Mechanism Design of an Insulator Cleaning Robot for Suspension Insulator Strings

Lin Wang, Hongguang Wang, Yong Chang, Xin’an Pan and Hongzhi Zhang

Abstract—Cleaning contaminated insulators is an effective way to protect power transmission lines from accidental power outages caused by flashovers due to wet polluted insulators. Traditional cleaning methods are risky, inefficient, expensive and labor-intensive. This paper presents an insulator cleaning robot mechanism which is mainly consisted of locomotion mechanism, cleaning mechanism and the frame. The structure is introduced and the principles of moving and cleaning are analyzed. The kinematic equations are established. Simulation results of the downward moving process prove the robot is able to move along the suspension insulator string and has such advantages as stability, large load carrying capacity and adaptability to dimensional variations of the insulator.

I. INTRODUCTION

The insulators, which are intended for electrical insulation and mechanical fixing of conductors, are one of the key components of power transmission lines. Exposed insulators are subject to surface dirt deposits in all operating areas. Most commonly encountered contaminants have little influence on insulator performance as long as they are dry. However, fog, mist, or light rain usually creates conditions that produce a conducting film on the dirty insulator surface [1]. The wet pollutants may cause a flashover which leads to a power blackout. In order to protect the power transmission lines from power failures, it is necessary to maintain the insulation resistance of the insulator strings by cleaning them periodically.

The existing cleaning methods can be classified into two categories, namely, de-energized cleaning and energized cleaning, according to whether or not the line is energized [1]. The traditional cleaning method, hand cleaning, is inefficient, dangerous and expensive in terms of manpower and outage time. Fig. 1 shows how the linemen clean the suspension insulator chain. The energized cleaning methods include water washing with different pressures, compressed air cleaning and hot wiping using a live-line tool. Nevertheless, the application of water washing is limited in mountainous areas due to water supplement, compressed air cleaning is not suitable for insulator strings of energized lines as the equipment is rather complicated, and hot wiping is not applicable to lines operating at voltages higher than 69kV. For these reasons, new techniques using robots have been developed.

Many researchers in United States, Italy, Korea and China have carried out several insulator cleaning robots since 1990s. In 1992, Luigi Parisi [2] presented equipment which can carry out maintenance operations, particularly washing on insulator chains of high voltage electric lines. The washing of the insulators was performed through jets of washing water sprayed over the contour of the insulator. In 1993, Wuhan High Voltage Research Institute [3] proposed a live-line washing-brushing robot for 500kV DC transmission lines. The robot is mainly composed of the upper clamp arm, the lower clamp arm, the driving arm, spray pipes and spray nozzles. Moreover, it possesses washing, brushing and gas blowing function and its cleaning method is very flexible. However, the robot is heavy and not applicable to insulator cleaning task. In 1995, Shigeo Hirose and Sanehito Aoki developed an insulator washing robot named Insulator Washer-I [4]. The robot includes an orbit rail, a cylindrical coordinate type arm and a rotating washing unit. Its cleaning methods are water jetting and washing. Experiments show the robot has sufficient cleaning capability. However, the robot is too heavy. Korea Electric Power Research Institute introduced an insulator cleaning and inspection robot for double tension insulator strings in 2006 [5]-[8]. The robot is mainly consisted of a moving mechanism, a cleaning mechanism and a wing connection mechanism. The robot uses dry cleaning method to clean the insulator and measures the insulator resistance to determine whether the robot is faulty. The robot is light-weighted, simple in structure and safe. However, the robot cannot adapt to the variations of the dimensions of insulators. Other researchers provided some cleaning robots for substations post insulator [9]-[13].

Figure 1. Cleaning suspension insulator string by hand cleaning.
The existing insulator cleaning robots have some limitations, such as the inconvenience of wet cleaning and the insufficient adaptability to the insulator dimensions. This paper focuses on the cleaning task of suspension insulator strings in 500kV power transmission lines and proposes an insulator cleaning robot mechanism. Compared with the existing prototypes of insulator cleaning robots, the presented mechanism has sufficient adaptability of the variations of dimensional parameters, namely, the spacing and the shed diameter. Moreover, the grip force of the mechanism can be large enough to grasp the insulator, which makes the mechanism stable and safe. The cleaning efficiency is high as three rotating brushes are used to cleaning the surface of the insulators simultaneously. The rest of this paper is organized as follows. The task object and the requirements of the robot are analyzed in section II. Section III describes the configuration and working principles of the robot and establishes the kinematic equations. Simulation is carried out in section IV. Finally, a conclusion is drawn in section V.

II. TASK ANALYSIS

In this paper, we choose an XWP2-160kN insulator which is widely used in the suspension insulator strings of 500kV power transmission lines as the target. The suspension insulator chain is normally consisted of 25~32 pieces of insulators covered with RTV coating. Fig. 2 shows a live-line suspension insulator string and the main dimensions of the target insulator.

Exposed to the atmosphere, the surface of the insulator is covered with contaminants, and the adhesive rate of pollutants depends on the structure of the insulator, size of the contaminants and atmospheric condition such as wind and rain [1]. It is found that the airborne contaminates tend to build up on the underskirt of the insulator rather than the topside of the main insulator shed and that both sides are polluted.

The robot works in complicated and dangerous condition with high voltage and in high locations, and the cleaning task is complex. For this reason, the following requirements should be satisfied.

- **Autonomy:** The robot should work automatically after installed on the insulator chain if a starting command is given. The robot can make decisions such as cleaning, moving upwards and moving downwards without any interference from linemen.
- **Safety:** The number of insulators contacted by the robot should not exceed three to ensure the safety of the insulator string. The robot should not drop from the insulator chain.
- **Electromagnetic compatibility:** The robot and its control system can work reliably in the environment with electromagnetic interference.
- **Adaptability to environments:** The robot should adapt to the variations of the dimensions of the insulator to some extent.
- **Efficiency:** The robot should clean the surface of the insulator with a relative high efficiency and the cleaning result meets the demands of cleaning task.
- **Usability:** The robot should be light-weighted and easy to use in high locations for linemen.

III. MECHANICAL DESIGN AND ANALYSIS

A. Robot Configuration

The mechanism of the insulator cleaning robot for suspension insulator strings is composed of the locomotion mechanism which enables the robot to move along the insulator chain, the cleaning mechanism which accomplishes the cleaning task and the frame to which the locomotion mechanism is attached, as shown in Fig. 3.

The robot performs insulator cleaning task in the following procedure. After installed on the insulator string by linemen, the robot begins to move from the top end of the string to the bottom end of the string if a start command is given. It stops to clean the insulator when the robot moves down an insulator. When the robot reaches the bottom end of the insulator chain and finishes cleaning, it returns to its start position. Finally, the robot is removed by linemen.

The mechanism is adaptive to insulators with different spacing as the displacement of the lifting mechanism can be adjusted according to the spacing of the insulator. Besides, the mechanism can adapt to insulators with different shed diameters as the locomotion mechanism engages the cap of the insulator. Moreover, the mechanism can apply a large gripping...
force to the insulator string, which improves the stability, safety and load carrying capacity. The robot mechanism is efficient because three brushes simultaneously clean the dirty surface of the insulator.

B. Locomotion Mechanism

The locomotion mechanism is consisted of the lower gripping platform, the upper gripping platform and the lifting mechanism. The lower gripping platform includes a driving motor, a worm drive, three spur gears, two arms and two clamps, as shown in Fig. 4. The structure of the upper gripping platform is similar to that of the lower gripping platform except for its way of connection to the frame. The upper gripping platform is grounded to the frame while the lower gripping platform is connected to frame through the lifting mechanism. The clamps of the upper and lower gripping platform are able to transit between an open position where there is no interference between the robot and the insulator string when the robot moves and a closed position where the clamps engage the insulator. The lifting mechanism is mainly composed of a lead screw, a nut, a pair of spur gears, a driving motor and two guide pillars. The lead screw is fixed to the frame and the lower gripping platform can move along the axis of the lead screw with the help of the rotating nut and guide pillars.

In order to move upwards or downwards along the insulator string, the clamps of the upper gripping platform and the clamps of the lower gripping platform alternately grasp the cap of the insulator while the motor of the lifting mechanism located on the lower gripping platform rotates accordingly. The robot mechanism moves down the insulator string in the following manner:

- The robot is installed on the insulator string with the clamps of the upper and lower gripping platform closed. Both the cleaning mechanism and the lower gripping platform are in zero position, as shown in Fig. 5(a).
- The clamps of the upper gripping platform move to its open position, as indicated in Fig. 5(b). The weight of the robot is held by the lower gripping platform.
- The driving motor of the lifting mechanism rotates and the upper gripping platform, the cleaning platform and the frame simultaneously move downwards for a certain distance which equals to the height of an insulator, as illustrated in Fig. 5(c).
- The clamps of the upper gripping platform move to its closed position and the weight of the robot is held by both the upper gripping platform and lower gripping platform, as shown in Fig. 5(d).
- The clamps of the lower gripping platform move to its open position and the weight of the robot is held by the upper gripping platform, as shown in Fig. 5(e).
- The lower gripping platform moves along the lead screw of the lifting mechanism for a distance which equals to the height of an insulator, as indicated in Fig. 5(f).
- The clamps of the lower platform move to its closed position and the weight of the robot is held by both the upper gripping platform and lower gripping platform, as illustrated in Fig. 5(g).

By taking the above process, the robot mechanism moves down an insulator. The upward moving procedure is similar to the downward moving procedure. Tab. 1 lists the status of the clamps of the gripping platforms and the position of the lower gripping platform.
The cleaning mechanism is simple in structure as only two motors are used and is safe as the circular motion guide and the circular motion slider can form a circle to surround the insulator when the robot is moving along the insulator chain. The cleaning efficiency is high as three brushes clean the topside of the insulator at the same time.

Fig. 6 shows the conceptual cleaning flow diagram of the cleaning mechanism. Fig. 7(a) is the initial state of the cleaning mechanism. Once the robot starts to clean the insulator, the cleaning motor rotates and three rotating brushes begin to clean the insulator. Meanwhile, the circular motion motor rotates to drive the circular motion slider anticlockwise, as shown in Fig. 7(b). When the circular motion slider reaches the leftmost position, the circular motion motor reverses to drive the circular motion slider clockwise, as shown in Fig. 7(c). The circular motion motor reverses again when the circular motion slider reaches the rightmost position and finally the circular motion motor stops when the circular motion slider is in the initial position. The upper skirt of the insulator is cleaned when the above-mentioned process finishes. The platform lifting motor rotates to move the cleaning platform downwards and the cleaning process starts again to clean the lower skirt of the insulator as the target insulator has two skirts. When an insulator is cleaned entirely, the cleaning platform goes back to its initial position.

The mechanism is adaptive to variations of the spacing of the insulator to a certain extent because the moving distance of the lifting mechanism can be determined by the sensors which are installed on the mechanism to detect the skirt of the insulator. As the clamp is attached to the arm through a passive joint and engages the cap of the insulator, the mechanism is able to adapt to the variations of the shed diameter of the insulator. The locomotion mechanism is simple. Besides, the inner side of the clamps is elastic and the shape of the clamps is designed to fit in the cap of the insulator.

C. Cleaning Mechanism

The cleaning platform is composed of the cleaning mechanism which is intended for insulator cleaning task and the lifting mechanism which enable the cleaning mechanism to move along the lead screw shared by the moving mechanism of the locomotion mechanism. The cleaning mechanism consists of the circular motion motor, the circular motion guide, the circular motion slider, timing belts, a high-speed cleaning motor and three rotating brushes distributed evenly on the circular motion slider. The circular motion slider is able to move relatively to the circular motion guide with the help of the circular motion motor. The mechanism can clean the entire topside of the insulator using dry cleaning method as it is not convenient for the mechanism to carry a water tank in high locations. The cleaning platform is able to move relatively to the frame using the lifting mechanism which is composed of a platform lifting motor, a pair of spur gears, a nut and a lead screw which is part of the lifting mechanism of the lower gripping platform.

![Figure 6. Conceptual design of cleaning mechanism.](image)

![Figure 7. Cleaning flow diagram of cleaning mechanism.](image)

D. Kinematics of the Mechanism

The coordinate system of the mechanism is established, as shown in Fig. 8. \( \{O_u - X_u Y_u Z_u\} \) is the global coordinate system and \( Z_u \) coincides with the axis of the suspension insulator string. \( O_u \) is the center of the top surface of the cap of the top side insulator. \( X_u \) is vertical to the plane determined by the axes of the passive joints of the upper gripping platform. \( \{O_v - X_v Y_v Z_v\} \) is the coordinate system of the upper gripping platform, which is attached to the frame. \( X_v \) is parallel to \( X_u \), \( Z_v \) and \( Z_u \) coincide. \( O_v \) is a point whose distance to the upper side of the clamp is equal to that to the lower side of the clamp. \( \{O_c - X_c Y_c Z_c\} \) is the coordinate system of the lower gripping platform. \( X_c \) is parallel to \( X_u \).
and $O_L$ coincide. $O_L$ is a point whose distance to the upper side of the clamp is equal to that to the lower side of the clamp. $\{O_C - X_C Y_C Z_C\}$ is the coordinate system of the cleaning platform. $X_C$ is parallel to $X_G$. $Z_G$ and $Z_O$ coincide. $O_C$ is the intersection of the axis of the insulator chain and the upper side of the circular motion guide.

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\begin{align*}
\frac{\hat{\mathbf{O}_C}}{\mathbf{t}} & = 0 0 -(n_i H + z_0)T \\
\frac{\hat{\mathbf{O}_G}}{\mathbf{t}} & = 0 0 -(n_i H + z_0 + d_{\text{max}}) + d_LT \\
\frac{\hat{\mathbf{O}_C}}{\mathbf{t}} & = 0 0 -(n_i H + z_0 - d_G)T
\end{align*}
\]

where $n_i$ is the number of the insulator which is engaged by the clamps of the upper gripping platform.

The inverse kinematics of the mechanism is apparent and omitted.

IV. SIMULATION

The model of the above-mentioned mechanism is created in SolidWorks and the insulator is XWP2-160kN which is widely used in suspension insulator strings of 500kV power transmission lines. The downward moving process of the mechanism is simulated. In the simulation, the motion law of each joint is trapezoidal [15]; it takes 4s for the clamps of the gripping platform to transit between their open position and closed position and it takes 5s for the lower gripping platform to move from its zero position to its maximum position. In total, it takes 26s for the mechanism to move down an insulator. Fig. 9 shows the position and orientation of the mechanism at some time instant.

The velocity of each joint and the displacement of gripping platforms are obtained using the inverse kinematics. Fig. 10
presents the motion curve of the mechanism of its downward movement process. As shown in Fig. 10(a), \( \omega_L \) and \( \omega_U \) are the angular velocity curves of the arms of the lower gripping platform and that of the upper gripping platform. Fig. 10(b) is the velocity curve of the lifting mechanism of the locomotion mechanism. The curves of displacement along \( Z_U \) of the gripping platforms are given in Fig. 10(c), and \( z_L \) is the displacement curve of the lower gripping platform while \( z_U \) is the displacement curve of the upper gripping platform.

The simulation of the downward movement of the mechanism demonstrates that the mechanism is able to move along the suspension insulator string. Besides, the mechanism is stable and adaptive to the variations of the dimensions of the insulator to some extent.

![Figure 10](image)

(a) angular velocity curve of arms of gripping platforms. (b) velocity curve of lifting mechanism. (c) displacement curve of gripping platforms

V. CONCLUSION

This paper proposed a cleaning robot mechanism for suspension insulator strings to meet the demands for insulator cleaning task. The robot is mainly consisted of a locomotion mechanism which includes a fixed platform with clamps and a slidable platform with clamps, a cleaning mechanism which is comprised of a platform-lifting mechanism, a circular guide and three brushes evenly distributed on the circular guide, and a frame. The moving procedure and the cleaning process are analyzed. The kinematics is given. Simulation results of downward moving show that the mechanism is able to move along the insulator string. The mechanism has good stability, load carrying capacity and adaptability to the variations of the insulator. Future work focuses on optimizing dimensional parameters, designing the control system, developing prototype of the robot and carrying out experiments.

REFERENCES


