Sustainable Development Research; Vol. 7, No. 3; 2025
ISSN 2690-9898 E-ISSN 2690-9901
https://doi.org/10.30560/sdr.v7n3p1

A Self-Inspecting Hanging Rod Locking Mechanism, Locking Frame, and Self-Locking Fall Arrester Device for Transmission Towers

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Received: June 2, 2025 Accepted: July 13, 2025 Online Published: July 15, 2025

This work was financially supported by the Science and Technology Project of State Grid Shanxi Electric Power Company (entitled "Development of a Mechanical Self-locking Rapid Installation and Disassembly High-altitude Operation Anti Fall Device", Grant No. 5205ww240007).

Abstract

The rapid advancement of power grids stands as a pivotal indicator of technological progress and industrialization in modern society. Overhead line operations, characterized by high difficulty and risk, are prone to accidents such as high-altitude falls and electric shocks, which significantly undermine the safety and economic efficiency of power systems. Particularly in the context of smart grid construction, more stringent requirements have been imposed on overhead line operations. With maintenance tasks becoming increasingly refined and workloads escalating, there is an urgent need to optimize and upgrade existing fall arresters to enhance their intelligence, operational convenience, and safety reliability, thereby providing comprehensive safeguards for maintenance operations. This paper presents a self-inspecting hanging rod locking method, a locking frame, and a self-locking fall arrester tailored for transmission towers. Integrating UAV technology, recognition and control technology, and fall arrester technology, this equipment offers all-round safety protection for high-altitude power grid workers.

Keywords: UAV technology, recognition and control technology, fall arrester technology, high-altitude operation

1. Introduction

Overhead line operations, plagued by complex environments, high technical difficulty, and stringent operational requirements, expose operators to multiple safety risks—including high-altitude falls, electric shocks, and short circuits—which severely impact the safe operation and economic benefits of power systems [1–3]. With the in-depth advancement of smart grid construction, higher standards have been set for safety protection equipment in overhead line maintenance. As maintenance tasks grow more refined and workloads continue to expand, optimizing and upgrading existing fall arresters has become imperative—for instance, enhancing their intelligence, operational convenience, and safety reliability—to provide comprehensive guarantees for maintenance operations [4]. Notably, the traditional climbing mode relying solely on switching between two safety hooks can no longer meet the safety requirements for mitigating high-altitude fall risks [5-6].

Existing fall arresters are inadequate in practicality, reliability, and intelligence for current operational needs. The guide rail-type fall arrester features a vertical guide rail fixedly installed on transmission towers, allowing the arrester to move freely along the rail; braking is triggered by cam friction when a fall occurs. However, it has notable limitations: it is only applicable to new towers; frictional braking causes wear, shortens the service life, and delays braking, which increases the fall distance and impact force; additionally, external factors such as corrosion, rust, and icing may lead to jamming [7–8]. The lanyard-type fall arrester, which includes combinations of safety ropes and fall arresters, is commonly used for low-height transmission towers [9–10]. Installation requires workers to climb with double hooks, hang it on support rods, or throw the device. Its internal structure is complex; to accommodate the safety rope, it has a large volume and high self-weight, making it cumbersome to carry. Although the safety rope retracts automatically after use, the uncontrollable retraction speed may impact internal components, reducing the service life [11-12]. Furthermore, drone-type fall protection devices assist workers in climbing by using drones to transport hangers with safety ropes to overhead crossbars for installation, but they also have drawbacks [13–14]. Ground operators face difficulties in controlling hanger installation due to visual deviations caused by spatial misalignment and the distance between the drone and the hanger, leading to time-consuming operations; moreover, there is a lack of post-installation status monitoring, making the hangers prone to detachment due to wind, misoperation, or large body movements during climbing [15–17].

To achieve intrinsic safety in infrastructure construction, researching anti-high-altitude fall devices is critical. This paper proposes a self-patrolling hanging rod locking method, a locking frame, and a self-locking fall arrester for transmission towers, aiming to address the aforementioned limitations. Featuring a simple structure, ease of manufacturing, and low cost, this innovation resolves issues with existing hangers—such as difficulty locating hanging rods due to visual errors, time-consuming positioning, and low efficiency in high-altitude operations.

2. System Design

2.1 Overall Architecture

At present, during the climbing process of high-altitude operations for maintenance of transmission line towers in China, workers still lack suitable, simple, efficient, economical and practical fall protection measures. [13]This paper proposes a self-patrolling hanging rod locking method, locking frame and self-locking fall-arresting device for transmission towers. In order to solve the difficulties of insufficient practicability and low intelligence of fall protection devices in high-altitude operations of overhead lines, and to address the problems that existing hangers are difficult to find hanging rods due to visual errors during high-altitude operations, and the time-consuming and inefficient alignment.

The research and development of mechanically self-locking quick-installation and disassembly overhead work fall arresters mainly includes three aspects: UAV technology, Recognition and Control technology and Fall arrester technology.

2.1.1 UAV Technology

Regarding UAV technology, special attention should be paid to flight stability, which is crucial for ensuring that the mounting platform remains stable during UAV operations and guaranteeing the safety and efficiency of high-altitude work. Specifically, the stability control system must integrate multi-dimensional attitude sensing modules, which help the UAV counteract the effects of air currents and wind by collecting flight data in real time and dynamically adjusting motor output, thus ensuring precise control of the flight trajectory. In terms of mechanical design, the mounting platform should adopt a combination of high-strength lightweight materials and shock-absorbing buffer structures. By optimizing the center of gravity distribution and rigid connection design, it can effectively suppress resonance during flight, prevent operational errors such as misjudgment of capacitive sensing elements or loosening of mechanical components caused by platform jitter, and ensure the safety and efficiency of high-altitude operations at the hardware level. In the platform design process, the compatibility with different models and sizes of UAVs should also be fully considered. Through modular interfaces and adjustable bracket structures, it can achieve rapid adaptation to different aircraft types such as multi-rotors and fixed wings to meet the diverse needs of different scenarios such as plain inspections and mountain operations.

2.1.2 Recognition and Control Technology

Research on Recognition and Control Technology for Anti-Fall Device Installation. This technology uses unmanned aerial vehicles (UAVs) as carriers to construct a closed-loop system integrating "visual perception - intelligent analysis - dynamic control," achieving full automation and intelligence in the installation process of anti-fall devices. Specifically, high-resolution cameras mounted on UAVs enable real-time recognition and positioning of characteristic structures such as power tower crossarms and vibration dampers. The system employs a two-stage strategy: initial rapid localization of target attachment points through image recognition, followed by millimeter-level position calibration using capacitive sensing components. The innovation lies in creating an integrated "installation - monitoring - protection" intelligent system. In the event of an accidental fall by an operator, the system triggers immediate locking to prevent further descent, thereby safeguarding the operator's life. This approach combines computer vision algorithms optimized for power infrastructure, edge computing for real-time processing, and adaptive control mechanisms to ensure precise and reliable deployment across diverse tower geometries and environmental conditions. The technology represents a paradigm shift from passive safety measures to proactive, AI-driven protection systems in high-altitude operations.

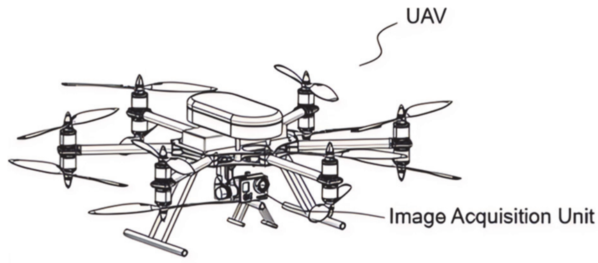
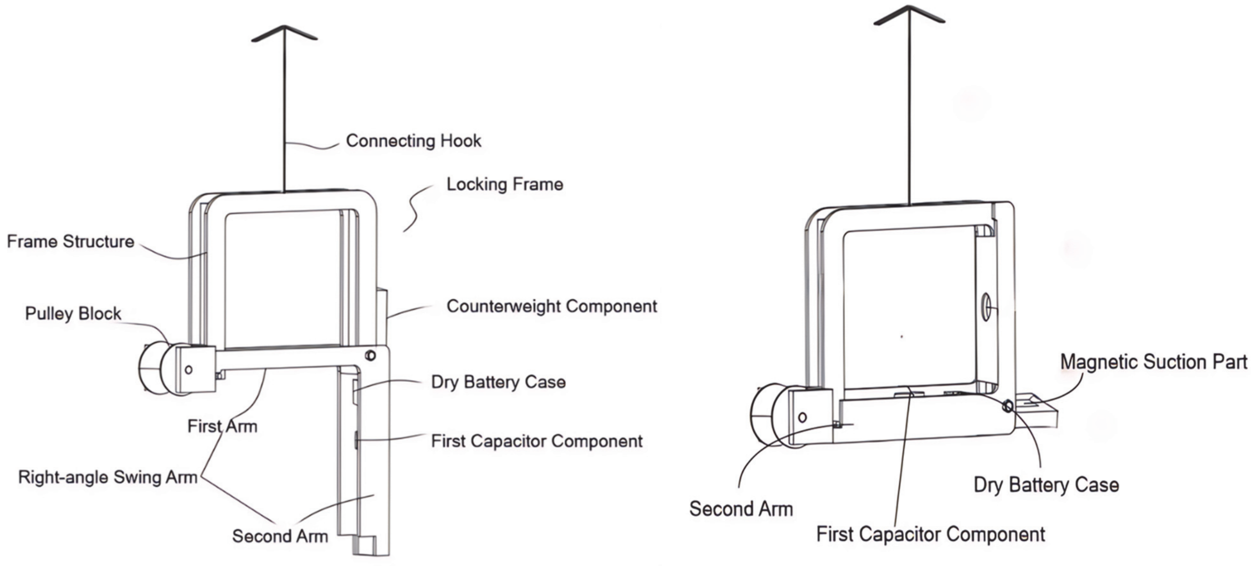


Figure 1. UAV and Recognition Control Technology Module

2.1.3 Fall Arrester Technology

Aiming at the industry pain points of cumbersome installation and poor adaptability of fall protection devices in high-altitude operations, the self-locking mechanism takes the design core of "gravity-driven - unpowered triggering", breaking through the dependence of traditional mechanical structures on manual operation. Its core functions include: realizing the automatic locking of the fall protection device and the tower materials of the power tower through a modular self-locking module - when the device comes into contact with the tower materials, the locking action is triggered by its own gravity; the disassembly can also be automatically unlocked, and no additional power source is required for the whole process. The mechanism design takes into account different tower structures and tower material types, and can achieve rapid adaptation from angle steel to round pipes, from standard tower types to special-shaped components, and can stably bear the combined load of operators and safety ropes after locking, meeting the safety protection needs of high-altitude operations.



(a) **(b)**

Figure 2. Fall arrester technology .(a) Initial state. (b) Locked state.

2.2 Working Principle

The The self-locking fall arrester device comprises a UAV, a locking frame, a safety rope, a control component, and a brake. The UAV is equipped with a binocular visible-light camera (resolution >2 million pixels, frame rate >30fps) and a wavelength infrared thermal imager (384×288 resolution) for night-time perception. It can be operated via a remote control or fly autonomously after programming by the control component. The safety rope is made of high-strength wire rope or steel cable, validated through static and dynamic load tests for quality and reliability. The brake consists of a base shell, spring, brake wheel, and connection structure. The base shell connects to the worker via the connection structure, housing the spring and brake wheel; the safety rope passes through the shell and abuts the brake wheel. In case of a fall, spring force pushes the brake wheel against the rope, instantly clamping and locking it. The control component is signal-connected to the UAV's image acquisition unit and capacitive components, storing and comparing collected data with preset values, then issuing commands to the UAV. The locking frame is constructed from stainless steel or alloy stainless steel for sufficient hardness and rigidity, ensuring stable hanging on crossbars without easy detachment.

The working method involves analyzing data from the UAV's image acquisition unit and a first capacitive component (mounted inside the locking frame's right-angle swing arm). The hook connects to the UAV via a rigid or flexible sleeve. The UAV flies to the tower's highest point; during ascent, the image acquisition unit first locates the crossbar at the vibration damper. After capturing the damper, the UAV hovers, collects images of nearby crossbars (front and rear), and sends them to a cloud server. The control component analyzes crossbar features (e.g., shape, texture), extracts hanging point characteristics, and matches them with predefined features to identify the target crossbar.

Then the UAV positions the locking frame above the target crossbar. Due to environmental factors (wind, debris on the crossbar surface), image acquisition errors, or positioning inaccuracies, the locking frame may sway. The first capacitive component includes two first capacitive elements with perpendicular sensing directions, each for sensing the position between the locking frame and the target crossbar. As the UAV descends, the capacitance values of the first capacitive element on the first arm and the first capacitive component on the second arm will sense the crossbar, triggering fluctuations in the capacitance values, resulting in sudden capacitance mutations. And it is necessary to ensure that the capacitance values generated by the first capacitive components on the first arm and the second arm both undergo upward mutations, and the capacitance value R remains in an upward trend within the manually set first time period T1. The position of this upward mutation is designated as the starting point H1, which is stored and set as the original position W where the target crossbar can be hung. According to the original position W and the manually set parameter compensation, the UAV can determine that the crossbar is within the hanging range of the right-angle swing arm.

The two first capacitive elements continuously sense (determine capacitance value changes every manually set first period K; in this study, the range of the manually set first period K is exemplified as 0.5-2 seconds). When the capacitance value R rises and exceeds the manually set first capacitance value R0, it is determined that the target crossbar is hung into the locking frame.

After hanging is completed, the time point S when the first capacitance value R0 is exceeded is used as the timing point and stored, indicating that the hanging state has been achieved. When the capacitance values R1, R2, R3, R4, R5….RN continuously collected by the two right-angled first capacitive elements tend to a stable change state, it is determined that the hanging is completed and the continuous locking state is maintained. Thus, the first capacitive elements not only enable precise and rapid hanging but also monitor whether the hanger remains stably hung. After the right-angle swing arm is flipped, the two first capacitive elements still face the crossbar, enabling real-time monitoring and judging whether drag hanging occurs by using capacitance value changes. The capacitance changes during the hanging process are shown in the following Figure 3.

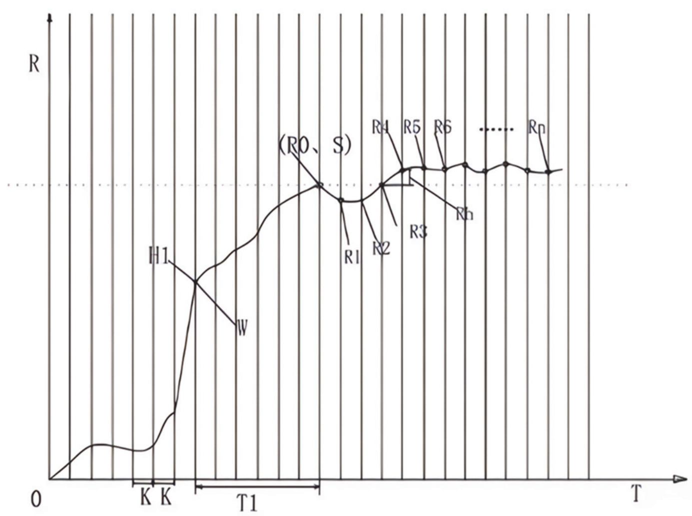


Figure 3. The capacitance changes.

The locking method, locking frame, and self-locking fall arrester device provided by this invention solve the problems of existing hangers, such as difficulty in locating hanging rods due to visual errors, time-consuming positioning, and low efficiency during high-altitude operations.

3. Results

The innovation of this study lies in the research on identification and control technologies for the hanging of fall arrester devices.

The study utilizes an intelligent identification system combined with sensor technology, image recognition technology, and data processing algorithms to achieve real-time monitoring and identification of the device's hanging status, while implementing precise control over the fall arrester device through a control system. Aiming to enhance work efficiency and safety, it involves identifying whether the fall arrester device is correctly hung in the corresponding position and conducting real-time monitoring and control of its status. This research considers aspects such as sensor technology and real-time monitoring and control technologies to ensure the fall arrester device can be accurately and stably hung in the required position, reducing human operational errors and enabling real-time monitoring and control of its status during high-altitude operations, thus improving work safety and efficiency. Based on the mechanically self-locking hanging and detaching structure, the study adds a hanging point identification function for the device. By equipping a UAV with a camera and image recognition processing technology, it realizes automatic identification and control of the hanging points and mounting status of the fall arrester device. The overall structure diagram of the actual device is shown in the following Figure 4.

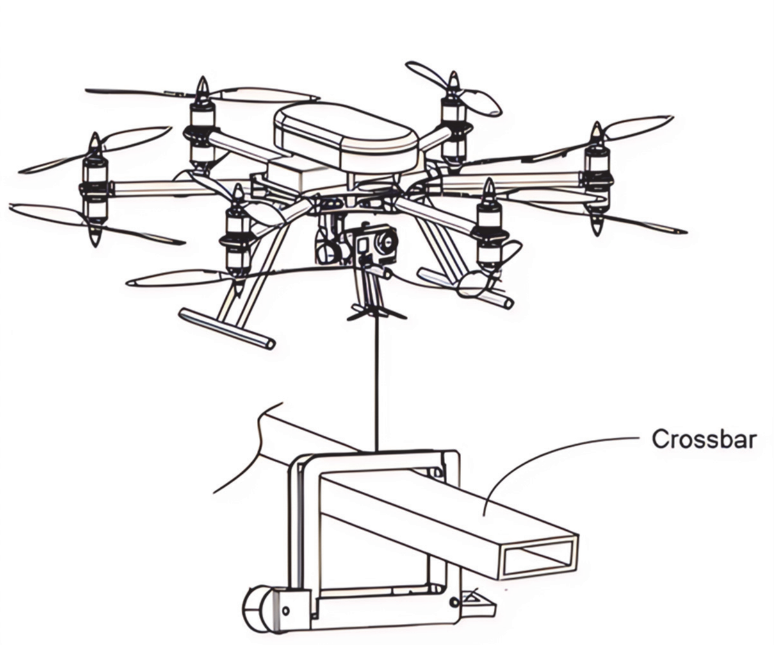


Figure 4. Overall structure diagram of the actual device

4. Conclusion

High-altitude falls and electric shocks in overhead line operations threaten operator safety and undermine power system safety and economic benefits. By upgrading existing fall arresters with intelligence and convenience, integrating sensors, image recognition, and data processing, this study enables real-time monitoring of hanging status and precise control via a control system. The developed arrester establishes a comprehensive safety guarantee system for power maintenance.

Acknowledgements

This work was financially supported by the Science and Technology Project of State Grid Shanxi Electric Power Company (entitled "Development of a Mechanical Self-locking Rapid Installation and Disassembly High-altitude Operation Anti Fall Device", Grant No. 5205ww240007).

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