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Abstract

Fast Marx Generators (FMG's) are being developed[1,2] as an affordable approach to 50MA PRS Drivers[3] and as options for upgrading existing pulse power drivers (e.g. Decade & Double-EAGLE). FMG designs conceptualized in a DTRA sponsored power flow study[4] are based on the integration of new flat, wide capacitors coupled to rail gap switches. This results in a short Fast Marx stage discharge time ($(LC)^{½} < 300$ns) and low stage impedance ($(LC)^{½} < 0.5\Omega$) with high current capability ($I \cong 250$kA). General Atomics Energy Products developed a 1.35μF, 100kV, 2.6x24x38" plastic case capacitor with rails terminals along each end for this application. Titan integrated two such capacitors with a rail gap switch to create a FMG stage. This configuration resulted in Marx stage inductance <100nH. Prototype Marx's up to four stages have been successfully tested. This paper describes the FMG capacitor, its basic design and presents performance test data. Further developments to resolve manufacturing issues and to reduce cost are also discussed.

I.INTRODUCTION

Specialized prototype capacitors are being developed by General Atomics Energy Products (GAEP) for Fast Marx Generators (FMG's). Performance requirements for these FMG's and consequently the stage capacitors, are set by the applications where the intrinsic FMG discharge time, $(L_{MG}C_{MG})^{½}$, is to be between 100 and 300ns. For selected stage voltage, minimum achievable inductance sets maximum permissible stage capacitance and resultant peak current, determining the number of parallel Marx's required for the application. A discharge time of ~ 300ns was set for this FMG development. Stage impedance, $(L_S/C_S)^{½}$, has to be ~ 0.5Ω results in significant charge transfer and peak current from switch and capacitor. Faster, higher impedance stages are possible with reduced capacitance at lower current.

Impedance and discharge time set the stage capacitance and inductance at ~600nF and ~150nH respectively. The stage voltage is 200kV. A stage capacitor is then two ~1.2μF, 100kV units in series, folded and switched by a 200kV rail gap switch. This scheme and the use of plastic case capacitors are intrinsic to the low inductance design. Capacitor cases are thin (7cm), flat (97cm) and wide (61cm) minimizing length in the direction of increasing Marx voltage. The large transverse dimension perpendicular to current flow also contributes to inductance reduction. A capacitor inductance goal of ≈20nH with a close fitting ground return is easily met with many small internal capacitor windings in parallel connected to a full width terminal rail. The total inductance associated with stage capacitance will then be determined by the inter-capacitor separation plus internal inductance. With a relatively large capacitance at high voltage the peak current can easily be a few 100kA, therefore the internal capacitor connections must be robust to prevent fusing and tearing.

II.INITIAL CAPACITOR SPEC

The general specifications for the capacitor, built in support of this program, can be found in Table 1. The initial capacitor concept was a single ended, 200kV 0.75μF plastic case capacitor, at about twice the size of the units built (5x24x36"). This would have been made up of two capacitors in series in one case. For a number of reasons including simplicity, the requirement was changed to two separate 100kV units in series. The capacitance was set at a maximum of 1.5μF (+0, -20%) at an operating voltage of 100kV, yielding at most 7.5 kJ. Normal operation was expected to have 15% voltage reversal at up to 250kA. The fault conditions were expected to be up to 80% voltage reversal and 500kA. The operating temperature would be within standard laboratory limits with the specification for this type of capacitor being +40 to –10°C. The design life of 6200 Charge/Discharge Cycles with 90% survival was based on calculations from life data of similar dielectric systems. The original Dissipation Factor was set at a conservative 0.70% level and the Inductance goal was set at 20nH. The capacitance and operating voltage are very similar to standard Scyllac style low inductance metal case capacitors (11x14x25"), but this requirement called for a very flat low inductance, double ended plastic case configuration. The goal was 2.55x24x ~37" long case with long rail terminals on each 2.55x24" end, designed to couple closely with the rail gap switch.

* Work supported by the Defense Threat Reduction Agency

Table 1.Fast Marx Capacitor Specifications.

Parameter	Value
Capacitance (120 Hz, Room Temp (R.T.))	1.5µF
Tolerance	+0, -20%
Rated Voltage	100kV
Test Voltage (60 second HIPOT)	110kV
Burn-in Test 100kV 20%VR ~250kA-Goal 75kV 50%VR ~125kA-Actual	10 cycles Charge/Discharge
Rated Energy	7.5kJ
Rated Voltage Reversal	15%
Max. Voltage Reversal	80% (fault)
Max. Peak Current	250kA
Max. Peak Current	500kA (fault)
Max. Operating Temp.	40°C
Min. Operating Temp.	-10°C
Design Life at Rated voltage and reversal	6200 cycles Charge/Discharge
Reliability at Life	90%
Max. Dissipation Factor (120 Hz, R.T.)	.70%
Approx. Inductance (Standing Wave)	20nH
Min. Insulation Resistance (V Decay 120 s/120 s @ R.T.)	1000 MΩ x µF
Case Size	2.6 x 24 x ~ 38 in 6.6 x 61 x ~97cm
Terminal – One Per End	1.25 x 21.75 in

III. THE CAPACITOR

The resulting capacitor was GAEP Model X39281, the actual size was ~2.6 x 24 x ~38 inches rail to rail, see figure 1. The dielectric system used multiple layers of high density kraft paper and castor oil with extended foil construction. The capacitor was designed with two parallel groups each with three winding stacks connected in series. These two parallel groups were separated by the case support brace.

Figure 1. Model X39281 Plastic Case.

Figure 2. Model X39281 Terminal.

The case was made of folded and welded acetyl co-polymer plastic with a center supporting brace welded down the middle to both 24” wide panels. GAEP has extensive experience using this case material; it has the high temperature capability required during the drying process. The center brace minimized any case bulging that would have increased the space between mounted units resulting in higher inductance. Because this was a new development and the unit experimental, it didn’t make sense to tool a case of this size, so a hand made case was used. Separate inner rails connect the two parallel capacitor groups to each terminal rail (Figure 2).

Production testing included a high voltage test to 110kV for 60 seconds and 10 burn-in charge/discharge cycles on 100% of the capacitors. The original goal of the burn-in cycles was to match the expected operating parameters of 100kV, 15% voltage reversal and 250kA, but the inductance of the test circuit could not be reduced enough. The final burn-in test was at 75 kV 48-50% reversal and ~ 125 kA peak current

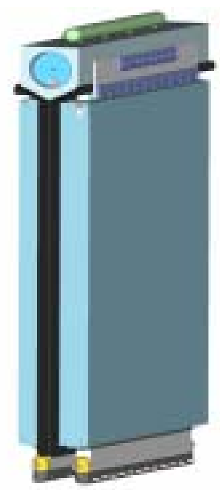

Figure 3. Single Stage Marx.

IV. PERFORMANCE

Tests were run with capacitors and switches configured in one, two, three and four stages. Figure 3 depicts a single stage FMG while figure 4 shows the actual four stage Marx. In the latter you can see the insulation between the two series capacitors butterfly out under the switch. There is also insulation between stages.

Figure 4. Four Stage Marx.

The design goal of $(LC)^{1/2}$ <300ns was successfully demonstrated on the prototype four stage Fast Marx.

Figure 5 shows the typical voltage and current waveforms into a short across the four-stage Marx output terminals. The Model X39281 capacitors at 60kV dc charge delivered 300kA current with 88% reversal, resulting in 1.3 coulombs charge transfer. The 1615ns ringing period yields a 257ns $(LC)^{1/2}$ time. In other words, we have achieved 100nH average stage inductance including the ground return, in a four-stage Fast Marx with a 0.17μF erected capacitance. For this Marx, $(L/C)^{1/2}$ = 1.6Ω, leading to a 0.4Ω average stage impedance. The Marx series resistance inferred from the 88% reversal, is around 150mΩ, or merely 40mΩ per stage. Therefore, the equivalent series resistance per capacitor is less than 20 mΩ at 600kHz ringing frequency. During routine tests into a nominal 1.6Ω dummy load, the four-stage Marx typically delivered around 285kA and 485kV at ± 100kV charge voltage as shown in Figure 6.

Table 2 summarizes the shot history of ten X39281 capacitors tested in the Fast Marx into short-circuit and resistive loads. We went through about 7000 capacitor shots over a ten months period. The Model X39281 capacitors endured all Marx tests without electrical failure. The capacitors lived through the 100kV charge voltage, 300kA current, charge transfer of 1.3 coulombs per shot, 88% reversal at 600kHz ringing frequency, and oil-arc faults at full rated voltage. The Fast Marx prototype capacitors have met the performance goals, albeit with some quality problems being addressed on the half-width production capacitors to be delivered later this year.

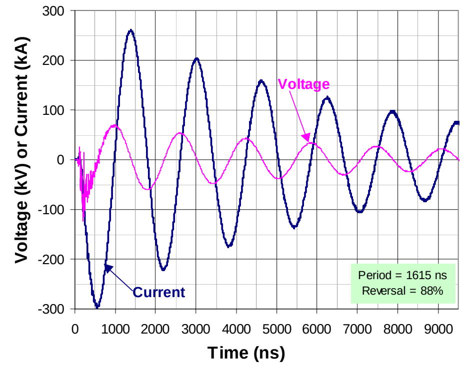

Figure 5. Typical short-circuit voltage and current waveforms for the four-stage Fast Marx at ± 60kV dc charge.

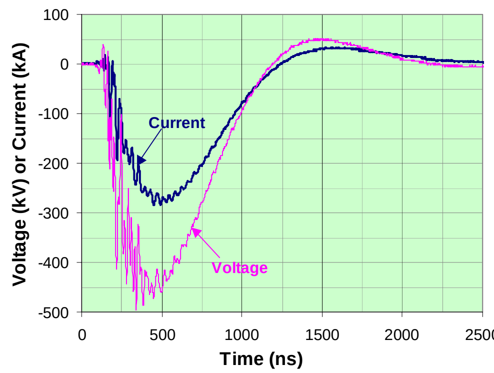

Figure 6. Typical voltage and current waveforms into a nominal 1.6Ω resistor for the four-stage Fast Marx at ± 100kV dc charge.

Table 2. Capacitor Shot History

Configuration		Single-stage	Low voltage 4-stage	85 kV 2-stage	85 kV 3-stage	High voltage 4-stage	100 kV 3-stage	100 kV 4-stage	Corona shield 3-stage	Total Shots
Serial No.	**Cap**	**92 shots**	**174 shots**	**194 shots**	**35 shots**	**300 shots**	**295 shots**	**42 shots**	**89 shots**	**1221 shots**
0211X10101	1.34 μF		Stage 1B	Stage 1B	Stage 1B	Stage 1B		Stage 4A		745
0212X0101	1.35μF	Stage 1A	Stage 1A	Stage 1A	Stage 1A	Stage 1A				795
0212X10102	1.34 μF		Stage 2B	Stage 2B	Stage 2B	Stage 2B	Stage 1B	Stage 1B	Stage 1B	1129
0212X10103	1.34 μF		Stage 2A	Stage 2A	Stage 2A	Stage 2A	Stage 1A	Stage 1A	Stage 1A	1129
0209X10102	1.34 μF	Stage 1B damaged	Stage 3B		Stage 3B	Stage 3B	Stage 2B	Stage 2B	Stage 2B	1027
0217X10101/D	1.36 μF		Stage 3A		Stage 3A	Stage 3A	Stage 2A	Stage 2A	Stage 2A	935
0209X10101	1.34 μF					Stage 4A	Stage 3A	Stage 3A	Stage 3A	726
0218X10104/D	1.33 μF		Stage 4A			Stage 4B	Stage 3B			769
0218X10103/D	1.36 μF		Stage 4B					Stage 3B		216
0218X0105/D	1.36 μF							Stage 4B	Stage 3B	131

V.DESIGN ISSUES & CHANGES

The development of Model X39281 did not proceed without its manufacturing issues. The case was difficult and expensive to build, three sides were .25" thick and one side was 3/16". This was done to minimize the distant between the two coupled capacitors, thus minimizing the inductance (thin sides faced each other). For the same reason the support brace in the middle of the 24" restricted case bulging. The plug welding of the support brace to the 3/16" panel, the case seam welds along the sides, top and bottom led to leaks. The drying and impregnation process caused the acetyl copolymer to shrink, unfortunately the various thickness shrunk at different rates causing cracks and a slight banana like warp to the case.

Leaking also took place at the current feed o-ring seals. At first the o-rings were too small and later the replace o-rings had set when they went through the full capacitor drying cycle. Because of these leaks some of the initial capacitors were contaminated in the water wash cleaning cycle. This procedure was changed to an alcohol-hand wipe down before leak test.

Changes are being incorporated in the second-generation capacitor Model No. X39285. This half size and capacitance design is in a more manageable case size, 2.55 x 11.62 x ~38". This places the two parallel caps in separate cases. The internal construction will be basically the same, but the case will be constructed from fiberglass. The body will be molded and G-10 end plates will be epoxied in place. This process was developed at GAEP to manufacture the 600lb LANL Atlas program capacitors Model No. 39232[5]. The o-ring material will be changed to avoid the thermo-set problem. These changes will over come all the previous case quality and leak issues.

VI. SUMMARY

General Atomics Energy Products is manufacturing capacitors required for the successful development of Fast Marx Generators, an affordable approach to 50MA PRS Drivers and for upgrading existing pulse power drivers. Titan-Pulse Sciences Division sponsored by DTRA is integrating GAEP's flat, wide, low inductance, double ended plastic case capacitors, Model X39281, coupled to 200kV rail gap switches into multiple stage FMG's. These initial capacitors have a capacitance of 1.35uF in a case size of about 2.6 x 24 x 38" long.

Capacitor testing by Titan demonstrated a stage inductance < 100nH and impedance ~ 0.4Ω with a life greater than 1000 shots, peak currents to 300kA, charge transfer of 1.3 coulombs, 88% voltage reversal at 600kHz ringing frequency and oil-arc fault discharges at full rated voltage. Issues like case warp and oil leakage as well as lower cost are being addressed in the next generation FMG half size capacitors to be delivered in 2003.

VII. ACKNOWLEDGEMENTS

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