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Performance and Safety of Large Energy Discharge Capacitors

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Abstract:

Large capacitors used in the pulsed power industry offer a unique challenge from both a design and application standpoint. The capacitors are getting larger, storing more energy, and delivering that energy in short pulses resulting in very high peak power output.

This paper examines the design and application considerations associated with large capacitors focusing on the capacitors built for two recent pulsed power machines, ATLAS and NIF. These capacitors represent large capacitors in the fast (<10uSec) and slow (<1mSec) pulsed discharge domain. The performance of the capacitors under normal conditions, fault conditions and failure conditions are discussed. Also, information concerning the safe operation of large capacitors is presented.

I BACKGROUND

The ongoing effort on the part of the capacitor industry to provide smaller, more cost effective components has resulted in evolutionary rather than revolutionary improvements in the use of dielectric materials to store energy effectively. In many applications, the total energy required is fixed and the capacitors have been getting ever smaller. In other applications where

banks of capacitors are used, such as high energy pulsed power applications, the maximum weight of an individual capacitor has remained about the same but the stored energy in the capacitors continues to increase.

Reliability is a major concern when more energy is being stored in a single capacitor. In the past, this has been a limiting factor. As the capacitors got larger, the probability of a dielectric breakdown somewhere in the dielectric system that would cause the entire capacitor to fail increased. In modern capacitors, this has been addressed by the manufactures in a number of ways. The most significant is the advent of self clearing electrodes being used in large energy discharge capacitors.

II METALLIZED ELECTRODES

A typical large metallized electrode capacitor is described in Table 1 as the National Ignition Facility (NIF) capacitor at Lawrence Livermore National Laboratories (LLNL). Reliability for this type of capacitor is achieved by designing and constructing the capacitor so that the breakdown of the dielectric results in the loss of a small amount of electrode. The only permanent change in the capacitor is the loss of a small amount of capacitance.

Typical Large Energy Storage Capacitors			
Item	Capacitor Application		Units of Measure
	1	2	
Project	NIF	ATLAS	Name
Laboratory	LLNL	LANL	Name
GA/Maxwell PN	32765	39232	Name
Discharge Rate	Fast	Very Fast	Type
Electrode	Metallized	Foil	Type
Failure Mode	Open (Self Healing)	Short	Type
Operating Voltage	24	60	kV
Capacitance	290	34.1	uF
Stored Energy	83.5	61.4	kilo Joules
Peak Current			
Normal	30	330	kAmp
Fault	95	750	kAmp
Inductance	~200	<20	nH
Physical Size			
Length	489	613	mm
Width	457	762	mm
Height	690	356	mm
Volume	0.154	0.166	m ³
Weight	171	270	kg
Energy Density (Volume)	0.542	0.370	J/cc
Energy Density (Mass)	0.488	0.227	J/g

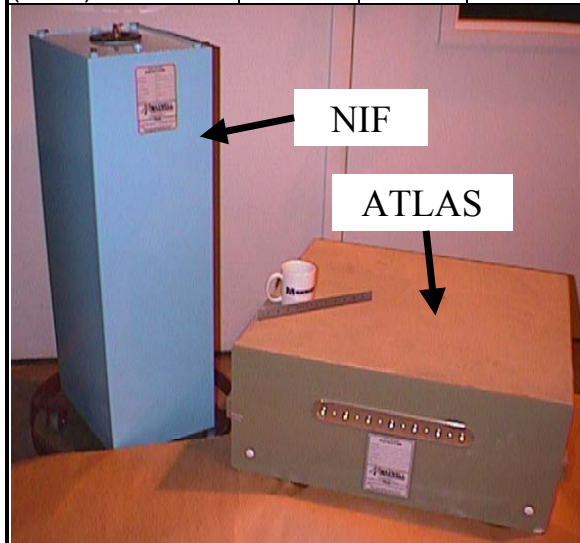


Table 1

End of life for a metallized electrode capacitor is defined as the loss of a specified amount capacitance, typically 5%. Figure 1 shows the typical decline in capacitance associated with the graceful degradation of a metallized electrode capacitor. For a capacitor of this size, the loss of 5% in capacitance represents the loss of electrode from hundreds of thousands of individual clearing events. The capacitors can be operated beyond the 5% capacitance loss limits but two things happen which makes this undesirable. First, the rate of capacitance loss starts to increase. Secondly, the probability that the capacitor will suffer a secondary fault which would defeat the graceful aging mechanism is increased.

Typical Life Test Date for NIF Capacitor GA PN 32765

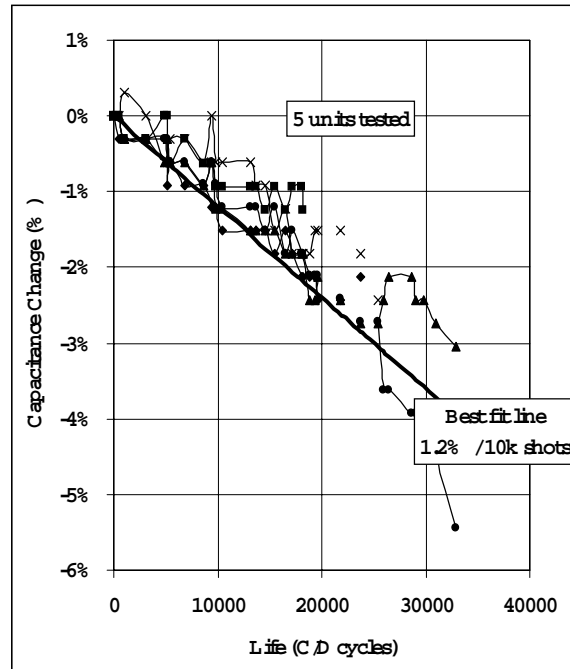


Figure 1

III FOIL ELECTRODES

While metallized electrode capacitor offer high value in some applications, there are many pulsed power applications where foil electrode capacitors, such as the ATLAS capacitor described in Table 1 provide higher value. In applications like ATLAS where high peak currents and high capacitor operating voltages are required the metallized capacitors are less desirable because it is harder to achieve an open circuit failure mode, or self clearing, all the time at higher voltages. Also, since the metallized electrodes are designed to clear when high current attempts to pass through the electrode, there is a practical current limit that must be observed.

End of life for a foil electrode capacitor comes when the individual windings inside the capacitor short out rather than clear, as a metallized electrode will do. The end of life is abrupt. The capacitors are designed to have a low internal impedance after failure so that the energy associated with the failure is dissipated in other parts of the circuit rather than dumped in the capacitor which could cause the capacitor case to rupture.

ATLAS Capacitor, General Atomics PN 39232 Qualification Life Test by LANL				
No. Of Units	Normal C/D Cycles	Fault C/D Cycles	Normal ized Total	Failed Or Good
1	8150		8150	Failed
1	7600		7600	Good
1	6200		6200	Failed
2	4000	300	4653	Good
5	4000		4000	Good
Normal - 330 kA, 15% Voltage Reversal Fault - 700 kA, 25% Voltage Reversal				

Table 2

The data from the qualification test done by Los Alamos National Laboratories (LANL) is shown in Table 2. The data was evaluated using Weibull Analysis. The statistics predict that 95% of the capacitors will have a shot life of at least 3431 shots and that the probability of a failure at 1000 shots is 5.4×10^{-7} . Further testing done on the ATLAS capacitors confirmed that the early statistics were accurate.

IV CAPACITOR FAILURE MODES

When large banks of capacitors like NIF or ATLAS are assembled with over 4000 or 400 capacitors respectively, managing the stored energy under normal and adverse conditions is a major consideration. Many capacitors built by General Atomics have been tested to end of life in both the NIF and ATLAS programs. To date, none have failed violently. In the case of the NIF capacitors, failures have exhibited only capacitance loss. In the case of the ATLAS capacitors, they have become terminal to terminal shorts without rupturing the case. It is known, however that violent case ruptures have occurred during the qualification test program at both projects. Violent failures can occur at end of life on large capacitors due to design problems, manufacturing problems, or the mishandling of the capacitor.

V EQUIPMENT DESIGN CONSIDERATIONS

Sometimes external devices such as fuses or resistors are added to a bank of capacitors in order to limit the amount of current seen by a capacitor when that capacitor fails. This helps to reduce the

energy dumped into a capacitor when it fails but it adds impedance to the circuit and often represents an undesirable reduction in circuit performance. Also, with large capacitors, there is more than enough energy stored inside the capacitor to rupture the case should an internal terminal to terminal fault occur.

One particularly violent failure mode that must be considered with large capacitor banks that are designed to operate in air, as opposed to under oil, is the ignition of a mixture of dielectric fluid and air after the capacitor has ruptured. In this scenario, when the capacitor case ruptures, it sprays the dielectric fluid into the air and then the arc caused by the internal fault ignites the mixture. The violence associated with this failure mode can be limited with the proper equipment design. Figure 2 shows a typical test cell with provisions to minimize damage from such an event.

High Energy Capacitor Operating Cell

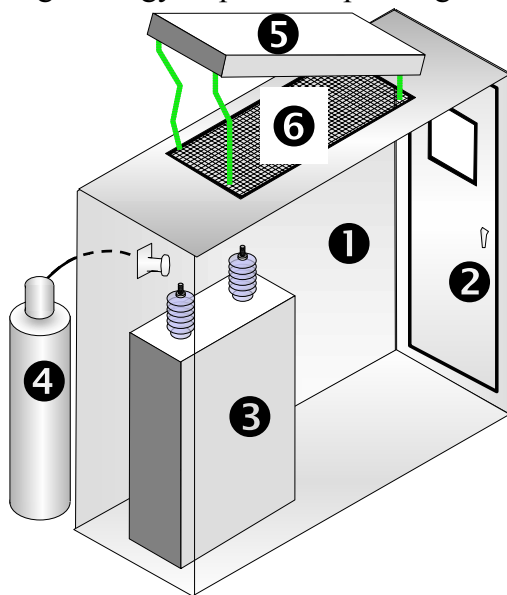


Figure 2

The test cell ① is designed of sturdy construction with the entrance ② located

so that there is a clear view of the capacitor ③ and other equipment from outside the door, when the door is open. The cell is equipped with an oxygen starvation device ④ which would flood the test chamber with inert gas should a fire start. Some chambers are designed to eliminate the oxygen before the testing starts. The chamber has a vent ⑤ shown in the open position that is designed to let the internal pressure, caused by a failure, escape rather than contain it. The vent is covered by a screen ⑥ that remains in place during the event. The screen should be designed to catch shrapnel and cool the escaping gasses to the point where no flames will leave the test chamber should a oil air mixture burn occur.

VI SUMMARY

Large energy discharge capacitors storing upwards of 100,000 joules are being built and operated in the pulse power industry. Highly reliable capacitors are available that cover both long and short pulse applications.

The possibility of a violent failure when working with high energy equipment is real. Caution should be used when designing and operating this type of equipment. Problems associated with handling larger amounts of energy and unplanned events can be minimized if taken into consideration when designing both equipment and operating procedures.

VII REFERENCES

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