36th International Electric Vehicle Symposium and Exhibition (EVS36)
Sacramento, California, USA, June 11-14, 2023

DC-Link-Capacitor Life Prediction in an Electric Motorcycle using the World Motorcycle Test Cycle

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Executive Summary

Carbon neutrality by 2050 has been a global trend since adoption of the landmark Paris Agreement on climate change [1]. As a result, demand for zero-emission electric motorcycles is expected to increase just as with other EVs. Here we predict the life of DC-link capacitors in the inverter of a drive motor in an electric motorcycle using the standard World Motorcycle Test Cycle (WMTC)[2]. We predict capacitor life considering self-heating during operation and environmental stress contributions when the motorcycle is not in operation.

1 Introduction

The life of a DC-link capacitor in any application depends on its operating temperature with shorter life at higher temperatures due to electrolyte loss by diffusion through polymeric package seals. Two factors contribute to capacitor temperature-related life-degradation, ambient temperature and the temperature rise caused by self-heating during operation. For an electric motorcycle, where operation is estimated to be about 1 hour per day (4.2% of the time), Miner's Rule [3] is not applicable during both operating and non-operating times.

Capacitor self-heating during operation is caused by ripple-current, which depends on the motorcycle power profile. Here the ripple current is simulated using the speed profile of the WMTC. To perform this calculation, we assume a vehicle gross weight of 320 Kg. This gross-weight value would be typical for a mid-size electric motorcycle with battery that is being ridden by a 7 kg driver.

2 Capacitor Self-heating

This analysis is for a Nippon Chemi-Con aluminum electrolytic capacitor series GXF rated at 200 μF, 160 V, and 3000 hours of life at 125 ℃. This capacitor reaches end of life, defined as 30% capacitance loss and/or a 300% dissipation factor increase, when its total electrolyte loss reaches 462 mg. Ripple current generates heat that causes the temperature rise in the capacitor, the amount of heat being proportional to the capacitor's equivalent series resistance (ESR). A thermal model for this capacitor is shown in Figure 1, where heat generated in the core of the capacitor then passes to the capacitor case and is shed to the ambient temperature Ta around the capacitor in a two-step process through thermal resistances $\theta r1$ and $\theta r2$ having thermal heat capacities $\theta c1$ and $\theta c2$. The diffusion rate of electrolyte out of the capacitor through package seals as a function of temperature is known for this particular component.

Using the WMTC speed profile shown in Figure 2, the vehicle gross weight, and the thermal model shown in Figure 1, capacitor ripple-current and temperature rise can be calculated along with the associated electrolyte diffusion rate out of the capacitor. The final calculation is the total mass of electrolyte that is lost. This is displayed in Figure 5.

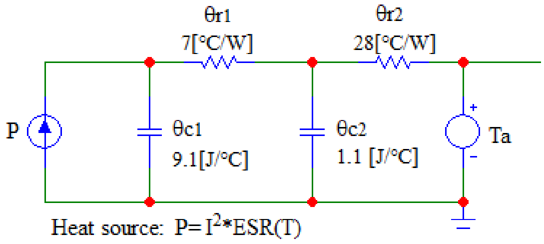

Figure 1: Thermal model of GXF-series capacitor rated at 200 μF, 160 V, 125 °C that was used in this analysis.

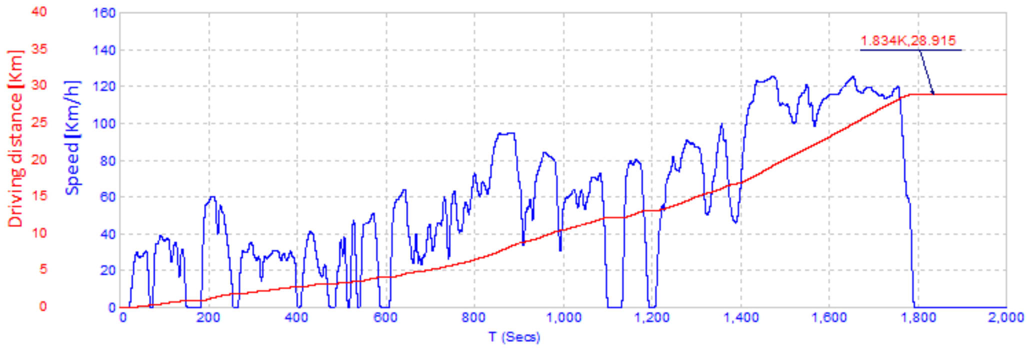

Figure 2: WMTC (World Motorcycle Test Cycle) standardized speed/time profile.

3 Contribution from Ambient Temperatures

The ambient temperature profile used in this analysis starts with the standard climate record for Phoenix, Arizona, US as shown in Table 1 [4]. This data has been rearranged into three temperature groups; 20, 30, and 40 °C.

We then assume that the motorcycle is subjected to 10 ºC higher temperatures during non-operation due to radiant heating from a sunny parking lot and 35 ºC higher temperatures during operation due to heat generation from the power electronics and the traction motor. Thus, the ambient temperatures experienced by the motorcycle are as shown in Figures 3 and 4. Motorcycle life is assumed to be 10 years, or ~87,600 hours.

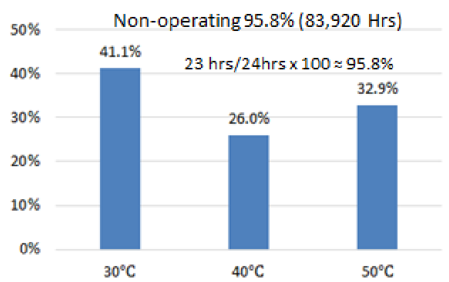

Figure 3: Ambient temperature of the capacitors. For example, over ten years, the capacitors will be at 40 ºC for 0.26 x 83,920 = 21,819 hours.

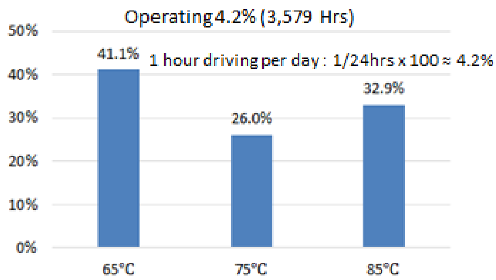

Figure 4: Capacitor ambient temperature during motorcycle operation, which is assumed to be 35 ºC above the non-operating temperature caused by heat generated in the power electronics and the traction motor.

Table 1: Assumed Phoenix, Arizona, US temperatures arranged into three groups from reference 4.

Period	Jan. To Mar, Nov to Dec	Apr to May, Oct	June to Sept
Duration (hours)	36,000	22,800	28,800
Environmental Temp (ºC)	20	30	40
Percent of time	41.1%	26.0%	32.9%

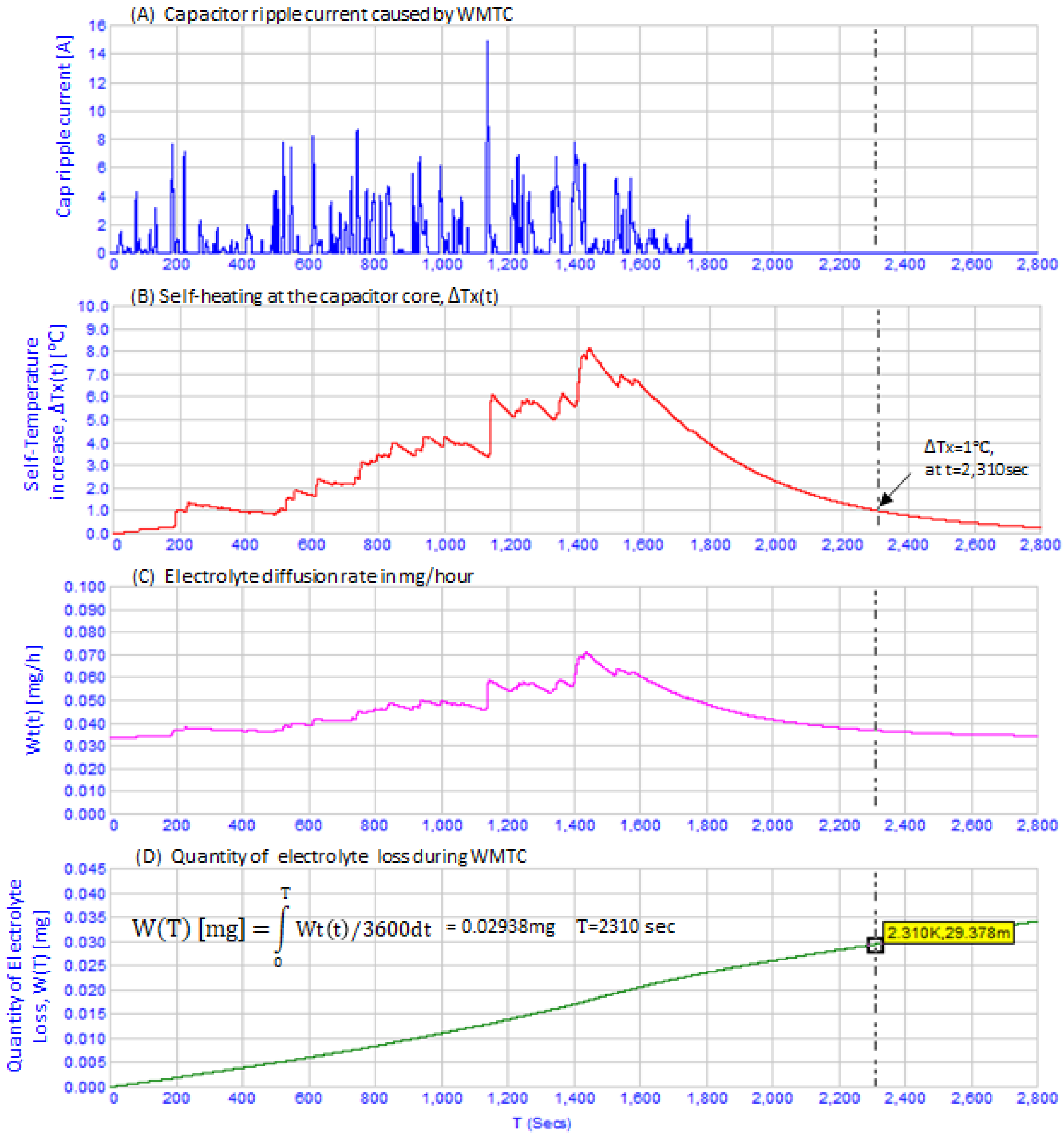

Figure 5: Approach to project capacitor life caused by electrolyte loss due to package seal diffusion at 105 ºC ambient during WMTC speed profile operation. (A): Capacitor ripple current during the WMTC (World Motorcycle Test Cycle), (B): Capacitor self-heating, ΔTx(t), (C): Diffusion rate of electrolyte at 105 ºC ambient temperature around the capacitor, and (D): Total electrolyte quantity lost due to diffusion.

4 Life Analysis

Capacitor end of life (EOL) is defined as the time at which the capacitance value has declined by 30% or the energy dissipation factor has increased by 300%. Both changes are due to electrolyte loss. When total electrolyte loss reaches mass Wo, the capacitor has reached its EOL. The electrolyte loss rate as a function of time, Wt(t), shown in Figure 5(C), is calculated using equation (1) [5].

$$Wt(t) = Ws\,(Ta) * K1^{(\Delta T(t)/K2)} \quad (1)$$

Here t is time, Ta is the ambient temperature, ΔT(t) is the change in temperature calculated for the drive cycle, Ws(Ta) is the electrolyte diffusion rate at the ambient temperature Ta, and K1 and K2 are known constants that are functions of temperature. The total mass lost during the drive cycle, equation (2), is calculated by integrating this equation over the time period of the WMTC drive cycle, which is shown in Figure 5(D).

The integration limit T is selected as the time it takes for the capacitor temperature to return to within 1 °C of its starting temperature.

$$\mathrm{Wm(T)}=\int_0^T Wt(t)dt \tag{2}$$

The total electrolyte lost during the WMTC drive cycle is 0.0293378 mg, calculated at T=2,310 seconds.

Capacitor life during operation, Lop, is calculated using equation (3):

$$\mathrm{Lop} = [\mathrm{Wo}/\mathrm{Wm(T)}]*\mathrm{T} \tag{3}$$

where Wo is the mass at which the capacitor reaches EOL, Wm(T) is the mass loss during the drive cycle, and T is the time needed to return to within 1°C of the ambient temperature. For this particular capacitor, EOL occurs when electrolyte loss reaches Wo=462 mg. Thus for the drive cycle at 105 °C associated with Figure 5, Wm(2,310sec) = 0.029378 mg, yielding a capacitor life prediction of Lop =10,090 hours.

4.1 Life study during operation

Miner's rule [1] is used to predict capacitor operating life for each temperature shown in Fig. 4 using equation (4):

$$Lx(operating\ )_{Ta} = 1/\sum {}^{R_m}/_{L_m} \tag{4}$$

where the summation is over the three calendar periods, Rm is the fraction of time that the capacitors spend at each temperature shown in Fig. 4, and Lm is the predicted capacitor life at each temperature.

Operating life predicted for a NCC GXF-series capacitor at each ambient temperature Lx(operating), calculated using Figure 6 (C), is shown in Figure 7. The overall life predicted for the operating period, i.e. by combining ambient temperatures profile shown in Figure 4, is calculated using Miner's rule by summing over the three operating temperatures:

$$\mathrm{Lx(operating)} = \frac{1}{\frac{0.411}{161{,}641}+\frac{0.26}{80{,}799}+\frac{0.329}{40{,}399}} = 71{,}920\ \mathrm{Hr} \tag{5}$$

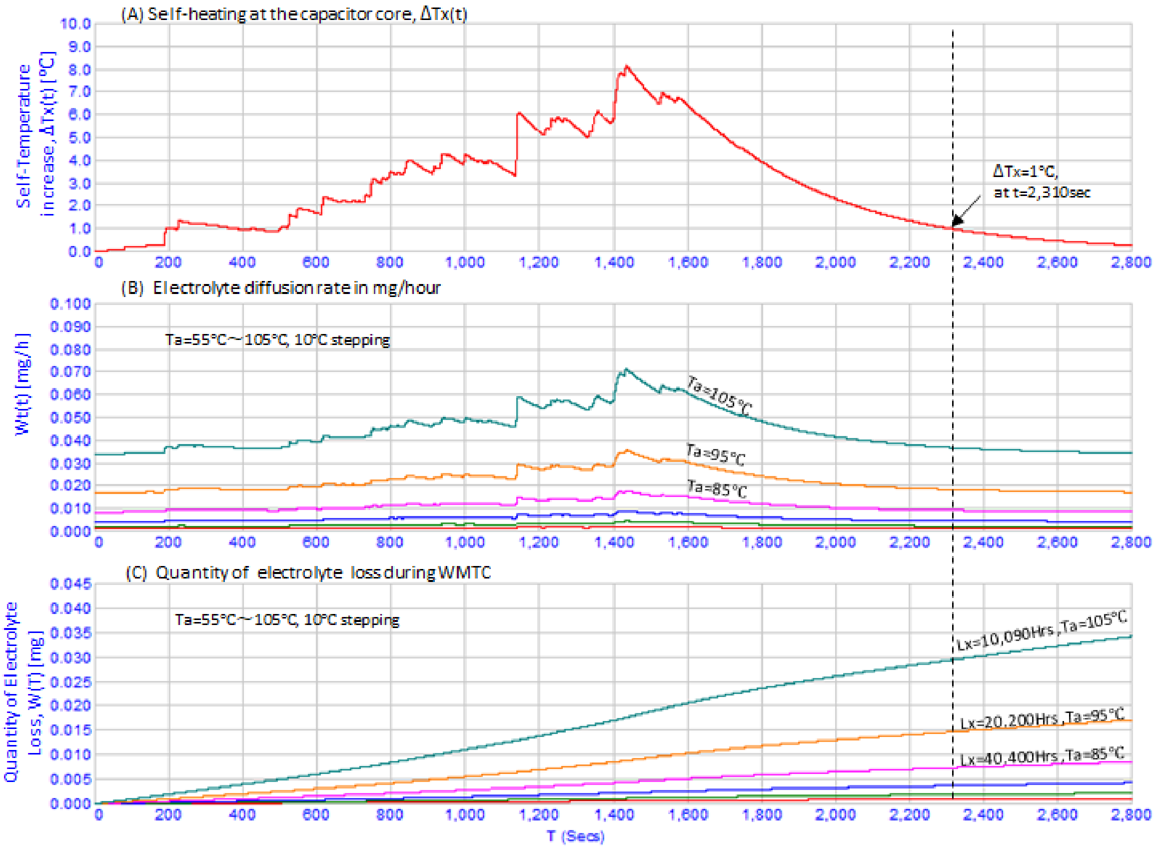

Figure 6: Life simulations during operation at three ambient temperatures; Ta= 85 °C, 95 °C, and 105 °C

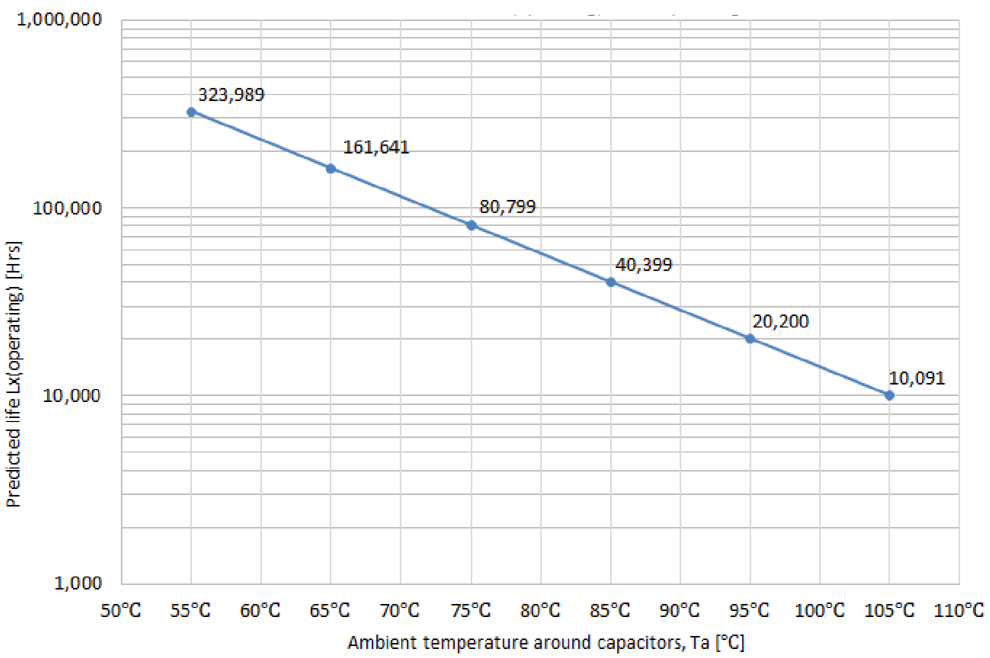

Figure 7: Predicted capacitor life Lx as a function of operating temperature.

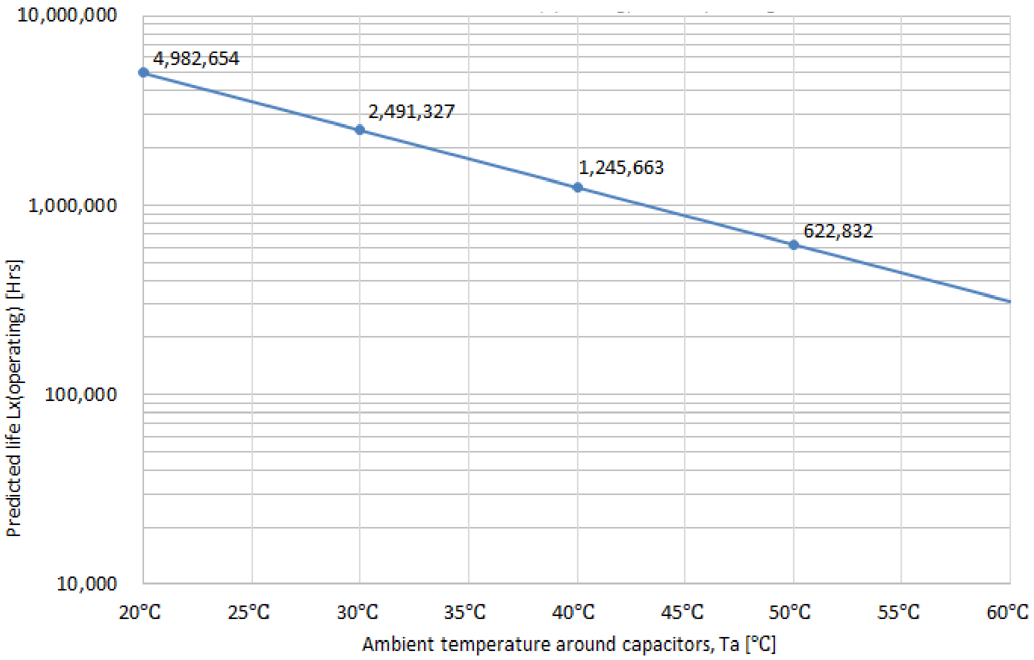

Figure 8: Predicted capacitor life Lx in non-operating mode.

4.2 Life study during non-operation

Capacitor life must also be derived at each of the ambient temperatures shown in Figure 3 when the vehicle is not operating. This life, L*xnon-op*, is calculated using equation (6)

$$L_{xnon-op} = {W_o}/{W_{s(Ta)}} \tag{6}$$

where Wo is the mass loss that causes EOL and Ws(Ta) is the electrolyte diffusion rate out of the capacitor package at ambient temperature Ta. Results for each temperature in Figure 3 are shown in Figure 8 and are combined to determine overall life during non-operation using Miner's rule:

$$\text{Lx(non-op)} = \frac{1}{\frac{0.411}{2{,}491{,}327} + \frac{0.26}{1{,}245{,}663} + \frac{0.329}{622{,}832}} = 1{,}108{,}735 \text{ hr} \tag{7}$$

4.3 Combining capacitor life values for operating and non-operating periods

Miner's rule is a method used to derive the life of a component that is subjected to multiple stress levels. The result is an intermediate value for life. This method is clearly not applicable when the contribution of non-operating time is added to that of operating time contributions because the result would be intermediate. When adding non-operating stress conditions the overall life must be less than the life calculated when only considering operating periods. A different method is required to combine the contributions of operating and non-operating mass losses.

This different method involves use of a correction term. The non-operating contribution is included as a correction term based on the time the vehicle is not operated H(non-op) and the life calculated for non-operating conditions, L(non-op), as shown in equation 8:

$$L_x(overall) = L_x(operating) * \left[1 - {H(non-op)}/{L_x(non-op)}\right] \tag{8}$$

For the above calculation, using values assumed here, H(non-op) = 83,920 hours and L_x(non-op) = 1,108,735 hrs, the ratio is 83,920/1,108,735 = 0.07569. The overall life of the capacitor is thus predicted to decrease by ~7.6% when the mass that is lost during non-operating times is included. Using equation (8) we calculate overall capacitor life as:

$$Lx(overall) = 71{,}920*(1-0.07569) \approx 66{,}000 \text{ hr} \quad (9)$$

5 Conclusion

In this paper, the life of a DC-link-capacitor in an electric motorcycle is calculated by using both its operating and the non-operating times when driven using the World Motorcycle Test Cycle. An alternate method to Miner's Rule was needed and used since it could not directly calculate life with both modes of operation.

Acknowledgments

We thank Katsuhiko Kohno, Keita Yukimoto, and the Products Development Department-II Team at Nippon Chemi-Con, Japan for their assistance.

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Presenter Biography

Toshihiko Furukawa earned his EE degree from Tokai University in Japan and has more than 20 years of experience in power electronics and high-frequency amplifier design. He currently is focused on capacitor technology, providing technical support and global-market business development for the United Chemi-Con / Nippon Chemi-Con Group. IEEE Membership number 92515077 and SAE Membership number 6125613949.

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