Life Testing of High-Value Annular Form Factor DC Link Capacitors for Applications with 105°C Coolant

M. A. Brubaker, T. A. Hosking, and T. F. Von Kampen

SBE, Inc. 131 South Main Street, Barre, Vermont, 05641-4854, USA
Phone: 802 476-4146 Fax: 802 476-4149 www.sbelectronics.com

The Power Point presentation will be made available after the conference.

Abstract

The SBE Power Ring Film Capacitor™ offers the advantages of high capacitance value, low equivalent series resistance and inductance, and minimal temperature rise using polypropylene film. Recent work has addressed optimization of the Power Ring for automotive DC link applications with funding from the US Department of Energy. Under this program, life testing of over 600 capacitors valued at 1000 μF has been performed to validate the design for coolant temperatures in the 105°C regime. This paper presents the methodology for the test program and describes the experimental apparatus. Results are discussed for testing to date, which has provided two million unit hours of exposure with only two failures observed after an initial pre-testing run which identified early failures later discovered to have defective film.

Introduction

The SBE Power Ring provides a unique annular form factor which allows for high capacitance with low losses and minimal temperature rise. This technology has been previously demonstrated for pulsed current [1] and ripple current applications [2]. More recent work funded by the US Department of Energy [3] has focused on optimization of the ring capacitor for electric vehicle applications using polypropylene film at coolant temperatures up to 105°C. Extensive electromagnetic and thermal simulations combined with experimental testing have demonstrated that operation in this regime is feasible with proper packaging.

Life expectancy of the capacitor remains a critical issue for acceptance in the automotive industry. While a wealth of data is available for life testing of conventional polypropylene film capacitors [4], existing results cannot be readily extrapolated to the Power Ring given the large differences in form factor and capacitance value. Furthermore, relatively recent advances in high-crystallinity and low-defect polypropylene film technology [5] allow for more aggressive dielectric stress at temperature. The need for relevant data has driven a significant life testing program to evaluate realistic stress effects in full-scale ring capacitors.

Life Test Methodology

Testing a statistically significant number of capacitors in complete inverter systems was not feasible in the cost and scope of the DOE project. However, a relevant testing scheme based on temperature and DC voltage over time was developed to provide realistic stress factors and define the safe limits of operation. A total of 672 parts with nominal values of 1000 μF were fabricated explicitly for this life test, which used approximately 1200 lbs of polypropylene film corresponding to nearly 70,000 m^2 of effective stressed area. Note that the life testing samples are representative of the SBE 700D348 capacitor rated at 1000 μF and 600 V.

The test protocol was defined to address the DOE Freedom Car specification [6], which requires 10,000 hours as the mean time between failures (MTBF). An informal survey of various automotive inverter customers showed a high level of interest in nominal operating voltages in the range of 350 V to 450 V. The soak temperatures were defined based on typical engine coolant conditions allowing for a temperature rise to the winding hotspot. For example, the worst case temperature rise for the SBE 700D348 was determined using a proprietary simulation tool as shown in Fig.1. The finite element model assumed 105°C coolant on the bus and case of the part with a corresponding temperature rise of less than 2°C for a 150 A rms ripple current at 20 kHz. Based on this result, a worst case temperature of 107°C was selected for testing, which is applied to the entire capacitor rather than just at the hotspot. A low end temperature of 100°C was selected to represent applications with coolant temperatures at 95°C and below.

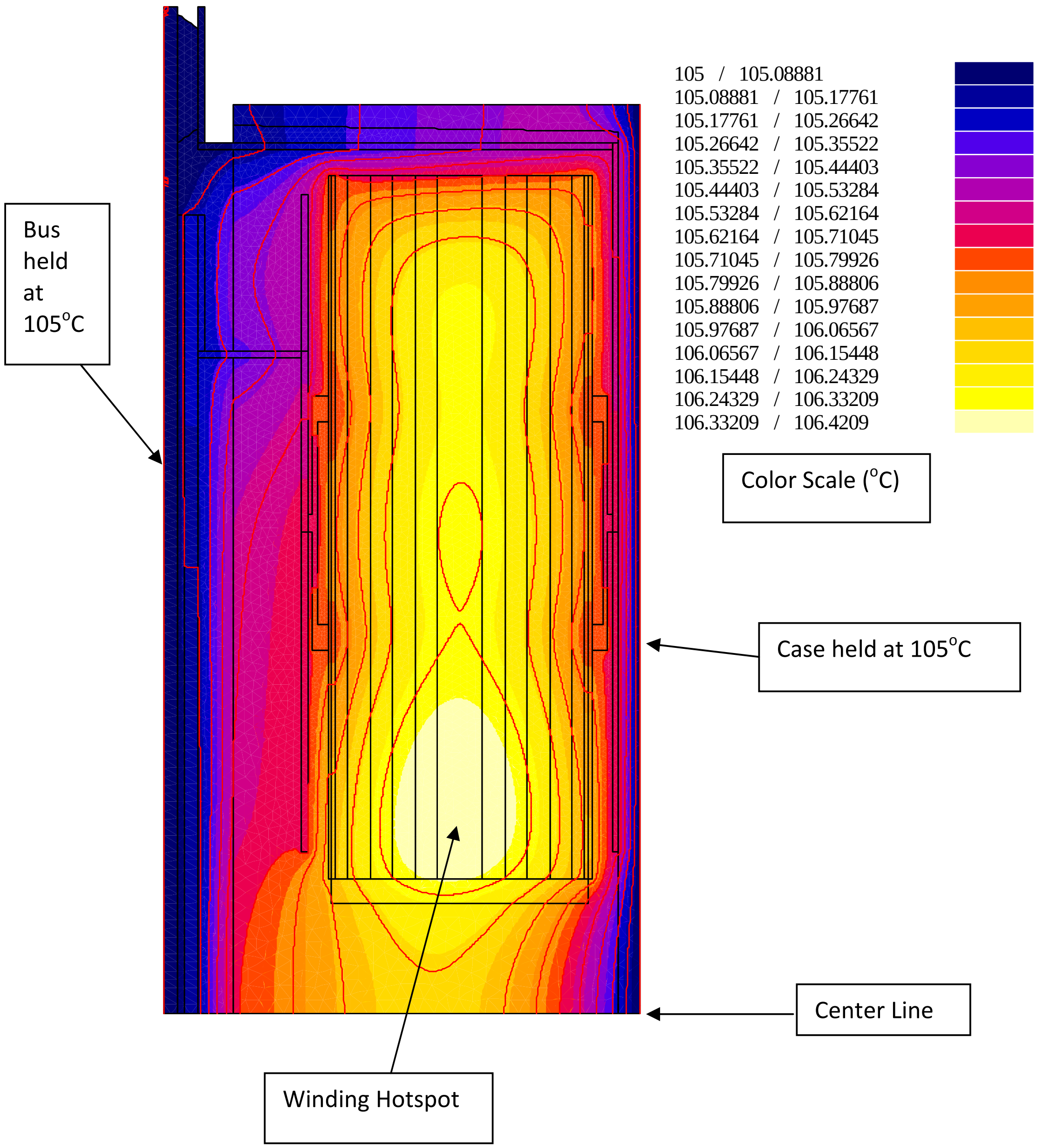

Fig.1. Temperature profile for a transient thermal finite element analysis of the 700D348 capacitor at equilibrium with 105°C coolant and 150 A rms ripple at 20 kHz.

Having defined an operating temperature and voltage range, preliminary testing was undertaken to identify voltage limits beyond which rapid failures occurred. This was necessary to validate the test regime and avoid unnecessary attrition of the expensive sample population. Based on this information, practical input on operating parameters from several automotive customers, and the simulation results discussed previously, the final test matrix was defined as per Table 2.

Oven	Number of Units	DC Voltage	Temperature
1	224	350	107^{o}C
2	224	400	107^{o}C
3	224	450	100^{o}C

Table 2. The final matrix for capacitor life testing.

Three thermal chambers were set up for testing with each chamber capable holding up to 224 capacitors on mounting racks as shown in Fig. 2. An external indicator lamp was wired in series with each unit to alert the test operator of excessive leakage current and possible failure. Given the expense of the samples and complexity of the test setup, a one week shake-out run was undertaken with the full system to validate operation. At this point, the formal life test was initiated, which has been running for several months to accumulate over two million unit hours.

Life Test Results

A total of five failures were observed during the initial shake-out of the equipment prior to beginning the formal life test. Note that a failure is defined as a catastrophic open or short circuit, or a significant drop in capacitance. Based on the traditional "bathtub" curve, these units could be classified as infant failures, having occurred within the first days of the shake-out test. However, four of the units were discovered to have obvious film defects during post mortem analysis. This leaves only one unit which failed prematurely in the test cycle with no clear cause. These failures were therefore addressed in terms of vendor and manufacturing process improvements and excluded from the actual life testing run.

Fig.2. Photograph of capacitor specimens and mounting rack for a single thermal chamber.

A total of two failures were identified after completing a two million total unit hour life test. Both parts exhibited a "soft" failure mode where the voltage recovered after the initial fault and turned off the indicator lamps. As such, the exact times to failure for these units are unknown other than that they occurred within the test interval. A summary of the test results to date are presented in Table 3. Note that the "+" indication on each of the oven run times indicates that further hours have been accumulated since this paper was written.

Oven	Temperature (^oC)	DC Voltage (V)	Run Time (Hours)	Pre-Test Failures	Life Test Failures
1	107	350	2500+	1	0
2	107	400	2500+	4	1
3	100	450	5000+	0	1

Table 3. Summary of life testing results to date.

The results were analyzed using both point failure calculations and assuming a Chi-Squared probability distribution. In each case, best and worst case MTTF was computed by excluding or including the pre-test failures where applicable. The MTTF results are presented in Table 4 and the best case Chi-Squared data is also plotted in Fig. 3.

Oven	Include Pre-Test Failures	Analysis	Temperature (^oC)	DC Voltage (V)	MTTF (Hours)
1	Yes	Point Failure	107	350	560,000
1	Yes	Chi-Squared	107	350	143,959
1	No	Point Failure	107	350	Singular
1	No	Chi-Squared	107	350	242,950
2	Yes	Point Failure	107	400	112,000
2	Yes	Chi-Squared	107	400	60,540
2	No	Point Failure	107	400	560,000
2	No	Chi-Squared	107	400	143,959
3	Yes	Point Failure	100	450	1,120,000
3	Yes	Chi-Squared	100	450	287,918
3	No	Point Failure	100	450	1,120,000
3	No	Chi-Squared	100	450	287,918

Table 4. Calculated MTTF results for the life test.

Test to Failure Methodology

The life test results to date are very promising in terms of reliability for automotive applications. In order to gain further understanding of the power ring form factor, some of the life test specimens were subjected to constant voltage and temperature at increased stress levels. Recognizing the "soft" failure mode discovered during life test where faulted units were able to recover, a digital camera was used to monitor the indicator lights. An image was taken every two minutes and stored on a local computer so that precise times to failure could be unfolded. A total of 15 groups each having 10 samples were evaluated under voltage and temperature conditions ranging from 600 V to 900 V and 85^oC to 110^oC.

Test to Failure Results

The intention of the testing was to develop Weibull parameters and understand the end of life behavior for the 1000 μF capacitor samples. However, a Weibull slope of less than unity was determined for each case with the failure rates decreasing over time. This suggests that the parts actually entered a new infant failure mode when exposed to the higher stress conditions. The probability of failure is presented along with the life test data in Fig. 3 which clearly defines a safe operating region. In general, a narrow threshold between safe operation and rapid failure was observed.

Conclusions

More than 600 annular form factor capacitor sections have been stress tested subject to practical automotive inverter operating conditions. The MTTF results have exceeded the DOE Freedom Car requirement of 10,000 hours in all cases and clearly demonstrate that the SBE Power Ring Film Capacitor™ can be utilized for 105°C coolant applications. Testing at higher voltage and temperature stress levels shows an abrupt transition to rapid failure moving away from the safe operation regime. As such, the safe envelope must be respected in the design process to obtain adequate reliability. Additional life testing time is presently being accumulated for Oven 3 with the capacitors held at 450 V while soaking at 100°C. These parts will be run in attempt to reach end of life or demonstrate life far exceeding automotive requirements.

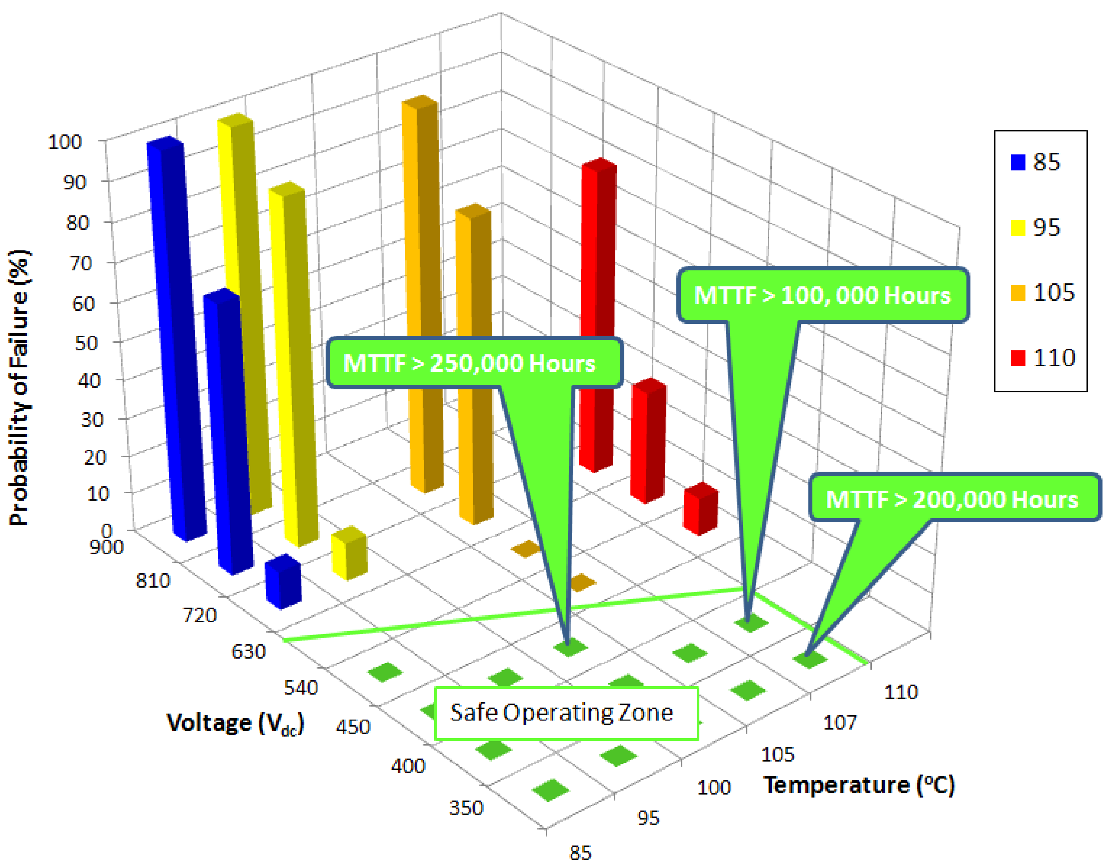

Fig.3. Probability of failure at increased stress levels presented in conjunction with best case Chi-squared life test results excluding infant failures.

References

[1] M. A. Brubaker and T. A. Hosking, “Annular Form Factor Film Capacitors”, Proceedings of the 2005 IEEE Pulsed Power Conference, Monterey, CA, June 13-17, 2005.

[2] E. D. Sawyer, “Low Inductance – Low Temp Rise DC Bus Capacitor Properties Enabling the Optimization of High Power Inverters”, PCIM Europe, May 4 - 6, 2010.

[3] Low-Cost, High Temperature, High Ripple Current DC Bus Capacitors for Hybrid Vehicles, US Department of Energy Grant number: DE-PS02-08ER08-17, 2008.

[4] D. Montanari, K. Saarinen, F. Scagliarini, D. Zeidler, M. Niskala, and C. Nender, “ Film Capacitors for Automotive and Industrial Applications”, CARTS Europe 2008.

[5] F. Jacobs, “PP for Film Capacitors: Origin, Manufacturing and Processing”, CARTS Europe 2006.

[6] B. Tuttle, “Capacitor Technologies: A Comparison of Competing Options”, Presented at DOE Hi-Tech Inverter Meeting, Baltimore, MD, October 14, 2004.