Optical Fiber Communication and Energy Efficiency Optimization in Photovoltaic Power Stations

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Abstract. In the field of new energy photovoltaics, optical fibers and cables play a crucial supporting role. Cables are responsible for transmitting electricity, while optical fibers are responsible for transmitting information. However, their integration remains inadequate, with relatively high costs and extensive land use leading to resource waste. Effective integration of these components could significantly improve energy efficiency, thereby enhancing the operational efficiency of photovoltaic power stations. This paper focuses on utilizing optical fiber communication to enhance the energy efficiency of photovoltaic power stations, ensuring stable power transmission and efficient system operation, and improving their applicability and economic performance. Additionally, this paper addresses the energy efficiency issues of photovoltaic power plants, discusses future development directions and challenges, and highlights the immense potential of optical-electrical composite cables.

Keywords: Fiber-optic communication, Photovoltaic power generation, Energy Efficiency Optimization, Optical-electrical composite cables.

1. Introduction

Solar energy plays a vital role in today's energy market. As a clean energy source, it effectively reduces dependence on fossil fuels while contributing to environmental protection. [1] Over the past few decades, large-scale photovoltaic projects have driven significant improvements in energy efficiency; however, they also present certain drawbacks and shortcomings that constrain the industry's development. During the actual operation of photovoltaic power plants, frequent daily malfunctions hinder their efficient and stable power generation. [2] Simultaneously, the efficiency of troubleshooting is constrained by the speed of fault identification and the expertise of maintenance personnel.[3] To address the current challenges, fiber optic communication can be deployed in photovoltaic power plants to integrate photovoltaic and optical systems, thereby enhancing energy efficiency and improving real-time monitoring capabilities.

Energy efficiency optimization remains a hot topic in the energy sector. A significant body of literature has examined how photovoltaic power generation can be made more efficient [4,5]. To protect the environment, clean energy sources such as solar power must be utilized effectively. Intelligent monitoring is crucial for ensuring the stable and efficient operation of photovoltaic power plants. Numerous studies have also been conducted on intelligent monitoring [6,7]. The economic viability of photovoltaic power plants requires improvement, as there is currently a mismatch between electricity consumption and construction costs. Therefore, adjustments are needed in the initial construction planning.[8] Due to their high construction costs, lengthy implementation cycles, and complex design planning, these solutions face implementation constraints, and few integrate monitoring with transmission. While each approach has its merits, they all significantly increase operational and maintenance expenses.

This review examines the interdisciplinary field of new energy and fiber optic communications, aiming to provide a comprehensive overview of the latest advancements, challenges, solutions, and future directions within this domain. By analyzing existing research findings and practical applications, this review aims to provide theoretical foundations and practical guidance for integrating fiber optic communications into new energy systems. The ultimate goal is to advance the convergence of these technologies, reduce costs, enhance efficiency, and thereby improve overall energy utilization.

2. Optical-electrical composite cables

Optical-electrical composite cables are integrated communication cables that combine optical signal transmission units (optical fibers) with electrical signal transmission units (conductors) within a single cable body. [9] They enable simultaneous high-speed data transmission and power supply, offering core advantages of simplified cabling and reduced costs. These cables are ideal for scenarios requiring both power extraction and data transmission. During construction, the installation of optical-electrical composite cables can reduce initial wiring costs and effectively enhance economic efficiency. Applying this technology to photovoltaic power plants can not only reduce costs but also enhance their energy efficiency.[10]

2.1 Reliability Analysis

The operation of a photovoltaic power station depends on two key links: one is DC/AC power transmission (from components to inverters, inverters to junction boxes/power grids), and the other is data monitoring transmission (power generation of components, inverter status, environmental temperature, and humidity data back to the monitoring system). The optical-electrical composite cables can carry both functions simultaneously through their integrated structure, which consists of a "power conductor + optical fiber unit" that perfectly matches the requirements.

The current technical specifications of photoelectric composite cables have been fully adapted to the operational environment of photovoltaic power stations, with no core technological bottlenecks.

The conductors in composite cables can be selected as either copper or aluminum, based on the voltage requirements of photovoltaic systems [11] (e.g., 380V and 10kV for distributed systems, 500V for centralized low-voltage applications). These conductors meet high-current-carrying capacity and insulation standards (such as weather-resistant XLPE insulation [12]), designed to handle daytime high-power generation demands while featuring UV resistance and temperature tolerance (-40°C to 85°C). This makes them ideal for outdoor environments with harsh conditions.

The built-in optical fiber unit (mostly single-mode/modulated optical fiber) of the composite cable can transmit low-speed data (such as current, voltage, and power) from the photovoltaic monitoring system stably [13]. The transmission distance covers the conventional span of a photovoltaic power station. Moreover, single-mode optical fiber can reach 20km without a relay, far exceeding the demand of most distributed power stations within 1km.

From the perspective of the safety and reliability of optoelectronic composite cables. The physical isolation design between power conductors and fiber optic units (including flame-retardant sheathing for fiber optic units and a layered arrangement with power conductors) prevents electromagnetic interference from power transmission from affecting fiber optic data. Additionally, the composite cable demonstrates flame-retardant and anti-aging properties that comply with photovoltaic power station safety standards (e.g., GB/T 19630).

2.2 Economic Efficiency of Fiber-Optic Composite Cables

The core economic benefits of optical-electrical composite cables lie in “cost reduction and efficiency enhancement.” By integrating power transmission and signal transmission functions, they significantly reduce redundant construction and operational maintenance costs while improving system reliability and overall utilization efficiency.

Compared to traditional solutions involving separate cable and fiber optic cable installations, optical-electrical composite cables offer greater advantages in terms of total lifecycle cost.

Construction costs are reduced by 20% to 30%. By eliminating one-time excavation, pipe laying, and fixing operations (traditional schemes require two wiring operations), especially in high-altitude work scenes such as roofs and walls, construction time can be reduced by more than 50% and labor costs can be lowered.

Although the cost per meter of composite cable is slightly higher than that of ordinary cable (about 10%-15%), it saves the cost of separately purchasing optical cable, optical cable junction box and additional conduit, and the overall material cost is basically the same; in the later maintenance, only one cable needs to be located to troubleshoot power and data problems at the same time, reducing maintenance hours.

Additionally, operational efficiency is enhanced as composite cables reduce the number of lines, enabling more efficient fault detection (eliminating the need to distinguish between cable and fiber faults). Some products feature built-in monitoring capabilities (such as fiber temperature sensing), providing early warnings for issues like line overheating. This shortens maintenance response times by 30%-50% and reduces indirect losses caused by downtime (e.g., power outages in industrial facilities or revenue losses from interrupted grid connections at renewable energy plants).

From a long-term comprehensive benefit perspective, the service life of composite cables is comparable to that of traditional cables and optical cables (typically 20-30 years). However, they eliminate the need for additional new line installations throughout their entire lifecycle and reduce space occupied by lines (e.g., in urban utility tunnels and substation equipment rooms), reserving resources for future expansion. Simultaneously, their strong anti-interference and stability characteristics reduce equipment failure rates, minimizing repetitive investments in replacements and repairs.

2.3 Energy Efficiency Optimization

Optical-electrical composite cables reduce transmission losses and simplify system architecture, representing a core advantage for optimizing the energy efficiency of photovoltaic power plants. They directly lower energy consumption and operational maintenance costs.

Optical-electrical composite cables reduce line losses. Traditional solutions require separate installation of power cables and optical cables; longer lines and more interfaces lead to greater energy losses. Composite cables integrate both, reducing line length and connection points, thereby lowering transmission losses by approximately 5%-10%. This makes them particularly suitable for long-distance transmission in large-scale power plants.

Optical-electrical composite cables enhance system efficiency. They simultaneously transmit electrical power and monitoring signals, enabling power plants to monitor component generation status in real-time and promptly identify faults, such as shading or component degradation. This prevents inefficient generation caused by malfunctions, indirectly boosting overall energy efficiency.

3. Applications of Fiber Optics in the Energy Sector

The core application of optical fiber in the energy sector is data monitoring and transmission. Leveraging its resistance to electromagnetic interference and tolerance for high temperatures and pressures, it addresses the shortcomings of traditional cables in energy scenarios.

In power systems, it is primarily used for current and voltage monitoring in smart grids—such as fiber optic current transformers and substation data transmission [14]—as well as temperature alerts for high-voltage cables to prevent overheating failures.

In oil and gas extraction, they enable real-time monitoring of downhole pressure and temperature in oil and gas wells through distributed fiber optic sensing, particularly suited for the harsh environments of deep wells with high temperatures and strong corrosion.

Within the new energy sector, such as in photovoltaic power plants and wind farms [15], they facilitate equipment condition monitoring and data backhaul [16], ensuring the stability of large-scale renewable energy grid integration.

Fiber optic technology, leveraging its core advantages of resistance to electromagnetic interference, high-temperature and high-pressure tolerance, and stable data transmission, has become a key enabler for intelligent monitoring and efficient operations in the energy sector. Its applications span power systems, oil and gas extraction, and the new energy industry, with real-world case studies validating its practical implementation value.

In oil and gas extraction, fiber optic technology effectively addresses monitoring challenges in extreme downhole environments. The “FiberInsight” model developed by CNOOC Energy Development Co., Ltd. integrates AI algorithms with distributed fiber optic sensing technology. By utilizing downhole fiber arrays to collect real-time temperature, acoustic, and pressure data, it achieves 98% accuracy in identifying reservoir water cut. This technology not only enables precise monitoring of offshore oilfield production but also locates residual oil reservoirs, providing data support for formulating potential development plans for oilfields. At the Yu37 gas storage reservoir test well in Changqing Oilfield, an innovative configuration—combining “external horizontal section + internal vertical section + multi-point fiber optic pressure gauges”—established a permanent monitoring network across the entire wellbore. Even under extreme conditions, such as depths of 5,000 meters and temperatures exceeding 100° C, this system captures minute wellbore changes, ensuring the long-term safe operation of the storage reservoir.

In the power and new energy sectors, fiber optic technology serves as a critical defense for system stability. The distributed fiber optic monitoring system developed by the Harbin Institute of Technology's Zhengzhou Research Institute played a pivotal role in monitoring ice accumulation for Henan Province's ultra-high voltage transmission lines. During the 2021 winter, it successfully identified two high-risk ice accumulation points across the Yellow River section, buying crucial time for regulatory decision-making. This technology has also been deployed in major national projects such as the Baihetan-Zhejiang UHV transmission line. Indigo's FOTS-9000-N Fluorescent Optical Fiber Temperature Monitoring System enables 24/7 online monitoring of high-voltage switchgear contacts in Dongfang Electric Group's wind power projects. Leveraging its high-voltage insulation and anti-interference capabilities, it effectively prevents equipment overheating failures, supporting stable wind power system operation.

In practical applications, fiber optic technology not only overcomes the scenario limitations of traditional monitoring methods but also provides a core technical pathway for upgrading energy production toward safety, efficiency, and intelligence through precise data collection and analysis.

4. Future Directions

Photovoltaic power plants (primarily distributed and complex scenarios) benefit from the core advantages of optical-electrical composite cables: mature technology, controllable costs, and efficient installation. There are no fundamental feasibility barriers. Numerous practical cases (such as commercial and industrial rooftop PV systems and agro-photovoltaic complementary power stations) have already been implemented. Composite cables represent one of the mainstream trends for future PV power plant wiring. They only require matching the voltage, insulation, and protection specifications to the specific application scenario.

With the application of new materials and manufacturing processes, optoelectronic composite cables will enhance transmission speed and capacity, improve transmission efficiency and stability, and reduce transmission losses and interference by increasing the number of fiber cores and optimizing cable conductor structures and materials.

Future optoelectronic composite cables will evolve toward multifunctional integration, enabling communication, power transmission, monitoring, and other functions within a single cable. Simultaneously, the integration of sensors and network management systems will enable intelligent monitoring and remote management, improving maintainability and management efficiency.

Optical-electrical composite cables will not only find extensive application in traditional communication and power transmission fields. Still, they will also play a significant role in specialized environments such as smart cities, data center interconnections, aerospace, and oilfield communications. Driven primarily by the construction of 5G networks and the expansion of data centers, market demand for these cables is expected to continue growing.

With heightened environmental awareness, the production of optical-electrical composite cables will increasingly prioritize eco-friendly materials and recyclable technologies. This shift aims to reduce energy consumption and environmental pollution during manufacturing while strengthening corporate social responsibility.

5. Conclusion

Real-time monitoring of photovoltaic power stations is crucial for their normal operation, enabling the timely identification and rapid localization of faults. Traditional fiber optic cable distribution layouts often result in delayed monitoring and imprecise fault localization. In recent years, photovoltaic-optical composite cables have seen widespread adoption across various sectors. The optoelectronic composite approach offers significant economic benefits and promotes enhanced energy efficiency. Its application in the energy sector is increasingly widespread, playing a crucial role in monitoring and data transmission. Their integration into the energy sector, coupled with emerging technologies such as AI, promises to revolutionize the industry. Advances in materials and computational technology will drive the development of increasingly sophisticated and intelligent monitoring systems for photovoltaic power plants. By enhancing technical capabilities and reducing various losses, these innovations will fundamentally transform existing models, ushering in a revolutionary breakthrough for photovoltaic power generation.

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