Electrolytic Capacitor Thermal Model and Life Study for Forklift Motor Drive Application

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Abstract

Electrolytic Capacitors (E-Cap) are commonly used as ripple-current filters at the input of the inverter of AC motor drive control systems used in electric vehicles. These capacitors have a ripple-current rating but may in fact be used at values higher than this rating. Ripple current causes heating of the E-Cap, which can significantly impact its life and thus be a major influence on the reliability of the entire system. Here we discuss how to develop a thermal model of the E-Cap that can be used in the system control algorithm to monitor, and if necessary, reduce transient core temperature response of the E-Cap to maintain the system life and increase reliability. The model described in this paper is a second-order thermal model used to allow operational conditions that limit the temperature increase to < 30^{o}C. An E-Cap life study will be also discussed for the worst-case environment temperature.

Keywords: Electrolytic Capacitors (E-Cap), Thermal model, AC motor drive, ripple-current, reliability

1 Introduction

Electrolytic Capacitors (E-Caps) are commonly used as ripple filters at the input of the inverter for an AC motor drive control system. Ripple current (including that over the rated value) causes heating of the E-Cap, which will significantly impact its life and thus can be a major influence on the entire system reliability. An example of this type of motor control unit with the E-Caps, shown in Figure 1, is used, for example, in forklifts, golf cars, and other electric motor drive vehicles. A diagram of the E-Cap used in this study is shown on the right side of Figure 1. The model developed here is a second-order thermal model and is used to limit E-Cap core temperature increase to <30 ^{o}C. The thermal model can be implemented in the system control algorithm to monitor the transient core temperature response, which will help maintain the system life and reliability.

Figure 1. The pictures on the left and in the center show a motor control unit with E-Cap-Bank, courtesy of Curtis Instruments Inc. The diagram on the right shows the dimensions of the model LXZ 63V 820 capacitor used in the unit.

2. Thermal model study

The thermal response of the capacitor is modelled with two steps where 1) heat generated in the core of the capacitor because of the ripple current is transmitted to the capacitor case and 2) then heat is transferred to the ambient, surrounding conditions. For each step of the heat flow there is a thermal capacity and a thermal resistance. The model, with the derived parameters, is shown in Figure 2.

The basic theory is well known for C-R transient circuit analysis. In the electronic model, when a DC voltage E is applied at t=0 to the series circuit of C and R. The transient voltage response V(t) can be expressed as $V(t) = E*(1-e^{-t/CR})$. The time constant τ in the circuit is defined as $\tau = C*R$. In the thermal model, the time constant $\tau = \theta c*\theta r$ where θc is the sum of the thermal capacities and θr is the sum of the thermal resistances.

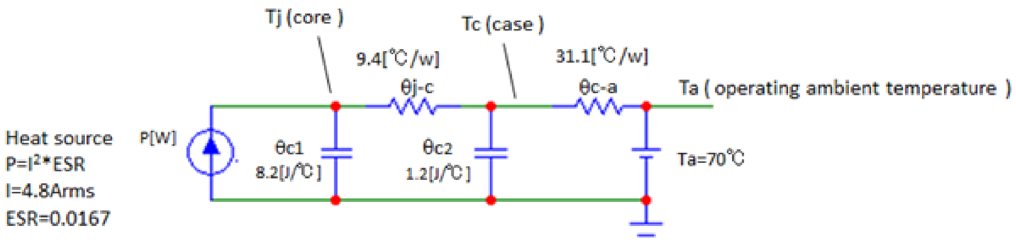

Figure 2: Thermal model developed for the tested capacitor. ESR: Internal resister of E-Cap.

In Figure 2, Ta is the ambient temperature (70 °C), θc-a is the thermal resistance to heat flow between the case and ambient with units of °C/W, θc2 is the heat capacity of the case with units of J/°C, θj-c is the thermal resistance to heat flow between the case and capacitor core with units of °C/W, θca is the heat capacity of the capacitor core with units of J/°C, and P[W] is the power dissipated in the capacitor due to the filter ripple current and the equivalent series resistance (ESR) of the capacitor. This model is analogous to a C-R electronic circuit where voltage changes cause current flow in the electronic circuit. Temperature drives heat flow in the thermal model.

The thermal capacity and thermal resistance values for the model are obtained from temperature test data. A known power was applied to the test capacitor and the temperatures of the E-Cap core and case were monitored. Ambient temperature Ta = 70 °C. The result is shown in Figure 3. In this study, ESR=0.0167 Ω and the ripple current used is 4.8 A_{rms} for an E-Cap with a ripple current rating of 2.59 A. The thermal time constant, $\tau = \theta c*\theta r$, is defined as the time at which the temperature reaches 63% (i.e. 1-1/e) of the steady state value. In this case the thermal time constant is $\theta c*\theta r = 382.5$ s as shown in Figure 4.

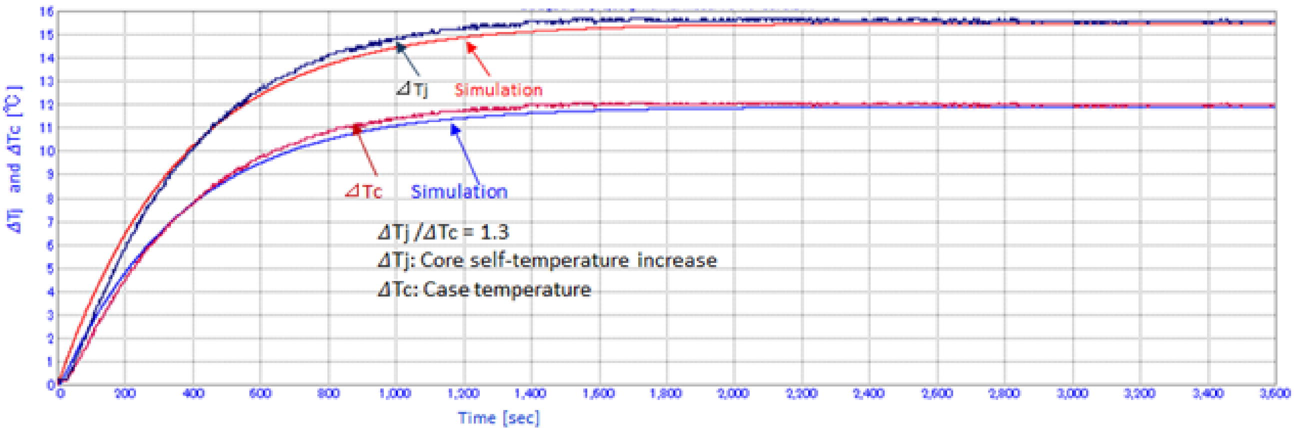

Figure 3. Thermal transient response for 4.8 Arms for the test E-Cap that has a rated ripple current of Io = 2.59 A.

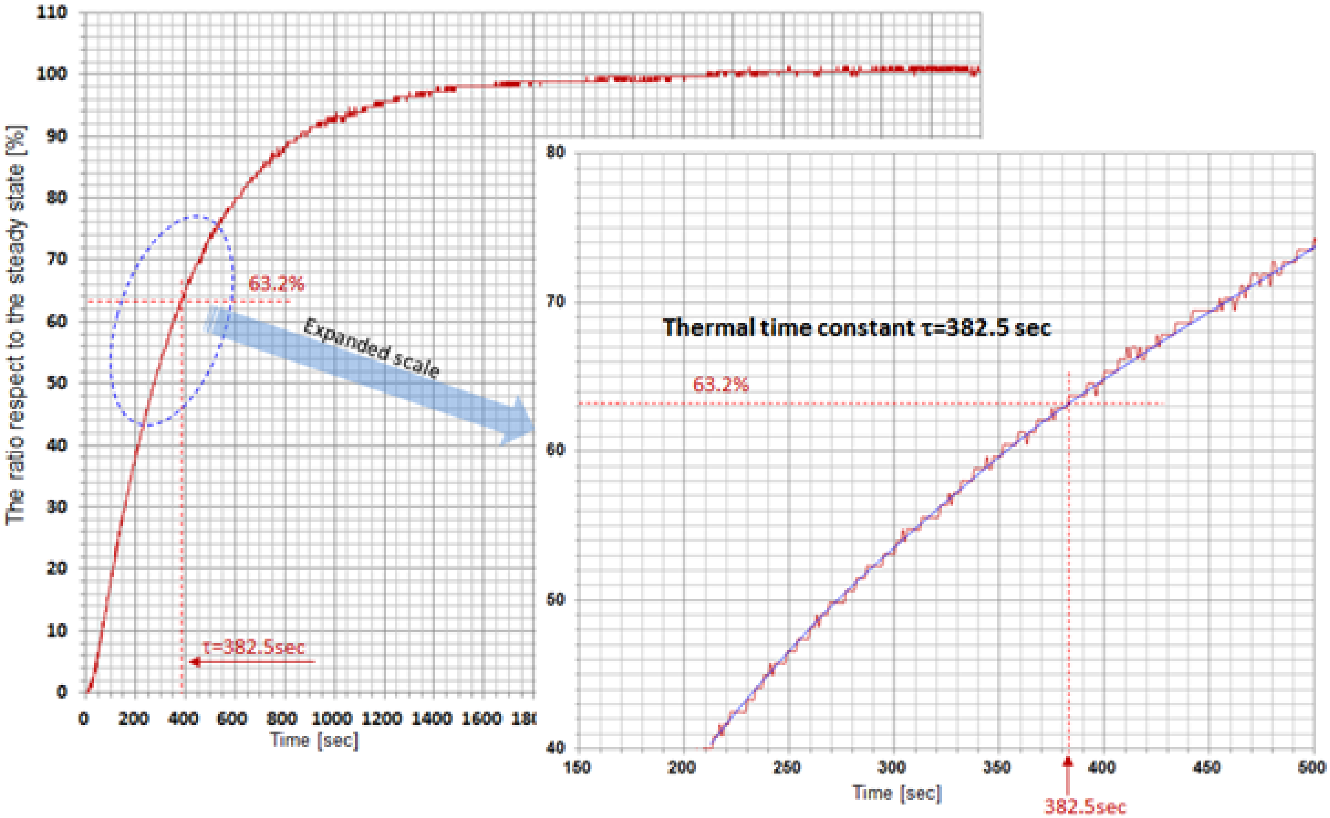

Figure 4: Core temperature increase with the steady state temperature value is shown as 100%.
The thermal time constant is the time at which the temperature reaches 63% of the steady state value.

The heat source power at the core is P= 4.8^2*0.0167=0.385 W. θr is determined from the total temperature rise and the power dissipated in the capacitor: θr = 15.6 °C/0.385 W =40.5 °C/W. Thus, θc= 382.5 s/40.5 °C/W = 9.4 J/°C.

Values for the individual thermal resistances and thermal capacities of the model shown in Figure 2 are calculated as follows. The thermal resistance for flow of heat from the core to the case is calculated from the difference in the temperature of the case, Tc, and the temperature of the core, Tj, and the power dissipated in the E-Cap. θj-c= (Tj-Tc)/P = (15.6-12℃0)/0.385 W = 9.4 °C/W. The thermal resistance for flow of heat between the case and ambient is θr - θj-c = 40.5 – 9.4 =31.1 °C/W.

The thermal capacity of the E-Cap case is a known quantity since the case is Aluminium with a specific heat of 0.905 kJ/(kg-°K) and a density of 2688 kg/m^3.

For the test capacitor, model LXZ 63V 820 shown in Figure 1, the total volume of aluminium in the case ϕ18 x 25 mm with a thickness t=0.3 mm is V=$5x10^{-7}m^3$. Thus, the calculated aluminium case thermal capacity $θc_2$=1.2J/ °C. The thermal capacity of the core is then θc - $θc_2$=9.4J/°C-1.2 J/°C = 8.2 J/°C.

Differences between measured temperature values and calculated temperature values using the Figure 2 model are shown in Figure 3 for both the temperature of the core and the temperature of the case.

The model is accurate in predicting both temperature values with a maximum error of 1.3 °C for the core temperature, as shown in Figure 5. The model is well-suited for predicting core temperature rise to ensure ΔTj <30 °C.

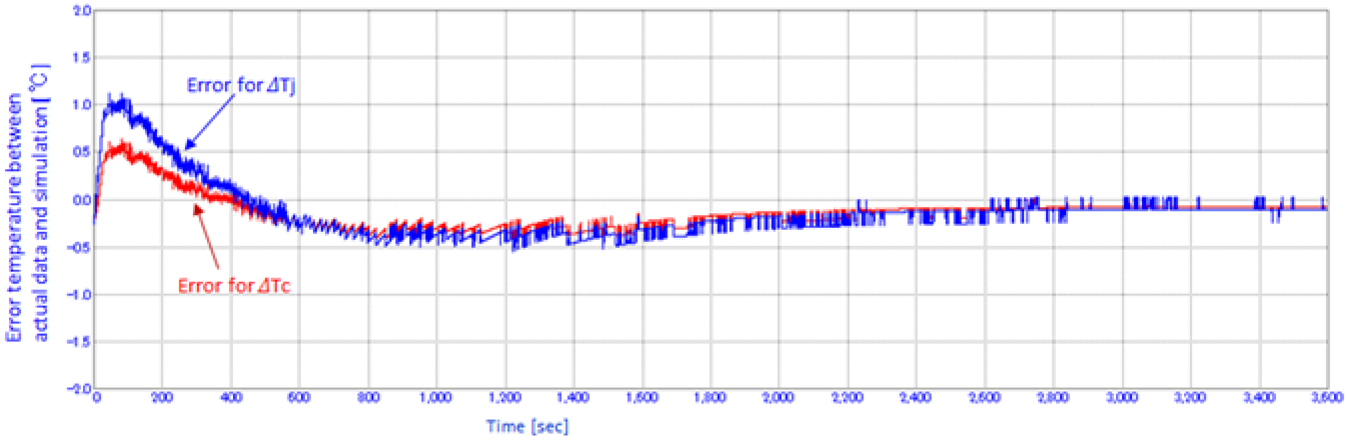

Figure 5: Error between the actual thermal transient and the simulation

3. Life study

The life required for the capacitor in the worst case temperature scenario is 15 years. The equation used to describe life as a function of ambient, rated, and operational temperatures is:

$$Lx = Lo*2^{(To - Tx)/10} *2^{(\Delta To - \Delta T)/k} \quad (1)\ [5]$$

where Lo is the rated life, To the rated temperature, Tx: the ambient temperature, ΔTo is specified by manufacture, and ΔT is the operational temperature increase caused by the ripple current. Note, no degradation of capacitor parameters is included. Actual usage will be in a variety of different climates and may be in a warehouse or outside. We derive a worse-case scenario assuming the system temperature is 20 °C above ambient temperatures for the state of Arizona in the USA. This ambient temperature distribution is shown in Figure 6 and tabulated in Table 1.

The life expectancy is calculated based on number of hours at each temperature (including the +20°). The temperatures and number of hours at each temperature based on the Arizona temperatures were simplified, as shown in Tables 2 and 3, to assume the capacitor experiences 3600 hrs at 40 °C, 2280 hrs at 50 °C, and 2880 hrs at 60 °C during one year.

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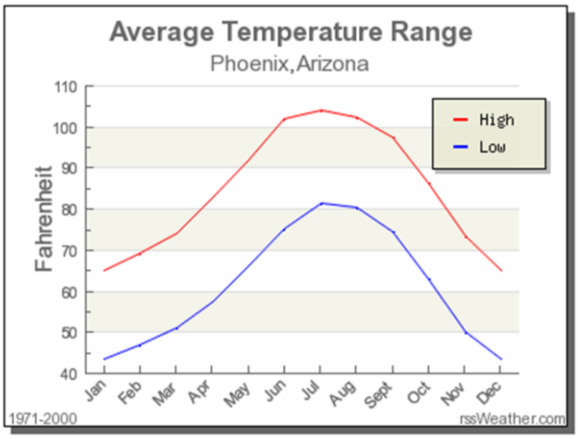

Figure 6: Average temperature distribution for YR1971 to 2000. [4]

Table-1: High temperature profile[℃] from Figure 6

Month	High/C
Jan	18.3
Feb	20.8
Mar	23.5
Apr	28.3
May	33.3
Jun	38.9
July	40.1
Aug	39.1
Sept	36.3
Oct	30.2
Nov	22.9
Dec	18.3

Table-2: Hours at each temperature in one year used for the worst case scenario life calculation.

Month	Jan-Mar Nov-Dec	Apr, May Nov, Dec	Jun - Sept
Number of Hours	3600 hrs	2280 hrs	2880 hrs
Temperature	20℃	30℃	40℃
Inside of system +20℃	40℃	50℃	60℃

Table-3 Fraction of time at each temperature for one year.

T[℃]	Hours	Ratio
40	3600	0.41
50	2280	0.26
60	2880	0.33
Total	8760	1.00

The tested E-cap is a LXZ series 820uF/36V. Manufacture specifications are: Rated life, Lo: 8000hrs, rated temperature To: 105 °C, (ΔTo: 3 °C, K=5), and rated ripple current Io: 2.59Arms.

E-Cap temperature T will be proportional to the heat power $P=ESR*I^2$ on the ESR. $T = K*ESR*I^2$.Where, K is a coefficient number.

The self-heating temperature increase ΔT depends on the actual ripple Ix and the rated ripple current Io and can be expressed as:

$$\Delta T = \Delta To*(Ix/Io)^2 \qquad (2)$$

or

$$Ix/Io = \sqrt{\frac{\Delta T}{\Delta To}} \qquad (3)$$

Figure 7 shows the calculated life expectancy for individual E-Cap ambient temperature Tx = 40 °C℃ 50 °C ℃ and 60 °C. Figure 8 shows the worst case scenario descussed above using the different number of hours at each temperature each year.

The calculated life expectancy for this particular LXZ series 820uF/63V is 200,000 hrs and above when Ix/Io = 1.5. However, the actual expected life could be 15 years (131,400 hrs) to 20 years (175,200 hrs) due to the degradation of the capacitor, specifically of the rubber sealing material.

The Figure 8 shows that if the motor control system could monitor the E-Cap self-temperature increase ΔT with thermal model built in the system control algorism, the life can be expected 15 years or more by maintaining total RMS ripple current ration less than Ix/Io= 1.5. See formula (3).

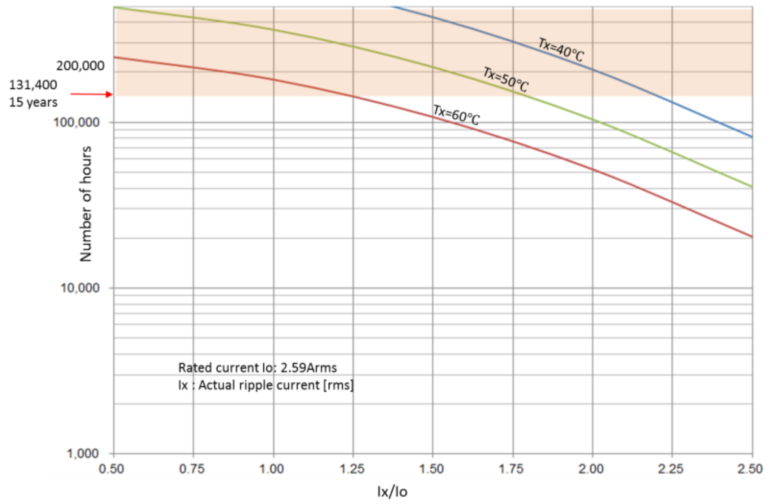

Figure 7: Life expectancy for E-Cap ambient temperature Tx = 40 °C, 50 °C and 60 °C.

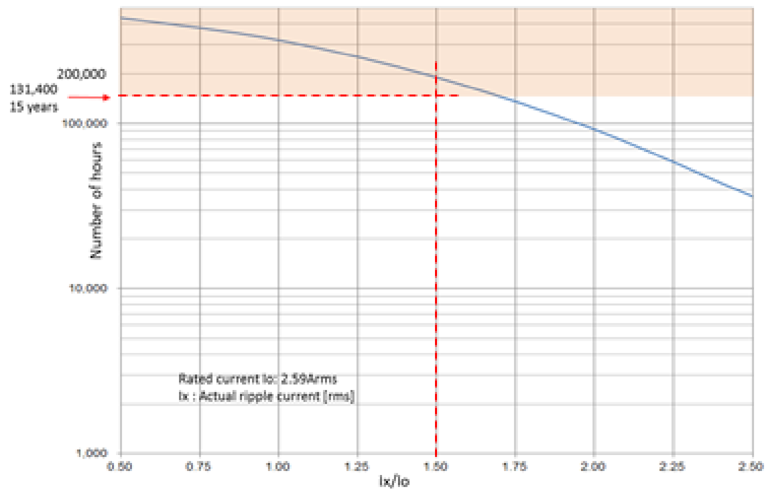

Figure 8: Life expectancy with the worst case scenario temperature profile at Phoenix Arizona USA. See Table-2 and 3.

The Transient of the core self-temperature increase ΔT must be monitoring for <30℃ because of safe operation of the system reliability issues. When the ΔT reached 30℃, the system shuts off the current to E-Cap to avoid failure. The assumption of the life calculation is that E-Cap life follows the Arrhenius' Law during operation.

4. Basic system block diagram

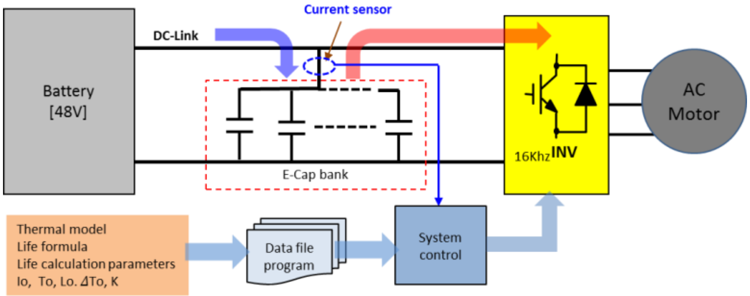

Figure 9: The basic block diagram.

When the temperature in the thermal model reached ΔT=30 ^{o}C, the drive power to motor can be reduced with system control. For a 30% reduction in drive power, the ripple current will be reduced approximately 50%.

5. Summary

- ➢ Thermal model can be developed from temperature transient response data.
- ➢ The developed thermal model can be used to monitor the core temperature transient response and steady state to maintain the system reliability.
- ➢ The transient temperature rise monitoring ΔT < 30 ^{o}C is to avoid a failure that no longer follows the Arrhenius' relationship.
- ➢ The steady state ΔT with life equation (1) can be monitored for real time life expectancy.
- ➢ The thermal parameters can be implemented into the system control algorithm for reliable motor control system design.

Acknowledgments

The authors would like to thank the assistance provided by Scott Bowman, Bob Fusco and Doug Carpenter at Curtis Instruments Inc., Kentaro Nakaaki/Director of engineering, and Kazuhiro Seya who recorded much of the temperature test data for this project at Nippon Chemi-Con. The authors also thank Toshi Takasugi, Koich Fumoto, Yoshihisa Yura and George Iftimie at United Chemi-Con, Inc for support of the project.

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