ONTOSOLOGY DESIGN AND DEVELOPMENT OF TRANSMISSION LINE IN INSPECTION ROBOT

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Abstract - The progress of robot technology is increasingly rapid with information technology and artificial intelligence development. First, the basic principle of the transmission line is analyzed. Then, the inspection robot's device design and transmission line analysis are conducted according to the transmission line characteristics. Moreover, the weight of the suspended robot is experimentally analyzed according to the different heights of the inspection robot under different voltages of the transmission line. The results show that using the power frequency voltage of the transmission line can suspend the robot with maximum weight, reducing the gap between the live part of the transmission line and the pole and tower components and reducing the operation and maintenance cost. For the linear tower and tension tower in a continuous transmission line, the maximum weight of the suspension robot allowed for the transmission line with corresponding voltage level shall be the small value of the linear tower and tension tower. For transmission line inspection robots with different heights, the smaller the robot's height is, the greater the robot's weight borne by the transmission line is. When robot's height in the transmission line is 0.5m, 1m, and 1.5m, respectively, the maximum weight of the robot borne by the 500kV transmission line is 125kg, 105kg, and 90kg, respectively. The minimum weight of the robot borne by 110kV and 220kV transmission lines is 60kg. This thesis has a certain reference in the design and development of transmission line inspection robots.

Keywords: Transmission line; Inspection robot; Device design; Power frequency voltage.

1. Introduction

Present power line inspection in most areas of China is still dominated by manual inspection, which is inefficient and poses a certain threat to the safety of inspectors [1,2]. The traditional patrol inspection mode of high-voltage overhead transmission line, namely manual patrol inspection mode, is that the patrol personnel patrol or detect tower by tower along the line, and climb the tower for patrol inspection when necessary. This working model has low efficiency and high labor intensity, and there are problems such as equipment missing inspection and inspection dead corner [3-5]. Some units have carried out aerial helicopter surveys to inspect high-pressure routes in recent years. However, due to the high cost, weather constraints and aviation control, it is only conducted in high, extra-high and ultra-high voltage line sections that are difficult for personnel to reach, such as mountainous areas and large spans [6,7].

Domestic inspection robot manufacturers mainly use lidar navigation, and a few uses magnetic navigation. The proportion of indoor application is much larger than that of outdoor application, because the magnetic strip is easy to be damaged and the maintenance workload is heavy, especially outdoors [8]. The main problem of lidar is that it is easy to get lost, because lidar uses terrain contour as navigation reference, which is similar to holding a piece of picture puzzle to find out its position in the whole puzzle pattern. If the terrain contours are similar and even the difference points are less than the noise, it is almost impossible to puzzle accurately even if the later algorithm is improved [9-11]. Power inspection robots are widely used to inspect the outdoor high-voltage equipment of unattended or less attended substations. By collecting the operation status information of power equipment, they can detect abnormal phenomena such as thermal defects and foreign matter suspension of power equipment to ensure the safety of power production [12,13]. At present, the navigation mode of the power inspection robot generally adopts magnetic track navigation, which is to install a magnetic track on the inspection route of the substation.

The power inspection robot detects its offset relative to the magnetic track through the magnetic sensor array (magnetic sensor) installed in its front
and controls its operation along the magnetic track through two-wheel differential speed [14-16].

First, the basic principle of the transmission line is analyzed. Then, the inspection robot's device design and transmission line analysis are conducted according to the transmission line characteristics. Finally, the weight of the suspended robot is experimentally analyzed according to the different heights of the inspection robot under different voltages of the transmission line.

2. Key Technology and Principle of Transmission Line Inspection Robot

2.1 Foundation Analysis of the Transmission Line

In the power system, most power plants are built in the location of power resources. Hydropower plants are built at water resources points, that is, they are concentrated in places with large water level drops in river basins. Thermal power plants are mostly concentrated in the producing areas of coal, oil and other energy. Large power load centers are mostly concentrated in industrial areas and large cities, so power plants and load centers are often far away, resulting in the problem of power transmission, which requires power transmission lines [17]. Therefore, the transmission line is an important part of the power system. It undertakes the task of transmitting and distributing electric energy. Transmission lines can be divided into overhead lines and cable lines.

According to the nature of electric energy, there are alternating current (AC) transmission lines and direct current (DC) transmission lines. According to the voltage level, there are transmission lines and distribution lines. The voltage level of the transmission line is generally 35kV and above. At present, the voltage levels of transmission lines in China mainly include 35kV, 60kV, 110kV, 154kV, 220kV, 330kV, 500kV, and 1000kV AC as well as ±500kV and ±800kV DC. Generally, the larger the transmission capacity is and the farther the transmission distance is, the higher the transmission voltage is required.

The distribution line is the line responsible for distributing electric energy. The voltage levels of distribution lines in China are 380/220V, 6kV and 10kV. Table 1 shows the composition of transmission lines.

<table>
<thead>
<tr>
<th>Composition of transmission line</th>
<th>Connecting part</th>
<th>Effect</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse</td>
<td>Erected on tower</td>
<td>Conducting current and transmitting electric energy</td>
<td>Steel cored aluminum strand, aluminum clad steel cored aluminum strand, steel cored aluminum alloy strand, anti-corrosion steel cored foot wire</td>
</tr>
<tr>
<td>Earth wire</td>
<td>Erected on the tower top</td>
<td>Reducing the chance of lightning strike on the conductor and ensuring the safe power transmission of the line</td>
<td>Galvanized steel strand, steel cored aluminum strand, optical fiber composite overhead ground wire</td>
</tr>
<tr>
<td>Pole and tower</td>
<td>Overhead transmission line</td>
<td>Supporting traverse and lightning conductor</td>
<td>Lineal tower, load-bearing tower, suspension angle tower</td>
</tr>
<tr>
<td>Insulator</td>
<td>Supporting insulation between traverse and tower</td>
<td>Causing insulation between traverses and between traverses and the earth</td>
<td>Ordinary type, pollution resistant type, aerodynamic type, and spherical type</td>
</tr>
<tr>
<td>Armour clamp</td>
<td>Shaped parts for connecting transmission lines</td>
<td>Protecting the accessories used</td>
<td>Cable clamp, link fitting, splicing fitting, protective fitting, Pull hardware</td>
</tr>
<tr>
<td>Foundation of pole and tower</td>
<td>Overhead power line towers generally have the functions of downforce, uplift force and overturning forces</td>
<td>Stabilizing the tower</td>
<td>Precast foundation, cast-in-situ foundation, pile foundation and metal foundation</td>
</tr>
</tbody>
</table>
The upper end is connected with the cable hold hoop and cable, and the lower part is connected with the pull hardware, anchor rods and anchor plate.

Balancing the lateral load and traverse tension of the tower can reduce the tower consumption and reduce the line cost.

Galvanized steel strand

Grounding device

The grounding body is buried underground, and the grounding down lead is connected with the grounding body at the grounding bolt.

Discharging lightning current

The grounding body is divided into a horizontal grounding body and vertical grounding body.

Equation (1) represents the mechanical strength of insulators in Table 1:

$$ K = \frac{T_h}{T_{max}} $$

(1)

$K$ is the safety factor of the mechanical strength of insulator. $T_h$ is the bending failure load of porcelain cross-tam or the test load of 1-hour electromechanical test of suspension insulator. $T_{max}$ is the maximum service load of insulator. The horizontal distance between two adjacent towers is called span. Equation (2) is the horizontal span:

$$ \zeta_h = \frac{(L_1 + L_2)}{2} $$

(2)

$\zeta_h$ represents the horizontal span of two adjacent spans, and $L_1$ and $L_2$ are the horizontal distance between tower 1 and 2, respectively. Due to the different terrain and obstacles crossed by the transmission line traverses, the size of each span is different, the elevation of the traverses suspension point is different, and the stress of the traverses in each span is also different.

According to the calculation of traverse mechanics, the stress of horizontal tension of traverse in the whole tension section is the same, that is, the traverse of traverse at the lowest point of sag of each span is equal. The multi-span tension section with different sizes is replaced by an equivalent imaginary span, which is called regular span and expressed by equation (3):

$$ L_0 = \sqrt{\frac{\sum_{i=1}^{n} L_i^2}{\sum_{i=1}^{n} L_i}} = \sqrt{\frac{L_1^2 + L_2^2 + \ldots + L_n^2}{L_1 + L_2 + \ldots + L_n}} $$

(3)

$L_0$ is the imaginary span of the whole tensile mechanical law. $L_1$, $L_2$ and $L_n$ are the horizontal distances between towers 1, 2 and n, respectively. The load of various poles and towers under normal operation, disconnection, installation and special conditions of the route is generally calculated, and the load coefficient is set as $K_H$. Table 2 is the load factor of various poles and towers.

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Operation</th>
<th>Disconnection</th>
<th>Installation</th>
<th>Checking calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load combination coefficient</td>
<td>1.0</td>
<td>0.75</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

In Table 2, the loads under operation, disconnection and installation conditions are multiplied by the corresponding load coefficient $K_H$ to obtain the design loads under various conditions.

The same safety factor is adopted when calculated according to the design load. Equation 4 displays the calculation of vertical load:

$$ G = g_A l_v + G_j $$

(4)

$G$ is the vertical load of traverse or lightning protecting wire (N). $G_j$ is the vertical specific load ($g_1/g_2)(N/m \cdot mm^2$) of traverse or lightning protecting wire. $A$ is the interface of traverse or lightning protecting wire ($mm^2$). $l_v$ is the vertical
span \((m)\), and \(G_j\) is the total gravity of insulator string \((N)\).

When the wind direction is perpendicular to the line direction, the wind pressure load of the tower is calculated according to equation (5):

\[
P_a = CP \frac{v^2}{1.5}\]

\(P_a\) is the tower wind pressure \((N)\) when the wind direction is perpendicular to the line, and \(v\) is the design wind speed \((m/s)\). \(F\) is the projected area formed by the side of the tower in the wind pressure direction \((m^2)\), and \(C\) is the wind load form factor.

The ring section pole is set as 0.6, the rectangular section pole is set as 1.4, the angle steel tower is set as 1.4\((1+\eta)\), and the round steel tower is set as 1.2\((1+\eta)\). \(\eta\) is the reduction coefficient of wind pressure load on the leeward side of space truss.

In addition, equation (6) displays the wind pressure load of traverse and lightning protecting wire:

\[
P = gA_{iT} \cos^2\frac{\theta}{2} + P_j\]  \(6\)

\(P\) is the wind pressure load \((N)\) of the traverse and lightning protecting wire, \(\theta\) is the line angle \((\text{°})\), and \(l_A\) is the horizontal span. When the transmission line breaks down, the horizontal span of the broken line is taken as \(\frac{l_A}{2}\) and \(P_j\) is the wind pressure of insulator string \((N)\). When the transmission line turns, Figure 1 is the resultant force of the tower bearing along the cross-arm direction.

![Figure 1: Schematic diagram of transmission line corner](image)

In Figure 1, the resultant force of the tower bearing along the cross-arm direction can be expressed by equation (7). \(T_1\) and \(T_2\) are the tension on both sides of the tower \((N)\). \(T_a\) is the horizontal load perpendicular to the cross-arm direction, the unbalanced tension and broken tension of traverse and earth wire, the longitudinal wind load of tower, traverse and earth wire, and the tightening tension during installation \((N)\). \(T_b\) is the load acting perpendicular to the ground, including the dead weight of traverse, earth wire and accessories, the dead weight of tower and cross arm, icing weight and cable downward pressure, and the gravity of personnel, tools and instruments during installation and maintenance \((N)\). \(T\) is the horizontal load acting along the cross-arm direction, the wind load of traverse and earth wire, the wind load of tower body and the angular resultant force of traverse and earth wire \((N)\). In case of transmission line failure, the tension at the broken side is 0,

\[
T = (T_1 + T_2)g \sin \frac{\theta}{2}
\]

When the breaking span is close to the tension tower, the support force of the lightning protecting wire is the smallest. The maximum supporting force of lightning protecting wire is used to calculate the bending and torsion of the pole head. The minimum supporting force of lightning protecting wire is used to calculate the bending of pole root and foundation overturning. Equation (8) is the supporting force of lightning protecting wire:

\[
\Delta T = \frac{D_a T - \lambda_p}{D_b + \frac{D_p}{2}}
\]

\(\Delta T\) is the supporting force of the lightning protecting wire \((kN)\), and \(D_a\) is the flexibility factor of the pole top under the conductor breaking tension \((m/kN)\). \(D_b\) is the flexibility factor of the pole top under the support force of the lightning protecting wire \((m/kN)\). \(T\) is the breaking tension of the traverse \((kN)\). \(A_s\) is the sectional area of the lightning protecting wire \((mm)\), \(\lambda_p\) is the length of the suspension string of the lightning protecting wire \((m)\), and \(F\) can be calculated as a function of the stress and span of the lightning protecting wire before breaking the conductor.

### 2.2 Device Design of Inspection Robot

In the actual application of the unmanned aerial vehicle (UAV) patrol inspection in the transmission line, many manipulators need to manually control
UAVs to arrive at the operation site and perform patrol inspection tasks. However, the manipulator's control level directly determines whether the inspection quality meets the standard, and the operation efficiency, operation quality and operation frequency are difficult to meet the construction needs of the power grid in the Internet of things [18,19].

With the continuous upgrading of smart parks, intelligent inspection robots are widely used to inspect domestic factories and parks. According to different navigation modes, inspection robots are divided into magnetic navigation robots and laser navigation robots. Magnetic navigation is to bury permanent magnets on the inspection route of the robot, and the robot advances or retreats along the magnetic track.

At each detection point that needs to stop or action points such as curve speed regulation, an additional Radio Frequency Identification (RFID) tag needs to be buried next to the magnetic track. The electronic tag is equipped with the information injected during debugging, detection, speed regulation, and curve.

After the robot scans these labels, it adjusts and launches the corresponding patrol action. Figure 2 is the design diagram of the transmission line inspection robot.

In Figure 2, the transmission line inspection robot is mainly composed of Four-Wheel-Drive Chassis (4WD Chassis), laser sensor, visible light camera, infrared thermal imager and other components. There are also 6 magnetic sensors under the robot to ensure that the inspection robot moves along the predetermined magnetic track. When the transmission line inspection robot breaks out of the transmission line and the robot stops by default, the staff needs to reset the robot manually and find the way automatically after entering the transmission line. The robot can know its position and perform the current work task when the next tag is detected.

Transmission line inspection robot has the following advantages. First, it can conduct intelligent real-time inspection all day, with a low cost. Second, it can realize fault diagnosis of artificial intelligence expert system, with stable quality. Third, it has big data interest prediction and can improve the operation efficiency improvement. Fourth, it integrates detection, monitoring, and early warning, which is convenient for management. Figure 3 is the inspection line of the transmission line.

**Figure 2: Transmission line inspection robot**

**Figure 3: Inspection line of the transmission line**
In Figure 3, a charging device composed of a solar panel, battery and charging interface is installed on the power tower. During non-inspection time, the robot can return to the tower and automatically connect to the charging interface for charging. The robot is also equipped with an emergency risk avoidance function to ensure the safety of patrol inspection. In case of bad weather during patrol inspection, the inspection robot shall immediately stop driving and start the safety protection device to ensure that it will not fall. Moreover, the inspection device of the transmission line inspection robot can be hung on the earth wire above the overhead line, and has the functions of taking photos and video recording.

The image is transmitted to the server through Fourth-Generation/ Five-Generation (4G/5G) network. The patrol inspection report can be output after patrol inspection. However, a line patrol generates massive images or videos at one time. Manual troubleshooting is time-consuming and laborious, and there will inevitably be omissions, which will delay the best time to find hidden dangers. This thesis provides an inspection system and inspection method of the single-line transmission line inspection robot, which carries out image processing at the robot end, reduces the upload number of images and videos at the server end, and shortens the calculation time to the greatest extent. Figure 4 shows the single-line transmission line mode of the inspection robot.

When the single-line transmission line robot in Figure 4 performs patrol inspection, the control system module is connected with the transmission line voltage regulator and machine load, which is used for transformation and rectification through the control system module. The transformer has a fixed charging port. The inspection robot enters and exits the transmission line with automatic doors, which can detect the door opening and closing commands sent by the robot. After the robot performs a work task, it returns to the charging point by default and is charged by the power plant through the alternator and through the step-up transformer. According to the electronic tag from the detection point to the charging position, the magnetic navigation will match the laser navigation to the charging point, so that the retractable motor plug of the inspection robot extends and is inserted into the charging position.

Until the next task is to be executed, the patrol inspection robot stops charging, and the charging system retracts to perform the task. Figure 5 shows the remote-control circuit of the output circuit inspection robot.
In Figure 5, the robot and the background computer transmit data bi-directionally through the configured antenna. In this way, during the task process, the background computer can receive the real-time monitoring screen and assign new tasks to the robot at any time. Besides, it can also be connected to the power grid network to realize remote centralized control. The Camera Pan Tilt Zoom (Camera PTZ) is connected with the control server to form an operable control command and send the command to the control server to automatically adjust the camera attitude. In this way, the monitoring image of the transmission line inspection is not affected by the environment, and supports the up, down, left and right control of the Camera PTZ.

The temperature sensor control key is used to control the temperature sensor to collect temperature values. The temperature and humidity sensor control key is used to control the temperature and humidity sensor to collect humidity values.

The gas sensor control key is used to control the gas sensor on the inspection robot to collect the distributed gas value around the inspection robot.

3. Simulation Experiment and Result Analysis

3.1 Simulation Experiment

For the live part of the 110kV~500kV transmission line, the minimum gap between different nominal voltages and tower components is simulated and analyzed. When checking the gap according to the operating voltage, the basic wind speed is used to correct the value at the average height of the transmission line traverse, corresponding air temperature, and the 550kV air gap column. The data on the left are suitable for areas with an altitude of no more than 500m, and the data on the right are for areas with an altitude of more than 500m but no more than 1000m. Figure 6 shows the experimental analysis results.

![Figure 6: Minimum gap between live parts of 110kV~500kV transmission line and tower components](image)

<table>
<thead>
<tr>
<th>Nominal voltage (kV)</th>
<th>110</th>
<th>220</th>
<th>330</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power frequency voltage</td>
<td>0.25</td>
<td>0.55</td>
<td>0.90</td>
<td>1.20</td>
</tr>
<tr>
<td>Operating overvoltage</td>
<td>0.70</td>
<td>1.45</td>
<td>1.95</td>
<td>2.50</td>
</tr>
<tr>
<td>Lightning overvoltage</td>
<td>1.00</td>
<td>1.90</td>
<td>2.30</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Figure 6 reveals that the gap between live parts of power frequency voltage in transmission lines and pole components is maximum at 500kV and minimum at 110kV, which are 1.30m and 0.25m, respectively. The gap between the live part of the operating overvoltage transmission line and the pole components is maximum at 500kV and minimum at 110kV, which are 2.70m and 0.70m, respectively. The gap between the live part of the lightning overvoltage transmission line and the pole components is maximum at 500kV and minimum at 110kV, which are 3.3m and 1.00m, respectively. To sum up, between the live part of 110kV ~ 500kV transmission line and tower components, the greater the voltage is, the larger the minimum gap is.

3.2 Comparative Analysis of Results

The maximum weight of the suspended robot under the power frequency voltage of the transmission line at 110kV is analyzed according to the simulation experiment analysis in 3.1. The linear tower and tension tower are compared and analyzed. The inspection robots are compared at different heights of 0.5m, 1m and 1.5m of the transmission line. Figure 7 is the analysis of the maximum weight of the transmission line robot allowed to be suspended at different heights at 110kV.
Figure 7: Maximum allowable weight of transmission line robot at different heights at 110kV (a) the maximum weight of the suspended robot when the transmission line robot is 0.5m, b) the maximum weight of the suspended robot when the transmission line robot is 1m, c) the maximum weight of the suspended robot when the transmission line robot is 1.5m)

Figure 7 suggests that at 110kV, the weight of the suspended robot on the transmission line is smaller with the increase of robot height. Among them, for the linear tower, the weight of the suspended robot on the transmission line is greater with the increase of span.

Similarly, in different spans of tension tower, the weight of the suspended robot on the transmission line is also greater with the increase of span.

Figure 8 is the analysis of the maximum weight of the transmission line robot allowed to be suspended at different heights at 220kV.

Figure 8: Maximum weight of transmission line robot allowed to be suspended at different heights at 220kV (a) the maximum weight of the suspended robot when the transmission line robot is 0.5m, b) the maximum weight of the suspended robot when the transmission line robot is 1m, c) the maximum weight of the suspended robot when the transmission line robot is 1.5m)
Figure 8 shows that at 220kV, the weight of the suspended robot on the transmission line is smaller with the increase of robot height. For linear tower and tension tower, in different spans, the weight of the suspended robot on the transmission line is greater with the increase of span.

Among them, the maximum weight of the hanging robot on the tension tower transmission line can be 145kg. Figure 9 displays the analysis of the maximum weight of the transmission line robot allowed to be suspended at different heights at 330kV.

The maximum weight of the suspended robot of the tension tower is 198kg. Figure 10 shows the analysis of the maximum weight of the transmission line robot allowed to be suspended at different heights at 500kV.
Figure 10 shows that at 500kV, with the increase of robot height, the weight of the suspended robot on the transmission line is lighter. For the tangent tower and the tension tower, the weight of the suspended robot on the transmission line is heavier with the increase of span. Among them, the maximum weight of the suspended robot on the transmission line of the linear tower can be 275kg.

### 4. Conclusions

The inspection robot is designed based on the basic principle of the transmission line. The maximum weight of the robot that can be suspended by the power frequency voltage of the transmission line is analyzed. The weight of the suspended robot in the linear tower and tension tower of the transmission line at different voltages of 110kV, 220kV and 500kV is compared.

The results show that for the linear tower and tension tower in a continuous transmission line, the maximum weight of the suspended robot allowed for the transmission line with corresponding voltage level needs to be the small value of the linear tower and tension tower. Among the transmission line inspection robots with different heights, the smaller the robot’s height is, the heavier the robot’s weight borne by the transmission line is. When the height of the transmission line robot is 0.5m, the maximum weights of the robot borne by the 500kV, 110kV, 220kV and 330kV transmission line are 125kg, 80kg, 85kg, and 96kg, respectively. When the height of the transmission line robot is 1m, the minimum weight of the robot borne by the 110kV transmission line is 70kg, and the maximum weight of the robot borne by the 500kV transmission line is 105kg.

The robot weight borne by the 220kV transmission line is 75kg and that borne by the 330kV transmission line is 86kg. When the height of the transmission line robot is 1.5m, the maximum weight of the robot borne by a 500kV transmission line is 90kg, and the weight of the robot borne by a 330kV transmission line is 75kg. The minimum weight of the robot borne by 110kV and 220kV transmission lines is 60kg. Using the power frequency voltage of the transmission line can suspend the robot with the maximum weight, reducing the gap between the live part of the transmission line and the tower components and reducing the operation and maintenance cost.

This thesis has a certain reference in the design and development of transmission line inspection robots. However, it lacks actual environmental inspection, because it is based on transmission line research. It is hoped that it can be improved in the follow-up research.

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### References


