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HIGH-SPECIFIC-POWER CAPACITORS

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Abstract - **Energy density is not the only metric for capacitors. In high pulse repetition rate modulators and other types of power conditioning systems, the reactive power (kVAR) is often the factor driving the physical size of capacitors. The specific power (kVAR/cm^3) capability of a capacitor depends on many factors, including frequency, voltage, waveform, duty cycle, ambient temperature, and available cooling. The design of capacitors for high specific power requirements will be described. Designs using high-temperature polymer films as dielectrics and metallized electrodes will be compared to designs using common dielectrics such as polypropylene and both metallized and discrete foil electrodes.**

I. INTRODUCTION

In high-average-power electrical systems, capacitor size is determined by specific power (kVAR/cm^3) capabilities of the specific type of capacitor being used. The type of capacitor selected is generally determined by the voltage, frequency, and the value of capacitance. Requirements for large capacitance values (10E-07 F to 10E-01 F) operating at hundreds to thousands of volts at high average power are usually satisfied with polymer-film capacitors. Smaller capacitance values are usually achieved with ceramic-dielectric capacitors, and very small capacitance values, with gas-dielectric capacitors. This paper will focus on wound polymer-film capacitors for high-average-power applications.

Thermal models of three different designs for an 8.0 μF, 3100 V, 75 A_{rms}, 232 kVAR, 0.48 kVAR/cm^3 snubber capacitor will be presented. The first design is an extended-foil style with a three-layer dielectric. This design, built for a customer application, is shown in Fig. 1 and Fig. 2. The second is a metallized-film design with three series-connected capacitances within the winding, as depicted in Fig. 3. The third is a hybrid design with two series-connected capacitances within the winding, extended foils for the terminated electrodes, a floating-potential metallized electrode, and a two-layer dielectric. This design is shown in Fig. 4. All three designs use polypropylene film for the dielectric. The metallized-film design and the hybrid design are nominally self-healing, while the extended-foil design is not. The three different designs were constrained to fit into the exact same volume and meet the same performance criteria, and the results of the thermal modeling clearly indicate that the metallized-film design will rapidly overheat and fail due to poor thermal conductivity.

II. ESR AND SELF-HEATING

Inevitably, high average power leads to significant self-heating of the capacitor. The Equivalent Series Resistance (ESR) of a capacitor is used to determine the total power dissipated for a given RMS current. The ESR comprises all forms of energy loss within the capacitor, and as such it is in general dependent on temperature, frequency, voltage, and even the history of the individual device [1]. In most capacitors designed for high average power, however, the only losses of significance are the dielectric loss and the ohmic resistance in the electrodes and other conductors.

The dielectric loss depends on the material selected and the specific temperature and frequency. It is usually expressed in terms of the dimensionless parameter DF (dissipation factor) or tangent (d), where d is the defect angle, since it is independent of the capacitance value or voltage rating (or dielectric thickness). Low-loss polymers such as polypropylene (PP) and polytetrafluoroethylene (PTFE) have DF values of order 10E-05 to 10E-04, which makes them common choices for high-average-power capacitors. Other plastics used as capacitor dielectrics, such as polyethylene terephthalate (PET, aka PETE) and polyethylene naphthalate (PEN) polyesters and polyimide, have DF values of order 10E-03 to 10E-02.

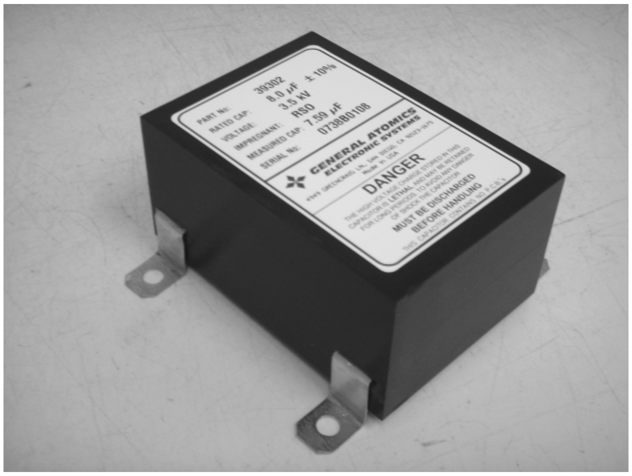

Fig. 1. Integrated Gate Bipolar Transistor (IGBT) Snubber Capacitor.

Ohmic resistance in metallic conductors and large-area electrodes is largely dependent on the style of capacitor. Many different configurations are used by different manufacturers. The lowest resistance values are achieved with extended-foil construction, using discrete aluminum-foil electrodes. However, manufacturers and users generally prefer self-healing capacitors, and a number of configurations using metallized dielectric films or separate metallized non-dielectric substrates may be used to achieve this. The metallized electrode surface resistivity is kept as low as possible while still providing the self-healing effect [2], but this resistance is still three to four orders of magnitude higher than that of the thinnest discrete aluminum foil. The current density in metallized electrodes is quite high, as seen in Fig. 5, where we have used the bulk conductivity of aluminum to approximate the thickness of the metallization of a known surface resistivity. In order to minimize the ohmic resistance in these designs, the width of the winding, which corresponds to the current path length, is minimized. An important design trade-off here is that the fraction of the winding volume that is contributing to the capacitance decreases rapidly as the material width decreases, due to fixed edge-margin and inner-margin dimensions required to avoid surface flashover.

Table 1 shows the calculated DF at 120 Hz and ESR at 8500 Hz (the nominal operating frequency) for the three winding designs modeled for this study. Fig. 6 and Fig. 7 show the watts of heat generated per cubic centimeter in the Metallized-Film design as a function of position along the z-axis. Fig. 6 shows the heating in the metallization alone, while Fig. 7 shows the heating in the dielectric and the total heat from all sources averaged over the total thickness of a winding layer.

TABLE 1
CALCULATED DF VALUES

Winding style	DF @ 120 Hz	ESR (ohms) @ 8500 Hz
Extended foil	0.00030	0.015
Metallized film	0.00124	0.206
Hybrid (extended foil / metallized film)	0.00109	0.181

III. HEAT CONDUCTION

Polymer capacitor dielectrics are not only excellent electrical insulators but also generally excellent thermal insulators. Heat removal from the windings is difficult, and actually depends mostly on the metal electrodes, even in metallized-film designs. The thermal conductivity parallel to the electrodes (parallel to the axis of winding, which we will refer to as the z-axis), is much greater than that in the radial direction. This can be seen in Table 2, which presents the calculated thermal conductivities (K) in the axial and radial directions and their ratio for the three winding designs being compared. Even the metallized-film design has five times greater conductivity along the plane of the electrode than in the radial direction. Also note that the hybrid design has about the same thermal conductivity in both directions as the extended-foil design.

TABLE 2
CALCULATED K VALUES

Winding style	K parallel to z-axis (W/ºK/cm)	K perpendicular to z-axis (W/ºK/cm)	Ratio
Extended foil	0.389	0.00142	274
Metallized film	0.00637	0.00117	5.43
Hybrid (extended foil / metallized film)	0.396	0.00142	278

Table 3 shows the calculated self-heating and resulting hot-spot temperature rise for each of the three winding designs. Fig. 8 shows the predicted temperature rise as a function of position for the metallized-film design. The metallized-film design is thus predicted to fail long before reaching thermal equilibrium since polypropylene will not survive such high temperatures. The hybrid design is actually quite resistive due to the metallized electrode used in this design, yet the presence of the metal foils is sufficient to reduce the hot-spot temperature rise to an acceptable value.

Table 3 also lists the dielectric stress (volts/micron) for each of the designs. These stress values are compatible with long-life capacitors as long as the hot-spot temperature is within normal limits. For the metallized-film design, the RMS current rating would have to be decreased from 75 amps to between 15 amps and 20 amps to avoid overheating.

Using the thermal model for the extended-foil winding design, the effect on the peak hot-spot temperature of varying parameters such as DF, film width, foil thickness, etc. was investigated while the total winding volume was held constant. The temperature rise depended linearly on the dielectric DF and on the square of the film width, and was inversely proportional to the foil thickness.

The model presented here is incomplete with respect to capacitor design and predictions of total hot-spot temperatures, as thermal impedances outside the windings themselves have been completely neglected. These aspects of capacitor thermal design, however, are common to the types of windings being compared here, and could be safely ignored for the purpose of this study.

TABLE 3
CALCULATED SELF-HEATING VALUES AND HOT-SPOT TEMPERATURE RISES

Winding style	Stress (V/μm)	Heat (watts)	Δ T Hot Spot (ºC)
Extended foil	152	84.4	0.747
Metallized film	172	1160	573 (FAIL)
Hybrid (extended foil / metallized film)	155	1020	9.85

IV. HIGH-TEMPERATURE POLYMER DIELECTRICS

The use of polymer-film dielectrics other than polypropylene is required for high-average-power capacitor dielectrics for applications where the ambient temperature is higher than about 100 ºC. One such material is polyimide, having a relative permittivity of 3.4 and a DF of 0.0018 at 1 kHz. Using this material in an extended-foil design for the same 8.0 µF 3100 V requirement, the higher permittivity of polyimide permits the use of both a thicker dielectric and thicker aluminum foils while maintaining the same total volume. The peak temperature rise was calculated to be 4.1 ºC with 643 watts of heat dissipated. In the case of the hybrid design, the thickness of the dielectric was increased, but not the foil, and the peak temperature rise was calculated to be 14.5 ºC. It remains to be seen whether a polyimide dielectric capacitor of either of these designs would have the dielectric strength and longevity to survive for many years of continuous duty at high temperatures.

Ideally, high-temperature dielectrics for high-average-power applications would have low losses like polypropylene. One such material is PTFE, which has a relative permittivity of 1.9 and a DF of 0.00008. Unfortunately the manufacture of thin films of this material is difficult, and the resulting breakdown strength is relatively low. A range of other high-temperature polymer films is available, including polyphenylene sulfide (PPS) and PEN, which are being used as capacitor dielectrics today, especially in small multilayer “chip” capacitors. In general these plastics are quite expensive compared to polypropylene due to relatively low production volumes, and the film and capacitor manufacturing technologies are not yet as mature as those for polypropylene and PET films.

V. CONCLUSION

High-average-power capacitors constructed using extended-foil or hybrid-electrode winding designs will have low hot-spot temperature rises compared to purely metallized-film designs, regardless of the specific dielectric films used. Hybrid designs are attractive because they can provide the benefit of self-healing while also providing excellent thermal conductivity.

ACKNOWLEDGMENTS

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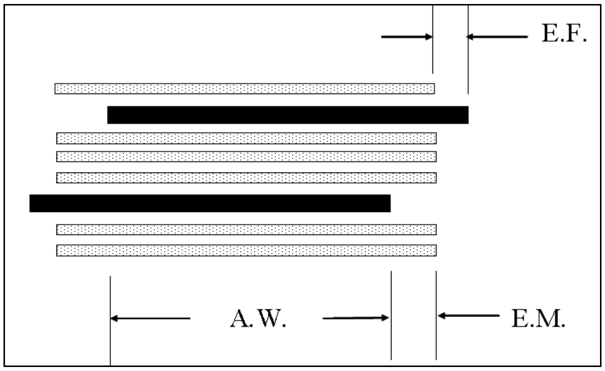

Fig. 2. Extended-Foil Design.
A.W. = active width, E.F. = extended foil,
E.M. = edge margin

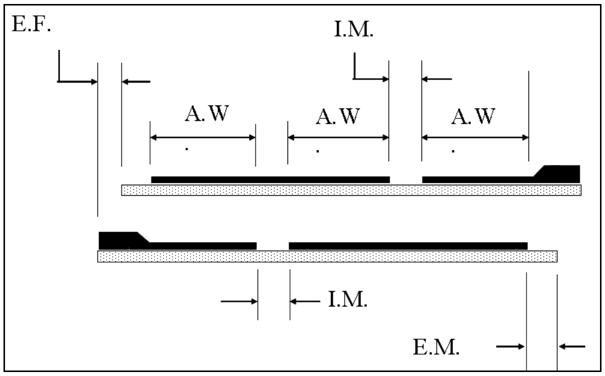

Fig. 3. Metallized–Film design - 3 Series Section design.
I.M. = inner margin.

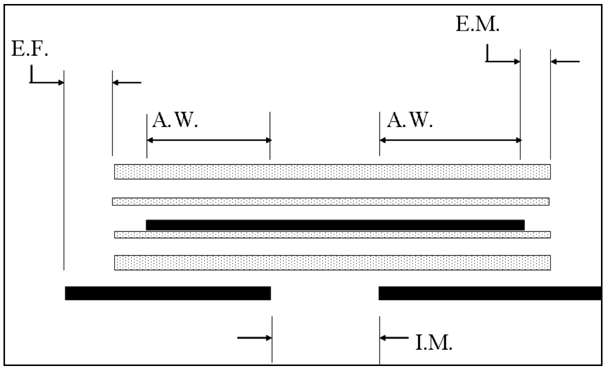

Fig. 4. Hybrid-Electrode design.

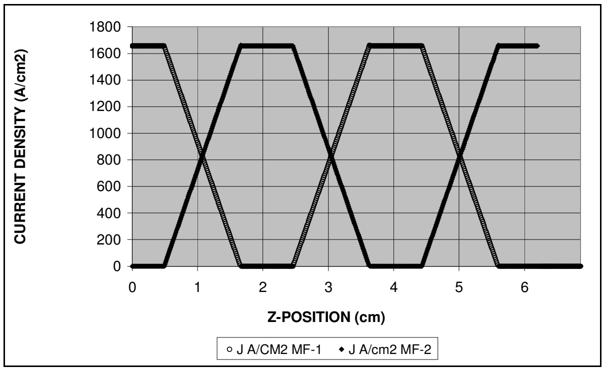

Fig. 5. Current density in Metallized-Film design - 3 Series Section design.

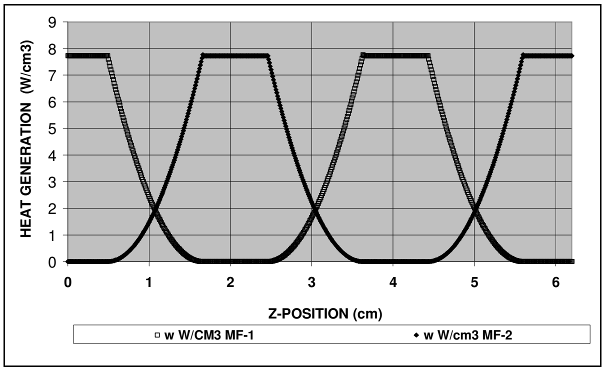

Fig. 6. Heat generated in the electrodes as a function of position in the Metallized-Film design.

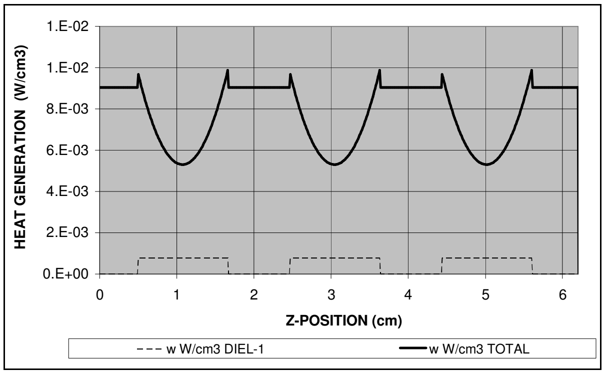

Fig. 7. Heat generated in the dielectric, and the total heat from all sources, as a function of position, in the Metallized-Film design.

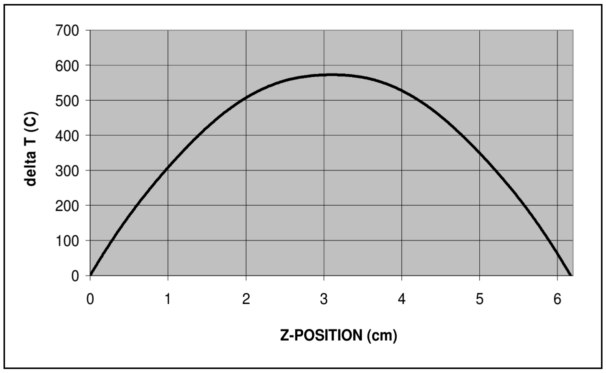

Fig. 8. Predicted temperature rise as a function of position along the z-axis in the Metallized-Film design.