A White Paper from the Experts
in Business-Critical Continuity™

Capacitors Age and Capacitors Have an End of Life

EMERSON
Network Power

Executive Summary

This white paper discusses large DC aluminum electrolytic and AC polymeric film capacitors for use in a UPS application: specifically field aging, failure modes, expected service life and preventative maintenance.

UPS systems use large capacitor banks. These capacitor banks are made up of both DC electrolytic and AC polymeric film capacitors. AC polymeric film and DC electrolytic capacitors both degrade under field operating conditions. The field aging of the capacitor is a slow process which takes place over years but eventually the field aging leads to a capacitor failure unless the capacitors are periodically replaced.

Introduction

High quality capacitor manufacturers all around the world provide a capacitor service life rating. The service life rating is, at best, a guideline. The number lacks sufficient accuracy to be used as a predictor of when the first capacitor in a large population will fail. Capacitor failure models do exist and will generate a failure time for a specific failure rate but the number contains a large variance and has a low confidence level. Replacing capacitors periodically is the only way to insure a very high MTBF for capacitors. This white paper discusses the reasons capacitors fail, the dispersion in time over which a group of capacitors fail, failure modeling for capacitors and the cost effective solution of a capacitor replacement program.

Capacitors are not the only component in UPS systems which experience field aging and can cause UPS systems to transfer offline or to a bypass source. Liebert has a list of components in UPS systems which field age and a corresponding list of recommended replacement times. For more information on *capacitor preventative maintenance* see the white papers *The Effect of Regular Skilled Preventative Maintenance on Critical Power System Reliability* and *Longevity of Key Components in Uninterruptible Power Systems*, available at www.liebert.com.

Why UPS systems use large power capacitors

On line UPS systems contain five main parts: as shown in Figure 1.

1. An AC filter at the input line
2. A rectifier which converts the filtered AC to DC
3. A DC bus, containing both a large battery bank and a DC capacitor bank for bus hold up and DC filtering
4. A power inverter, which converts DC to AC
5. An AC filter at the output line

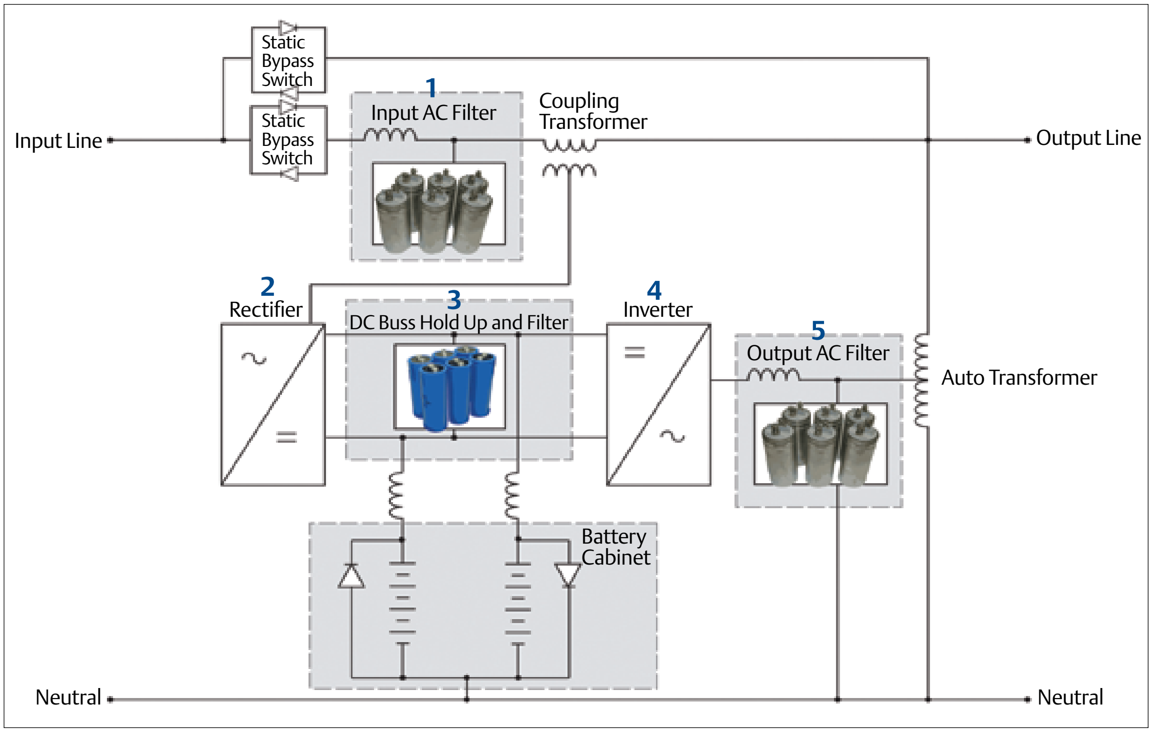

Figure 1. UPS circuit showing filtering banks.

DC electrolytic capacitors are used to filter the DC signal and AC polymeric film capacitors are used for filtering the AC signal. The DC electrolytic capacitors are also used to hold the DC bus voltage at a near constant level. Without the capacitor filters the UPS system would supply poor quality power, which is not an adequate AC source for highly reliable systems like a large electronic database.

The benefits of two different capacitor technologies

Capacitors are selected for electrical circuits based on a complete set of electrical, mechanical and environmental parameters. After narrowing the search based on the complete specification, then quality, size (energy density) and mounting configurations determine the final selection. DC electrolytic capacitors are smaller in size (larger energy density) than AC polymeric film capacitors. Unfortunately, DC electrolytic capacitors can only be used on DC circuits. AC polymeric film capacitors can be used on both circuits but using AC film capacitors for DC circuits would increase the size and cost of a UPS system. As a result, DC electrolytic capacitors are used in the DC circuit and AC polymeric film capacitors are used in the AC circuits.

Basic design of an AC Polymer Film and DC Aluminum Electrolytic capacitor.

Capacitors in general are constructed with two main components: a very thin dielectric material with a large surface area and two thin conducting plates, referred to as current collectors. For both capacitor technologies, the dielectric material and the two current collectors are rolled into a section which looks very similar to a roll of paper towels. The AC polymeric film capacitors are packaged in a large round metal or a large plastic case. The DC electrolytic capacitors are only packaged in large round aluminum metal cases. Pictures of a typical large AC polymeric film and DC aluminum electrolytic capacitor are shown in Figure 2. As you can see, these are large components typically 60 mm to 100 mm in diameter and can vary in height from 120 mm to 220 mm.

The polypropylene dielectric film used in AC polymeric film capacitors is extruded from dielectric grade resin (very pure polypropylene resin which contains a minimum of contaminates but it is not zero) into a thin film which is then stretched to achieve a very thin film (3 µm to 20 µm). The average film thickness can vary by ± 3 to 4% over the web width. In addition, the film contains thickness variances on a small area scale (smaller than the cross section a human hair). The contaminants have both an average concentration on a large surface area scale and variances on a small area scale. The non uniformities in materials and processing drive variances in the capacitor performance This is a very simplistic model but it serves to introduce the concept that performance variances play a major role in determining the service life and the reliability of a capacitor. The difference between service life and reliability will be discussed in section 7.

Typical AC polymeric film capacitance ratings for large UPS applications are 50 µF to 200 µF (microfarads). This is a single capacitor rating. These capacitors typically have a dielectric

Figure 2. The shiny metal case is the AC polymeric film capacitor and the blue insulated metal case is the DC electrolytic capacitor. The grid in the background is 1 cm by 1 cm squares.

surface area in the range from 10 m^2 to 40 m^2 (this is a general number and varies with the voltage and service life of the capacitor). The scale of these dimensions can be visualized as a sandwich of two large garage doors with a layer of shrink-wrap plastic between them. This sandwich contains material and geometry variances and the weakest point in the dielectric sandwich becomes the weak link for the capacitor performance.

DC aluminum electrolytic capacitors use an aluminum oxide layer as the dielectric material and a dielectric grade aluminum foil as the current collector. The aluminum oxide layer is grown on a dielectric grade aluminum foil. The aluminum foil current collector is first etched to achieve a large surface area (composed of many small diameter tunnels which do not penetrate through the aluminum foil) before the aluminum oxide is grown on the aluminum foil. Both the materials and the processing have non uniformities on a small scale. Typical DC electrolytic capacitor ratings for large UPS applications are in the 1,500 μF to 16,000 μF (these values vary with the voltage and service life of the capacitor and are common ratings for capacitors in the 350 to 400 Vdc level). DC Aluminum electrolytic capacitors with these capacitance ratings typically have a surface area in the range of 30 m^2 to over 300 m^2. Like polymeric film capacitors, this is a very large surface area, and material plus processing variances (in addition to other issues) lead to weak points within the capacitor. Once again, the weakest points in the large surface area become the weak link for the capacitor performance.

Capacitor field aging

Two basic mechanisms lead to capacitor field aging. The first mechanism is chemical reactions. Combinations of heat and chemical contaminates (oxygen, moisture, and halogens for electrolytic capacitors are just a few examples) lead to deterioration of the dielectric materials (polymeric film and aluminum oxide layer) which reduces the voltage withstand capability of small localized areas. These chemical reactions lead to an increase in the probability that the dielectric material will not withstand the applied voltage.

The second mechanism has to do with the leakage current. Dielectric materials are often thought of as insulators which do not conduct current when voltage is applied across the insulation. In fact, all insulating materials conduct a very small current when voltage is applied. This current is a conduction (electrons and ions move physically through the material and not by an electronic mechanism) current and is usually called a leakage current. The magnitude of this current is very small (typically a millionth of a millionth of an Ampere per cm^2). Even though the leakage current is very small it flows in a very small channel and gives rise to localized heating and material electron interactions.

The aging mechanism presented in this white paper is very superficial but it introduces the concept of capacitor aging. Capacitors are not static electrical components which just sit and operate in a circuit. Over time, the internal reactions and the leakage current lead to a reduction in the dielectric voltage withstand capability (increase in the probability for a capacitor to fail). As the reactions progress, the capacitance value slowly decreases and the resistance value slowly increases. (All capacitors have an equivalent series resistance).

Capacitors have an end of life

The aging process in the capacitor can be visualized by considering a water dam with a small leak. Over time, the small water leak grows. The movement of the water through the dam causes deterioration within the dam structure. In spite of the growth in the leak rate, the leak rate is still small and the dam still functions as a dam. As water continues to leak, the structure of the dam is compromised. When sufficient damage occurs, the probability for a near term failure becomes very high and the dam needs to be taken out of service.

During the capacitor aging process the electron leakage current and the chemical reactions both cause a decrease in the capacitance value and an increase in the resistance value. Both of these changes (decrease in capacitance and increase in the resistance) are tied to damage taking place inside of the capacitor. Once sufficient damage to the capacitor has been sustained, the probability for the capacitor to fail increases and when this probability becomes high, the capacitor should be taken out of service.

Capacitor industry guidelines exist which define end of capacitor service life. These are based on a decrease in the capacitance and/or an increase in the series resistance. Typical values are shown in Table I. The capacitor still operates at end of life, just as the dam still holds water, but the capacitor has a high probability for a short circuit failure and the capacitor should be taken out of service. Note that after years of capacitor industry experience, the end of life numbers still cover a range and are only guidelines.

Failure mode for a capacitor as it approaches its end of life

Both capacitor technologies age by losing capacitance and developing higher internal resistance. If this process is allowed to continue, a point will be reached where the capacitor will fail into a short circuit and will lose the ability to withstand the rated voltage. The capacitor aging process also generates gas which increases the internal gas pressure in both capacitor constructions. The polymeric film capacitor has a pressure interrupter built into the case and when the pressure reaches a preset value, the interrupter opens inside of the capacitor case and disconnects the capacitor from the circuitry. The pressure interrupter design for large polymeric film capacitors are based on a notched wire which breaks open as shown in Figure 3B. When the pressure interrupter operates, the capacitor case expands upward and is very visible indicating the capacitor has reached end of life and is no longer in the circuit. Other pressure interrupter designs are used around the world but they all open under pressure and disconnect the capacitor from the circuitry. For DC aluminum electrolytic capacitors, the build up in pressure pushes up a rubber bung at a pre set pressure. The rubber bung is shown in Figure 3A. This does not disconnect the capacitor from the circuit but it provides

Elements	Film Technology	Aluminum Electrolytic Technology
Max loss of capacitance	-5% to -10%	-15% to -20%
Max increase in series resistance	+100% to +150%	+200% to +300%

Table 1. End of Life Parameters.

a visible sign when the capacitor is reaching end of life. (Simple voltage interrupter switches do not exist for DC circuits and as a result DC electrolytic capacitors do not contain pressure interrupters.

The UPS system monitors the quality of the AC power being supplied by the UPS system and can detect reduction in capacitance for both the AC and the DC capacitor banks. The UPS actually monitors power quality not capacitance or resistance but the two are related. When the UPS detects that a preset value of capacitance reduction has taken place, a signal and or alarm is sent to an appropriate location indicating servicing of the unit is required. As capacitance decreases increase stress on the remaining capacitance can develop. In the event a pressure interrupter does operate, additional stress can also be placed on the remaining

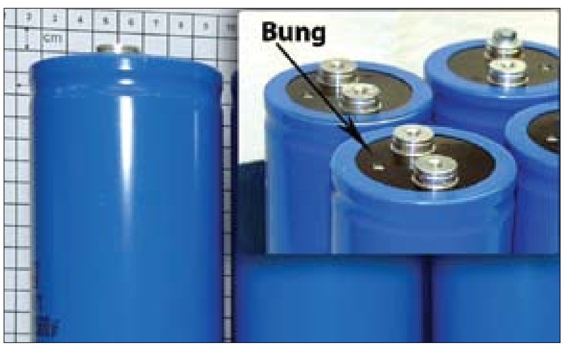

Figure 3A. Rubber bung is shown for the DC electrolytic capacitor.

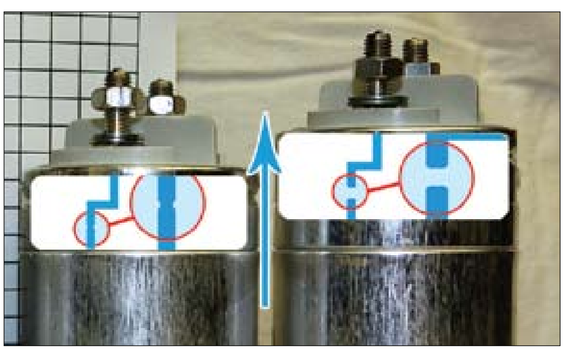

Figure 3B. Notched wire is shown for the AC polymer film capacitor.

capacitors which again will impact power quality. In the extreme case where the loss of capacitance can lead to a problem with the UPS, the UPS will go to by-pass mode which maintains the load but the UPS is no longer in the circuit. In both cases (when the pressure interrupter opens or the rubber bung pops up), the capacitor is at its end of life and should be replaced.

The aging AC polymeric film capacitor contains a large reactive power flow in addition to an internal gas pressure (relative to atmospheric pressure). The DC aluminum electrolytic capacitor contains a large electric potential energy in addition to the internal gas pressure. If the capacitor develops a short circuit, there is the potential for a large energy flow (capacitors assembled into large banks can discharge all their energy into the one failed capacitor) in a very short period of time and it is not always possible to disconnect the capacitor before damage has been done to the UPS system.

The difference between expected service life and reliability

Expected service life and reliability are similar concepts but they are not the same. Expected service life is a general classification for the service life. It is a general classification, like one year, five years, ten years, etc. It does not mean that all the capacitors fail after five years if it is a five year design. Capacitors can and do fail inside the expected service life rating. The expected service life rating can only be used as a general guideline. Reliability is a probabilistic statement of the cumulative failure probability for a specific set of operating conditions and a specific operating time.

A reliability number has the following format:

"Maximum cumulative failure of 5% when operated for 50,000 hours at max rated conditions with a confidence level of ± 90 %" (95% is also very common).

A simple representation of capacitor aging in Figure 4 shows what is going on.

In the ideal world each capacitor manufactured with the same model number and operated in the identical rated conditions, would all reach the expected service life at the same time and fail slightly over the expected service life as shown in Figure 4.

In the real world, a group of capacitors all manufactured with the same model number and operated under the same max rated conditions would all fail at different times as show in Figure 4. A few of these capacitors would actually fail inside of the expected service life.

The challenge is to calculate the operating time for a small cumulative failure rate, like 0.01% with a high confidence level. The high confidence level deals with the variance in the sample test data (see the next paragraph).

The issue associated with sample testing is easily understood by looking at Figure 5.

The top box in Figure 5 shows a small group of 24 capacitors which are being tested to failure. The small round capacitors plotted along the test time axis, show the first capacitor to fail, then the second capacitor to fail (this is a longer time than the time it takes for the first capacitor to fail), the third capacitor to fail and finally the fourth capacitor. In a perfect world, the test should be continued until all the capacitors fail, but that takes too long and is rarely done.

The second box shows the measured data being curved fit to a distribution curve (for capacitors this curve is usually a 2 parameter Weibull function). An analytical relationship is required if a failure time for a small cumulative failure rate like 0.01% is the number being sought. Measuring a cumulative failure time of 0.01% would require testing a group of over 10,000 capacitors. This is just not practical.

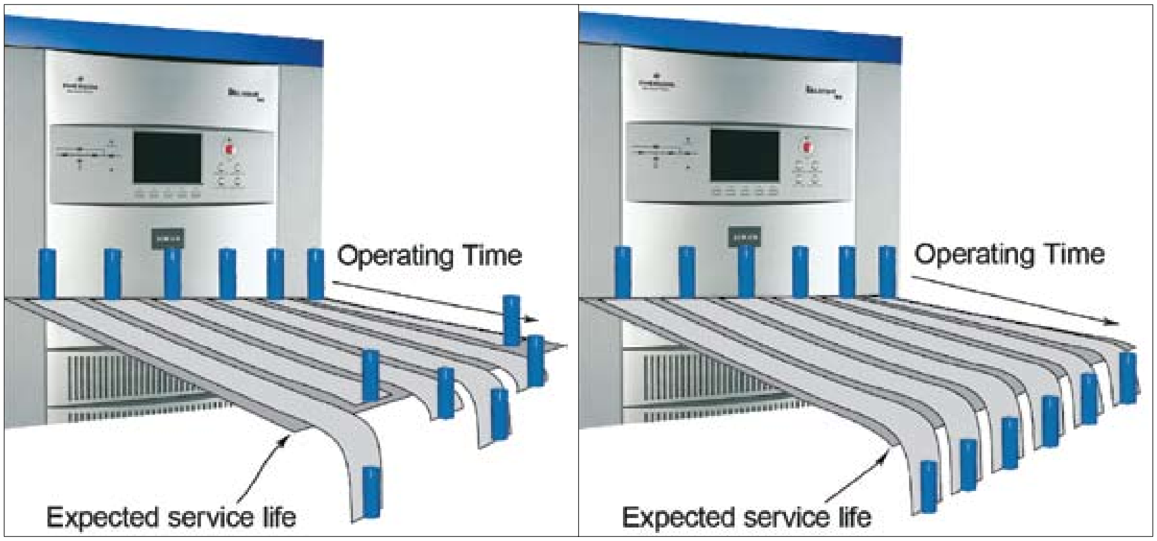

Figure 4. A simple figure representing capacitor aging. The right figure shows ideal aging, and the left figure shows aging in the real world.

The third box shows the cumulative failure rate for 0.01% being added to the measured data.

The bottom box shows what would happen if another set of 24 capacitors were pulled from the total capacitor population. Each time the experiment is repeated, the measured results would be different. If the experiment is repeated N times each with a different set of capacitors, there would be N measured/calculated times. Confidence

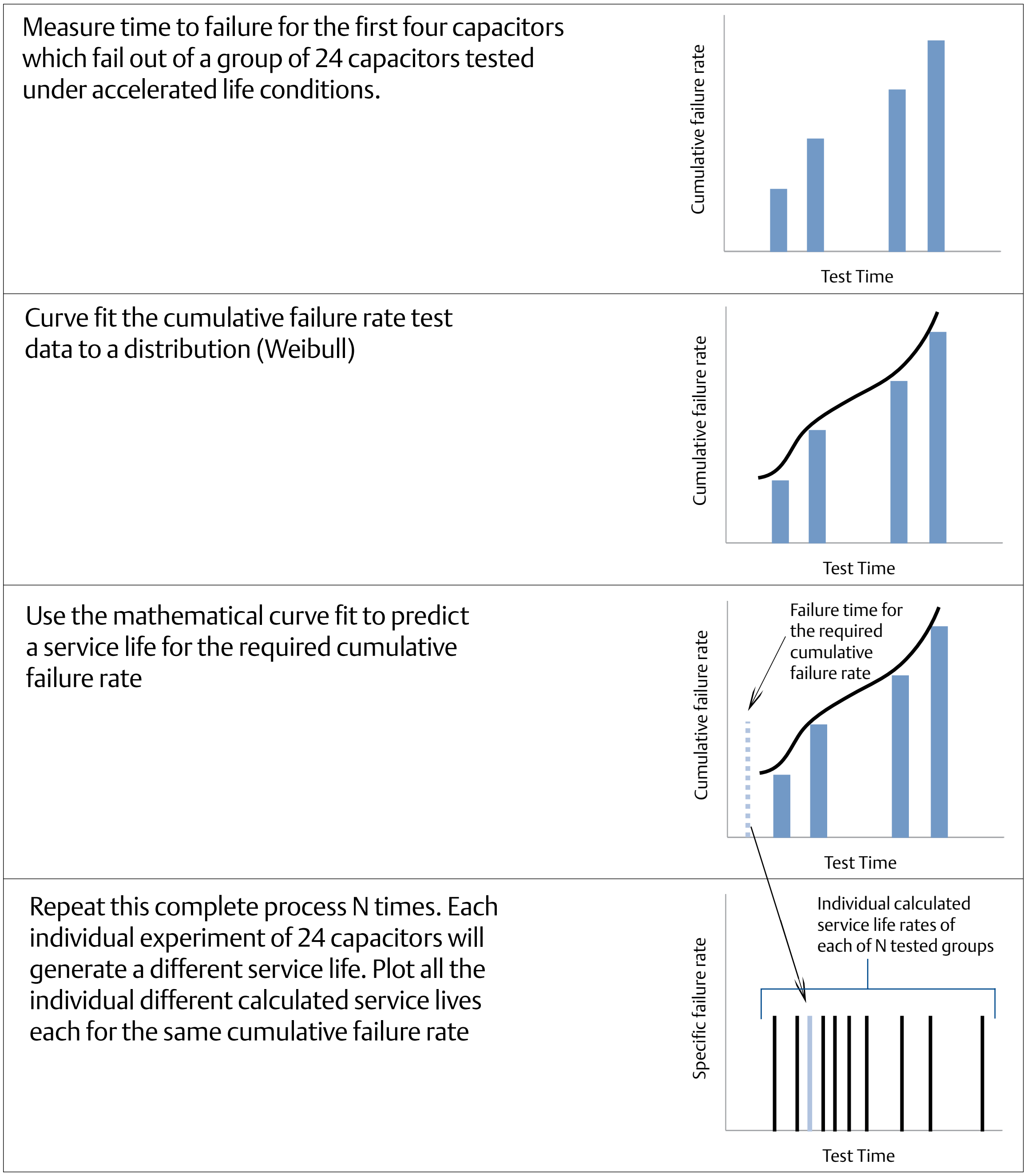

Figure 5. Chart showing the testing and analytical process for calculating reliability.

level mathematics must be applied to the set of N measured/calculated times to get a final number.

The capacitor manufacturer produces a large quantity of capacitors with a single part number. The quantity of capacitors with a single part number purchased by a large UPS company can easily exceed one million. The number of capacitors within this group that are tested by the capacitor manufacturer would typically be less than 150 units, made up of 6 to 8 sample sets. The sample size providing the tested data used to predict reliability is very small. Reliability numbers can be generated and are generated by the industry but it is clear from the process that achieving a high degree of accuracy is very difficult. This leaves the industry with preventative maintenance including field capacitor replacement, based on years of operating experience, as the most accurate approach to insure capacitors in UPS systems last well beyond the service life of the UPS itself.

Statistical modeling is required to predict failure probability for capacitors.

The problem has been described in the expected life and reliability. Distribution curve fitting and statistical modeling are required when calculating failure time using measured accelerated life test data from a small set of capacitors relative to the total population of capacitors. There are three distribution models which have been used over the years: a Weibull distribution, an exponential distribution (which is a subset of the more general Weibull distribution) and a log normal distribution. Capacitor failure data are not modeled using a bell shape curve (Gaussian). The failure distribution is non-symmetrical (there are tails in both directions but the tail which stretches to the right is much larger than the tail which stretches to the left) and the distribution is very wide. Of the three models which have been used, the exponential curve is by far the most prevalent because it has the easiest math. The exponential model is the basis for the “bathtub curve” which is still actively referenced in the industry. The Weibull model is the second most popular and the log normal curve is still used but has been largely replaced by the Weibull model over the past 20 years. An example of failure modeling for AC polymeric film capacitors is shown in Figure 6. Figure 6A shows actual AC film capacitor data supplied to Emerson Network Power by a capacitor manufacturer. One curve shows the failure density and the second curve shows the cumulative failure probability.

As can be seen from Figure 6A, the reliability for a cumulative failure of 0.1% is more than 48,000 hours. The 48,000 hours looks good but when confidence levels are applied, the 48,000 hours becomes a much smaller number.

The curves in Figure 6A have a 60% confidence level.

The instantaneous failure rate can be calculated using equation 1:

$$\text{Instantaneous Failure Rate} = \frac{\text{(probability density function)}}{\text{(cumulative failure)}}$$

Using the actual life test data in Figure 6A and equation 1, the instantaneous failure rate has been calculated as shown in Figure 6B. The solid line is the actual calculated curve. The bathtub curve model assumes a constant instantaneous failure rate with a sharp rise time on the front end which is associated with infant mortality and a sharp rise on the back end which represents end of life. The calculated curve is not quite flat. It does have rise on the front end but no rise on the back end. This is just a test issue. The original test data was not carried out far enough to see a large increase in the end of life failures. The dashed line is hand drawn, and is intended to simulate the bathtub curve, giving the actual data. As can be seen, the bathtub curve is not bad, although the actual data does have some differences from the bathtub curve model. The graphs look very impressive but they still lack statistics and contain large variances. The graphs could be different for a different set of sample capacitors. This issue can only be handled with confidence statistics.

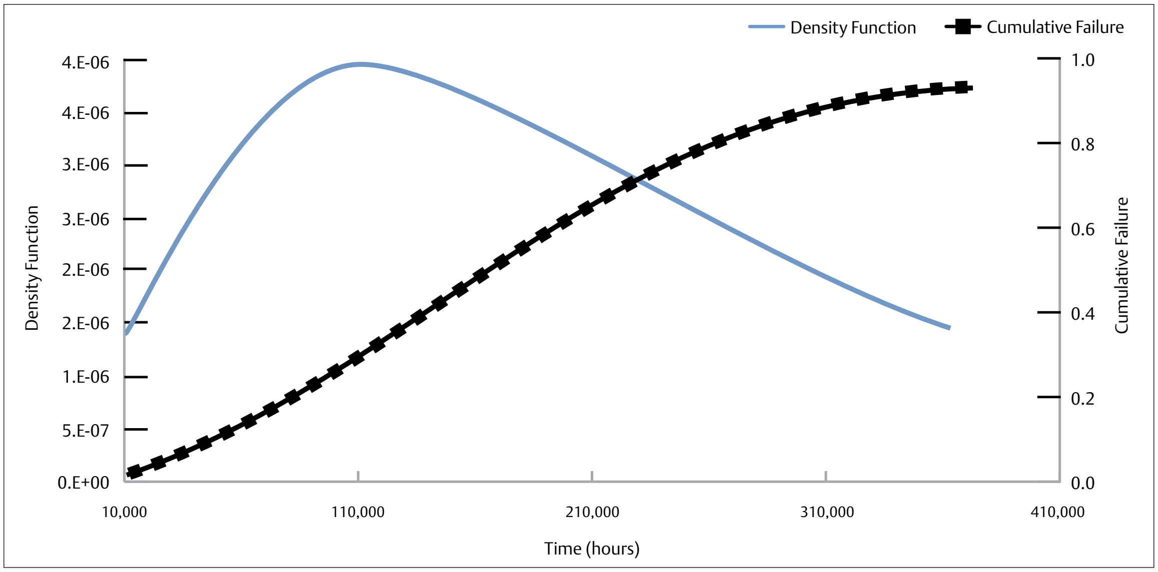

Figure 6A. Failure probability density function and cumulative failure probability (reliability) as a function of test hours.

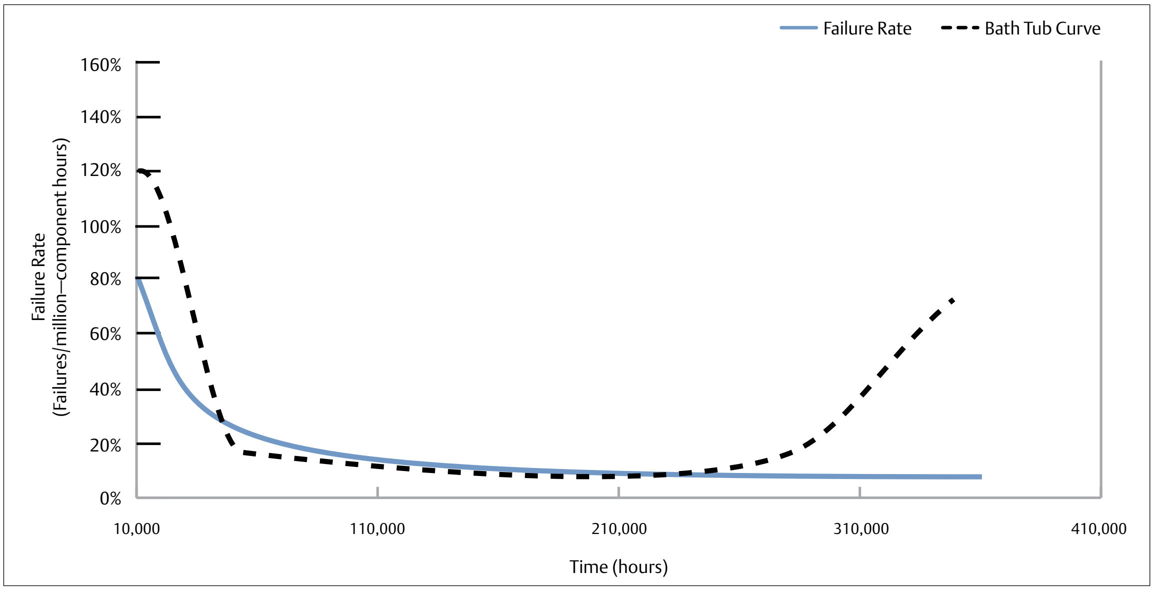

Figure 6B. Instantaneous failure rate as a function of test hours. Solid line uses data from Figure 6A. Dashed line (bathtub curve) is approximate.

A very similar set of curves is measured when testing DC aluminum electrolytic capacitors.

Use of accelerated life test factors used in the capacitor industry

DC aluminum electrolytic capacitors typically have service life ratings at max rated conditions in the range from 1,000 to 12,000 hours. This is a very short time considering that a year contains 8,760 hours and a UPS system will run for many years. To achieve a long life, the DC aluminum electrolytic capacitor is normally operated at reduced conditions (temperature, voltage, ripples current, etc). The measured life test performance of the capacitor at max rated conditions must be transformed back to operating conditions to calculate a reliability at operating conditions. To calculate the expected performance, accelerated life factors must be applied for DC aluminum electrolytic capacitors.

AC polymeric film capacitors at max rated conditions typically have service life ratings in the range from 60,000 hours to 150,000 hours. It is not practical to do life testing on AC polymeric film capacitors using max rated conditions since the test would last for many years. Instead, AC polymeric film capacitors are typically tested at elevated parameters and accelerated life test factors are used to predict reliability under operating conditions which are usually below max rated but not to the degree that DC aluminum electrolytic capacitors are de-rated.

Accelerated life test multipliers have been used in the capacitor industry for years. Typical industry applied multipliers for AC film capacitors are shown in Figure 7.

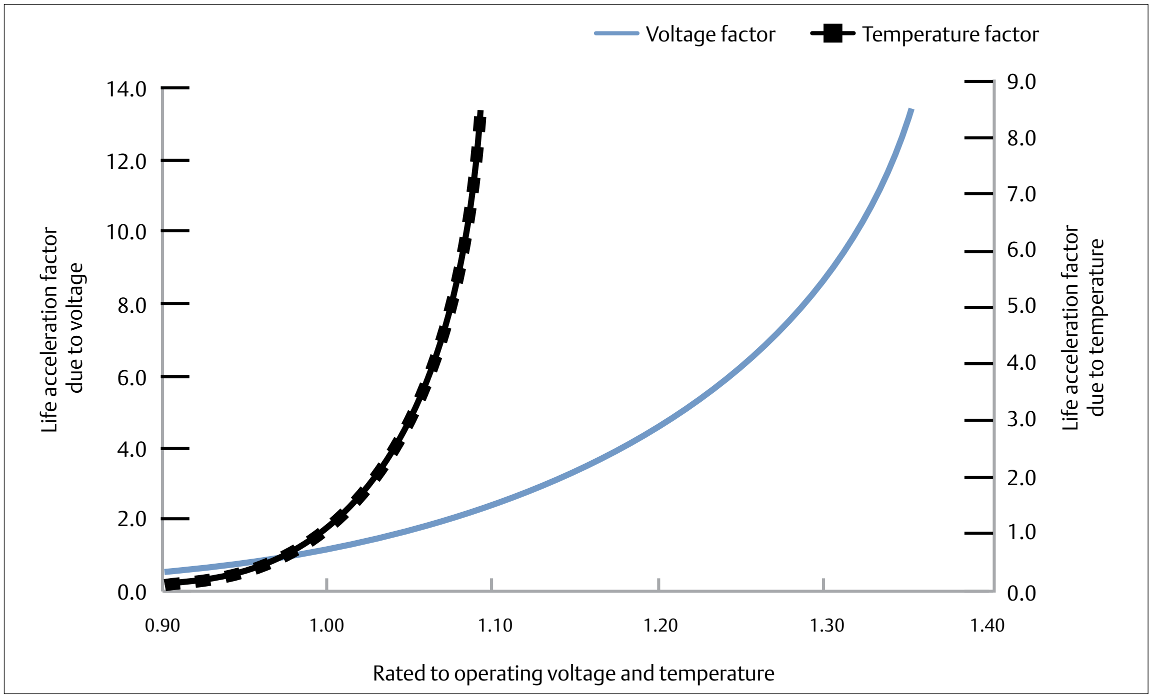

Figure 7. Typical service life multipliers for AC film capacitors. The voltage scale goes from 90% to 135% of rated voltage and the temperature goes from 40°C to 100°C for a rating of 70°C (the scale on the graph is an absolute scale °K).

Increasing the operating parameters above the rated parameters for the capacitor, of course, decreases the life of the capacitor. Decreasing the operating parameters below the rated parameters results in increasing the life of the capacitor. These are being referred to as industry multipliers but there are different factors used across the industry. For AC polymeric capacitors, the voltage scaling is usually a voltage ratio taken to a high power. The relationship is shown in equation 2:

$$L_{voltage} = \left(\frac{V_{max\text{-}rated}}{V_{operating}} \right)^{n} \qquad (2)$$

The exponent used by many large capacitor manufacturers varies from around 7 to 9.4. This is a large range and reflects the differences which exist within the industry.

The thermal multiplier is usually a factor of 2 for every 10°C difference from the max rated ambient temperature. Studies have been done for many years demonstrating that the thermal accelerated life factor is a good guideline but it is only an approximation. The actual thermal multipliers vary with the absolute temperature as well as the difference in the temperature between operating and max rated.

Accelerated multipliers for DC electrolytic capacitors also exist in the industry, but they vary from manufacturer to manufacturer (the electrolyte chemistry is proprietary and varies from supplier to supplier which generates different accelerated life testing factors) and there is no standardization in the industry. These accelerated life testing multiples also contain a high degree of error and are only guidelines. Accelerated life testing factors further reduces the accuracy of the capacitor failure prediction under operating conditions.

Aging capacitors can be detected and isolated during field maintenance

Both DC electrolytic capacitors and AC polymeric film capacitors contain devices which expand due to gas generation as the capacitor ages. As gas develops inside of the AC polymeric film capacitor shown in Figure 3B the expansion of the capacitor can be easily seen. Liebert uses round metal case AC polymeric film capacitors with built in pressure interrupters. For the round design, all the swelling takes place around the cover which can be seen during field maintenance. Liebert uses a design in which the round case contains a small bellows which allows the case to expand in the length direction by about 3 mm and again can be easily seen during field maintenance. The DC electrolytic capacitor has a rubber bung in the plastic deck which pops up about 2 mm when the internal pressure builds and reaches a trigger level. This can also be seen during field maintenance. The capacitors can be removed during preventative maintenance and replaced with no damage to the UPS systems assuming the maintenance is done by a certified Liebert technician.

Replace the whole capacitor bank when one capacitor has experienced significant field aging

Capacitor aging for capacitors within the same UPS system (capacitors within a capacitor bank and therefore exposed to the same field aging conditions) has a cumulative failure probability distribution which is compressed on the front end (see failure distribution curve in Figure 6A and 6B). When one or two capacitors reach the end of their life by operation of the pressure interrupter, other capacitors in the bank can see increased stress and accelerating aging. Once the first capacitor in the bank has failed, the probability of additional failures is high.

For maximum reliability, Liebert recommends that all the capacitors in the bank be replaced once the first capacitor has reached end of life. This resets the clock for capacitor aging.

The individual capacitors (both DC aluminum electrolytes and AC polymeric film) are assembled into capacitor banks. The capacitor bank needs to be removed from the UPS system in order to replace a single capacitor. Once the capacitor bank has been removed from the UPS system, the additional time to replace all the capacitors is a small incremental investment.

Recommended capacitor replacement program

A recommended replacement program for the AC polymeric and DC electrolytic capacitors is shown in table II. The table shows typical life testing times, and expected service life at operating conditions. The time ratios for both of these capacitor technologies are very similar. For DC electrolytic capacitors, the testing is done at max rated conditions for a time period around 2,000 to 5,000 hours and the reliability is calculated for a performance time around 150,000 hours by de rating. For AC polymeric film capacitors, the testing is done at accelerated conditions for a time period around 2,000 to 3,000 hours and the reliability is calculated for a performance time around 100,000 hours by operating slightly below operating conditions. As can be seen, the ratios in the two numbers are in the 50 range. This is a very large number and is part of the problem. Testing over a short period of time, with a small set of capacitors, and using this data to predict life performance more than 50 times longer than the testing period, can be done, and is done, but the accuracy which can be achieved is limited. A replacement program for capacitors based on years of field data is the best method for high reliability, at least for now.

Component	AC polymeric film	DC aluminum electrolytic
Expected service life at max rated conditions	60,000 to 150,000	1,000 to 12,000 hours
Typical life test conditions	Accelerated rated (125% or rated voltage and 10°C above max ambient)	max rated
Typical life testing time at test conditions	2,000 to 3,000 hours	2,000 to 5,000 hours
Expected service life at operating conditions	100,000 hours	150,000 hours
Recommended replacement time	45,000 to 50,000 hours	45,000 to 50,000 hours

Table 2. Recommended Capacitor Replacement Program.

Conclusion

A brief introduction into the construction, aging process, end of life criteria and reliability calculations for large AC polymeric film and DC aluminum electrolytic capacitors has been presented. The information demonstrates that large AC polymeric film and DC electrolytic capacitors are not static elements and age under field operating conditions. The aging process deteriorates the capacitors slowly over time and eventually brings the capacitor to the point where it needs to be replaced in the UPS systems. Operating large AC polymeric film and DC aluminum electrolytic capacitors after they have sustained a large degree of deterioration exposes the UPS system to a failure from a capacitor short circuit.

This white paper demonstrates that statistics must be used to calculate the failure probability for AC polymeric film and DC aluminum electrolytic capacitors because only a small population of the total manufactured quantities of the capacitors can be tested. Even with a rigorous statistical model, the calculation has a significant degree of uncertainty due to the limited test data. The test data lacks sufficient accuracy to be used to establish an accurate MTBF (mean time between failures) and a reliability number for UPS systems. Replacing the bank of AC polymeric film capacitors and the bank of DC aluminum electrolytic capacitors before they age to the point where there is a significant probability for a capacitor short circuit, provides a much more reliable approach to insuring a long service life for the UPS system without encountering an uncontrolled down time for the UPS system.

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