Development of Live Working Robot for Distribution Network

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Abstract. The distribution network is the key link to ensure the continuous power supply. The live working of the distribution network has become an important means to ensure the reliability of power supply and improve the reliability of power supply. This article designs a suitable application according to the task of live working of the distribution network and the analysis of the working objects. A live working robot which is used for distribution network with a voltage level of 10 kV or less. The robot is composed of a mobile insulation platform, a robot body, a working end, an insulation protection system, and a control system, where in the robot body includes a control box, a work robot, and a work tool transfer device. The end of the operation includes a grip end, a wire stripping end, and a clip mounting end. The results show that the robot can replace the manual task of charging and disconnecting wires, reduce the labor intensity of the operators and ensure the safety of the operators.

1. Introduction

Distribution network is at the end of power system, and a key link to ensure the continuous supply of power. The live working of distribution network has become the most direct and effective means to reduce the outage time and improve power supply reliability and service level of the distribution network[1][2]. Among them, the live disconnection and connection workings play a very important role in the live working of the distribution network[3]. Conventional live disconnection and connection workings mainly rely on manual work, which feature great labor intensity, high working risks and are easy to cause personal casualty events[4]. Therefore, the development of a distribution network live working robot can substitute manual live disconnection/connection of leading wires, and is very significant for improving the working safety and guaranteeing the safety and reliability of power grid.

Many countries in the world have carried out the research of live working robot. In 1980s, Japan had begun the research of live working robot, and successfully developed the first generation of master-slave mode live working robot Phase I, and the prototype of the second generation Phase II in 1993. Research on such technologies have also been carried out in the United States and Canada[5]. The research of live working robot has begun in China since the end of 1990s. In the early 21st century, Shandong Electric Power Research Institute and Shandong University of Science and Technology have successfully developed live working robot[6]. However, these robots have some
problems, such as low degree of autonomy, poor adaptability and so on, making them unable to meet the requirements of live wire disconnection/connection workings of distribution network in China.

2. Analysis on working task and object

The main task of the robot is to carry out live disconnection and connection of leading wires on distribution network wire. The arrangement forms of the lead wire of the involved distribution wire are mainly triangular arrangement, vertical arrangement and horizontal arrangement; and the working space is relatively compact[7][8]. According to the different types of disconnection/connection of leading wire, the live disconnection/connection of leading wire can be divided into the live disconnection/connection of branch leading wire, the live disconnection/connection of tension rod leading wire, etc.[9], as shown in Figure 1. Because different types of working have different working conditions, it is necessary to design a robot operating platform that can adapt to different environments to meet the needs of live working of the robot.

The working objects of the robot mainly include: wire clamp, leading wire, conductive grease and insulating protective cover; the lead wire is coated with conductive grease; the leading wire is connected with the lead wire through the wire clamp; the connecting end between the wire clamp and the lead wire is provided with an insulating protective cover for insulation protection[10][11], therefore, it is necessary to design different working ends to realize the peeling, clamping and wire clamp mounting and other functions for the insulated lead wire[12][13].

![Figure 1. Robot working environment.](image1)

![Figure 2. Structure diagram of The Robot.](image2)

1. Self-leveling mobile insulation platform; 2. Working body of the robot; 3. Control base station; 4. Operation end ((1) Peeling end, (2) Clamping end, (3) Clamp mounting end)

3. General design of robot

The distribution network live working robot is suitable for the distribution wire of 10kV and below. It can be used for the distribution network live disconnection and connection workings without power failure. The main components of the robot are: mobile insulation platform, robot body, master control system, slave control system, insulation protection system, operation end, etc. The structure of the robot is shown in Figure 2.

The chassis of the mobile insulating platform adopts crawler type, with four self-leveling landing legs arranged symmetrically on both sides as the leveling mechanism of the insulation platform. The upper end is connected with the hydraulic lifting arm and the telescopic arm through the 360° rotating platform; the lifting arm and the telescopic arm can be folded in transportation to reduce the occupied space, and can be upward moved to lift the working body of the robot to the nearby of the working
position. The operating body of the robot is connected with the end of the telescopic arm of the mobile insulating platform, and adopts the motor drive mode to accomplish the working tasks through the cooperation of multiple working arms. The main body of the robot is designed with control system and power supply system to realize the operation control and continuous power supply of the robot, and adopts Wi-Fi communication mode to realize the information exchange with the ground operating system.

3.1. Mobile insulation platform

The mobile insulation platform is mainly composed of the lifting arm mechanism, the telescopic arm mechanism, the swing mechanism, the leveling mechanism, the walking device, the supporting leg, the hydraulic system, the electrical control system and the power device, as shown in Figure 3.

![Figure 3. Structure diagram of mobile insulation platform.](image)

1. Base turntable; 2. Chassis; 3. Crawler; 4. Lifting arm; 5. Hydraulic pump of telescopic arm; 6. Telescopic arm; 7. Folding arm mechanism; 8. Telescopic arm; 9. Folding arm mechanism; 10. Engine; 11. Front support leg; 12. Rear supporting leg; 13. manipulator arm

In order to meet the working requirements under different working conditions, the mobile insulation platform adopts crawler walking mechanism, and has four leveling mechanisms with self-leveling legs arranged symmetrically around to ensure capability of walking and stability on the uneven ground or steps. The end of the folding arm is hinged with the head of the telescopic arm, which can rotate relative to the main arm in the vertical plane. The main arm, the turntable and the variable amplitude hydraulic cylinder are hinged in pairs separately. Under the action of the variable amplitude hydraulic cylinder, the main arm can continuously change the elevation angle from 0° to 86° in the vertical plane. The main arm is composed of three sections of arm which are set together. Under the action of a telescopic hydraulic cylinder, the turntable is connected with the frame through a rotary mechanism. The power system is equipped with a low noise diesel engine and an AC motor. With the cooperation of the above devices, the mobile operating platform can meet different operational requirements.

3.2. Robot body

3.2.1. Overall structure of robot body. The body of the robot uses the mobile insulation platform as the carrier, and consists of a control box, an X-axis and Y-axis position and pose adjustment cross sliding table, an annular tool transfer device, a gripping manipulator, an insulated lead wire peeling manipulator and a device wire clamp mounting manipulator, as shown in Figure 4.
Figure 4. Structure diagram of Robot body.

1. Robot control box; 2. Cross transverse sliding table; 3. Griping manipulator; 4. Annular tool transfer device; 5. Cross longitudinal sliding platform; 6. Equipment wire clamp mounting manipulator; 7. Insulated wire peeling manipulator; 8. Focusable vision sensor; 9. Wireless communication device

The control box of the robot moves along the mobile insulation platform through the X and Y axes cross sliding table, which ensures the valid space for the multi-manipulator to work together; the manipulator of the insulated lead wire peeling device has 6 degrees of freedom, and can reach any position within the range of working point and can independently complete the task of peeling the insulation layer; the gripping manipulator mainly completes the working tasks of lead wire cleaning, coating conductive grease, and mounting of insulation protective cover, and can fix the device wire clamp to the terminal actuator of the device wire clamp mounting manipulator; the device clamp mounting manipulator is installed on the lead wire with the equipment clamp. During the working, the gripping manipulator and the insulated lead wire peeling manipulator work together to neaten the leading wire; the insulated lead wire peeling manipulator controls the proper position of the lead wire to prevent the lead wire from touching the adjacent live phase; the gripping manipulator controls the leading wire connection end to insert the leading wire into the device wire clamp; the nut fastening mechanism motion at the working end on the device clamp mounting manipulator realizes the fastening of the bolt.

3.2.2. Working manipulator. In order to increase the working range and flexibility of the robot, a six-degree-of-freedom joint manipulator is used in the working manipulator, as shown in Figure 5. The bottom of the chassis is connected to the box body by flange; arm I has the degree of freedom of rotation, and is connected to the chassis via the cross roller bearing, and can rotate around the center shaft of the chassis; arm II and arm I, arm III and arm II, arm IV and arm III are all connected with pitch joints, and can rotate around the center shaft of the hinge joint and increase the extension length of the manipulator; arm IV and arm III have similar mechanical structure, one end of which can be connected with the upper stage through the hinge joint; the other end of which can rotate around its center shaft, and features flexible movement mode.

3.3. Working end

According to the live disconnection/connection operation flow of the distribution network, in the working process, procedures such as peeling, clamping and installing wire clamp can be carried out on the lead wire, so designing the working end suitable for the robot to carry and convenient for completing the corresponding action is an important condition for ensuring the operating quality and velocity. Since the robot is in a live working environment, it is necessary to consider the convenience of replacing the working end. The working ends of the distribution network live working robot are
mainly clamping end, lead wire peeling end and bolt fastening end, which are respectively nested on the robot arm to realize the replaceability of the working end.

![Figure 5. Six-degree-of-freedom manipulator configuration.](image)

1. Chassis; 2. Arm I; 3. Arm II; 4. Arm III; 5. Arm IV

3.3.1. **Clamping end.** The main tasks of the robot clamping end are to clamp various special tools for leading wire cleaning, conductive grease coating and mounting of insulation protection cover, and to clamp the leading wire connection end and insert it into the wire clamp while disconnecting/connecting the leading wire, as shown in Figure 6. The clamping end is mainly composed of insulated clamping finger, crank slider mechanism, screw nut mechanism and driving motor. The clamping finger is made of insulating material. In operation, the motor is used as the driving element to change the rotating motion into the linear motion of the nut through the screw nut mechanism; the nut is connected with the symmetrically arranged insulating clamping finger through the double-crank slider mechanism, drives the clamping finger to separate or close, so as to realize the gripping function of the clamping end.

![Figure 6. Clamping end configuration.](image)

1. Insulated clamping finger; 2. Crank slider mechanism; 3. Screw nut mechanism; 4. Driving motor

3.3.2. **Peeling end.** In the distribution network system, in consideration of the factors such as pedestrian and traffic safety, more than 80% of overhead wires adopt cross-linked polyethylene insulating lead wires, which, according to different loads, include models such as 90, 120, 150, 240 and so on. Therefore, it is necessary to properly design the clamping device and cutting blade structure size, broaden the scope of application of the peeling end, and improve its practicability.

The structure of peeling end is shown in Figure 7, which consists of upper end peeling device and lower end drive device, which are both driven by motor. The upper end peeling device can rotate around the central axis of the lead wire to cut the lead wire insulation layer, rely on the cutting force to realize the axis feed; the lower end transmission device is connected with the motor output shaft; the rotating motion of the output shaft is transformed into the rotary motion of the peeling device perpendicular to it to enhance the smooth operation of the peeling device.
4. Insulation protection system

Effective insulation protection is the primary condition for the robot to carry out live working[14]. Robot insulated isolation and shielding mainly include the insulated isolation technology for the mechanical parts and the shielding technology for the control part[15][16]. The insulated isolation of mechanical system mainly considers the insulation of mobile platform against ground, the insulation between the robot body and the mobile platform, the entire insulation inside and outside the manipulator, the insulated isolation at the end of the working, and the solid insulated isolation of the robot against the ground, the phase and the adjacent wires, and mainly adopts physical insulated isolation method[17][18]; the control system is designed in Faraday Cage principle to realize the anti-electromagnetic interference of electronic components.

The insulated isolation and shielding measures of the robot mainly include the following 6 aspects:

1. All the working ends are made of metal and insulating materials in a composite manner; the parts carrying high stress are made of metal materials; the parts in contact with charged body are made of insulating materials; this ensures the possession of insulation function, making the wire current not to flow through the inside of the robot;

2. The overall protection of the manipulator arm: the outer part is coated with insulating protective layer; the active part is sealed by the insulating cloth for external insulation; the fixed part is made of nylon material to protect the effective insulation between the robot and the conductive body, and to prevent the short circuit between the phases;

3. The rotating platform of the mobile insulation platform is effectively isolated from the robot body by using insulating materials;

4. The forearm of the mobile insulation platform adopts epoxy resin composite material and is mounted with leakage current detector for insulated isolation against the ground and insulation effect evaluation, so as to ensure the safety of operation.

5. The robot case is made of metal material, packaged and shielded in a complete manner.

6. The wire part adopts soft copper wire sheath for shielding.

5. Control system

The operation conditions of distribution network are very complex, which involve different spaces and heights of different working environments, so it is very difficult to form a unified working environment. The pure intelligent identification control strategy of robot is difficult to satisfy the complex and changeable conditions, so the robot adopts master-slave control mode[19][20], and the operators can use remote control and visual system to put the works of working robot in place. The active-passive remote control working manipulator control system is composed of the active system and the passive system. The master system consists of a master manipulator and its driving device; and the slave system consists of a slave manipulator and its control drive device. The master manipulator and the slave manipulator have a corresponding motion range and the same number of moving joints.
The operator operates the master hand to produce the given value of the position; the slave manipulator follows the movement of the master manipulator to move, thus accomplishing the task of remote control operation.

The general master-slave control strategy of the master-slave control system is as follows:

$$
\tau_m = \left[ K_{mpm} + K_{mpm} \frac{d}{dt} + K_{mpm} \frac{d^2}{dt^2} K_{mf} \right] \left[ X_m \right] f_m - \left[ K_{mps} + K_{mps} \frac{d}{dt} + K_{mps} \frac{d^2}{dt^2} K_{fs} \right] \left[ X_s \right] f_s \tag{1}
$$

$$
\tau_m = \left[ K_{xpm} + K_{xpm} \frac{d}{dt} + K_{xpm} \frac{d^2}{dt^2} K_{xs} \right] \left[ X_m \right] f_m - \left[ K_{xps} + K_{xps} \frac{d}{dt} + K_{xps} \frac{d^2}{dt^2} K_{fs} \right] \left[ X_s \right] f_s \tag{2}
$$

Where, $K_{mpm}$, $K'_{mpm}$, $K''_{mpm}$ and $K_{mf}$ is the position, velocity, acceleration and force feedback gain matrix of the master manipulator determined by the master manipulator controller; $K_{mps}$, $K'_{mps}$, $K''_{mps}$ and $K_{fs}$ is the position, velocity, acceleration and force feedback gain matrix of the slave manipulator determined by the master manipulator controller. The driving force $\tau_m$ of the master manipulator is determined by Formula 1.

$K_{xpm}$, $K'_{xpm}$, $K''_{xpm}$ and $K_{xs}$ is the position, velocity, acceleration and force feedback gain matrix of the master manipulator determined by the slave manipulator controller; $K_{xps}$, $K'_{xps}$, $K''_{xps}$ and $K_{fs}$ is the position, velocity, acceleration and force feedback gain matrix of the slave manipulator determined by the slave manipulator controller. The driving force $\tau_s$ of the master manipulator is determined by Formula 2.

![Master-slave control system schematic.](image)

Because of the good real-time performance and the ability of perceiving the motion state information of the manipulator used by the live working robot, the specific information such as position, velocity, acceleration and force feedback can be obtained in real time Formula 1 and Formula...
2. Thus, the actuator can be driven to achieve real-time accurate control. According to the motion control requirements of the manipulator, the overall control system is designed, as shown in Figure 9. The control system uses the ARM microprocessor as signal processing terminal, and the displacement sensor and force sensor as the intermediary for signal measurement and closed-loop feedback. The main function modules include: master controller, slave controller, manipulator position detection, communication and power supply, driving signal conversion.

6. Conclusion
According to the needs of distribution network live working, a kind of distribution network live working robot is designed. The robot is composed of crawler mobile insulation platform and robot body; the robot body has 3 kinds of working manipulator, which respectively carry the clamping end, the lead wire peeling end, and the wire clamp mounting end, and accomplish the distribution network live working tasks through the cooperation of the multi-working manipulators, so as to substitute the manual completion of the distribution network live working, which greatly improve the safety performance of operators, and have a positive impact on the mode of distribution network live working of China.

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