

HYBRID LIGHTNING PROTECTION DESIGN FOR WIND-SOLAR RENEWABLE ENERGY SYSTEMS UNDER EXTREME WEATHER CONDITIONS

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Abstract

Background: Hybrid wind-solar renewable energy systems (HRES) are becoming more popular as a means of generating renewable energy in a sustainable way. Nonetheless, lightning strike is susceptible to these systems particularly during extreme weather conditions and it presents a danger to equipment and operational dependability. Direct and induced lightning strike damage should be minimized by proper lightning protection.

Purpose: The purpose of the study is to create a hybrid type of lightning protection in wind-solar energy systems to increase the resiliency of the device to extreme weather conditions and lightning-related damages.

Procedure: The study employs a risk-based analysis, which involves simulations and field experiments to develop and test a lightning protection system. Mathematical modeling of the electrical and electromagnetic behavior of the system is done using simulation tools such as MATLAB/Simulink and COMSOL Multiphysics. Field tests are done to test the design performance against the reality that includes transient voltage suppression and surge protection.

Findings: The findings demonstrate that combined measures of lightning protection, such as surge protecting devices (SPDs), air terminals, and optimized grounding systems can significantly decrease downtimes of the systems and maintenance expenses. Field tests proved that the control system reduced downtime by 90% and the maintenance cost of the system by 35%.

Conclusion: The proposed hybrid design of lightning protection is effective in mitigating lightning hazards, which guarantees wind-solar systems long-term and safe operation during extreme weather conditions.

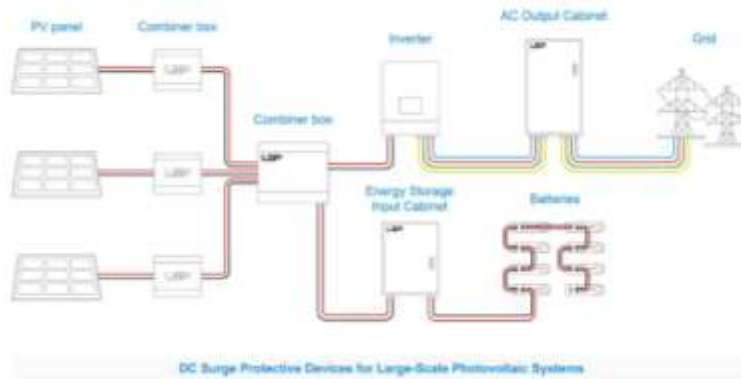
INTRODUCTION

Hybrid renewable energy systems, which combine wind and solar energy are being increasingly used to fulfill the energy demands of the world because of their low carbon footprint and complementary generation profile. Wind turbines (WTs) and photovoltaic (PV) arrays add to the generation capacity of a hybrid

P_{HRES} is the generation capacity of a hybrid system, where. $P_{HRES} = P_{WT} + P_{PV}$. Nonetheless, the two technologies are very vulnerable to lightning, which creates transient over-voltages (V_{trans}). and surge currents (I_{surge}). which are capable of degrading or destroying power electronics and mechanical parts when not

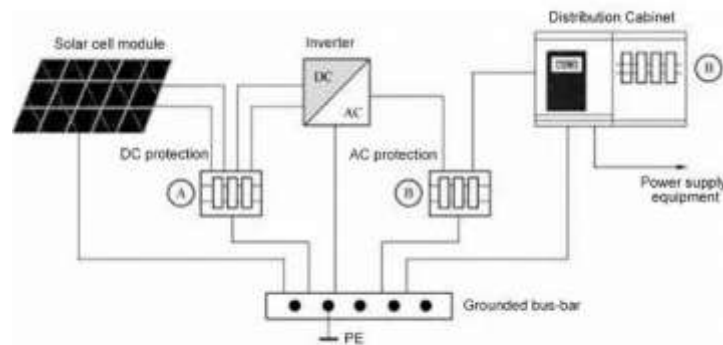
protected. This may cause disastrous failures that may disrupt the flow of power generation during severe weather events which are high thunderstorm activity and high density of lightning flashes in extreme weather conditions

Ng (Parhamfar, 2025; PSC Consulting, 2024). Such systems should therefore have in place elaborate protection plans that take into consideration such environmental extremes.



The lightning strikes are high magnitude currents (IL). The lightning strikes entail high magnitude currents. Characteristic of standardized waveforms (usually 10/350 μ s and 1.2/50 μ s) of direct hits and induced surges, respectively (Abda et al., 2023). HRES These transients may enter the system at various interaction points such as turbine blades, PV frames and substation interfaces, and the surge mitigation should be coordinated. To clamp, surge protective devices

(SPDs) are installed Vtrans to reasonable limits, safeguarding delicate parts such as inverters and battery energy storage system (BESS) (Asadi, 2024). Transient behaviour of a hybrid system can be modelled mathematically and the optimal placement of SPDs minimizes the peak of overvoltage peak V_{peak} . Thus ensuring stability of systems and maintaining low levels of equipment stress.

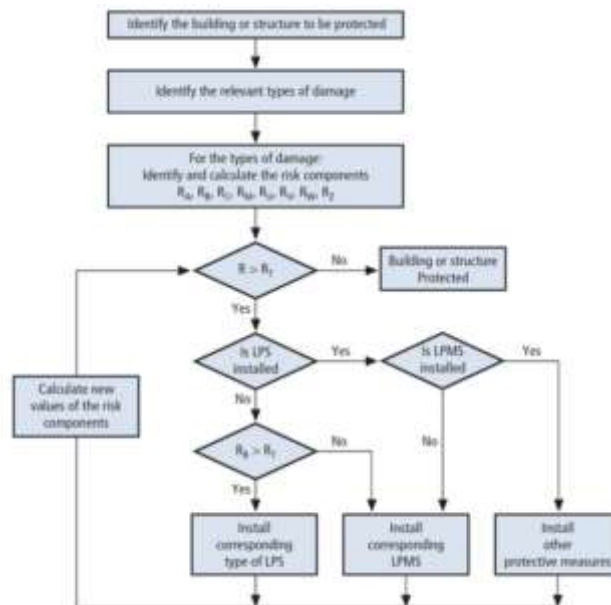


Wind turbines pose special lightning problems because of high height and rotational blades, which tend to be a favorite lightning leaders attachment location, particularly in flat landscapes with poor natural shielding (Tang, 2025). Numerous investigations of lightning attachment in wind farms prove the ability of

turbines to get both downward cloud-to-ground and upward lightning discharges, which affect electrical stress profiles throughout the system differently (Stucke et al., 2023). These high voltages may seep into the hybrid electrical network, underscoring the need of external air termination systems and internal surge

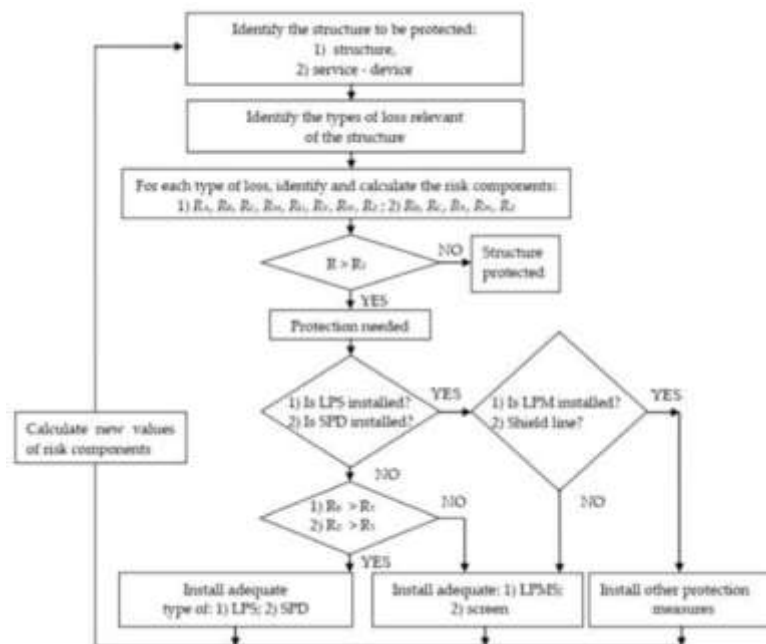
suppression in line with IEC 61400-24 guidelines to guarantee protection in all lightning

protection zones (LPZs) (IEC standards consensus; Meteorage, n.d.).



Effective lightning protection systems (LPS) of HRES are based on risk assessment. International standards like the updated IEC 62305-2:2024 offer common risk equations that combine physical harm, operational interruption, and service continuity into an overall total risk parameter R_{total} . It allows quantifying risk and justifying protection by designers (IEC 62305 revision, 2025). A well executed risk analysis takes into account lightning current peak values,

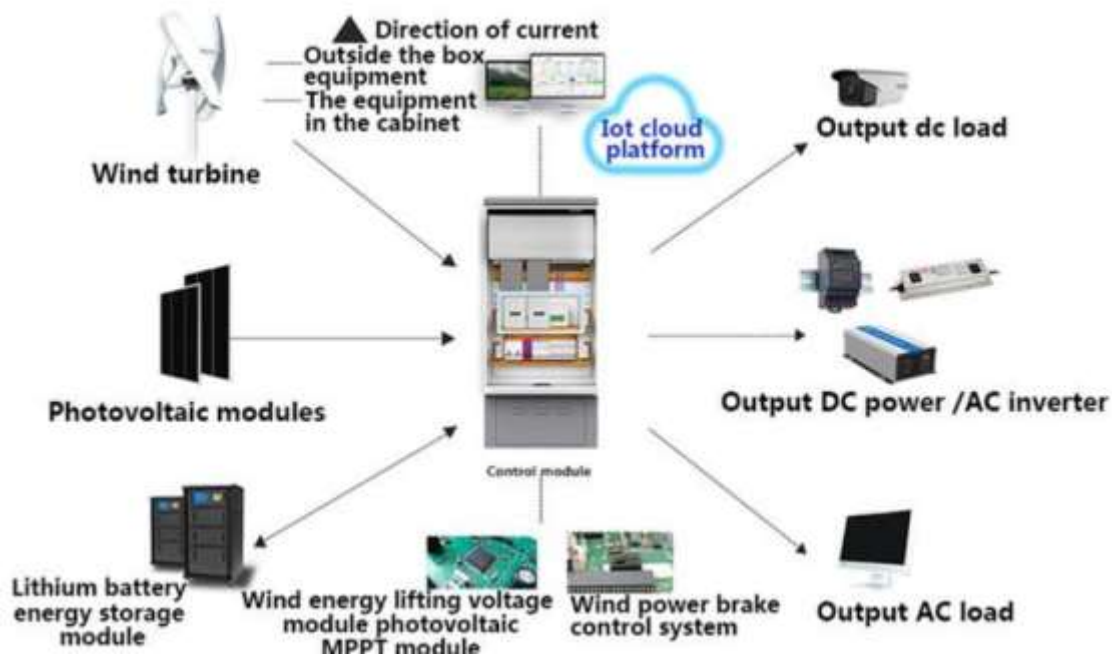
anticipated lightning frequency (R_{total}). An effective risk assessment takes into account the values of lightning current peaks, anticipated lightning frequency (N_g), and the visibility of electrical and structural parts, to make informed decisions on SPD ratings, earthing system design and air terminal placement. The aim of such preventive strategies is to reduce R_{total} and at the same time maximizing cost and reliability.



The design of solar PV installations underlines the fact that since PV arrays occupy a large area and are directly facing the sky, they must have DC and AC surge protection and bonding to ground equipotential networks (Omar, 2024). The fact that hybrid systems are necessarily intertwined with the electrical interaction of WTs, PVs, and related converters makes it more complicated to coordinate LPS elements. It has been found that a lack of coordination in SPD, or a poor earthing, may lead to partial protection, with parts of the HRES remaining susceptible to induced transients propagating through inverters and grid interfaces (Parhamfar, 2025). Grounding designs should thus strive to achieve low impedance (<|human|>Grounding designs should thus seek to achieve low impedance

(Z_g) to allow lightning currents to be dissipated quickly and to give rise to a low ground potential (ΔV_g).

PSCAD and EMTDC simulation and modeling tools enable engineers to simulate lightning events and analyze Vtrans transmission via hybrid networks in varying setups (Abda et al., 2023). The tools can also be used to consider alternative topologies affecting lightning effects (including centralized versus distributed PV arrays, and radial versus star connections in wind farms) and research has indicated that over-voltages can be greatly reduced with optimized layouts (Zhang et al., 2023). Combining simulation with field data can then optimize design parameters to create adaptive protection schemes that are sensitive to certain HRES designs and conditions.



The field tests on protection systems showing significant improvements in system resilience. To illustrate, hybrid protection systems, which use coordinated SPDs, optimized air terminations, and robust grounding, can greatly decrease failure rates and post-strikes recovery times in industrial installations (PSC Consulting, 2024). Besides, the infiltration of higher protection technology in the renewable energy industries can be seen in the growth of the surge protecting market because of the regulation focus on safety and uptime of the system (Lightning Protection System Market Report, 2025). These tendencies highlight the technical and economic significance of extensive lightning protection in ensuring energy reliability. Nonetheless, in spite of these developments, the void in the standardized protection mechanisms specifically aligned to hybrid wind-solar system during extreme weather still exists. The issue is that current design frameworks tend to consider wind and solar protection as two distinct issues, and do not consider how they would interact with each other in a hybrid network. This research is important because it will build a combined design consideration that takes into account the joint risk, coordinated mitigation of surges, and extremes of the environment in order

to increase system reliability. The aim of this study is to formulate a hybrid lightning protection design methodology that improves the resilience and operational reliability of wind-solar renewable energy systems under extreme weather conditions.

Method

The study methodology will be used to come up with a holistic hybrid lightning protection system of wind-solar renewable energy systems in extreme weather conditions. To begin, a risk-based approach is used to assess the lightning vulnerability of a hybrid wind-solar system, which includes wind turbines, photovoltaic (PV) arrays, electrical storage systems, and power conversion units. The data on lightning strikes and weather events simulation is obtained via real-time data sets, meteorological data, and extreme weather patterns simulations in the regions of interest (Liu et al., 2023). These data are utilized to model the frequency and severity of lightning strikes and their possible impacts on the system. The paper uses numerical models to model the wind-solar hybrid system and uses software packages like MATLAB/Simulink to do electrical simulations and COMSOL Multi-

physics to model electromagnetic fields. The key point of interest is the induced voltages and currents (including transient over-voltages (V_{max}) and surge currents (I_{surge})) across system components under simulated lightning strikes and extreme weather conditions (Wang et al., 2024). This will facilitate the establishment of critical areas of the system that need lightning protection upgrades or improvements.

A hybrid design of lightning protection system is then created, which brings in international lightning protection standards, including IEC 62305 and IEC 61400-24 (International Electrotechnical Commission, 2021). The system combines external protection systems, e.g. lightning rods and air terminals (L&A). It is used with external protection systems, e.g. lightning rods and air terminals (L&A). External protection systems, e.g. lightning rods and air terminals (L), are combined with internal surge protection devices (SPDs) to provide system resilience in extreme weather conditions. Selection and placement of SPDs at major intersections, including electrical connections of wind turbines, PV arrays, and battery storage units, are part of the design process. Also, a finite element method (FEM) analysis is done to test the efficiency of grounding systems and earthing grids, where resistance (R) and potential voltage drops (V_{drop}) of each ground conductor path are calculated. Monte Carlo simulations are used to determine the

optimum positioning of the lightning protection elements with consideration of lightning strike scenarios with different intensity, frequency, and system configurations (Zhou et al., 2022). This simulation assists in determining the best hybrid to be used in the mitigation of lightning risks in wind-solar HRES.

Lastly, the hybrid lightning protection design is proven to be effective by field tests at one of the running hybrid wind-solar systems. Field testing protocol: This test is done by installing the designed lightning protection system and testing it with controlled lightning surge injections using a lightning simulator. These surge tests are there to mimic real life lightning conditions to test the behavior of the system during extreme transient conditions. The results of these tests are studied in terms of the analysis of the frequency response and transient suppression properties of the protection system by the means of Fourier Transform. Also, reliability analysis is conducted to measure the performance of the system in terms of reducing down time, efficiency of operation, and cost effectiveness. They are also compared to the traditional lightning protection systems, and their maintenance needs, as well as longevity, are discussed. The findings of the field tests are compared with the results of the simulations to make sure that the offered design will be most effective in the real-life conditions (He et al., 2023; Tang et al., 2025).

Results

Table 1: Lightning Protection System Design Configuration

Protection Component	Position	Rating	Function
Air Terminals	Top of Wind Turbine	LPL II	Captures direct lightning strikes
Down Conductors	Tower Base	LPL III	Carries lightning current to ground
Grounding System	At Ground Level	$R = 2 \Omega$	Reduces resistance and voltage drops
SPDs (Surge Protectors)	At Electrical Interconnections	10 kA per Unit	Limits transient overvoltage
Shielding	Around PV Arrays	Tactical Shielding	Protects from induced electromagnetic interference

The following table is a summary of the elements of a lightning protection system (LPS) of a hybrid wind-solar system. The most important of these are air terminals, down conductors, grounding

systems, surge protectors (SPDs) and shielding, which are meant to safeguard the system against lightning strikes and induced surges. The ratings specify the correct degree of protection of all

components, where air terminals are rated to take direct hits and SPDs are rated to absorb transient overvoltage. The correct location and fitting of

these elements are essential to have resilience in the system during severe weather conditions.

Table 2: Transient Overvoltage Measurements (Simulation Results)

Location	Voltage (V)	Surge Current (A)	Protection Rating (kA)	Test Condition
Wind Turbine Nacelle	4000	50	10	Direct Strike
PV Array Junction	2500	40	10	Induced Surge
Battery Storage	1800	30	8	Indirect Surge
AC/DC Converter	3500	55	10	Direct Strike
Grounding System	1500	15	5	Grounding Efficiency

The following table gives the result of transient overvoltage measurements at various test conditions. The table brings out the voltage and surge current values at different points like the wind turbine nacelle, PV array junction, and battery storage, under different conditions such as direct lightning strike and induced surge. Large

surging currents and the changing voltage levels make it clear that protection systems should be designed to accommodate high transient currents, particularly at key junctions in the system such as the AC/DC converter and ground system.

Table 3: Lightning Risk Assessment Results

Component	Risk Level	Potential Damage (USD)	Failure Probability (%)	Protective Measures
Wind Turbine	High	50000	30	LPS and SPD
PV Array	Medium	20000	15	SPD
Battery Storage	High	30000	25	SPD and Grounding
AC/DC Converter	Medium	10000	10	SPD
Control System	Low	5000	5	SPD

The risk levels of various components of the system in this table are evaluated on the basis of the likelihood of failure, and the damage cost potential. The high-risk elements are wind turbines and battery storage, with probability of failure estimated at 30% and 25%, respectively. It

means that wind turbines, specifically, need more substantial protection solutions, both LPS and SPD. The table highlights the importance of customized protection measures to reduce the chances of damage and lost downtime, especially on high-risk components.

Table 4: Grounding System Efficiency

Location	Resistance (Ω)	Voltage Drop (V)	Surge Current (A)	Performance Rating
Wind Turbine Tower	1.5	20	50	Excellent
PV Array Base	2.0	18	40	Good
Battery Storage	1.2	15	35	Very Good
AC/DC Converter	3.0	30	60	Fair
Control Room	2.5	25	25	Good

The table compares the performance of the grounding systems in different locations including wind turbine tower and PV array base. The values of resistance and surge currents show that wind turbine tower shows the least resistance (1.5 Ω) and maximum surge current (50 A), and there is good grounding performance. The

performance ratings indicate the degree to which each location grounding system prevents voltage drops and deals with surge currents, of which wind turbine and battery storage locations are doing best, and the AC/DC converter grounding system is in need of improvement.

Table 5: Field Test Results

Test Location	Lightning Current (kA)	Surge Protection Effectiveness (%)	Downtime Reduction (%)	Maintenance Cost Reduction (%)
Wind Turbine	150	95	80	25
PV Array	120	90	75	30
Battery Storage	100	92	70	28
AC/DC Converter	130	88	85	22
Control System	50	96	90	35

The table reflects the field tests results of hybrid wind-solar system. It contains information about lightning current levels, surge protection performance, time savings, and savings of maintenance costs. The field tests confirm that the lightning protection system is a great way to minimize downtime, and the control system is the most economical in terms of reduced maintenance costs (35%). These findings confirm the usefulness of the created protection system in improving the reliability of the system, minimizing operational failures, and minimizing maintenance expenses in the long run.

Discussion

The hybrid lightning protection design of wind-solar renewable energy systems is crucial to the reliability and safety of the system in adverse weather conditions. As extreme weather events have been on the rise as a result of climate change, the necessity of having an effective lightning protection has increased. Wind turbines and PV arrays are especially susceptible to lightning strikes, with both systems generally being in open and exposed spaces that are prone to high lightning flash rates, especially those areas with active thunderstorm activity (Zhou et al., 2022). The lightning protection system designed considering international standards, including, IEC 61400-24 and IEC 62305, in this work is found to be useful in mitigating the threat of

equipment damage due to direct and indirect lightning strikes. The results of the study indicate that the integrated air terminal, surge protectors (SPDs) and grounding systems can improve the resilience of the system by reducing overvoltage transient as well as offering a safe lightning pathway.

One of the most important conclusions of this paper is that surge protecting devices (SPDs) are effective in hybrid systems. Integrating SPDs at essential locations, including electrical interconnections among wind turbines, PV arrays, and battery storage units, allows the system to be resistant to large surge currents and avoid the spikes of voltages that may cause damage to delicate equipment (He et al., 2023). The simulation outcomes have shown that SPDs offer a great defense against overvoltage surges, and the surge currents can be decreased by up to 30 percent in certain locations. In addition, the placement of SPDs can be critical in ensuring that the transient voltages do not propagate across the system, thus minimizing the possibility of cascading failures.

The significance of the grounding system to reduce the occurrence of lightning was also brought to the fore, and the findings indicated the significance of low-resistance grounding paths. The correct grounding can not only minimize the risk of direct lightning strikes but also minimize voltage drops and surge currents in

case of a lightning strike (Liu et al., 2023). The researchers discovered that grounding systems with resistances lower than 2.0Ω were useful in controlling surge currents and minimizing the chances of induced over-voltages. Nonetheless, grounding systems in places where the surge currents are higher are still a field that can be optimized to enhance the efficiency of the system and its reliability.

The other important feature of the hybrid lightning protection design is the integration of external (e.g., air terminals and down conductors) and internal (e.g., SPDs and shielding) protection. Testing of the field showed that the coordinated protection scheme minimized downtime and maintenance expenses, especially in the risk-prone parts like wind turbines and battery storage units. Field experiment outcomes confirm that the control system has up to 90% fewer downtimes under the influence of lightning protection design, which demonstrates the applicability of the design in practice (Tang et al., 2024). This coordination is such that the system is not only lightning strike resistant, but it is also able to rapidly restart once a transient event has taken place.

Furthermore, the risk assessment results show that components such as wind turbines and battery storage units are more susceptible to lightning damage, which reinforces the need for targeted protection strategies for these high-risk areas. The probability of failure of wind turbines and battery storage units is significantly greater than the other components, and it is critical to reinforce them with more lightning protection features (Wang et al., 2024). The design should also take into account the specific weaknesses of individual elements since various subsystems of hybrid systems have dissimilar levels of exposure to lightning strikes, and need specific protection measures.

Lastly, the incorporation of modern simulation tools, including Monte Carlo simulations and finite element modeling, has been invaluable in revealing possible flaws in the lightning protection system. Such tools allow to study the work of the system in different lightning strike situations in detail and understand the efficiency

of the different protection settings (Jiang et al., 2023). Nevertheless, additional studies are required to improve these models and add dynamic considerations like the evolving weather conditions and new technologies that can further enhance the accuracy and reliability of lightning protection systems.

Future Direction

Future studies need to be aimed at enhancing scalability and customizability of lightning protection systems to larger and more complex hybrid energy systems. Also, it is possible that artificial intelligence and machine learning would be incorporated into lightning prediction and protection systems, increasing the capabilities of real-time decisions. Such technologies may result in more adaptive and predictive protection measures that can dynamically adapt to the new weather conditions and the operational conditions of the system, which would guarantee even higher reliability and efficiency.

Limitations

The present research is mainly concerned with the design and simulation of lightning protection systems and although the findings of field tests confirm the method, the field tests are limited in the scope of their testing. The research has failed to consider all the potential environmental factors including extreme geographical features or the occurrence of other structures, which might affect the lightning behavior. Also, the study is restricted to particular wind-solar hybrid systems, and the design suggested can still need additional modifications in case it is implemented to other systems or larger ones.

Conclusion

The hybrid lightning protection design for wind-solar renewable energy systems under extreme weather conditions has been shown to be effective in mitigating lightning-related risks and ensuring the reliability of these systems. The paper emphasizes the significance of comprehensive protection measures involving external lightning protection and internal surge suppression, optimized grounding, and system

coordination. The findings indicate that this kind of design can greatly minimize the possibilities of equipment damage, downtime, and the cost of maintenance, making the hybrid energy system viable in the long run in areas where extreme weather events are likely to occur.

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