TECHNICAL PAPER IV

This paper will explain why the Motor Run Capacitors are a mature technology but not a commodity. Critical differences can exist for motor run capacitors from supplier to supplier even enough they are of the same rating and case size.

Motor Run Capacitors are not a commodity

NG
RELIABLE CAPACITORS

NUEVA GENERACION MANUFACTURAS, S.A. DE C.V.			
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1. Introduction

Metallized film motor run capacitors are a mature product but this is not as saying it is a commodity. Mature product statuses result from relatively stable technologies and a commodity is viewed as a "class of components for which there is a demand but which is supplied without differentiation across a market".

A characteristic of a commodity is availability from many suppliers without any significant physical or performance differentiation. While the physical look of a motor run capacitor is consistent across a market, the performance of the capacitor can vary greatly. The consistent physical look of the capacitor comes from industry standards~~,~~ which have worked for years to establish and drive the industry into fixed sizes and similar packages[1]. A capacitor from different suppliers may look the same but they rarely perform the same.

Base materials, like dielectric grade polymeric resin, and dedicated manufacturing equipment, like large metallizers and clearing machines, used in the metallized film capacitor industry come from a small set of large worldwide suppliers and can be very similar. In spite of the similarity, technology differences in metallized film capacitors almost always exist from supplier to supplier. The differences come from design and process differences~~,~~ which exist from capacitor supplier to capacitor supplier. Examples of some of the differences are referenced below:

- Processing of the dielectric grade resin into thin dielectric grade film.
- Contamination control for metallic materials used in the metallization process which is normally Zinc and/or Aluminum.
- Differences between metallization profiles. The metallization coatings are very thin but major differences still exist.
- Composition and process differences in the dielectric potting materials, like polyurethanes and epoxies plus many different fillers.
- Design and use of plastic insulation parts within the capacitor.
- Composition and processing of dielectric fluids, usually vegetable based. Today's fluids, all of which use some additives like epoxides, desiccants or aromatic hydrocarbons all require processing for dying and degassing.
- Control and settings of the winding machines

Design and processing information for capacitor manufacturers are internally developed, evolve over years, and are a combination of science and art. This information is carefully protected and is not taught in universities (basic tools are of course taught). The processing and design of metallized film capacitors has a large impact on the aging and performance of the metallized film capacitor.

Reviewing the data sheets~~,~~ from different suppliers can reveal some major performance differences in motor run capacitors even though they have similar appearance. A few specific examples are shown below:

- A safety listing is not required for motor run capacitors. Under IEC 60252-1, listing for a P-2 motor run capacitor requires an interrupter system (Can be either pressure interrupter or segmented film) ensuring the capacitor fails in an open condition in the event of a capacitor failure. Other~~s~~ capacitors, listed as P0 or P1, may or may not fail in an open condition
- In the case of UL and CSA listed capacitors, some are listed with a safety rating while others are listed with a construction only rating. Both listings (construction and safety) show a CUL logo on the capacitor label and only careful reading of the label will tell you if it is safety listed or construction only listed.
- Endurance listings, under the IEC standard 60252, can be for ~~a~~ 1,000 Hrs, 3,000 Hrs, 5,000 Hrs, 10,000 Hrs and in some cases 30,000 Hrs ratings. The reliability

[1] EIA-456A, IEC 60252-1, UL 810 and C22.2 No. 190 as examples

performance of capacitors with different endurance ratings is very different.
- Maximum and minimum temperature ratings can be different as well. For example common low temperature ratings can be -55°C, -40°C or -25°C while common high temperature ratings can be 70°C, 85°C or 90°C.
- Damp heat ratings can also be very different from supplier to supplier. Some motor run capacitors have a damp heat rating while others do not. Those that do have a damp heat rating are almost always tested under different test conditions. A few of the different test conditions could be: with or without applied voltage, damp heat soak or damp heat cycling, temperature and relative humidity values and the length of test time. In addition, much of the damp heat critical information is often not provided on the motor run data sheet.
- Reliability and endurance are not the same performance characteristic and are often confused. Endurance has to do with the expected or useful life for the capacitor and is often referred to as MTBF (mean time between failures). Reliability is a rating which defines the max failure rate under a specific set of conditions for a specific operating time.

Motor run capacitors today are certainly a mature product. The motor run capacitor size and basic technology description has not changed much in over 30 years. A lower cost and equivalent performing technology has not been developed to replace metallized film technology for motor run applications. Alternatively, the basic package size and general description of the motor run capacitor have also not changed in over 30 years. In contrast, the technology has and continues to evolve leading to major performance differences from supplier to suppler. Metallized film motor run capacitor technology is mature but this does not mean it is a commodity and it does not mean the product performance can be taken for granted. Motor run capacitors are not the same from supplier to supplier even though the product has been successfully listed to under agency standards which contain a reliability specification. This paper will explore the performance differences between various motor run capacitors.

2. Motor Run Capacitor Data Sheet Parameters

In general the data sheet for a motor run capacitor contains four groups of ratings:

- Electrical
- Mechanical
- Environmental
- Reliability

Quality control parameters are equally important in today's world but are rarely contained on the data sheet.

Examples of the ratings, which are normally included in the group of electrical, mechanical, environmental and reliability, are shown below. The ratings listed below are not meant to be a complete set. They only serve to show examples.

- Electrical
  - Nominal capacitance
  - Capacitance tolerance
  - Rated AC voltage
  - Frequency range
  - Dissipation factor
  - Insulation resistance
  - Max leakage current
  - Max surge voltage
  - Max VAR power due to the combination of voltage and capacitance tolerance (this is not the same as a max harmonic distortion rating).
  - Self-protected or non-protected (construction only)
  - Frequency coefficient for DF and capacitance
  - Temperature coefficient for DF and capacitance

- Mechanical
  - Nominal dimensions
  - Max dimensions
  - Terminal configuration and dimensions
  - Terminal withstand force, terminal withstand torque
  - Case material/case finish
  - Mass
  - Labeling information
  - Flammability rating for exposed plastic parts
  - MSDS (material safety data sheet)

- Environmental
  - Max temperature
  - Minimum temperature
  - Damp heat withstand
  - Salty spray withstand
  - Max altitude
  - Vibration withstand capability

- Reliability
  - Expected service life (endurance)
  - Reliability
  - Leak rate for liquid filled capacitors
  - Life scaling multipliers for temperature, voltage and humidity.
  - Etc.

The collection of industry standards provides a definition for these ratings and a list of preferred values. However, the manufacturer has the flexibility to select the specific value and in some cases to even decide if a specific rating needs to be specified. As an example, the damp heat standards[2] define the test procedure and a rating structure, but it does not specify the required performance rating. Terms dealing with safety classifications are defined in the standards but performance ratings are not required by the standards and vary across suppliers (standards define P2 but a P2 performance is not required). General comments regarding the standards were briefly presented in the introduction section. Detailed examples regarding the standards are discussed below:

- Endurance per IEC 60252-1:
  - Class A, 30,000 Hrs: 125% of rated voltage, max rated temperature, 6,000 Hr test, max failure rate of 3% using decrease in cap, decrease in insulation resistance and increase in series resistance as the failure criteria for a specific sample size.
  - Class B, 10,000 Hrs: 125% of rated voltage, max rated temperature, 2,000 Hr test, max failure rate of 3% using decrease in cap, decrease in insulation resistance and increase in series resistance as the failure criteria for a specific sample size.
  - Class C, 3,000 Hrs: 125% of rated voltage, max rated temperature, 600 Hr test, max failure rate of 3% using decrease in cap, decrease in insulation resistance and increase in series resistance as the failure criteria for a specific sample size.
  - Class D, 1,000 Hrs test: 125% of rated voltage, max rated temperature, 200 Hrs, max failure rate of 3% using decrease in cap, decrease in insulation resistance and increase in series resistance as the failure criteria for a specific sample size.

- Endurance Per EIA 456A:
  - Class E: 60,000 Hrs: 125% of rated voltage, 10°C + max rated temperature, 2,000 Hrs, max failure rate of 6% using decrease in cap, decrease in insulation resistance and increase in series resistance as the failure criteria for a specific sample size.

- Steady state damp heat
  - Relative Humidity (RH): 40% to as high as 93%, 85% is slowly becoming the industry standard
  - Temperature: 65°C to 93°C, 85°C is slowly becoming the industry standard
  - Withstand time: 4 to 56 days with 10 (240 Hrs) and 21 days as common ratings.

- Protection per IEC-60252-1
  - P0: indicates that the capacitor type has no specific failure protection.

[2] IEC 68-2-3, IEC 60252-1, EIA 456, EIA RS-186 are a few examples.

- P1: indicates that the capacitor type may fail in the open circuit or short circuit mode only and is protected against fire or shock hazard.
- P2: indicates that the capacitor type has been designed to fail in the open circuit mode only and is protected against fire or shock hazard.

- Protection per EIA 456 A
  - Must pass UL 810 test protocol
  - Self-protected
    - Fails open W/O fire or shock hazard.
    - Withstand open circuit voltage for 3 minutes.

In summary, there is a large difference between the completeness of motor run data sheets between different suppliers. Often the motor run data sheet does not contain a complete set of performance characteristics for the capacitor or capacitor series. In some cases, the motor run data sheet from different suppliers may look similar but a closer examination almost always reveals missing information and major differences in the performance characteristics.

3. Inside of the Black Box

Motor run capacitors with the same capacitance and voltage rating can have very different design parameters. Different design parameters can also lead to different performance characteristics for two motor run capacitors each with the identical capacitance and voltage ratings. A brief example will be presented in the following section.

Polypropylene dielectric film[3] is the predominant dielectric material used in motor run capacitors. As a result, two motor run capacitors with a specific capacitance and the same film thickness must have the identical surface area. A specific surface area can be developed from a wide film width (like 100 mm) and a relatively short length or a narrow film width (like 30 mm) with a longer length. A wide film width generates a small diameter section and a relatively short length of film. This compares to a small film width, which generates a larger diameter section with a longer length of film. This can be easily visualized from the diagram Figure 1.

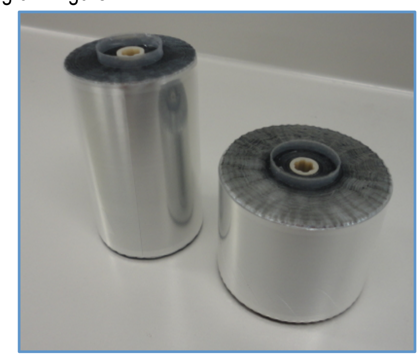

Figure 1, section on the right fabricated from small width film and yields a large diameter section. The section on the left is fabricated from large width film and yields a small diameter section. These two sections have the same area and the same capacitance value.

Figure 2 shows the unwound film materials and the linear current density (rated current divided by the length of the unwound film). Two capacitors with the same capacitance and the same voltage rating will draw the same current. The linear current density for these two capacitors will be very different. The heat generated at the end-spray section interface is a function of the linear current density and the metallization properties so this operating characteristic is also different.

[3] NG white paper, "The Roll of MPP Film in Motor Run Capacitor".

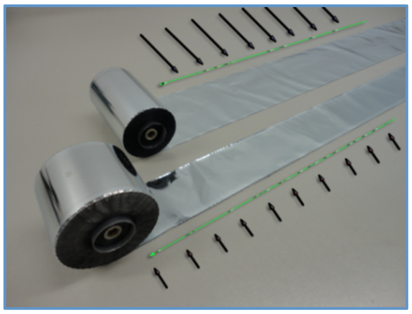

Figure 2, shows the metallized film unwound from the sections (wide web width and small web width). The top and bottom arrows show the current flow into the edge of the metallized film and the other arrows (green) shows the linear direction. These drawings are pictorial and are not drawn to scale.

A second major result of two sections, each with different aspect ratios (film width to section diameter), is the thermal resistance[4]. The section thermal resistance along with the specific heat generated inside of the section (both are a function of location inside of the section) determines the section hot spot temperature rise inside of the capacitor section. The heat flow inside of the section is determined by the heat transfer coefficient of the polypropylene film and the metallized coating the inter face layer stacking density[5] between the polypropylene layers and finally the geometry of the section. A 40 μF motor run section can easily have 1,000 interface layers which develops a large thermal resistance. The polypropylene film is not smooth as it has a surface roughness within the 0.4 μm range. This rough surface in combination with all the layers leads to a high thermal resistance in the radial direction. As a result, most of the heat is transferred longitudinally (along the film width) and not radially through the section. In addition most of the heat transfer is through the metallized coating and not the polypropylene film. Using material properties and material thickness values as shown below:

Al (and Zinc):	126 W/(M-°C)
OPP:	0.185 W/(M-°C)
OPP thickness:	6 μm
Metal coating thickness:	0.035 μm

The ratio of the longitudinal heat flow between the metallized coating and the OPP film is shown in Figure 3.

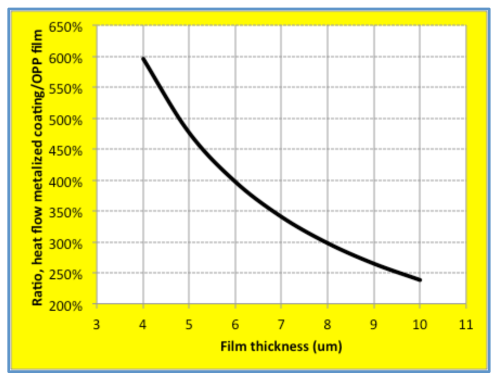

Figure 3, ratio of longitudinal heat flow (along the axis of the section) between the metallized coating and the dielectric film as a function of the dielectric film thickness.

The section, "Inside of the black box" further demonstrates that motor run capacitors are not commodities. Even though the two designs have the same capacitance rating and the same voltage rating the two designs can and will perform very different and cannot be treated as a commodity.

4. Film Motor Run Capacitors Age Over Time

Film motor run capacitors age over time. The aging takes place when voltage is applied to the capacitor or under certain conditions the motor run capacitor can

[4] Normally expressed as a coefficient in units of °C/W
[5] For tight wound sections, the interface layer space can reduce the section density by 2% to 4%. This reduced density is composed of air.

age without the application of voltage. Clearing events drives normal field aging, which involves corona, ablation and vaporization all of which results in mechanical and chemical changes at the localized polymeric level. This process gives rise to the expected service life rating. In contrast, normal aging without voltage is usually driven by oxidation reactions at the current collector. This gives rise to the shelf life rating. In both cases the degree of aging is measured by the amount of change in the film motor run capacitor operating parameters (series resistance, parallel resistance and capacitance) and is expressed as ratios as shown below:

- Ratio of series resistance to capacitance reactive impedance (often referred to as Dissipation Factor or tanδ)
- Ratio of capacitance to the delivered capacitance
- Parallel resistance (insulation resistance).

As the film motor run capacitor ages, the three operating parameters normally change as follows:

- The series resistance increases
- The capacitance decreases
- The parallel resistance decreases.

There are special aging conditions under which one or two of the parameters age while the other one or two do not change. In general, film motor run capacitor aging leads to a change in all three of these parameters.

Capacitor end of life is defined when any one of these operating parameters reaches a limit. All three parameters are not required to reach the aging limit to establish end of life. The end-of-life-limits are established by the individual capacitor suppliers and have some variability from supplier to supplier. In general they have the following limit range:

- Max increase in the series resistance:
  100% to 150%
- Max decrease in the capacitance:
  -3% to -10%
- Max decrease in the parallel resistance:
  -50% to -75%

Field aging can be modeled and the modeling is used to define reliability[6]. Shelf life can also be modeled but the models are very different than the models used for field aging. A short discussion of reliability is presented in the next section.

5. Reliability Modeling of Film Motor Run Capacitors

Reliability modeling is the process of fitting a mathematical function to a set of highly accelerated life test (HALT) data[7]. Once a mathematical function has been fit to the data it can be used to predict specific failure rates corresponding to specific times. Without getting too involved in the mathematics there are two other important parts of the reliability analysis, which need to be understood. The first has to do with the variance in the sample set performance used for the HALT data. The second has to do with translating the model results from the HALT conditions to the operating conditions of the specific capacitor in the field.

Dielectric systems, in general, and capacitors specifically generate a large variance in their performance. A typically film motor run capacitor part number could easily have a total population of well over 10 million units. The sample size used for the HALT data is normally in the range of 10 to 25 units. There are many different sample sets, which can be pulled from the total population. This leads to the question, "how would the modeling function change if a different sample set were used for the modeling"? This is address statically with a variance analysis leading to

[6] Reliability is max failure rate under a specific set of operating conditions for a specific operating time. Expected life is a nominal operating life used to narrow down the family of MR capacitors for a specific application.

[7] Weibull distribution is the most common function in use today but log-normal is also used.

confidence interval for a specific probability. As an example, reliability data in film motor run data sheets typically represent around the 50% confidence level. This means that if a population set were selected at random from the total population, it would only have a 50% probability that it would perform to or exceed the data sheet rating. Corresponding there is a 50% probability that it would not meet the data sheet rating. For a high confidence level one normally requires a ± 95% confidence range which will reduce the rating in the data sheet by a considerable amount. The variance data and confidence intervals are almost never provided in the film motor run capacitor data sheet and can have a large variance from supplier to supplier.

Dielectric systems, in general, and capacitors specifically have a strong performance dependence on both temperature and voltage. This leads to the specific application question, "what is the corresponding data sheet rating for the actual operating conditions"? The actual field operating conditions are almost always different than the operating conditions used for the HALT predictions in the data sheet. Models exist which can be used to translate HALT data at one set of operating conditions to another set of operating conditions. Most film motor run capacitor data sheets do not provide these life multipliers.

6. Conclusion

Today, motor run capacitors are supplied from many different suppliers located around the world. From the outside, these capacitors can and often do look very similar. Under more careful study one can see that many of these have different characteristics. For a commodity, a motor run capacitor with the same capacitance (plus tolerance), voltage and packaging should have equivalent performance. This is not the case for film motor run capacitors. The complete set of data sheet ratings can be significantly different form supplier to supplier. Equally important, the variance from supplier to supplier can also be very different. Even though two different suppliers may list the same U50%/50%[8] rating on their data sheet, the U95%/5%[9] data can be very different. In many cases today, smaller suppliers cannot even provide the variance data. Metallized film motor run capacitors are not a commodity even though they are a mature product. Film motor run capacitors must be selected based on the application and a careful review of the data sheet.

[8] Max failure rate for a specific time with a 50% confidence level.
[9] Max failure rate for a specific time with a 95% confidence level.