Research on Unmanned Operation and Maintenance Mode of Ultra High Voltage Equipment for Modernization of Power Safety Governance

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ABSTRACT
This article focuses on the operation and maintenance of ultra-high voltage equipment oriented to the modernization of power safety management. In view of the limitations of traditional operation and maintenance mode in efficiency, cost and personnel safety, this article focuses on the potential of unmanned operation and maintenance mode in improving operation and maintenance level. Through the comprehensive application of multidisciplinary theoretical knowledge, this article analyzes the cooperative application mechanism of unmanned equipment in ultra-high voltage equipment operation and maintenance, and deeply discusses the selection and configuration of unmanned equipment, the design of cooperative operation and maintenance mechanism, and the architecture of operation and maintenance management system. Unmanned operation and maintenance mode has the advantages of improving operation and maintenance efficiency, reducing costs and ensuring personnel safety, but it also faces challenges such as technology, data security and laws and regulations. Based on this article, the development strategy covering technology research and development, management optimization and policy support is put forward, which provides innovative ideas and feasible solutions for the operation and maintenance of ultra-high voltage equipment in the power industry and helps the modernization process of power safety governance.

Keywords: *Ultra-high pressure equipment, Unmanned operation and maintenance mode, Power safety management, Unmanned equipment.*

1. INTRODUCTION

As an important support of national economic development, the safe and stable operation of electric power industry is very important. Under the background of modernization of power safety management, the operation and maintenance of EHV equipment is facing new challenges and opportunities [1]. In the face of the increasingly complex and huge EHV power grid, the traditional operation and maintenance mode has exposed many disadvantages, such as low efficiency, high labor cost and personnel safety risks, which has been difficult to meet the strict requirements of modern power system for reliability and efficiency [2]. Therefore, it is urgent to explore an innovative operation and maintenance mode of ultra-high voltage equipment. Unmanned operation and maintenance mode is gradually becoming the focus of power industry due to its obvious advantages in improving operation and maintenance efficiency, reducing operation and maintenance costs and ensuring personnel safety [3]. The rapid development and technological breakthrough of unmanned equipment such as robot dogs, unmanned aerial vehicles and unmanned vehicles provide a solid technical foundation for the realization of unmanned operation and maintenance mode of ultra-high voltage equipment [4]. These unmanned devices have the characteristics of flexible movement, efficient monitoring and accurate operation, and can perform diversified operation and maintenance tasks in complex and dangerous ultra-high pressure environment [5].

The purpose of this study is to deeply explore the unmanned operation and maintenance mode of EHV equipment oriented to the modernization of power safety management. Through the comprehensive application of multidisciplinary theoretical knowledge, this article analyzes the cooperative application mechanism of unmanned equipment in ultra-high voltage equipment operation and maintenance, and constructs a scientific and reasonable unmanned operation and maintenance model. It is expected that through this study, innovative ideas and practical solutions will be provided for the operation and maintenance of ultra-high voltage equipment in the power industry, and the modernization process of power safety governance will be promoted to a new level.

2. THEORETICAL BASIS OF UNMANNED OPERATION AND MAINTENANCE OF EHV EQUIPMENT

The basic theory of operation and maintenance of EHV equipment expounds that EHV equipment consists of transformers, circuit breakers and other components, and realizes power transmission and distribution through electromagnetic induction and other principles [6]. Traditional operation and maintenance is based on regular inspection and fault maintenance, which requires manual judgment of equipment status. The principle of unmanned operation and maintenance technology is based on the flexible movement of robot dogs, the high-altitude overlooking of drones and the large-capacity transportation capacity of unmanned vehicles. Robot dogs use quadruped bionic structure to adapt to complex terrain, unmanned aerial vehicles rely on flight control system to realize accurate flight monitoring, and unmanned aerial vehicles rely on autonomous driving technology to carry materials and equipment [7]. These unmanned devices collect data through sensors and transmit them to the control center through the communication network to realize real-time monitoring and operation and maintenance of ultra-high voltage equipment. The modernization theory of power security governance emphasizes prevention, and uses advanced technology and scientific management to improve the security and reliability of power system [8]. It covers many aspects, such as equipment operation management and personnel safety training, and provides direction guidance for unmanned operation and maintenance mode to ensure that unmanned operation and maintenance can be carried out efficiently under the premise of ensuring power safety.

3. KEY ELEMENTS OF UNMANNED OPERATION AND MAINTENANCE MODE FOR EHV EQUIPMENT

The efficient operation of unmanned operation and maintenance mode of EHV equipment depends on several key elements, which cooperate with each other to ensure the smooth operation and maintenance work.

3.1 Selection and Configuration of Unmanned Equipment

According to different operation and maintenance scenarios and task requirements of EHV equipment, it is very important to select and configure unmanned equipment reasonably. For example, in areas with complex terrain and narrow space, it is suitable to choose flexible robot dogs. With the advantage of quadruped walking, it can cross obstacles and detect equipment at close range. For large-scale line inspection, UAV can play its fast and efficient characteristics and realize large-scale aerial monitoring [9]. Unmanned vehicles can be used to transport heavy operation and maintenance tools and materials. “Figure 1” shows the recommended selection and configuration basis of unmanned equipment in different scenarios.

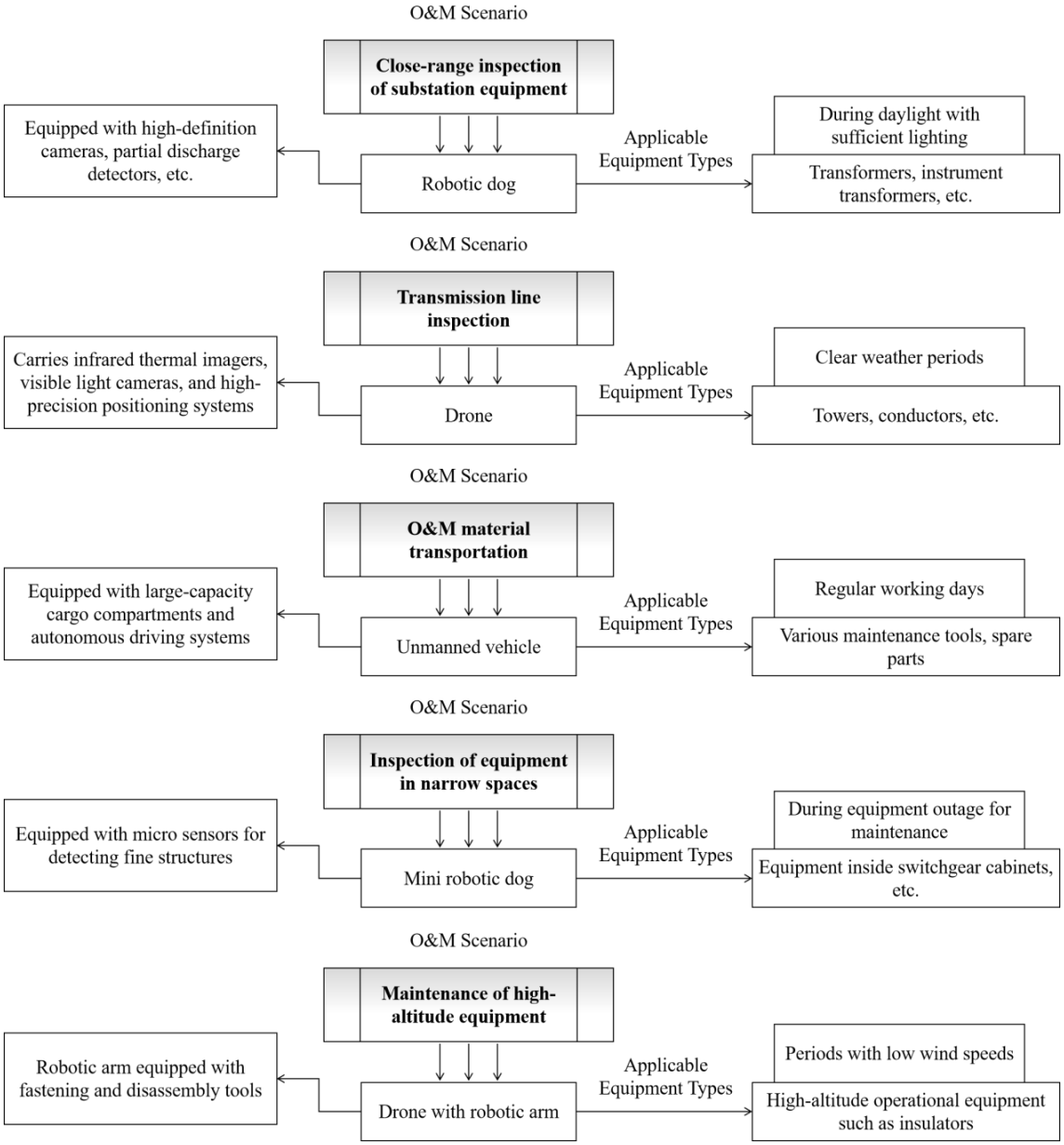


Figure 1 Unmanned equipment selection and configuration for different O&M scenarios of UHV equipment.

3.2 Design of Collaborative Operation and Maintenance Mechanism

An effective collaborative mechanism should be established between unmanned devices to realize information sharing and task collaboration. Through the Internet of Things technology, all devices upload monitoring data to the central control system in real time, and the system intelligently assigns tasks according to the data analysis results, so that all devices can work cooperatively and improve the operation and maintenance efficiency.

3.3 Operation and Maintenance Management System Architecture

The architecture should include a data acquisition layer to collect monitoring data of unmanned equipment; Data processing and analysis layer, mining data value to evaluate equipment status; Decision-making and scheduling layer, according to the analysis results, issues operation and maintenance instructions to realize comprehensive and scientific management of unmanned operation and maintenance of ultra-high voltage equipment.

4. ADVANTAGES AND CHALLENGES OF UNMANNED OPERATION AND MAINTENANCE MODE FOR EHV EQUIPMENT

4.1 Advantages of Unmanned Operation and Maintenance Mode

Unmanned operation and maintenance mode of EHV equipment, as a new operation and maintenance mode in power industry, has brought many advantages to the modernization of power safety management, but it also faces some challenges [10]. The unmanned operation and maintenance mode of EHV equipment has obvious advantages. From the perspective of operation and maintenance efficiency, unmanned equipment such as robot dogs, drones and unmanned vehicles can carry out multiple operation and maintenance tasks at the same time according to preset procedures, greatly shortening the operation and maintenance time. See "Table 1" for the comparison of traditional and unmanned operation and maintenance efficiency of EHV equipment.

Table 1. Comparison of efficiency between traditional and unmanned operation and maintenance for ultra-high voltage equipment

Operation and Maintenance Item	Traditional O&M Time Consuming	Manpower	Unmanned O&M Time Consuming	Manpower	Efficiency Improvement Ratio	Cost Reduction Ratio
Inspection of 50km Transmission Line	5 days	10 people	2 days	3 people	60%	40%
Substation Equipment Inspection	3 days	8 people	1 day	2 people	67%	50%
Inspection of 10km Cable Tunnel	4 days	6 people	1.5 days	1 person	62.5%	60%
Auxiliary Maintenance for Large Transformers	2 days	5 people	1 day	2 people	50%	40%
High-voltage Tower Climbing Inspection	3 days	4 people	0.5 day	1 person	83.3%	50%

In terms of cost control, unmanned operation and maintenance reduces manpower input, which can save a lot of labor costs and training expenses in the long run. Unmanned equipment can accurately detect hidden dangers of equipment, warn faults in advance, and reduce equipment maintenance costs and power outage losses. Unmanned equipment can also work in a high-risk environment, avoiding the exposure of operation and maintenance personnel to danger and effectively ensuring the safety of personnel.

4.2 Challenges Faced by Unmanned Operation and Maintenance Mode

The unmanned operation and maintenance mode also faces some challenges. On the technical level, the reliability and stability of unmanned equipment need to be improved. For example, bad weather may affect the flight of unmanned aircraft, and complex electromagnetic environment may interfere with the signal transmission of robot dogs. In terms of data security, a large number of sensitive data collected by unmanned equipment are at risk of leakage. Once the data is stolen or tampered with, it will threaten the security of the power grid. At the level of laws and regulations, the current policies and standard systems for unmanned operation and maintenance are not perfect, and the industry lacks clear basis in key links such as responsibility definition and accident handling. This system gap has brought substantial obstacles to the popularization and application of unmanned operation and maintenance mode.

5. DEVELOPMENT STRATEGY OF UNMANNED OPERATION AND MAINTENANCE MODE FOR EHV EQUIPMENT

In order to promote the wide application and sustainable development of unmanned operation and maintenance mode of ultra-high voltage equipment, relevant subjects need to formulate

scientific and effective implementation strategies from multi-dimensions such as technology research and development, management optimization and policy support.

5.1 Technology Research and Development Strategy

Increasing the investment in unmanned equipment technology research and development constitutes the core path to improve the efficiency of unmanned operation and maintenance mode. On the one hand, the industry urgently needs to improve the environmental adaptability of unmanned equipment. Research institutions can focus on developing unmanned aerial vehicles with stronger wind, rain and dust resistance, so as to ensure that they can still perform inspection tasks stably under bad weather conditions. The engineering team should improve the chassis structure and material properties of the robot dog and enhance its passing ability in complex terrain. On the other hand, the technology research and development department should focus on improving the intelligent level of equipment and develop an algorithm system with autonomous learning and intelligent decision-making ability, so that unmanned equipment can dynamically adjust its operation and maintenance strategy according to real-time monitoring data. “Table 2” shows the main technology research and development directions and the corresponding expected results.

Table 2. Key research and development directions and expected effects of unmanned equipment technology

Research and Development Direction	Specific Measures	Expected Effect	Estimated R&D Cycle	Estimated R&D Cost (10,000 yuan)	Impact on O&M Cost
Environmental Adaptability Improvement	Equip drones with high-performance meteorological sensors and adaptive flight control systems; add sealing protection and anti-slip tracks to robotic dogs	Drones can operate normally in winds of up to Force 8, moderate rain, and sandstorms; robotic dogs can walk stably on slopes of over 45° and muddy terrain	1-2 years	500	Long-term cost reduction of 20%
Intelligence Level Enhancement	Introduce deep learning algorithms to build fault prediction models; develop intelligent scheduling systems for multi-device collaboration	Fault prediction accuracy of unmanned equipment exceeds 90%; multi-device collaborative operation efficiency increases by 30%	2-3 years	800	Cost reduction of 30% due to efficiency improvement
Communication Stability Enhancement	Adopt new anti-interference communication technologies and build redundant communication links	Communication interruption rate in complex electromagnetic environments drops to below 1%	1-1.5 years	300	Reduce O&M costs caused by communication delays
Energy Efficiency Optimization	Develop high-efficiency battery technologies and optimize energy management systems	Single-charge endurance of unmanned equipment increases by 50%	2-2.5 years	600	Reduce energy supply costs by 15%
Detection Accuracy Improvement	Upgrade sensors and adopt intelligent data processing algorithms	Detection accuracy of key equipment parameters increases by 20%	1-1.5 years	400	Reduce O&M cost increases caused by misjudgments

5.2 Management Optimization Strategy

Electric power enterprises should improve the operation and maintenance management system, clarify the specific responsibilities of various departments and post personnel in the unmanned operation and maintenance system, and build standardized operation and maintenance processes and operational norms. Enterprises also need to strengthen the construction of personnel training system, and strive to cultivate compound talents

who not only master the professional knowledge of electric power but also are familiar with the operation and management of unmanned equipment. For example, the operation and maintenance unit can regularly organize operators to participate in unmanned equipment operation skills training and emergency handling drills, so as to improve their actual combat ability to deal with emergencies. The management department should establish a life-cycle management system for equipment, and carefully track and manage the whole process of unmanned equipment from procurement, deployment, use to scrapping, so as to ensure that the equipment always maintains a good running state.

5.3 Policy Support Strategy

Industry organizations should actively strive for policy support and push government departments to introduce special preferential policies to encourage the development of unmanned operation and maintenance technology, such as implementing tax relief and R&D subsidy measures to effectively reduce the cost of enterprise technology R&D. Standardization organizations need to accelerate the construction of industry standard system, and clarify the technical parameter standards, safe operation specifications and operation and maintenance service quality evaluation standards of unmanned equipment. Enterprises should actively strengthen communication and coordination with regulatory authorities, ensure that unmanned operation and maintenance practices meet the requirements of existing laws and regulations, and jointly create a policy environment conducive to technological innovation. Through the system coordination of technology research and development, management optimization and policy support, the unmanned operation and maintenance mode of EHV equipment will help the modernization process of power security governance more effectively.

6. CONCLUSION

In this article, the unmanned operation and maintenance mode of EHV equipment oriented to the modernization of power safety management is studied comprehensively and deeply. In today's power industry development demand, the shortcomings of traditional ultra-high voltage equipment operation and maintenance mode have become increasingly prominent, and unmanned operation and maintenance mode has become an inevitable development direction. In this study, the theoretical basis of unmanned operation and maintenance of EHV equipment is systematically sorted out, and the theoretical basis of this model in terms of technical support and power safety management concept is clarified. The discussion on the advantages and challenges of unmanned operation and maintenance mode fully presents the characteristics of this emerging mode. Its advantages are remarkable. In terms of operation and maintenance efficiency, compared with the traditional operation and maintenance, the time is greatly shortened. Taking transmission line inspection and substation equipment inspection as examples, the efficiency is obviously improved. In the dimension of cost control, enterprises have effectively reduced the total cost of operation and maintenance by reducing on-site labor input and reducing the frequency of unplanned downtime and maintenance of equipment. In the dimension of personnel safety, unmanned equipment replaces manpower to enter high-risk working environment, which fundamentally avoids personal safety risks. However, this model also faces many challenges, such as improving the reliability and stability of unmanned equipment in technology, preventing the risk of data leakage and tampering in data security, and improving relevant policies and standards in laws and regulations.

In view of the above practical challenges, the trinity strategy system of technology research and development, management optimization and policy support proposed in this study shows strong practical guiding value. The main body of technology research and development focuses on enhancing the adaptability of equipment environment and improving the level of intelligent decision-making algorithm. Electric power enterprises pay attention to improving the inter-departmental collaborative management system and strengthening the training of compound operation and maintenance talents. Industry organizations actively promote policies such as tax incentives and R&D subsidies, and take the lead in formulating industry standard systems covering technical parameters, safety norms and service quality. With the collaborative promotion of technical iteration, management innovation and policy improvement, this model is expected to systematically improve the operation and maintenance efficiency of ultra-high voltage equipment in the power industry and inject sustained impetus into the modernization process of power safety governance.

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REFERENCES

[1] Fang Xiaoming, Liu Yanli, Tian Dahai. Automatic operation and maintenance control of high-voltage electrical equipment based on PLC and configuration feedback technology[J]. Machine Design and Research, 2024, 40(06): 270-276. DOI: 10.13952/j.cnki.jofmdr.2024.0238.

[2] Qian Jin, Chen Yuanzhong, Xu Hanlin. Analysis of security operation and maintenance for secondary equipment in power systems based on continuous condition monitoring[J]. Electronic Design Engineering, 2025, 33(10): 31-34+39. DOI: 10.14022/j.issn1674-6236.2025.10.006.

[3] Zhao Shice, Zhao Hongshan, Shou Peiyao. Discussion on key technologies and operation & maintenance of intelligent power equipment[J]. Automation of Electric Power Systems, 2020, 44(20): 1-10. DOI: 10.7500/AEPS20200303004.

[4] Qi Lizhong, Liu Ding, Zhang Zhuoqun. Overview of digital construction for UHV projects based on BIM technology[J]. Electric Power Construction, 2025, 46(02): 61-73.

[5] Ren Yan, Yu Zebang, Xin Cheng. Optimal selection method for power grid production equipment suppliers based on maintenance and operation data[J]. Construction Economy, 2023, 44(S2): 122-126. DOI: 10.14181/j.cnki.1002-851x.2023S2122.

[6] Xie Qing, Wang Chunxin, Li Fan. Review of knowledge and data-driven health management methods for primary power equipment[J]. High Voltage Engineering, 2024, 50(02): 605-620. DOI: 10.13336/j.1003-6520.hve.20230764.

[7] Yuan Hongtuan. Design and research of a security operation and maintenance management system for smart grids based on cloud computing[J]. Automation & Instrumentation, 2021, (06): 120-122+127. DOI: 10.14016/j.cnki.1001-9227.2021.06.120.

[8] Li Xubin, Tian Fuqiang, Guo Yike. Exploration of key technologies for health management and intelligent operation & maintenance of power equipment in new power systems[J]. Power System Technology, 2023, 47(09): 3710-3727. DOI: 10.13335/j.1000-3673.pst.2022.2451.

[9] Tan Jinlong, Wang Kaike, Yu Bing. Health state assessment of secondary power equipment based on entropy weight method[J]. Journal of Shenyang University of Technology, 2025, 47(04): 425-431.

[10] Pu Tianjiao, Qiao Ji, Han Xiao. Research and application of artificial intelligence technology in operation, maintenance, and inspection of power equipment[J]. High Voltage Engineering, 2020, 46(02): 369-383. DOI: 10.13336/j.1003-6520.hve.20200131001.