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A Critical Review of Resilient Power Electronics for Extreme Environmental Conditions in Renewable Energy Systems

Yaw Sefa Boateng [a], Joshua Asiektewen Annankra [b], and Zakaria Yakin [b]

[a] *Department of Engineering, Norfolk State University, USA*

[b] *Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*

A B S T R A C T

Resilient power electronics is crucial to the development of robust renewable energy systems which are often subjected to harsh environmental conditions. The purpose of this study is to investigate the resilient and innovative systems being applied to power electronic components in the renewable energy industry in order to make them withstand the varying environmental and operational conditions they are often subjected to. This review conducted a critical review of a total of 22 papers over the past 10 years only from varying journals and articles. There is an increasing evolution in the use of Wide Band Gap materials in the design of power electronics as they are able to withstand harsh operational and weather conditions. Very effective power systems are characterised with qualities such as Resistance, Reliability, Redundancy and Response/Recovery. Key findings revealed the effects of temperature, humidity and dust on the reliability of power systems. Manufacturers of renewable energy systems should explore the potential WBG's have in their system designs. The research proposed adoption of a resistor-less gate driver with two auxiliary MOSFETs that have adjustable gate-source voltages, adoption of GaN in large scale power electronics. The study concluded by highlighting the importance adopting of various resilience strategies such as System Hardening, Smart Grid Technology, and improved packaging techniques and Failure models such as the combination of various failure modes and Monte Carlo Simulation to understand and detect potential failures.

Keywords: Power-Electronics, resilience, Wide-Bandgap, weather, renewable energy

1. Introduction

Despite the fast-paced development of the application of power electronics in Renewable Energy Systems, there have been very limited studies in regard to how these electronic components are able to withstand harsh weather conditions given the fact that most renewable systems such as wind and solar are often situated in harsh and unfavorable terrains. Component failures are common in power systems and may arise due to weather or its stochastic nature. However, majority of power systems have been designed to resist stochastics component outages. Over the past decades, natural disasters and man-made attacks have been major challenges to power systems. (Bie et al., 2017)

Though electrical power systems are designed to be reliable during foreseeable abnormal contingencies, there is an apparent need for these systems to be resilient to high-impact low-probability events such as weather which is a major threat to resilience of electrical networks. (Panteli & Mancarella, 2017). A review paper provided by Bhusal et al., 2020 made comprehensive and critical review of current practices of power system resilience metrics and evaluation methods and discusses future directions and recommendations for practiced resilience enhancement methods.

Heatwaves, extreme rainfall, droughts, have potential to affect the normal functioning of energy systems. When these events occur, there is an interruption of generation and transmission of power often leading to electricity shortages and potential spikes in power prices (Brás et al., 2023).

In the wake of the technological revolution, the increase in demand for energy and the quest to satisfy our energy demands, renewable energy systems are undoubtedly one of the key sectors many nations are looking to meet these needs. Renewable energy systems have a heavy reliance on power energy electronic systems to make them perform the functions for which they are designed.

With the increase in demand, many renewable systems are being situated in areas where the weather conditions are harsh. For instance, wind energy systems are now being installed offshore whilst some solar systems are being installed in desert areas. These most likely expose them to harsh environmental conditions including high temperatures, humidity, extreme cold, dust, etc. As power systems form an integral part of renewable energy systems infrastructure, they must be built in a way that makes them resilient to these unfavorable conditions.

Despite the rapid development of power electronics applications in renewable energy systems, there is a notable lack of comprehensive studies focusing on their resilience under extreme environmental conditions. This gap in knowledge poses potential risks to the reliability and longevity of these systems. In recent times climate change has driven even harsher weather conditions and therefore it has become increasingly important to develop robust power systems. In times where harsh weather impacts these components, there can be serious downtimes and economic implications, hence enhancing or improving the resilience of these components can improve the cost-effectiveness and reliability of renewable energy systems. With the development of novel technologies in this area, there is a chance to improve the effectiveness and reliability of renewable systems to withstand adverse conditions.

Insights from this review could ultimately inform deeper research into the selection and application of more robust power systems in renewable energy systems development that are exposed to very tough weather conditions.

1.1 Technological Advancements in Resilient Power Electronics

Power electronics have been manufactured from silicon since the 1950's, however with the limitations in application of silicon based in power control applications, the emergence of Wide Band Gap promises to satisfy these limitations. For instance, Silicon Carbide (SiC) have demonstrated some challenges in their application in power electronics applications including Metal Oxide Semi-Conductor MOS Channel and Gate Dielectric Reliability Challenges, Material Defect-Related Performance Issues (Reduction in breakdown electric field & Increased leakage current due to material defects) and High-Temperature Performance Limitations (Increased leakage current in SiC Schottky devices at elevated temperatures) (Ranbir Singh, 2005).

In light of such limitations, power electronics have evolved over the years to be compact with high power densities with added operational advantages in very extreme temperature environments as well as large thermal cycles. Consequently, researchers are making efforts to develop effective thermal systems to improve their reliability. For example, with the development in research centered around wide band gap semiconductors, Gallium oxide ($Ga_2O_{3)}$ has evolved to become the forefront in the development of semiconductor technologies. Having a favorable intrinsic property namely, critical field strength, widely tunable conductivity, mobility, and melt-based bulk growth, this material is widely used in high performance power electronics, promising to be a replacement for Silicon based power devices. The material has a collection of properties that, until recently, has not been observed in one system. Amongst these properties is: Low thermal conductivity. Ultimately, β-Ga_2O_3 has an ultra-wide bandgap of nearly 5 eV (Green et al., 2022). There is therefore a high tendency for SiC to be replaced by Ga2O3 in the near future. Gallium (III) oxide, commonly called gallium oxide, has emerged as a new semiconductor material for power electronics devices. Another novel discovery is Gallium Nitride (GaN). GaN has an attractive feature of high electron mobility allowing for high switching mobility. Additionally, diamond offers high switching properties, high-temperature operations, radiation hardness, high output power, and can be synthesized to be used in electronic devices (Javier et al., 2021).

The development of wide-bandgap (WBG) devices has revolutionized the performance of power devices in the sense that they have superior functionality, can withstand high voltage/current stresses, have lower power losses, exhibit high switching frequencies, and are characterized by high temperature operational capabilities (Tang et al., 2022). In a report to explore the Wide Bandgap (WBG) Power Electronics market, it was identified that development of WBG materials will require some resource investments from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE EERE). U.S. energy demands are rising, hence there is the growing need to increase system efficiency in the renewable energy industry. The report stated that WBG power electronics can reduce the energy lost during power conversion and do so with a smaller footprint and lighter weight. For example, WBG-integration into motor drives have proven to have very significant energy impact. Motor drives have been estimated to potentially save between 150 – 410 PJ of primary energy for electricity in 2025, depending on the fraction of motors with drives (and assuming 100% penetration of WBG into motor drives) (Armstrong & Marlino., 2017).

1.2 System Resilience

In recent years, when we talk about resilience, we have technically recognized a new design and operation goal for any critical infrastructure (Bie et al., 2017). Apart from qualitative systems resilience evaluation, system resilience is more often than not measured quantitatively. This is useful when we are measuring the effectiveness of precise resilience measures or making comparisons between resilience measures. Resilience is attributed or is measured to the decline in magnitude and or duration of deviation from the targeted performance. There are generally three methods of evaluating system resilience as outlined by Bie et al., 2017 which include; simulation-based method, the analytic method, and the statistical analysis. Bras et al. (2023) defined resilience as capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances.

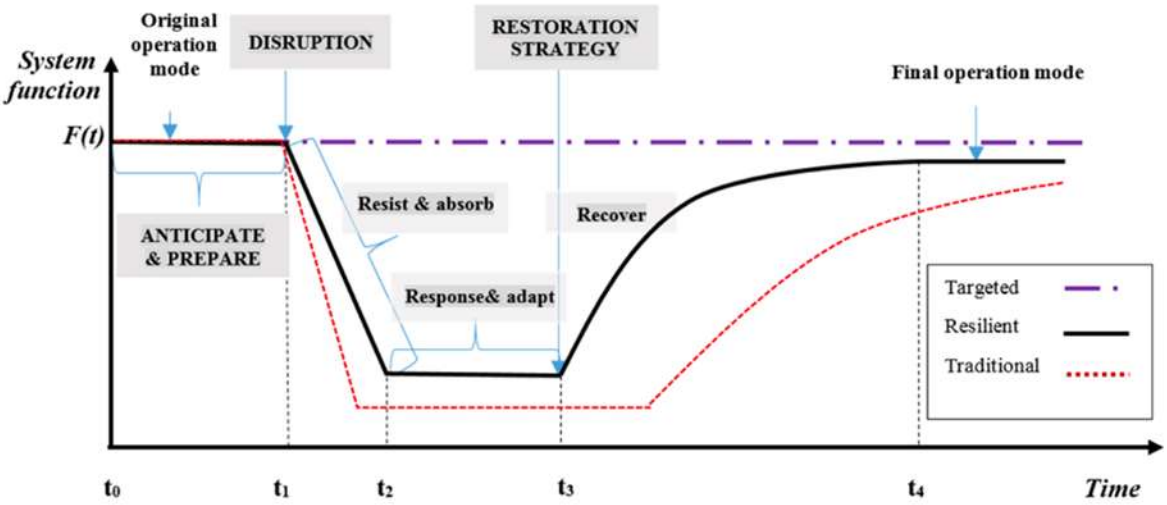

Fig 1: An illustrative process of a resilient power system undergoing disruption and recovery

This paper also highlighted the main resilience features to include:

1. Resistance: The ability to prevent damage or disruption by intrinsic features that equip the system with the strength to resist hazard or impact.
2. Reliability: A feature that ensures that the components operate other a wide range of conditions
3. Redundancy: Availability of installation backups to provide switching to alternative routes
4. Response and Recovery: After disruptive events, the system should have the ability to recover quickly and timely.

Power systems undoubtedly are the backbone of the modern society and plays a crucial role in the optimum performance of many infrastructures ranging from communication, healthcare, etc. it is therefore imperative that robust systems that meet the above resilience features are setup to prevent disruptive threats (Panteli et.al., 2017).

2. Impact of Environmental Conditions

2.1 Impact of Environmental Conditions-Temperature

Studies have identified thermal stress as one of the most critical causes of failures in power electronics components. Due to the differences in the coefficients of thermal expansions of the power electronic materials, mechanical strain between the layers in the devices often arise. In the publication Lifetime Extension of Power Semiconductor Devices by Closed-Loop Junction Temperature Control, a closed loop temperature control system was proposed to curtail this problem. This approach is able to reduce temperature swings thereby reducing the extent of damage and ultimately extending the expected lifetime of the devices. This approach also adopted an online junction temperature measurement system to give a real time report of temperature fluctuations within the system. A key issue affecting power devices, particularly Silicon Caribide Metal Oxide Semiconductor Field Effect Transistor (SiC MOSFETs), is junction temperature fluctuation. While active temperature control can enhance reliability, existing solutions often compromise system efficiency and require complex hardware.

The article presented new approach using a resistor-less gate driver with two auxiliary MOSFETs that have adjustable gate-source voltages. This design allows precise control of switching losses while maintaining efficiency. The researchers developed a power loss model and detailed the temperature controller's design principles.

Key findings:

- Junction temperature fluctuation reduced by 24.1%

- Device lifetime increased by 3.92 times

- Energy efficiency improved by 4.15% during testing

- Method is applicable to both SiC and traditional silicon-based devices

This innovative solution addresses both reliability and efficiency concerns, offering a practical advancement in power device management (Ding et. al., 2022).

Additionally, in a study under different temperatures of up to 700K, the injection current-dependent internal quantum efficiency and current-voltage characteristics of commercial (gallium-nitride) InGaN/GaN MQW blue LED were examined. It was discovered that the peak energy varies from 77K to 700 K due to career localization and as the temperature changes, the LED's performance changes too. The LED reached maximum efficiency of 58.5% at very high temperatures of 700K when a specific electric current of (2A/cm2) was applied. This underscores the potential of GaN in large-scale power electronics applications. (Madhusoodhanan et. al., 2020).

With a combination of 3-D finite difference modeling, parametric loss models, and model truncation techniques a compact thermal real-time model is derived for monitoring of temperature distribution and device losses within power electronics modules. This approach helps to keep computation of temperature losses at critical locations within the power module. The approach also allows for band-width partitioning for estimation of temperature across the power module for every switching period with a nearly zero lag. Estimates of errors in the loss prediction process can easily be tracked over the lifespan of the power module allowing for the detection of degradation of the devices in the power module (Van der Broeck et.al., 2019).

2.2 Impact of Environmental Conditions-Humidity

A summary of the results of climatic field measurement campaigns in 31 wind turbines of different manufacturers and types located in Europe, Asia and North America was conducted. This was carried out by evaluating converter-specific failure data through the past years in these regions.

This failure dataset currently covers more than 10,000 WT across Europe, Asia, Australia, North and South America. The figure below represents the most prominent of these seasonal patterns, which has been observed in a wind turbine fleet with liquid-cooled converters in India. The chart below indicates that during the humid months between June and September, the failure rates of the core converter components rise to multiples of the previous months and decrease again notably towards the end of the year.

Similar research investigates how humidity impacts the performance of a Gallium Nitride (GaN) class-F power amplifier (PA), through controlled environmental testing using a specialized environmental test chamber. The experiments revealed significant performance degradation as humidity levels increased, specifically observing reductions in output power, power-added efficiency, large-signal gain, and drain current. (Shaohua Zhou, 2023)

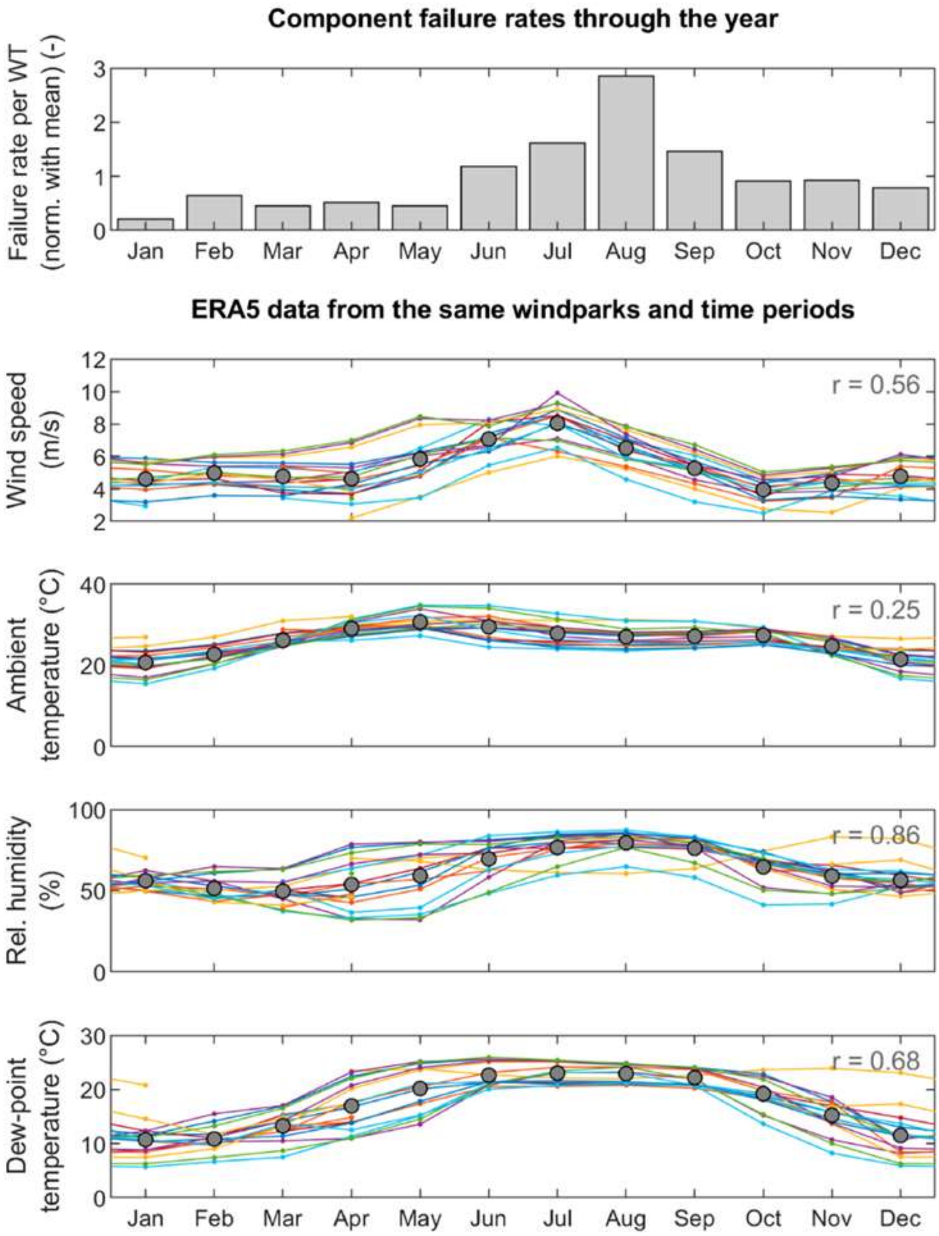

Fig. 2 Seasonal variation of phase-module failure rates in a WT fleet with liquid-cooled converters in India (based on field failure data from 590 WT operating years, cf.) with corresponding monthly average wind-speed and environmental conditions (each line represents one wind farm, grey markers indicate the average across the wind farms, r values describe the correlation with the failure rates) (Fischer et.al., 2021).

2.3 Impact of Environmental Conditions-Dust

In a study, 16 types of dust particles were monitored in the air to determine their effects on photovoltaic (PV) performance. A variety of variables were measured, including current and voltage, to determine how dust affects the PV performance. In all the tests, carbon accumulation had the highest impact on the PV performance thus reduced efficiency by about 99% when it was accumulated at a density of 20.54 g/m2 whereas sodium chloride had the least. (Sopian et.al 2024)

In a similar study, the impact of dust deposition on photovoltaic panel performance, with a focus on solar energy production in desert-like climates was investigated. Conducted at the Solar Energy Research Center (CIESOL) at the University of Almería, the research revealed an average 5% power reduction due to dust contamination. By simulating this effect across different-sized photovoltaic installations—ranging from 9 kWp to 50 MWp—the researchers quantified potential economic losses, which could exceed €150,000 annually for large industrial plants. Additionally, the study proposed a cleaning strategy, acknowledging the significant long-term economic investment required to maintain optimal panel performance. (Alonso-Montesinos et al., 2020).

3. Resilience Improvement Methods

Zhaohong et al. in their study identified various resilience improvement methods that can identify the strengths and weaknesses inherent in power grid systems allowing for implementation of proposed improvement strategies within the system. Taking into consideration the expectancy of disasters and the balance between system resilience and cost involved, the paper identified two broad aspects: system hardening and operational resilience strategies. Thus, outlining that a more robust way of improving system resilience is a combination of both strategies.

3.1 Resilience Strategies - System Hardening

This is the reinforcement of physical structures like substations and transmission towers to withstand extreme events higher winds, flooding, earthquakes, and other hazards. Some of the hardening practices identified include.

1. Undergrounding the distribution/ transmission lines
2. Upgrading poles with stronger, more robust materials
3. Elevating substations and relocating facilities
4. Redundancy in transmission and distribution system
5. Tree trimming/vegetation management

3.2 Resilience Strategies – Smart Grid Technology

Smart grid systems are designed to enhance efficiency in the operations of the power system, system visibility, and response to faults and outages. Among the smart grid technologies identified include:

1. Risk assessment and management for evaluating and preparation.
2. Disaster assessment and priority setting.
3. Installation of distributed energy network (der) or other onsite generation units.
4. Accurate estimation of the natural disaster location and severity.
5. Fault location, isolation, and service restoration.
6. Demand side management.
7. Microgrid island operation.
8. Advanced control and protection schemes.

Some trends in Power Electronics for Renewable Energy Systems Integration include

3.3 Materials

We see the development of high-power silicon-based semiconductors including the development of WBG devices i.e., SiC and GaN components. These have introduced a positive advantage of high switching frequencies and low power losses of WBG devices whilst improving the power densities of converters.

3.4 Packaging

Conventional soldering and bond-wire connection in chips have proven to be a disadvantage of large thermal resistance. Improved methods such as press-pack base plate soldering include press-pack-based plate soldering, sinter technology to avoid the chip soldering, as well as replacing the bond wire with new materials to reduce the coefficient of thermal expansion. The advantages these techniques offer range from the improvement of connection of chips by direct press-packing, offering the advantage of low short circuit failure, high power density and enhanced cooling efficiencies. These press-pack devices, including silicon-based and wide-bandgap (WBG) devices, are expected to be utilized more widely in the future (Bie et al., 2017).

4. Reliability and Failure Modes

Modern electronic devices are often susceptible to faults, hence various checks are put in place during the manufacturing stage to curtail these faults. In the prior chapter where we highlighted on the effect of environmental factors on the resilience of power devices, we cannot totally dismiss these effects when addressing failure modes. The process of detecting devices that are susceptible to failure are most often not straightforward and have to go through series of testing to determine the resilience of the device. Challenge usually arises when testing for faults in analog devices, hence engineers often resort to qualitative assessment in such cases making the results generated for such models inexhaustive as they do not rely on precise device fault models. Based on this, Davide et. al., in his research on Reliability in Power Electronics and Power Systems concluded that it is not possible to assess the real effectiveness of a test method for analog devices.

The study by Davide Piumatti demonstrates how well different testing methods work for detecting faults in power devices, using new fault models developed by researchers and industry experts. The main goal was to create ways to measure how effective a testing strategy is by calculating something called Fault Coverage (FC) - basically, how many potential faults a test can find in power devices and systems.

The study developed an approach that works with various power devices, particularly Insulated Gate Bipolar Transistors (IGBTs) and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs). One of the key innovations of this method is that it can automatically generate a comprehensive list of possible faults. This automation makes it much easier to run fault simulations and calculate how well the tests are working. The study showed that with an adequate combination of different test methods, it is possible to reach high FC of at least 90% of the potential faults. This study also highlighted the effect of junction temperature that often cause breakdown phenomena often as a result of heatsink failures. As part of this analysis it is imperative to check the assembly and operations of heatsinks used in power devices. It highlighted that though x-rays are used to check the optimal performance of heatsinks, this approach gives only a qualitative approach. This study used electrical measurements to estimate thermal resistance within the system allowing for a more quantitative of the heatsink assembly. These experimental results proved very promising. When this method was tested on an actual system, it was able to detect improper heatsink installation with 100% accuracy across all test cases. The proposed approach allows the systematic and automatic identification of critical faults in a cyber-physical system.

The Monte Carlo-simulation has been used extensively in the assessment of power electronics reliability. This paper carried out an in-depth analysis of Monte Carlo simulation applied to reliability assessment of power devices in power electronic systems. In this paper, the Monte Carlo-based reliability assessment methods are applied to a case study of power devices in PV inverters. This study made a comparison of 3 different Monte Carlo simulation methods. i.e., A) Monte Carlo with Static Parameters: It requires a conversion of the dynamic thermal stress profile to an equivalent set of static parameters. B) Monte Carlo with Semi-Dynamic Parameters: During each Monte Carlo simulation, one sample is randomly picked from the variance distribution and this same variance applied across the entire thermal profile. and C) Monte Carlo with Dynamic Parameters: Here the parameter variation range that is being applied during one Monte Carlo simulation will not be constant but dynamically change over time. The findings revealed that use of conventional Monte Carlo simulation with static parameters is faster but with a higher margin of error of up to 30% compared to the other two methods with dynamic parameters. The study also demonstrated that the reliability of the test results converges when the number of simulations reaches 1000.

5. Conclusion

Power electronic devices have evolved over the past years to involves a wide variety of innovative technologies including the adopting of WBG material which offer enhanced thermal properties and resilience to a variety of stresses. As power electronics are increasingly becoming a component on major renewable energy systems, it is imperative that these devices a built to withstand the harsh conditions they are often subjected to. This review unravelled that the major components of resilience manufacturers should consider which include Resistance, Reliability, Redundancy and Response/Recovery. The study also highlighted that one of the key contributors to failures in power electronics include junction temperature fluctuations, however literature shows that the impact of temperature can be curtailed by adopting a resistor-less gate driver with two auxiliary MOSFETs that have adjustable gate-source voltages, adoption of GaN in large scale power electronics applications as well as real time monitoring models. The review also highlighted the effect of humidity on wind turbines where there was a degradation in the output power, efficiency, signal gain, and draining current under humid conditions. These findings highlight the importance for accounting for environmental conditions like humidity when designing power electronic devices. The review also underscored the effect of dust highlighting reduced performance in photovoltaic devices performance exposed to dust depositions a phenomenon more acute in desert climates. The study also delved into various Resilience strategies such as System Hardening, Smart Grid Technology, and improved packaging techniques to power components exposed to very harsh environmental conditions. The review concluded my looking at some failure modes. The research highlighted the use of fault detection methods through automated fault assessments and thermal resistance measurements highlighting that a combination of different test could detect as much as 90% of the potential faults. Finally, Comparative analysis using the Monte Carlo simulation methods revealed that while static parameter simulations are faster, dynamic parameter approaches offer superior accuracy with up to 30% less error margin.

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