Optimal design and stress analysis of the transmission line inspection robot along the ground line

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Abstract: Most of the previous literatures of the transmission line inspection robot along the ground wire tend to focus on the obstacle-surmounting method and motion characteristics. There is less research on the mechanics calculation of the corresponding ground wire. Most of the existing robots are designed with the wheel-claw mechanism. There is less research on other types of robots. A caterpillar track robot along the ground line is designed in this study. The optimisation design of the obstacle-surmounting method is carried out. The typical 500 kV transmission line model is established. The stress of the ground wire in the process of robot moving along the ground wire is calculated and analysed under different control climate conditions with the elementary method. The results show that the stress of the ground wire has a certain safety margins. However, it may exceed the safety range under harsh climate conditions when the transmission line has heavy gradient. The inspection robot operations need reasonable planning according to the calculation results and the transmission line conditions.

1 Introduction
In order to ensure the safe and stable operation of the transmission line, it is necessary to inspect regularly. The traditional inspection is mainly done by manual work. For instance, telescopes are used for inspection under the transmission line, workers climb the towers and use the gondolas suspended on the overhead ground wires (OGWs), and the helicopter is also used for inspection. However, some defect faults are not easily observed under the transmission line, and some complex terrain areas are not suitable for manual inspection. The gondolas are in a high altitude and under a high voltage environment, and the workers have a large amount of work with high risk. The inspection with helicopter is expensive and is greatly affected by the environment and weather. In recent years, more and more attention has been paid to the autonomous inspection robot which can take place of workers to complete inspection tasks [1, 2].

The inspection robot can be divided into a robot along the conductors and a robot along the ground line. The structure of the conductors is more complex. It mainly consists of quad-bundled conductors and other fittings. The robot along the conductors is in a strong electric field and a high voltage environment. It is more difficult to cross the barrier than the robot along the ground line [3]. As early as in the 1990s, the transmission line inspection robot was studied. An algorithm proposed to guide the inspection robot surmounts the obstacles in [4]. According to the kinematic model of the inspection robot, the rotary angles can be programmed, and the arm can implement autonomously to be on OGWs reliably. An obstacle-navigation control strategy for an inspection robot suspended on OGWs of the transmission line was introduced in [5]. A mobile teleoperated robot working on live lines is proposed for 735 kV and 1000 A with line scout technology. An inspection robot was developed with three arms for the 110 kV transmission line in [6]. A mobile robot is developed that can crawl along the OGWs to clear such obstacles as counterweights, anchor clamps, and torsion tower, and perform part transmission line inspection tasks [7]. A broken strand detection method is presented in [8] which can be practically applied by maintenance robots. A corrosion detection robot is described in [9], which carries an eddy current sensor. It is installed on a live overhead conductor and controlled by the ground-based operator using a portable computer and a radio link. The active and passive mechanisms are designed in the robot to enable it to move over various obstacles on ground wires, such as clamps, warning balls, and mast tips [10]. The active mechanisms contain seven rubber-coated rollers (i.e. four vertical rollers and three horizontal rollers) as well as three mechanisms in order to make horizontal rollers move vertically. The passive mechanisms also include a set of spring dampers installed in each joint of robot arms. Based on the above-mentioned researches, robots with different structures and control modes are designed. Most of these studies focus on the way of moving over various obstacles, and the simulated obstacle-surmounting test is carried out in the laboratory. However, there is a lack of research and analysis of the mechanical properties of robots running on the transmission lines. Especially for some transmission lines in special climate and geographical conditions, there may be a shortage of robot design.

This study is aimed at the inspection of a 500 kV transmission line in the Tibetan area with a high altitude and a complex meteorological environment. A caterpillar track robot along the ground line is proposed. The structure and obstacle-surmounting method are optimised. The maximum stress and sag of the ground line are calculated when the robot is in a different position. The influence of the weight of the inspecting robot and the different climatic conditions on the displacement and stress of the ground line are analysed. The calculation results can provide reference to the inspection.

2 Optimisation design of the robot structure
2.1 Climatic conditions of the inspecting transmission line
A robot is designed for the maintenance work of the 500 kV transmission line of the Tibetan area. There are high altitude, high elevation, and complex and changeable climate in some part of Tibet. Partial transmission lines are not suitable for manual inspection. The climatic conditions of a typical 500 kV transmission line corridor in the Tibetan area are introduced in detail below.

The terrain where the transmission line located is mountainous and hilly. There are many glaciers. Climate changes greatly with the season and terrain. The annual average precipitation is around 800 mm. There is a heavy snowfall in winter. The annual mean...
Fundamental wind pressure is 0.35 kN/m² by the local altitude is 26.9 m/s. Due to special climatic conditions, the difference of them make the working conditions of robot worse. Some strain sections have a small span and large height difference. So the general conductor icing thickness is ∼400 mm under some extreme micro-landform and micro-climate could exert great influence on conductor icing. So the general conductor icing thickness is ∼5 mm. The maximum conductor icing thickness is ∼10 mm under some extreme micro-climate conditions.

2.2 Structure design of the inspection robot

Some strain sections have a small span and large height difference. Transmission line icing over long period time and large height difference of them make the working conditions of robot worse. Whether the robot is rolling or crawling along the ground lines, the ability to climb the slope is limited. It will be more difficult to climb in the case of icing. Therefore, a caterpillar track robot is designed as shown in Fig. 1. The robot includes the motion control system, the power system, two caterpillar tracks, the communication system, the detection instruments, two support rollers, the auxiliary roller, and so on. The motion control system and the communication system are on the top of the robot. The caterpillar tracks are on both sides of the robot and tightly nip the ground line. The power system and the detection instruments are at the bottom of the robot. They have a large weight and can ensure that the centre of gravity of the robot is just below the ground line. The robot reversing can be effectively prevented. The roller and hollow groove at the bottom of the robot can effectively make the robot get over the obstacles, such as counterweight. The auxiliary roller and the side wall of the hollow groove can help the robot go back to the right track in the case of swinging of deflecting, so as to pass the obstacles. The support roller is used to support the weight of the robot and prevent the caterpillar tracks from pulling out of the ground line under gravity.

There are two typical obstacles when the robot inspects along the ground line: one is counterweight and the other is the head of the tower. The tower can be divided into a tangent tower and a torsion tower. The torsion tower is more difficult for the inspection rotor to cross. The obstacle-surmounting method for the designed robot is described below. When an obstacle is detected, the robot slows down. When the robot does not swing, the counterweight can normally pass through the hollow groove. When the robot swings, the side wall of the hollow groove will first contact the counterweight. The position of the robot will gradually correct to make the counterweight pass through by the tilted side wall. When crossing the head of the torsion tower, an auxiliary bridge needs to be installed as shown in Fig. 2. When the robot moves closer to the bridge, the auxiliary roller in the upper part of the robot first contacts the auxiliary bridge. The concave structure of the auxiliary roller makes the robot gradually swing to the right position. Under the joint action of the auxiliary bridge and the support roller, the robot moves from the ground line to the auxiliary bridge. The robot returns to the ground line from the bridge in the same movement mode.

Compared with the existing wheeled or clawed robot, the caterpillar track robot designed in this study has the following advantages:

(i) Compared with the wheel-claw mechanism, the caterpillar track structure increases the applied stress area and makes the stress even more uniform. Thus, more power can be generated, and it is more conducive to the climbing of the robot. It can still work under smaller icing conditions.
(ii) The robot with a contact roller and a connecting rod usually has a long arm and need to pass the obstacles under the ground line. It is more difficult to cross the torsion tower. It is easy to produce other dangers because of the higher body. The caterpillar track robot is more compact. The obstacle-surmounting method is more convenient.
(iii) The robot with the wheel-claw mechanism is more likely to be swung by the wind. The swing of the caterpillar track robot is smaller. It has less influence on the ground line.

3 Stress analysis of the ground line

3.1 Simulation method of ground line stress

The form-finding analysis of cable structures is used to calculate the force of the transmission lines under different external loads. That is required to determine the initial configuration of the overhead transmission line under the action of gravity. The steps of the finite element analysis of the conductor and the ground line are as follows. Firstly, the initial stress of the conductor and ground line are given in advance according to the basic meteorological conditions, and the specific load under the installation meteorological state is applied. The preliminary shape in theory can be found through the parabolic equation of the conductor and the ground line. Then, the appropriate elements are used to discretise the conductor and ground lines into a series of interconnected elements according to the cable equation. Finally, the non-linear static analysis under the gravity field is performed to determine the precise shape of the conductor and ground lines.

The type of transmission line selected in this study is as follows. The conductor is adopted with 4 × JL/G1A-500/45 aluminium conductor steel-reinforced, and the ground line is adopted with 1 × 19-13.0-1270-B-galvanised steel wire. As shown...
3.2 Stress and displacement analysis of the ground line when the robot moves to different positions

Due to the low speed of the robot while it patrols the line, the damping force caused by the motion can be neglected. Compared to the total weight of the robot, the mass of the track is very small. The inertia force caused by the track rotation can be neglected. Therefore, the statics calculation is just used to study the stress of the ground line.

The weight of the robot is set to 50 kg. The concentrated force is used to simulate the static load of the robot on the ground line. The stresses of the ground line when the robot moves on the three transmission line sections are calculated by the finite element method when the robot moves to different locations on the ground line. The calculation shows that no matter the robot moves to any position, the stress at the higher suspension point of the section is the largest one. When the robot moves to the maximum sag point, the ground line has the maximum stress. For instance, the maximum stress of the ground line Section 1 is shown in Fig. 3. The maximum sag of the ground line with the robot is shown in Fig. 4. The maximum stress of the ground line is 256.83 MPa. The maximum tensile stress is 608.6 MPa from Table 2. Considering that the safety factor is 3, there may be a potential safety hazard.

3.3 Influence of the weight of the inspecting robot on the stress of the ground line

The weight of the robot is set to be 20, 40, 50, 60, 80 kg, respectively. The influence of the robot weight on the stress of the ground line is calculated. On the basis of the results given in Section 3.2, the robot is placed at the maximum sag. The results are shown in Table 3. With the increase of the weight of the robot, the stress of the ground line increases linearly. When the transmission line has a heavy gradient, the stress of the ground is very large under the action of self-weight. If the weight of the robot is large, the stress of the conductor may exceed the safety range. The weight of the robot needs to be reduced according to the transmission line conditions.

3.4 Influence of bad climate on robot inspection

In high altitude and alpine region, some transmission lines may be covered with ice for a long time a year. They may need to be inspected in bad conditions, and it is necessary to analyse the force of the ground line with robot under different climate conditions.

Transmission lines are vulnerable to the terrain and weather conditions. The icing and wind loads on the conductors and ground lines are often inhomogeneous, and it is difficult to use numerical simulation to accurately simulate. Therefore, in the design of transmission line, the icing cross-section is usually treated as the hollow ring with the same thickness, and can be simplified to the uniformly distributed icing load. The effect on the wind is equivalent to the uniform force of the whole line. The equivalent method of icing and wind load is shown in Fig. 5.

In this study, the additional force simulation method are used to simulate icing and wind loads on the conductors and ground lines, and the method generally adopts equidistance point force to simulate the static load of icing on the conductors and ground lines.

According to the combination condition of design wind speed and ice in the transmission line in the area where it is located, the following four weather conditions may become the key meteorological conditions in general:

(a) 5°C, no wind, no ice;
(b) −5°C, no ice, maximum wind speed 30 m/s;
(c) −5°C, no ice, design wind speed 26.9 m/s;
(d) −5°C, the maximum ice coating 5 mm, combined wind speed 10 m/s;
(e) −5°C, the designed ice coating 10 mm, combined wind speed 10 m/s.
Table 3  Maximum stress of the ground line with different weight robot (MPa)

| Transmission line | 20 kg  | 40 kg  | 50 kg  | 60 kg  | 80 kg  |
|-------------------|--------|--------|--------|--------|--------|
| Section 1         | 243.45 | 252.37 | 256.83 | 261.29 | 270.37 |
| Section 2         | 122.18 | 138.24 | 146.09 | 154.16 | 169.26 |
| Section 3         | 156.20 | 167.88 | 173.66 | 179.40 | 190.75 |

Fig. 5  Equivalent method of icing and wind load

Table 4  Maximum stress of ground line under different weather conditions (MPa)

| Weather conditions | 20 kg  | 40 kg  | 50 kg  | 60 kg  | 80 kg  |
|--------------------|--------|--------|--------|--------|--------|
| a                  | 243.45 | 252.37 | 256.83 | 261.29 | 270.37 |
| b                  | 281.25 | 288.71 | 292.48 | 296.27 | 303.74 |
| c                  | 270.32 | 278.23 | 282.21 | 286.21 | 294.26 |
| d                  | 305.51 | 313.89 | 318.08 | 322.27 | 330.66 |
| e                  | 389.10 | 396.82 | 400.68 | 404.55 | 412.27 |

First, the initial state of three typical sections is calculated under different meteorological conditions. Then the specific load of the corresponding conductors and ground lines are calculated according to the wind speed and thickness of ice coating. Finally, they are converted into equidistance point force and applied evenly on the line.

The maximum force needs to be analysed. The above studies proved that the ground line is subjected to the maximum force when the robot load is applied to the central point of the span. The maximum stress value of the ground line is calculated under different meteorological conditions with different weight robots, as shown in Table 4. The calculation results show that the maximum ground stress with a different weight robot is within the range of safe operation under the previous four conditions. However, the maximum stress under some conditions is close to the allowable stress. The maximum stress exceeds the allowable stress under the fifth meteorological climatic condition. Also, it is a high risk to do the inspection of the transmission line. If the robot has to work under the bad condition, the safety of the robot and the normal operation of the line with the thickness of the icing not exceeding 5 mm can be ensured.

4 Conclusion

The caterpillar track robot is designed and the structure is optimised to be more compact. The caterpillar track structure provides greater power. The auxiliary roller, auxiliary bridge, caterpillar track, and support roller can make the obstacle-surmounting more simple and effective. The mechanical simulation analysis is carried out for the typical 500 kV transmission line in Tibet. The stress of the ground line in the process of robot moving along the ground line is calculated and analysed under different climate control conditions. The calculation results provide reference for the actual operation of the inspection robot.

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6 References

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