A COMPACT 700-KV ERECTED PULSE FORMING NETWORK FOR HPM APPLICATIONS[Σ]

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Abstract

Increased interest in deployable High Power Microwave systems has led to demand for compact pulsed power drivers for HPM loads, such as magnetrons, that are sensitive to pulse shape. APELC has developed a 600-J, erected pulsed-forming network capable of delivering a 200-ns square pulse to HPM loads. The generator consists of eight, erected pulse-forming sections charged from a common supply. The resonant sections combine to produce a Fourier-approximated square pulse at the load. Pulse characteristics include a FWHM of 200-ns, risetime of 25 ns, and a decay time of 60 ns. The generator is housed in an 18” diameter by 60” long pressure vessel and uses only compressed dry air for insulation. The generator is capable of 50-Hz pulse repetition frequency and features soft-failure modes for continued operation in the event of component failure.

I. BACKGROUND

Interest in deployable High Power Microwave (HPM) systems has led to demand for compact pulsed-power drivers for HPM loads, such as magnetrons, that are sensitive to pulse shape. HPM loads such as the relativistic magnetron benefit greatly in terms of lifetime and performance from pulsed power that can deliver a 200-ns square pulse of hundreds of kV with a relatively flat top. The deployment of modern HPM loads would typically benefit from a high-energy-density, small diameter pulse generator that can deliver the desired pulse shape to the load.

Pulsed power generators designed for HPM production have been typically limited to resonant transformers and pulse forming networks driven by Marx generators [1-3]. Both methods deliver high voltages with large amounts of energy. Disadvantages of the transformer-based method include large volume, transformer oil requirements, and slow rise time pulses. The Marx generator-based method is characteristically hindered by large component counts and cumbersome assembly and maintenance [4]. Neither approach yields a generator with a graceful failure; the generator either operates as specified or fails, with no smooth gradation between operation and failure [5].

II. DESIGN

APELC’s generator is shown in Figure 1. The design is based on a multiple-section erected-PFN concept that addresses disadvantages characteristic of conventional HPM pulsed-power generators. The fast risetime is attained by virtue of the leading section Marx topology. The pulse flat-top is accomplished by conventional PFN synthesis. Since eight erected sections feed the load, the failure of one component or one Marx leaves the system with only reduced pulse fidelity and not total failure. This type of ‘graceful failure’ is the main advantage over a single-Marx based pulse generator. A combination of pressurized dry air and solid dielectric insulation allows for increased energy density (i.e. smaller generator diameter) without SF6 or transformer-oil collateral costs.

Figure 1. APELC EBU erected-PFN pulse generator shown being installed in pressure housing.

Additional generator specifications are given in Table 1.

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Table 1 Electrical Specifications of the Erected PFN

Symbol	Parameter	Value	Units
N	Number of PFN section/ Marxes	8	-
V_E	erected voltage	700	kV
V_{ch}	maximum charge voltage	30	kV
	charge voltage range	10-30	kV
E_{pulse}	maximum energy per pulse	600	J
P_{25}	Maximum power on a 25 ohm load	5	GW
C_{stage}	Capacitance per stage	300	nF
	Erected capacitance	11	nF
L_s	Series inductance	7000	nH
Z_{source}	Source Impedance	25	Ohms

A. Erected-PRN Topology

The erected-PFN concept centers on the Fourier approximation of the desired square pulse by the addition of a number of resonant LC sections. As depicted in Figure 2, each LC section delivers a current pulse based on its resonant frequency. The net pulse is the addition of each individual pulse at the load. Since this must be an erected PFN to achieve the necessary voltages, each section contains a distributed parasitic inductance characteristic of the erected Marx circuit.

This parasitic inductance prevents more precise network synthesis since it cannot be eliminated as in classical type-E PFNs as in [6]. This erected-PFN pulse generator is designed for HPM application, compact operational platforms, and for continued (but reduced-fidelity) operation in the event of component failure.

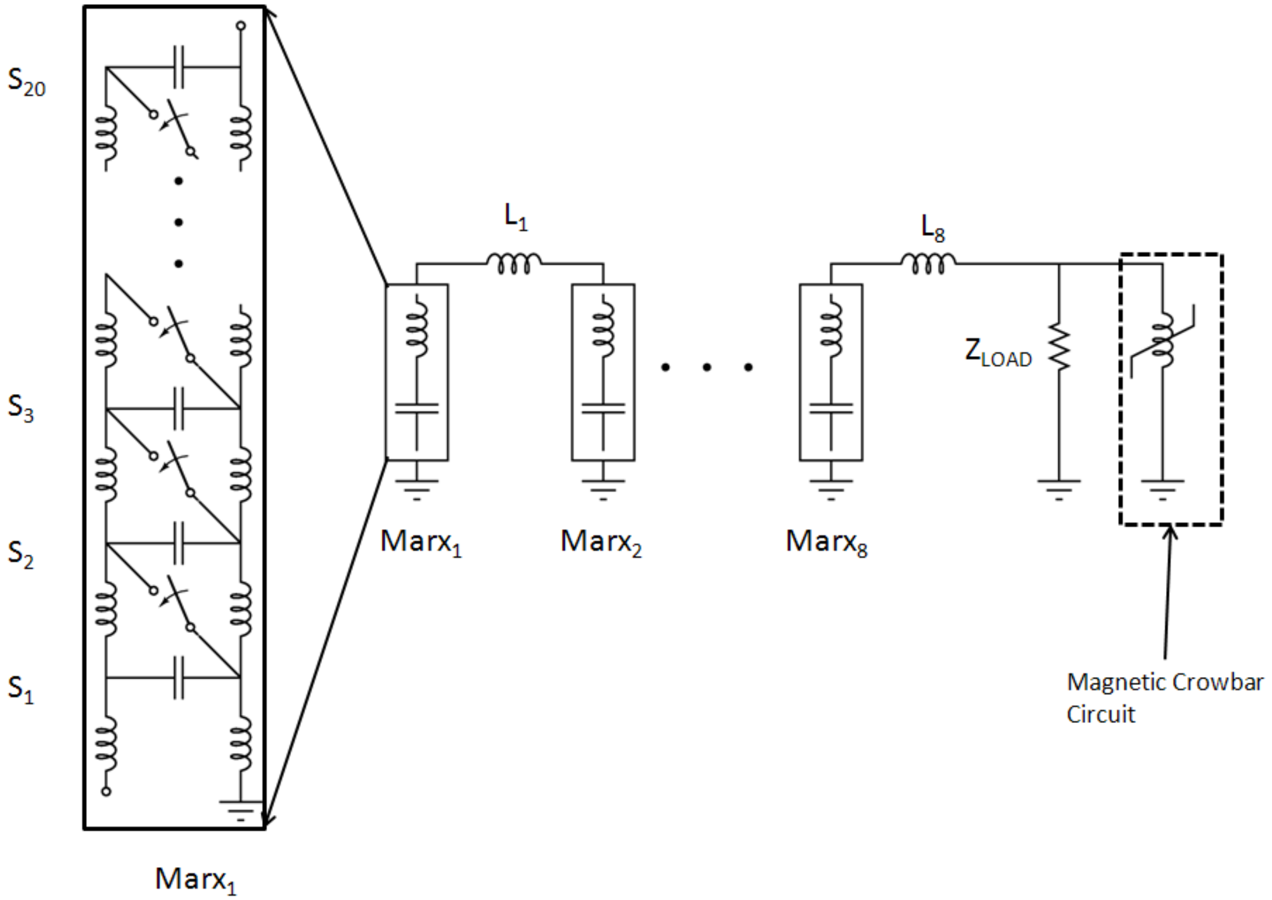

Figure 2 Schematic of the eight-section erected PFN.

B. Prior Design: Sequentially-Fired Pulse Generator

The erected-PFN topology was chosen after a thorough investigation of the feasibility of a sequentially-fired Marx generator for the purpose of driving an HPM load. The original planned method of operation for the Phase II system was the Sequentially-fired Marx-bank method. This method has been previously investigated for driving rail guns, electric launchers, or other nonlinear loads albeit for much longer pulse lengths [8]. In this version, eight 96-J Marx generators would be fired into the load on a predetermined schedule for a total stored energy per pulse of 768 J. This method required: (1) Marx generators to erect only when triggered and (2) the individual Marx jitter to be much less than the net pulse-width. Efforts taken to satisfy these two fundamental requirements were complex, expensive, and ultimately unsuccessful.

Upon the initial construction and low-voltage testing of the sequentially fired Marx system, two major obstacles were identified which prevented pulse shaping by sequentially triggered Marx bank. The first behavior was inconsistent, spuriously large Marx jitter. The second was an over-voltage condition induced by capacitive coupling from a triggered Marx to untriggered adjacent generators. The induced over-voltage caused several generators to self-erect, which removes trigger control of the generators and results in slow rise-times.

In order to assess the timing and triggering performance, each Marx was charged to 28.5 kV and sequentially fired according to the schedule set by the delay-line triggering scheme. Each separate load voltage was measured with a voltage divider and referenced to the 1st trigger pulse as t0. The compiled results can be seen in Figure 3. The risetime as determined by the rise of the first Marx is less than 20 ns. The aggregate pulse width in this example is ~ 200 ns. It should be noted that the relative amplitudes are not consistent since the voltage divider ratio is affected by the value of each load resistor which varies by more than 20% in this instance.

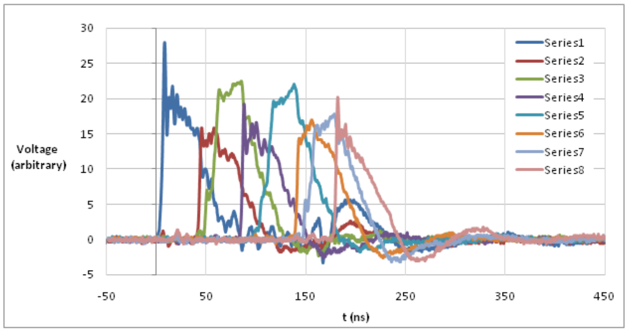

Figure 3 Compiled output pulse of the sequentially-fired arrangement, with each Marx circuit terminated into a separate load.

The charge voltage for this data set was 28.5 kV. Vessel pressure was 70.5 PSI. The results in this example are the best-case observed during the effort using the sequentially fired arrangement. However, the behavior was typically inconsistent from shot to shot due to the induced self-break behavior. One major contribution to this problem was that each generator's array of spark gaps was operated within 20% of its self-break voltage level.

C. Magnetic Crowbar Circuit Design

In an effort to mitigate the negative effects of the energy contained in the long falling edge of the Marx pulse on a Relativistic Magnetron cathode, a crowbar circuit was designed and implemented to shunt the generator current to ground at ~200ns. During the design process, traditional gas switches were ruled out for their inability to hold off hundreds of kilovolts for hundreds of nanoseconds. The more suitable crowbar circuit was a saturable magnetic switch.

Two sample cores were obtained from MK Magnetics and consist of .5" wide Metglas SA1 rolled into 2-inch I.D., 3-inch O.D. toroids. A housing was fabricated to contain the cores and suspend them in an oil medium. Seven parallel windings of three turns each were wound around the housed cores in order to achieve the flux density necessary to saturate the core at the specified voltage and time while maintaining a low enough saturated inductance to realize a relatively fast fall-time. The magnetic crowbar switch is shown in Figure 4.

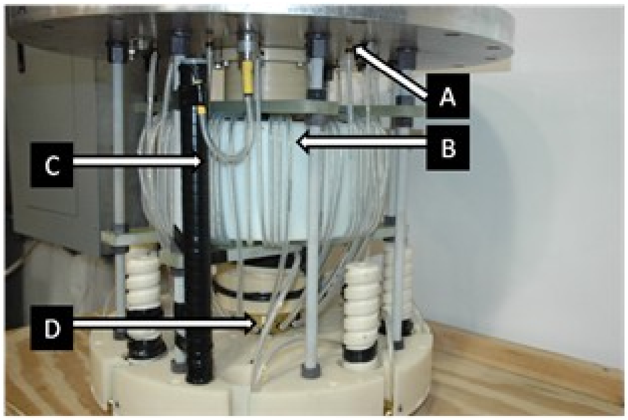

Figure 4 Magnetic Crowbar housing and assembly: (A) crowbar ground connection, (B) one-piece nylon crowbar housing, (C) inductively isolated reset circuit, (D) crowbar center conductor connections.

III. PERFORMANCE

In order to evaluate the pulse characteristics and failure points the generator was arranged as shown in Figure 5. The output of the generator was connected to a coaxial CuSO4 resistor through 100-ft of coaxial high-voltage cable. The current pulse on the cable was measured with an inline CVR. 100 ft of output cable was used to provide diagnostics with sufficient clear time to provide a waveform free from distortions cause by reflections at the load. A picture of the experimental setup and the fully housed generator is shown in Figure 7.

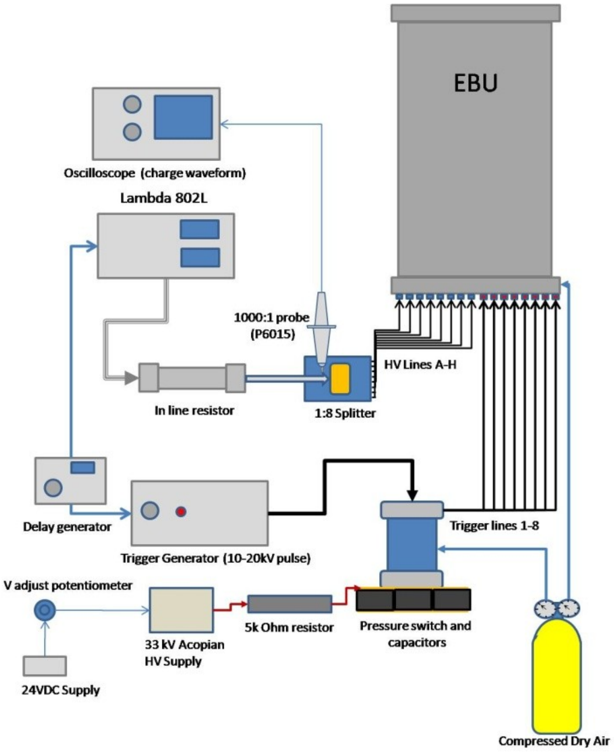

Figure 5. Schematic of performance test and system burn-in testbed.

An output pulse for a 15 kV charge voltage is shown in Figure 6. This pulse was delivered to a 50-ohm cable and measured by a coaxial inline CVR at the generator output. Typical pulse characteristics include a pulse-width (FWHM) between 180 and 220 ns, risetime less than 40 ns, 90-10 decay (without crowbar) of ~100 ns, ripple between 10 and 20 %. The erected (open circuit) voltage of the PFN is typically ~20 x Vcharge. Charge voltages up to 35kV are allowable, which corresponds to an erected voltage of 700 kV. When the output is connected to a 60-ohm cable load, voltage efficiency from erected to cable is typically less than 50%.

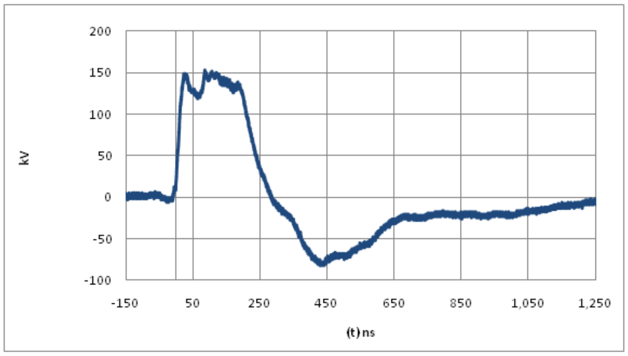

Figure 6. Load voltage waveforms for 15kV charge voltage.

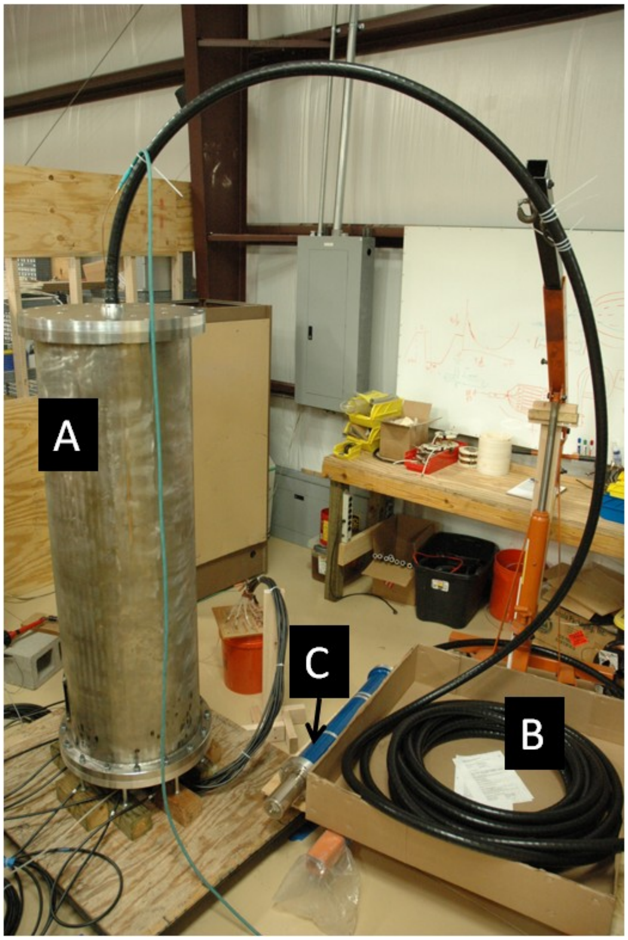

Figure 7 Erected pulse-forming network (A) with common cable load (B) and matched Copper-Sulfate resistor (C).

IV. CONCLUSIONS

This paper described the design and performance of a 1.8-kJ, 700-kV erected pulsed-forming network. Typical pulse characteristics include a pulse-width (FWHM) between 180 and 220 ns, risetime less than 40 ns, 90-10 decay (without crowbar) of ~100 ns, ripple between 10 and 20 %. The erected (open circuit) voltage of the PFN is typically ~20 x Vcharge. Charge voltages up to 35kV are comfortably reached, which corresponds to an erected voltage of 700 kV. When the output is connected to a 60-ohm cable load, voltage efficiency from erected to cable is typically less than 50%.

With the existing infrastructure and capacitors the best way to deliver a reliable pulse generator for the end-user application was determined to be an erectable PFN. Using Guillemin pulse forming synthesis, the pulse shaping is controlled by passive components in the resonant sections of the network. This removes the need to sequentially and actively trigger multiple identical Marxes. Also, given the existing value of each section's erected capacitance, it was possible to synthesize a network with impedance on the order of the intended load impedance.

With the advantages offered by the PFN also came trade-offs. Graceful failure was still a feature of the delivered pulser, but the temporal triggering agility of a sequentially switched generator was lost. Graceful failure was manifested since a 7-section PFN can create a similar waveform with less fidelity than an 8-section PFN. Insulation was more heavily taxed since longer pulses existed inside the generator. Increased PRF capabilities were realized by using inductive stage isolation elements and a high-power coaxial charge resistor. The PFN also features the benefit of experiencing less reversal than the sequentially-fired system which results in fewer capacitor replacements and less repair downtime.

In summary, the sequentially-fired system exhibited self breaks induced by dv/dt capacitive coupling between adjacent generators. With existing hardware, i.e. stage-level modularity, and eight Marxes in the pressure vessel this problems became prohibitively costly to solve. However, up to 4 Marxes were reliable sequentially triggered. With sufficient inter-Marx resistive and conductive isolation and modularity at the Marx level, eight Marxes in the subject volume would be viable for sequential firing.

The erected PFN proved to be more reliable, displayed excellent risetime (< 30ns), falltime (<80ns) and ripple for a 200-ns pulse. The main drawback of the erected-PFN system was a lack of timing agility and a larger than optimal source impedance.

V. REFERENCES

1 Barker, R.J., and Schamiloglu, E.: 'High-power microwave sources and technologies' (IEEE Press Piscataway, NJ, 2001. 2001)

2 Chen, Y.J., Neuber, A.A., Mankowski, J., Dickens, J.C., Kristiansen, M., and Gale, R.: 'Design and optimization of a compact, repetitive, high-power microwave system', Review of scientific instruments, 2005, 76, pp. 104703

3 Martin, T.H., Guenther, A.H., and Kristiansen, M.: 'JC Martin on pulsed power' (plenum press, 1996. 1996)

4 Obara, M.: 'Low-Impedance, Coaxial type Marx generator with a quasi-rectangular output waveform, 2nd IEEE Inter', in Editor (Ed.)^(Eds.): 'Book Low-Impedance, Coaxial type Marx generator with a quasi-rectangular output waveform, 2nd IEEE Inter' (Pulsed Power Conf Lubbock, Texas, 1979, edn.), pp.

5 Novac, B.M., Istenic, M., Luo, J., Smith, I.R., Brown, J., Hubbard, M., Appelgren, P., Elfsberg, M., Hurtig, T., and Moller, C.: 'A 10-GW pulsed power supply for HPM sources', IEEE Transactions on Plasma Science, 2006, 34, (5 Part 1), pp. 1814-1821

6 Glasoe, G.N., Lebacqz, J.V., Office of Scientific, R., Development, United, S., and National Defense Research, C.: 'Pulse generators' (McGraw-Hill, 1948. 1948)

7 Nunnally, W.C., Huenefeldt, S.M., and Engel, T.G.: 'Performance and Scalability of MJ Sequentially Fired Pulse Forming Networks for Linear and Nonlinear Loads', IEEE Transactions on Plasma Science, 2007, 35, (2 Part 3), pp. 484-490