Analysis of Equipment Management Methods for Pumped Storage Power Stations Under the "Dual-Carbon" Goals

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Abstract. Pumped-storage, as the most mature technology, economically optimal, and most suitable for large-scale development, plays a crucial role in promoting the consumption of clean energy and supporting the construction of new energy systems. Pumped-storage power stations involve various types of equipment such as hydraulic and electrical devices. The frequent start-stop operation in the context of new energy system construction will pose significant challenges to the equipment. This paper proposes a reliability-centered health management method for pumped-storage equipment. It implements differentiated and hierarchical management strategies for various types of equipment and establishes differentiated equipment maintenance strategies based on this.The project takes the manhole door of a power station governor pressure oil tank with nitrile rubber sealing ring as an example to calculate the service life in actual working conditions. Through calculation, it is considered that when reliability is 99%, the service life can be extended for more than 5 years, and if the reliability is 100%, the service life can be extended for more than 1 year.

1 Introduction

China has set an ambitious goal to reach a carbon peak by 2030 and achieve carbon neutrality by 2060 [1]. The power industry is the main battlefield for these "dual carbon" goals, and the new power system primarily consisting of new energy sources will gradually form in the future. An increasing proportion of new energy implies intermittent power generation and frequent random fluctuations in output, causing significant impacts on the power system, necessitating the support of energy storage facilities. Pumped storage, as the most technologically mature, economically optimal, and most suitable for large-scale development among flexible regulation devices in the power system, will play an increasingly prominent role in promoting the consumption of clean energy and strongly supporting reliable power supply.

Accompanying the construction of the new power system, the operation intensity of pumped storage power station equipment has significantly improved compared to the past, with units frequently starting and stopping, posing immense challenges to the equipment's operational maintenance management. Refined daily operation and maintenance management of the equipment is crucial to ensure that the equipment is ready to operate on-demand, thereby fully ensuring the healthy and stable operation of the equipment.

2 Characteristics of pumped storage equipment

A pumped-storage power station primarily comprises upper and lower reservoirs, high-pressure water conveyance systems, low-pressure water conveyance systems, underground powerhouses, switch stations, and transmission lines. The underground powerhouse accommodates major electromechanical equipment, including the energy storage units, main transformers, and common unit equipment [2]. The energy storage unit, being the core equipment of the pumped-storage power station, essentially consists of seven subsystems: the generating motor, unit busbar equipment, pump-turbines, speed controllers, main inlet valves, tailwater accident gates, and technical water supply systems (Figure 1). The following illustration enumerates the subordinate equipment of two subsystems: the generating motor and the pump-turbines[3].

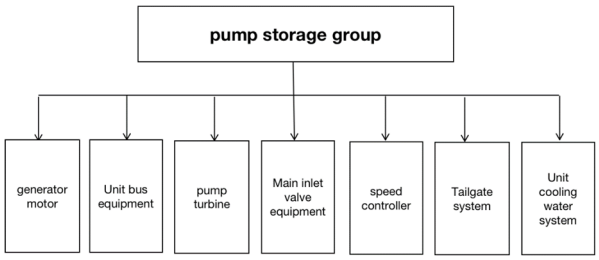

Fig. 1. Equipment tree of the pumped storage unit

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The energy storage unit equipment primarily exhibits the following characteristics.

(1) Structural Complexity: From a structural standpoint, the energy storage unit is intricate, consisting of numerous subsystems, including high-voltage insulation, hydraulic machinery, hydraulic equipment, thermal engineering instruments, and automatic control devices, categorizing it as a complex system. Due to its various operational conditions and functionality, the equipment structure is more sophisticated compared to conventional hydroelectric units. This complexity leads to a diversity of failure modes, making a comprehensive analysis of equipment failure modes exceptionally challenging.

(2) Operational Variability: Analysing from an operational perspective, the energy storage unit operates under multiple conditions such as the power generation, water pumping, the phase adjustment in power generation and pumping, and black start, among others. These various operational states present significant disparities in relevant operational parameters, complicating the precise execution of equipment status evaluation. The unit demands high reliability, with rigorous assessment target like success start-up rates and unplanned outage factors. The tolerance towards failure risks is low. The frequent start-stop cycles, coupled with short operational durations—averaging 2-3 start-ups daily, with each lasting around 10 hours or merely over 10 minutes—intensify wear and fatigue in bearings and rotational components, adversely impacting the lifespan of equipment components [3]. Being a part of the electrical system's reserve capacity, the unit often undergoes emergency start-ups, necessitating high equipment availability.

(3) Maintenance Considerations: In terms of maintenance, the energy storage unit requires lengthier repair durations relative to standard hydroelectric units—typically, minor repairs last about 15 days, and major overhauls extend up to 120 days. The maintenance process is inherently complex due to the involvement of numerous components in large industrial equipment, making the disassembly and reassembly process technically demanding, thereby heightening the risks associated with maintenance quality. Moreover, the cost associated with spare parts is substantial. Earlier, the domestic production rate of pumped storage equipment was relatively low, making import reliance necessary for spare parts, which added to the overall cost.

Consequently, as a sophisticated large-scale equipment, the energy storage unit is characterized by multifaceted operational conditions, heightened reliability and availability requirements, significant maintenance complexities, and elevated maintenance costs.

3 Reliability-centered maintenance concept for pumped-storage equipment

Based on the management characteristics of pumped-storage equipment, a reliability-centered maintenance concept is introduced. This approach involves comprehensive reliability analysis and logical decision-making processes, taking into consideration factors such as the importance of graded equipment classification and risk levels, to establish differentiated maintenance strategies, optimize the allocation of maintenance resources, enhance equipment reliability, and effectively improve the efficiency and lean management level of equipment operation and maintenance[4].

Specifically, the concept includes:

(1) Emphasizing Control at the Source and Practicing Full-Process Management: It is essential to advance the management focus of the equipment, as statistics show that management before equipment commissioning plays a crucial role in the subsequent operation and maintenance management. This implies that considerations for long-term post-commissioning equipment management needs must be incorporated during planning, design, manufacturing, and installation stages [5]. Also, operational maintenance personnel, as equipment owners, should be deeply involved in early stages of equipment management, integrating future management needs and past management experience into preliminary management stages, to achieve cohesive management throughout the equipment's life-cycle and improve the management efficiency and benefits[6].

(2) Emphasizing Condition Monitoring and Promoting a "Repair-as-Necessary" Philosophy: Condition assessment forms the basis for equipment maintenance work. Collecting and acquiring various types of information and data that directly or indirectly reflects the operating status of equipment are essential for accurately evaluating the health status of equipment. The "repair-as-necessary" philosophy involves not only referring to protocols and manufacturer requirements but also conducting comprehensive condition assessments to fully and accurately understand the health status of the equipment[7]. Maintenance strategies are then reasonably developed based on the results of the equipment condition evaluations, clarifying the cycles and scopes of equipment maintenance and testing, ultimately forming executable maintenance plans.

(3) Emphasizing Scientific Decision-Making and Implementing Reliability-Centered Management: In combination with classification and hierarchical management methods for pumped-storage equipment, a robust reliability-centered maintenance standard is established, conducting the reliability analysis based on equipment health management. Analysing equipment failure modes and systematically assessing equipment failure risks allow for the creation of differentiated maintenance strategies and guidance for on-site maintenance. Especially under the current technical and management levels, the “reliability analysis results” and “maintenance compliance needs” can be deeply integrated when formulating maintenance strategies (reliability analysis results are based on actual condition monitoring to determine maintenance strategies, and maintenance compliance needs refer to conducting maintenance activities according to relevant protocols, standards, and manufacturer manuals) [8]. This primarily involves overlaying condition monitoring results on periodic maintenance plans, adjusting maintenance cycles based

on actual conditions, reducing excessive maintenance, and enhancing meticulous management.

4 Reliability-centered management method of pumped-storage equipment

The core of the reliability-centered management method for pumped-storage equipment lies in the classification and grading implementation of equipment management, thereby establishing differentiated equipment inspection and maintenance strategies, as illustrated in Figure 2. The equipment risk control levels are divided into “Level Ⅰ, Level Ⅱ, Level Ⅲ, and Level Ⅳ” (from high to low).

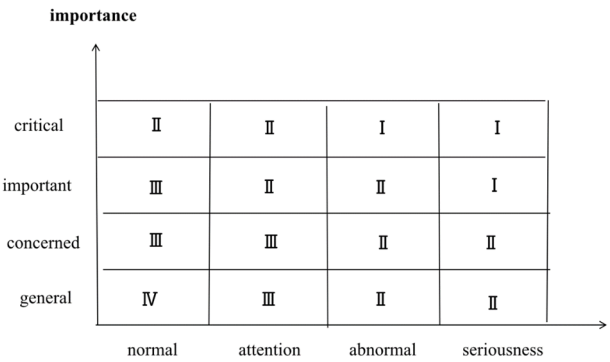

Fig. 2. Equipment risk management matrix

In accordance with the cyclical planned maintenance requirements and combined with the results of status monitoring, adjustments to different maintenance cycles will be made under categorized risk control levels, guiding actual equipment management. As shown in Figure 3, when the equipment is in a "seriousness state," maintenance should be arranged as soon as possible, and monitoring patrols must be strengthened before maintenance is implemented. When the equipment is in an “abnormal state”, timely maintenance (to be conducted within one year) should be arranged, along with strengthened monitoring patrols. When the equipment is in an "attention state," priority should be given to enhancing equipment monitoring patrols, but the maintenance cycle must not exceed the base cycle. When the equipment is in a “normal state”, its maintenance cycle can be extended. According to the national standard “Guidelines for Maintenance of Pumped Storage Power Stations” (GB/T 32574-2016), preventive maintenance of storage units can be divided into four levels: A, B, C, and D [9-10]. Where A-level maintenance corresponds to major overhauls, B-level to intermediate repairs, C-level to minor repairs, and D-level to daily defect elimination. The national standards have specific provisions on the cycles and durations for regular maintenance of the storage units. The C-level maintenance cycle of the storage units is one year, and the A-level is ten years, setting the standard items for A and C level maintenance, meaning almost all components are maintained or inspected at the same cycle. After extending the maintenance cycle, focus should be on analyzing subsequent equipment states. If dynamic adjustments of the maintenance cycle can reduce non-stop time and enhance equipment health, it should be noted to provide a reference for similar types of equipment comprehensively.

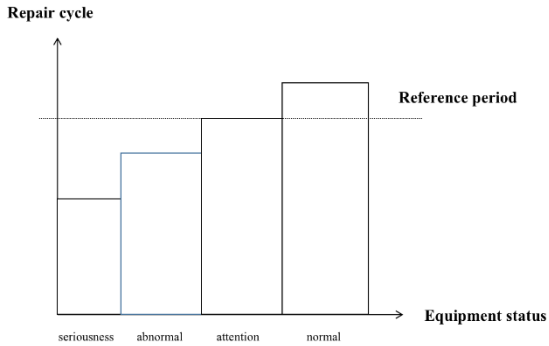

Fig. 3. Determination of the actual maintenance cycle

5 Empirical study of reliability-centered management of pumped storage devices

In a certain power station, the manhole cover of the governor's pressure oil tank is sealed with a nitrile rubber ring. According to the average lifespan provided by the manufacturer, it is approximately 10-15 years. Given that the tank pressure is 64 MPa, a leak could result in safety consequences [11]. The power plant chooses a higher safety factor ns of 5, thus, the safe lifespan of this sealing ring is 2-3 years [12]. In practice, the ring is replaced annually, leading to a certain degree of waste, and there is potential for further optimization of this maintenance cycle.

Assuming that the failure time distribution of the sealing ring follows a normal distribution, the failure distribution function and the reliability function within the maintenance cycle T is as equation (1) [13]:

$$F(T)=\varphi\left(\frac{T-\mu}{\sigma}\right)$$
$$R(T)=1-F(T)=1-\varphi\left(\frac{T-\mu}{\sigma}\right) \tag{1}$$

In this case, with μ=12.5 and δ=2.5, we calculate the reliability for T=1, 2 and 3, obtaining R(T=1) =1, R(T=2) =1, and R(T=3) =0.9999. If a reliability of 0.99 is required, the formula calculates T=6.6841 years. These results indicate that the current practice of annual replacement of the sealing ring is overly wasteful. If a 100% reliability is mandated, the ring could be replaced every two years, whereas, for a 99% reliability requirement, the replacement cycle could be extended even further.

6 Conclusions

The pumping and storage power station involves many types of hydraulic equipment and power equipment, etc. The project research puts forward the concept of health management of pumping and storage equipment with reliability as the center, comprehensively considers the importance of equipment classification, the risk level and other factors, determines the health status of equipment, so as to formulate differentiated maintenance strategies. The project takes the manhole door of a power station

governor pressure oil tank with nitrile rubber sealing ring as an example to calculate the service life in actual working conditions. Through calculation, it is considered that when reliability is 99%, the service life can be extended for more than 5 years, and if the reliability is 100%, the service life can be extended for more than 1 year. It proves that reliability-based equipment management can extend equipment life and reduce management waste while ensuring safety.

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