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CHARACTERISTICS AND PERFORMANCE OF ALUMINUM ELECTROLYTIC CAPACITORS (AEC) IN SOLAR PANEL AND WIND TURBINE SYSTEMS

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ABSTRACT

Aluminum electrolytic capacitors (AECs) are widely used in renewable energy systems due to their high volumetric capacitance, low cost, and compatibility with compact power electronic designs. However, their performance is significantly affected by environmental and operational conditions. This review investigates the reliability challenges faced by AECs in photovoltaic and wind turbine systems, especially under thermal, electrical, and humidity stresses. In coastal regions like Balikpapan, high humidity accelerates corrosion, while in mountainous areas like Sidrap, seasonal wind speed fluctuations impose voltage instability and thermal cycling that degrade capacitor lifespan. The discussion highlights the increase in Equivalent Series Resistance (ESR) and electrolyte degradation as key failure mechanisms. The study emphasizes the need for improved materials, protective strategies, and application-specific capacitor selection to enhance system stability and efficiency in diverse environmental conditions.

1. INTRODUCTION

Along with the rapid development of modern technology and the continuous improvement of capacitor performance, aluminum electrolytic capacitors are now widely used in various industrial sectors, including consumer electronics, renewable energy, automotive industry, and aviation (Bai, 2024). In renewable energy systems such as solar panels and wind turbines, passive components such as aluminum electrolytic capacitors (AECs) have an important role that is often overlooked compared to active power electronic devices. AECs are used in DC-DC converters and inverter circuits to store energy, stabilize voltage, and dampen ripple currents. These capacitors are chosen for their high volumetric capacitance, low cost, and compatibility with compact power device designs (Ahmad et al., 2016).

To make AECs more resilient to operational challenges in extreme environments, future research needs to focus on improving the quality of their constituent materials and thermal protection systems. AECs are known as components that are prone to failure due to their limited lifespan, mainly due to electrolyte degradation, increased Equivalent Series Resistance (ESR), high operating temperatures, and long-term stress (Slimani et al., 2025). In photovoltaic systems, an increase in ESR causes ripple voltage spikes that decrease the efficiency of Maximum Power Point Tracking (MPPT), thereby reducing overall system performance (Ahmad et al., 2016). Meanwhile, in wind turbine systems using modular multilevel converters (MMCs), AEC aging causes voltage imbalances between modules and weakens the energy buffering capacity, which can lead to systemic disruptions (Vorobev et al., 2025).

To address these issues, a deeper understanding of the material characteristics and operational performance of aluminum electrolytic capacitors (AECs) is key to improving the efficiency and reliability of renewable energy systems. Innovations in capacitor condition monitoring and additive manufacturing-based materials engineering show that a multidisciplinary approach involving materials engineering, control systems and power electronics design has great potential to address these challenges. AEC works specifically on two major renewable energy systems, namely solar panels and wind turbines, which each have different load characteristics, environments, and operational demands.

2. METHODS

The method used was a literature review focused on scientific articles published in the IEEE Xplore database. The search process was conducted using main keywords such as “aluminum electrolytic capacitor,” “renewable energy applications,” “solar photovoltaic,” and “wind turbine.” The selection of articles was based on the criteria of relevance to the topic, publication year from 2015 to 2024, and quality of IEEE-indexed journals with a focus on the characteristics, performance, and reliability of aluminum electrolytic capacitors in renewable energy systems.

3. RESULT AND DISCUSSION

Aluminum electrolytic capacitor (AEC) is a passive component in electronic circuits that functions to store and release electrical energy in the form of charge (Torki et al., 2023). In renewable energy systems, especially solar panels and wind turbines, AEC plays an important role in maintaining the stability and efficiency of dynamic electrical power flow due to changes in environmental conditions (Guo et al., 2025). In photovoltaic solar panel systems, AEC is usually installed at the input and output sides of the DC-DC converter as well as inside the inverter circuit as a voltage ripple filter, short-term energy buffer, and DC voltage stabilizer (Ahmed et al., 2016). Meanwhile, in modern wind turbine systems, especially those adopting the Modular Multilevel Converter (MMC) configuration, the AEC functions as a voltage balancer between submodules, a transient absorber, and a momentary energy store during the switching process. The naturally changing wind speed causes voltage and current variability that must be addressed quickly and effectively to prevent power distribution imbalance (Li et al., 2020). The parameters that must be carefully considered in the design of renewable energy systems in order to function optimally in a dynamic operational environment are as shown in the following table:

Table 1. AEC Performance Parameters

Parameters	General Value	Explanation	Sources
Capacitance	0.1 μF–2.7 F	The capacitance range is wide for various applications, including energy storage and voltage ripple suppression	Yadlapalli et al., 2022
Voltage	4 V–630 V	The maximum voltage that a capacitor can withstand without damage	Ebel, 2022
ESR	0.13–30 Ω	Lower ESR increases efficiency and reduces internal heating	Vicentini et al., 2019
Life Time	2,000-25,000 hours at 105°C	Service life depends on operating temperature and ripple current, service life increases at lower temperatures	Normandin & Banks, 2015

3.1 Structure and Composition of Aluminum Electrolytic Capacitors

Structurally, aluminum electrolytic capacitors consist of three main components: aluminum foil as electrodes (anode and cathode), porous separator paper, and electrolyte solution as the liquid conductive medium. Anode Made of ultra-high purity aluminum (≥99.99%), pure aluminum was chosen for its ability to form an oxide layer (Al_2O_3) that is stable, thin, and has excellent dielectric properties. This layer serves as the main dielectric in the capacitor (Sato et al., 2018). Cathode Made of aluminum with lower purity (99.8%). To lower contact resistance and prevent the formation of excess oxides, this foil is often combined with additional metals such as copper or titanium (Kim & Lee, 2020). Separator A special electrolyte paper made of highly absorbent and porous cellulose fibers is used, allowing the electrolyte to bridge the anode and cathode without direct contact (Shibata et al., 2017).

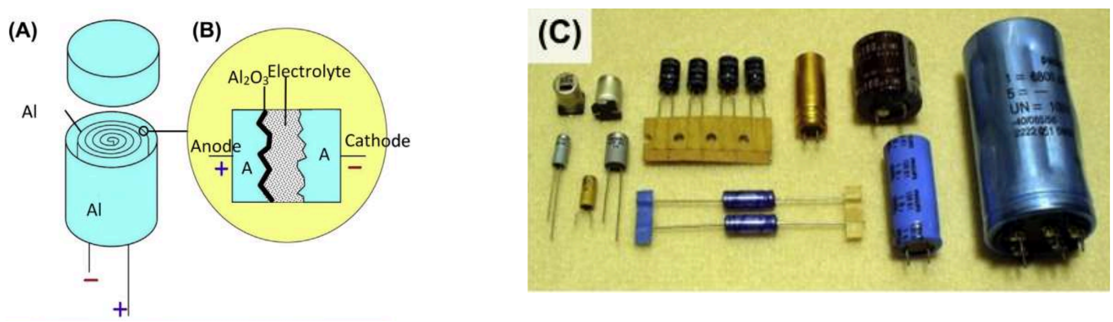

Figure 1. (A-B) Cross-sectional view of a typical device; (C) Electrolyte capacitors of various shapes and sizes
Source: Elcap (2017)

Based on the type of electrolyte used, aluminum electrolytic capacitors are classified into three main types (Faizan et al., 2020). Liquid electrolytes usually consist of solvents such as ethylene glycol or dimethylformamide and acidic additives such as boric acid. It is commonly used in capacitors with a voltage of 4-630 V, with capacitance values ranging from 0.47 μF to 100,000 μF. Its main advantages are size flexibility and economical price, although it has a higher ESR (Equivalent Series Resistance) and limited service life (Li et al., 2016).Manganese Dioxide Solid Electrolyte Uses MnO_2 solids as a conductive electrolyte. Offers high temperature (>125 °C), humidity, and long life resistance. Suitable for high-reliability applications. Capacitance generally ranges from 0.1 μF to 470 μF (Yamamoto et al., 2015).

3.2 Mechanism of Action and Characteristics

The working mechanism of aluminum electrolytic capacitors (AECs) is based on the principle of storage and discharge of electrical charges through an internal structure consisting of an aluminum anode, liquid electrolyte, and aluminum oxide dielectric layer. In solar panel systems, AECs play an important role on the DC-link side of converters and inverters to filter out voltage ripple (ripple filtering) and maintain output voltage stability when the intensity of sunlight changes. This is important to maintain the performance of the Maximum Power Point Tracking (MPPT) algorithm, as small voltage fluctuations can interfere with achieving the maximum power point (Ahmad et al., 2016). On the other hand, in wind turbine systems, AEC is used to absorb transient surges as well as stabilize the voltage between submodules in the Modular Multilevel Converter (MMC) topology. This reliability is critical because fluctuating wind speeds can result in continuous variations in current and voltage, so capacitors must respond quickly to these changes in order to keep the system synchronized and not experience resonance or power imbalance (Li et al., 2020; Cai & Bréon, 2021). The efficiency of the AEC working mechanism is also highly dependent on internal parameters such as the equivalent series resistance (ESR). High ESR causes an increase in internal temperature, accelerates electrolyte degradation, and decreases capacitor lifetime (Vicentini et al., 2019).

High volumetric capacitance allows AECs to store large charges in a relatively small physical form, making them ideal for space-constrained solar inverters or wind converters (Nguyen et al., 2020). The fixed polarity nature makes AECs suitable only for direct current (DC) systems, which are commonly used in the DC-link configuration of inverters and converters. Other crucial characteristics are working voltage and lifetime. Generally, AECs for renewable energy systems have a working voltage between 63-600 V, depending on the circuit design and power requirements and voltages that exceed specifications can damage the aluminum oxide layer that functions as a dielectric (Gu et al., 2020). Proper capacitor selection based on the characteristics of the application environment is critical to ensure long-term system stability, especially in outdoor solar panel systems and offshore wind turbines (Schroder et al., 2018).

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3.3 Effect of Geographical Conditions on Wind Turbine Capacitors

Wind turbines in coastal Balikpapan, East Kalimantan, operate at low wind speeds of 3.7-5 m/s, generating voltages of 3-4 volts that are sufficient for small scale. However, high humidity in the region accelerates corrosion, especially of aluminum electrolytic capacitors (Saputra et al., 2024). In contrast, the turbine in Sidrap, South Sulawesi, is located in a mountainous area with stronger winds of 5.0-7.7 m/s during the dry season (Lisapaly, 2021). This comparison shows that environmental conditions greatly affect the capacitor specifications needed at each location.

Table 2. Comparison of Environmental Characteristics and Requirements of Aluminum Electrolytic Capacitors in Wind Turbines in Coastal and Mountain Regions

Aspects	Balikpapan's Wind Turbine	Sidrap's Wind Turbine
Wind Velocity	3.7-5.0 m/s	5.0-7.7 m/s
Voltage Stability	stabil	Fluktuatif
Humidity	Tinggi	Rendah-sedang
Components Risk	Korosi tinggi	Overheating
Voltage	3-4 Volt DC	690 Volt AC

Source: Risna et al. (2024) & Lisapaly (2021)

3.4 Comparison of AEC on outdoor and indoor solar panels

Figure 2. Indoor and Outdoor Solar Panels
Source: Olusanya et al. (2024)

From Fig. 2 the characteristics of AEC on solar panels are of course strongly influenced by the environment used in the placement of solar panels, where solar panels can be placed indoor or outdoor. So that the characteristics of outdoor or indoor conditions will affect the performance of the characteristics of electrolytic capacitors, especially aluminum.

Table 3. Comparison of AEC Characteristics of Indoor and Outdoor Solar Panel Systems

Condition	Environmental Factor	Performance
Indoor	Light intensity 300-1000 lux, stable temperature 20-30°C	Stable voltage ±0.5 V, low power 1-1.5 mW, long life

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Outdoor	Light intensity >80,000 lux, temperature >50°C	0.7V higher voltage, 4mW more power, and high degradation risk

Source: Olusanya et al. (2024)

The characteristics listed in Table 3 show that aluminum electrolytic capacitors are greatly influenced by differences in environmental conditions, namely indoor or outdoor (Liu et al., 2024). In indoor AEC solar panels, performance is more stable, with the voltage generated by indoor or indoor solar panels generally lower and more stable (0.5 volts) and the power generated also relatively small at around 1-1.5mW). In indoor environments, the intensity of incoming light tends to be lower, ranging from 300 to 1000 lux, which reduces the risk of overvoltage. The temperature in indoor environments is also stable, around 20–30°C, so AEC here has a longer lifespan and high performance and energy storage without leakage current (Zhang et al., 2016). Meanwhile, the use of aluminum AEC in outdoor systems faces harsh weather conditions, where solar panels are directly exposed to sunlight, resulting in higher voltages up to 0.7 volts and greater power output up to 4 mW (Wang et al., 2016). In this environment, light intensity is also significantly higher, exceeding 80,000 lux, which causes an increase in temperature during operation, potentially exceeding 50°C outdoors. Under such conditions, AEC degradation occurs rapidly, leading to leakage current. Therefore, the use of aluminum AEC in outdoor systems requires additional protection, such as cooling, meaning that aluminum AEC is more suitable for indoor solar panel systems due to their more stable conditions compared to outdoor environments. While outdoor use is still possible, additional measures are needed to ensure the AEC is more resistant to environmental conditions that could damage the components (Wicaksanajati et al., 2024).

3.5 Aluminum Electrolytic Capacitor Fabrication/Manufacturing

The manufacturing of solar panels and wind turbines both aim to produce electricity-generating devices from renewable energy, but their production methods are very different. Solar panels are made from silicon that is cleaned and processed into thin sheets, which are then converted into solar cells that can capture sunlight and generate electricity. These cells are then assembled and covered with protective glass to form a single panel (Fraunhofer, 2022). Meanwhile, wind turbines are made from large components such as blades, tower masts, and generators. All these parts are produced using heavy machinery and metalworking techniques, then assembled, often directly at the installation site due to their large size (Irena, 2017).

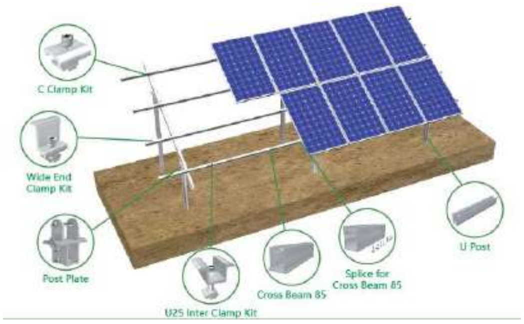

Figure 3. The Components of Solar Panel
Source: Irena (2017)

The C Clamp Kit functions as a lock in the middle of the panel to prevent it from shifting, while the Wide End Clamp Kit keeps the panel strong at the ends and prevents it from lifting. The Post Plate connects the support pole to the horizontal beam to support the weight of the panel. The U25 Inter Clamp Kit is used as a connector between two panels to ensure they are securely attached. The Cross Beam 85 is the main beam that supports and keeps the panel stable, and if necessary, this beam can be extended with a Splice for Cross Beam 85 without reducing its strength. The entire structure is supported by U Posts, poles planted in the ground as the foundation of the frame to keep it sturdy (Irena, 2017).

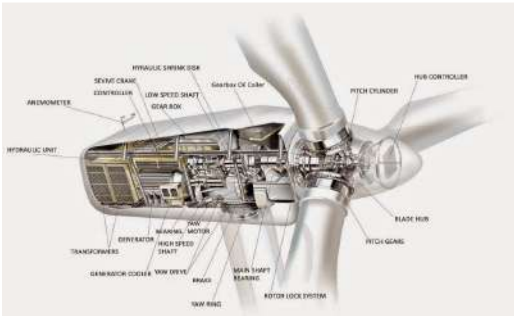

Figure 4. The Components of Wind Turbine
Source: Burton et al. (2011)

The controller is responsible for automatically regulating turbine operations, including the start and stop processes. Anemometers and wind vanes are used to measure wind speed and direction, which are then used as references for the yaw system to direct the nacelle so that the blades always face the wind direction (Burton et al., 2011). All of these components are placed in a nacelle located at the top of a tall tower in order to capture the wind optimally.

Table 4. Solar Panel Development from Year to Year

Year	Technological Development	Main Use	Sources
2000	Monocrystalline panels become globally popular	Household, small applications	Green, 2000
2006	Thin-film technology is developing rapidly	Commercial building, wall & roof	National Renewable Energy Laboratory, 2024
2012	PERC began to be used in commercial panels	Households and small industries	Kojima et al., 2009
2016	Bifacial panels are widely introduced	Large-scale solar power plant (two sides absorbing light)	International Energy Agency, 2020

2019	TOPCon and HJT start tested for higher efficiency	Large projects and industrial roofs	Renewables Global Status Report, 2022
2022	Commercial panels achieve 22-23% efficiency	Rooftop, national solar PV, commercial projects	Parida et al., 2011
2024	Silicon-perovskite tandem cell research reaches 26% (lab)	Still in research, not yet in mass production	Razykov et al., 2025
2025	Bifacial solar panels + TOPCon dominate the market	Industrial and large utility PV systems	Luque & Hegedus, 2011

Table 5. Wind Turbine Development from Year to Year

Year	Technological Development	Main Use	Source
2000	Turbine capacity is increasing rapidly, starting at 1–2 MW per unit	Medium-scale project	International Renewable Energy Agency, 2020
2009	Siemens release 3-5 MW turbines for large projects	National power plant	Ragheb, 2014
2015	Offshore technology begins to dominate in Europe and Asia	Offshore utility-scale	U.S. Department of Energy, 2020
2020	3.6 MW onshore turbines become global standard, offshore turbines reach 10 MW+	Offshore wind farm	European Wind Energy Association, 2013
2023	New generation offshore turbines designed up to 15 MW (Haliade-X)	Large-scale national renewable energy projects	Manwell et al., 2010
2025	Target development of turbines >20MW with AI control and large rotors	Floating wind farm, deep sea project	GWEC *Offshore Wind to 2030,* 2021

3.6 Advantages and Disadvantages

Table 6. Advantages and Disadvantages of AEC in Wind Turbines

No.	Advantages	Disadvantages	Sources
1.	High capacitance ideal for temporary DC-link energy storage	Decrease in capacitance over time (aging), especially at high temperatures	Ko et al., 2018

2.	Low cost and frequently used in electronic devices	Costs increase if replaced frequently, making it uneconomical for large-scale electronic devices	Hassanzadeh et al., 2017
3.	Compact and easy to arrange in parallel or series in electronic devices	Relatively large size for long-term performance	Cognet et al., 2020
4.	Widely available commercially in various capacities and voltages	Relatively short service life	Letzgus & Müller, 2023

Table 7. Advantages and Disadvantages of AEC in Solar Panel

No.	Advantages	Disadvantages	Sources
1.	Dampens switching frequency oscillations and reduces voltage ripple at the PV terminals	ESR can increase and cause an increase in voltage ripple and a decrease in power extraction efficiency from the PV in solar panels	Ahmad, 2016
2.	Has high power storage capacity and is inexpensive	Has a short service life of around 9-10 years	Arya et, al, 2017
3.	Reduces voltage fluctuations in PV panels, thereby maintaining the stability of the solar panel system's output	Sensitive to temperature; at high temperatures, the electrolyte may evaporate, causing AEC to age more quickly	Anusree R et, al, 2018
4.	Easy to install in solar panel electronic devices such as boost converters	When the frequency exceeds 20 kHz, the equivalent series inductance (ESL) may affect capacitance calculations for capacitors, making them inaccurate	Lam and pong, 2019

4. CONCLUSION

Aluminum electrolytic capacitors (AECs) are indispensable passive components within power conversion systems for renewable energy, notably in photovoltaic panels and wind turbine applications. Their widespread usage stems from several advantages, including low manufacturing cost, high volumetric capacitance, and adaptability to compact designs required by modern electronic systems. However, this review underscores that AECs are highly susceptible to degradation under specific environmental and operational stressors.

Climatic conditions such as persistent humidity in coastal areas or thermal cycling in mountainous regions pose significant threats to AEC longevity. These factors accelerate core degradation mechanisms, including electrolyte evaporation, rising Equivalent Series Resistance (ESR), and dielectric breakdown, which in turn compromise electrical performance. Operational challenges like long-term voltage stress and ripple current further intensify the rate of failure, leading to voltage instability, lowered power conversion efficiency, and increased likelihood of system malfunction.

To address these vulnerabilities, it is crucial to improve the thermal and chemical stability of AEC materials, enhance protection against environmental stressors, and integrate advanced monitoring systems. Moreover, design customization based on the geographic and operational profile of the energy system is recommended to ensure optimal reliability. Future research must continue to bridge material science, electronics engineering, and environmental resilience to extend the service life and efficiency of AECs in renewable energy infrastructures.

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