Avoiding AC Capacitor Failures in Large UPS Systems

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Revision 2

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> Executive summary

Most AC power capacitor failures experienced in large uninterruptible power supply (UPS) systems are avoidable. Capacitor failures can give rise to UPS failure and in some cases can cause critical load drops on stand-alone and paralleled systems. AC capacitor failures have historically been ascribed to unavoidable random failure or supplier defect. However, recent advances in the science of capacitor reliability analysis show that capacitor failures can be controlled by system design. This paper explains AC capacitor failure mechanisms and demonstrates how UPS designers and specifiers can avoid most common AC capacitor failures and the associated consequences.

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Introduction

AC power capacitor failures have historically been the primary cause of UPS field failures. Even today, with improved capacitor manufacturing processes and capacitor quality, capacitors continue to cause UPS failures in some designs. In addition, AC capacitor failures have been known to create failure modes that cause unexpected and undesirable loss of redundancy or a critical load drop, even in fault tolerant or paralleled UPS installations. Therefore, it is imperative for the UPS designer to minimize the total number of predicted capacitor failure occurrences over the life of the system, as well as to develop a robust strategy to manage the power protection system whenever an internal failure event occurs.

The lifetime of a capacitor in service is statistically predictable and depends on the voltage, current, and temperature stresses it is subjected to. Therefore, the design of the UPS can and does have a dramatic impact on the frequency of capacitor failures. UPS designs vary significantly in the way that capacitors are utilized and stressed. Through understanding capacitor failure mechanisms, UPS designers and specifiers can predict lifetime with statistical models and even specify factors that will dramatically extend lifetime, by decreasing capacitor failure rate.

In this paper, the applications of power capacitors in UPSs are reviewed and then the capacitor failure mechanisms are outlined. Finally, guidance is provided regarding proper UPS specification for avoiding capacitor failures.

Applications of AC power capacitors in UPS

There are two principal applications of AC power capacitors employed in most UPSs today. AC capacitors using a wrapped metallized film construction are used for input and output filters as well as controlling power factor. A UPS may contain hundreds of AC and DC capacitors in various internal applications like snubbers and DC electrolytic capacitors. For the purposes of this paper, the discussion is restricted to the high power AC capacitor applications that have the most impact on system availability and the most serious consequences during failure. These applications are summarized in **Table 1**:

Table 1

Power capacitor applications

Power capacitor application	Purpose
AC input power capacitors	Input harmonic filtering and power factor control
AC output power capacitors	Output filtering of inverter switching frequency and harmonic distortion Supply reactive power to non-linear loads

Power capacitor failure mechanisms

Historically, there have been periods of elevated failure rates for power capacitors as used in both the input and output filters of UPSs. In the past, this failure rate was usually attributed to poor quality control in the dielectric or electrode materials, failure to eliminate all contaminants during construction or deficiency caused by a design omission. However, capacitor materials and construction have steadily improved over the years and production facilities have refined their internal processes. Well-documented and mature application performance information now enables the designer to optimize UPS designs for long capacitor life and minimum failure rates. Capacitor technology has advanced to the point where most power capacitor failures are avoidable by proper UPS design.

The definition of failure for a capacitor is simple: failure to meet the specified performance. However, for power capacitors, failure to meet specification frequently gives rise to dramatic consequences. **Table 2** shows the principal failures associated with power capacitors along with their consequences.

Table 2

Power capacitor failures

Failure	Application	Cause	Result	Prevention
Film dielectric breakdown	AC input or output filters	High operating voltage Over voltage and/or over temperature	Internal breakdown of capacitor leading to explosion and possible fire; hard short or open condition	Reduce voltage stress Reduce ambient temperature
Film termination failure	AC input or output filters	High peak current	Increase in series resistance resulting in localized heating leading to localized arching. This ultimately may lead to metallized film dielectric breakdown as described above.	Limit peak currents by design Proper capacitor application

The summary of **Table 2** shows that voltage, temperature, and current stresses are the drivers of capacitor failures. The design and manufacturing process for capacitors is now sufficiently mature that capacitor suppliers are able to create reliable mathematical models that can predict statistical failure rates under various voltage, temperature, and current stresses. These models can demonstrate that a correlation exists between high and low failures rates in the field. From the models come four core elements as shown in **Table 3**.

Table 3

Power capacitor failure rate models

Factor	Effect	Example of effect (typical UPS)
Temperature	Power capacitor lifetime is halved for every increase of 10 degrees C (18 degrees F) in case temperature. Case temperature is the temperature of the external capacitor casing. The temperature rise results from heating due to ac current. This relationship becomes inaccurate as temperature drops below 50 degrees C (122 degrees F).	Capacitor lifetime increases by a factor of 2 by decreasing the case temperature from 70 to 60 degrees C.
Voltage	Power capacitor lifetime varies with the n^{th} power of voltage when operated near the design value. Depending on the supplier this power can range from 7 to 9.4. This relationship is lost as the operating voltage drops below ½ of the design value.	For a 440V capacitor with a 6.8 μm film, lifetime increases by a factor of 17.3 for a 30% reduction in operating voltage.
Pulse current	As long as the peak current ratings are not exceeded, termination failure does not occur. As the capacitor is subjected to pulse currents, degradation of the current connection interfaces occurs until finally resulting in an open circuit or a catastrophic failure.	A capacitor will fail open after being struck about 1000 times with a pulse current, 200 times the name plate current rating.
Peak voltage	Unlike RMS voltage, peak voltages across a capacitor generally present themselves as high frequency spikes as a result of utility events or state changes in a UPS. These spikes damage the capacitor film and eventually lead to premature capacitor failure.	A peak AC voltage above 1.8 - 2.1 times the design AC voltage is the DC voltage equivalent that can lead a capacitor to fail short.

Table 3 shows that small changes in voltage stress have the largest affect on power capacitor lifetime when compared with other factors. Note that the steady state voltage across AC capacitors is completely independent of the UPS load and therefore, reducing the load on the UPS will not reduce the voltage stress on the capacitors. This may or may not be the case for transient voltages across the capacitor as it depends on the UPS design. Differences in

temperature and current stress for UPS designs have the potential to affect power capacitor lifetimes substantially as well, but their effects are less than when voltage stress is varied. **Figure 1** below shows a typical AC capacitor bank, also known as a capacitor rack.

Figure 1

UPS output AC capacitor bank

Preventing power capacitor failures

Robust UPS design minimizes UPS load drops due to AC capacitor failures. By analyzing why and how a capacitor fails, also known as physics of failure analysis, one can begin to understand how to extend the lifetime of its capacitors.

How do capacitors fail?

The film of an AC power capacitor acts to separate the positive and negative charge thus allowing the capacitor to store energy. As the voltage across the dielectric film increases so does the energy stored. The limit of the energy storage capability of a capacitor is reached when the voltage potential meets the dielectric withstand voltage of the film. When the dielectric withstand voltage of the film is exceeded (volts per micron of film thickness), the film no longer is able to support the applied voltage. Eventually the self-healing characteristics of the capacitor become ineffective and the capacitor shorts between line to line or line to neutral, depending on how the capacitor is connected in the particular UPS design. Furthermore, higher applied voltage causes the film to degrade and suffer reduced dielectric withstand voltage over time.

Temperature also plays a role in degrading the film over time, however, as described in a previous section, to a much lesser extent when compared to voltage.

There are two failure modes that can occur due to current. One is termination failure and the other is dielectric breakdown failure. If a capacitor is applied properly, termination failures are not likely. Nonetheless, current will increase temperature, which leads back to the effect of temperature on the dielectric.

The effects of voltage and temperature stress on the expected life of a specific capacitor can be computed using a mathematical model, which is provided by the capacitor manufacturer. A description and explanation of this model is provided in the **Appendix**.

The failure rate of AC power capacitors subject to any continual voltage and temperature stress is not zero, and therefore no UPS design can completely prevent power capacitor failure. However, a UPS design can prolong the life of a capacitor bank simply by reducing the voltage and temperature stress applied to the capacitors. **Figure 2** illustrates this by plotting the characteristic life against percent voltage de-rating. A characteristic life is defined as the point in time where 63.2% of the population fails. By operating capacitors at lower voltage and temperature stress, the typical lifetime of a capacitor bank can be greatly extended. Using capacitors with voltage ratings substantially higher than the nominal UPS operating voltage, and increasing the effective airflow that cools the capacitor bank are two UPS design parameters that can dramatically increase capacitor lifetime. However, voltage should be the primary concern given that capacitor lifetime is most sensitive to voltage and that the steady state voltage across a capacitor is completely independent of the UPS load. In actual UPS products available for purchase today, the design life of the AC power capacitors varies from 3 years to 15 years. Such variation has a substantial impact on the overall reliability of the power system because the consequences of capacitor failure can be a load drop, even in a redundant system.

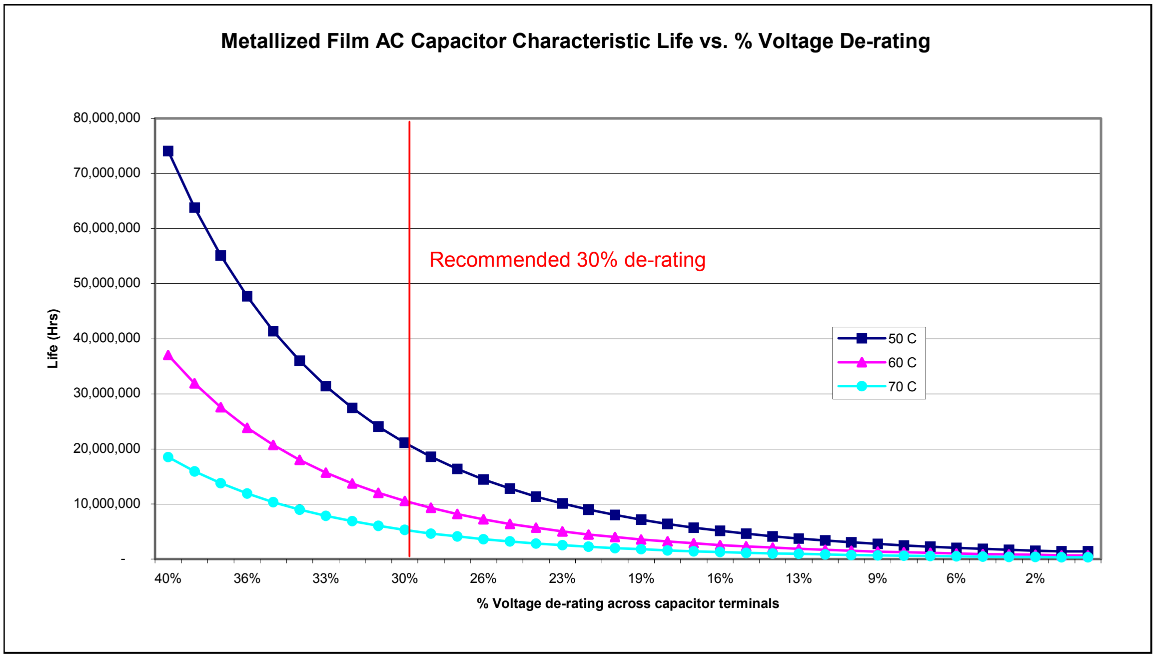

Figure 2

AC power capacitor characteristic life vs. % voltage de-rating

Example of UPS design variations affecting AC power capacitor timeline

The following example compares two actual similarly sized 3-phase UPS designs from two different manufacturers to show how the expected capacitor lifetime varies. In UPS design "A" the output capacitors are used in a line-to-neutral configuration while in UPS design "B" the output capacitors are used in a line-to-line configuration. Capacitor data for both UPSs was obtained from the capacitor labels. Both UPS designs share the same AC capacitor manufacturer. The voltage across the capacitors was determined by measurement of the actual UPS systems at half load. Temperature was kept constant for both units so as to compare only the effects of voltage de-rating. The lifetime effects are calculated using standard equations obtained from the capacitor manufacturer and described in **Appendix A**. The relevant data regarding the designs is summarized in **Table 4**:

Table 4

UPS capacitor design comparison

	UPS design A	UPS design B
Rated UPS power capacity	320 kVA / 320 kW	400 kVA / 320 kW
Year UPS was manufactured	2000	2000
Capacitance	56 F	92 F
Rated capacitor voltage	440 V	535 V
Rated capacitor temperature	70°C	70°C
UPS voltage applied to capacitor (measured)	277 V (Line to Neutral)	480 V (Line to Line)
Case temperature at steady state operation	60°C (Assumed)	60°C (Assumed)
Voltage scale factor	8	8
Temperature scale factor	2	2
ß (shape parameter)	1.6	1.6
Quantity of capacitors used in capacitor bank	24	18
Capacitor voltage de-rating factor	37%	10%
Characteristic lifetime per capacitor at rated conditions	350,000 Hrs	350,000 Hrs
Characteristic lifetime per capacitor at applied conditions	28,371,435 Hrs	1,667,241 Hrs
Capacitor bank mean time to fail (MTTF) at 20 years	15,637,178 Hrs	223,710 Hrs
Likelihood of capacitor bank failure at 20 year UPS life	0.70%	38.71%

Before discussing the results of this comparison it must be made clear that the results of each capacitor bank are based on statistical methods and calculations that result in some level of uncertainty. However, when comparing the relative differences between two or more capacitor banks, a much higher level of confidence can be placed on selecting the better design. It is assumed that for proper UPS operation, all the capacitors in its bank must be functioning properly.

The comparison shows that the expected lifetime of a capacitor bank in commercially available UPS can vary by approximately a factor of 60. This significantly affects the likelihood that a customer will experience a capacitor failure during the lifetime of the UPS.

Notice also that despite having six more capacitors, UPS Design "A" exhibits more than 55 times the capacitor reliability of UPS Design "B". This stems primarily from the 37% voltage de-rating factor.

To better understand how temperature affects capacitor lifetime, the comparison in **Table 5** holds the de-rating percentage constant but changes the temperature. The temperatures are purely assumed for the purpose of this comparison.

With percent de-rating held constant at 37%, this second comparison shows that the expected lifetime of a capacitor bank varies only by a factor of six compared to a factor of sixty when voltage de-rating is varied. This isn't to say that capacitor cooling shouldn't be a factor when evaluating one UPS over another. However, temperature has a second order effect on capacitor lifetime compared to voltage de-rating which has a first order effect.

Table 5

UPS capacitor design comparison with varying temperature

	UPS design A	UPS design B
Rated UPS power capacity	320 kVA / 320 kW	400 kVA / 320 kW
Year UPS was manufactured	2000	2000
Capacitance	56 F	92 F
Rated capacitor voltage	440 V	535 V
Rated capacitor temperature	70°C	70°C
UPS voltage applied to capacitor (measured)	277 V	337 V (Assumed)
Case temperature at steady state operation	50°C (Assumed)	70°C (Assumed)
Voltage scale factor	8	8
Temperature scale factor	2	2
ß (shape parameter)	1.6	1.6
Quantity of capacitors used in capacitor bank	24	18
Capacitor voltage de-rating factor	37%	37% (Assumed)
Characteristic lifetime per capacitor at rated conditions	350,000 Hrs	350,000 Hrs
Characteristic lifetime per capacitor at applied conditions	56,742,870 Hrs	14,185,717 Hrs
Capacitor bank mean time to fail (MTTF) at 20 years	47,403,061 Hrs	6,877,794 Hrs
Likelihood of capacitor bank failure at 20 year UPS life	0.23%	1.58%

Guidelines for designers and specifiers

UPS designers can extend power capacitor lifetimes through a conservative design approach. The design guidelines below are quantifiable, thereby allowing the UPS designer and specifier alike to easily make decisions regarding the reliability of a capacitor bank.

- De-rate AC capacitor voltage by at least 30% thereby increasing the characteristic life by a factor of 17.3. Voltage stress across the capacitor film is a similar method of de-rating. Capacitors should be subjected to less then 45 volts per micron of film thickness. Note that the steady state voltage across AC capacitors is completely independent of the UPS load. De-rating factors of greater than 30% rapidly increase UPS footprint and cost, making a 30% de-rating factor a good guideline value.
- Place the capacitor bank in a direct air stream – a drop of 10°C in case temperature will increase lifetime by a factor of 2.
- Limit all voltage and currents transients to the AC capacitor specification.

By following and specifying these design guidelines, the frequency of capacitor replacements may be lowered dramatically and even eliminated. Lowering the frequency of capacitor replacements has another added benefit. The process of capacitor replacement creates risks related to downtime. According to the Uptime Institute, over 50% of all data center infrastructure failures are human error related. Therefore, human factor design should play a large role in designing a UPS, especially with regard to servicing and maintaining it.

A UPS ought to have easily accessible, standardized, and modular components that decrease the probability of human error during service. Capacitor banks should be designed so that the service technician has sufficient room to work. They also should be easily accessible so as to avoid contact with any other UPS components. Ideally, capacitors would be contained in swappable pluggable modules that eliminate all wiring and fastening procedures during service.

Conclusion

When selecting or specifying a UPS, most users fail to specifically address the issue of AC power capacitor failure rate, despite the fact that such failures are historically a primary driver of UPS failure rates. The science of power capacitor reliability has advanced to the point where users can predict lifetime and even specify design parameters that will drastically increase capacitor reliability. A small increase in the percent safety margin between the capacitor rated voltage and the operating voltage results in very large changes in the expected lifetime of the capacitors. This parameter can be specified, or it can be compared when selecting a UPS. In addition to capacitor reliability, UPS specifiers should look for design characteristics that reduce human error through easily accessible, standardized, modular components.

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Victor Avelar is a Senior Research Analyst at Schneider Electric. He is responsible for data center design and operations research, and consults with clients on risk assessment and design practices to optimize the availability and efficiency of their data center environments. Victor holds a Bachelor's degree in Mechanical Engineering from Rensselaer Polytechnic Institute and an MBA from Babson College. He is a member of AFCOM and the American Society for Quality.

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References

1. Moynihan, John D., *Selection and Application of Capacitors*, Second Edition. Huntsville: Components Technology Institute, 1993, pp. 69-81.
2. Tortai, J. H., Denat, A., Bonifaci, N., *Self-healing of capacitors with metallized film technology: experimental observations and theoretical model*, Journal of Electrostatics, vol. 53, pp. 159-169, 2001.
3. Fuchang, L., Xin, D., Zonggan, Y., Nanyan, W., *On the Failure Mechanism of Metallized Pulse Capacitors*, 2000 Conference on Electrical Insulation and Dielectric Phenomena, Victoria, British Columbia, Canada, Oct 2000, pp. 592-595
4. Dodson, B., Nolan, D., *Reliability Engineering Handbook*, New York: Marcel Dekker, Inc., 1999, pp. 49-53, 141-142.
5. Dialogue between Dr. Martin Hudis at Aerovox, New Bedford, MA

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Appendix: Mathematical model for capacitor lifetime

After about 25 years of research, capacitor manufacturers have been able to accurately predict the expected lifetime of AC capacitors by using mathematical models. The accuracy of these models is validated by actual field data. The mathematical models discussed here are specific to film capacitors and are developed mainly by performing accelerated life testing on large quantities of capacitors. Since AC capacitors exhibit a failure rate that is not constant but increases with time, they are best modeled using the Weibull distribution given its ability to approximate time-varying failure rates. The reliability function for the Weibull distribution is:

Equation 1:

$$R(t) = \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right]$$

Where ***R(t)*** is the probability that a single capacitor will be operational after time *t*
$\boldsymbol{\theta}$ is the characteristic life of the capacitor in hours. Characteristic life is defined as the point in time where 63.2% of the population fails.

$\boldsymbol{\beta}$ is the shape parameter and is assumed to be independent of voltage or temperature therefore it remains constant

The 0 and b parameters are statistical variables that are dependant on varying

The hazard function, or instantaneous failure rate, for the Weibull distribution is:

Equation 2:

$$h(t) = \frac{\beta t^{(\beta-1)}}{\theta^{\beta}}$$

Where ***h(t)*** is the failure rate for a single capacitor at a time, *t*, in the capacitor's lifetime.

For this particular capacitor manufacturer, the parameter β is determined by accelerated life testing and field failure data and is found to be approximately 1.6 for typical AC metallized film capacitors. The parameter θ, the characteristic lifetime at steady state operating stress, is a function of the voltage and temperature stress on the capacitor as expressed in the following formula:

Equation 3:

$$\theta = Life\ At\ Name\ Plate\ Rating \times \left(\frac{Rated\ Cap\ Voltage}{UPS\ Applied\ Cap\ Voltage}\right)^{Vscale} \times 2^{\left(\frac{Rated\ Temp - Temp\ at\ steady\ state}{10}\right)}$$

Where ***Life At Name Plate Rating*** is characteristic life at the capacitor's rated voltage and temperature stress. This value varies with film thickness.

Vscale is the scaling factor assigned for voltage stress.

Rated Temp is the case temperature for which the capacitor is rated. Most capacitors of this type are rated at 70°C.

Temp at steady state is the steady state case temperature of the capacitor in the UPS application.

The calculations in **Tables 4** and **5** use a “Life At Name Plate Rating” value of 350,000 hours. Because capacitors are manufactured in batches, this value varies from batch to batch. The reasons for this variation stem from material and process variations such as film thickness, metallization, humidity, etc. Ultimately what matters is that AC power capacitors are extremely sensitive to steady state voltage and this sensitivity is entirely independent of the “Life At Name Plate Rating” value.

The voltage-scaling factor varies by capacitor manufacture and ranges from 7 to 9.4. It’s important to know that this scaling relationship for characteristic life becomes invalid for applied voltages that are less then ½ of the rated capacitor voltage. The temperature scaling relationship becomes inaccurate as the case temperature drops below 50°C (122°F)

To calculate the reliability of all the capacitors in the capacitor bank, given that all capacitors in the bank are required for normal operation, equation 4 may be used. This assumes that each capacitor is independent and no external failure mechanism occurs.

Equation 4:

$$R_{Bank}(t) = \prod_{i=1}^{Qnty\ Caps\ in\ bank} R_i = \left(R_{SingleCap}\right)^{Qnty\ Caps\ in\ bank}$$

Where $R_{SingleCap}$ is calculated by using Equation 1.

To calculate the failure rate of the entire capacitor bank, given that all capacitors in the bank are required for normal operation, equation 5 may be used. This again assumes that each capacitor is independent and no external failure mechanism occurs.

Equation 5:

$$h_{Bank}(t) = \sum_{i=1}^{Qnty\ Caps\ in\ bank} h_i = h_{SingleCap} \times Quantity\ of\ \ Caps\ in\ the\ bank$$

Where $h_{SingleCap}$ is calculated by using Equation 2.