Design and Testing of Capacitors for Uninterruptable Power Supplies

Forward

Uninterruptable Power Supplies (UPS) have become a necessity for any system or data that can be lost, damaged or impaired by an unexpected power failure. Common backup power applications range from medical instruments to computing servers and data centers. Even the common home computer may be backed up by such a power supply. According to the Transparency Market Research, the worldwide UPS market will have a compound annual growth rate (CAGR) of 7.5 percent between 2017 and 2025 and will be worth $9,881.9 million by the end of the year 2025. With many devices becoming more dependent on data storage, it's easy to understand the market growth. A UPS may be designed to provide operating power for an extended period of time or just long enough to allow for an orderly shutdown of the systems protected. Many UPS devices have built-in intelligence to perform this function automatically.

All UPS applications share a common requirement—THE UPS HAS TO WORK AND NOT BE DOWN! That requirement holds regardless of what comes down the power line, such as high voltage transients, noisy power conditions or adverse operating parameters that exceed listed nominal design limits. So, how does an engineer design circuitry to meet that requirement? An important part of the solution is the selection of power film capacitors that can handle unexpected operating conditions, such as high voltage transients and heat without failing short or completely open. This paper will take a close look at two new series of film capacitors offered by Cornell Dubilier, types 951C and 953B, designed with these applications in mind. The development of these component series resulted from multiple customers requesting AC output filter capacitors that would meet or exceed their most demanding UPS requirements.

Film dielectric materials are often the best choice for output filter applications in UPS systems that range from 0.1µF to 100µF, 50 Vac to 1000 Vac. Film capacitors are non-polar devices and typically have lower dissipation factor than other capacitor dielectrics.

With the right selection of electrode type, film capacitors can be made to handle high voltage transients and exhibit reliable self-healing properties.

Polypropylene is generally the preferred dielectric for AC output filter capacitors. It exhibits low dielectric losses, has high voltage breakdown strength (volts/micron) and low leakage current. When metallized with thin layers of metallic deposit, polypropylene capacitors exhibit reliable self-healing characteristics. Polypropylene is readily available at a moderate cost and is easily wound to form a capacitor. The temperature capability of polypropylene is not as high as some other film dielectrics, such as polyester, but is typically more than adequate for UPS applications.

The two basic choices for *electrodes* are aluminum foil and vapor-deposited metallized electrodes. The discreet aluminum foil has an advantage in the amount of current it can carry, but it has several drawbacks. Film capacitors made with aluminum foil electrodes have lower voltage breakdown strength and lower corona inception than metallized types. Aluminum foil electrodes do not self-heal and are much thicker than metallized electrodes. Considering that relatively large values of capacitance are needed in UPS systems on the AC output, the size reduction afforded by the metallized approach is essential.

Within the metallized film approach, there are several sub-choices. Aluminum metallization is moisture resistant but takes more energy to clear a self-healing event and typically exhibits excessive metal loss in AC applications. Zinc metallization is used extensively in oil-filled AC capacitors. It self-heals easily, exhibits low capacitance loss and interfaces easily with the Schooping (end spray) material (typically zinc or tin-zinc). On the negative side, thin layers of pure zinc electrode oxidize easily, especially with moisture present. Pure zinc electrodes are generally used in oil-filled capacitors, encased in a metal can, where the near-hermetic seals protect the capacitor winding from exposure to the elements. Zinc-aluminum alloy metallization offers the best of both worlds for dry AC capacitors. It retains the self-healing properties of zinc, has low capacitance loss with life, as compared with pure aluminum electrodes, yet provides resistance to oxidation.

The metallization can be deposited so that it is thicker at the film's edge with a lighter, uniform metallized layer deposited across the remaining width of the film. This metallized pattern is commonly referred to as "heavy edge". The heavy edge provides better connection to the Schooping (several passes of fine particles of tin/zinc spray that connect the many turns of metallized film together to create a low resistance construction). The lighter metallization applied across the remaining width of the film is optimized for current carrying ability and self-healing properties. Thicker metallized deposit improves current capability while less metal improves self-healing capability.

To ensure fail-safe operation, additional fault protection is typically needed for UPS applications because capacitors are often connected across the power line and are therefore exposed to large energy content during self-healing (clearing). In addition, there is a constant exposure to high amplitude power line noise and large voltage spikes.

What happens when a fault occurs?

When a fault within the capacitor occurs, energy stored by the capacitor and available from the outside circuitry will rush through the low resistance path created by the fault. Within a few microseconds the electrode surrounding the fault will heat and vaporize the electrode metal surrounding the fault site. The metal-free area stops current from flowing through the fault and effectively clears the fault. It normally requires just a few micros or milliwatts of power to achieve a clearing. The lighter the metallization, the quicker the clearing occurs and the less energy needed. Once self-healed, the capacitors continue to operate normally with minimal capacitance loss from the fault.

In applications where the available power is large, the clearing becomes more violent and high-pressure gas or plasmas develop in the localized areas. This can result in physical damage to the dielectric in the form of melted plastic, with cracks into the surrounding electrode area. These cracks weaken the plastic and create new fault sites which, if they occur in rapid succession before the capacitor can self-heal, could progress to a catastrophic failure.

So, what to do?

Typically, AC film capacitors are designed to handle transient voltages well in excess of their rms and peak ratings. However, the amplitude and duration of irregular events such as power line surges from lightning or other high energy events are unpredictable and it would be difficult to design capacitors to withstand them without significantly increasing their size. Externally fusing the capacitor would protect the capacitor but may not be a good strategy if the capacitor must come back on line without a manual reset. It would seem logical, if at all possible, to just “fuse” that part of the capacitor where the fault occurs.

Fortunately, such fault protection schemes are possible with metallized capacitors. The concept is to limit the fault site to a small area and interrupt its progression before additional damage can be done. To achieve this result, an electrode is metallized on the film in a mosaic pattern. The electrode segments are interconnected by very small paths of electrode metal which serve as “fuses.” These fused areas will open-circuit in the event of a fault and the clearing will be limited to the area of the segment. This produces a small capacitance loss that is proportional to the area of the pad, but the part will continue to work within specifications. It takes a large amount of segmented loss to cause a significant capacitance loss. An example of a typical mosaic metallized pattern is shown in Figure 1. An actual metallized mosaic segment with fuse links is shown in Figure 2. Figure 3 shows a mosaic segment with the fuse links blown as the result of a clearing event within the segment area.

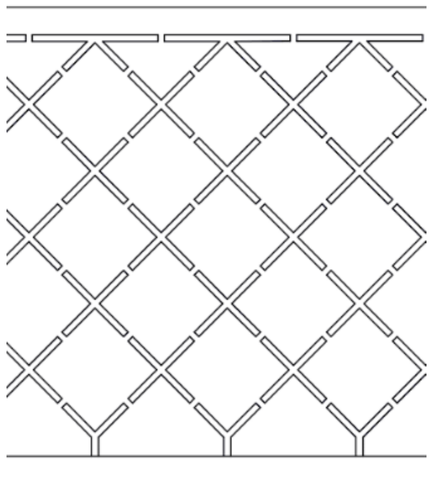

Figure 1

Typical diamond mosaic metallized pattern.

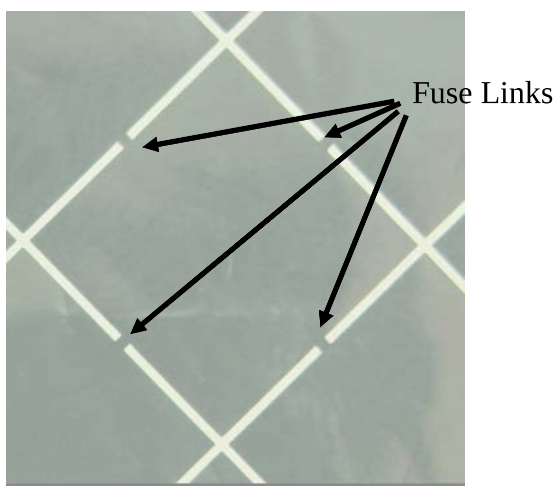

Figure 2

Photo of a segment with inactivated fuse links. Gray areas are metallized and white areas are non-metallized areas of the film. Note the narrow, metallized areas between adjacent segments that act as fuses.

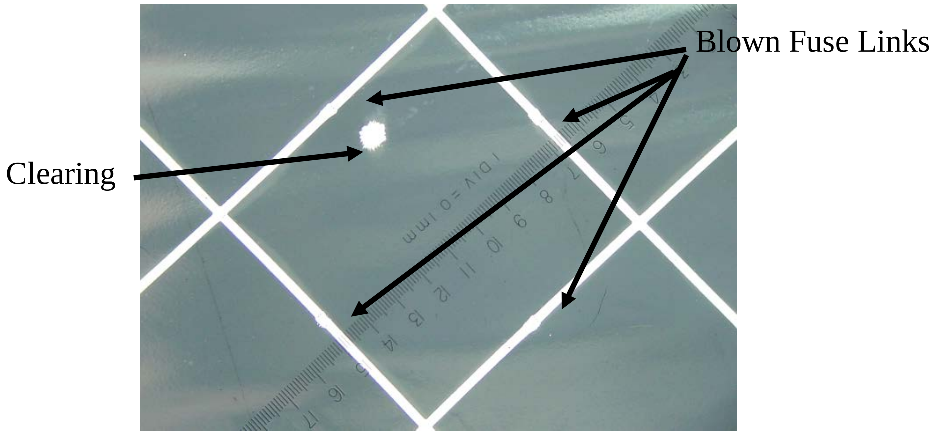

Figure 3.

Picture of a segment with all four fuses activated by a clearing event that electrically isolated the failed segment from the rest of the capacitor

Incorporating mosaic fault protection into the design.

To actually use this technique for fault protection the capacitor designer must adjust the thickness of the metallization (measured in ohms per square) to ensure the capacitor can withstand normal operating and expected peak conditions while retaining the ability to open the mosaic fuses during significant events that could otherwise cause the part to fail. Often a “heavy edge” is used to improve the peak current rating of the capacitor. There are a myriad of variables that can affect the proper functioning of the fuse links, such as metal thickens, fuse link size, segment size and dielectric thickness, to name several. Much of the optimization of these parameters is the direct result of exhaustive testing of capacitors under induced fault conditions.

Qualification and Performance Verification of AC Output Filter Capacitors for UPS Systems

The rugged operating environment and performance requirement for UPS capacitors demands rigorous qualification and performance verification tests.

Testing capacitors of this type typically focuses on two areas:

1) **Pulse Endurance Tests**: Tests that verify the integrity of the metallic interfaces between end-spray and the interconnection with the electrode, as well as lead welding and terminations. This will determine if the design and construction can hold up to heavy charge/discharges resulting from large transient waveforms, as well as normal operation.
2) **Benign Failure Mode:** Tests that verify that the long-term performance of the part ensuring it will demonstrate a benign failure mode.

Let's examine a typical test methods used to achieve these two test results.

Short Circuit Endurance Testing of Termination

Typically, 10 samples are tested from the test sample population; and all must pass this test. Each is tested for 100 cycles. Pass/Fail criteria are established to evaluate performance. A typical set of parameters follows:

> ***ESR*** *at 10kHz or 100kHz. To be measured prior to the test. All parts must fall within the product specification prior to testing. This parameter is then measured after test and a deviation from pretest to post test is determined. Typically, +20% change from pretest is allowed.*
>
> ***Capacitance*** *at 1 kHz. This is a typical measurement frequency for the product definition. Again, all products must be within the initial tolerance specified for the product. Measurements are pretest and post-test. A capacitance change of ≤0.5% is*

allowed. This is particularly important when evaluating mosaic segmented electrodes. Large changes in capacitance may be a sign of segment disconnect.

Dissipation Factor *at 1 kHz. This is a standard product measurement and is usually read along with the capacitance test. A typical maximum change from pretest to post test is +10%.*

Test Cycle Capacitor Charging-- *It is important that this portion of the cycle is done at a relatively slow rate until the maximum specified dc voltage is attained. The max current during the charge should be far below the maximum specified for the product. This dc voltage, if not specified at a higher value, should be the ac rating for the part times 1.414 + 10 volts. For example, a 250vac part should have an applied dc charge voltage of 363 volts.*

Test Cycle Discharging --*The discharge cycle is particularly important. The most strenuous discharge for a capacitor system is a direct short. Typically, a relay or shorting semiconductor is used. The actual value of the discharge is dependent upon the discharge circuit loop inductance and resistance. The discharge circuit inductance should be kept between 300 and 450 nanoHenries and a loop resistance of 16 to 30 milliohms. These loop values should be measured once the discharge circuit is built. The discharge loop and the capacitor under test forms a simple RLC circuit model for which peak current can be calculated from the peak discharge voltage. Using the above discharge circuit parameters, a 20µF capacitor rated at 160 Vac and charged to 236 Vdc should produce currents between 1,350 and 1,750 Amps peak.*

Actual Discharge Test Results for Types 951C & 953B

The following results apply to types 951C & 953B specifically designed for UPS applications. Ten units were built and tested for 100 cycles. The results of the discharge test were:

Capacitance @ 1kHz Change*-- -0.04% average with a maximum of -0.05% and a minimum of -0.02%. All were within the -0.5% allowed.*
(+ Changes are not considered a failure.)
Dissipation Factor @ 1 kHz – *0.88% average with a maximum of 5.88% and a minimum of 0%. All were within the +10% allowed change.*
(a decrease in DF is not considered a failure because a lower DF indicates product parameter improvement.)

ESR @ 10 kHz – *The average DF* **change** *was +1.05% with a maximum of 5.07% and a minimum of -0.57%. All were within the +20% allowed change. (A decrease in ESR would indicate a product parameter improvement).*

As can be readily seen, the product met the criteria of the short circuit endurance test. The change values proved that the segment fusing, end spray and termination processing were verified for this product. Thus, the product met the 0 of 10 failure requirement.

Benign Failure Mode Verification Test

If the capacitors survive the Pulse Endurance Test, it is then necessary to determine if the capacitor design can survive induced faults, by clearing the fault and still function without a catastrophic failure. In actual applications such breakdowns can come from defects in the film, dielectric wear out from aging or long-term overstress. These clearings normally occur in isolated locations within the capacitor.

The concept behind this test is to induce failure in the capacitor by applying increasing levels of DC voltage that cause repetitive clearing, followed by the application of rated AC voltage to ensure that the capacitor remains healed and operating at rated AC conditions without catastrophic failure. In addition to the voltage step test the capacitor may be wrapped tightly in white cheesecloth or cotton prior to testing. Any discoloration of the material is an indication that smoke is being generated, a sign of catastrophic failure. The application of DC and AC voltage is repeated for a specified number of cycles, typically 10 cycles per voltage step. After all of the cycles are completed at each voltage stress level, capacitance is measured and the percent capacitance change calculated. If the change in capacitance is low (typically less than 5%), the voltage is increased, usually by increments of 100 Vdc for each successive step. After repeated steps have resulted in 95% capacitance loss, testing is discontinued. The number of steps, number of cycles per step, voltage hold times and other test parameters, are typically agreed upon by the capacitor manufacturer and UPS customer when customer-specific designs are tested.

Benign Failure Test Results for Types 951C and 953B

To ensure fail-safe operation of types 951C and 953B segmented film capacitors, tests were performed on samples using the above cycle tests method. Ten samples, rated 20 µF at 250VAC, were tested for 5 seconds starting with 2000Vdc, followed by 5 seconds at 250 Vac. The DC voltage was raised by 100 Vdc increments when capacitance change measured after each step was less than 5%. The test was terminated after 95% capacitance loss was observed.

Tests and measurements for one of the units from the test group is is shown below.

Sample ID, Unit #1, 20µF 250Vac *Test Sequence =* *5 seconds AC\5 seconds discharge\5 seconds dc*					
Cycles	**Cap µF**	**1 kHz %DF**	**100 kHz ESR(mΩ)**	**Pulse dc voltage**	**% Cap loss**
0	19.422	0.146	15.4	0	0.00
10	19.412			2000	0.05
20	14.910			2400	23.23
30	12.538			2400	34.45
40	11.851			2400	38.98
50	10.685			2400	44.99
60	9.182			2600	52.72
70	7.939			2600	59.12
80	6.692			2600	65.54
90	4.331			2600	77.70
100	3.616			2600	81.38
110	3.170			2600	83.68
120	1.916			2700	90.14

130	1.357			2700	93.01
140	1.241			2700	93.61
150	0.894	0.056	64.2	2800	95.40
No catastrophic failures. Unit passed					

The remaining units from the test group had similar results. None of the samples failed catastrophically. All units had successfully failed-safe with the proper activation of the segmented fuse links. Additionally, each part had been wrapped in cheesecloth and unwrapped post-test. There was no evidence of discoloration of the material for any of the samples.

Figure 4

Picture of cheesecloth removed from a sample capacitor after test. There was no evidence of discoloration.

Conclusion

The demands of the UPS capacitor application are very rigorous. This paper has shown how capacitors can be designed with segmented metallized polypropylene and tested to meet the fail-safe requirements of UPS and other critical applications in AC output filtering. The successful testing of types 951C and 953B were repeated by Underwriters

Laboratories and both series are recognized as “protected” under UL 810 File number E71645.