Development of Live Working Robot for Replacing Insulators on Power Transmission Lines

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Abstract: The paper presented the independently developed live working robot for replacing insulators on 110-220kV power transmission lines. By control system and simulating the manual equipotential live working process of replacing insulators, the robot is designed to be composed of a non-obstacle-surmounting platform, a control platform and a ground base station, among which the non-obstacle-surmounting platform mainly consists of the robot body, two robot arms, two robot hands, and two end-effectors, the control platform consists of a motion control system, a communication system, an image capture system and a power management system, and the ground base station consists of an industrial PC equipped with a wireless network interface card and a 3G network interface card. Moreover, the robot is designed to be protected against electromagnetic interference. The robot presented in this paper is the first of its kind in China.

1. Introduction
Live working is an important means for inspecting, overhauling and upgrading power grid equipment [1]. It contributes a lot to improve power supply reliability, reduce power outage loss and ensure safe and stable operation of the power grid [2]. Traditional live working is performed manually, which may impose great risks and easily cause personal injury and fatal accidents due to a high-altitude working environment with strong magnetic fields. Especially for double-circuit and multiple-circuit transmission lines on the same tower, because of denser wire arrangement and smaller phase spacing, the electrician’s activity space is greatly confined, thus bringing more inconvenience in work; in addition, UHV AC/DC power grids rapidly developed in recent years resulting in a higher field intensity on the body surface of the electrician carrying out live working, and a greater pulse current at the time of potential shift [3], which creates more challenges to live working. Robots replacing electricians in live working can increase the work safety and efficiency, which is an inexorable trend of economic and social development [4]. Therefore, the robot developed, designed and manufactured...
in this paper to replace widely used suspension insulator strings on 110–220kV power transmission lines according to the manual working procedures is of great significance.

In fact, the development of live working robots has a history of more than 30 years, originated from Japan, America, Canada and other countries [5]. So far, the R&D of live working robot in Japan has stepped into the third generation [6]. In recent years, as the requirement for power grid stability is more stringent, live working robots are also rapidly developed in China, and Chinese scientific and technical engineers have conducted research on the master-salve robot control system [7], the design and optimization of robot arms [8], the intelligent robot control system [9] and so on. Against this background, the present research simulated the working procedures to replace suspension insulator strings, and successfully developed the live working robot for replacing suspension insulator strings on power transmission lines. The robot has passed the field test on real power transmission lines.

2. Working object and design ideas

2.1 Analysis of working object
A porcelain insulator, as shown in Fig. 1, consists of a porcelain disc, a steel socket cap and a steel ball pin. Two insulators are connected by side-inserting the steel ball pin of the upper insulator into the cap socket of the lower insulator, and locked with a W-shaped or R-shaped push-pull type spring lock pin. In the case shown below, a W-shaped lock pin is adopted. The physical dimensions and model of an insulator are dependent on the weight of wires and hardware used on the actual transmission line. Meanwhile, Fig. 1 also shows the working object of the live working robot, i.e. the connecting structure of single suspension insulator string on a single-split line. The upper end of the suspension insulator string is suspended on the transmission tower cross arm through a ball eye, while the lower end is connected with the socket clevis using a W-shaped lock pin. The robot mainly works on the W-shaped lock pin.

![Fig. 1. Structures of porcelain insulator (a) and single suspension insulator string on a single-split line (b)](image)

1. Steel ball pin; 2. Steel socket cap; 3. Porcelain disc; 4. Insulator; 5. W-shaped lock pin; 6. Socket clevis; 7. Wire; 8. Suspension clamp.

2.2 Work planning and design ideas
The robot is designed to replace the electrician carrying out equipotential working on the transmission line to remove and install the insulator connected with the socket clevis, and then cooperate with the
electrician on the transmission tower cross arm so as to realize semi-automatic insulator string replacement. Therefore, the robot needs to simulate the operation of the electrician carrying out equipotential working on the transmission line. In combination with the actual working process, the work plan of the robot to replace insulator strings with human assistance is made as shown in Fig. 2.

3. Overall design of the robot
The robot system consists of a mobile non-obstacle-surmounting platform and a control platform, wherein the mobile non-obstacle-surmounting platform is composed of the robot body, robot arms, the traveling wheel mechanism, robot hands, clamping jaws, equipotential wheels and end-effectors, and the control platform is composed of a motion control system, a communication system, an image capture system and a power management system. The ground base station consists of an industrial PC equipped with a wireless network interface card and a 3G network interface card, which realizes wireless remote control of the robot body through the wireless local area network or the 3G network. The robot system is connected with the ground base station via the communication system (Fig. 3).

3.1 Main body of live working robot for replacing insulators
3.1.1 Mobile working platform
The mobile working platform of the robot, namely the non-obstacle-surmounting platform, is as shown in Fig. 4. Two robot arms are asymmetrically arranged at a certain distance respectively on the two sides of the robot body. The traveling wheel mechanism is connected with the robot arms, which travels along the transmission line. A clamping jaw is arranged inside each traveling wheel to clamp and protect the line. In order to meet the equipotential working requirement of the robot, an equipotential wheel is installed beside the clamping jaw. The system also includes two robot hands 1 and 2, respectively of 3-DOF and 4-DOF configuration arranged on the two sides of the robot body. The robot hand has a rotary joint, a telescopic joint and a longitudinal moving joint, which respectively realize rotation of the robot hand in a vertical plane, vertical movement of the end-effector and adjustment of the position of the end-effector's central plane relative to those of the socket clevis and the insulator string. The robot hand 1 is fixed onto the robot body, while the robot hand 2 has an additional transverse moving joint to realize transverse movement of the robot hand 2 along the robot body. All joints work in a collaborative manner to drive the end-effector to or away from the working plane.

![Fig. 4. Mobile working platform of live working robot: front view (a), side view (b)](image)

1. Traveling wheel; 2. Clamp; 3. Rotary joint of robot hand 1; 4. Equipotential wheel; 5. Telescopic joint of robot hand 2; 6. Grading ring; 7. Transverse moving joint of robot hand 2; 8. Longitudinal moving joint of robot hand 2; 9. Longitudinal moving joint of robot hand 1; 10. Rotary joint of robot hand 2; 11. Rotary joint of robot hand 2.

### 3.1.2 End-effector of live working robot

The end-effector of live working robot for replacing insulators is composed of a W-shaped lock pin pushing mechanism and an insulator string pushing mechanism (see Fig. 5). The socket clevis clamping jaw of the W-shaped lock pin pushing mechanism clamps the socket clevis along with the
movement of the socket clevis clamping slide, while the W-shaped lock pin push-out and push-in blocks on the socket clevis clamping slide respectively push the W-shaped lock pin out of and into the socket clevis. The clamping of the socket clevis and the pushing of the W-shaped lock pin are monitored by three cameras in an all-around manner, with the camera #1 installed on the socket clevis clamping base to observe the clamping condition of the socket clevis clamping jaw, and cameras #2 & #3 installed respectively on the outer sides of the socket clevis clamping slide, which respectively coincide with the center lines of the W-shaped lock pin push-out and push-in blocks to observe the push-out and push-in conditions of the W-shaped lock pin. The clamping jaw of the insulator string pushing mechanism is opened or closed through the four-link mechanism to release or clamp the insulator. The clamping and pushing conditions are observed by the camera #4 installed on the central axis of the insulator clamping base.

Fig. 5. End-effectors of live working robot: (a) W-shaped lock pin end-effector, (b) Clamping jaw end-effector

1. Camera 1; 2. Camera 2; 3. Camera 3; 4. W-shaped lock pin pushing-out block; 5. W-shaped lock pin pushing-in block; 6. Socket clevis clamping jaw; 7. Camera 4; 8. Insulator clamping jaw.

### 3.2 Control system of live working robot

#### 3.2.1 Motion control system

The robot is composed of the mobile robot body and the end-effectors (W-shaped lock pin pushing mechanism and insulator string pushing mechanism). Based on the motion decomposition of the working process, the robot needs 15 motors in total: 11 ones for robot arm motions, and the remaining 4 ones respectively for socket clevis clamping, W-shaped lock pin pushing-in and pushing-out, and insulator clamping. The 15 motors are driven by 6 Elmo motor drivers: 2 ones for driving the two traveling wheels respectively, and the remaining 4 ones for driving the other 13 motors. DC motors are adopted for the robot, with an output speed deviation of $\Delta \omega$. If the excitation voltage increment is selected as the input, then the motor transfer function is:
\[
\frac{\Delta \omega(s)}{\Delta u_{sd}(s)} = \frac{k_{id}(1+T_q) - \frac{\alpha_d}{r_{sd}^{*}u_{sd}}}{(T_d s + 1)(T_m^{*} s + T_m s + 1)}
\]  

Where, \(T_q\) is the time constant of the motor rotor winding; \(T_m\) is the electromechanical time constant of the motor; \(T_d\) is the time constant of the motor stator winding; and \(k_{id}\) is the amplification coefficient of the rotor voltage to the excitation voltage when the motor is in a steady state.

During the work, all motors operate in a collaborative manner. In order to keep good slip control of traveling wheels, the traveling wheels are required to have a good speed and position control capability. The control system is required to accurately control the position, speed and force of motors.

The motion control system includes an industrial PC which comprises an I/O expansion card, an AD/DA expansion card, a serial port expansion card, an interface board, etc., as shown in Fig. 6. The industrial PC collects information via the expansion cards and then controls motor motion according to the information processing results. The interface board collects and re-distributes the information from the expansion cards by collecting the information detected by robot sensors via electrical connections with the strong current commutation circuit, the signal switching circuit and the digital and analog interface circuits to realize switching control of motors.

3.2.2 Communication system

The live working robot communicates with the ground base station via a wireless local area network or Wi-Fi. The communication distance is controlled within 1 km so that the robot body can transmit video or image information in real time to the ground base station and the ground base station can transmit motion commands to the robot body. Since the proposed robot is an inter-section non-obstacle-surmounting robot, wireless Wi-Fi communication can meet the design requirement of the system. The configuration of the complete communication system of the live working robot is as shown in Fig. 7, in which the industrial PC, the video server and the ARM chip are connected with the wireless router via the network, and the wireless router establishes Wi-Fi communication with the ground base station equipped with a wireless network interface card so as to realize real-time communication between the robot body and the ground base station.

3.2.3 Image capture system
The live working robot is equipped with 4 micro-cameras and a video server used for acquiring video and image information of the working environment and transmitting such information to the ground base station through Ethernet. Meanwhile, the cameras receive control signals sent by the ground base station through Ethernet interfaces. The video and image capture system is as shown in Fig. 8, of which the interface board is used for distribution of image signals and interfaces.

![Diagram of communication system](image1)

Fig. 7. Configuration of communication system

The live working robot is powered by a single power supply. The power monitoring and management system takes an STM32F103VB ARM chip as the control core, which is mainly used for monitoring the supply voltage and current variation during working of the robot, evaluating the remaining capacity, giving robot voltage feedback to the ground base station, and managing the energy of the devices arranged on the robot. The power supply is controlled via an electronic switching circuit which is controlled by the single-chip industrial PC to realize control, power-on and reset of the robot power supply system. Since the robot operates on high-voltage transmission lines, the robot battery voltage is very important for the robot operator. In order to ensure the safety of the robot and transmission lines, the power management system includes a battery voltage monitoring system. The configuration of the power management system is as shown in Fig. 9.

![Diagram of image capture system](image2)

Fig. 8. Configuration of image capture system

### 3.2.4 Image capture system

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3.3 Ground base station

The ground base station should be able to control the robot in real time, facilitate manual control of the robot through the HMI, and give on-line feedback about some important status information of the robot so as to enable the user to know the operating condition of the robot in real time and effectively ensure smooth replacement of suspension insulator strings by the living working robot. The configuration of the ground base station and its connection with the robot body are as shown in Fig. 10.

4. Protection against electromagnetic interference

Since the live working robot operates in a high-voltage live environment, in order to prevent the electromagnetic fields around the transmission lines from interfering with the robot hardware system, the strong current ground and the weak current ground in the robot are isolated and connected via a magnet so as to effectively reduce interference between strong and weak current signals, and meanwhile both the strong and the weak current grounds are connected with the robot body via magnets [10]; in addition, the transmission cables of motors and sensors are wrapped with shielded tapes which are connected with the robot body to establish connection between the transmission cable surfaces and the robot body. In order to reduce point discharge of the robot in strong electromagnetic fields, the sharp points of the robot are chamfered during mechanical processing, and both ends of the
robot control box is equipped with a grading ring to reduce the impact of point discharge of the robot control box edges on the robot hardware control system. Equipotential wheels are installed at the front ends of the traveling wheels to keep good contact between the robot body and the transmission lines and minimize the potential difference so that external current cannot intrude into the robot system and interference of strong electromagnetic fields with the robot hardware control system can be significantly reduced.

5. Field on-line test
The field test was carried out on Phase A (right), #006 Tower, 220kV Wangpei I line in the State Grid Hunan Live Working Center, with the tower type being ZB1-24, the line type being LGJ-400/50, the insulator type being XP-7, and the number of insulators being 13. The power transmission line for the test of single suspension insulator string replacement with the live working robot is as shown in Fig. 11.

The robot was hung on the 220kV high-voltage transmission lines by a crane, which was controlled via the control panel at the ground base station. The test was designed to examine the robot’s capability of replacing insulators in a live working condition and provide a basis for the control algorithm of the live working robot. With human assistance, the robot successfully removed and installed insulators on live transmission lines according to the work flow as designed in Fig. 2. During the replacement process, all robot joint motors operated normally; the clamping of socket clevis and insulator, and the pushing-in and pushing-out of W-shaped lock pin and ball pin met the requirements; the robot responded accurately in real time to the control commands from the ground base station; and the ground base station received the feedback information from the robot accurately in real time. It took about 35 minutes for the robot to complete one insulator replacement task. The working scene of the live working robot for replacing insulators is as shown in Fig. 12.

![Fig.11. Transmission line for the test of insulator string replacement with the live working robot](image-url)
6. Conclusion

The live working robot for replacing insulators successfully passed the power-frequency voltage-withstand test, the simulated on-line work test and the field on-line live working test, indicating that the robot can realize live replacement of suspension insulator strings through collaboration among the non-obstacle-surmounting platform, the control platform and the ground base station, and fully meet the requirement for electromagnetic interference immunity during live working on 110–220kV transmission lines. The robot lays a foundation for the R&D of live working robots operating on EHV and UHV transmission lines.

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