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Yao, Bo; Wei, Xing; Zhang, Yichi; Zhao, Shuai; Wang, Huai

Published in:
2023 IEEE Energy Conversion Congress and Exposition, ECCE 2023

DOI (link to publication from Publisher):
10.1109/ECCE53617.2023.10362274

Publication date:
2023

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Yao, B., Wei, X., Zhang, Y., Zhao, S., & Wang, H. (2023). A Mission Profile based Stress Emulation Method for Capacitors in High-power Converter Systems. In *2023 IEEE Energy Conversion Congress and Exposition, ECCE 2023* (pp. 6516-6520). Article 10362274 IEEE. https://doi.org/10.1109/ECCE53617.2023.10362274

A Mission Profile based Stress Emulation Method for Capacitors in High-power Converter Systems

1st Bo Yao
Department of Energy
Aalborg University
Aalborg, Denmark
ybo@energy.aau.dk

2nd Xing Wei
Department of Energy
Aalborg University
Aalborg, Denmark
xwe@energy.aau.dk

3rd Yichi Zhang
Department of Energy
Aalborg University
Aalborg, Denmark
yzhang@energy.aau.dk

4th Shuai Zhao
Department of Energy
Aalborg University
Aalborg, Denmark
szh@energy.aau.dk

5th Huai Wang
Department of Energy
Aalborg University
Aalborg, Denmark
hwa@energy.aau.dk

***Abstract*—This paper presents a dynamic operation profile emulation method for capacitors used in high-power converters. It preserves the advantages of a recently reported method with a minimum required power supply and is robust to testing sample degradation. This method is suitable for application-oriented stress emulation testing with different types of DC / AC capacitors and multi-condition operation in high power converter systems, such as wind power and railway systems. The circuit architecture and testing ability of this method are presented. Taking the mission profile of the AC capacitors in a railway traction system as an example, proof-of-concept experimental results are presented to verify the feasibility of the proposed test method.**

***Index Terms*—Capacitor testing method, mission profile, high power converter, stress emulation**

I. INTRODUCTION

Capacitor is one of the highest failure rate components in power electronic systems [1]. The realistic stress emulation testing is a significant part of the performance characterization and reliability analysis of capacitors, which can help build reliable capacitor parametric models and optimize design margins [2]. Application-oriented stresses emulation based mission profiles for capacitor testing in power converter applications is of great interest.

In recent studies, extensive efforts have been made to capacitor stress emulation. The [3] and [4] use a circuit structure in which a converter is connected in series with Capacitors Under Testing (CUTs), and the ripple current can be configured according to the converter parameters. Nevertheless, the converter needs to directly withstand the DC voltage component of the CUTs in those methods, which cannot be tolerated when extended to the high-power capacitor testing with thousands of volts of DC voltage. The commercial ripple current testers of Chroma 11800 emulate up to 30-100 V ripple voltage and 10-30 A ripple current for CUTs, and their output ripple power range is limited to 1k VA [5]. Ref.[6] proposes a method for stress emulation of the voltage components of the submodule in the multilevel converter (MMC) systems. A reliability testing method for PV inverter DC link capacitors based on mission profiles (taking into account solar irradiance and ambient temperature) is presented in [7]. However, because of the limitations of power design in the topology, these methods are still just suitable for aluminum electrolytic capacitors testing with kW level [6] [7]. The power converters are used in the voltage sources with the fixed 120-degree three-phase symmetrical voltage in [8]-[10]. Different electro-thermal stresses can be emulated by using dynamically changing reference points [9] [10]. Although the ripple voltage and ripple current can be expanded according to the control system, the realistic electro-thermal stresses with mission profiles applied on long time scales are not considered in [9] and [10]. This paper explores the method to achieve dynamic electro-thermal profile emulation, as a further research based on the [9] and [10].

This paper proposes a capacitor testing method, which can emulate the electro-thermal stresses based on the actual mission profile, with the following novel features: Firstly, the method can emulate the mission profiles of practical applications, such as ripple voltage, ripple current, and DC voltage for multi-condition operation; Secondly, the proposed test method can continuously apply for regulated kV and kA electrical stresses with multiple time scales.

II. PROPOSED STRESS EMULATION METHOD

A. Railway Traction System with its Mission Profile

As shown in Fig. 1, an example of a railway traction system with its mission profile is given [11]. The capacitor banks include DC-link capacitors, resonant capacitors, and AC filter capacitors. Affected by actual operation conditions such as running speed and slope, the ripple current, ripple voltage, and DC voltage for the capacitor change dynamically. At the same time, due to the change of operating line and time and the influence of other heat sources inside the converter, the external ambient temperature and humidity of the capacitor also fluctuate concurrently [12]. The data such as voltage, current, and temperature are stored in the Multifunction Vehicle Bus (MVB) system [13]. Therefore, how to simulate the actual operating conditions of the capacitor by reading the MVB data and according to the mission profile becomes the proposed problem.

B. Proposed Architecture of the Stress Emulation Method

The circuit architecture of the proposed method is shown in Fig. 2. Firstly, the robust capacitor testing is achieved by the electrical stress generators and controller, which respectively

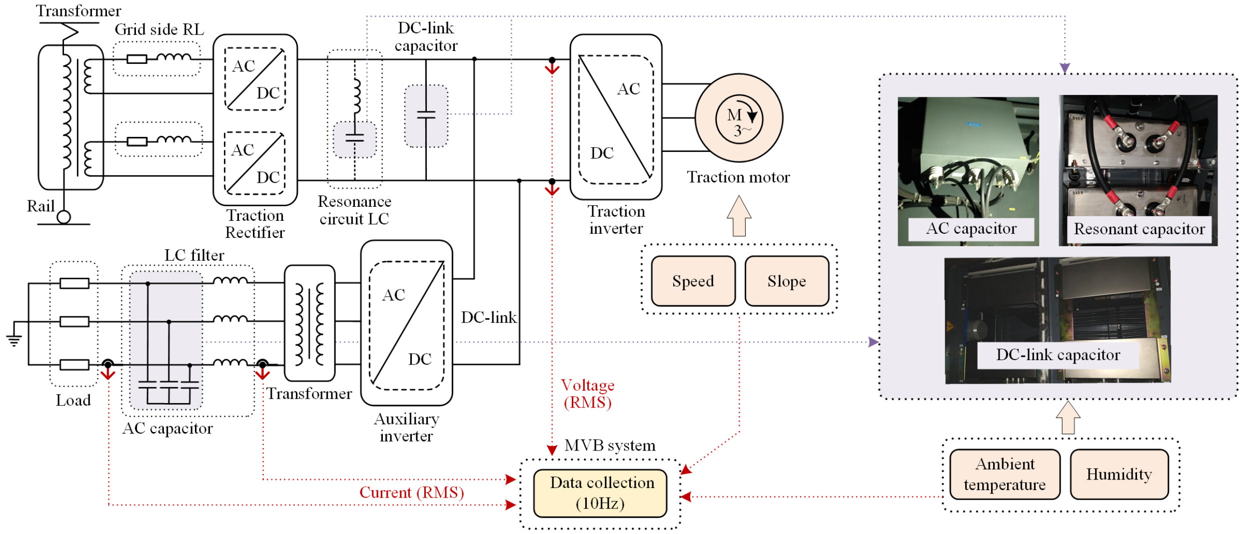


Fig. 1. Railway traction converter system and its mission profile for the capacitor banks. (1. Capacitor banks include DC-link capacitors, resonant capacitors, and AC filter capacitors; 2. Mission profile data of voltage, current, and temperature are stored in the Multifunction Vehicle Bus (MVB) system.)

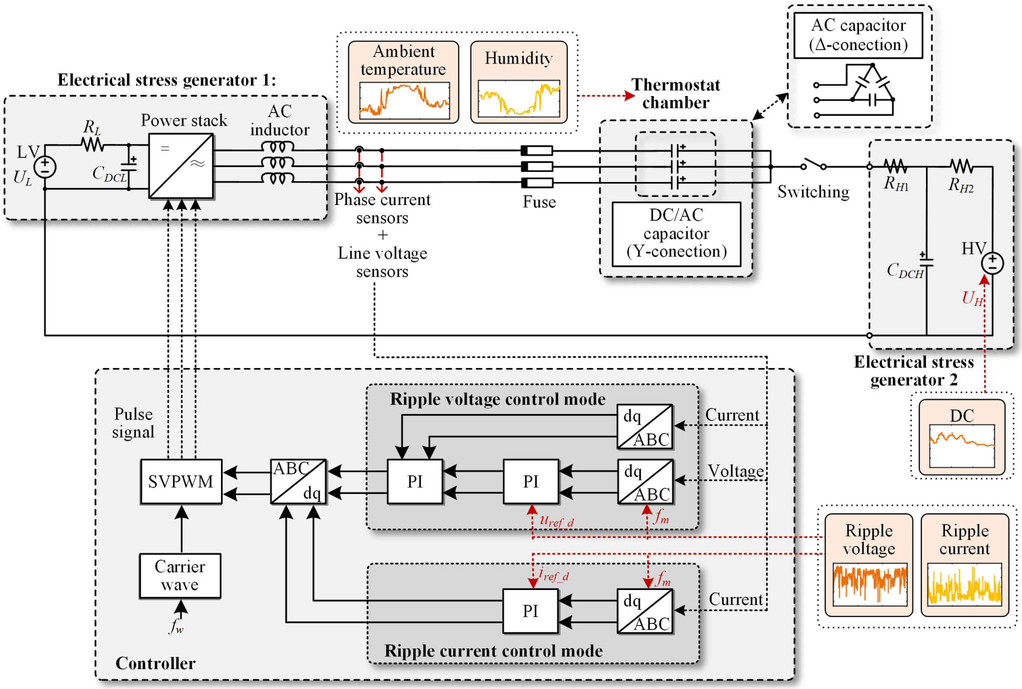
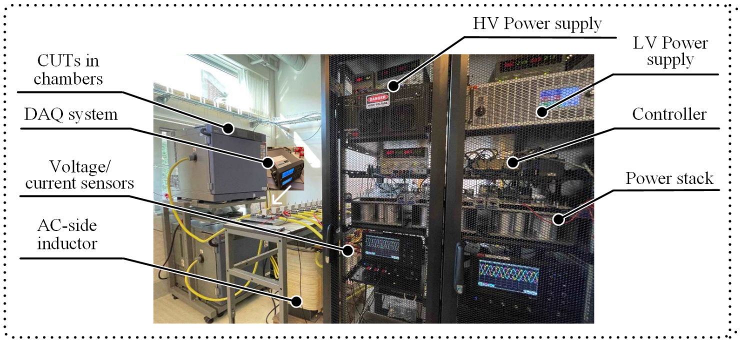


Fig. 2. Circuit architecture of the proposed method. (for AC capacitor testing, HV source U_H, filter capacitor C_{DCH}, resistors R_{H1}, and R_{H2} can be excluded)

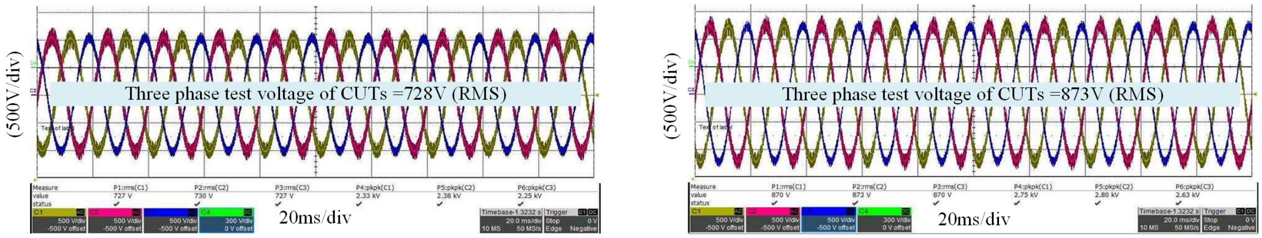
decouple the AC ripple voltage generator 1 and DC voltage bias generator 2, by the low voltage (LV) power supply plus the PWM inverter and high voltage (HV) power supply [9]. It can achieve mission profile-based stress emulation with the closed-loop control system, the HV voltage source control, and the thermostat chamber setting. Secondly, the amplitude of ripple voltage or ripple voltage in the mission profile is used as the given value u_{ref-d} or i_{ref-d} in the controller. The testing ripple frequency is set to f_m and the switching frequency is set to f_w in the controller. The ripple voltage and ripple current real-time collected are continuously tracked by the PI controller for the given value, thus making the testing ripple voltage and ripple current consistent with the input mission profile. The mission profile of the DC voltage is programmatically controlled through the HV power supply. In addition, the mission profile of ambient temperature and humidity can be set by the thermostat chamber.

When the electrical stresses are applied to the capacitors testing, the RMS (root mean square) value of ripple voltage $U_{\text{ripple(t)}}$ can be given as:



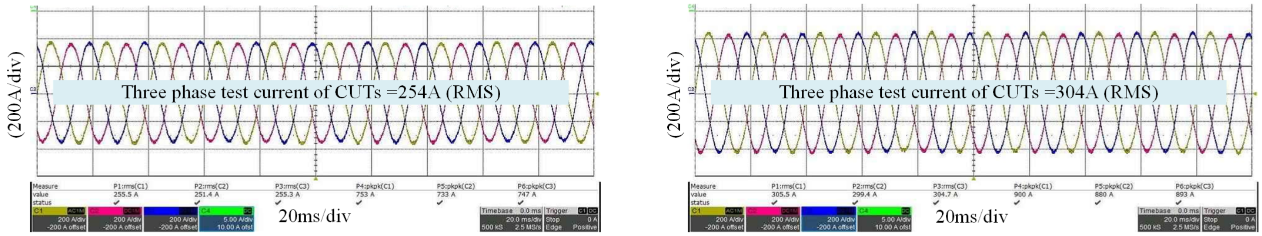
System parameters	
Main inductor	2.5 mH
LV output voltage	750 V
HV output voltage	Up to 10 kV
Switch frequency	5000Hz
CUTs parameters	
Test capacitor	AC capacitor (Δ-conection)
Capacitance of single CUT	75*9 μF
Ripple testing voltage (RMS)	Up to 1200 V
Ripple testing current (RMS)	Up to 400 A
Ripple frequency	50 Hz

Fig. 3. Experimental platform and main parameters.



(a) Voltage waveform in AC capacitors testing (Given RMS voltage of the mission profile = 730V)

(c) Voltage waveform in AC capacitors testing (Given RMS voltage of the mission profile = 876V)



(b) Current waveform in AC capacitors testing (Given RMS current of the mission profile = 255A)

(d) Current waveform in AC capacitors testing (Given RMS current of the mission profile = 306A)

Fig. 4. Voltage and current testing results with different operation conditions.

$$U_{\text{ripple(t)}} = \frac{1}{\sqrt{3}} U_{\text{line (t)}} \tag{1}$$

where $U_{\text{line (t)}}$ represents the line voltage output by the power stack. Its value can be dynamically adjusted by the control module of Fig. 2, thus inputting the ripple voltage of the actual mission profile.

According to the impedance relationship of the capacitor, its ripple current $I_{\text{ripple(t)}}$ can be expressed as:

$$\begin{aligned} I_{\text{ripple(t)}} &= \frac{1}{\sqrt{3}} U_{\text{line (t)}} \times 2\pi f_m C_{\text{test}} \\ &\leq \frac{U_m}{\sqrt{3}\left|\frac{1}{2\pi f_m C_{\text{test}}} - 2\pi f_m L\right|} \end{aligned} \tag{2}$$

where f_m and C_{test} represent the test ripple frequency and capacitance of the tested capacitors, respectively. U_m and L represent the rated output voltage of the power stack and the three-phase inductance value on the output side, respectively.

In addition, the DC voltage component $U_{DC(t)}$ for the DC capacitors of CUTs can be given as:

$$U_{DC(\text{t})} = U_{HV(\text{t})} - \frac{1}{2} U_{LV(\text{t})} \tag{3}$$

where U_{HV} and U_{LV} represent the output voltage of the HV power source and LV power source in Fig. 2, respectively.

III. EXPERIMENTAL VERIFICATION

A. Experimental Setup

Taking the mission profile of the AC capacitors in a railway traction system as an example, the experimental platform and main parameters are shown in Fig. 3. The testing capacitors are placed in the thermostat chambers, and the programmable thermostat chambers can simulate the converter temperature by importing the actual temperature mission profile. Thermocouples are installed in the location of the hot spots and cases of the CUTs to obtain the hot spot temperature and case temperature. The three-phase line voltage and three-phase phase current of the test capacitors are collected by the voltage sensors and current sensors, respectively. Meanwhile, the electrothermal stresses are collected in real-time by data acquisition (DAQ) systems in real-time. The control system is

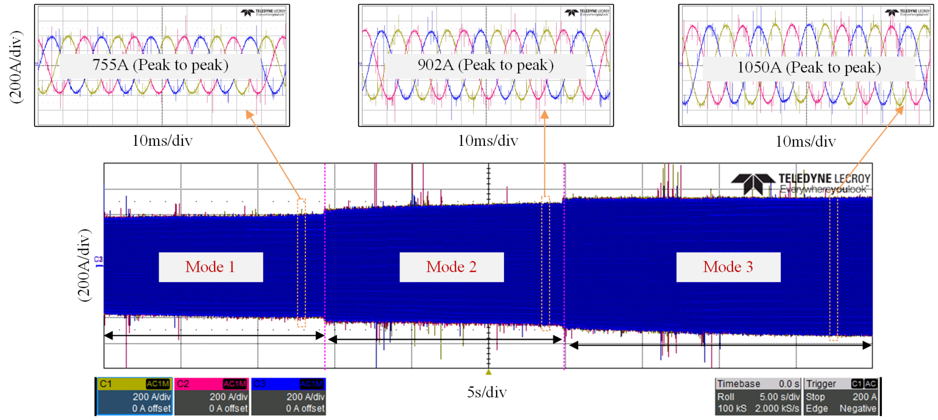
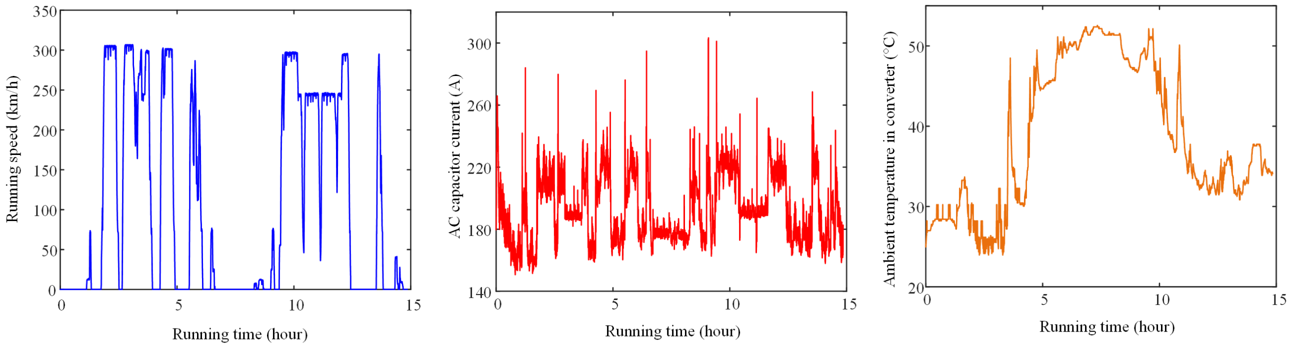
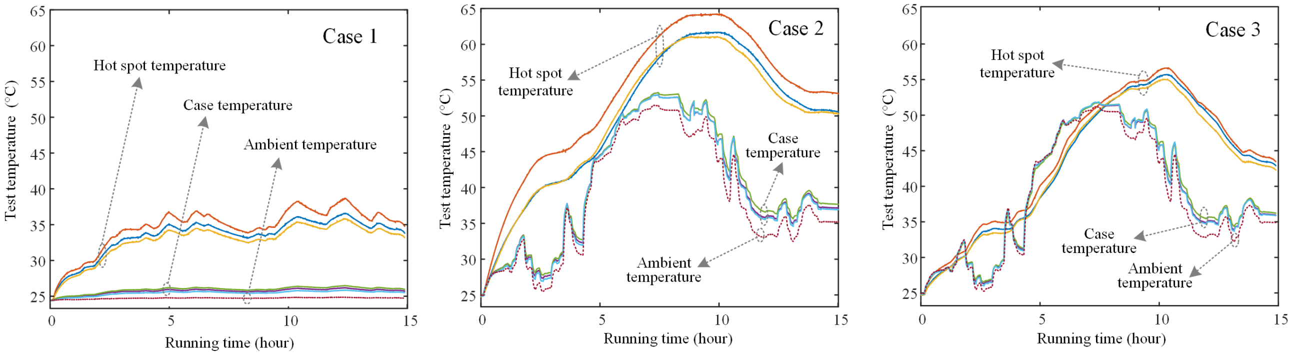


Fig. 5. Dynamic testing profile with three modes of current and voltage levels.



(a) Mission profile of the running speed (b) Mission profile of the AC capacitor current (c) Mission profile of the ambient temperature

Fig. 6. A mission profile scenario for AC capacitors in the railway traction converter system.



(a) Test temperature results of Case 1 (b) Test temperature results of Case 2 (c) Test temperature results of Case 3

Fig. 7. Temperature testing results for three cases in the derived mission profile scenario. (Three colors represent three individual capacitors)

carried out through the RTbox controller to set the required electrical stresses.

B. Experimental Testing Results

The test results of the AC capacitor with different electrical operation conditions are shown in Fig. 4, and the ripple frequency in this case is 50 Hz. It shows the ripple voltage and ripple current of the three-phase CUTs. In this testing, the electrical stress of 730 V / 876 V ripple voltage and 255 A / 306 A ripple current are applied to the CUTs. The ripple voltage and ripple current waveform are shown in Fig. 4 (a)-(b) and Fig. 4 (c)-(d), respectively. It can be seen from the results that by setting different scaling factors of ripple voltages and ripple currents, different electrical stress testing requirements can be emulated. The actual experimental ripple voltage and ripple current have the error of less than 1% compared to the set values. The results show the accuracy of emulation of voltage and current compared to the given references.

For the different current and voltage levels in Fig. 5, three testing modes are configured to emulate the dynamic testing profile of the ripple current. In mode 1, the given ripple current is 270 A (rate current: 30A and 9 CUTs in parallel). In mode

2, the given ripple current is 324 A (acceleration factor: 1.2). In mode 3, the given ripple current is 378 A (acceleration factor: 1.4). The result indicates that it is possible to emulate the dynamic ripple current of the AC capacitor. Application-oriented mission profiles can be achieved by emulating multiple gradients of electrical stresses in the testing. Due to the closed-loop control system, the actual ripple current gradually increases with the given current until it reaches the given one.

Further, the AC capacitor of the railway traction system is used as an example to simulate the actual mission profile, as shown in Fig. 6. The mission profile of the running speed can be converted into the ripple current of the AC capacitor, which is input data through the controller. The ambient temperature of the converter can be set in the thermostat chamber.

Fig. 7 shows the temperature testing results of the three capacitor units with the mission profile. There are three cases of different mission profile combinations, including Case 1: dynamic ripple current (Fig. 6(b)) with fixed ambient temperature of 25 °C; Case 2: fixed ripple current of 260 A with dynamic ambient temperature (Fig. 6(c)); Case 3: dynamic ripple current (Fig. 6(b)) and dynamic ambient temperature (Fig. 6(c)). From the results, the hot spot temperature is dynamic according to the mission profile. The hot spot temperature and case temperature are different in different cases. Therefore, this test method can provide a reference for thermal management and lifetime evaluation of high-power converter capacitors.

IV. Conclusion

This paper extend the application of the method proposed in [9] and [10] for dynamic electro-thermal profile emulation of capacitors in high-power converter applications. Compared with existing testing methods, the proposed one can emulate the mission profile for practical applications (e.g. ripple voltage, ripple current, and DC voltage). The circuit architecture of the proposed method is given, which is suitable for application-oriented testing with the multi-condition operation. The error of the experimental obtained electrical stresses compared to the set values is less than 1%. Proof-of-concept experiment testing of dynamic and mission profile results verify the feasibility of the proposed testing method for high power converter applications.

References

[1] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, “An industry-based survey of reliability in power electronic converters,” *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1441–1451, May-Jun. 2011.

[2] H. Wang, M. Liserre, and F. Blaabjerg, “Toward reliable power electronics: Challenges, design tools, and opportunities,” *IEEE Ind. Electron. Mag.*, vol. 7, no. 2, pp. 17–26, Jun. 2013.

[3] M. Makdessi, A. Sari, P. Venet, P. Bevilacqua, and C. Joubert, “Accelerated ageing of metallized film capacitors under high ripple currents combined with a dc voltage,” *IEEE Trans. Power Electron.*, vol. 30, no. 5, pp. 2435–2444, May 2015.

[4] W. Zhou, M. Wang, Q. Wu, L. Xi, K. Xiao, K. P. Bhat, and C. Chen, “Accelerated life testing method of metallized film capacitors for inverter applications,” *IEEE Trans. Transport. Electrific.*, vol. 7, no. 1, pp. 37–49, Mar 2021.

[5] “Ripple current tester model 11800/11801/11810.” Chroma ATE Inc, https://www.chromaate.com/en/product/ripple_current_tester_239, 2012.

[6] K. Ma, B. He, X. Xin, and X. Cai, “Capacitor voltage control for mission profile emulator of submodule in modular multilevel converter,” *IEEE Trans. Power Electron.*, vol. 36, no. 11, pp. 12 355–12 364, Nov. 2021.

[7] A. Sangwongwanich, Y. Shen, A. Chub, E. Liivik, D. Vinnikov, H. Wang, and F. Blaabjerg, “Design for accelerated testing of DC-link capacitors in photovoltaic inverters based on mission profiles,” *IEEE Trans. Ind. Appl.*, vol. 57, no. 1, pp. 741–753, Jan.-Feb. 2021.

[8] X. Wang, M. Karami, and R. M. Tallam, “Test fixtures to apply variable DC bias and AC ripple current for reliability testing of electrolytic capacitors,” *IEEE Trans. Ind. Appl.*, vol. 55, no. 4, pp. 4073–4079, Jul.-Aug 2019.

[9] B. Yao, Q. Wang, H. Wang, K. Hasegawa, and H. Wang, “A robust testing method for DC and AC capacitors with minimum required power supply,” *IEEE Trans. Power Electron.*, vol. 37, no. 5, pp. 4942–4946, May 2022.

[10] B. Yao, H. Wang, Q. Wang, and H. Wang, “A unified capacitor stress emulation method for high-power converter applications,” *IEEE Trans. Power Electron.*, vol. 38, no. 8, pp. 10 213–10 226, Aug. 2023.

[11] B. Yao, X. Ge, D. Xie, S. Li, Y. Zhang, H. Wang, and H. Wang, “Electrothermal stress analysis and lifetime evaluation of DC-link capacitor banks in the railway traction drive system,” *IEEE J. of Emerg. Se. Topics in Power Electron.*, vol. 9, no. 4, pp. 4269–4284, Aug. 2021.

[12] D. Zhou, Y. Song, Y. Liu, and F. Blaabjerg, “Mission profile based reliability evaluation of capacitor banks in wind power converters,” *IEEE Trans. Power Electron.*, vol. 34, no. 5, pp. 4665–4677, May 2019.

[13] B. Yao, X. Ge, H. Wang, H. Wang, D. Zhou, and B. Gou, “Multi-timescale reliability evaluation of DC-link capacitor banks in metro traction drive system,” *IEEE Trans. Transport. Electrific.*, vol. 6, no. 1, pp. 213–227, Mar. 2020.