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Research on Innovative Strategies and Application Practices for the Operation and Maintenance of Hydropower Plants

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Abstract: In the context of energy structure transformation, digital and intelligent technologies have been introduced into the field of hydropower, which has accelerated the technological and equipment innovation of hydropower plants. However, it has also brought severe challenges to the operation and maintenance of hydropower plants. Traditional hydropower plant operation and maintenance suffer from problems such as low efficiency, equipment aging, and high labor costs, which seriously hinder the innovation and upgrading of hydropower plant operation and maintenance. Therefore, this article focuses on the operation and maintenance of hydropower plants, summarizes a series of innovative strategies, and applies them in practice to effectively improve the operation and maintenance level of hydropower plants.

Keywords: Application practice; Innovative strategy; Operation and maintenance; Hydropower plant

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1. Introduction

Hydropower is a clean and renewable energy source that has contributed significantly to achieving the "dual carbon" goal and ensuring energy security. As the domestic installed capacity of hydropower continues to expand, the system complexity increases, and the traditional operation and maintenance model, which mainly focuses on regular inspections, gradually exposes its drawbacks. It not only fails to respond to fault handling demands in a timely manner but also increases cost losses, which is contrary to the economic, safe, and efficient operation of modern hydropower plants. Therefore, exploring innovative digital and intelligent operation and maintenance strategies in the new era has become an effective means to improve the operation and management level of hydropower plants, which is of great significance to the transformation and development of China's energy structure.

2. Current status of hydropower plant operation and maintenance

2.1. Analysis of traditional operation and maintenance models

After long-term development, the hydropower industry has formed a relatively mature management framework and technical system. Specifically, it involves formulating annual and quarterly equipment maintenance plans based on the equipment operating cycle, including generator stator winding insulation tests, hydraulic turbine guide vane clearance measurements, etc. When equipment operating parameters exceed limits or abnormal noises occur, the post-maintenance process is immediately initiated, and faulty parts are replaced after precise manual fault location. During the early operational stage of hydropower plants, this standardized operational process effectively ensured the basic operational safety of the equipment. In terms of technical means, hydropower plants mainly rely on personnel carrying portable equipment for routine inspections and measurements, such as temperature measuring instruments, multimeters, etc., to measure equipment vibration, temperature, pressure, and other parameters at regular intervals and record the data in local documents. Offline detection methods include regular sampling and winding DC resistance testing to evaluate whether there are hidden faults in the equipment of hydropower plants [1]. In terms of equipment configuration, conventional sensor devices are often selected. The collected data is transmitted via cables to the PLC control cabinet. Once the limit is exceeded, an automatic warning is issued. However, the system does not have the ability to predict and analyze faults, so there is often a problem of delayed fault warnings.

2.2. Problems in operation and maintenance

Currently, in the operation and maintenance of hydropower plants, equipment condition monitoring is relatively lagging. The traditional offline detection method follows a 2-hour cycle, which fails to accurately capture various data indicators during intense load fluctuations. For example, in a certain hydropower plant, the data collection interval for the displacement sensor of the main pressure regulating valve of the speed regulator is 10 minutes. As a result, the swing fault of the servomotor was not discovered in a timely manner, leading to a severe power fluctuation accident. Monitoring parameters lack systematicity. Some hydropower plants focus primarily on conventional indicators such as temperature and vibration, while parameters such as partial discharges in generator stator bars or dissolved gas components in transformer oil receive insufficient attention. This significantly affects early warning and handling of equipment failures.

Decision-making in hydropower plant operation and maintenance is overly coarse, relying heavily on personnel experience and dominated by a “time cycle-led” mindset, lacking precise real-time monitoring of equipment operating parameters. According to the maintenance plan of a certain hydropower plant, the maintenance cycle for 10 units of the same model internally is 8000 hours. However, due to differences in operating parameters such as load or head during equipment operation, there are significant variations in equipment wear and aging, resulting in over-maintenance of some equipment and inadequate maintenance of others. In the equipment fault diagnosis process, technicians rely too much on their own work experience, and there are even cases where different fault solutions are provided for the same fault point, which inevitably weakens the accuracy of equipment fault diagnosis [2].

3. Innovative strategies for hydropower plant operation and maintenance

3.1. Implementing intelligent operation and maintenance technologies

Innovation in hydropower plant operation and maintenance should focus on the introduction and application of intelligent operation and maintenance technologies. Specific manifestations include the following points:

(1) Building an intelligent sensor network: Combining the needs of digital and intelligent transformation in

hydropower plants, widely deploy a sensor network across the entire equipment chain to provide a basic guarantee for intelligent operation and maintenance. Introduce sensors such as optical fiber temperature sensors with a temperature measurement accuracy of ±0.5℃ and a sampling frequency of not less than 10 kHz. Install online monitoring devices for dissolved gases in oil to achieve real-time monitoring of various parameters such as transformers, hydraulic generators, and switchgear. Due to the significant wear and aging in the guide bearing area of the hydraulic turbine, a three-axis vibration sensor is configured to simultaneously collect parameters such as phase, amplitude, and oil film pressure from the X, Y, and Z dimensions, establishing a comprehensive dynamic sensing system [3].

(2) Establishing an AI fault prediction and health management system: In the era of artificial intelligence, integrate technologies such as cloud servers and edge computing nodes to establish a layered AI analysis platform, facilitating early prediction, analysis, and assessment of equipment health status when equipment failures occur. Deploy neural network models at the edge layer to extract real-time equipment operating temperature, vibration, and other data parameters. When abnormal data is detected, compress the data scale and upload it to the cloud in a timely manner. Establish a convolutional neural network and a long short-term memory network fusion model in the cloud, collect historical data, train the model, and provide support for equipment fault prediction and identification. Simultaneously, establish a supporting equipment health index evaluation system to evaluate data such as equipment fault history and operating conditions, quantifying the operational status of hydropower plant equipment as a value between 0 and 100. Once the equipment health index drops below 60, automatically issue warning information, generate work orders, and provide equipment operation and maintenance suggestions to improve the rationality of maintenance decision-making [4].

(3) Intelligent scheduling of operation and maintenance resources: Establish a dynamic resource allocation mechanism based on IoT technology, equipped with intelligent terminals that integrate functions such as AR navigation and RFID identification for precise positioning of various resources and personnel locations. The spare parts warehouse is equipped with an RFID tag management system and smart shelf devices, enabling real-time monitoring of spare parts inventory data changes and automated replenishment based on inventory variation needs. When the system detects equipment operation faults, it promptly issues warning information, automatically matches qualified technical personnel, and plans the optimal problem handling path.

3.2. Introducing digital twin technology

A digital model is established using 3D laser scanning with a point cloud density of no less than 100 points per square meter, combined with BIM technology to create a digital model that includes hydropower plant equipment, buildings, and pipelines. Based on the digital model, millimeter-level reverse modeling of core equipment such as transformers and generator sets is performed to provide precise feedback on building structure and material properties. For auxiliary systems like cable trays, designers choose parametric modeling methods to create digital models. Various parts of the hydropower plant are visualized in the model, and advanced technologies such as terrestrial laser scanning and drone oblique photography are used to establish a digital model with high efficiency and precision. The digital model can integrate operational data, equipment ledgers, and later operation and maintenance information from multiple sources, establishing a full lifecycle archive for equipment and providing real and comprehensive data support for later simulation and intelligent operation and maintenance [5].

For core equipment in hydropower plants, such as main transformers and hydro-turbine generator sets, the focus is on establishing digital twins, specifically in terms of physical mechanisms and data-driven aspects. The former emphasizes establishing a coupled model integrating mechanical, fluid, electromagnetic, and other physical fields to dynamically simulate vibration responses and temperature distribution under different working conditions. The latter dynamically corrects and improves the mechanism model based on real-time monitoring data from sensors, optimizing model parameters to ensure that the final output deviation from the actual equipment remains within a controllable range. Additionally, digital twin technology is introduced to establish a closed-loop operation and maintenance monitoring system [6]. Real-time monitoring systems can input collected data on equipment operating temperature, frequency, and amplitude into the digital twin to simulate and predict equipment operating conditions within the next 72 hours. If equipment failure risks or significant performance degradation are predicted, the best maintenance plan is selected based on the maintenance plan output by the digital twin, considering factors such as cost, safety, and convenience. The comparison of application benefits between digital twin technology and traditional technology is significant, as shown in **Table 1**.

Table 1. Comparison of application benefits

Indicator	Traditional mode	Digital twin mode
Fault diagnosis time	48h ~ 72h	≤4h
Maintenance solution	Relies on manual experience; High trial-and-error cost	Simulation-verified; First-time success rate >90%
Maintenance cost	Single overhaul exceeds ¥10 million	Virtual pre-rehearsal reduces actual costs by 30%

3.3. Introducing automation and robotics

The introduction of automation and robotics technology into the operation and maintenance of hydropower plants can replace manual labor to complete high-risk and intense work tasks, achieving precise and unmanned operation throughout the entire maintenance process. The application of core technologies and their application paths are shown in **Table 2**.

Table 2. Core technologies and application paths

Category	Function	System composition	Application scenarios
Underwater inspection robot	Precise inspection in confined spaces	Remotely Operated Vehicle (ROV), Autonomous Underwater Vehicle (AUV)	Turbine blade corrosion detection, Debris removal in water channels
Aerial inspection drone	Large-scale monitoring	Multi-rotor drones with automatic drone stations	Slope stability monitoring, Power line inspection, Dam crack scanning
Corridor operation robot	Collaborative operations in enclosed environments	Robotic arm + Tracked chassis + (SLAM+UWB) precision positioning system	Generator air duct automated cleaning, Repairing steel lining defects in tunnels

3.4. Innovative operation and maintenance management model

To innovate the operation and maintenance management model of hydropower plants, we should abandon the traditional emphasis on technology over management and establish a management system that involves process reengineering and full participation, thereby optimizing the efficiency of hydropower plant operation and maintenance. See **Figure 1** for details.

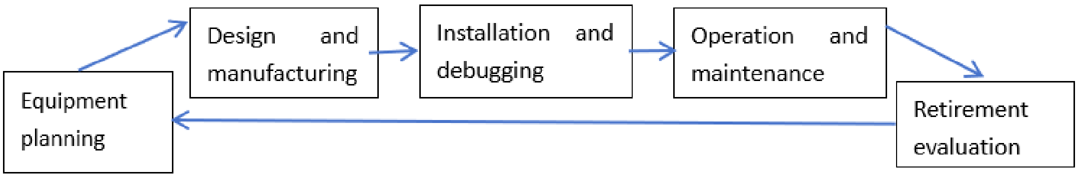

Figure 1. Lifecycle management model

Establish a flat operation and maintenance organization with equipment as the main focus, integrate professionals from maintenance, operation, technology, and other fields, and establish a cross-departmental operation and maintenance management team [7]. On this basis, each engineer is responsible for the full lifecycle management of their corresponding equipment. When equipment fails, resources are allocated across departments and positions, and with the gathering of multi-disciplinary professionals, equipment failures can be quickly resolved to avoid significant losses caused by deterioration. Implement a project manager system simultaneously. For major technical renovation projects, establish a dedicated project manager and grant them corresponding resource allocation and decision-making authorities. They can plan project resources and implementation schedules in an integrated manner, shorten the completion cycle of renovation projects, and reduce the total project cost.

We should adhere to a data-driven approach to establish an operation and maintenance decision system. This involves collecting and integrating equipment monitoring data, historical fault data, and maintenance data. After cleaning and mining multi-source heterogeneous data, it is recorded in the equipment fault resource library. When equipment malfunctions, similar cases from the resource library can be automatically matched, intelligently recommending solutions [8].

4. Practical application cases

4.1. Project background

A hydropower plant with an installed capacity of 1280 MW and an annual power generation of 30 billion kWh faces issues such as equipment aging, increasing equipment failures, and rising maintenance costs as equipment service time increases.

4.2. Implementation path of innovation strategy

(1) Construction of an intelligent sensing layer: An additional 2350 high-precision sensors form a global sensor network with a sensor size of $\varphi < 5$ cm, which can be placed inside turbine blades to achieve precise monitoring of equipment operating conditions. The dam crest is equipped with six high-precision drones, and three robots are deployed underwater. A hydrometeorological station is established, integrating the BeiDou positioning system to achieve centimeter-level positioning.

(2) Establishment of an AI analysis engine: Data collected by sensors is input into a data platform. The AI analysis engine predicts equipment failures and evaluates health status based on this data. When equipment failures are detected, warning information is sent to the warning center, and equipment health evaluation results are fed back to the decision database.

(3) Establishment of a digital twin decision platform: Based on a high-precision unit model, the platform simulates changes in the stress and temperature fields of hydropower plant equipment in real-time.

Through innovative transformations in hydropower plant operation and maintenance, the early warning time for failures has been extended from within 24 hours to 72–120 hours. With the support of AI technology and robotics, the automatic identification rate of equipment defects has reached 98%. The number of unplanned outages has been reduced from 8.2 times per year to 2.1 times per year, significantly reducing the operation and maintenance costs of hydropower plant equipment and economic losses caused by equipment failures.

5. Conclusion

In conclusion, the operation and maintenance of hydropower plants are crucial to equipment stability. To reduce equipment failure rates and unnecessary losses, it is essential to introduce intelligent operation and maintenance technology, digital twin technology, automation, and robotics for upgrading and innovating the hydropower plant operation and maintenance management model. This can significantly improve the efficiency and effectiveness of hydropower plant operation and maintenance, ensuring the continuous and stable operation of hydropower plant equipment.

Disclosure statement

The authors declare no conflict of interest.

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