Reliability of Aluminum Electrolytic Capacitors in Cold Environments

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Aluminum electrolytic capacitors (AECs) are vital in efficiently operating switched-mode power supplies (SMPSs) by regulating energy storage and voltage. These capacitors are widely used due to their high capacitance and cost-effectiveness. However, their performance at low temperatures is a critical aspect that demands a thorough investigation, particularly in applications where SMPSs are subjected to sub-zero operating conditions.

aluminum electrolytic capacitors | cold experiment | discriminative features | signal processing | machine learning | data-driven process

1. Introduction

Aluminum electrolytic capacitors (AECs) are vital in efficiently operating switched-mode power supplies (SMPSs) by regulating energy storage and voltage. These capacitors are widely used due to their high capacitance and cost-effectiveness. However, their performance at low temperatures is a critical aspect that demands a thorough investigation, particularly in applications where SMPSs are subjected to sub-zero operating conditions. Understanding the behavior of aluminum electrolytic capacitors in such environments is essential for ensuring the reliable and stable performance of power supply systems across a broad spectrum of operating conditions [1][2][3][4]. The low-temperature performance of aluminum electrolytic capacitors can be significantly affected by various factors, including temperature-dependent capacitance, leakage current, and the impact on overall power supply efficiency. The capacitor's characteristics can deviate from their nominal values at low temperatures, leading to degraded performance and potential failure. It is imperative in aerospace, automotive, and telecommunications applications, where SMPSs are exposed to extreme temperature variations [5][6]. Despite the significance of low-temperature performance, more comprehensive experimental investigations need to focus specifically on aluminum electrolytic capacitors in SMPSs. Most existing studies in the field have primarily concentrated on the behavior of other capacitors or explored the impact of temperature on capacitors without delving into the specific nuances of aluminum electrolytic capacitors in SMPS applications [7].

Cold experiments have been conducted to study the impact of low temperatures on aluminum electrolytic capacitors. It has been observed that cold environments can significantly affect the performance and reliability of these capacitors. One prominent effect is the decrease in capacitance at lower temperatures. The dielectric oxide layer on the aluminum anode tends to thicken, reducing the effective surface area and decreasing capacitance [8][9][10][11]. Additionally, the capacitors' equivalent series resistance (ESR) tends to increase in cold conditions, impacting their overall impedance characteristics. Furthermore, the mechanical integrity of aluminum electrolytic capacitors can be compromised in cold environments. The contraction and expansion of the aluminum can and sealing materials due to temperature changes can induce mechanical stress, leading to potential damage and reduced reliability. Long-term exposure to low temperatures can also degrade the performance and reliability of aluminum electrolytic capacitors. Aging tests conducted under cold conditions have shown a deterioration in their electrical properties and decreased operational lifespan. Researchers have examined different approaches, like fine-tuning electrolyte compositions, employing cold-temperature electrolytes, and enhancing packaging designs to augment the efficiency and dependability of aluminum electrolytic capacitors in chilly conditions. These efforts aim to mitigate the adverse effects of low temperatures and ensure the reliable operation of these capacitors in cold applications. Understanding the impact of cold temperatures on aluminum electrolytic capacitors is crucial for designing and operating systems in cold environments [12].

2. Reliability of Aluminum Electrolytic Capacitors in Cold Environments

AECs are widely used in electrical and electronic applications due to their high capacitance, low cost, and robustness. They consist of an anode and a cathode separated by an electrolyte-soaked paper or polymer separator. The anode is formed by an aluminum foil with a thin oxide layer, which acts as the dielectric. The electrolyte facilitates ion movement, creating a stable oxide layer on the anode. Aluminum electrolytic capacitors offer high capacitance values and can handle high voltage ratings. They find applications in power supplies, audio equipment, motor drives, and many other electronic systems requiring energy storage and filtering capabilities. AECs typically consist of several layers. A protective sleeve or coating provides insulation and mechanical protection for the outermost layer. Beneath that is an anode foil made of high-purity aluminum, forming one electrode. The anode foil is covered with a dielectric layer, usually created by an aluminum oxide film. The dielectric layer acts as the insulating material. Next, a paper or polymer separator is soaked in an electrolyte, facilitating ion movement. Finally, a cathode foil, typically aluminum, forms the second electrode. The tightly rolled or stacked layers ensure a compact structure with a high capacitance-to-volume ratio.

The research provide different methods for studying and monitoring the condition of aluminum electrolytic capacitors. It presents a methodology for studying the impact of thermal cycling on the wear-out of aluminum electrolytic capacitors used in automotive cases [13]. It introduces an approach for investigating the influence of thermal cycling on the deterioration of aluminum electrolytic capacitors utilized in automotive applications [14]. It introduces a trial offline method for assessing the status of aluminum electrolytic capacitors by estimating equivalent series resistance and capacitance parameters [15]. It suggests an approach for determining the hotspot temperature of aluminum electrolytic capacitors using the linear relationship between capacitance and temperature [16]. This study presents a fault diagnostics framework for aluminum electrolytic capacitors in power supplies. Long-term frequency monitoring and statistical feature extraction were used to detect anomalies, achieving improved performance with increased data capacity. The k-nearest neighbors algorithm showed the highest accuracy (98.40%) and lowest computational cost [17]. This study focuses on monitoring electrolytic capacitors using a parameter observer (PO) to determine their equivalent capacity and serial resistance. The PO estimates the discharging circuit's time constant based on voltage measurements, enabling the calculation of the capacitor's parameters. Experimental results show that the proposed observer has faster error tracking than other methods, with the potential for real-time implementation due to its low computational requirements [18]. This paper introduces a data processing method using the box diagram technique to identify outliers in sensor data. Outliers are classified based on their persistence over time and linkage to other sensors. A clustering algorithm is employed for data reclassification. A risk coefficient is calculated using persistence and linkage, and a threshold is defined to differentiate between risk-specific and non-risk anomalies. A comprehensive evaluation model is established using quantitative scoring, principal component analysis, and 0.1 planning. The proposed evaluation method is evaluated objectively [19]. This research deals with the issue of identifying faults in squirrel cage induction motors (SCIMs) when operating under conditions of low load. By employing stator current information and an approach assisted by feature engineering, a technique for fault categorization is formulated using the support vector classification (SVC) algorithm. The method utilizes the Hilbert transform and filter-based feature selection for precise fault categorization. The SVC exhibits remarkable diagnostic performance accuracy (97.32%) and surpasses alternative classifiers in accuracy and computation speeds [20]. This research focuses on monitoring switch-mode AC/DC power supplies (SMPSs) to identify switching device and capacitor issues. By utilizing dual sensing of current and voltage signals and applying statistically derived characteristics, an integrated approach is suggested for diagnosing system faults. The selection of features is carried out using correlation-based methods, and machine learning-based classifiers are utilized for fault detection and isolation (FDI). The outcomes demonstrate that random forest and gradient boosting classifiers are highly dependable but computationally demanding, whereas the decision tree classifier offers cost-effectiveness with reliable diagnostic results. The proposed framework is effective for diagnosing switching device issues and categorizing various states of the SMPSs [21]. This research focuses on the significance of sturdy power converter designs and regulatory techniques in LED lighting setups. It introduces an innovative health assessment system that employs the brief duration least square Prony's method for identifying capacitor issues in a resilient LED driver. The setup enables constant monitoring of electrolytic capacitor status, preventing complete system breakdowns; it exhibits remarkable efficiency despite a restricted amount of data instances [22]. This research emphasizes the significance of preserving the robust functioning of capacitors in renewable energy generation setups. It suggests a non-intrusive method for identifying faults, using random forest classification to detect the critical level of aluminum electrolytic capacitors, eliminating the necessity for extra sensors in the converter [23]. Precise capacity assessment is vital for the secure and effective functioning of batteries. This research introduces an innovative approach to gauge the capacity of extensive LiFePO4 batteries, utilizing actual information obtained from electric vehicles. A comprehensive dataset from 85 cars is compiled, and a capacity prediction method that involves classification and aggregation is formulated. This technique combines a battery aging trial with extensive data analysis to estimate even under diverse and authentic circumstances accurately. The suggested models, encompassing linear regression and neural networks, demonstrate dependable capacity prediction with minimal relative error. The effectiveness of these methodologies is confirmed through an aging experiment, offering valuable insights for capacity estimation based on real-world data [24]. This article focuses on temporal features and their importance in comprehending data patterns. The laborious manual extraction of features from extensive time-based datasets is time-consuming and demanding automation. The article introduces a correlation-dependent feature selection algorithm assessed on stress-predictive data, attaining superior classification accuracy (98.6%) in contrast to conventional statistical characteristics (67.4%). The research underscores the significance of analytical attributes over traditional statistical features for precise stress categorization [25]. The swift expansion in energy requirements compels the exploration of energy conservation. Demand flexibility (DF) initiatives and live meters (LMs) offer crucial data for managing energy consumption on the consumer side. This research suggests cluster algorithms that employ discrete wavelet transformation (DWT) to partition consumers according to their daily load patterns. The approach is deployed on the Manhattan dataset, demonstrating enhanced cluster efficiency and easing the analysis of electricity usage patterns [26].

With its abundant presence in the Vellore locality, sunlight energy can be tapped using solar PV modules. A machine learning-based MPPT controller improves the PV array's effectiveness, ensuring ideal torque and steady speed for electric vehicles (EVs) under different load circumstances. The research employs a solar cell, SVPWM inverter, and DC-DC voltage booster to energize the EV, and the system's performance is assessed using MATLAB Simulink [27]. Microbe fuel cells (MFCs) transform organic substances into electric energy utilizing microorganisms, yet their limited power constrains their feasible use. This research utilizes machine learning techniques, encompassing support vector regression, artificial neural networks, and Gaussian process regression, to establish ideal data-informed models for MFCs. Fine-tuning hyperparameters through Bayesian, grid, and random exploration yields models with 99% precision for forecasting power density and output voltage, facilitating enhanced MFC optimization [28]. This paper introduces a synthetic neural network-centered (SNN) energy management approach (SMA) for a hybrid AC/DC microgrid. It employs a dual-phase technique to ascertain the operational state and regulate the replenishment and release of the energy storage system. The microgrid integrated diverse converters and effectively functioned and governed with the suggested SNN-based EMA, as evidenced by empirical findings on a laboratory-scale setup [29]. Scientists have sought to enhance the effectiveness of photovoltaic systems (PVS) by forecasting weather conditions that influence PV module performance. This research suggests employing artificial neural networks (ANNs) to anticipate the PV system's temperature and radiation, utilizing JAYA-SMC hybrid control to identify the peak power point and duty cycle for a DC motor. The approach was proven exceptionally efficient, assessing maximum power and stability for energy monitoring and control [30]. This article suggests a mixed AC/DC microgrid (MG) utilizing solar and wind renewable resources. The management of coordination and identification of faults are implemented to guarantee steadiness and equilibrium between generation and consumption and facilitate rapid fault localization and restoration. A proportional resonant (PR) current regulator lessens harmonics, while an artificial neural network (ANN) ensures precise fault detection. MATLAB simulation outcomes exhibit the efficiency of the suggested control approach in preserving stability, fulfilling load requirements, attaining energy equilibrium, and anticipating faults [31]. This research presents a modeling framework for a hybrid electric vehicle setup, emphasizing bidirectional DC-DC converters and coordinated regulation of energy sources. An artificial neural network (ANN) is implemented to optimize feedback control within the converter circuit to enhance traditional control techniques. The results indicate that the ANN controller significantly improves performance compared to conventional methods, as demonstrated through MATLAB/Simulink simulations. These simulations underscore the effectiveness of the ANN controller in diminishing the steady-state error, peak overshoot, and settling time during both vehicle powering and regenerative braking modes [32]. These papers, as a whole, propose that the statistical feature engineering method and artificial neural network implementation can be utilized to monitor the status of aluminum electrolytic capacitors and forecast their lifespan and ensure their dependability.

References

1. Kareem, A.B.; Hur, J.-W. A Feature Engineering-Assisted CM Technology for SMPS Output Aluminium Electrolytic Capacitors (AECs) Considering D-ESR-Q-Z Parameters. Processes 2022, 10, 1091.
2. Jami, T.; Charles, J.; Ali, S. Electrolytic capacitor: Properties and operation. J. Energy Storage 2023, 58, 106330.
3. Shahraki, A.F.; Al-Dahidi, S.; Taleqani, A.R.; Yadav, O.P. Using LSTM neural network to predict the remaining useful life of electrolytic capacitors in dynamic operating conditions. J. Risk Reliab. 2023, 237, 16–28.
4. Duan, C.; Chen, P. Adaptive Maintenance Scheme for Degrading Devices With Dynamic Conditions and Random Failures. IEEE Trans. Ind. Inform. 2023, 19, 2508–2519.
5. Wei, Y.; Hossain, M.; Mantooth, H.A. Evaluation and Modeling of SiC Based Power Converter for Low-Temperature Operation. IEEE Trans. Ind. Appl. 2023, 59, 3660–3673.
6. Zeng, X.; Bian, J.; Liang, L.; Cao, Q.; Liu, L.; Chen, X.; Wang, Y.; Xie, X.; Xie, G. Preparation and characterization of an anode foil for aluminium electrolytic capacitors by powder additive manufacturing. Powder Technol. 2023, 426, 118602.
7. Tan, S.; Yang, H.; Zhang, Z.; Xu, X.; Xu, Y.; Zhou, J.; Zhou, X.; Pan, Z.; Rao, X.; Gu, Y.; et al. The Progress of Hard Carbon as an Anode Material in Sodium-Ion Batteries. Molecules 2023, 28, 3134.
8. Wang, Y.; Wu, T.; Che, L.; Huang, G. Microstructure and Recrystallization Behavior of Heating Rate-Controlled Electrolytic Capacitor Aluminum Foil under Cold Forming and Annealing. Materials 2023, 16, 4128.
9. Banerjee, R.; John, D.; Zhang, C.; Agarwal, A.; Raj, P. Cold-sprayed aluminium capacitors on lead frames for 3D power packaging. In Proceedings of the 2023 Fourth International Symposium on 3D Power Electronics Integration and Manufacturing (3D-PEIM), Miami, FL, USA, 1–3 February 2023; pp. 1–4.
10. Both, J. The modern era of aluminium electrolytic capacitors. IEEE Electr. Insul. Mag. 2015, 31, 24–34.

11. Yao, B.; Zhao, S.; Zhang, Y.; Wang, H. A Health Indicator of Aluminum Electrolytic Capacitors Based on Strain Sensing. IEEE Trans. Power Electron. 2023, 38, 7982–7987.
12. Suskis, P.; Zakis, J.; Suzdalenko, A.; Van Khang, H.; Pomarnacki, R. A Study on Electrolytic Capacitor Aging in Power Converters and Parameter Change Over the Lifespan. In Proceedings of the 2023 IEEE 10th Jubilee Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), Vilnius, Lithuania, 27–29 April 2023; pp. 1–5.
13. Cousseau, R.; Patin, N.; Monmasson, E.; Idkhajine, L. A methodology for studying aluminium electrolytic capacitors wear-out in automotive cases. In Proceedings of the 2013 15th European Conference on Power Electronics and Applications (EPE), Lille, France, 2–6 September 2013; pp. 1–10.
14. Bhargava, C.; Banga, V.K.; Singh, Y. Condition monitoring of aluminium electrolytic capacitors using accelerated life testing: A comparison. Int. J. Qual. Reliab. Manag. 2018, 35, 1671–1682.
15. Amaral, A.M.R.; Cardoso, A.J.M. Using Newton-Raphson Method to Estimate the Condition of Aluminum Electrolytic Capacitors. In Proceedings of the 2007 IEEE International Symposium on Industrial Electronics, Vigo, Spain, 4–7 June 2007; pp. 827–832.
16. Jedtberg, H.; Buticchi, G.; Liserre, M.; Wang, H. A method for hotspot temperature estimation of aluminium electrolytic capacitors. In Proceedings of the 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA, 1–5 October 2017; pp. 3235–3241.
17. Kareem, A.B.; Hur, J.-W. Towards Data-Driven Fault Diagnostics Framework for SMPS-AEC Using Supervised Learning Algorithms. Electronics 2022, 11, 2492.
18. Bărbulescu, C.; Căiman, D.-V.; Dragomir, T.-L. Parameter Observer Useable for the Condition Monitoring of a Capacitor. Appl. Sci. 2022, 12, 4891.
19. Zhou, Y.; Liao, R.; Chen, Y. Study on Optimization of Data-Driven Anomaly Detection. In Proceedings of the 2022 International Conference on Data Science and Its Applications (ICoDSA), Bandung, Indonesia, 6–7 July 2022; pp. 123–127.
20. Okwuosa, C.N.; Hur, J.-W. A Filter-Based Feature-Engineering-Assisted SVC Fault Classification for SCIM at Minor-Load Conditions. Energies 2022, 15, 7597.
21. Kareem, A.B.; Ejike Akpudo, U.; Hur, J.-W. An Integrated Cost-Aware Dual Monitoring Framework for SMPS Switching Device Diagnosis. Electronics 2021, 10, 2487.
22. Laadjal, K.; Bento, F.; Cardoso, A.J.M. On-Line Diagnostics of Electrolytic Capacitors in Fault-Tolerant LED Lighting Systems. Electronics 2022, 11, 1444.
23. Amaral, A.M.R.; Laadjal, K.; Cardoso, A.J.M. Advanced Fault-Detection Technique for DC-Link Aluminum Electrolytic Capacitors Based on a Random Forest Classifier. Electronics 2023, 12, 2572.

24. Zhou, X.; Han, X.; Wang, Y.; Lu, L.; Ouyang, M. A Data-Driven LiFePO4 Battery Capacity Estimation Method Based on Cloud Charging Data from Electric Vehicles. Batteries 2023, 9, 181.

25. Iqbal, T.; Elahi, A.; Wijns, W.; Amin, B.; Shahzad, A. Improved Stress Classification Using Automatic Feature Selection from Heart Rate and Respiratory Rate Time Signals. Appl. Sci. 2023, 13, 2950.

26. Cen, S.; Yoo, J.H.; Lim, C.G. Electricity Pattern Analysis by Clustering Domestic Load Profiles Using Discrete Wavelet Transform. Energies 2022, 15, 1350.

27. Viswa Teja, A.; Razia Sultana, W.; Salkuti, S.R. Performance Explorations of a PMS Motor Drive Using an ANN-Based MPPT Controller for Solar-Battery Powered Electric Vehicles. Designs 2023, 7, 79.

28. Oyedeji, M.O.; Alharbi, A.; Aldhaifallah, M.; Rezk, H. Optimal Data-Driven Modelling of a Microbial Fuel Cell. Energies 2023, 16, 4740.

29. Kim, T.-G.; Lee, H.; An, C.-G.; Yi, J.; Won, C.-Y. Hybrid AC/DC Microgrid Energy Management Strategy Based on Two-Step ANN. Energies 2023, 16, 1787.

30. Jlidi, M.; Hamidi, F.; Barambones, O.; Abbassi, R.; Jerbi, H.; Aoun, M.; Karami-Mollaee, A. An Artificial Neural Network for Solar Energy Prediction and Control Using Jaya-SMC. Electronics 2023, 12, 592.

31. Jasim, A.M.; Jasim, B.H.; Neagu, B.-C.; Alhasnawi, B.N. Coordination Control of a Hybrid AC/DC Smart Microgrid with Online Fault Detection, Diagnostics, and Localization Using Artificial Neural Networks. Electronics 2023, 12, 187.

32. Sankar, R.S.R.; Deepika, K.K.; Alsharef, M.; Alamri, B. A Smart ANN-Based Converter for Efficient Bidirectional Power Flow in Hybrid Electric Vehicles. Electronics 2022, 11, 3564.