CORNELL DUBILIER

ENERGIZING IDEAS

Technical Note

The Impact of Metallized Electrodes on High Energy Density Pulse Power Capacitors

ABSTRACT

Over the past few years, CDE has been replacing foil electrode construction with metallized electrode construction in a variety of high energy density pulsed power capacitors. These capacitors are used in defibrillators, copy machines, nuclear fusion experiments, electric armament, and similar applications. The use of metallized electrode capacitors in these applications affects many capacitor characteristics including life expectancy, energy density, fault current withstands, reversal capability, and dissipation factor.

This paper discusses the design experience using metallized electrode construction on high energy density pulse power capacitors.

INTRODUCTION

Developments in the area of base materials and designs have resulted in ongoing improvements in pulse power capacitor performance. Metallized electrode capacitors are currently being introduced in applications where solid aluminum foil capacitors were used in the past. During the past decade CDE has changed from aluminum foil construction to metallized electrodes for most applications at higher voltages, (500 volts to 44,000 volts), where oil filled capacitors are generally used.

There are a number of significant advantages associated with the use of metallized electrode capacitors. The capacitors are normally designed to be self-healing and will not fail to function should a single fault site occur between the electrodes. Rather, the extremely thin electrodes, typically a few hundred Angstroms thick, are evaporated or converted

to a metal oxide by the energy that attempts to flow through the fault. The net result is a very small loss of capacitance rather than a shorted capacitor.

Since metallized electrode capacitors are self clearing, they can be designed to the average, instead of the minimum, capability of the dielectric material. This allows the dielectric materials to be operated at higher stresses and store more energy in a smaller volume. For the design to be successful, the reduction in volume must be great enough to off-set any cost increases associated with the more expensive metallized dielectric material and perform better than a solid foil electrode in the given application.

With metallized electrode capacitors, there are normally hundreds or thousands of dielectric failures that occur over the normal life of the capacitor. Each fault results in an incremental loss of capacitance. The accumulation of faults can easily be monitored by observing the change in capacitance. The end of life for these capacitors must be defined. For the most, part capacitance loss is used to define end of life. The 5% loss of capacitance point is often chosen as the point of failure since the possibility of achieving a secondary failure due to the accumulation of gas inside the capacitor is minimal.

Like any other capacitor, metallized electrode capacitors must be designed to meet specific applications. The extremely predictable nature of the metallized electrode capacitors makes it relatively easy to meet the needs of specific applications. Capacitors can be designed to function under a wide variety of normal plus fault discharges. Requirements like high fault current, high voltage reversal, high repetition rate, or long hold times can be accommodated with high energy density metallized electrode capacitors. The predictable nature of these capacitors makes it unnecessary to over-specify the capacitor when the application parameters are known and well defined.

There are a wide variety of specific application requirements that are satisfied by metallized electrode capacitors. This has resulted in a number of different capacitor designs to satisfy these divergent requirements. Three of the more popular designs are described below along with their typical performance characteristics.

Not all metallized electrode capacitors have the same clearing capability. Some capacitors are designed for long life or high current densities where the enhancements of these qualities result in a reduction of the capacitor's ability to clear faults. The reduction in fault clearing capability will not have an adverse effect on the capacitor as long as the applied voltage is kept below the maximum voltage that can be successfully cleared.

METALLIZED POLYPROPYLENE CAPACITORS (CDE TYPE Z)

The metallized polypropylene (CD-Aero Type Z) capacitors are commonly used for applications in the 500 volts to 2000-volt range. They are used in a number of applications including flash lamps, airport lighting, lasers, and DC filtering, where they have replaced both foil type capacitors and, in some cases, electrolytic capacitor banks. The normal design life of the capacitors is in the 10 Exp 6 to 10 Exp 10 discharge range. When operating under DC conditions the capacitors are normally designed to operate for approximately 60,000 hours.

These capacitors have a number of unique features. The insulation resistance is normally over 100,000 ohm farads, the ESR is in the low milliohm range, and the dissipation factor (DF) is less than 0.15% at 60 Hz. Type Z capacitors are highly efficient and will operate with high RMS currents from ripple filtering or fast pulse rates without overheating. These capacitors have excellent thermal stability when used in applications where the discharge rate is in the 2 per second range.

A typical metallized polypropylene capacitor is shown in Figure 1. The thin layer of metal deposited on the film acts as an electrode. These electrodes are bonded at their edges by end spray which provides excellent current carrying capability. In the Type Z capacitor metallized polypropylene dielectric is surrounded with a non-PCB oil. The oil suppresses corona in the end region of the section, dissipates heat, and limits the amount of oxygen that is accessible to the electrode.

TYPICAL TYPE Z CAPACITOR

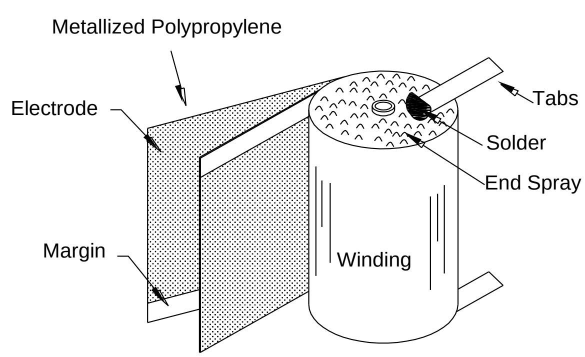

Fig. 1

OPERATING VOLTAGE VS LIFE FOR TYPE Z, Y, AND K CAPACITORS

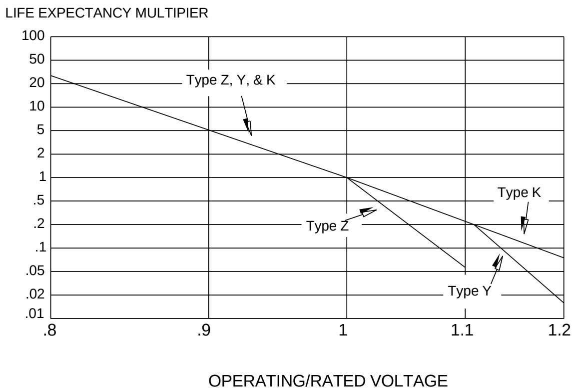

Fig. 2

The life vs. operating stress relationship for Type Z, Y, and K capacitors is shown in log-log plot of Figure 2. For the Type Z capacitors, life is based on a nominal shot cycle with a .5 second charge time, a .2 second hold time, a .004 second discharge with a maximum 10% voltage reversal. The stress on the dielectric is such that the capacitor will survive more than 10 Exp 6 shots. Increasing the hold time, voltage reversal, or operating temperature will have a negative effect on the life of the capacitor.

The relationship between the operating stress and life is often expressed in terms of a power rule. The predominant power rule for the metallized capacitors is the 15th power which is represented by the straight line that travels across Figure 2. When increasing the stress beyond the rated stress for the type Z capacitors, the rate of degradation increases as shown due to the introduction of new failure mechanisms.

TEMPERATURE VS LIFE FOR TYPE Z, Y, & K CAPACITORS

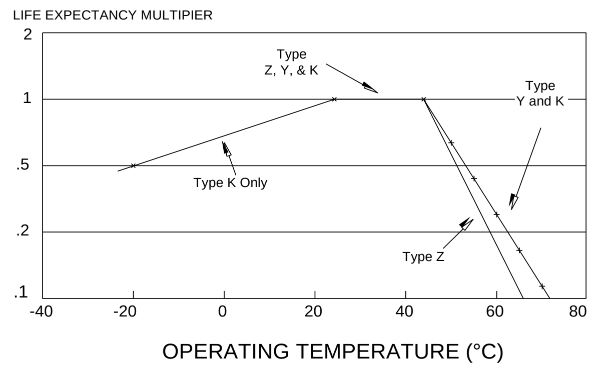

Fig. 3

The effect of operating a capacitor at elevated temperatures will generally shorten the life of the capacitor. Figure 3 shows the effect that operating temperature will have on the life of the metallized electrode capacitors discussed in this paper. The data for the Type Z capacitors in Figure 3 starts at 20 Deg. C only because testing below this level is not complete at this time.

The metallized design approach for this type of capacitor has both reduced its size and increased its energy density considerably when compared with the older aluminum foil electrode type designs. The metallized electrode units are typically 40% of the size of aluminum foil electrode units for the same application.

The metallized polypropylene construction of the Type Z capacitor yields a low DF and high IR, but the inability to fully impregnate this type of dielectric system limits the useful voltage range to a maximum of 2 kV. The low DF, plus improvements in the ability of then Type Z construction to withstand high peak currents, makes it an excellent capacitor for low voltage pulse power applications while the CDE Type K and Y capacitors are used for higher voltages. Recently, the Type Z capacitors have been used in place of electrolytic capacitors. This has occurred above 800 volts, where high ripple current are needed, and when long term maintenance is a concern.

HYBRID ALUMINUM FOIL & METALLIZED ELECTRODE CAPACITORS (CDE TYPE Y)

The CDE Type Y capacitor is the capaci-tor of choice for use in medium voltage (2 kVDC - 6 kVDC) and medium rep rate (20 pulses per minute to 5 pulses per second) energy discharge capacitors. Most commonly, these types of capacitors are used for pulsed lighting applications, such as photocopier, flashlamp and airport lighting.

The pulsed lighting applications typically require stored energies in the range 100 to 500 Joules and call for discharge currents in the 200 to 2000 amp range. There is usually no voltage reversal on discharge in these pulsed lighting applications since the discharge load (inductor and lamp) is either over damped or a clipping diode is used in the circuit.

The Type Y capacitors have the unique capability of lasting millions of cycles at energy densities as high as 6 Joules/cu. in. without degradation of DF (less than .003 at 1 kHz) or IR (greater than 1000 ohm x farads). This is more than twice the energy density than is normally achievable using traditional discrete foil technology for comparable cycle life. The internal heat conductivity of this type of metallized capacitor matches the high heat conductivity of foil capacitors, permitting stable operation at relatively high energy densities, rep rates of 2 Hz, and elevated temperature of 65 Deg. C simultaneously.

The CDE Type Y capacitor employs a hy-brid metallized/foil electrode system in combination with a fully impregnated mixed polypropylene and paper dielectric system. An impregnated dielectric system is a prerequisite for successful operation in the 2 kV to 6kV range. The hybrid electrode system is arranged with the aluminum foil connected to the positive terminal and the metallized electrode connected to the negative terminal. This eliminates the problem of metallized electrode loss due to anodic degradation while retaining the ability of the capacitor to self-heal by clearing at the negative electrode.

VOLTAGE STRESS VS LIFE FOR TYPE Y CAPACITORS

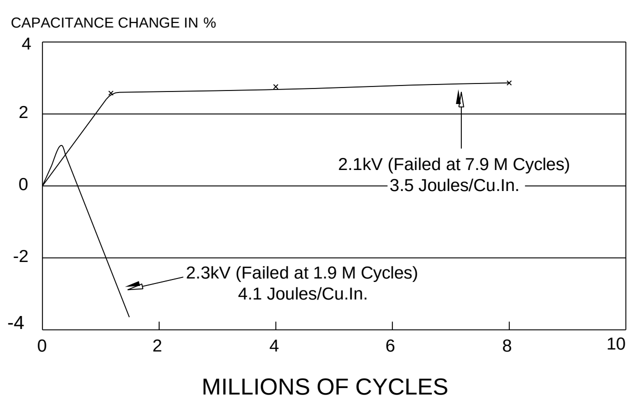

Fig. 4

TEMPERATURE VS LIFE FOR TYPE Y CAPACITORS AT 6.3 JOULES/CU. IN.

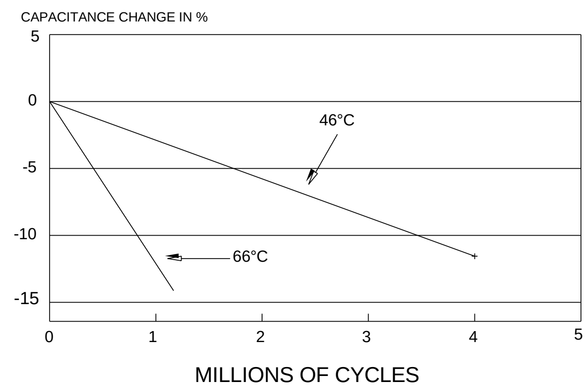

Fig. 5

The effect of stress and temperature on the life of the Type Y capacitors is included in Figures 2 and 3. Typical life test data is shown in Figures 4 and 5. The accelerated life testing at two different voltages on two 50 µF, 2 kVDC, Type Y capacitors in Figure 4 shows a cycle life reduction consistent with the 15th power voltage stress aging rule as plotted in Figure 2. The accelerated life testing at two different temperatures on two each, 23 µF 4 kVDC, Type Y capacitors plotted in Figure 5 shows a fourfold increase in the rate of aging when the test temperature is raised from 49 Deg. C to 66 Deg C, which is consistent with the 8 Deg. C aging rate doubling rule.

The Type Y and Z capacitors are both excellent long life and high rep rate energy discharge capacitors that frequently are used in very similar applications. The difference in the two is that the highly efficient Type Z capacitors are cost effective up to 2 kVDC. The fully impregnated Type Y and K dielectric systems are required above 2 kVDC, and in fact, higher energy densities are more easily achieved at the higher voltages.

The hybrid electrode system used by the Type Y capacitor is what makes it possible to operate at greater cycling rates and much longer cycle life than the Type K capacitor. This is achieved at the expense of clearability which is the reason energy density for predictable life is limited to a maximum of 6 J/cu. in. This is one third the energy density limit for reliable operation for the Type K capacitor. In addition, the end of life of the Type Y capacitor occurs as a much more sudden dielectric failure in contrast to the pure capacitance loss of the Type K capacitor.

IMPREGNATED FILM METALLIZED ELECTRODE CAPACITORS (CD-AERO TYPE K)

CDE Type K capacitors are suitable for both short lived energy discharge and long life DC filtering capacitor applications between the ranges of 2 kV to 44 kV. They are suitable for portable defibrillators, laser equipment, other DC pulses and DC filter applications.

Pulse discharge applications using the Type K capacitor typically require stored energy from 100 to 50,000 joules, discharged through a load with a current range of 65 to 50,000 amps. Voltage reversal may be varied from 0 to 90% depending upon the specific application.

DC filtering applications require the capacitor to withstand DC voltage for continuous operation over a period of many years. Here the Type K capacitor is capable of providing the small but fast pulses associated with applications such as DC Links and RADAR modulators.

The Type K capacitors are short lived and cost effective high energy density capacitors. They operate reliably and predictably at very high energy densities of up to 20 Joules per cubic inch. Further, they do not fail abruptly due to dielectric breakdown rather, end of life is defined by the percentage of capacitance loss in both the discharge and filtering applications. Because of the predictable nature of the capacitor, the capacitors are used in a number of unusual applications where the capacitors are discharged in hundreds of microseconds to tens of milliseconds. The Type K capacitors are particularly tolerant of fault conditions which often occur on experimental equipment.

The CDE Type K capacitors utilize a metallized electrode which provides the self clearing characteristic, and an impregnated dielectric where most of the energy is stored in polypropylene film. The aging process for these capacitors is the slow loss of capaci-tance due to clearings in the capacitor. The failure mode is typically defined as 5% ca-pacitance loss even though the capacitors are still operational. After the 5% capaci-tance loss, enough gas is generated inside the capacitor to raise concerns about a sec-ondary fault in the capacitor.

The Type K capacitors, when used for pulse discharge applications are designed to operate from 1,000 cycles to more than 100,000 cycles at rated voltages with a 95% survival rate. The life time of the capacitors is dependent upon the operating stress. The relationship between life and stress is expressed by the 15th power rule as shown in Figure 2.

The testing data in the Figure 6 and figure 7 were collected at CDE in the past few years. Figure 6 shows DC voltage withstand testing of three each Type K capacitor at 4.9 kV, 5.1 kV and 5.5 kV. Figure 7 shows charge discharge cycle testing at 25 Deg. C of a typical high energy density Type K capacitor at 5.1 kV and 5.7 kV. This data has demonstrated the validity of the 15th power rule to approximate the relationship of life time and stress of the Type K capacitor shown in Figure 2.

Figure 6 describes the loss of capacitance for the Type K capacitor operating as a filter capacitor for a few hundred hours at relatively high stress. The Type K capacitors are capable of withstanding operating DC voltage continuously for considerably more than 5 years at lower voltage stresses.

DC VOLTAGE STRESS VS LIFE FOR TYPE K CAPACITORS AT 25 DEG.C

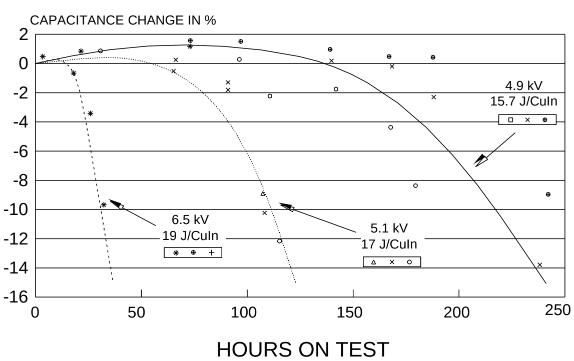

Fig. 6

VOLTAGE VS LIFE FOR TYPE K CPACITORS ON DISCHARGE TESTS

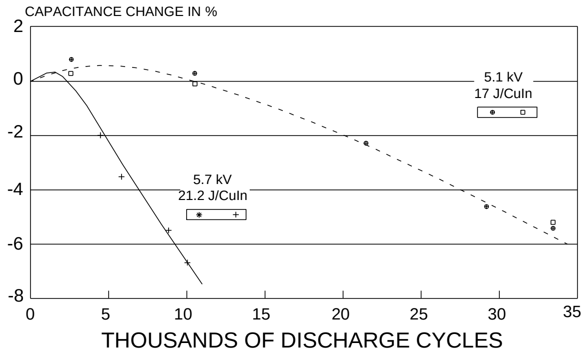

Fig. 7

TEMPERATURE VS LIFE FOR TYPE K CAPACITORS

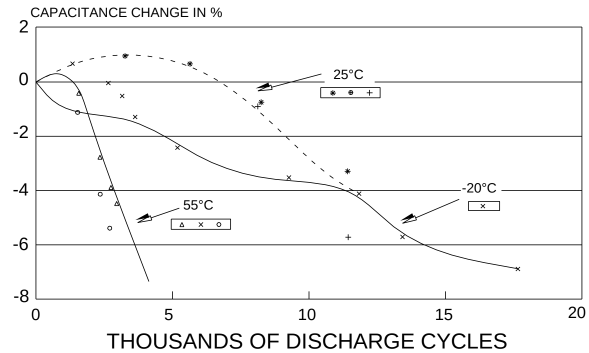

Fig. 8

Type K capacitors are designed to operate over a wide range of temperatures. As shown in Figures 3 & 8, the longest life is obtained when the capacitors are operating between 20 Deg. C and 55 Deg. C. Between 40 and 65 Deg. C, capacitor life is decreased by 1/2 for every 8 Deg. C of operating temperature increase. Above 65 Deg. C the capacitor degrades even more quickly. Limited test results have indicated Type K capacitors operate consistently between -20 Deg. C and 20 Deg. C with a slight decrease in life at the lower temperatures.

CONCLUSIONS

Metallized electrode capacitors have proven to be highly reliable. The size of the capacitors is about 1/2 the size of discrete foil capacitors with the same life characteristic as shown in Table 1. A variety of metallized capacitors have been developed to satisfy a wide range of applications. The metallized electrode technology is still considered to be young and the rate of evolution is rapid. Improved metallized electrode capacitors can be expected in the future.

ENERGY DENSITY IMPROVEMENT FOR EQUIVALENT METALLIZED vs FOIL ELECTRODE CAPACITORS			
Capacitors Type w/ Metallized Electrode	Life Expectancy in Shots	Energy Density in Joules/Cubic Inch	
		With Metallized Electrodes	Equivalent Foil Electrodes
Z	10 M	2	0.7
Y	10 M	5	2.5
K	10 M	20	8.0

Table 1

LIST OF REFERENCES

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CDE
167 John Vertente Blvd.
New Bedford, MA 02745
Tel: 508-994-9661
Fax: 508-995-3000