DESIGN AND TESTING OF A COMPACT ELECTROMAGNETIC ARMOR POWER SYSTEM (U) *

Richard D. Ford, Gregory B. Dorr, and Alan J. Toepfer
Science Applications International Corporation
Albuquerque, NM 87106

The design and testing of a transportable, compact power supply that serves as both a TACOM -technology demonstrator for a future electromagnetic armor system for top attack protection, and a DARPA pulse forming network (PFN) test bed for a hybrid electric combat vehicle will be presented. This second generation PFN now addresses electromagnetic armor integration concerns from a combat vehicle design standpoint. The design, which is based on one previously tested, [1,2] employs state-of-art metallized foil capacitor technology to increase the total energy stored, a more compact switch design, and innovative high power transmission line technology to minimize EMI, while dramatically reducing system space and weight. The system will initially be proven in field tests against CE threats at the Army Research Laboratory, and upon completion of these tests, will be integrated into the DARPA Combat Hybrid Power System Vehicle, System Integration Laboratory (SIL).

(U) Background:

(U) Over the past 20 years, pulsed discharge capacitor energy density has been improved by more than ten-fold. As a result, pulsed discharge system applications are moving from laboratory experiments to technical demonstrator projects. Ongoing materials research promises to increase capacitor energy density by another factor of 10 in the near future (Ref.1). When these advancements in energy storage are realized, size and weight of auxiliary components such as bus-work and switching hardware will become as crucial to PFN size and weight reductions as increasing capacitor energy density.

(U) A TACOM sponsored Electro-Magnetic Armor (EMA) technology demonstrator project was initiated to evaluate feasibility of utilizing state of the art components in a small transportable vehicle, to demonstrate effectiveness of lightweight EM Armor. In the first phase of this project, a prototype self-contained energy storage PFN, whose components consisted of "off the shelf" technology, was assembled and installed in a 42 cubic foot volume within an 8' x 10' trailer. The system was transported to Aberdeen Proving Grounds, Md. and was used in three highly successful test series (Ref. 2). Results from these and other tests have been used to refine EM Armor software. Some results are presented in the paper “Modeling of Electromagnetic Armor Phenomenon“ at this conference. Based on successful test results and improved model predictions, a follow-on program was initiated to upgrade system design and expand capability. The EMA Upgrade Demonstrator is presently undergoing laboratory checkout and will be field-tested at the Army Aberdeen test range in April of this year. This paper describes the EM Armor PFN design which has reduced system size and weight by a factor of two and expanded performance to support the DARPA CHPS electric vehicle program.

(U) Upgrade Demonstrator Design Goals:

(U) Goals for the upgrade system development include increasing discharge pulse energy and duration by approximately 20% while reducing size and weight by approximately a factor of 2, adjusting pulse waveform for improved efficiency in field tests by using independent control of each PFN segment, reducing EMI emission during discharge, and the ability to support other pulsed electric systems (CHPS ETC Gun). Additionally, development goals in cooperation with the DARPA program include rapid re-charge capability for burst repetitive operation, and development of control system concepts and components which permit full integration of the EMA demonstrator into the DARPA System Integration Lab (SIL), for future use (Ref. 3).

(U) System Electrical Performance Modeling:

(U) The upgrade system requires some adjustments to the prototype system electrical design based on field test results and improved armor modeling. Additionally, desired component size reduction and use of a bus-bar feed-line in place of cables changes high frequency circuit resistance. A Spice based transient analysis program, ICAP 4, was used in parameter studies to model the effects of these changes on PFN waveforms. Additionally, a newly developed model, FFEXM, was used to evaluate circuit energy distribution and effects of current commutation by means of current initiation fuses.

(U) The circuit used in the analysis includes four identical PFN circuits with pairs of PFN assemblies connected to a common output closing switch. Circuit component values were adjusted to reflect anticipated design changes. Analysis performed and laboratory testing are based on use of a fixed 5 mil-ohm test load. Parameter studies show that changes to PFN component values have little effect on performance, due to parallel connections. However, rise-time and peak current depend strongly on the load circuit parameters. Modeled circuit waveforms agree well with waveforms obtained in system checkout tests performed to date.

(U) Circuit values obtained from ICAP-4 analysis were used in the FFEXM program to review the resulting energy distribution and the effects of current commutation fuse performance. Analysis which incorporates final selected component values show that approximately 25% of stored energy is dissipated outside the load.

(U) System Design:

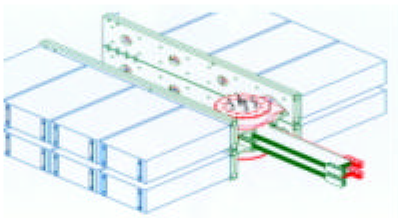

Figure 1: Conceptual four section PFN upgrade system with switches and output bus.

(U) The Demonstrator Upgrade design shown in Figure 1 includes four identical four-leg PFN assemblies, each storing 50 kJ at 10 kV charge. Two PFNs are combined at each output switch to form independently operated 100 kJ capacitor bank assemblies. Both assemblies may be discharged in parallel for maximum current, sequentially discharged for pulse stretching, or used independently to support weapons system needs. Components are selected for minimum size and weight, and the control system is designed for either manual operation or fully automatic operation controlled by CHPS system software. Individual component design details are discussed below.

(U) Energy Storage Capacitors:

(U) The EMA upgrade capacitor uses best state of the art metallized foil technology for fast pulsed discharge. Each capacitor stores 12.5 kJ at 10 kV. The design was tailored to SAIC/TACOM specifications and fabricated by Aerovox Corporation as type LM103EW250D21A. The capacitor uses a conventional steel outer cover measuring 10.25" x 6" x 18 ". It has a standard single insulated stud at its smallest surface, uses four weld nuts for common circuit connection, and is modified to include four weld-nut attachment points at the opposite face. This simplifies enclosure design by allowing use of the capacitor steel enclosure as the PFN support structure.

(U) Pulse Forming Inductor:

(U) The four PFN array, designed to match a 5 mΩ load impedance, requires a 120 nH inductor at three of the four capacitors in each PFN. A coaxial inductor, shown in Figure 2, was developed for this application and integrated into the PFN header assembly. The three coaxial center conductors are assembled as a continuous unit and insulated using PVC shrink tubing over each long conductor segment, and wrapped self-fusing high voltage tape over corner connections. Insulation at capacitor high voltage studs include a modified 1.5" PVC plumbing tee and a 2" PVC plumbing union. Each of the three 120 nH coaxial leg inductors in a PFN section require a circuit path 29" long having an OD/ID ratio of approximately 2. The three inductor layout shown is folded to fit within the 7.63" x 42.5" PFN header. FFEXM circuit modeling indicates that an inductor skin resistance less than 1mΩ is desired for limiting energy losses. An inner conductor diameter of 0.75", producing an AC resistance of 0.67 μΩ, was selected for this design. Hemispherical 1.75" diameter grooves, milled within each of two 7/8" thick aluminum plates, combine to form the coaxial return circuit for each inductor. Since coaxial current carrying circuits are self-shielding, inductor EMI emission is eliminated with this design.

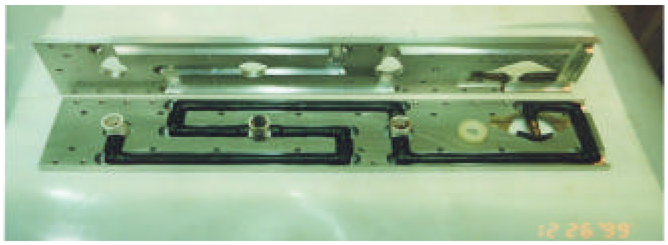

Figure 2: PFN header with enclosed coaxial pulse forming inductors.

(U) The fourth capacitor in the PFN string is connected directly to the switch assembly using a low inductance tri-plate bus connection which provides support against magnetic forces and also helps to minimize EMI emission. The tri-plate output bus is insulated by wrapping edges and corners with overlapping layers of teflon tape and by separating high voltage and current return conductors with polyethylene sheet insulation. The combination of coaxial and tri-plate compact shielded inductors reduce system size and weight, provide containment for magnetic forces, minimize EMI emission, and provide high voltage protection for personnel. To assure high voltage reliability, each PFN header is assembled, installed on a test fixture, and hi-pot tested to more than twice its operating voltage, prior to installation of capacitors.

(U) Vacuum Flashover Output Switch:

Figure 3: Triggered vacuum flashover switch

(U) The EM Armor demonstrator design is unique in that it incorporates a closing switch between the PFN high voltage and external loads. Use of an output switch provides a number of benefits, including reliable performance independent of environmental conditions, and a high level of personnel safety since voltage is not present outside the PFN until the switch has been closed. The prototype EMA system successfully used an large triggered vacuum switch designed for a more demanding application (Ref.5). A cooperative switch re-engineering effort between the DARPA/CHPS program and the

TACOM EM Armor program has reduced overall switch size and weight. The re-engineered switch, shown in Figure 5, is only 7" in diameter and weighs 13 lbs, compared to the earlier switch which was 12" in diameter and weighed 30.5 lbs. The switch includes disk shaped anode and cathode electrodes separated by an annular polyethylene insulator. Six "spark plug" trigger electrodes are uniformly spaced around the perimeter of the anode to provide multi-point switch initiation, producing a low inductance, large area current discharge within a central vacuum region. The switch is capable of holding off voltage higher than 20 kV for long duration, but can be reliably triggered at voltage as low as 3 kV. The high voltage hold-off permits the system to operate in a standby/ready state, while low voltage triggering capability permits PFN segments to be triggered sequentially.

(U) Switch triggering occurs when a fast rising 8 kV pulse applied to the trigger electrodes produces a surface discharge across ceramic insulators inside the vacuum region. Ultraviolet photons generated by the discharge illuminate the switch insulator, producing multiple point electron avalanche to initiate a large area discharge, with peak current as high as 500 kA up to 50 coulombs. At the designed 10 kV operating voltage, switch closure time is typically 200 nS. The re-engineered switch has been installed on the upgrade PFN and preliminary discharge tests have been performed with good results. Full energy test preparations are in progress.

(U) Switch Interface:

(U) A tri-plate bus assembly, shown in Figure 4, connects two opposing PFN assemblies to a centrally positioned cylindrical switch enclosure. The triggered vacuum switch is installed coaxially within the cylinder, forming a shielded, uniformly distributed current path to the load circuit output bus. The switch / tri-plate interface was insulated for initial testing using overlapping teflon tape at edges and self fusing high voltage tape at difficult conductor joints. A simplified insulating technique using vacuum formed polyethylene insulators will be incorporated later as a retrofit.

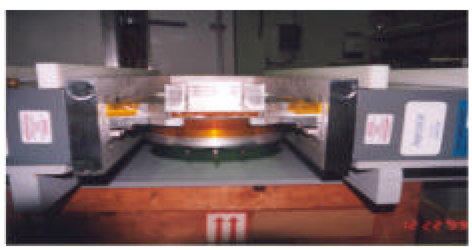

Figure 4: Tri-plate output bus with cylindrical switch enclosure

(U) Interleaved Output Feed-line:

(U) The prototype EM Armor system required 24 Belden YK198 cables per switch to minimize losses and reduce inductance to the load. While this flexible cable approach is excellent for use with single shot events in laboratory and field tests, components become excessively large and heavy when considered for most vehicle applications. Additionally, connection to an array of load modules is difficult when cable terminations are used.

(U) Figure 5 shows a section view of an interleaved transmission plate feed-line developed to reduce size and weight for the armor application. The feed-line is formed using 7 common bus-plates (1) and 6 high voltage plates (2), with polarities alternated. A plate thickness of $1/16^{th}$ inch was selected based on useful current penetration depth at the system operating frequency. In the upgrade system, the outer common plates are electrically connected through a conductive shunt, eliminating EMI emission and providing insulator protection. Current breakout points may be inserted at any location along the line, as shown in Figure 6, to accommodate multiple parallel connected load modules.

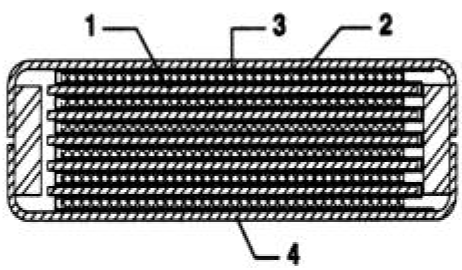

Figure 5: Interleaved output bus

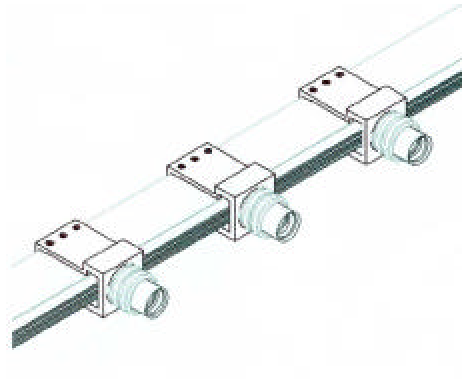

Figure 6: Interleaved bus with 3 coaxial connectors.

(U) The alternating plate design provides a current path between each pair of conducting surfaces. In the design shown, a total of 12 current paths connected in parallel reduce feed-line inductance to only 6.85 nH/M. Inductance may be reduced further by increasing the number of conductor pairs, reducing conductor separation distance and increase plate widths, if needed. Since total current in each conductor is reduced by the number of current paths and magnetic fields around conductor pairs cancel, electromagnetic forces are reduced by a factor of more than 1,000 in the 12 pair configuration, allowing the feed-line forces to be contained by simply wrapping the plate assembly with glass re-enforced dielectric tape.

(U) <u>Control System</u>:

(U) The demonstrator upgrade system is designed to support both EM Armor and CHPS system requirements. Normally, system status is monitored and the PFNs are configured for either EM Armor or CHPS applications through software control. However, a manual operating mode is provided for checkout, laboratory operations, and for single event field tests. Each 100 kJ PFN assembly is fully isolated from the other during both re-charge and pulse discharge cycles. During EM Armor operations, the high voltage system is electrically isolated from the vehicle chassis, so that no current flows through the vehicle structure during system discharge. The PFN may be automatically re-configured for a ground reference when used for CHPS applications. Discharge is controlled using a separate triggering circuit for each PFN - switch assembly. Each trigger circuit includes a pulsed discharge capacitor charged to 5 kV, a Krytron switch, and a coaxial voltage step-up transformer. Power for both the 5 kV trigger circuit and for impact sensor circuits embedded in each load module is derived directly from the charged PFN. Additionally, provisions are made for operating the trigger circuit from either 110 VAC power or from batteries for CHPS use and for laboratory operation. Control circuits are electrically isolated from the high voltage PFN via fiber-optic links.

(U) For EM Armor operation, the control system permits each PFN to be held in a ready state at 90% of operating voltage for a long duration. The PFNs may be pulse charged to full capacity on command. Voltage is not present at the feed-line bus or armor module except for the millisecond discharge duration after a switch has been triggered. Each armor module connected to the feed-line bus via quick change plug-in contacts include at least two electrically isolated "Walker" plates and an impact sensor. A switch triggering circuit includes two firing command inputs, and requires a power enable command from the control system to operate. When trigger circuit power is turned on, a "watch-dog" trigger ready pulse train is fed back to the control system, and a charge received signal is returned for diagnostic purposes after each trigger command. Discharge may be controlled by means an electrical impulse from either an impact sensor within the EMA armor module or from the control electronics. On projectile impact, the sensor sends a firing pulse to each trigger circuit, closing the triggered vacuum switch and applying voltage to all

Walker plates in a load array within 400 nS. This corresponds to a penetration distance of typically 3 mm. Current discharge occurs only within the impacted module.

(U) In CHPS ETC Gun applications, the EM Armor switches generally are not used. The load requires burst repetitive operation for relatively low current discharges, each having a several milli-second pulse duration. This capability is provided using high current cables to connect either PFN assembly to the CHPS load circuit through a pulse shaping inductor. A triggered vacuum switch designed for rapid voltage recovery and long discharge pulse duration is fired under program control to deliver bursts of electrical pulses to the desired load.

(U) System Assembly and Checkout:

(U) The EM Armor upgrade system design incorporates several unique features to facilitate easy assembly, maintenance, and operation. During initial laboratory assembly, two headers containing coaxial pulse forming inductors and output tri-plate bus-bars may be assembled as a unit and bench tested to verify high voltage hold-off capability. The rigid header assembly may then be moved to the desired location and capacitors added. System energy may be adjusted by stacking completed 100 kJ units as shown in Figure 7. The top assembly rests on a polyethylene track and may be moved forward or backward for access to the switch - feed-line interface. If maintenance is required, any capacitor may be unbolted and extracted or replaced without disturbing the remainder of the assembly. The fully assembled system is mounted onto a wooden pallet with wheels and may be re-positioned within the lab as needed. The pallet also provides forklift access so that the compact and relatively light weight system can be lifted and installed in or removed from into the transport vehicle as a complete unit. This capability permits the system to support either field tests or laboratory research, with almost no down time.

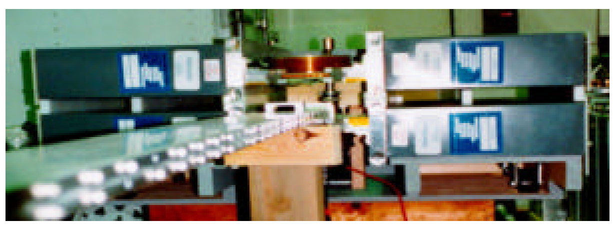

Figure 7: Full 4 section, 200 kJ PFN assembly with shielded output bus.
Sections are Stacked for compactness and ease of transporting.

(U) Table 1: Energy, volume and weight comparison for the prototype and upgrade EM Armor transportable pulsed discharge system

	PFN Prototype	PFN Upgrade
Stored Energy	175 kJ	200 kJ
System Volume	42 Cu. Ft,	23 Cu. Ft.
	Weight, lbs.	Weight, lbs.
Capacitors	2192	1008
Switches	61	40
Switch Bus	109	86
Header Bus	120	120
Inductor	25	25
Feed-line	109	86
Support Structure	90	10
Vacuum Pump	55	36
Totals	2761	1411

(U) Summary:

(U) A compact second generation pulsed power EM Armor Technology Demonstrator has been assembled and is ready for field testing. This versatile pulsed discharge power system meets many of the needs for both field and laboratory testing, and fulfills a dual mission requirement by providing appropriate power for CHPS weapons system operation. In planning the design, special consideration was given to personnel safety from electrical hazards and equipment safety from EMI emissions. The demonstrator design uses state of the art components, resulting in a size and weight reduction of a factor of two, compared to the earlier prototype system. Table 1 provides a comparison of the two designs. An advanced capacitor design reduced weight by eliminating a need for a capacitor support structure typically used in similar applications. Pulse forming inductors embedded co-axially within the capacitor header reduce both size and weight while containing magnetic forces and eliminating EMI emission. A re-engineered triggered vacuum switch reduced switch size and weight without degrading sub-microsecond turn on capability. A novel interleaved feed-line bus design reduced feed-line size and weight compared to coaxial cables having similar electrical capability. The interleaved bus design eliminates feed-line EMI emission and the need for magnetic force containment clamping. A re-designed discharge trigger control circuit derives power form the charged PFN. This design promises improved reliability since the trigger circuit is active only during the short duration charge and fire cycle, and the use of PFN charge voltage eliminates the need for several sensitive low voltage electronic components. In reviewing technology which went into the upgrade demonstrator final design and relating it to size and weight of developmental technology now being tested, it appears that an additional reduction of two in size and weight should be attainable near term.

(U) References

* Work supported by the US Army TACOM under Contract No. DAAE07-96-C-Xl27, and DARPA under Contract No. MDA97-97-C-0032.

(1) Windsor, P. *et. al "Pulsed Power Capability of High Energy Density Capacitors Based on New Dielectric Materials"* Proceedings 12th IEEE International Pulsed Power Conference, Monterey, Ca. 1999, P 102 - 105

(2) Toepfer, A. J., Ford, Richard D., and Dorr, Gregory B., *Plug-In Electromagnetic Armor Modules,* Proc. 10th Annual Army Ground Vehicle Survivability Symposium (April, 1999)

(3)Freeman, M.M.,Perschbacher "*Hybrid Power - An Enabling Technology for Future Combat Systems*" Proceedings 12th IEEE International Pulsed Power Conference, Monterey, Ca. 1999, P 17 - 22

(4) Toepfer, A. J., *et. al, "Electromagnetic Armor Demonstration Tests,"* proc. 9 Ih Annual Army Ground Vehicle Survivability Symposium (March 30 - April 2, 1998).

(5) Ford, R.D. *et al "High Coulomb Triggered Vacuum Flashover Switch"* 11th IEEE Pulsed Power Conference, Baltimore, Md. 1997, P893 - 898