Reliability Considerations of Inverter/DC Link Capacitor Using PP Film and 105°C Engine Coolant

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Abstract

A new Inverter DC Link Capacitor will facilitate 105°C coolant operation and greatly increase power density at elevated temperatures without sacrificing reliability. The Annular Form Factor Film Capacitor provides for extremely low heat generation under typical 100 - 400 Arms ripple current loads of HEV and PHEV automobiles. DoE funded research at SBE has found that if a capacitor hot spot temperature remains below 125°C it could be reliable enough to provide the required service life of the automobile industry. The article discusses the design concept and resulting temperature performance of the proposed capacitor, modeling results, and a reliability testing methodology.

Key words: Inverter, Capacitor, Reliability, DC-Link, MTBF, Automotive

Introduction

The power inverter systems integrated into an under-the-hood traction drive require capacitors capable of carrying substantial high frequency currents to minimize the impact of high ripple currents on high energy density storage devices like super-capacitors and battery packs, load-sensitive power sources such as fuel cells, and to ameliorate the impact of switching voltage transients on power semiconductor devices such as IGBT's and PowerFET's. Additionally, the inverter semiconductor devices themselves require cooling and an efficient topological layout to provide high volumetric power density.

Aluminum Electrolytic capacitors are prevalent in today's DC bus filter (or DC Link Capacitor) applications for inverters, especially lower voltage systems in smaller HEV drivetrains and small electric vehicles, and along with standard, packaged semiconductor devices, are typical for the active inverter electronics design. These combine for good energy and capacitance density, reasonable performance and low component cost, but at a price of stringent cooling requirements and sometimes significant volumetric inefficiency. This is partly because electrolytic capacitors have fundamental material limitations, which prevent their use at temperatures exceeding +70ºC when de-rated for even medium-term reliability and for operating, or even short duration voltages over 400 VDC[1]. The electrolytic capacitor's Effective Series Resistance (ESR) is high and rises dramatically at low temperatures, limiting its ability to absorb and deliver energy at the low ambient temperatures frequently experienced in a large portion of the nation. This limits the overall performance and power density of the inverter both directly due to the capacitor and indirectly as the semiconductors are affected by the ESR and the Effective Series Inductance (ESL) due to packaging inefficiencies.

Recent efforts by many in the industry to substitute polymer film capacitors, with higher voltage ratings of 500 – 1000 VDC, for electrolytic capacitors in inverters have used banks of parallel and series connected conventional cylinder-shaped, or flattened cylindrical sections, of smaller capacitors to form a complete module in order to achieve the required voltages to distribute the current flow, or achieve the desired amount of total capacitance required. This approach severely limits the designer's ability to remove heat generated by the capacitors and interconnects, limits the choices on locations for the capacitor bank, increases the ESR, increases the total volume needed, and adds considerable complexity and cost. Similar packaging issues remain a problem for typical electrolytic capacitor form factors as well but are increased with the film solution due to the natural disadvantage that film capacitors have in terms of capacitance density. In fact, universally, it has been found that, unless a capacitor has been carefully designed for long-term operation at elevated temperatures, high-temperature failures observed in commercially available components will most often be related to the individual devices' packaging and contacts technology, rather than the dielectric materials employed[2].

Consequently, it is the heat dissipation of the DC Link Capacitor bank while it is under the load of 100 – 400 Arms ripple current (typical of most HEV and PHEV applications), which is rapidly becoming one of THE design limiters for the HEV and PHEV transportation inverter solutions available to industry today. Any proposal to change the DC Link capacitor or minimize the cooling requirements must carefully analyze what the reliability impacts might be.

One of the more significant issues preventing the largest reduction in system volume, weight, and cost in the HEV and PHEV traction drive inverter systems envisioned for a next generation of these vehicles is the requirement of currently available polymer film, such as polypropylene (PP) film, capacitor technology to be cooled so that the hot spot temperature of the capacitor, while under load conditions, is lower than 85°C for long term reliability[3]. In order to achieve this condition, the capacitor must be cooled below that point even as it is self heating due to ripple current pass-through. In a traditional film capacitor form factor, such self heating can result in a 25 - 50°C rise from ambient surrounding temperature[4]. This can necessitate coolant temperatures of between 45 - 60°C in order for the film capacitor to remain reliable under full current rating conditions or 55 -70°C if much larger than minimally necessary capacitors are used and subsequently de-rated to a lower than normal maximum ripple current rating.

A typical system design engineering approach to this self heating and subsequent cooling requirement need of PP film capacitors is to allow the temperature of the hot spot to rise above the accepted 85°C long term reliability temperature point and distribute the inverter's DC Link ripple current across a larger number of PP film capacitors. This technique, known in the industry as "de-rating" can allow the temperature to rise within the capacitor to as much as 95 - 105°C and still remain a long term reliable solution but at reduced maximum total current allowed through any individual capacitor section[5].

A further enhancement to this solution is to use High Temperature PP film such as High Crystalline PP film. Such film is described to have increased high temperature characteristics which may make it usable up to 115 or even 125°C[6]. This would allow the possibility of current distribution across a somewhat smaller number of sections than that required by standard PP film or might allow a somewhat higher coolant temperature for a single capacitor. However, such PP film material capacitors of this design would still require a coolant temperature of 60 - 80°C for conventional designs.

Recent research work performed by SBE Inc under the Department of Energy's SBIR program has focused on the dielectric properties of PP film and HC PP Film especially as they apply to hot spot temperatures and reliability implications.

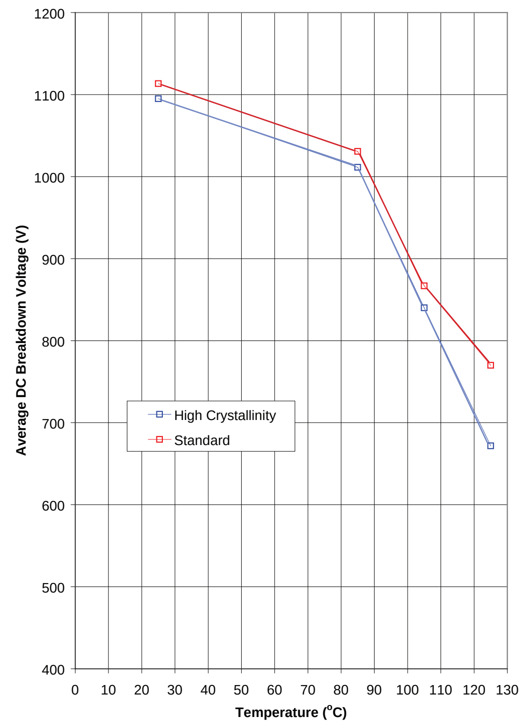

Figure 1 - Breakdown strength data with respect to temperature for small capacitors and two types of polypropylene film[7]

As you can see from this graph, the actual usability of HC PP in the inverter application could be severely limited by voltage and leakage characteristics which become more restrictive as the temperature increases.

I. Innovative Approach

The wound-film capacitor ring geometry shown in figure 2 has been demonstrated to greatly increase capacitance density for film capacitors[8].

Additionally, the technique of locating a load (i.e. electronic, semiconductor package, etc.) inside the center hole of this annular capacitor greatly reduces the ESL (inductance) as can other innovative connections taking advantage of the round (coaxial) total geometry.

Figure 2 – Power Ring Picture

However, the greatest impact of an annular shaped capacitor as is described, is the improvement that such a shape has in heat generation under strenuous current load as is the case in the Hybrid Inverter application. This is because the thermal paths of generated heat are significantly reduced and therefore greatly more efficient. Figure 3 shows the temperature profile of an example annular film capacitor under 100 Arms conditions. The total temperature rise under these conditions is 5.5°C. It is interesting to note that the hot spot temperature is at the farthest away location from the connection point. It is this point which will have the greatest impact on the reliability of any capacitor and is ironically the most difficult spot to measure temperature while testing a system under load.

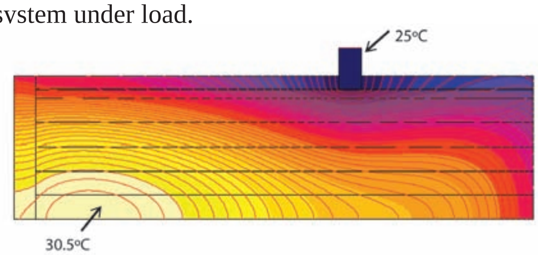

Figure 3 - Thermal profile for an early prototype annular form factor capacitor with a symmetric contact located outside the mean radius and under 100 Arms load[9].

SBE modeling suggests that the annular shaped capacitor represents the best ratio of cooling surface area to current density within the capacitor and subsequently the lowest possible temperature rise under heavy current load conditions such as those in an HEV inverter.

SBE Inc. has conducted preliminary tests and performed parallel modeling of this type of current distribution under room ambient conditions for a 240 Arms PHEV type ripple current application[10] and compared the results of those with a typical DC Link capacitor arrangement made up of standard shaped film capacitors. It should be noted that the assumption is that both cases use exactly the same PP film, 3.8 micron width standard PP. The graphed results in Figure 4 show how greatly the temperature rise differs in the annular form factor capacitor vs. that of the standard Film Capacitor array. The specific example design used for the graphed comparison is that of the Toyota Prius.

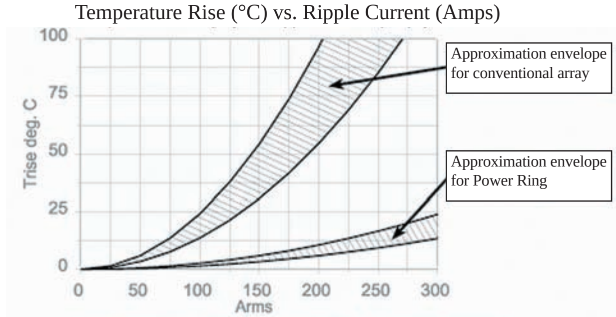

Figure 4 – Temperature Rise of Annular DC Link vs. Conventional Film Capacitor Array for a 25°C ambient example.

It is generally accepted in the Film Capacitor industry that the hot spot temperature should be maintained at or below 105°C for long term reliability. The research performed by SBE for the DoE offers some data as to why this is the case. Figure 5 shows the modeling results of internal temperature vs. external temperature of all of the composite materials which make up a film capacitor: PP, end-spray, metallization when under a current load. The graph shows that up to 105°C, the materials themselves do not measurably contribute to generated heat but above 105°C the PP starts to contribute and above 125°C the PP starts to show a likely un sustainable reaction under load.

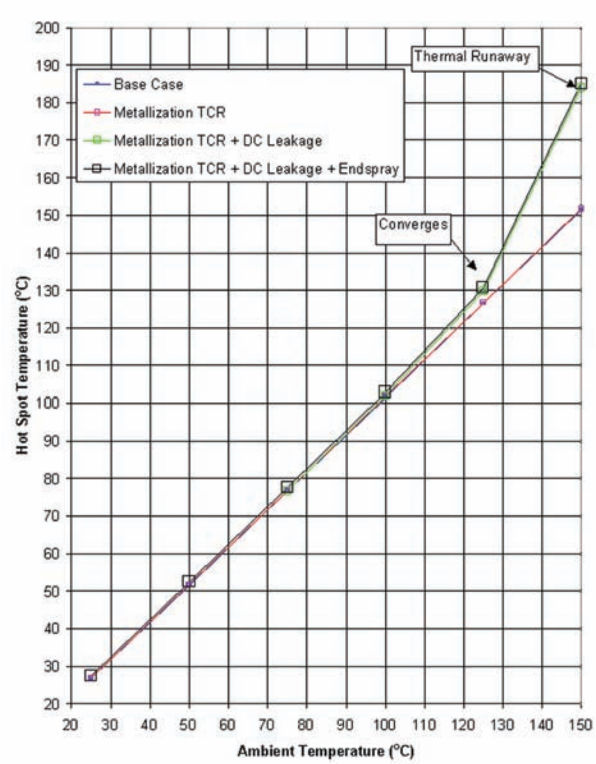

Figure 5 - Hotspot calculations for the initial parametric sequence[11]

It is this region between 105 and 125°C which holds promise for strategically increased capacitor hotspot temperature which will exhibit the long term reliability necessary for Automotive applications but also allow the flexibility of only 105°C coolant or greatly increased power density in cooled inverters without fear of reliability degradation.

If you look at the case of 105°C coolant and assume no more than 2°C cooling inefficiency from a hot plate, it becomes quickly apparent that any internally generated heat from a capacitor solution which generates even 20°C will not likely be reliable due to thermal runaway at the material property level of PP. The closer the hot spot temperature is to 105°C the more reliable the solution.

Based on the previously discussed comparison between the conventional Film capacitor array and the SBE annular form factor capacitor, it becomes quickly apparent that there is no chance for a conventional array to stay within the reliable material properties at any usable ripple current in excess of 50 Arms.

Clearly the Annular Form factor solution could be reliable in that region if the reliability in the 105 - 125°C hot spot region can be predicted.

So, how should we best predict the reliability in this region? For this, we need to turn to accepted reliability prediction methods for Capacitors.

II. Predicting Reliability

In order to be successful for the goal of long term reliability using the 105°C ICE coolant temperature or other inverter dense temperature conditions, we believe that a temperature rise of less than 10°C will be required while operating at maximum rated operating temperature. This would establish a maximum hot spot temperature of less than 115°C within the capacitor. As discussed earlier in this article, there is clear evidence that 125°C is too high a temperature of the hot spot to give long term reliability. What temperature is likely to provide long term reliability yet be high enough to meet the design goal? Since a 10°C budget would allow for up to 200 Arms ripple current rating, we have selected 115°C as the highest temperature to design for. The question is, how to predict reliability of the device under these conditions?

There are two ways of getting the meaningful data for MTBF. The first is to take a general product line and run life tests at the product ratings for very long periods of time and then observing performance, monitor parameter shifts and watch for any catastrophic events. This method is seldom used as it is highly cost ineffective and is plagued by test equipment failures, etc.

The second method is to use accelerated life tests at conditions exceeding the product ratings and then mathematically relating these back to the standard operating conditions or product ratings. This produces useable results in a shorter time period, are far less expensive and easier to monitor with test equipment failures (a very real threat) less likely. There are two readily accepted acceleration modes: Voltage and temperature. These effects are cascaded so you can calculate the acceleration of one factor then plug that into the next factor. The voltage acceleration factors follow a power law and are derived from long term test programs themselves. The use of industry accepted power values are common when specific factors are not available. Temperature acceleration factors come from the old physics and chemistry law that says reaction rates are roughly doubled for a 10°C rise in temperature. Unfortunately, there isn't much room for temperature acceleration without causing unintended failure.

To get to an acceptable failure rate and MTBF estimate one must establish the test conditions. (i.e.- # of units, temperatures for test, voltages for test and most importantly a definition of a parameter failure. Actual test conditions under accelerated conditions must be carefully examined to be certain that product capability is not exceeded and premature failures are not forced. In the example of the DC Link Capacitor and our SBIR Research that shows significant detrimental effects at 125°C, forcing a test to operate at, say, 150°C may cause an unrealistic failure to occur which will drastically affect the predicted MTBF from the test.

For our test plan, we need to consider a desired lifetime of 15 years or 130,000 hours. Operational exposure might be more on the order of 15,000 to 25,000 hours.

Temperature: In the actual application, the environmental ambient temperature of the capacitor ranges between -40°C and 105°C in the proposed application. However, the percentage of time where the ambient is 85°C or greater is considerable during the operational time. The challenge of the tests is to provide any level of increased temperature to provide acceleration data without inducing unintended failure due to temperature extreme.

Voltage: The voltage applied to the capacitor over this lifetime is variable but can be considered to be at 300 – 400 VDC with some small periods of time at possibly 500 – 600 VDC (likely 5% or less of operational life). Since there is operational usefulness of the capacitor up to 800 VDC at the elevated temperatures, the increased voltage acceleration method may offer some opportunity to predict MTBF over 25,000 hours.

Data confidence: In using the various design acceleration factors, a statistical confidence factor (CF) must be established to help understand the data. CF's in the 90-95% areas are commonly used when lots of unit hours are available and the failure rates are low (i.e. Automotive applications).

Acceleration Factors: Now applying acceleration factors we can reduce the time and units in the following fashion. There are some generally accepted formulas for both voltage and temperature accelerations. The biggest difference may lie in the acceleration factors being used. For purposes of this discussion, the two formulas and the acceleration factors are:

Voltage Acceleration factor:

FR@V2 /FR@V1 = [V2/V1]K
Where:
FR@V2 = New failure rate
FR@V1 = Old failure rate
V2=New voltage
V1=Old voltage
K = Acceleration factor = 8 (Arrhenius coefficient)[12]

Temperature Acceleration factor:

FR@T2/FR@T1 = 2 [(T2-T1)/K]
Where:
FR@T2 = Failure rate at Temperature 2
FR@T1 = Failure rate at Temperature 1
T2 = Temperature in °C
T1 = Temperature in °C
K= Acceleration factor = 7 (Arrhenius coefficient)[12]

These values are pretty common. Other values for K are used depending on the dielectric and specialized studies. As it can be seen from these formulas and the previous concerns, it will be easier to use acceleration factors using voltage than temperature.

It is possible that after the reliability predictions are completed, we may need to reduce the ripple current stress somewhat at these elevated temperatures to insure the required life or reduce the voltage stress by using a slightly thicker dielectric. This most reliable implementation might require some additional film volume and so consequently additional film capacitance volume to reach the desired HEV, PHEV and EV inverter ripple current or voltage requirements may be required. This is not necessarily a significant problem to the goal of increased energy density as it might seem. The reason for this is that the volumetric efficiency of the annular form factor is up to 35% more efficient than a corresponding capacitor bank solution by geometric design[13], so some additional capacitance for this "de-rating" purpose will have a minor effect on total volumetric efficiency vs. existing designs, especially when the possible complete elimination of the presently required cooling loop is factored in or the much greater flexibility of component placement within the inverter is enabled.

III. Increasing Capability Further through Symmetry

In theoretical analysis of understanding the current flow in a large distributed capacitance where single element analysis is no longer sufficient to describe the self heating properties (i.e. an annular form factor), SBE has earlier demonstrated that in order to maximize the total current handling capabilities of such a capacitor, as equal currents as possible need to be flowing through the capacitor[13].

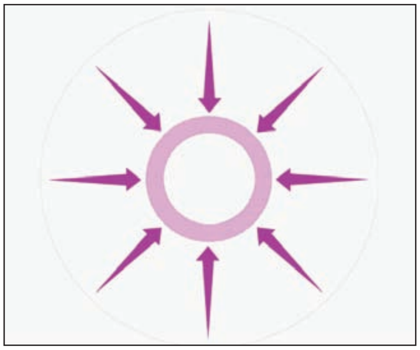

Figure 6 – Distributed Current in an Annular Ring Form Factor Capacitor[13]

This is because the maximum current rating of the device under long term conditions will result from identifying the worst case hot spot temperature and establishing current limits to keep this hot spot below the point where permanent heat damage will occur to the PP film in that area.

SBE research has found that because symmetrical optimization result in the lowest hot spot temperature, one of the most significant things that can be done with the annular form factor capacitor is to connect it to an inverter bus structure in such a way that the currents remain uniform. In doing so, the maximum ripple current is obtained for a given volume and still maintains the desired reliability. The actual placement of the terminals and orientation of the IGBT switches can result in significant improvement in the performance and reliability of the device and the overall inverter system.

One of the concepts to consider is to place the IGBT modules inside the hole of the annular form factor capacitor itself. If the switches can be laid out correctly, this can force symmetry by attaching to the inner ring of the capacitor for example.

One might consider that if the hole of the capacitor needs to become too large to accommodate the necessary power semiconductors then the resulting circle of the annular form factor capacitor might need to become too large for the necessary capacitance of the DC Link. However, geometry is helpful in this regard since a reasonably large center hole can be created without great loss of capacitance of the remaining ring due to the volumetric formula of:

$$\pi r2w$$

Where r is the radius of the capacitor area and w is the width of the capacitor film. A reasonably large portion of the total radius of the annular form factor capacitor can be removed for electrical use such as IGBT switches and still leave useable capacitance in the remaining ring. As an example, 50% of the radius could be left available for electrical use and the corresponding reduction of capacitance would only be approximately 25%. Since the authors have calculated that the annular form factor shape results in up to a 35% increase in volumetric capacitor efficiency vs. the currently used capacitor banks in many HEV and proposed PHEV/EV inverters, it is quite possible that the power electronics of the proposed inverter could be completely contained within the “underutilized space” of today’s inverter capacitor banks. Yet the performance would be far greater and cooling needs greatly reduced.

IV. Summary & Conclusions

In this paper, we have shown that the material properties of PP are likely to prevent any reliable operation in the automotive environment at temperatures of greater than 125°C measured at the capacitors hotspot. Furthermore, we have proposed a methodology being pursued by SBE to provide appropriate MTBF calculations for the automotive user yet providing significant power density for the inverter.

The unique characteristics of the annular form factor allow for significantly reduced temperature rise under the typical HEV, PHEV, and EV ripple current loads. This lower temperature will result in a more reliable device.

With a goal of reliable inverter operation using nothing more than 105°C Engine Coolant, there does not need to be a compromise made between high current capability however to get the highest possible current rating for the inverter there must be thought into how to connect the IGBTs to the DC Link capacitor so as to try and equally distribute the current.

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