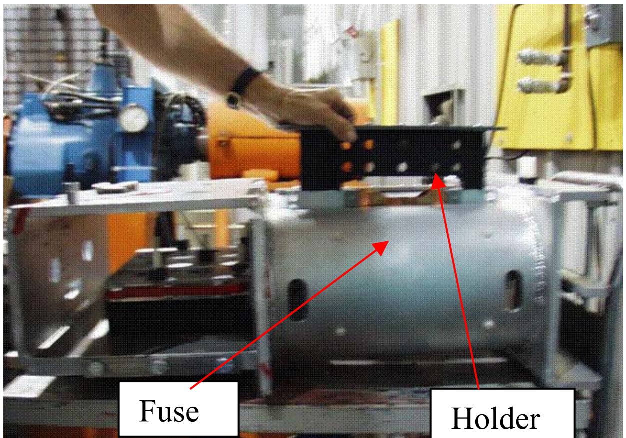

Figure 10. EMA Fuse inserted in the EMA load

The EMA fuse is composed of either two 8 mil thick, or four 4 mil thick, copper foil elements clamped onto the fuse holder. The final parts of the load are the Z-fold resistors mounted on the brackets. The EMA load is designed to accommodate up to 14 such resistors. Any even number of resistors can be used to tailor the load resistance so that the current through the load will meet the requirements for annihilating the fuses.

Charger

The PFN charger is a switched, pulse width modulated (PWM) power supply. The power supply incorporates IGBTs as switching elements in an H-bridge configuration. Other features of the charger are:

- switching frequency 15kHz
- laminated bus structure to minimize inductance
- adiabatic operation (no cooling necessary)
- PWM current control

The charger is capable of charging the PFN1 for ETC shots in about four seconds. The charge rate was tested and confirmed at ~30kJ/s, a rapid charging rate sufficient for PFN1. Figure 11 shows the PFN charger with its housing opened to show the charger components.

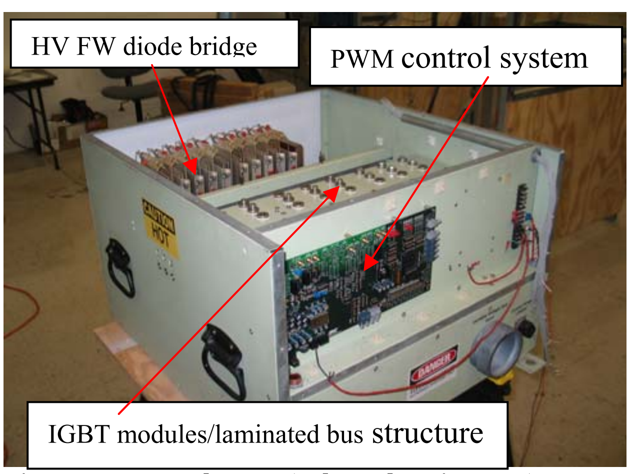

Figure 11. PFN charger (30kJ/s charging rate)

Control system

The PFN control system provides for the safe operation of the PFN and PFN Charger hardware within the SIL hardware environment. The overall SIL control system is a hierarchical control topology; in particular the PFN control system provides a bi-directional interface with the SIL CHPS controller. The PFN controller provides local interlocks to ensure safing of the PFN capacitors, and to ensure that the capacitors are properly charged. Hardware safety monitoring ensures that critical system limits are maintained (e.g. capacitor over-voltage detection) as required to assure safe operation of the PFN. In summary, the PFN control system provides control and monitoring of the following functions.

- Controls the charging sequence
- Dumps the PFN energy in case of an emergency
- Shorts the PFN after a shot is completed
- Fires one to five shots of the ETC load
- Fires the EMA load
- Reports PFN Voltages and discharge currents

Figure 12 shows a block diagram of the control system.

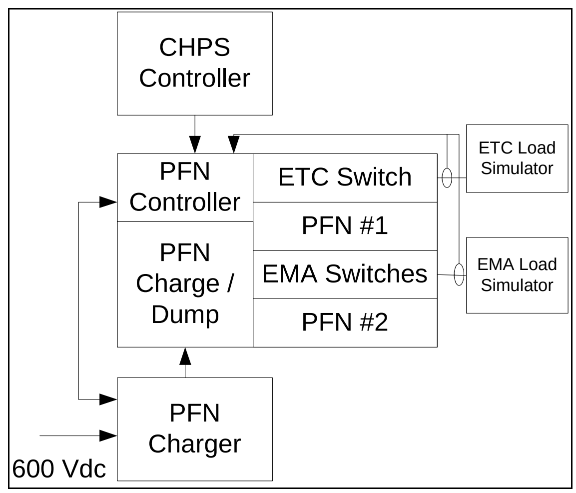

Figure 12. PFN Controller bock diagram

2.2 DP-PFN Testing

The DP-PFN is currently being tested in the SIL. The objectives of the test are summarized below.

- Demonstrate the operation of the PFN in a hybrid vehicle environment.
- Verify the PFN meets load requirements such as current levels, voltage levels, and pulse shapes.
- Demonstrate five rapid shots of the ETC gun.
- Demonstrate that the PFN can be charged as quickly as required in the actual operation.
- Demonstrate that the PFN's control system operates correctly in the "noisy" hybrid vehicle setup.
- Determine whether there is interference between the PFN and the vehicle control system

A test plan has been prepared to accomplish these objectives. The plan is organized according to each of two types of tests that will be performed.

- EMA tests
    - Static (resistive) load
    - Dynamic load
- ETC tests
    - Static (resistive)
    - Dynamic load

The resistive load tests will be performed to ensure that all subsystems are in good working condition and to prepare the system for the upcoming tests. Dynamic load tests will be performed after these preliminary tests are completed. The ETC dynamic load tests will include the actual ignition element used in ETC 60 mm guns. The EMA load tests will involve the two fuses used in Electromagnetic armor. Current and voltage data from the load will be collected and used to calculate the energy and power transfer to the load as well as the load impedance.

Preliminary tests have already been performed during the development of the PFN and of the loads. These tests have produced valuable data about the behavior of the ETC and EMA loads. Figure 13 shows the current and Figure 14 shows the voltage of the FLARE ignition element during its development for the SIL tests.

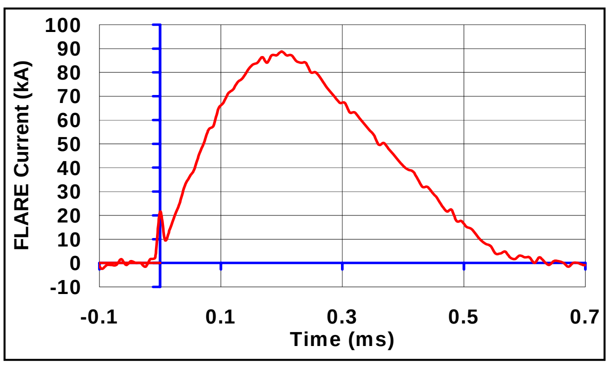

Figure 13. Current of the FLARE ignition element during initial testing of the development phase.

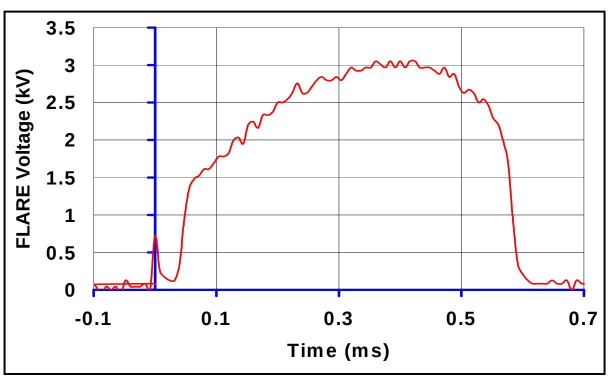

Figure 14. Voltage across the FLARE ignition element during the development phase

3. SECOND-GENERATION PFN

Design of a variable pulse forming network (VPFN) is underway at SAIC's Adelphi MD facility as a second generation DP-PFN. The VPFN will advance Pulsed-Power technology while providing the SIL with a useful and cutting-edge simulation tool. It has a modular architecture and uses modern solid-state switching technology that will enable it to produce a variety of waveforms suitable for various different EMA and ETC applications. Furthermore, modern capacitors and DC/DC converters will be integrated in the VPFN to provide the system with enhancements in high energy density and quick recharge capacity relative to the first generation PFN.

3.1 VPFN at the SIL

The VPFN depicted in Figure 15 is being designed to enable the SIL to remain up to date with the latest pulsed power applications. This VPFN will be capable of simulating a variety of existing PFNs that are currently in use at Aberdeen Proving Grounds and elsewhere. It will have the ability to simulate different PFN architectures and be able to produce many different waveforms and hit locations. The VPFN will have a centralized system that consists of a single large capacitor bank combined with a system of many small capacitors for producing many different waveforms. Also, it will have the ability to control hit locations to enhance the ability to simulate most waveforms since hit locations greatly affect the resulting pulse from different PFNs. As EMA technology progresses and waveforms are developed, the desired waveforms and total energy of the system can be changed with the addition or removal of the capacitors.

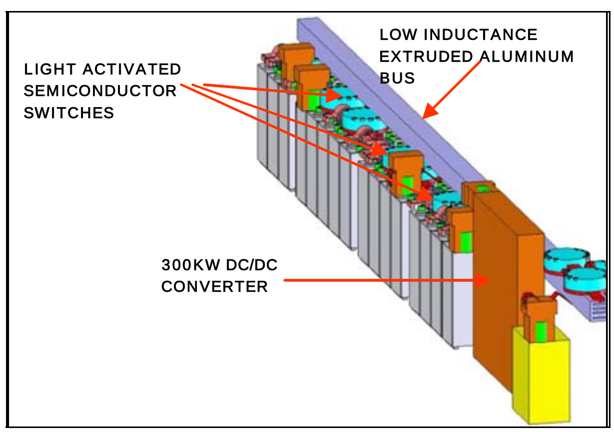

Figure 15. VPFN

3.2 Potential of the VPFN

The VPFN has the potential to further vehicle pulsed power system technology. Soon, new sensors will be developed that will enable a vehicle system to detect and identify threats to that vehicle during or even before penetration of the vehicle's outer skin. The VPFN can utilize this information to effectively and efficiently manage the expended pulse energy based on what is determined to be necessary to defeat the threat(s). That is, the VPFN will provide a correctly shaped pulse with a proper duration that uses no more energy than is required to defeat the incoming jet as it traverses the circuit. The VPFN will also be capable of discharging with various peak currents to efficiently counter jets of various diameters. These capabilities contrast with standard PFNs which use a capacitor that will continue to discharge through an arc even after the offending jet has been destroyed. Furthermore, the standard PFN's can discharge only a fixed amount of energy that can be either short with a large peak current or long with low peak current. The VPFN is thus less restricted than other PFNs and can be adjusted independently to accommodate developing technologies.

3.3 VPFN Architecture

The VPFN will consist of groups of capacitors that are connected to a low inductance bus through multiple inductors and switches. The basic system schematic is shown in Figure 16. Each group of capacitors may be discharged through the appropriate inductor to produce the desired waveform, or be left charged as needed. The sum of all the discharged capacitors will result in the overall waveform in Figure 17.

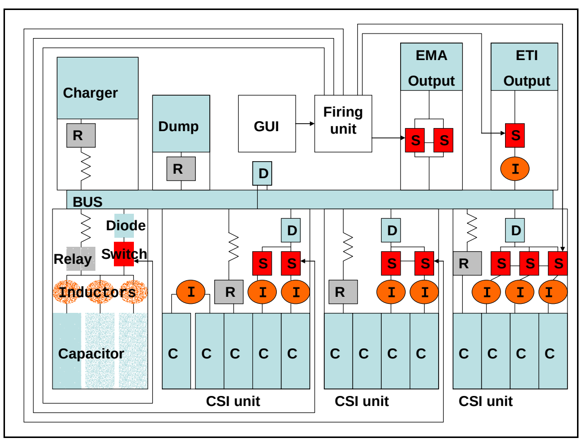

Figure 16. VPFN

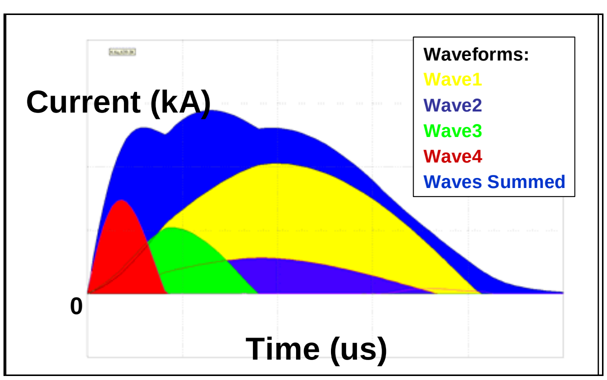

Figure 17. Waveform

Extrude-a-bus

The main transmission bus, named Extrude-a-bus, consists of a set of interlocking aluminum extrusions shown in Figure 18. The extrusions provide a low inductance path for the output pulse and for the charging and dumping of individual capacitors. The bus also incorporates a low voltage line for delivering power to various components. Electrical Connections to the Extrude-a-bus are made through a T-slot so that components can be easily placed anywhere along the bus' length.

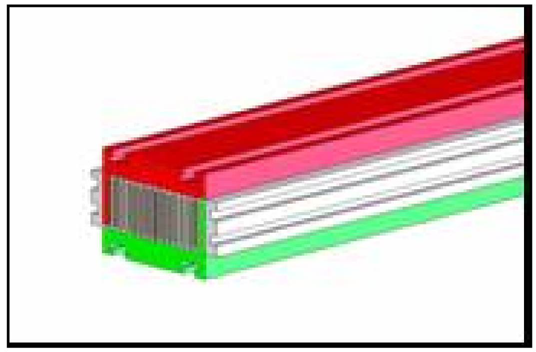

Figure 18. Extrude-a-bus

CSI units

There are four capacitor switch inductor (CSI) units in the system. Each CSI unit is connected to the Extrude-a-bus through a relay and a laser activated semiconductor switch (LASS). The LASS shown in Figure 19 was developed by OptiSwitch Technology Corporation to achieve the necessary dI/dt rating that cannot be achieved with traditional electrically gated thyristors. OptiSwitch designed the optical activation of the thyristor to greatly increase the dI/dt rating so the area of the switch is determined only by the temperature rise in the wafer.

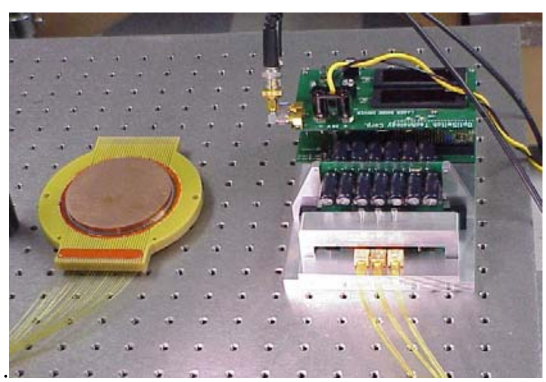

Figure 19. LASS

Each CSI unit has a control system that monitors its status. Each of the control systems will determine if the CSI unit is in need of charging and, if so, will connect the appropriate relays and order the LASS to engage the charger. The CSI units can be placed anywhere along the Extrude-a-bus.

Charging

High speed charging is accomplished with SatCon's 175 KW/300 KW peak dc/dc converter. The converter relies on an input voltage of 600 Volts DC to produce the necessary 10,000 volt bank voltage. Despite its small size of 1.4 cubic feet, it will recharge the entire system in less than 2 seconds. The converter's output is directed through a normally open relay to the Extrude-a-bus. Charging is activated from a request from the CSI units either after a shot or to compensate for any leakage. The charger can be placed anywhere on the transmission bus.

System Safety

A load resistor will be built into the system that can safely shut the system down. The load resistor is connected across the Extrude-a-bus through a normally closed relay that is held open by the low voltage bus line. When power is cut to the system by interlock or by user command, the system automatically dumps the charge. The Dump unit can be anywhere on the Extrude-a-bus.

Multiple Outputs

Two separate outputs will connect the Extrude-a-bus to either the EMA or ETC load through the LASS. The EMA Output will provide a direct connection between the Extrude-a-bus and the EMA load while the ETC output will include an inductor. The output units can be anywhere along the length of the Extrude-a-bus.

System interface

Communication between the SIL's graphical user interface (GUI) and the VPFN is accomplished with the firing unit. The firing unit monitors the ready signals of the CSI units in addition to the output of the EMA impact sensor and the ETI trigger. The firing unit triggers the appropriate LASS according to the CSI units that are available and what pulse is desired. The firing unit will provide the closest waveform possible dependent upon if it discharged recently. The firing unit displays the status of the CSI units and charger for the user, and can be placed wherever is convenient.

User friendly simulations

The SILs graphical user interface will allow the lab user to effectively simulate the impact of a jet or the firing of an ETC gun. The user will be able to specify a series of desired waveforms and the time interval between them. The GUI will send the appropriate signals to the firing unit at the appropriate times and the VPFN will do the rest. The user will also be able to simulate failures such as a shorted capacitor or failed switches.

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CONCLUSION

The development, integration, and testing of the PFNs described herein mark great milestones for the SIL. The currently integrated DP PFN provides the SIL with the capability to emulate the major hybrid-electric mobility, lethality, and survivability functions of future hybrid-electric ground combat vehicles. Extensive testing is now underway using the DP PFN to emulate loads for advanced hybrid-electric combat vehicles. The VPFN under development will enhance the capabilities of the SIL by enabling the emulation of a wider variety of pulse waveforms while providing both enhanced high density energy storage and fast recharge capabilities. In addition the VPFN will be able to more efficiently use stored energy to defeat threats based on what is ascertained from new sensor capabilities as technology is improved. Thus, the VPFN will have the flexibility to adapt to new technologies that arise down the road.