GENERAL ATOMICS ENERGY PRODUCTS
Engineering Bulletin

LARGE HIGH ENERGY DENSITY PULSE DISCHARGE CAPACITOR CHARACTERIZATION

Fred MacDougall, Joel Ennis, Xiao Hui Yang, Ken Seal,
Sanjay Phatak, Brian Spinks, Nathan Keller, Chip Naruo
General Atomics Energy Products
General Atomics Electronic Systems, Inc.
4949 Greencraig Lane, San Diego, CA 92123-1675 USA

T. Richard Jow
Army Research Laboratory
2800 Powder Mill Road, Adelphi, MD 20783

Presented at:

15th IEEE International Pulsed Power Conference
June 13 – 17, 2005 Monterey CA

GENERAL ATOMICS
Energy Products
GENERAL ATOMICS ELECTRONIC SYSTEMS INC.
4949 GREENCRAIG LN, SAN DIEGO, CA 92123-1506
858.522.8400

LARGE HIGH ENERGY DENSITY PULSE DISCHARGE CAPACITOR CHARACTERIZATION

Fred MacDougall, Joel Ennis, Xiao Hui Yang, Ken Seal, Sanjay Phatak, Brian Spinks, Nathan Keller, Chip Naruo
General Atomics Energy Products
General Atomics Electronic Systems, Inc.
4949 Greencraig Lane, San Diego, CA 92123-1675 USA

T. Richard Jow
Army Research Laboratory
2800 Powder Mill Road, Adelphi, MD 20783

Abstract

The energy density of film capacitors continues to increase. This paper discusses the performance issues of limited life pulsed discharge capacitors operating at better than 2 J/cc (2MJ/m3) in the 5kV to 20kV range. Self-healing metallized electrodes have been utilized in these designs to provide graceful aging at electric fields greater than 500 MV/m. A variety of polymer films have been evaluated for use in these capacitors. The pulse rise times where the capacitors find application are in the range of microseconds to milliseconds. Life tests have been performed with the goal of achieving at least 1000 charge/discharge cycles at maximum energy density. Failure modes in normal charge/discharge pulse service, and short-circuit fault conditions have been evaluated. Design modifications to increase life and energy density were made based on those analyses. Capacitors delivering greater than 100kJ above 2 J/cc have been built, tested, and shipped.

I. Acknowledgements

The research reported in this document/presentation was performed in connection with contract W911QX-04-D-0003 with the U.S. Army Research Laboratory. The views and conclusions contained in this document/presentation are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the U.S. Army Research Laboratory or the U.S. Government unless so designated by other authorized documents. Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

II. Applications for Pulse Power Capacitors

The high power energy discharge market is relatively small compared to other capacitor markets. It includes applications for medical equipment like defibrillators and X-Ray equipment. Large science experiments like the Z upgrade at Sandia National Labs or NIF at LLNL are another major segment of the market. Presently there is significant activity on the part of the military for capacitors that will meet the needs of Future Combat Systems (FCS).

The requirements for the capacitors needed for FCS are more taxing than that of other segments of the market for several reasons. The two primary reasons are that the systems are mobile rather than fixed emplacements; and the systems operate in hostile environments rather than a laboratory. In recognition of this, a number of development programs have been initiated to meet these special needs. Since the platforms are mobile, there is a premium placed on the energy density of the capacitors. Since the environment is hostile, a premium is placed on achieving a wide range of operating conditions. These are the primary requirements that separate military from commercial pulse power capacitors.

III. Recent History of Capacitor Development

The capacitor development process has been evolutionary rather than revolutionary. Early development was primarily driven by the need for banks of low cost energy storage capacitors used in large pulse power systems, such as those used in simulating EMP and radiation effects of nuclear weapons. In the early 1980's the 50kJ high energy density capacitors operating at 0.6 J/cc at voltages of 11, 22, 33, 44, and up to 66 kV. These capacitors were based on high-density Kraft paper, extended aluminum foil electrodes, and castor oil impregnation. In the early 1990's, 100kJ metallized electrode capacitors became available at energy densities of about 1 J/cc for equivalent life performance. These capacitors had lower peak current capability than the foil capacitors, and higher inductance, but were well-suited for millisecond-discharge applications, such as railguns and flashlamps.

Also, in the same time period, high energy density capacitors using high dielectric constant PVdF film were manufactured in significant quantities with energy densities of 2.4J/cc. The PVdF dielectric capacitors were expensive, suffered from a high dielectric losses, had difficulty in operating at high repetition rates, and delivered significantly less energy for fast pulses. These advances in energy density were driven by military research in directed energy weapons and kinetic energy weapons, such as railguns.

The major driver for the development of large energy storage capacitors in the mid- to late-1990's was the National Ignition Facility (NIF), a U.S. Department of Energy facility now being built at Lawrence Livermore National Laboratory in California. The NIF system requires 4800 units of high reliability, low cost capacitors, each storing about 83 kJ at 24 kV, to drive flashlamps used in laser beam energy amplification.

In the last few years, military interest in directed and kinetic energy weapons, as well as in EM armor concepts, has again begun to drive development of higher energy density capacitors. In 2004 the delivery of 100kJ, 2.2 J/cc capacitors for the Army/United Defense ETIPPS program was reported at the IEEE Power Modulator Conference [1].

GA-ESI has also produced 130kJ capacitors for the General Atomics' Navy railgun program in the past year, as well as substantial design verification and validation data to support a reliable lifetime of more than 10,000 cycles.

This year, quarter megajoule ("*MJ/4*") capacitors operating at 2.6 J/cc have been demonstrated. These capacitors have a low dissipation factor (DF) and high energy efficiency. The self-healing ability has made it possible to store this amount of energy in a single component of reasonable size.

A comparison of some of the milestone-setting capacitors that have been developed over the years is given in Table 1. It should be noted that while the PVdF capacitors built in 1993 has a relatively high energy density in terms of J/cc, the *MJ/4* capacitor is >50% higher in energy density in terms of J/g.

Milestone Setting Large Millisecond Energy Discharge Capacitors				
Year	Description/Application	Energy in kJ	kVolt	ED in J/cc
1990	First Large Metallized Electrode Capacitors used by LLNL & Other	86.1	24	0.68
1993	ETC Gun Caps (PVdF) for NSWC	125	16	2.40
2000	Navy Railgun Caps	130	11.3	1.12
2004	ETI Gun Caps for United Defense	113	6.5	2.38
2005	*MJ/4* EM Guns	293	6.64	2.68

Table 1- Millisecond Discharge Capacitors

All of the capacitors listed in Table 1 are of the self-healing construction using metallized electrodes. This type of construction allows the capacitors to operate close to their average breakdown voltage stress rather than below their minimum breakdown stress. End of life results from the slow loss of capacitance as the dielectric breaks down and the electrodes are consumed in the self-healing process.

Figure 1 - Small Scale Capacitor

The self-healing capacitors have an advantage in the development process. The laboratory investigation of a new dielectric system often starts with small capacitors where the best performing systems are chosen for further development in larger capacitors.

Figure 1 shows the typical small-scale capacitor used to develop capacitors like that shown in Figure 2. Self-healing capacitors tend to have higher energy densities when scaled up in size due to improved packing factor, whereas foil electrode capacitors suffer from an area scaling effect that reduces breakdown strength and operating fields with size.

IV. Quarter Megajoule Capacitors *MJ/4*

The new quarter megajoule capacitors perform well in high repetition rate applications. Like their predecessors they are designed to operate in the millisecond time frame but can be designed to operate in the microsecond time frame with some reduction in energy density.

The first quarter-magajoule capacitor built is shown in Figure 2. The dimensions and electrical ratings are listed in Table 2.

Figure 2- First Quarter-MegaJoule Capacitor

V. Delivered Energy

The quarter-megajoule capacitors are highly efficient with only a small fraction of the energy delivered wasted in the form of heat. In fact, measuring the efficiency of a circuit using this type of capacitor may show unexpectedly high output energy. This can be caused by an increase in capacitance that occurs in most capacitors when the capacitor is put under stress. For the quarter-megajoule capacitor, the added stored energy associated with the increase in capacitance, is greater than the thermal losses during a typical charge/discharge cycle. This phenomenon should be considered when calculating the capacitor efficiency defined as:

$$\textit{Energy Efficiency} = \textit{Delivered Energy}/(\tfrac{1}{2}\, C\, V^2)$$

Where the capacitance "C" in the equation should be based on the capacitance value at the operating voltage. If this is not done, the calculated efficiency can exceed 100%

GENERAL ATOMICS ELECTRONIC SYSTEMS INC MJ/4 CAPACITOR TEST RESULTS	
Capacitor Dimensions	
Length	33.3 cm
Width	40.4 cm
Height	81.3 cm
Volume	109,224 cc
Electrical Parameters	
V_{Test}	6,640 Volts
Capacitance @ V_{Test}	13,842 uF
Stored Energy	305 kJoules
Pulse Discharge	
Peak Current	49.4 kAmp
Rise Time	180 uSec
Measured Delivered Energy	293 kJoules
Energy Density	2.68 J/cc

Table 2 - Quarter Megajoule Capacitor *MJ/4* Performance

Unlike past advances in capacitors, the development of the quarter magajoule capacitor has not resulted in an increase in cost. This new generation of capacitors generally cost significantly less than their predecessors in terms of $/Joule of stored energy.

VI. Conclusions

The development work presently under way in the area of high energy density capacitors has been steadily increasing the performance of capacitors particularly for specific military applications. The new generation of capacitors is outperforming pervious capacitors in many areas. The capacitors are higher in energy density, lower in cost, and safer to operate than their predecessors. Continued work in this area will result in continued improvements and even more cost effective capacitors in the future. More importantly, the capacitors will evolve into the equipment needed for the specific requirements of the US military's present and future combat systems.

VII. REFERENCES

[1] J.B.Ennis, X.H. Yang, F.W. MacDougall, K. Seal J Herbig High Energy Density Capacitor Characterization In Proc. 2004 IEEE-Power Modulator Conference, San Francisco, CA, May, 2004.

[2] J.B. Ennis, F. W. MacDougall, R.A. Cooper, J.F. Bates, N. Ozkan. "Recent Developments In Pulse Power Capacitors". In Proc. of 2nd International Symposium on Pulsed Power and Plasma Applications Korea Electrotechnology Research Institute Chang-Won, Kyung-Nam, Korea, October 2001.

[3] J.B. Ennis, F.W. MacDougall, R.A. Cooper, J.F. Bates. "Self-Healing Pulse Capacitors For The National Ignition Facility (NIF)". In Proc. of IEEE Pulsed Power Conference, June 1999.

[4] F.W. MacDougall, J.B. Ennis, R.A. Cooper, J.F. Bates, N. Oskan. "Energy Density of Film Capacitors for ETC Gun Applications". presented at 18th Meeting of the Electric Launcher Association, San Diego, California, October 10th, 2001.