Next Generation Dry Film AC Filter Capacitor Eliminates Catastrophic Failures

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Abstract

AC filter capacitors are a limiting factor for reliability of power conversion systems in network power and alternative energy applications. Conventional capacitors with pressure interrupters or fuses often fail catastrophically with significant collateral damage. A next generation annular form factor dry-film capacitor has been developed to eliminate catastrophic failures using proprietary end connection and segmentation technology. By accepting some small additional capacitance loss over life, potential failure sites are disconnected before they can transition into dangerous faults. Extreme accelerated failure prediction results at 100^{o}C and 127% of rated voltage are presented with capacitance loss measurements under more practical operating conditions.

1. Introduction

Inverters utilized for network power and alternative energy applications generate unwanted switching harmonics on the AC output. These harmonics are typically managed using passive filters comprised of series inductor-capacitor branches deployed from line-to-line or line-to-neutral which minimize distortion of the 60Hz waveform. The series impedances are selected such that the capacitor sees essentially the entire AC voltage thus minimizing the size and cost of the iron core inductor. While this tradeoff certainly makes sense at the system level, the end result is that the AC filter capacitors operate at high temperature and voltage stresses. Therefore it is not surprising that AC filter capacitors often define the reliability limits for this type of inverter system thus requiring routine maintenance for quality monitoring and periodic replacement long before the inverter itself would have any typical expectation of failure.

Polypropylene metallized film capacitors are normally used for AC filter applications given the combined advantages of very low dielectric losses and the ability to self-heal. Traditionally, such capacitors are impregnated with oil to increase the corona inception voltage and deployed in hermetically sealed cans fitted with pressure interrupters. Note that dry type capacitors using an impregnating resin instead of oil are also available with similar interrupt devices. If an internal fault develops in the capacitor winding, the resulting pressure increase actuates an internal disconnect to remove the capacitor from the circuit. However, pressure interrupters do not always achieve the desired disconnect in time to prevent capacitor explosion and collateral damage to the rest of the system. Should the interrupt device work as intended, a “dropped” capacitor represents a significant capacitance loss to the AC filter characteristic until replacement during routine maintenance – which can often be at 6-month intervals. This reduced capacitance is typically not considered in life analysis, but is tolerated in real applications.

AC filter capacitor reliability is acknowledged as a problem across the power conversion industry and system vendors have been forced to address the issue. Finite capacitor lifetimes are now accepted as a reality and maintenance strategies are tailored to monitor and replace parts to minimize downtime, but this is a costly solution in an ever more competitive market. Capacitor life has been studied extensively and is generally accepted [1-3] to follow a power law relationship with voltage stress while approximately doubling for every 10^{o}C reduction in temperature. One approach to improving life is thus de-rating of the AC filter capacitor by operating at voltages and/or temperatures below nominal [2] with the penalty of increased cost and volume. However, even this technique does not eliminate the potential for catastrophic failure nor guarantee that less frequent maintenance will be adequate. The question remains as to what can be done at the fundamental capacitor design level to provide acceptable reliability without the need for de-rating.

2. Defining Life

In order to understand what is possible with new AC filter capacitor technology, it is first necessary to clearly define the meaning of capacitor life. Typically, AC filter capacitors are specified as having a life of 60,000 hours, however general practice allows some percentage of the population to fail over that time. There are actually three definitions of capacitor failure:

1) Catastrophic failure where the capacitor suffers an internal fault and the pressure interrupter does not actuate in time to prevent explosion.
2) Benign failure where a defective capacitor disconnects from the system via pressure interrupt actuation.
3) The capacitor value (or collective bank value) gradually decreases to the point where the filter characteristic no longer meets the system total harmonic distortion (THD) limit.

By definition, catastrophic failure implies collateral damage to the rest of the system resulting in down time and unscheduled field service. In contrast, a benign failure is manifested as a change in the AC filter characteristic due to a sometimes significant reduction of capacitance, but does not result in shutdown. The benign failure will ultimately be revealed by increased total harmonic distortion on the 60Hz AC waveform or during a scheduled maintenance inspection. A clear understanding of the “functional” versus “defined” specification is critical in this case to understand a practical lower bound for the third failure definition in terms of minimum allowed capacitance. As discussed in the previous section, significant capacitance reduction will occur when interrupt devices function as intended and the issue is not simply linear capacitance reduction due to device aging.

The practical meaning of capacitor life is ultimately defined in the context of field service experience. In some cases, service personnel are inspecting capacitor banks as often as every six months and replacing any defective parts observed. This begs the question of how many capacitors in the bank are actually from the original installation when the “end of life” is reached after some number of years. Typically, AC filter capacitors are specified as having less than three percent capacitance loss over a service life of 60,000 hours. However, dropping out one or more capacitors due to pressure interrupter actuation between maintenance intervals can lead to a bank capacitance reduction much larger than 3%. Furthermore, the 60,000 hour number must be challenged if any of the capacitors in the bank are replaced before this life time is actually achieved. Customer feedback indicates that capacitance reductions in the range of 20-30% are routinely tolerated in the field and the biggest concern is catastrophic failure. Industry data does not appear to exist on the topic of how often a full bank of capacitors reaches the expected 60,000 hour life with no individual capacitors requiring replacement during the period. However customer feedback has indicated that it is VERY common for a bank to have seen one or more replacements before a 60,000 hour life is completed. Therefore, the practical goal for AC filter life should be elimination of catastrophic failures while providing a capacitance loss of less than 20-30% of nominal over a life of 60,000 hours without field replacement.

3. Next Generation AC Filter Capacitor

A next generation AC filter capacitor has been developed to address the industry need for improved reliability. The key targets for this design are defined as follows:

1) Eliminate catastrophic failure (benign failure mode)
2) No need for internal fuse or pressure interrupter
3) Reduced hotspot temperature
4) Oil-free
5) Explosion proof package
6) Increased life

The basis for the next generation capacitor is the SBE Power Ring Film Capacitor^{TM} which has already been well proven for DC link applications [4]. The annular form factor provides the longest possible end connection length to the metallized film along with excellent heat transfer from the winding hotspot to the end faces. By combining this form factor with end connection and metallization segmentation technology developed for high-reliability pulse applications [5], a dry-type AC capacitor which meets all of the design targets listed above has been achieved. While the segmentation approach is generally well known in the film capacitor industry [6, 7], the efficacy is greatly improved as compared to conventional “can” style capacitors using a patented pattern matched to the long end connection length and short width of the Power Ring.

The ring capacitor approach enables a completely different filter mechanical architecture as illustrated in Figure 1. In this case, a three-phase capacitor bank is implemented with 12 windings of 312.5μF to achieve 1250μF per phase. This structure fits in the same space as a bank of conventional cans that achieve the same capacitance value with some notable improvements. First, the capacitors are spaced on a central support mandrel such that vertical cooling channels are available to support free convection. This allows even better utilization of the improved heat transfer provided by the annular form factor windings. Second, the capacitors are oriented within each phase so that the adjacent end faces are at the same voltage. When combined with the long insulation path between the end faces of each winding, the strike distance between bus voltages is significantly increased relative to conventional cans with stud terminals on one end. Finally, the windings are not enclosed in a hermetic metal case, so explosion hazard due to overpressure is eliminated.

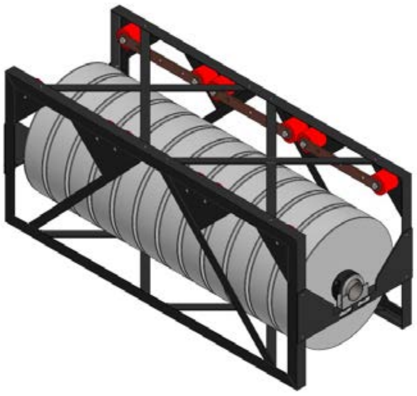

Figure 1. Illustration of a three-phase capacitor bank with 1250μF per phase implemented using annular form factor windings on a central support.

A further evolution of the ring capacitor AC filter implementation is presented in Figure 2, which depicts a single phase bank of 1250μF. As such, the three-phase bank is realized with three individual phase assemblies that can be safely lifted by a single service technician. While the rotation of the windings to the horizontal plane has reduced the free convection, this type of configuration has been demonstrated to run 20^{o}C cooler than an equivalent bank of cans in a 750kVA uninterruptable power supply. The ability to mount the windings using their hollow cores and a suitable support member opens up a wide variety of low-cost mounting configurations for both single and three-phase bank assemblies.

Figure 2. Photograph of a single-phase 1250μF bank where each phase is deployed on a separate support structure.

4. Accelerated Testing

A significant testing effort has been undertaken to validate the dry film annular form factor capacitor for AC filtering applications. Testing under extreme voltage and temperature conditions was first performed to verify that the segmentation and end connection design would prevent catastrophic failure. Long term accelerated testing at more practical voltage and temperature conditions was then performed to look at the rate of capacitance loss.

4.1. Testing to Failure

A total of nine prototype 92μF capacitors based on a custom film design rated for 480VAC nominal were fabricated for testing to failure. The parts were mounted in a thermal chamber using rods running through the capacitor cores as illustrated in Figure 3. Each capacitor was instrumented with thermocouples mounted on the end faces to provide an indication of over temperature rise due to an internal fault. The samples were energized to 625VACrms (60Hz) with the chamber temperature at 100^{o}C for 128 hours and carefully monitored. One event was observed over this time period where a capacitor exhibited excessive temperature rise. The segmentation and end connection strategy was found to work exactly as designed and this part was run for over 45 minutes without developing a hard fault. A subsequent teardown of this sample showed that the event was not catastrophic with only some minor venting of melted polypropylene as shown in Figure 4. At the conclusion of the 128 hour run, the oven temperature was gradually raised to 125^{o}C in an unsuccessful attempt to initiate more failures. The experiment was terminated at this time due to concerns about the temperature rating of the power supply cables.

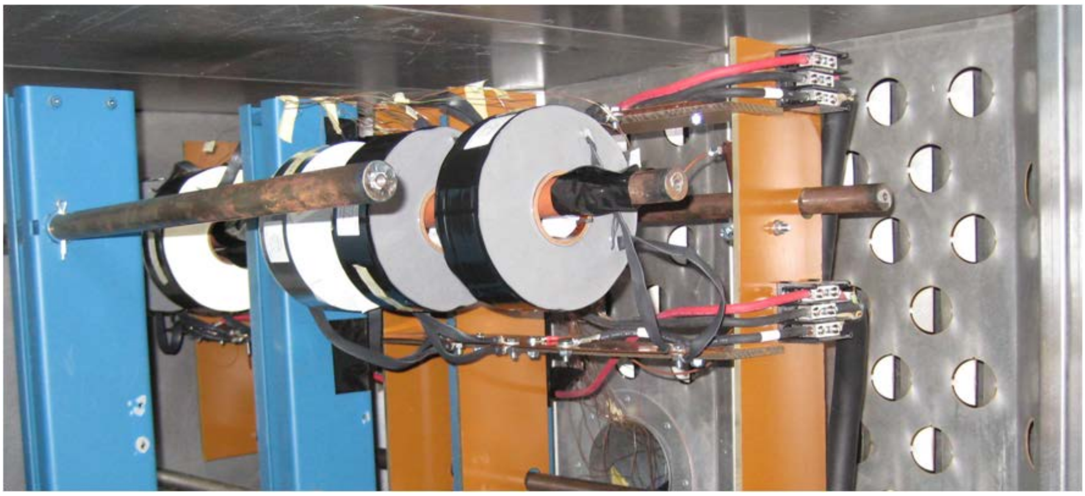

Figure 3. Prototype capacitors deployed in thermal chamber for accelerated testing. Note that different end fill materials were tested for comparison.

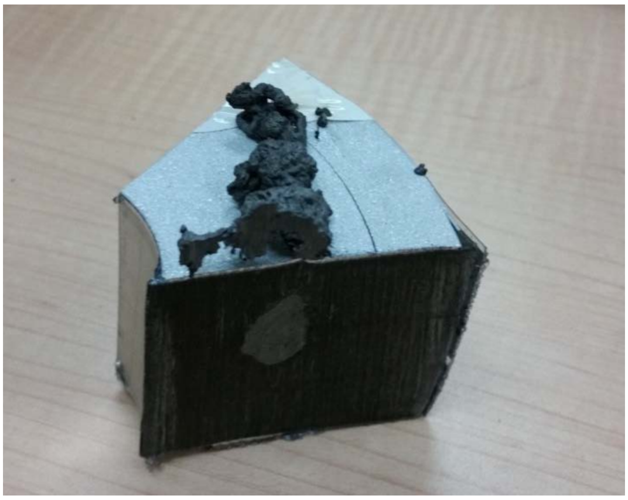

Figure 4. Section of capacitor which began to develop an internal fault but could not achieve catastrophic failure.

4.2. Capacitance Loss Testing

An additional 18 of the 92μF samples used for testing to failure were fabricated for capacitance loss testing. All of the parts were subject to a room temperature burn in at 625VACrms for 19 hours. The samples were then split into two groups of nine and deployed for testing at 36.7°C with respective voltages of 500VACrms and 625VACrms. The testing was performed for over 2000 hours with regular measurements of the capacitance values and DF losses. The DF measurement is important since many customers use it as a metric for capacitor field replacement.

The average percentage of capacitance loss over time for the 500VACrms sample group is presented in Figure 5. Note that two of the samples showed excessive capacitance loss during burn in and would have been rejected in production. These samples were left in place during the experiment to provide a balanced three-phase load, but their readings are not included in the average. A linear regression fit to the last four points in the plot indicates an operational life of 81,000 hours for the average capacitance to drop to 30% below the nominal value of 92μF. Alternatively, a three-point derivate method indicates a nominal life of

84,000 hours to reduce 30% from nominal. Applying error analysis to the three-point derivative indicates a maximum life of 104,000 hours and a minimum life of 71,000 hours. Note that even the worst case exceeds the 60,000 life that is desired, but not achieved, by many customers.

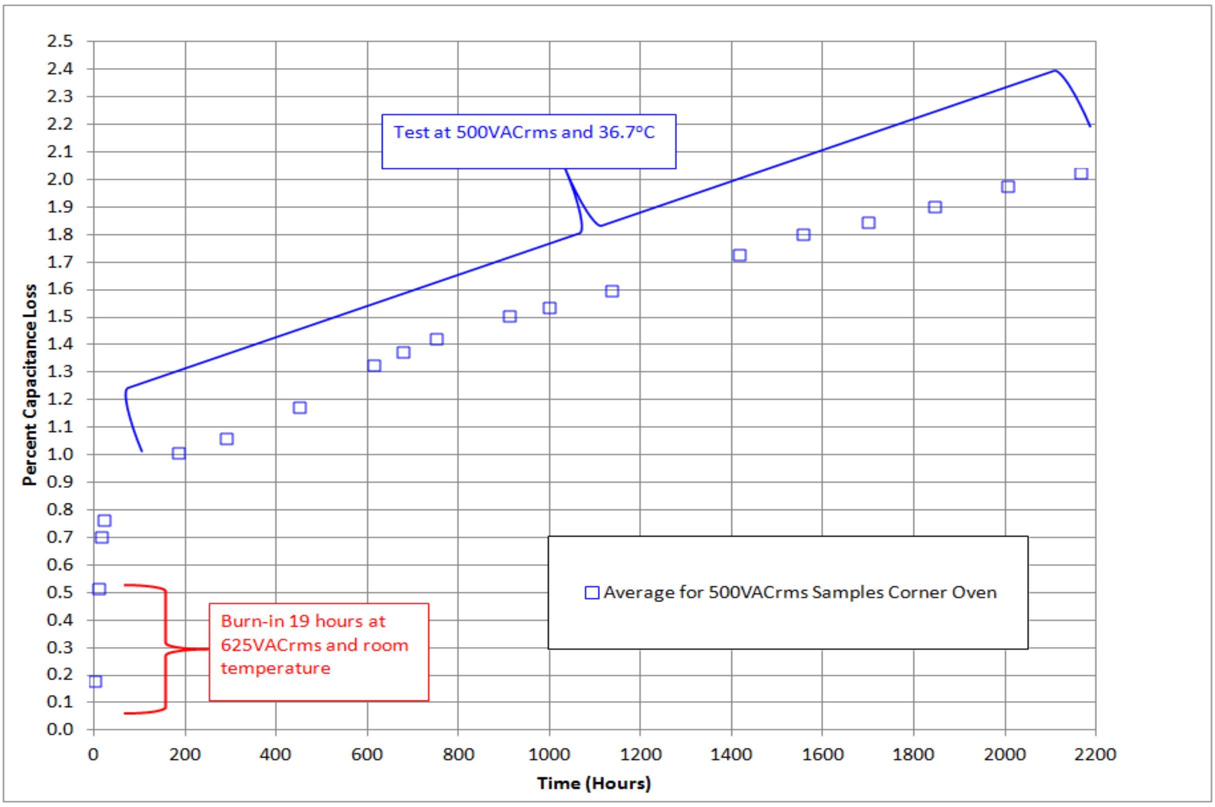

Figure 5. Average percent capacitance loss over time for sample group at 500VACrms and 36.7°C

The dissipation factor measurements for the 500VACrms samples are presented in Figure 6, which shows the readings for all of the parts, including the units that would have been rejected at burn in. As a point of reference, typical nominal and replacement values of DF are provided for conventional AC filter cans. These results are very significant in that the Power Ring dissipation factor is much smaller than conventional cans, and is remarkably stable over the 2000 hour test. This is a direct result of the patented segmentation design used for these parts to prevent “unzipping” of the end connection which leads to very rapid capacitance decline and increase in DF. The segmentation design effectively prevents circumferential current flow in the winding.

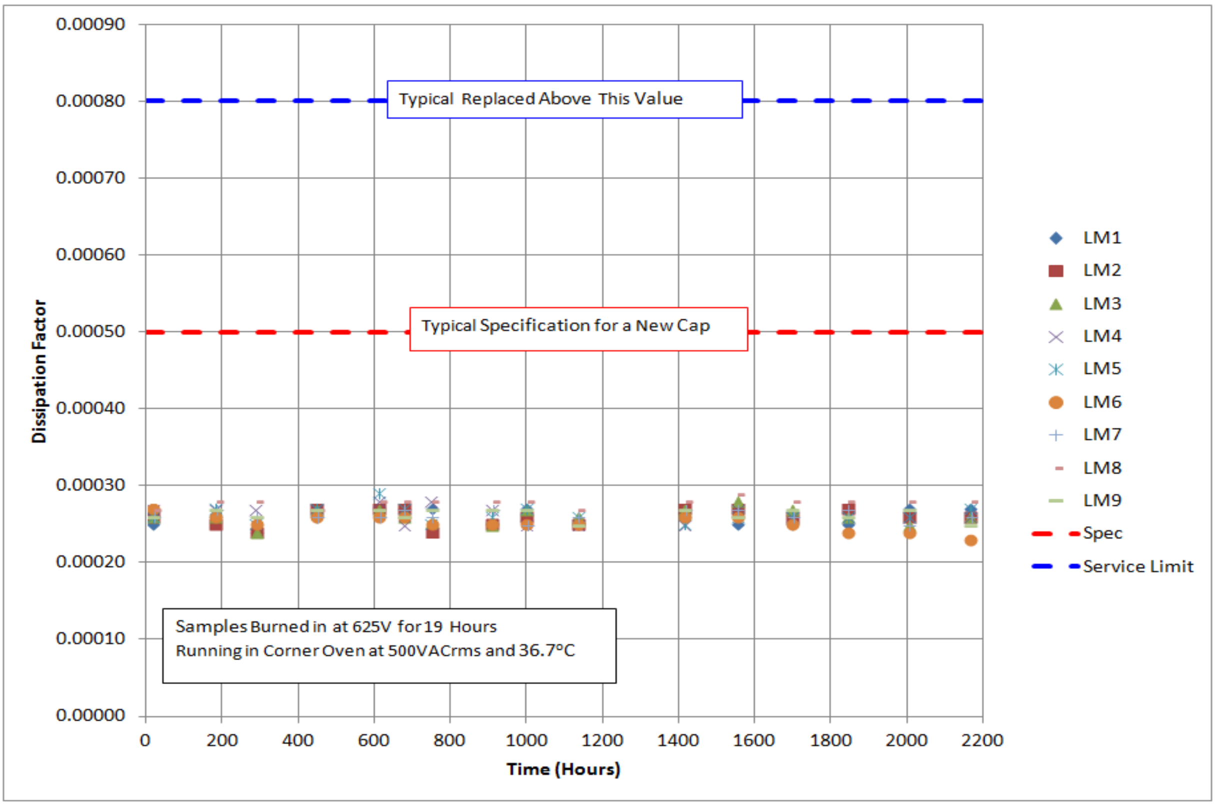

Figure 6. DF readings over time for sample group at 500VACrms and 36.7°C

The 625VACrms sample group showed exactly the same behavior in the DF in spite of the significantly higher stress applied to the parts. Once again, this clearly illustrates that the optimized segmentation design is working. The average slope with the higher voltage stress was a factor of 4.7 higher than the slope of the 500VACrms parts which predicts a nominal life of 17,000 hours at 36.7°C. Note that this scaling is almost exactly consistent with the typical rule of thumb [3] which states that life scales with voltage as.

$$L = \left(\frac{V_2}{V_1}\right)^7$$

5. Conclusion

A next generation dry type metallized film capacitor has been demonstrated to eliminate the catastrophic failures prevalent with conventional AC filter capacitors. The annular form factor combined with a novel, patented, end connection and segmentation scheme does exhibit some capacitance loss, but does not achieve a hard fault condition even operating beyond 100°C at 127% of rated voltage. This technology changes the definition of filter capacitor failure from catastrophic with collateral damage to benign based on capacitance loss limited by total harmonic distortion. Testing for over 2,000 hours at 36.7°C and 500VACrms (480ACrms rated) has provided trending data supporting that 81,000 hours of life can be achieved before dropping 30% below nominal cap value. Customers acknowledge that capacitor banks in the field can drop to 20-30% below nominal through actuation of pressure interrupters, so the traditional specification limit of 3% capacitance loss is not really correct.

Furthermore, a defined capacitance drop over 60,000 hours is preferred to catastrophic capacitor failures which take down the system. Finally, system testing has demonstrated a 20^{o}C lower temperature rise for a given power level than conventional AC capacitors, thus introducing a host of opportunities in the marketplace.

6. References

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