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Design and Optimization of Solar Photovoltaic Brackets in Mountainous Areas Adapted to Complex Wind Environments

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Abstract With the increasing global demand for renewable energy, the application of photovoltaic power generation in mountainous areas is gradually increasing. However, the complex wind environment in mountainous areas poses severe challenges to the design and optimization of solar photovoltaic brackets. Traditional design methods are difficult to cope with the changeable wind speed and direction in mountainous areas, resulting in structural instability or material waste. Researchers have identified the key factors affecting wind response through parametric research and dynamic wind response analysis, so as to optimize the brackets design and improve its adaptability and stability in complex wind environments. In this paper, the complexity of wind speed, wind direction and turbulence characteristics in mountainous areas and their influence on brackets design are explored. Through static and dynamic wind load analysis, the geometrical shape and material selection of the bracket are optimized to enhance its wind resistance. The application of multi-objective optimization model and intelligent optimization algorithm provides an effective solution for the design of solar photovoltaic brackets, ensuring their safety and reliability in complex wind environments.

Key words Solar photovoltaic brackets, Complex wind environment, Optimization design, Intelligent optimization algorithm

1 Introduction

In recent years, with the continuous growth of global energy demand, the application of photovoltaic power generation as a clean and renewable energy in mountainous areas has gradually increased. However, the complex wind environment in mountainous areas poses severe challenges to the design and optimization of solar photovoltaic brackets. The changeable terrain in mountainous areas and the uncertainty of wind speed and direction increase the difficulty of designing photovoltaic support structures. Traditional photovoltaic bracket designs often fail to adequately cope with these complex wind environments, resulting in structural instability or material waste[1]. In order to improve the adaptability of solar photovoltaic brackets in complex wind environments in mountainous areas, scholars have begun to pay attention to the optimization of structural parameters and the analysis of dynamic wind response. By performing a parametric study of the brackets structure, the key factors affecting the wind response can be identified, thus optimizing the brackets design to reduce material usage and improve structural stability. Furthermore, advanced wind analysis methods such as unsteady aerodynamic models and consistent mass-spring-damping models can more accurately predict the behavior of photovoltaic brackets under dynamic wind action. At present, the design and optimization of solar photovoltaic brackets in complex wind environment has become a research hotspot at home and abroad. Studies have shown that wind load has a significant impact on the dynamic response of photovoltaic brackets, especially in complex terrain such as mountainous areas, where the characteristics of wind are more variable, which brings challenges to the design of brackets[1]. In order to improve the stability and economy of photovoltaic systems, scholars have adopted various methods for optimization. For example, through parametric studies and semi-deterministic time-domain wind analysis methods, the structural parameters of the brackets are optimized to cope with the dynamic wind action. Researchers are also exploring the use of new materials and technologies to enhance the wind resistance of solar photovoltaic brackets. The application of 3D printing technology makes the brackets design more flexible and enables its structural stability to be verified through simulations and experiments[2]. In addition, the initial shape optimization of flexible solar photovoltaic brackets has also become an important research direction. By analyzing the cable force and displacement, the shape of the brackets is optimized to reduce steel consumption and cost[3].

However, there are still some problems in the current research, such as insufficient research on the long-term performance of brackets in complex wind environments, and how to balance cost and performance in practical applications. In this paper, the complexity of wind speed, wind direction and turbulence characteristics in mountainous areas and their influence on brackets design are explored. Through static and dynamic wind load analysis, the geometrical shape and material selection of the bracket are optimized to enhance its wind resistance. The application of multi-objective optimization model and intelligent optimization algorithm provides an effective solution for the design of solar photovoltaic brackets, ensuring their safety and reliability in complex wind environments.

2 Analysis of complex wind environment characteristics in mountainous areas

2.1 Wind speed and direction characteristics in mountainous areas In the system design of solar photovoltaic brackets, it

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is crucial to accurately grasp the characteristics of wind speed and direction in mountainous areas. The unique topography of mountainous areas leads to significant variability of wind speed and wind direction in spatial and temporal dimensions. Specifically, the wind speed is significantly affected by the topographic effect, which is accelerated by topographic contraction in the valley zone, while it may be weakened by openness in the hilltop zone. This change not only increases the difficulty of wind speed prediction, but also puts forward higher requirements for the bearing capacity and stability of solar photovoltaic brackets.

The complexity of wind direction cannot be ignored either. Complex topographic structures in mountainous areas, such as peaks and canyons, as natural wind barriers, have a significant guiding and barrier effect on wind direction, resulting in rapid changes in wind direction within a short distance. In addition, the change of wind direction is also affected by multiple factors such as terrain orientation, slope and local terrain characteristics, showing a high degree of spatial heterogeneity. These characteristics require that the design of solar photovoltaic brackets fully consider the diversity and uncertainty of wind direction to ensure that the system can operate safely and stably in different wind directions.

Furthermore, the seasonal changes of wind speed and direction in mountainous areas also need special attention. With the change of seasons, the alternating action of monsoon and local wind system makes the wind speed and direction show significant seasonal differences. This change not only increases the challenge of photovoltaic bracket design, but also requires that the influence of seasonal factors be fully considered in the design stage to improve the adaptability and stability of the system.

2.2 Turbulence characteristics in mountainous areas The turbulence characteristics of mountainous areas have an important influence in the design of solar photovoltaic brackets. The research shows that the complexity of wind environment in mountainous areas is mainly reflected in turbulence intensity and spectrum characteristics. Turbulence intensity refers to the severity of wind speed fluctuations, usually caused by factors such as topographic undulations and vegetation cover. The mountainous area has complex topography and frequent and irregular wind speed changes, which makes the turbulence intensity increase significantly.

Turbulence spectrum characteristics describe the distribution of different frequency components in turbulence. The turbulence spectrum in mountainous areas usually exhibits a wide frequency band, which means that wind speed fluctuations may have an impact on photovoltaic brackets at different time scales[4]. This spectral characteristic requires that the joint action of various frequency components must be considered in the design of the bracket structure to ensure its stability under various wind conditions.

Turbulence characteristics in mountainous regions are also affected by seasonal variations. There may be significant differences in wind speed and turbulence characteristics between winter and summer, which requires a comprehensive dynamic analysis during the design process. Through in-depth study of turbulence characteristics, it can provide important parameter support for the optimal design of solar photovoltaic brackets, ensuring their reliability and economy in complex wind environments.

3 Wind load analysis of photovoltaic brackets in mountainous areas

3.1 Static wind load analysis Static wind load analysis is of great significance in the design of solar photovoltaic brackets in mountainous areas. Due to the complex terrain and variable wind speed and direction in mountainous areas, the brackets structure must be able to withstand wind loads of different directions and strengths. Firstly, the geometrical shape of the brackets needs to be optimized to reduce wind resistance and eddy current effects, thereby improving structural stability. Secondly, the choice of materials is also crucial. High-strength and corrosion-resistant materials need to be selected to ensure long-term use in harsh environments.

In the static wind load analysis, it is necessary to consider the influence of wind pressure on all parts of the bracket, especially the key connection points and supporting components. Through finite element analysis, the stress distribution at different wind speeds can be simulated and possible weak links can be identified. In addition, special attention should be paid to the foundation design of the bracket to ensure the overall stability under strong wind conditions.

In order to further optimize the design, parametric modeling techniques can be used to adjust the tilt angle and height of the bracket to achieve the best wind resistance[5]. This method can not only improve the wind resistance of the brackets, but also reduce the material cost and construction difficulty to a certain extent[6]. Through in-depth analysis and optimization design of static wind load, the safety and reliability of solar photovoltaic brackets in mountainous areas can be effectively improved.

3.2 Dynamic wind load analysis In the design of solar photovoltaic brackets in mountainous areas, dynamic wind load analysis is an important link to ensure structural stability and safety. Due to the complex terrain in mountainous areas and the changing wind speed and direction, solar photovoltaic brackets need to have good wind resistance. It is shown that fluctuating wind load and aerodynamic instability are the key factors affecting the dynamic response of solar photovoltaic brackets.

Pulsating wind loads are caused by random fluctuations in wind speed, which can lead to nonlinear responses of the brackets structure. In order to accurately evaluate the influence of fluctuating wind load on the brackets, time-domain wind tunnel test or numerical simulation methods are usually used for analysis. These methods can simulate the transient influence of wind speed change on the bracket, thus providing data support for structural optimization.

Aerodynamic instability refers to the possible vibration phenomenon of brackets structure under specific wind speed and direction conditions. This instability can lead to structural fatigue or even failure, so it must be considered during the design process. By establishing the mass-spring-damping model of the bracket, its dynamic response characteristics can be effectively described, and

its wind resistance can be improved by adjusting the structural parameters.

By optimizing the geometrical shape and material selection of the brackets, its adaptability in complex wind environments can be further enhanced. Optimization processes typically involve multi-objective optimization algorithms designed to minimize material usage and cost while meeting strength requirements. This optimization design not only improves the safety and reliability of the bracket, but also provides a guarantee for the long-term stable operation of the photovoltaic system.

4 Photovoltaic bracket structure design in mountainous areas

4.1 Optimization of bracket structure In the design of solar photovoltaic brackets in mountainous areas, optimizing the structure of the brackets to improve their wind resistance is the key. First, it is necessary to consider the use of flexible solar photovoltaic brackets, which can reduce steel consumption and cost by adjusting the initial morphology of the cable, while improving economic efficiency. The design of flexible brackets needs to consider parameters such as cable deflection, span and cross-section size to ensure stability in complex wind environments.

Single-column support structures have significant advantages in ground-mounted photovoltaic power plants. Compared with the traditional double-column structure, the single-column structure reduces the amount of foundation engineering and simplifies the construction process[7]. This structural form not only reduces the difficulty of construction, but also improves the stability of overall operation.

The dynamic wind response analysis shows that the dynamic response of the brackets structure shows a highly nonlinear relationship with the changes of multiple structural parameters. Therefore, in the design process, special attention should be paid to structural parameters and field wind parameters to realize the optimal design of the brackets[1].

4.2 Bracket material selection In the design of solar photovoltaic brackets in mountainous areas, the choice of materials is crucial. The mechanical properties of the materials need to be considered to ensure that the bracket can remain stable in complex wind environments. Steel is often used in the design of solar photovoltaic brackets because of its high strength and durability. Its excellent wind resistance makes it ideal for coping with dynamic wind loads. However, the heavy weight of steel may increase the difficulty of transportation and installation, especially in mountainous areas with complex terrain.

Economy is also an important factor in material selection. Although steel has superior properties, its costs are high and it may not be suitable for projects with limited budgets. Therefore, lightweight materials such as aluminum alloys are also considered for the design of solar photovoltaic brackets. Aluminum alloy not only has good corrosion resistance, but also can effectively reduce transportation and installation costs. In addition, the application of 3D printing technology makes it possible to use plastic materials, which have the advantages of low cost and easy processing, but their mechanical properties need further verification.

Environmental factors also need to be taken into account. The mountainous environment is complex and changeable, and materials need to have good weather resistance to withstand the impact of extreme weather conditions. Considering the mechanical properties, economy and environmental adaptability, choosing appropriate materials will help to achieve the optimal design of solar photovoltaic brackets.

5 Optimization design method of solar photovoltaic brackets in mountainous areas

5.1 Multi-objective optimization model Multi-objective optimization models are crucial in the design of solar photovoltaic brackets in mountainous areas, especially in complex wind environments. In order to achieve the balance between wind resistance and economy, many factors need to be comprehensively considered. Firstly the dynamic wind response of the brackets structure needs to be analyzed in detail to ensure the stability and safety under different wind speed and direction conditions. By establishing a parametric model, the influence of different structural parameters on the wind load response can be simulated, thus optimizing the design of the bracket.

Secondly, economy is another key goal of the optimization model. Costs can be effectively reduced by reducing steel usage and optimizing material selection. In this process, the manufacturing and maintenance costs of the brackets need to be considered to ensure the maximum overall economic benefit.

In addition, the optimization model also needs to consider the adaptability and flexibility of the brackets to cope with the variability and complexity of mountainous terrain. By introducing flexible structure design, the adaptability of the bracket on uneven terrain can be improved. At the same time, it is necessary to ensure the durability and reliability of the bracket under extreme weather conditions to extend the service life and reduce the frequency of maintenance.

5.2 Application of intelligent optimization algorithm The application of intelligent optimization algorithm in the design of solar photovoltaic brackets in mountainous areas is of great significance. Genetic algorithm and particle swarm optimization are two commonly used intelligent optimization tools, which can effectively deal with complex nonlinear optimization problems. By simulating natural selection and genetic mechanism, genetic algorithm gradually optimizes the design parameters of the brackets to improve the wind resistance and stability of the structure. In the application process, genetic algorithm generates new design schemes through operations such as selection, crossover and mutation, so as to find the optimal solution among many possible solutions.

Particle swarm optimization accelerates the convergence process by simulating the foraging behavior of birds and sharing information among individuals. The algorithm approaches the optimal solution step by step by updating the position and velocity of particles, which is suitable for dealing with multi-objective optimization problems. In the design of solar photovoltaic brackets in mountainous areas, particle swarm optimization can effectively op-

timize the geometric parameters and material selection of brackets to cope with complex wind environments.

Combining these two algorithms, a hybrid optimization strategy can be formed, which makes full use of the global search ability of genetic algorithm and the local search ability of particle swarm optimization, thus improving the optimization efficiency and the reliability of the results. This intelligent optimization method can not only reduce material costs, but also improve the safety and durability of the bracket, providing guarantee for the stable operation of photovoltaic power stations in mountainous areas.

6 Conclusion

This study explores the design optimization strategies of solar photovoltaic brackets under complex wind environment conditions in mountainous areas, aiming to propose a series of design optimization schemes aimed at enhancing the wind resistance of brackets through systematic analysis and practical innovation. The core of the research is to reveal the key role of optimizing the structural layout of the bracket and rationally selecting materials in improving its stability and economy, as well as multi-objective optimization models and intelligent optimization algorithms to comprehensively improve the performance of solar photovoltaic brackets.

Looking forward to the future, there are still many directions worthy of further exploration in this research field. First of all, with the continuous progress of materials science, new lightweight and high-strength materials such as composite materials and nanomaterials have great application potential in the field of photovoltaic brackets, and their research and application are expected to further promote the double leap of bracket performance and cost-effectiveness. Secondly, strengthening the refined simulation and analysis of photovoltaic brackets in dynamic wind environments, combined with advanced wind engineering experimental technology, can more accurately predict and respond to extreme wind loads and ensure the safe and reliable operation of the brackets.

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