Development of Live-working Robot for Power Transmission Lines

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Abstract. Dream-I, the first reconfigurable live-working robot for power transmission lines successfully developed in China, has the functions of autonomous walking on lines and accurately positioning. This paper firstly described operation task and object of the robot; then designed a general platform, an insulator replacement end and a drainage plate bolt fastening end of the robot, presented a control system of the robot, and performed simulation analysis on operation plan of the robot; and finally completed electrical field withstand voltage tests in a high voltage hall as well as online test and trial on actual lines. Experimental results show that by replacing ends of manipulators, the robot can fulfill operation tasks of live replacement of suspension insulators and live drainage plate bolt fastening.

1. Introduction

Live working refers to a working method of overhauling and testing on high voltage electrical equipment [1] without power outage. Live working is an effective measure to avoid repair with power off so as to guarantee normal power supply. At present, the live working manner for power transmission lines in China is still manual live working, and operator work in an adverse environment with high altitude and high voltage. Thus, developing a live-working robot suitable for power transmission lines is of great significance.

Since 1980s, many countries have done researches on automated mechanical devices successively, such as Japan, Spain, the USA and France [2] in order improve automation level and safety of live working and reduce labor intensity of operators and physical threats of strong electrical field to operators. However, live-working automated mechanical devices at home and abroad are developed focusing on maintenance of distribution network lines, and matching with an aerial life device with an insulating boom to carry an intelligent automatic tool to carry out line breakage and connection and replacement of insulators and lightning arresters. Kyushu Electric Power Company successfully developed Phase-I, Phase-II and Phase-III robots [3-5] in 1990, 1996 and 2001 respectively, among which the intelligence level gradually rises. Robot Robtet [6-7] is successfully developed in Spain in 1998, which is at the same level with Phase-II. China’s Shandong Electric Power Research Institute developed a robot for distribution network lines in 2003 [8-9]. The above robots are all based on the technology of aerial life device with an insulating boom with an working arm mounted at the tail end of the aerial life device with an insulating boom, and can only applied to the distribution field with low line construction height.
Although power transmission lines are deemed as “arteries” of power transmission, few researches on live-working robots for 110kV and above high voltage transmission lines have been done at home and abroad. Representatives are Hydro-Quebec Research Institute of Canada, and Wuhan University and Shandong Electric Power Research Institute [10] of China.

China is vast in territory, its energy distribution does not match with economic development, and power transmission in China has formed a pattern of west-east power transmission and north-to-south power transmission. With implementation of UHV grid construction strategy of State Grid, the coverage area of transmission lines will be more wide and live-working operations for power transmission lines will increase sharply, therefore study on live-working robots for transmission lines, which can replace operators to carry out dangerous live working, is in urgent need.

2. Working operation and object
Live replacement of suspension insulators and drainage plate bolt fastening are the most routine live-working items of 110-220kV transmission lines, and for the transmission lines, insulators (as shown in figure 1) are mainly used for supporting lines and keeping enough distance between the lines and the ground. During manual replacement, an operator needs to replace insulators with a wire grip to tension lines at first, and then loosen the wire grip until new insulators are mounted. The difficulty of this replacement process lies in pushing out W pins in the old insulators. The working space is small, thus the safe ground potential working manner can not be used, and the replacement process can be only carried out in a manner that the operators wear shielding clothes to enter an equipotential condition for operation. To liberate the operators from dangerous high electrical field, robots are used to enter an equipotential condition to replace operators to push W pins in old insulators out, and then push the W pins in after new insulators are installed. The robot can fully replace electricians, and then coordinate with a ground potential electrician to realize ground potential live replacement of suspension insulators.

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In the past, drainage plate (as shown in figure 2) bolt fastening was carried out only in a manner than an electrician wearing shielding clothes enters the high electrical field to conduct equipotential working. Now, robots can be used to replace equipotential electrician to perform drainage plate bolt fastening working in an automatic mode.

3. Mechanical structure part
The Dream-I live-working robot for power transmission lines is shown in figure 11. The prototype main consists of a robot general platform, an insulator replacement end, a bolt fastening end, a control system, an image system and a control base station, wherein the general platform is combined with the insulator replacement end to complete insulator replacement, and the general platform is combined with bolt fastening end to realize bolt fastening. An operator performs information interaction with the robot body through a wireless network on the ground base station, and controls the robot to carry out live working remotely.

3.1. Robot general platform
The general platform includes two moving manipulators, two operation manipulators and a control body, wherein the two moving manipulators are used for connecting the body with lines, the end of each moving manipulator is of a wheel and jaw composite structure, the robot moves relative to lines
through wheels, and two clamping jaws of each moving manipulator are used for clamping lines and fix the position of the robot relative to the lines so that ends of the two operation manipulators of the robot can be positioned relative to the working object.

Figure 3. Robot general platform structure sketch map.

The two operation manipulators match with each other to enable operating ends to reach designated position. The operation manipulator 1 has three degrees of freedom, which is illustrated by an xyz coordination system established at the lower right corner of Fig. 2, wherein the x axis is parallel to lines, with the moving manipulator 2 pointing to manipulator 1; the y axis is parallel to the ground and perpendicular to the lines to extend outwards; and the z axis is perpendicular to the ground, pointing into the sky. Suppose the position that the end needs to arrive at is (x,y,z), the x-axis coordination of the operation arm 1 is provided by traveling wheels at the end of the moving manipulators, the y coordination is provided by a longitudinal moving joint of manipulator 1 in Fig2, and z coordination is provided by the telescopic joint of manipulator 1. In order to deal with the problem that lines may be not totally perpendicular to insulators, a rotary joint capable of rotating around y axis is added to manipulator 1 correspondingly. Joints of manipulator 2 are similar to those of manipulator 1. The x axis can not adopt the traveling wheel mechanism, thus a traversing joint is additionally designed for manipulator 2.

3.2. Insulator replacing end
In order to replace insulators, the end of manipulator 1, as shown in figure 4(a) is used for clamping a socket clevis and pushing W pins out or in, and it is provided with three joints. The end of manipulator 2, as shown in figure 4(b) is used for clamping porcelain insulators, and is equipped with only one joint. Porcelain insulators are driven by the traversing joint of manipulator 2 to separate from or connect with the socket clevis.

Figure 4. Insulator replacement end.

3.3. Bolt fastening end
Regarding the bolt fastening working, end devices are a nutting device and a bolt fixing device respectively, wherein the nutting device is, as shown in figure 5(a), is used for fixing nuts through a revolute, a rotary shaft is connected with a sleeve in a cross hinge mode to adapt to the drainage plate
with different inclination angles, further to sleeve the nut and fasten the bolt. The bolt fixing device, as shown in figure 5(b), reaches the head of the bolt with motion of manipulator 1, the sleeve shaft of the bolt fixing device is divided into two sections which are connected with each other in a cross hinge mode so that the bolt head can be fastened by the sleeve shaft, and further the bolt head can be locked.

Figure 5. Drain bolt fastening end.

4. Electrical control part
The control object of the electrical part of the live-working robot comprises motors, sensors and cameras. The robot general platform includes 11 motors in total, the insulator replacing end consists of 4 motors, and the bolt fastening end includes 2 motors, as shown in table 1.

| No. | Motor name                                         | Remarks                                      |
|-----|----------------------------------------------------|----------------------------------------------|
| 1   | Traveling wheel motor of manipulator 1             | General platform motor                       |
| 2   | Traveling wheel motor of manipulator 2             |                                              |
| 3   | Clamping motor of manipulator 1                    |                                              |
| 4   | Clamping motor of manipulator 2                    |                                              |
| 5   | Rotary joint motor of manipulator 1                |                                              |
| 6   | Rotary joint motor of manipulator 2                |                                              |
| 7   | Telescopic joint motor of manipulator 1            |                                              |
| 8   | Telescopic joint motor of manipulator 2            |                                              |
| 9   | Longitudinal moving motor of manipulator 1         |                                              |
| 10  | Longitudinal moving motor of manipulator 2         |                                              |
| 11  | Traversing motor of manipulator 2                  |                                              |
| 12  | Socket clevis clamping motor                       | Special motor for insulator loading and unloading |
| 13  | W pin push-out operation motor                      |                                              |
| 14  | W pin push-in operation motor                       |                                              |
| 15  | Insulator clamping motor                           |                                              |
| 16  | Bolt clamping motor                                | Special motor for strain clamp bolt fastening |
| 17  | Nutting motor                                      |                                              |

4.1. Camera system
4 micro-cameras and a video server arranged on the live-working robot are used for acquiring video and image information of working environments and transmitting them to the ground base station through Ethernet. Meanwhile, the cameras receive control signals sent by the ground base station through Ethernet interfaces.

4.2. Sensor system
The live-working robot need to monitor various sensors in real time. Sensors of the robot are divided into two types, one type is internal sensors, such as tilt sensor, photoelectrical limit sensor, Hall location counting sensor, power source monitoring sensor and temperature and humidity monitoring sensor, and the other is external sensors mainly including 4 micro-cameras, wherein the micro-cameras acquire image and video information through the video server, and sensors of the other type acquire sensor data through AD conversion circuits and digital interface circuits.

4.3. Power monitoring system
The live-working robot is powered by a single power source. The power source monitoring management system adopts an STM32F103VB ARM chip as the control core, is mainly used for monitoring voltage of power source and current variation during working of the robot, evaluating remaining capacity, and at the meantime managing energy of devices arranged on the robot.

4.4. Wireless communication system
The live-working robot is in wireless communication with the ground base station with a communication range within 1km, the robot body can transmit video or image information to the ground base station in real time. The proposed robot is a inter-section non-obstacle-surmounting robot, and wireless wifi communication can meet design requirement of the system.

4.5. Overall schematic design of electrical control system of robot
To realize above functions, the control system of the robot adopts the implementation scheme shown in figure 6. The control system consists of a motion control system, an image and video acquiring system, a power source control system and a communication system. The core of the motion control system is a PC104 industrial personal computer which acquires motion status of the mechanism arms through information of the limit sensor and the inclination angle sensor, and then controls action of each joint motor, including 17 motors and 6 elmo motor drivers, among which each of the two traveling wheels is independently driven by one driver respectively, the other 15 motors share 4 drivers, and control is realized by close loop transform. The image and video acquiring system mainly includes 4 channel micro-cameras and video servers arranged on the robot body, which acquire videos and images of the working site and send them to the ground base station through the Ethernet so that users can make corresponding control decisions when controlling the robot. The power source management system is mainly used for effectively managing power source distribution of the robot in a unified mode so as to ensure power supply controllability and reset operation. The power source control model utilizes ARM chips are the main controller, and the ARM chips are also responsible for acquiring information of voltage detection, main circuit current detection, the inclination angle sensor and the temperature and humidity sensor. The communication system is mainly used for intercommunication between each electrical system part and the ground base station. Cable communication is used inside the robot while wireless local network communication is applied outside the robot.
5. Operation plan and simulation of robot

5.1. Live suspension insulator replacement with robot

The robot is adaptive to line environment of 110-220kV single-bundle single-string suspension insulator lines. As required working of robot, a wire tightener, an insulator string hoisting pulley and a robot hoisting pulley should be installed on transmission lines before the robot is applied to the lines. A virtual line environment is shown in figure 7. The operation plan of live suspension insulator string replacement with the robot is described as follows.

Figure 6. Control system block diagram.

Figure 7. Insulator replacement robot operation preparatory environment.

Figure 8. Robot replacement for insulator operation plan.

1) Collision detection suspension clamp of the robot
Carrying out rough positioning on collision detection suspension clamp of the front wheels of the robot.

2) W pin pushing device positions and grips the socket clevis
Enabling the traveling wheels to move backwards, observing pose of the socket clevis clamping jaws of the W pin pushing device relative to the socket clevis through camera 1 and 2, performing fine adjustment on joints of the manipulator 1 so that the socket clevis is positioned in the middle of the clamping jaws, and then enabling the clamping jaws to move oppositely to clamp the socket clevis, as shown in figure 8(a).

3) The insulator string pushing device protects insulator caps
Carrying out fine adjustment on two joint motors of the manipulator 2, observing pose of jaws of the insulator string pushing device relative to caps through camera 4, driving the insulator string pushing device to the position of caps of the insulator string, adjusting flare angle of the jaws to enable the insulator string pushing device to protect insulator caps, as shown in figure 8(b).

4) Pushing W pins out
The W pin push-out block of the W pin pushing device pushes W pins from the opening of the socket clevis to a bayonet and then returns, as shown in figure 8(c) and (d).

5) The wire tensioner tensions lines.

6) Pushing insulator string out
The traversing joint of manipulator 2 moves backwards, driving the insulator string pushing device to move the insulator string ball out of the opening of the socket clevis.

7) The wire tensioner loosens lines
The wire tensioner loosens lines to enable the insulator ball to rise above the socket clevis.

8) Insulator string replacement
Releasing jaws of the insulator string pushing device, enabling manipulator 2 to move to a non-working position, lifting a new insulator string through the insulator string hoisting pulley, and connecting the last insulator with the cross beam of a tower by working staff.

9) The insulator string pushing device positions and protects caps
Enabling manipulator 2 to move to the working position again, observing pose of the insulator string pushing device relative to the insulator, carrying fine adjustment on the insulator string pushing device to reposition and protect the cap of the insulator through camera 4, and enabling the robot to return to the status specified in figure 8(e) relative to the insulator string.

10) The wire tensioners tensions lines

11) Pushing the insulator string in
The traversing joint of manipulator 2 moves forwards to drive the insulator string pushing device to move the insulator string ball into the opening of the socket clevis.

12) The wire tensioner releases lines
The wire tensioner releases the lines so that the insulator string ball is positioned on the top of a groove of the socket clevis.

13) Pushing the W pins in
The W pin push-in block of the W pin pushing device pushes the W pins from the bayonet to the opening of the socket clevis, as shown in figure 8(f).

5.2. Working simulation of bolt fastening of robot
The robot runs to the drainage plate, the original bolting position according to images observed by the cameras, as shown in figure 9(a), the operation plan is described as follows.
Figure 9. Robot fastening bolt operation plan.

1) The bolt fixing device fixes the bolt head

Enabling the rotary joint of manipulator 1 to rotate forwards, observing images of the cameras, carrying out fine adjustment on the rotary joint and the telescopic joint of manipulator 1 to enable the hexagonal socket of the bolt fixing device to coaxial with the bolt head, and then enabling the longitudinal moving joint of manipulator 1 to approach the bolt head until holding the bolt head down so as to limit rotation of the bolt head, as shown in figure 9 (b).

2) The nutting device tightens the nut

Enabling the rotary joint of manipulator 2 to rotate forwards, observing images of the cameras, carrying out fine adjustment on the traversing joint and the telescopic joint of manipulator 1 to enable the hexagonal socket of the bolt fixing device to coaxial with the bolt head, placing the longitudinal moving joint to manipulator 2 close to the nut until sully sleeving it, enabling the motor of the nutting device to rotate to tighten the nut, as shown in figure 9 (c).

3) End return

The nutting device and the bolt fixing device are carried to the external limit position through manipulator 1 and manipulator 2 respectively, as shown in figure 9 (d).

6. Tests and conclusion

6.1. Withstand voltage test

In order to test the voltage endurance capability of the robot and obtain the working voltage grade of the robot, power-frequency voltage-withstand tests were carried out on the robot in the High Voltage and Insulation Laboratory of Wuhan University, as shown in figure 10, and the testing equipment is YDJC-2000KVA/1000KV power frequency testing transformer/ultraviolet imager. Test results are recorded in table 2.
According to the test results, under high voltage of 220-330kV, each index of the robot is normal, the robot can accurately receive and respond to control signals sent by the ground base station in real time, the ground base station can accurately receive the status feedback information of the robot in real time, the four cameras operate normally, and transferred video and image information is clearly and smoothly.

Table 2. Test case of robot high voltage hall.

| Voltage grade | Insulator replacing device | Bolt fastening device |
|---------------|---------------------------|----------------------|
| 220kV        | 330kV                     | 220kV                |
| 330kV        |                           | 330kV                |
| Test time    | 7:10-7:40                 | 7:40-8:10            |
|              | 8:10-8:40                 | 8:40-9:10            |

| Robot responds to base station instructions | Normal | Normal | Normal | Normal |
| Ground base station receives feedback information of robot | Normal | Normal | Normal | Normal |
| Working condition of camera | Normal | Normal | Normal | Normal |

6.2. In-site experiments

Table 3. Robot performance parameters.

| Item                        | Parameter                                      |
|-----------------------------|------------------------------------------------|
| Applicable line             | 110kV/220kV single-wire transmission lines     |
| Conductor type              | LGJ240~LGJ400                                  |
| Power frequency withstand voltage | No less than 330kV                          |
| Insulator type              | XP—7                                          |
| Maximum push-out/push-in force of W pins | 1609N                                      |
| Maximum clamping force of socket clevis | 1072N                                     |
| Maximum clamping force of caps | 300N                                       |
| Push-pull force of insulator (string)ball | 1015.6N                                    |
| Maximum torque for bolt fastening | 120Nm                                    |
| Power supply for robot body | Power by lithium battery, capacity 36V40Ah   |
| Power supply for base station | Power by lithium battery, capacity 36V40Ah   |
| Operation mode              | Image and video based human-machine interaction operation of ground base station |
| Communication mode          | Wireless Ethernet                             |
| Communication distance      | Approx. 2km                                   |
| Image resolution            | 628 x 582                                     |
| Robot weight                | Approx. 52kg                                   |
| Overall dimensions of robot body | L*W*H:1000*350*650mm                        |

By means of withstand voltage tests and simulated line experiments, key performances of the robot are obtained, as shown in Table 3. Finally, live test of the robot is carried out on actual operating transmission lines.
Experiments of single suspension insulator string replacement with the robot were carried out on Phase A (right), #006 Tower, 220kV Wangpei line in State Grid Hunan Live Working Center. Tower type ZB1-24, line type LGJ-400/50, insulator type XP-7, and number of insulators 13. Experiment of single suspension insulator string replacement with the robot is shown in figure 11(a).

Experiments of live strain clamp drainage plate bolt fastening with the robot were carried out on Phase A (right), #003 Tower, 220kV Wangpei line in State Grid Hunan Live Working Center. Tower type is SDN31-18 and line type is LGB20A-95/55. Experiment of live strain clamp drainage plate bolt fastening with the robot is shown in figure 11(b).

According to above experiments, conclusions are drawn as follows.

(1) The robot can realize live working of insulator replacement. The function of insulator replacement can be achieved through human-machine interactive rough positioning, accurate positioning of socket clevis, W pin push-in/push-out, cap clamping, ball push-in/push-out and other operations in working process. In the working process, the two manipulators and their ends do not interfere with each other in respective working space, and the key action positioning can meet requirement.

(2) The robot can achieve live working of strain clamp bolt fastening and unscrewing. The function of live working of strain clamp bolt fastening and unscrewing can be realized through human-machine interactive operation, using the bolt fixing device to accurately position the bolt head, using the bolt fastening device to align to and accurately position the nut, and other control operations in the working process. In the working process, the two manipulators and their ends do not interfere with each other in respective working space, the key action positioning can meet requirement, and the nut and bolt head can be connected to and separated from the end operating mechanism steadily.

(3) The end tool of the robot can be replaced. The end tool of the robot adopts the design of combination of dovetail grooves with pins, the dovetail grooves are connected with the longitudinal moving mechanism of manipulator 1 and manipulator 2, and the pins are used for preventing displacement thereof. Each of the ends can be connected with robot body through a pluggable connector so as to maintain line connection during end replacement. The ends with the mechanical structure and line connectors can be replaced quickly when operations change, and have sufficient stability and reliability, realizing the function of end tool replacement.

References
[1] Zhao Y, Tsotras P 2013 Analysis of energy-optimal aircraft landing operation trajectories. Journal of Guidance, Control, and Dynamics 36 833
[2] Zhu Xinglong, Zhou Jiping and Wang Hongguang 2009 Transmission line inspection and test of robot mechanism. Journal of Mechanical Engineering 02 119
[3] Lu Shou Yin, Fu Mengchao and Li Bingqiang 2005 DWR-I teleoperation live working robot. Journal of Shanghai Jiao Tong University 06 910
[4] Lu Shou Yin, Ma Peisun and Qi Hui 2003 Development of live working robot. Automation of Electric Power System 17 56

[5] Zhang F, Liu G and Fang L 2012 Estimation of battery state of charge with H observer: Applied to a robot for inspecting power transmission lines. IEEE Transactions on Industrial Electronics 59 1086

[6] Wu Hua, Meng Lingzhi and Liu Changan 2013 Anti sway control of cable tunnel inspection robot for hybrid dynamical systems. Journal of Huazhong University of Science and Technology (Natural Science Edition) s1 440

[7] Wen Xuefeng, Dian Songyi 2013 Study on Mechanism of double arm type climbing robot for overhead lines. Mechanical Design and Manufacturing 07 168

[8] Song Bo, Xiao Shide and Hua Shirong 2007 Automatic inspection robot attitude adjustment method research based on MSP430. Robot 02 117

[9] Codino, A., Wang, Z., Razzaghi, R., Paolone, M., and Rachidi, F. 2017 An alternative method for locating faults in transmission line networks based on time reversal. IEEE Transactions on Electromagnetic Compatibility 99 1

[10] Vijay, M., & Jena, D. 2016 Intelligent adaptive observer-based optimal control of overhead transmission line de-icing robot manipulator. Advanced Robotics 30 1