Film Capacitor Thermal Strategies Increase Power Density

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Abstract

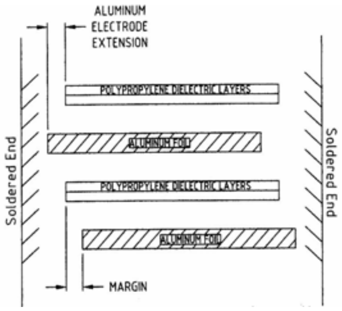
Capacitors with film and metallized film dielectrics are employed in many large power systems due to their relatively low heat dissipation and inherent reliability. This paper examines the construction of various large polypropylene dielectric film capacitors for power applications and compares their heat rise performance with respect to electrodes, terminals, form factors and packaging techniques. Thermal behavior is considered for the internal construction of the capacitors, and their packages with regards to various external cooling methods including convection, conduction and liquid cooling. Also considered is heating induced from eddy currents from electromagnetic interference in relation to the position of the capacitors.

I. Introduction

Film capacitors are known to 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 it having a constant dielectric loss factor, irrespective of temperature and frequency up to 1 Mhz. Polypropylene film capacitors for power and power electronic applications have two basic construction types, all film with aluminum foil and metallized film. These two types of polypropylene capacitors are depicted in Figures 1 and 2 respectively.

The all polypropylene film with aluminum foil electrode capacitors are typically oil impregnated with a synthetic oil and packaged in a metal case. The most common types of all film capacitors have a maximum continuous temperature capabilities approaching 85ºC. Metallized polypropylene capacitors of the most recent generation have a dielectric designated as high crystalline which increases the voltage and temperature stress capabilities [1]. Metallized polypropylene capacitors can be packaged in many types of metal and polymer case types. The metallized polypropylene film elements are usually surrounded by dielectric oils or electrically insulating resins. Depending upon the case type and the insulating media, metallized high crystalline polypropylene capacitors have maximum continuous temperature capabilities of approximately 115ºC.

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



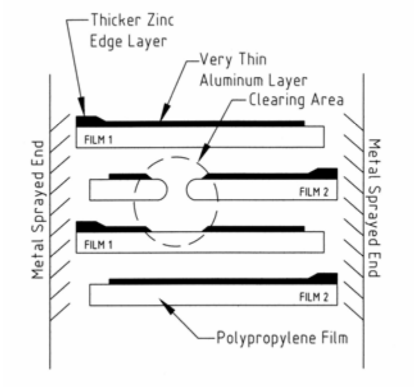


Figure 1: Schematic of an all film construction. **Figure 2:** Metallized film capacitor schematic

II. Heat Transfer Analysis

In both types of capacitors, the control of internal and external heating produces increased lifetimes. With the all film with aluminum foil construction, this understanding will be increase the time before the capacitor fails and needs replacement if the failure is before the system end of life. With the metallized polypropylene film construction the slope of the capacitance loss curve will change depending upon the capacitor hot spot. In the case of the segmented metallized polypropylene 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 70ºC. Test data has shown this life relationship to be approximately half the life for both design types for every 10ºC. However, as a design approaches its maximum temperature capability the life relationship is more pronounced such as half the life for every 8ºC.

The hot spot for an all film with aluminum foil polypropylene capacitor or a metallized polypropylene capacitor can be calculated using equations (1) to (3) below [3].

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

$$P_d = [\, ½ \cdot C_n \cdot (V_{Ripple})^2 \cdot f \,] \cdot (2 \text{ x } 10^{-4}) \tag{2}$$

$$P_t = R_s \cdot I^2_{rms} \tag{3}$$

Where θ_{HS} is the hot spot temperature (the highest temperature obtained inside the case of the capacitor in thermal equilibrium) [ºC], θ_{amb} is the ambient temperature [ºC], P_d represents the dielectric losses [W], P_t represents the thermal losses [W], R_{th} is the thermal resistance [ºC/W], C_n is the nominal value of the capacitance [F], V_{Ripple} is the peak to peak ripple voltage [V], *f* is the voltage working ripple frequency [Hz], R_s is the equivalent series resistance or ESR [Ω] and I^2_{rms} is the rms current value for continuous operation [A].

Due to the dielectric loss factor for polypropylene of 2 x 10^{-4} being constant with temperature and with frequency (up to 1 Mhz), the total dielectric loss factor P_d does not change for a given set of externally applied electric conditions on either polypropylene capacitor type. The non-dielectric losses or P_t are manipulated in capacitor design by reducing the equivalent series resistance (ESR). This reduction in ESR is accomplished by selection of the conductor and terminal materials and also by the capacitor geometry.

A major factor relating heat rise to capacitor geometry is that heat is easily conducted along the path of the aluminum foil conductors and metallization on the polypropylene parallel to their path. However, heat can not be easily transferred by radiation or conduction thru the polypropylene dielectric due to the much lower thermal conductivity of the film versus the conductors [2,4]. It also follows that the shorter the distance that the heat must travel, the lower the heat rise. Therefore a capacitor design with shorter electrodes will usually have lower heat rise than one with longer electrodes with the capacitance and the electrode composition being 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 relationship between aluminum and all 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 the metallized polypropylene 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** as 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] and s is the material thickness [m].

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

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

Material:	Cu	Alum.	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%

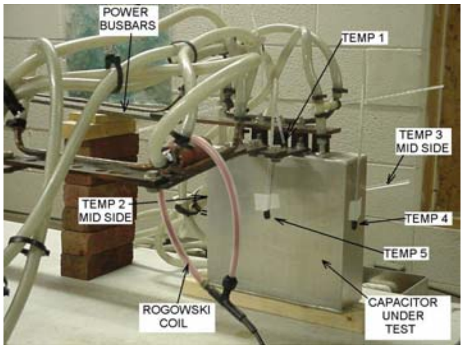
III. Thermal Studies of Capacitors

NWL produces polypropylene film with aluminum foil and metallized polypropylene capacitors of many types for power and power electronic applications. These include all film capacitors up to 6000 KVar (Kilo-volt-amp) and metallized polypropylene capacitors up to 3500 amps (rms). Capacitors used at these power levels can not rely on normal cooling methods alone and have water cooling tubes installed. 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 synthetic oil filled AC capacitor.

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

The high power film capacitors with water cooling are used in such applications as the DC filter capacitors and the resonant capacitors in induction heating and high technology materials processing. As a method for increasing power in an induction heating system, the converter output current is increased. 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].



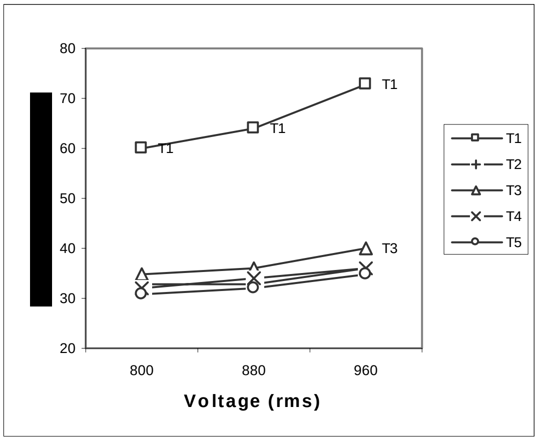


Figure 5: Water cooled AC capacitor power test set-up. **Figure 6:** Power test measured TºC vs applied $V_{rms.}$

NWL performs power testing on various capacitors of the all polypropylene film with aluminum foil and metallized polypropylene types. Operating conditions are simulated with ripple frequencies and resonant circuit frequencies between 60 Hz and approximately 0.5 Mhz. This is done in order to verify that the actual achieved heat 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 all film with aluminum foil oil filled AC type with a measured capacitance of 81.3 µF, with a nominal voltage of 800 Vrms and operating frequency of 3 Khz. This water cooled capacitor is connected to a Pillar 200 Kw power supply in a parallel resonant with 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 3 are on opposite large faces of the capacitor can.

The power test shown was run by starting at the nominal voltage of 800 Vrms at 3 Khz and an ambient temperature of 21ºC and waiting for thermal equilibrium which in this case was 2 hours. The temperatures at each location was recorded and then the temperature was increased 10% of the rating to 880 Vrms and an additional 10% to 960 Vrms and the temperatures were recorded after equilibrium was reached at each level which again was 2 hours. 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 main voltage level for temperature measurement of interest was 880 Vrms which was a 10% acceleration factor for voltage providing a safety margin quality factor for the capacitor. The 10% increase in voltage 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). It can be observed that the highest temperature measurement at 880 Vac was 64ºC or a 43ºC rise for Temp 1 on the capacitor cover. It can also be seen that the second highest measurement at 880 Vac was Temp 3 on one of the large faces of 36ºC or a 15ºC rise. The other three locations at 880 Vac were very similar between 32 and 33ºC measured. 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 higher temperature (Temp 1) can be understood by the discussed thermal conductivity relationships whereas the lowest thermal resistance is the internal conductors leading to the terminals, which in this design are multiple thin copper tabs. The consistently higher temperatures seen on one large face (Temp 3) with respect to the three remaining locations, 2, 4 and 5 can also be understood by the conduction theory and Figures 1 and 5. In this 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 faces which are measured by thermometers 3 and 5 respectively. The capacitor case ends are separated from the metallic conductors by multiple layers of the wound polypropylene and additional insulation which are very good thermal insulators which accounts for the Temp 2 and Temp 4 values. The cooling coil is a copper tube that is parallel to the face where the Therm 5 measurement is taken so its lower temperature value with respect to the similar geometry face, Temp 3 can be understood.

Conclusion

Theories have been presented for how heat is generated and is removed from film capacitors of both the all film with aluminum foil electrode construction and the metallized polypropylene film 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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