Article

2025 International Forum on Smart Energy and Power Engineering Technologies (SEPET 2025)

Research on GIS Pipeline Precision Docking Device Based on Multi-Degree of Freedom Robot Arm Control

Jinghui Liu [1,*], Xiabo Chen [1], Guangze Zhu [2], Lihui Zhou [3], Ti Liu [4], Boming Li [2] and Zhengming Ye [4]

1 Shaoxing Power Supply Company, State Grid Zhejiang Electric Power Co., Ltd., Shaoxing, Zhejiang, China
2 Zhejiang Power Transmission and Transformation Engineering Co., Ltd., Hangzhou, Zhejiang, China
3 Jinhua Power Supply Company, State Grid Zhejiang Electric Power Co., Ltd., Jinhua, Zhejiang, China
4 Construction Branch, State Grid Zhejiang Electric Power Co., Ltd., Hangzhou, Zhejiang, China
* Correspondence: Jinghui Liu, Shaoxing Power Supply Company, State Grid Zhejiang Electric Power Co., Ltd., Shaoxing, Zhejiang, China

Abstract: Gas-Insulated Switchgear (GIS) is widely used in substations of various voltage levels due to its compact size and high reliability. However, manual installation of GIS equipment faces challenges such as limited space, low alignment accuracy, low efficiency, and safety risks. To address these issues, this paper proposes a precision alignment technology that integrates six-degree-of-freedom robotic arms. By developing a precision alignment device for GIS pipeline busbars using multi-degree-of-freedom robotic arm control, the system can achieve millimeter-level accuracy in automatic pipeline alignment. This platform significantly enhances pipeline installation efficiency and equipment reliability, filling a gap in China's GIS intelligent construction equipment and enhancing the quality and efficiency of power construction.

Keywords: Gas-Insulated Switchgear (GIS); six degrees of freedom robotic arm; precision docking

Received: 24 May 2025
Revised: 30 May 2025
Accepted: 13 June 2025
Published: 30 June 2025

1. Introduction

This article addresses the urgent need for improving the alignment accuracy of on-site GIS (Gas-Insulated Switchgear) pipeline installation. To meet this demand, the study proposes and applies an intelligent six-degree-of-freedom robotic arm technology. This advanced system is designed to eliminate deviations caused by human error and the limitations of traditional tools during installation [1]. By achieving high-precision alignment and effectively identifying and preventing potential equipment defects and hazards, this technology significantly enhances the long-term operational safety and reliability of GIS systems. Ultimately, it aims to establish a precision alignment platform that ensures safe, stable, and efficient operation of power transmission infrastructure [2].

1.1. Technical Challenges in GIS Pipeline Installation

GIS pipeline busbar installation is known for its inherent technical difficulties, including narrow spatial environments, complex manual procedures, high precision requirements, and elevated safety risks [3,4]. These constraints make traditional alignment methods inadequate for ensuring long-term equipment reliability. To overcome these challenges, this study carries out targeted and systematic technological innovation.

1.2. Development of a Six-Degree-of-Freedom Precision Platform

This study has developed a six-degree-of-freedom precision adjustment platform based on the principle of parallel mechanisms. The platform features a compact structure, high load-bearing capability, and fast dynamic response, making it ideal for use in confined working environments [5]. It is capable of achieving millimeter-level or even sub-millimeter-level positioning and attitude adjustment in six degrees of freedom — three translations and three rotations. This platform can flexibly accommodate GIS pipelines of various diameters and lengths, thereby fundamentally resolving the difficulties associated with high-precision alignment in complex spaces.

1.3. Multi-Degree-of-Freedom Collaborative Control System

To realize smooth and precise operation of the adjustment platform, the study introduces an advanced collaborative control system. This system integrates high-precision sensor feedback, real-time motion planning, and robust control algorithms into a customized wireless manipulator [6]. Through remote, intuitive, and real-time operation, users can achieve precise control over the entire alignment process, embodying the "what you see is what you control" concept. This significantly reduces on-site risks and improves alignment efficiency.

1.4. Intelligent Fixture with Embedded Edge Computing

A multifunctional intelligent mechanical fixture has also been designed specifically for GIS equipment. It features a modular jaw structure that allows rapid adaptation to different pipe diameters. More importantly, it integrates an edge computing unit capable of real-time perception and local decision-making. The fixture can monitor clamping force, contact state, and pipe posture, and automatically adjust its grip to ensure secure clamping while avoiding deformation or damage to insulating components [7]. This provides crucial support for ensuring alignment safety and installation quality.

2. Research Content

2.1. Design and System Integration of the Precision Docking Device for GIS Pipeline Busbars

To effectively tackle the persistent challenges in the high-precision installation of high-voltage gas-insulated switchgear (GIS) cabinets — particularly the high risk of human-induced alignment errors, limited operating space, and low construction efficiency — this study proposes the design and development of an advanced precision docking device for GIS pipeline busbars [8]. As illustrated in Figure 1, the system is built around a multi-degree-of-freedom robotic arm control framework and integrates mechanical, hydraulic, and electrical control subsystems into a coordinated whole, forming a highly adaptive and intelligent installation platform.

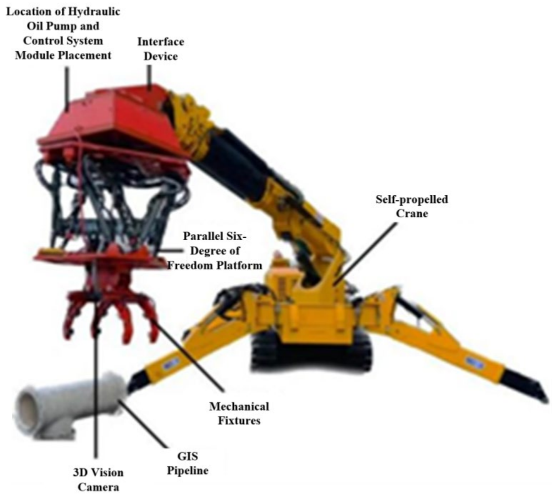

Figure 1. Precision Docking Device for Pipeline Busbar of High Voltage Combined Electrical Appliances.

The mechanical subsystem serves as the core structural and functional foundation of the device. It comprises a balancing mechanism to stabilize the overall structure during operation, a rotary mechanism to enable angular alignment adjustments, a parallel six-degree-of-freedom positioning platform for precise spatial alignment, and a flexible clamping mechanism tailored to accommodate pipelines of varying diameters. This subsystem is specially designed to function within the spatially constrained and structurally complex environments of high-voltage GIS cabinets, ensuring the accuracy and stability of the docking process.

The hydraulic subsystem functions as the main power unit of the device, providing continuous and reliable actuation force for all major mechanical operations. Given the high mass and rigidity of GIS pipeline components, the hydraulic system is optimized for long-duration load-bearing performance, enabling smooth motion control and resistance to mechanical fatigue during repetitive installations [9]. Its inclusion not only guarantees the force required for precise manipulation but also ensures consistent performance under varying field conditions.

The electrical control subsystem acts as the intelligent command center of the entire system. Through the integration of sensors, feedback loops, and programmable logic controllers (PLCs), it facilitates real-time monitoring, dynamic decision-making, and adaptive control of each functional unit. This subsystem enables the entire docking process to be operated with minimal manual intervention. Operators can issue commands remotely, monitor the status of alignment in real time, and achieve seamless docking even in complex pipeline arrangements. Moreover, the system supports the automatic identification of pipe length and diameter, as well as compensation for positioning deviations, further reducing operational risk and human error.

By combining mechanical precision, hydraulic power, and intelligent control, the proposed docking device significantly enhances the efficiency, safety, and accuracy of GIS pipeline busbar installation [10]. It provides a highly integrated technical solution that not only overcomes the limitations of traditional manual alignment but also sets a new benchmark for intelligent construction in the field of high-voltage electrical equipment.

2.2. Wireless Control Integration of the Six-Degree-of-Freedom Robotic Arm

Based on a comprehensive analysis of the constraints and challenges present in the actual GIS pipeline busbar installation environment, this study has developed an advanced control technology for a six-degree-of-freedom robotic arm, seamlessly integrated into a custom-designed wireless operation handle [8]. The adoption of wireless control effectively overcomes the limitations of traditional wired control systems, which are often hindered by restricted movement, cable entanglement, and safety risks in confined substation environments.

The wireless operation handle is equipped with multiple intuitive input devices, including joysticks, push buttons, and trigger controls, enabling operators to remotely manipulate key platform functions with ease. The communication between the handle and the control system employs a robust wireless protocol optimized for low latency and high interference immunity, ensuring reliable command transmission even in electrically noisy environments [11].

Through the wireless interface, construction personnel can perform precise control of platform rotation, enabling clockwise or counterclockwise movement by directly commanding the servo motors in the rotary mechanism. Additionally, the system interprets feedback signals from integrated limit switches and sensors to autonomously regulate the servo motors responsible for the automatic opening and clamping of mechanical fixtures, maintaining optimal gripping force while preventing damage to the GIS pipeline components.

The control system incorporates advanced algorithms to maintain the robotic docking platform in a stable horizontal orientation throughout the installation process, compensating for external disturbances and operator inputs. Real-time sensor feedback allows for continuous adjustment, enhancing both the safety and accuracy of operations under varying working conditions.

Overall, this wireless control integration offers a significant improvement in operational flexibility, allowing construction teams to conduct precise alignment and docking tasks remotely, thereby reducing on-site risks and enhancing installation efficiency. Future developments will focus on extending wireless range, improving battery life of the handheld device, and integrating haptic feedback for enhanced operator situational awareness.

2.3. Design and Application of the Intelligent Automatic-Sensing Mechanical Fixture

To meet the operational demands of smart construction, an intelligent and highly adaptive mechanical fixture for GIS pipeline installation has been developed, as shown in Figure 2. This fixture features an integrated high-precision weight sensing system. Its built-in sensors continuously monitor pipeline weight and dynamically adjust clamping force via control algorithms to maintain balance during movement. This ensures that the pipeline remains stable during transport and positioning, preventing damage caused by vibration, inertial impact, or external force.

Figure 2. Modular Design of Carrier Interface.

In addition to its precision control capabilities, the fixture is engineered for high adaptability. Its modular mechanical design and flexible control logic allow it to rapidly accommodate GIS pipelines of varying sizes and shapes. Whether dealing with standard or custom-made pipelines, the system can be quickly calibrated through simple parameter adjustments or adapter replacement. It also supports multi-scenario deployment, offering reliable performance in a wide range of environments — including areas with large temperature variations, tight indoor spaces, and elevated outdoor platforms.

When used in conjunction with the parallel six-degree-of-freedom positioning platform, this fixture enables highly efficient and accurate installation of GIS pipeline busbars. The system achieves an automatic alignment accuracy of ±3 mm, angle alignment accuracy of 1°, and auxiliary manual alignment accuracy of ±1 mm. These results provide a strong technological foundation for promoting intelligent, safe, and efficient construction practices in high-voltage GIS installation projects.

3. Conclusions

This paper presents an innovative installation technology for GIS equipment, specifically focusing on the development of a precision docking device for GIS pipelines based on multi-degree-of-freedom robotic arm control. This advancement effectively fills a critical gap in the industry by addressing the longstanding challenges of achieving high-precision alignment in complex and confined installation environments.

By employing a six-degree-of-freedom motion platform, the proposed system enables precise and reliable docking of GIS pipeline busbars, which substantially supports the delivery of high-quality construction in substation projects. The integration of fully automatic sensing mechanical fixtures further elevates operational accuracy, with the system achieving a best automatic docking accuracy of ±3 mm, an angular alignment precision of 1°, and an auxiliary manual docking accuracy of ±1 mm.

Moreover, the adoption of this intelligent installation equipment significantly reduces the need for labor-intensive trial-and-error adjustments, thereby greatly improving construction efficiency and worker safety. The improved precision and automation ensure the safe and stable operation of power systems, contributing to enhanced reliability and longevity of GIS equipment.

Given it demonstrated technical effectiveness and practical benefits, this precision docking technology offers substantial value for engineering applications and possesses broad market potential, positioning it as a promising solution for advancing smart construction in the high-voltage electrical equipment sector.

References

1. Z. Faizol, Z. Zulbirri, et al., "Detection method of partial discharge on transformer and gas-insulated switchgear: A review," *Appl. Sci.*, vol. 13, no. 17, p. 9605, 2023, doi: 10.3390/app13179605.
2. Y. Xing, Y. Yunqi, et al., "Defects and failure types of solid insulation in gas-insulated switchgear: in situ study and case analysis," *High Volt.*, vol. 7, no. 1, pp. 158–164, 2022, doi: 10.1049/hve2.12127.
3. Y. Wang, X. Yanxin, et al., "Gas-insulated switchgear insulation defect diagnosis via a novel domain adaptive graph convolutional network," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–10, 2022, doi: 10.1109/TIM.2022.3160543.
4. B. Lu, et al., "The study on a new method for detecting corona discharge in gas insulated switchgear," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–8, 2021, doi: 10.1109/TIM.2021.3129225.
5. B. Wang, et al., "Numerical study on temperature rise and structure optimization for a three-phase gas insulated switchgear busbar chamber," *Energy*, vol. 254, p. 124463, 2022, doi: 10.1016/j.energy.2022.124463.
6. D.-E. Kim, et al., "Trends in Measuring Instrument Transformers for Gas-Insulated Switchgears: A Review," *Energies*, vol. 17, no. 8, p. 1846, 2024, doi: 10.3390/en17081846.
7. Y. Wang, X. Yanxin, et al., "A domain adaptive deep transfer learning method for gas-insulated switchgear partial discharge diagnosis," *IEEE Trans. Power Del.*, vol. 37, no. 4, pp. 2514–2523, 2021, doi: 10.1109/TPWRD.2021.3111862.
8. Y. Wu, et al., "Defect recognition and condition assessment of epoxy insulators in gas insulated switchgear based on multi-information fusion," *Measurement*, vol. 190, p. 110701, 2022, doi: 10.1016/j.measurement.2022.110701.
9. Y. Wang, X. Yanxin, et al., "A novel federated transfer learning framework for intelligent diagnosis of insulation defects in gas-insulated switchgear," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–11, 2022, doi: 10.1109/TIM.2022.3190529.
10. Q. Xiong, et al., "Mechanical defects diagnosis for gas insulated switchgear using acoustic imaging approach," *Appl. Acoust.*, vol. 174, p. 107784, 2021, doi: 10.1016/j.apacoust.2020.107784.
11. Y. Wang, et al., "A novel hybrid meta-learning for few-shot gas-insulated switchgear insulation defect diagnosis," *Expert Syst. Appl.*, vol. 233, p. 120956, 2023, doi: 10.1016/j.eswa.2023.120956.