Film Capacitors with Integral Water Cooling Provide Efficient Heat Transfer and System Thermal Management.

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Abstract:

An increasing number of power electronic systems require film with foil and metallized film capacitors to handle high currents. These systems generally rely on water cooled chill plates for thermal management of their components (IGBTs and capacitors). However, integrating water cooling to film capacitors is a technique that until recently was reserved for the Induction Heating market. Water cooled capacitors have a forty year history of reliability in these industries. Effective heat transfer using various types of integral water cooling methods for film capacitors is demonstrated in this study as well as its effect on capacitor performance. This study also shows that direct water cooled capacitors occupy much less volume than their air cooled counterparts.

Introduction:

Capacitors generate heat via dielectric losses and connection losses between the dielectric and the terminals. These losses can be modeled as a series combination of the capacitor and ESR.[1] Thermal changes can be calculated simply heat generated minus the heat dissipated. The heat rise during operation can then be expressed as a thermal resistance with units of ºC/watt.

DC Link and AC filter capacitors with very high current requirements are common in power inverters and power supplies. Capacitor packaging plays a major consideration in system design; some people use a single large unit, while others prefer bundling smaller capacitors into banks. The packaging decision also affects the appropriate cooling method.

For induction heating and melting applications, high operating currents preclude the use of electrolytic capacitors. For applications such as medium voltage motor drives and wind or solar power systems, designers have a choice between film and electrolytic capacitors. Cost, volumetric efficiency, and maintainability are the major factors in this decision. As metallized film capacitor manufacturing techniques and materials continue to improve, their volumetric efficiency and cost have become increasingly attractive. As many power systems are installed in applications that make servicing difficult, it is important to select the right capacitor(s) and to ensure they meet the appropriate cooling guidelines.

The life of a film capacitor with the appropriate assembly technology is usually defined by a lifetime at a given hotspot and voltage. As the voltage increases or decreases versus the voltage rating, the life is affected by a ratio of the application voltage versus the rated voltage raised to an acceleration exponent. Equation (1) shows this relationship:

$$A_v = (V_R / V_A)^9 \qquad (1)$$

Where A_v is the acceleration due to voltage, V_A is the application voltage and V_R is the rated voltage.

The life expectancy versus a given temperature is usually not based upon the ambient temperature alone. It is more appropriate to specify the life versus a given hot spot temperature. The life expectancy versus a given hot spot temperature is given by an appropriate temperature dependence constant n. The life expectancy varies by 2 raised to the power of **n** as given by:

$$A_T = 2^{(HS_R - HS_A)/n} \qquad (2)$$

Where HS_R is the rated hot spot temperature and HS_A is the hot spot temperature in the application. It should be noted that the rated hot spot temperature is usually less than the maximum operating temperature. For typical chemical reactions which approximate film capacitor aging, the temperature dependence coefficient is about 10, which means a doubling of the reaction for every 10°C. Film capacitor data sheets assign **n** a value of 7 or 8, which is appropriate for hot spot temperatures over 85°C.

As an example, let’s assume an actual hot spot temperature of 60°C (rating is 70°C) and a standard life of 100,000 hours. The estimated life in hours is given by

$$100{,}000 * (V_A / V_R) * 2^{(70-60)/10} \qquad (3)$$

Each component in a power electronics system has a life expectancy that will vary according to operating temperature. If heat is removed from the capacitor by convection, it will contribute to a rise in the equipment cabinet temperature. If forced convection is used, fans or blowers must be sized for proper heat transfer.

In many power electronic systems, the temperature threshold has already been reached for various components where liquid cooling has been adopted. The DC Link and AC capacitors are considered critical components, yet are not in the liquid cooling loop. The capacitor is “on its own” with respect to thermal management. Designers use large banks of small capacitors in order to limit heat generation in a given part.

Another alternative is to use a film capacitor with integral water cooling. Using the liquid cooled polymer film capacitor technology, a system designer can realize a substantial reduction in parts used, volume and cost.

Cooling Coils:

The preferred cooling coil material is copper. Coil dimensions are typically 12 or 12.7 mm outside diameter with a wall thickness of 1.0 mm. For the highest power applications, the coil is connected to one or both poles of the capacitor and is electrically live. Examples of some capacitors with integral liquid cooling are depicted in Figure 1.

Figure 1. Capacitors with water cooling.

In designs where Aluminum is in the cooling loop, a copper coil cannot be used. These dissimilar metals will cause galvanic corrosion in the cooling loop. 316SS can be used in these circumstances, even though stainless steel has higher thermal impedance than the copper cooling.

Cooling Liquids:

The typical coolants used for capacitors with integral liquid cooling are water, de-ionized water, and mixtures of water and other liquids such as ethylene glycol. Suitable corrosion inhibitors are used with the cooling liquids. There are numerous studies that demonstrate the utility of glycol-water mixtures in sub-freezing conditions.[2]

Thermal Performance Testing:

Two NWL capacitor models with integral cooling coils were selected for testing. One of the capacitors had a nominal capacitance of 5000 µF with a nominal DC rating of 900 VDC. This capacitor was designed to be a high current DC filter capacitor with a maximum ripple current of 2500 Arms. The DC capacitor used polypropylene dielectric with special segmented metallization. The typical ripple frequency in the application for this DC capacitor ranges from 100 Hz to 2500 Hz.

The other capacitor had a nominal capacitance of 102 µF with a nominal AC rating of 1250 Vrms at 3 KHz. The AC rating produces a nominal AC power of 3000 Kilovolt-amps or KVar at maximum voltage. This AC capacitor has a maximum rated current of 2400 Amps. This capacitor used an All Film with metal foil technology. The electrical and the mechanical specifications of the two test capacitors are depicted in Tables 1 and 2. The actual measured capacitance is somewhat higher than the nominal due to the required manufacturing tolerance of +10 -0% on both of the parts.

NWL Model Number	Capacity (uF)	Voltage	Voltage Type (AC or DC)
WC1124	102	1250	AC
WB1128	5000	900	DC

Table 1. Electrical criteria of test capacitors.

NWL Model Number	Length (cm)	Width (cm)	Height (cm)
WC1124	34.3	14.6	47.0
WB1128	55.9	12.7	53.3

Table 2. Mechanical sizes of test capacitors.

The AC capacitor was installed in a test circuit at 2.98 KHz and was supplied by a 200 Kilowatt power supply in a resonant tank circuit with a water cooled inductor. The capacitor has two live cooling coils, one that is common to its aluminum case and a second one that is isolated from the aluminum case using ceramic insulators. Thermometers were affixed to the capacitor surfaces to monitor the surface temperatures. Tap water was run through the cooling coils at 3.78 liters/min. (1gal/min.) with a starting temperature of 14.5°C. The ambient temperature was 22°C. The capacitor under test is depicted in Figure 2. The applied current was measured using a Rogowski current transducer.

The AC capacitor test started with the voltage at 1100 Vrms, which produced a measured current of 2183 amps rms. The 1100 VAC condition was maintained until thermal stability was reached at 3 hours. The surface temperatures and the water output temperatures were recorded at the 1100 Vrms condition. The voltage was then increased to 1250 Vrms, producing a measured current of 2481 amps rms. Thermal stability was reached after an additional 3 hours, whereas the surface temperatures and the water output temperatures were again recorded. The temperature values obtained from the 1250 VAC power test are depicted in Table 3.

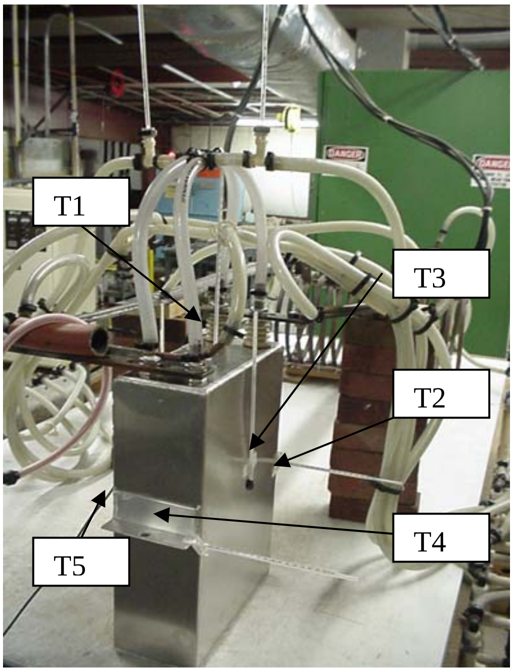


Figure 2. 1250 VAC capacitor under test.

Parameter	Amb. 22°C	Amb. 22°C
Voltage (rms)	1100	1250
Current (I_{rms})	2183	2481
T1°C	59	70
T2°C	52	66
T3°C	48	55
T4°C	53	69
T5°C	48	54
Maximum ΔT	37	48

Table 3. Temperatures of 1250 VAC Capacitor

The second test was performed on the 900 VDC rated capacitor using the 200 Kw power supply. In order to generate the high frequency ripple current on the large capacitance value within the constraints of the power supply, the DC capacitor was wired in series with a water cooled AC capacitor. A resonant tank circuit was by placing both capacitors in parallel with a water cooled inductor. The 900 VDC capacitor had two copper cooling coils that were both electrically live and isolated from its aluminum case using ceramic feed thru terminals.

The DC capacitor also had thermometers affixed to its surfaces and water was connected to the cooling coils. The ambient temperature was 22°C and the measured input water temperature was 13°C. Tap water was run thru the cooling coils at 7.56 liters/minute.

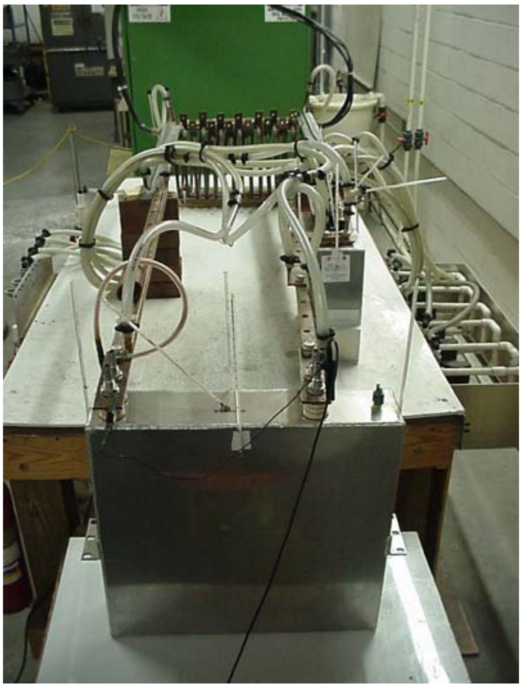


Figure 3. 900 VDC capacitor under test.

The DC capacitor power was adjusted to produce a ripple current at 3.12 Khz of 1600 Arms. The temperature was stable after 4 hours and the temperature readings were recorded for the surface thermometers and output water. The current was then increased to 2000 Arms and the temperature readings were read at stability after an additional 3 hours.

It was observed that the maximum surface temperature at the 2000 amp rms condition was 49°C or a ΔT of 27°C over ambient. We then sought to measure what the rms current could be run through an air cooled device at the same temperature readings. A welded, unpainted aluminum or stainless steel case has a thermal impedance of 0.023 watts/cm^2 (previously measured by NWL), resulting in a differential temperature of 10°C. The measured ESR of the 900 VDC test capacitor at 3 Khz was .00081 ohms. The total watts, Q is given by: [3]

$$Q = P_d + P_t \qquad (3)$$

Where:

$$P_d = [1/2 \cdot C_n \cdot (V_{pp})^2 \cdot f] \cdot (2 \times 10^{-4}) \qquad (4)$$

and:

$$P_t = R_s \cdot I^2_{rms} \qquad (5)$$

For this type of high frequency test on a DC capacitor, P_d can be ignored and $Q = P_t$ for our 900 VDC capacitor at 2000 Arms or:

$$Q = .00081 \cdot (2000)^2 = 3240 \text{ watts} \qquad (6)$$

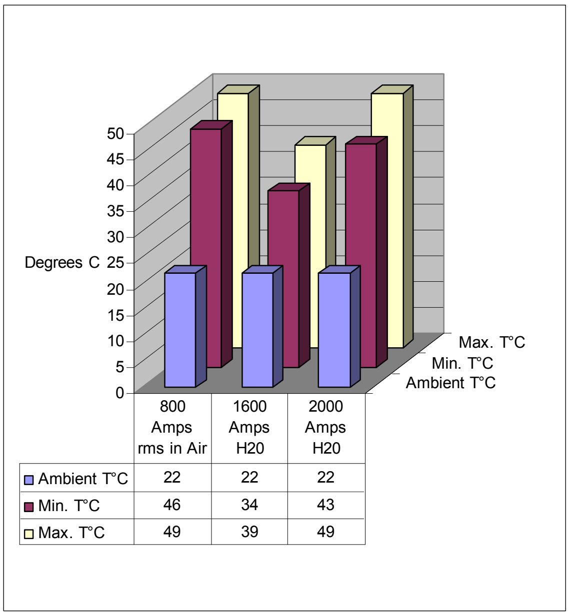
From table 2, the calculated surface area of the 900 VDC rated capacitor is 8732.6 cm^2. Given a thermal impedance R_{th} of 023 watts/cm^2 for ΔT of 10°C and assuming this parameter is linear with power level, then we are able to calculate that a differential of 27°C equates to a thermal impedance of 062 watts/cm^2. This capacitor requires 541.1 watts to produce a ΔT of 27°C without water cooling.

Using equation 5, we calculate the estimated current needed at 3 Khz to produce a 27°C increase in hot spot temperature should be 835.5 amps rms. Testing on this capacitor without water cooling started at 800 amps rms. Test frequency was 3.12 kHz with an ambient temperature of 22°C and natural convection. After 4 hours it was observed that the surface temperatures were stable with a maximum surface temperature of 49°C (ΔT = 27°C).

The results for the power testing of the 900 VDC rated DC capacitor are shown in Figure 4. In this graph is can be seen that the maximum hot spot temperature is 49°C and the ΔT from ambient of 27°C was the same value for both the 2000 Amp condition with water cooling and the 800 amp condition with no water cooling.

We will now examine the volume differences of water cooled and air cooled capacitors. From table 2, the 900 VDC capacitor (NWL model no. WB1128) has a total volume of 0.038 m^3. We also know that 2.5 air cooled capacitors would be required to handle the same current at the same hot spot temperature. NWL data has shown that similar results can be obtained with four natural convection cooled cases as shown in Figure 5. This is the typical air cooled strategy of multiple cases of up to 500 amperes each.

In figure 5, the air cooled cases are 11.7 cm x 34.0 cm and 53 cm tall. With a 2.5 cm gap between them, the volume is approximately 0.1 cubic meters. The volume of the liquid cooled capacitor is less than half of the convection cooled capacitors' volume.



	800 Amps rms in Air	1600 Amps H20	2000 Amps H20
Ambient T°C	22	22	22
Min. T°C	46	34	43
Max. T°C	49	39	49

Figure 4. Thermal results for 900 VDC rated capacitor.

AC capacitors present a greater cooling challenge compared with DC capacitors. The tested AC capacitor has a measured 3 Khz ESR of .00064 Ohms. At 1250 Vrms and 2481 Arms at 2980 Hz, the dielectric loss component, P_d is considerably higher than that calculated for the DC capacitor. We can convert the 1250 Vrms to 3535 Vpp and substitute into equation (4) to produce a P_d of 394.7 watts. Substituting into equation (5) we calculate P_t is 3939.4 watts.

We therefore have determined that for the AC capacitor or a DC capacitor with high ripple voltage, the dielectric losses due to the peak to peak voltage is no longer negligible. This fact contributes to additional cooling requirements which can make liquid cooling of greater consideration.

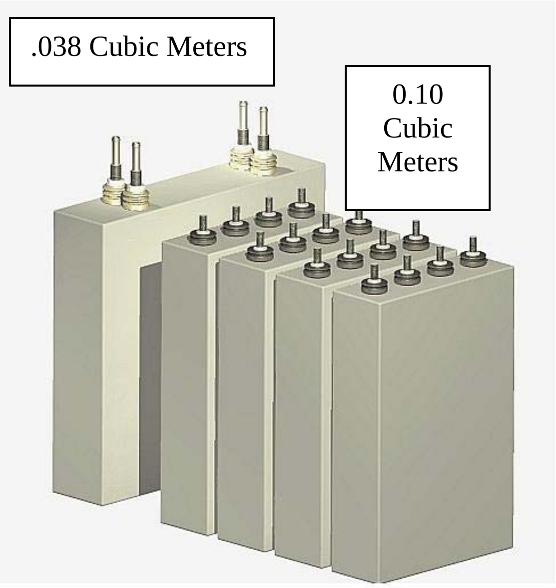


Figure 5. DC Filter capacitors volumes with air and liquid cooling.

Conclusion:

The application of liquid cooling for polymer film dielectric capacitors for AC and for DC applications was demonstrated. Liquid cooled capacitors will become more common as power electronics' energy densities increase.

References:

[1] J. Lee., K. Nam, "An Optimal Selection of Induction-Heater Capacitance Considering Dissipation Loss Caused by ESR". IEEE Transactions on Industry Applications, Vol. 43, No. 4, July/August 2007.

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[3] G. Buiatti, S. Cruz, A. Cardosa, "Lifetime of Film Capacitors in Single-Phase Regenerative Induction Motor Drives". IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, Cracow, Poland, pp. 356-362, 2007.