Advanced Capacitor Simulation Tools for Automotive DC Link Applications

SBE Inc. is a leading developer and manufacturer of film capacitor solutions that provide a much higher degree of reliability, higher power density, and simpler cooling infrastructure in demanding applications, particularly for automotive/transportation, alternative energy, utilities, power supplies/laser and military/aerospace. Originally a Sprague Electric Plant, SBE has been manufacturing capacitors for over 50 years; producing over a billion capacitors, including the renowned Orange Drop™. With the newer development of its Power Ring Film Capacitor™, SBE Inc. was awarded a $9.1 Million grant by the Department of Energy to build a world class facility for the manufacture of this line of capacitors used in drivetrain inverters for plug-in hybrid and electric drive vehicles. The company's headquarters, engineering, product development center and manufacturing operation are located in Barre, Vermont.

Overview

Understanding the capacitor winding hotspot temperature is critical to allow for optimal current rating where the minimum required capacitance can be utilized with acceptable service life. SBE has made a significant investment in the development of simulation tools to accurately model the losses and thermal performance of the Power Ring capacitor product line. Empirical measurements of key material properties have been integrated with detailed loss models to provide inputs for transient thermal finite element analysis. The simulation method has been carefully validated against temperature rise measurements of actual capacitors instrumented with thermocouples including independent testing performed at the US DoE Oak Ridge National Labs. This powerful design tool can predict the capacitor hotspot temperature for customer applications based on the ripple current rating and anticipated thermal environment. The simulation tool can also be used to better understand customer operating conditions given temperature rise measurements with embedded thermocouples in the capacitor. And all outputs can be related to peer-reviewed reliability predictions.

Model Inputs

Film capacitors are actually surprisingly complex with regard to both loss mechanisms and thermal performance. A wound section exhibits thermal properties that are not only much different from bulk materials, but also highly anisotropic in nature. As such, traditional handbook values do not necessarily apply, and extensive empirical measurements were required to provide a foundation for the finite element analysis. The measured properties are listed as follows:

1. Thermal conductivity of metallized polypropylene film
2. Specific heat of metallized polypropylene film
3. Density of metallized polypropylene film
4. Thermal coefficient of resistance for metallized electrodes on polypropylene film
5. Thermal coefficient of resistance for end spray
6. DC leakage of polypropylene film

Note that in all cases the capacitor film properties were measured using actual wound sections, which is critical to represent the behavior of a manufactured part.

An additional component of the thermal model is the losses associated with the capacitor terminal structure. A three-dimensional magneto-dynamic finite element model was developed to evaluate terminal losses as a function of ripple current frequency. The analysis domain as applied to the SBE 700D348 Power Ring with crown terminals is presented in Fig. 1 assuming 1/16th symmetry. Note that second order brick elements were utilized in the conductor cross section to accurately treat the skin effect. In addition to the terminal losses, the magneto-dynamic analysis can also calculate the inductance of the capacitor. For the 700D348 (1000 μF), the computed inductance is 3.2 nH, which has been confirmed by ring out measurements[1].

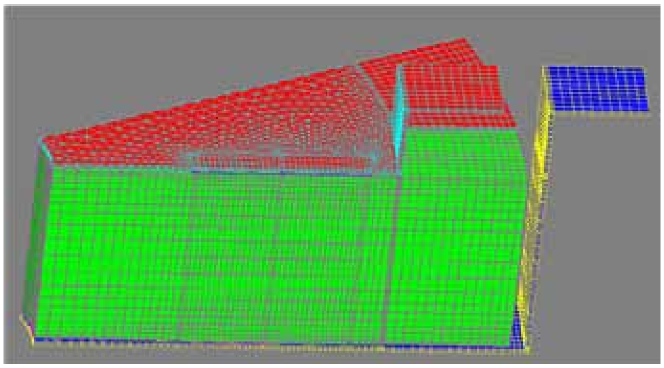


Figure 1: Magneto-dynamic finite element analysis domain for 700D348 Power Ring using 1/16th symmetry.

The loss models and material properties are combined to provide inputs for the transient thermal simulation as follows:

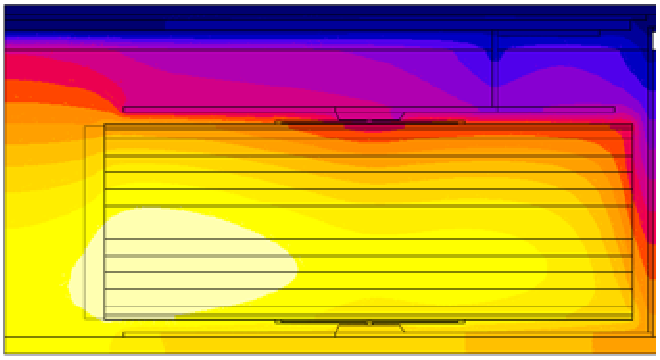
1. Losses
    a. Ohmic losses in metallized film electrodes (function of temperature and ripple current)
    b. Ohmic losses in terminals (function of temperature, ripple current and frequency)
    c. DC leakage losses in film (function of DC voltage and temperature)
    d. Dissipation losses in film (function of AC voltage, frequency, and temperature)
2. Materials
    a. Axial thermal conductivity in capacitor winding (measured)
    b. Radial thermal conductivity in capacitor winding (measured)
    c. Volumetric specific heat in capacitor winding (measured)
    d. Bulk materials treated as isotropic (vendor data)

Recognizing that the film electrode losses follow a quadratic distribution in the axial direction, the active area and margins of the winding are treated using discrete regions with the appropriate power densities computed based on the ripple current, mean temperature, DC voltage, and ripple voltage. The thermal domain is bounded with Dirichlet (constant temperature), Neumann (normal isotherms), or convection conditions as defined by the application. At time zero, the ambient temperature is assumed throughout the domain and the transient solution started using a suitable time step for sampling the anticipated thermal time constant of the geometry. The problem is run to equilibrium and further iterations are performed if the final mean temperature exceeds the value used for computation of the losses to verify convergence.

Model Outputs

The simulation provides both spatial and temporal results for the capacitor geometry. A typical thermal map for the 700D348 at equilibrium is presented in Fig. 2 for 200 Arms at 20 kHz. The figure represents a two-dimensional “slice” of the capacitor showing the winding, end connections and crown terminal feet interfaced with a laminar bus structure. Note that the top plate of the bus was held at an ambient temperature of 25°C and no heat transfer was allowed at any of the other surfaces. The temporal evolution of the hotspot temperature for this scenario is presented in Fig. 3, which also includes actual embedded thermocouple data. Excellent agreement between the simulated and measured hotspot time constant is demonstrated, which is critical relative to the electric vehicle duty cycle. Note that the absolute value of the temperature rise is highly dependent upon the tolerance of the film metallization sheet resistance.

This advanced capacitor simulation tool works in conjunction with SBE’s temperature rise test facilities and extensive life testing program to support next-generation film capacitor design. As such, the unique annular form factor of the SBE Power Ring can be exploited to offer the highest possible ripple current rating per unit capacitance with exceptional reliability. Please contact our applications engineering team for further information.



Color Shade Results (°C)

25/25.284	🟦
25.28/25.57	🟦
25.57/25.85	🟦
25.85/26.14	🟪
26.14/26.42	🟪
26.42/26.71	🟪
26.71/26.99	🟥
26.99/27.27	🟥
27.27/27.56	🟧
27.56/27.84	🟧
27.84/28.13	🟧
28.13/28.41	🟨
28.41/28.70	🟨
28.70/28.98	🟨
28.98/29.27	🟨
28.27/29.55	⬜

Figure 2: Thermal profile for the 700D348 at equilibrium for 200 Arms ripple current at 20 kHz.

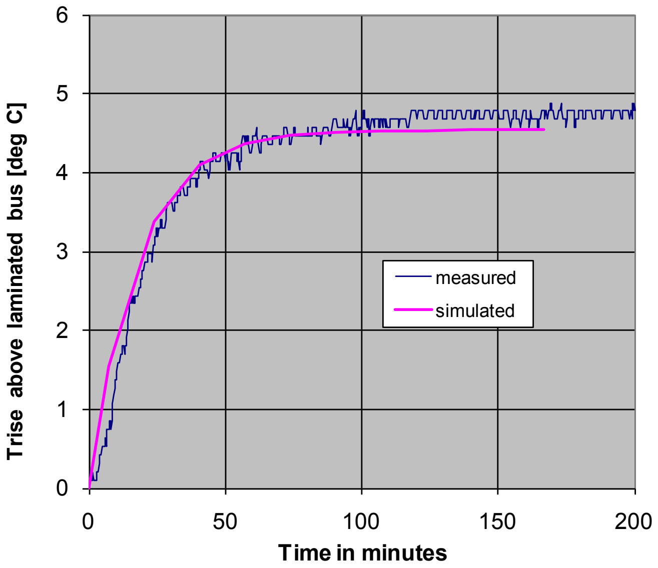


Figure 3: Temporal evolution of hotspot temperature for 700D348 with a 200 Arms ripple current at 20 kHz.

Reference: 1. Sawyer, Edward. *"Low Inductance – Low Temp Rise DC Bus Capacitor Properties Enabling the Optimization of High Power Inverters"*. Presented at PCIM Europe 2010.