Film Capacitor Thermal Strategies Increase Power Density

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Abstract

Polypropylene dielectric film capacitors of varying types are used in large power systems due to their low heat dissipation and inherent reliability. This paper examines the construction of these capacitors for power applications and compares their heat rise performance with respect to electrodes, terminals, form factors, and packaging. Thermal behavior is measured for the internal construction of the capacitors and packaging with respect to various external cooling methods including convection, conduction and liquid cooling. In addition, heat induced from eddy currents from electromagnetic interference in relation to the position of the capacitors will also be considered.

I. Introduction

Film capacitors have lower heat dissipation and longer life than capacitors of other dielectric types. Polypropylene dielectric is the most common dielectric used in power capacitors due to its constant dielectric loss factor for frequencies up to 1 MHz. Polypropylene film capacitors for power electronic applications have two basic construction types:

1. film with aluminum foil (FAF)
2. metallized film (MeF)

These two types of polypropylene capacitors are shown in Figures 1 and 2.

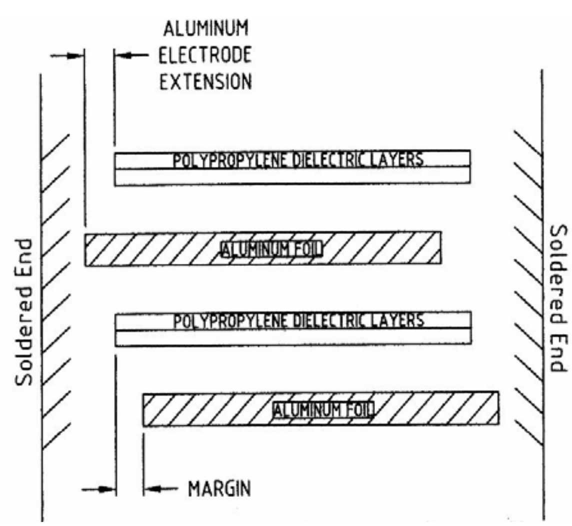

Figure 1: Schematic of an all film construction.

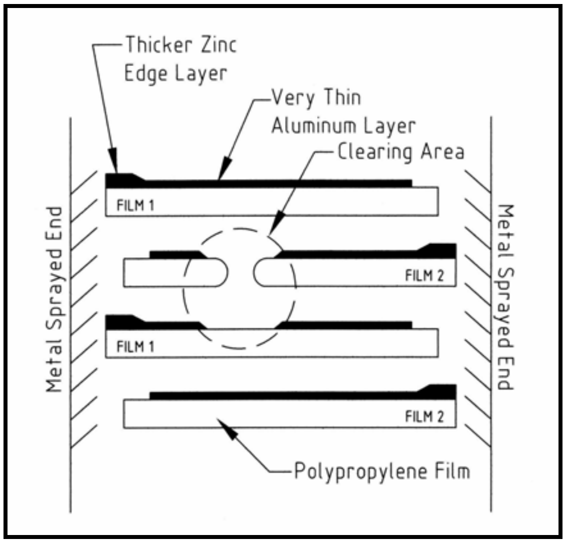

Figure 2: Metallized film capacitor schematic

FAF capacitors are typically oil-filled and packaged in a metal case. Most have a maximum continuous operating temperature of about 85º C. MeF capacitors have a high crystalline dielectric (which improves voltage and temperature stress capabilities[1]) and can be packaged in many types of metal and polymer cases. The MeF elements are usually surrounded by dielectric oils or electrically insulated resins. Depending upon the case type and the insulating media, these capacitors have a maximum continuous operating temperature of about 115º C.

Exposure to high temperature is a key aging factor for both FAF and MeF capacitors. Increases in internal temperatures must be considered to determine the likelihood of localized temperature hot spots that may lead to spatially preferential breakdowns[2]. These hot spots are generated by dielectric and ohmic losses caused by an externally applied electric field. Heat is absorbed due to proximity to other components and eddy currents related to capacitor position. Both internal and external heating sources shall be considered. A breakdown in FAF designs can lead to their short circuit failure; protective mechanisms such as fuses and pressure switches are often employed to guard against overpressure of their packages. With the more advanced MeF designs, segmented film or fuse patterns on the metallized film surface prevents any overpressure in the packages, and periodic self-healing events result in a small amount of capacitance reduction.

II. Heat Transfer Analysis

In both types of capacitors, controlling internal and external heating results in increased component life. In MeF construction, a hot spot will change the slope of the capacitance loss curve. In the case of segmented MeF construction, a typical specification may be a capacitance loss of less than 2% after 100,000 hours of operation at a maximum hot spot of 70º C. Test data has shown that component lifetime drops in half for every 10º C temperature increase.

The hot spot for an FAF or MeF capacitor can be calculated using equations (1) to (3) below[3].

$$\theta_{HS} = \theta_{amb} + (P_d + P_t) \cdot R_{th} \qquad (1)$$

$$P_d = [\ \tfrac{1}{2} \cdot C_n \cdot (V_{Ripple})^2 \cdot f\ ] \cdot (2 \times 10^{-4}) \qquad (2)$$

$$P_t = R_s \cdot I^2_{rms} \qquad (3)$$

Where:

$\boldsymbol{\theta_{HS}}$ is the hot spot temperature [ºC]
$\boldsymbol{\theta_{amb}}$ is the ambient temperature [ºC]
$\mathbf{P_d}$ represents the dielectric losses [W]
$\mathbf{P_t}$ represents the thermal losses [W]
$\mathbf{R_{th}}$ is the thermal resistance [ºC/W]

$\mathbf{C_n}$ is the nominal value of the capacitance [F]
$\mathbf{V_{Ripple}}$ is the peak to peak ripple voltage [V]
f is the voltage working ripple frequency [Hz]
$\mathbf{R_s}$ is the equivalent series resistance or ESR [Ω]
$\mathbf{I^2_{rms}}$ is the rms current value for continuous operation [A].

Due to the very small dissipation factor for polypropylene (> 5×10^{-4}), the total dielectric loss factor P_d does not change for a given set of externally applied electric conditions on either capacitor type. The non-dielectric losses, or P_t, are manipulated in capacitor design by reducing the equivalent series resistance (ESR). Lowering ESR is accomplished by selecting proper conductor and terminal materials and optimizing geometry.

Heat is easily conducted along the aluminum foil and metallized layers in both capacitor types. However, heat will not radiate nor conduct through the polypropylene dielectric due to its much lower thermal conductivity. It also follows that the shorter the distance that the heat must travel, the lower the heat rise. Therefore a capacitor design with short electrodes will have lower heat rise than one with longer electrodes, assuming the other parameters are equal.

Table 1 shows the thermal conductivity for various materials typically used in film capacitor manufacturing. Due to the fact that the primary material for thermal conduction out of the film capacitor elements shown in Figures 1 and 2 is aluminum, a comparison between aluminum and the other materials was calculated. The thermal conductivity of zinc is included since this is the primary material used in the metal spray and zinc reinforcement on the edge of the film for MeF construction. It can be seen that the thermal conductivity of copper is about twice that of aluminum and the polypropylene dielectric has .07% of the thermal conductivity of the aluminum. The equation used to express heat transfer is known as **Fourier's Law,** expressed in equation (4)

where:

q is the heat transferred per unit time [W]
A is the heat transfer area [m^2]
k is the thermal conductivity of the material [W/m·K]
dT is the temperature difference across the material [K or ºC]
s is the material thickness [m].

$$q = (k\ A\ dT)/s \qquad (4)$$

Table 1. Thermal Conductivity (k) values for materials used in Film Capacitor Manufacturing (W/m·K)

Material:	Cu	Al	Zinc	Solder	Steel	Epoxy	G10/FR4	Oil	Polypropylene
Grade :	C110	3003	N/A	60%Sn, 40%Pb	304L	Silica Filled	N/A	Canola	N/A
Value (k):	401	237	112	56.6	16.2	0.35	0.27	0.19	0.16
Versus Alum.	169%	100%	47%	24%	7%	0.15%	0.11%	0.08%	0.07%

III. Thermal Studies of Capacitors

NWL produces FAF capacitors up to 6000 KVar (Kilo-volt-amp) and MeF capacitors up to 3500 amps (rms). Capacitors used at these power levels require active cooling. Figure 3 shows a water cooled metal case all film AC capacitor, and Figure 4 shows a water cooled, dry resin sealed metallized polypropylene DC capacitor.

Figure 3: All polypropylene film water cooled oil filled AC capacitor.

Figure 4: Metallized polypropylene water cooled synthetic polyurethane filled DC capacitor.

Water-cooled, high-power film capacitors are used in induction heating and high technology materials processing because of the very high output currents that are generated. This increased output current in an induction heating system impresses high voltage on the resonant capacitors which are the all film type and can cause dielectric failure as well as excessive heat loading of the capacitors[5].

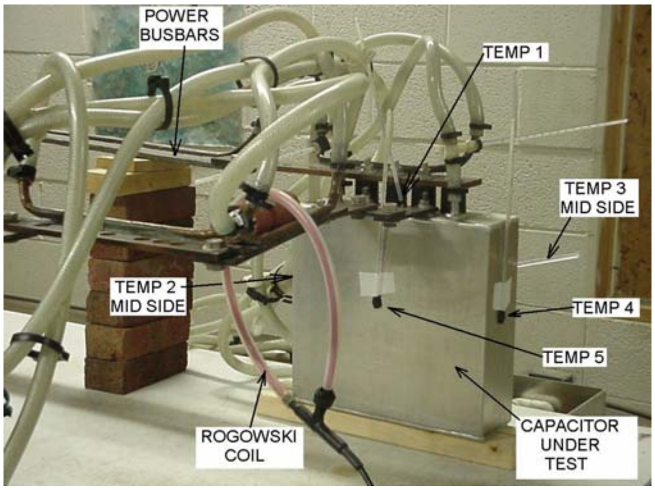

Figure 5: H_2O cooled AC capacitor power test set-up.

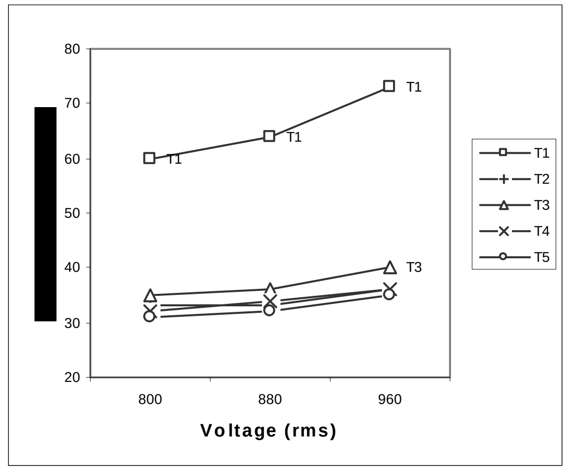

Figure 6: Power test measured Tº C vs. applied $V_{rms.}$

NWL performs power testing on both FAF and MeF. Operating conditions are simulated with ripple frequencies and resonant circuit frequencies between 60 Hz and 0.5 MHz. This is done in order to verify that the actual thermal measurements are within range of the calculated values. A test of this type is shown in Figure 5. The capacitor under test is an FAF oil-filled AC type with a measured capacitance of 81.3 µF, a nominal voltage of 800 V_{rms}, and operating frequency of 3 KHz. This water cooled capacitor is connected to a Pillar 200 kW power supply in a parallel resonant circuit by the power busbars shown. Thermometers were affixed to 5 locations on the capacitor case as shown. **Temp 1** is the cover where all the internal conductors connect to the terminal studs that are insulated from the cover by molded plastic insulators, **Temps 2** and **4** are opposite narrow ends of the capacitor can and **Temps 3** and **5** are on opposite large sides of the capacitor can.

The power test shown was run by starting at the nominal voltage of 800 V_{rms} at 3 KHz and ambient temperature of 21ºC and waiting for thermal equilibrium, which was 2 hours. The temperatures at each location were recorded. The voltage was increased to 880 V_{rms} and then to 960 V_{rms}. The temperatures were recorded after equilibrium was reached at each new voltage level. During the testing, a Rogowski coil was used to measure the actual current seen by the capacitor which was 1223.3, 1345.6 and 1467.9 amps respectively for the three test levels.

The temperature measurements for the power test are shown in Figure 6 with respect to the three voltage levels. The temperature measurement of interest was 880 V_{rms} which is a 10% increase in voltage. This represents a 21% increase in reactive power (KVar), which is seen experimentally in the increase in voltage ratio (880/800) multiplied by the current ratio (1345.6/1223.3). The highest temperature measurement at 880 VAC was 64º C for **Temp 1** on the capacitor cover. The second highest measurement at 880 VAC was 36ºC at **Temp 3**. The temperatures at the other three test points were very similar (between 32 and 33ºC). This same type of testing was performed on six capacitors of the same design with very similar results, including the hot spots for the covers measuring between 63ºC and 67ºC.

The **Temp 1** measurement is expected, due to the high thermal conductivity of the thin copper tabs leading to the terminals. The consistently higher readings at **Temp 3** compared to the other surfaces are a consequence of the capacitor design. The wound film with aluminum foil elements internal to the capacitor are oriented with the soldered surfaces per Figure 1 parallel to the large sides. The capacitor case ends are separated from the metallic conductors by multiple layers of the wound polypropylene and additional insulation, accounting for the low **Temp 2** and **Temp 4** values. The cooling coil is a copper tube that is parallel to the face where the **Temp 5** measurement was taken; better heat transfer in this region accounts for the lower temperature compared to **Temp 3**.

Conclusion

Theories have been presented for how heat is generated and is removed from film capacitors of both the all film with aluminum foil (FAF) and the metallized film (MeF) construction. It has been demonstrated that conduction is the main mechanism for removal of heat from the capacitor package and the main path for removal is parallel to the aluminum or metallized electrodes where it is conducted to what is typically a solder connection for the all film design and a zinc metal spray for the metallized film designs. As power systems come with increased packaged density and other components are water cooled, the use of a water cooled capacitor design for the higher power systems should become increasingly more common.

References

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