PERFORMANCE OF A 10 KV, 625 KA, 85 KJ ENERGY DISCHARGE MODULE UTILIZING A SOLID DIELECTRIC SWITCH.*

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Abstract

We have designed and tested an 87-kJ energy discharge system consisting of two 720-μF, 11-kV capacitors discharged through parallel coaxial cables into a 250 nH load. Data will be presented on the current and voltage waveforms, with calculated values of the system inductance and resistance. The bank uses a solid dielectric switch punctured by an explosive bridge wire (EBW) to initiate the discharge. With the capacitors charged to 9 kV, a 625-kA peak current is sent through the load with a ringing frequency of 6.8 kHz.

The coaxial cables used to transmit the current to the load are 3 m in length. Both RG-217 and YK-198 cable types were tested, which have an inductance of 74 nH/ft and 35 nH/ft respectively. Normal operation requires that each cable carry 52 kA. The cables were tested to 100 kA each by connecting fewer cables to the load, and gradually increasing the charge voltage.

The solid dielectric switch was chosen for high reliability. Details of the switch will be described and data on its performance will be presented.

Introduction

This paper presents the results from tests done on a 87-kJ energy discharge module, consisting of two capacitors, a solid dielectric switch, and 12 coaxial output cables. The module was tested using an inductive dummy load, and was allowed to ring with no damping other than that due to the stray circuit resistance (mostly in the cables and switch). A series of tests were done to characterize the switch, cables and capacitors. The cables and capacitors were tested to beyond their known design limits. This data is presented, with calculated values for the circuit inductance and resistance.

Experimental Apparatus and Diagnostics

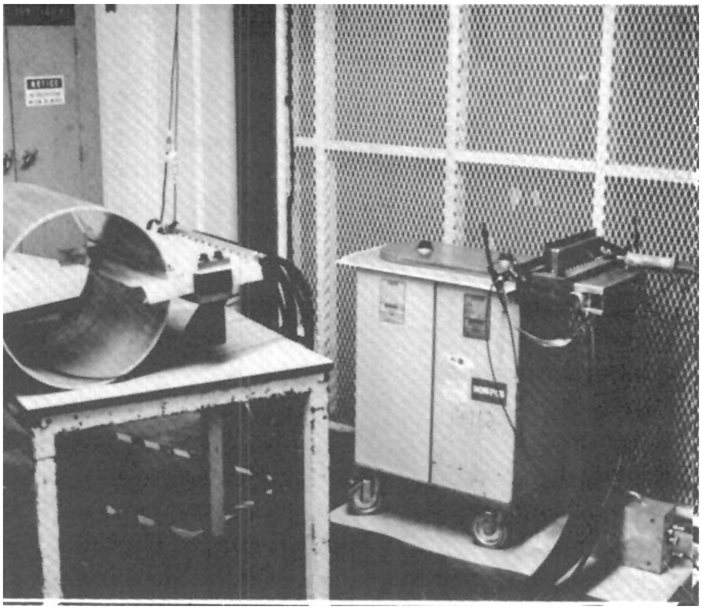

Fig. 1. Energy Discharge Module with Dummy Load.

The energy discharge module is shown in Fig. 1 feeding a dummy load. The module consists of two 43-kJ, 720-μF capacitors, a solid dielectric switch, and 12 coaxial output cables. The output transmission line is made of aluminum plate and bolted to the modified scyllac capacitor header, Fig. 2. The line insulation is made of a sandwich of two layers of 7-mil mylar separated by a layer of paper to distribute the surface charge.

The switch, Fig. 3, is insulated by a 5-mil Kapton sheet, which is punctured using two separate explosive bridge wires (EBW). The EBWs are backed with an 0.25-inch thick stainless steel plate to help absorb the shock. The plate has an 0.125-inch groove to channel away excess plasma generated during the shot. A similar plate with a machined knife edge is on the opposite side of the Kapton to help break the insulation and absorb the shock. The knife edge is partially eroded after the shot, and must be replaced after each switch operation.

The bridge wire is essentially a shorted, parallel plate transmission line of 0.5-inch width by six inch length, separated by 5-mil Kapton. One side of the line is made of 5-mil copper, and the other side is etched 0.175-mil copper. The fuse elements (2 per EBW) consist of 1/8 inch square constrictions in the etched layer. The EBW is entirely laminated with Kapton, except for the current connections. The EBWs are exploded using a 6-kV, 6-μF capacitive discharge unit (CDU) which is switched with a

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spark gap. These units are certified to provide 50 shots without pretrigger with >99.99% reliability.

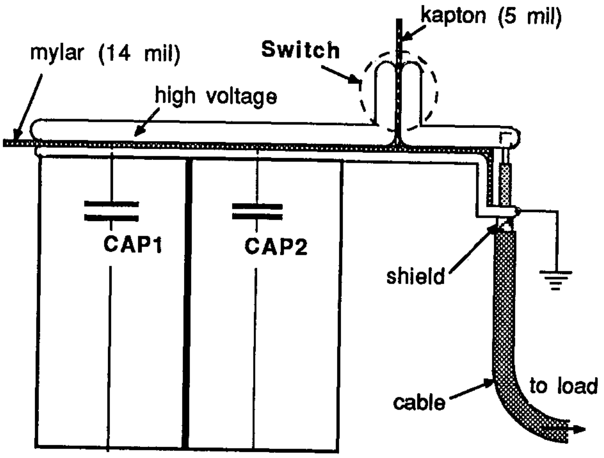

Fig. 2. Energy Discharge Module Sketch.

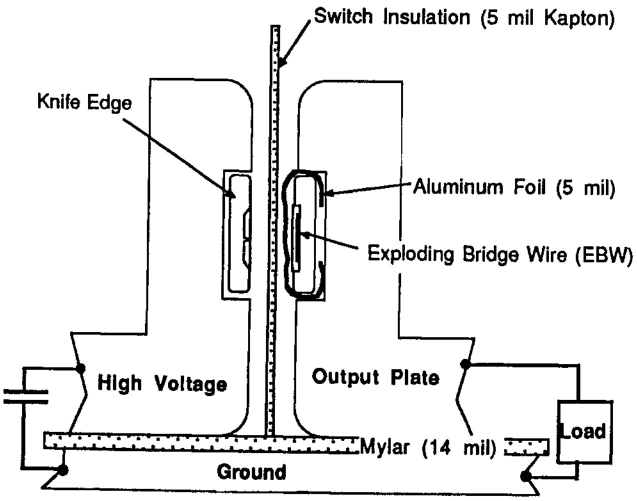

Fig. 3. Exploded View of Switch.

The 12 coaxial cables are terminated in 6-mm diameter silver plated pins which plug into multi-lam inserts (from Hugin, Inc.) threaded into the output switch plate. The cable shields are clamped onto brass stress relief inserts which are threaded into the ground plate. These inserts have a tapered surface which provides a gradual coaxial-to-planar transition which reduces electric field stress on the cable insulation.

The cables, either RG-217 or YK-198, are 10 feet in length and approximately 0.5-inch diameter.

The dummy load is a 16 inch diameter solenoid made of 0.25-inch aluminum with an axial length of 19 inches. The measured load inductance is 240 nH. The solenoid is bolted onto a short planar transmission line. The cables are connected to the transmission line using multi-lam inserts as before.

Diagnostics and Data Reduction

The current was measured using Rogowski coils which were placed around each capacitor header, around the ground plate just before the cables, around three of the cables in the dummy load feed section, and around the dummy load. In addition, a coaxial CVR was inserted in one of the cables, approximately one foot from the capacitor feed section. The CVR was equipped with GHV connectors which failed at about 30 kA, so this diagnostic was not present on the higher current shots.

The voltage was measured using a 100:1 voltage divider connected to the CVR, and with high voltage 1000:1 scope probes.

The Rogowski coil data was recorded directly and also integrated using RC integrators with time constants of $\approx 500\ \mu s$. The data was recorded using oscilloscopes with digitizing cameras or film. The digitized data was reduced by fitting the RLC equation, $i(t) = I_0 e^{-t/\tau} \sin(\omega t)$, using a least squares fit. The five parameters varied for the fit were ω, τ, I_0, as well as an amplitude and time offset. A typical fit is shown in Fig. 4, with data from an integrated Rogowski coil. The Rogowski integrator droop (an error of $\approx$ 5%) was corrected for numerically before fitting. Circuit non-linearities prevent exact calculation of the circuit inductance and resistance, but using ω and τ from the data fit and total capacitance of 1452 μF, the total circuit inductance and resistance using 12 YK-198 cables is 290 nH, and 3 mΩ. The circuit parameters with RG-217 cables are 350 nH and 3.5 mΩ. The unintegrated Rogowski coil data was fitted to di/dt, and the peak current, inductance, and resistance was in good agreement to the integrated data.

Switch Operation

The solid dielectric switch was tested using a 0.05-μF capacitor charged to 2 kV, and switched into a single 50-Ω cable which was terminated at a Tektronix 7104 scope. The switch rise time of about 3.6 ns, Fig. 5, was measured using the coaxial CVR with voltage divider. The ringing on the waveform is mostly from the inductance of the switch and the capacitance of the parallel plate output transmission line ($\approx$ 1.5 nF). From circuit analysis it was determined that the switch has an inductance of $\approx$ 1.5 nH.

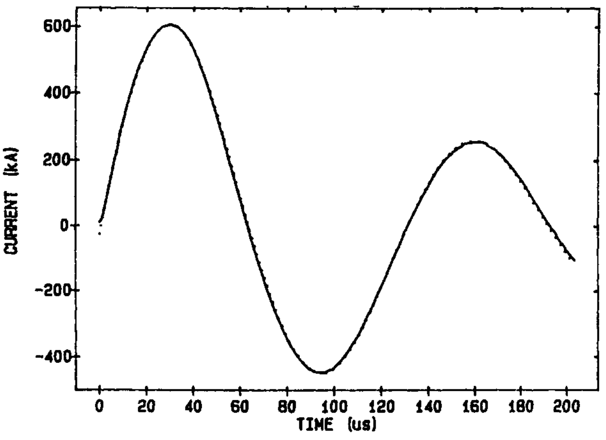

Fig. 4. Rogowski Coil Data with Fit (Dots).

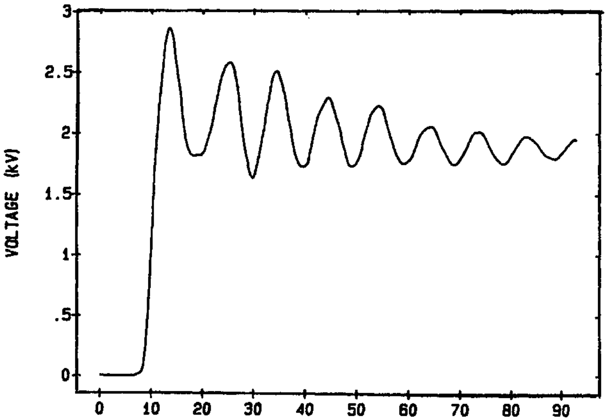

Fig. 5. Switch Risetime.

Cable Data

Two types of cables were tested: RG-217, which has a 50-Ω impedance, and YK-198 [1], which has a 14-Ω impedance. Both cables have a voltage standoff which exceeds the requirements of the design, but the current capacity was unknown. The YK-198 cable has half the inductance (35 nH/ft) of the 50-Ω cable, but has only a single braid inner and outer conductor. The RG-217 cable has a solid inner conductor and a double shielded outer conductor, and is thought to be more rugged and have better current carrying capabilities.

The cables were tested at currents ranging from 10 to 100 kA (double the nominal) and is summarized in Fig. 6. To reach the higher currents (greater than 50 kA) it was necessary to remove all but three of the cables. Also, testing was done with a single YK-198 cable connected. Decreasing the number of cables increases the inductance and resistance of the circuit which decreases the ringing frequency and the Q of the circuit. The ringing frequency varied from 4.7 to 7.7 kHz and the Q from 1 to 6.3 for the cable tests.

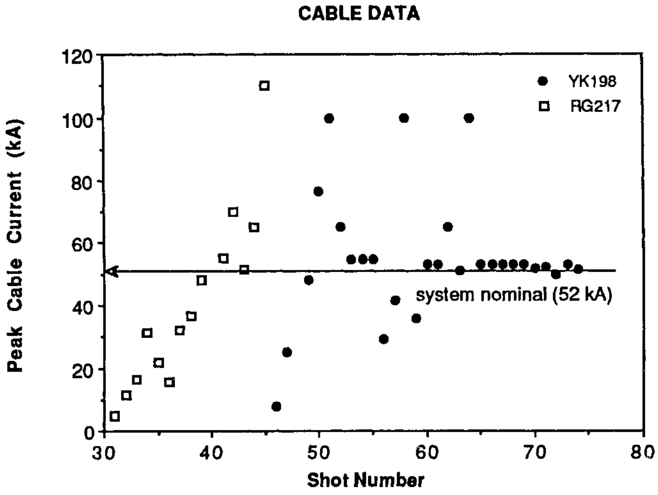

Fig. 6. Cable Test Data.

The testing was unable to fail or degrade either type of cable. However, the multi-lam connection began to fail at about 50 kA due to the excessive current through the multi-lam fingers which caused erosion of the metal. The size of the pin diameter was increased from 4 mm to 6 mm to reduce the current density through these connections. Occasional arcing and carbonization was observed on the pins at the nominal current (52 kA per cable) at the rate of approximately one connection per shot. This did not result in melting of the multi-lam, however, as was the case with the smaller diameter connections. Based on this data, the lower inductance YK-198 cable was chosen for this design.

Capacitor Data

The capacitors chosen were 43 kJ Maxwell model 32304. This model has a capacitance of 720 μF, 11 kV charge voltage, and is rated for 3000 shots at a 10% voltage reversal with a maximum output current of 125 kA [2]. For this design, the maximum output current is 320 kA, at a 9 kV charge and 60% voltage reversal, Fig. 7. Scaling laws [3] for charge voltage, voltage reversal, and ringing frequency (7.7 kHz) predict that the capacitor will have a life of ≈ 1000 shots. However, the maximum peak current is exceeded by a factor of 2.5. The excessive current will also shorten the capacitor life, but by an unknown amount. In the 40 shots taken, Fig. 8, we have not experienced a capacitor failure. Sixteen of these shots were above the 125 kA recommended maximum, with two shots at 600 kA. From this data we know that the capacitors will survive at least a limited number of shots.

Conclusions

We have designed a low inductance energy discharge module using a low- loss solid dielectric switch. It has been determined that both RG-217 and YK-198 type cables will withstand greater than 100 kA peak current at 7.7 kHz and Q of 6. The capacitor we used has survived for 14 shots at over double the rated current of 125 kA. The effect of this overcurrent on the lifetime of the capacitor is not yet known.

Acknowledgements

The authors would like to thank Don Rej of Los Alamos National Lab for providing the YK-198 cable used in the initial testing.

References

[1] G. P. Boicourt, "Evaluation of Coaxial Cable Performance at High Voltages: AN Interim Report," **Proc. 1966 Symposium on Engineering Problems of Controlled Thermonuclear Research**, p. 13. ,.

[2] Maxwell Laboratories, Inc. Series C High Energy Capacitors.

[3] Frank B. A. Früngel, **High Speed Pulse Technology, Vol. 3.** Academic Press, New York (1976).

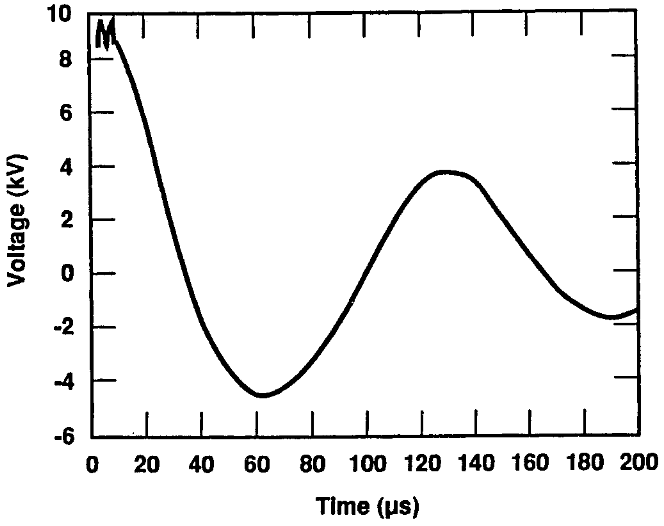

Fig. 7. Typical Capacitor Voltage.

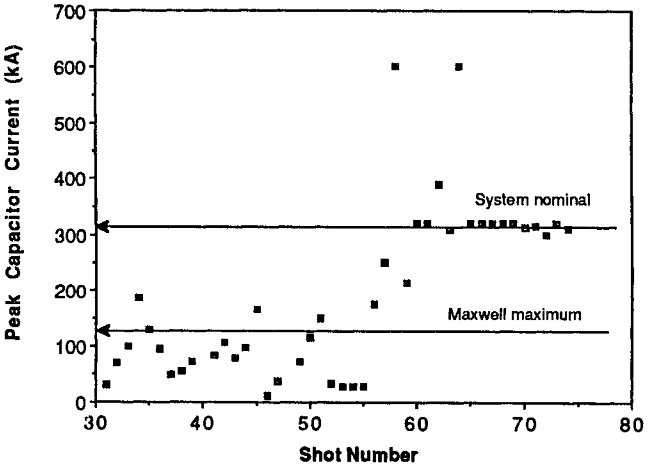

Fig. 8. Capacitor Test Data.