Simulation and Analysis of Arc-drop Deformation of High-voltage Cables with Three-dimensional Laser Scanning Point Cloud

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Abstract: In order to investigate the influence of environmental factors on the deformation problems occurring in high voltage cables, this paper proposes a method for analyzing the deformation of high voltage cables based on 3D laser scanning. Firstly high voltage cable point cloud data is acquired. Secondly, a single power line is segmented using a density-based clustering method, and a mathematical model of the high-voltage cable is established using the least squares method. Then the high-voltage cable is downscaled from three-dimensional points to two-dimensional points to do the fitting of parabola on the plane. Finally compare the horizontal displacement and vertical displacement of the lowest overhanging point of the high-voltage cable with the weather to affect its deformation causes. The experimental results show that: the parabolic approximate fitting equation of the high voltage cable can accurately express the shape of the cable, and the R value of the equation is around 0.999. The vertical displacement of the high-voltage cable in the high-temperature and high humidity environment changes significantly, up to 0.556 m. Horizontal displacement is significantly affected by the wind, the wind in the 7mph horizontal displacement change is the largest, the average displacement change of 0.197m.

Keywords: 3D laser scanning technology; High voltage cables; Point cloud processing; curve fitting; Wire deformation

1. Introduction

High-voltage cable circuit is one of the country's important electric power infrastructure, carrying the national production and life of the energy required for the lifeline [1] The high voltage cable circuit is one of the important national power infrastructure, carrying the energy lifeline for national production and life. China's vast geography, distribution of high-voltage cables around the long-term exposure to the complex and changing environment, suffering from rain, snow, ice, vegetation, gusty winds and high temperatures, prone to cable aging and mechanical damage and other problems. In order to ensure the stable operation of the power system, to avoid the national life and property and the national economy and society suffered great losses. It is necessary to regularly check the safety and stability of high-voltage cable circuits [2] to prevent the occurrence of safety accidents.

The traditional high-voltage cable detection methods to manual ground inspection, staff need to hike along the line, climbing poles after observation with the naked eye. This method is not only inefficient, but also unable to protect the personal safety of the staff. [3] This method is not only inefficient, but also unable to protect the personal safety of the staff. Three-dimensional laser scanning technology is an emerging measurement technology, in recent years has been widely used in high-voltage cable inspection research. yang et al. [4] According to the vertical parabolic model of a single power line and the linear model of the water surface, the complete power line is extracted by the model growth algorithm with an accuracy rate of 99.6%. Wu Qiangrong et al. [5] By calculating the distance between the convex envelope point of the vegetation point cloud data and the power line point cloud vector to determine whether it is a tree barrier hidden danger, to achieve the rapid detection of tree barrier hidden danger in transmission lines. Ma Weifeng et al. [6] The point cloud data and the equation of state are used to obtain the arc sag simulation equation, and the method is proved to have high simulation accuracy under the influence of four different kinds of weather. Wang Jun et al. [7] Combining the three methods of point cloud segmentation, cluster analysis and curve fitting, the fine 3D reconstruction of split conductors is achieved for the characteristics of split conductors. Lu Shihao et al. [8] A multi-source data modelling method is proposed, combining inclined aerial photography and UAV point cloud data for fine modelling, which can effectively improve the phenomenon of model distortion and missing. Ma Weifeng et al. [9] According to the effect of wind load on transmission line, the model curve under wind bias environment is established, and the least squares method is used to achieve the reconstruction of laser point cloud transmission line model in wind bias environment.

Aiming at the operational safety needs of high-voltage cables, this paper acquires multi-period high-voltage cable point cloud data by terrestrial three-dimensional laser scanning technology, and exports high-voltage cable point cloud data after point cloud data processing to establish a three-dimensional model of high-voltage cables. Then statistically change its vertical displacement and analyse the influence factors of high-voltage cable deformation.

2. Research Methodology

2.1 Data Acquisition Processing

Data collection was performed every Friday at 4pm from March to April 2023 and weather information such as temperature, wind and humidity at the time of scanning was recorded. Due to the long distance between high voltage cable towers, multiple scans are required before alignment to obtain complete point cloud data.The ICP (Iterative Closest Point) algorithm enables the stitching of point clouds [10] The ICP (Iterative Closest Point) algorithm can achieve point cloud stitching, which unifies the point cloud data with each individual coordinate system into the same coordinate system. The first point cloud data is used as the source point cloud, and the point clouds of the remaining stations are used as the target point cloud for alignment, the rotation matrix and translation matrix of each station are constructed and constantly debugged, and the Euclidean distances between eigenpoints of the same name are calculated, so that the best effect is achieved when the sum of the distances is the smallest, and the splicing is completed.

In order to facilitate the analysis, the point cloud splicing of the acquired four-phase high-voltage cable point cloud data, in this paper, the colour of the point cloud from phase one to four is set to yellow, blue, magenta and fluorescent green, and the hanging point of the high-voltage cable is taken as the common point for the alignment. It is observed that Fig. 1 shows that the point clouds of each phase are evenly distributed, and the density of the high-voltage cable point clouds increases with clear shapes.

2.2 Segmentation and Extraction of High Voltage Cables

Segmentation Extraction of High Voltage Cables Using a Density-Based Clustering Approach[11] . Two parameters need to be determined first: the radius epsilon and the minimum number of points MinPts. where epsilon is used to determine the neighbourhood range of data points with similar density and MinPts is used to determine whether a data point is a core point or not. Start by labelling all points as unclassified. Calculate the point P_i of the density of the data points ρ_i .

$$\rho_i = \sum_{j=1}^{n} \omega(d(P_i, P_j)) \qquad (1)$$

where n is the total number of points in the point cloud and $d(P_i, P_j)$ is the number of points P_i to the point P_j is the distance from the point. P_j is the distance from the point P_i is a point in the neighbourhood of the point, and ω is the kernel function, usually a Gaussian kernel function. All points with density greater than or equal to ρ_i {min} are labelled as "boundary points". For each cluster, start with all kernel points and expand along the density connectivity, adding all points connected to the density of the kernel points to the cluster. All unclassified boundary points are added to the cluster closest to them. After completing the clustering of all points, The selected points within the cluster where the high voltage cable is located are used to perform segmentation and extraction of the high voltage cable.

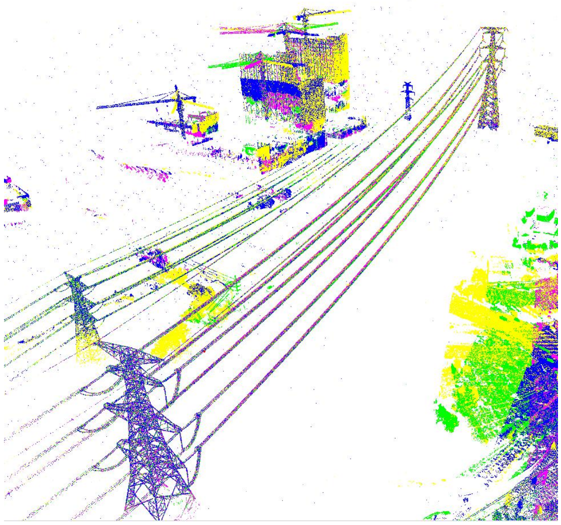


Figure 1. Comparison of different stations in point cloud fine splicing

2.3 High-voltage Cable Model Reconstruction

To model the high voltage cable, curve-fitting the point cloud of each cable is essential. The length of the high voltage cable is significantly greater than the diameter of the cross-section, which can be regarded as a flexible suspension cable in the ideal state, only considering the influence of its own gravity, and showing a natural drooping shape under the effect of gravity in the state of no wind bias. The point cloud of the high voltage cable contains geometric information that can be used to approximate the curve shape of the cable. This can be done by fitting a parabolic equation through curve fitting methods.

Curve fitting is based on the principle of least squares[12] . The principle of the algorithm is to minimise the sum of squares of the residuals between the fitted function and the sample data points. Suppose there are n sample data points (x_i, y_i) where x_i is the independent variable and y_i is the dependent variable. Suppose the function to be fitted is $y = f(x, \theta)$, where θ are the parameters to be fitted. The goal of the least squares method is to find a set of optimal parameters θ that reduce the sum of squared residuals between the fitted function $f(x, \theta)$ reduce the sum of squares of the residuals with respect to the sample data points, i.e.

$$\theta_{\min} \sum_{i=1}^{n} (y_i - f(x,\theta))^2 \quad (2)$$

The mathematical expression for the least squares method is given below:

$$\theta^* = \arg \theta_{\min} \sum_{i=1}^{n} (y_i - f(x,\theta))^2 \quad (3)$$

3. Example Analyses

3.1 Experimental Objects

Four experiments using 3D laser scanning of the transmission line between two towers as an object for the analysis of the deformation of high voltage cables were carried out using a RIEGL VZ-1000 3D laser scanner. The starting time was from 3 March 2023 to 3 April 2023, and the end time was from 3 March 2023 to 3 April 2023. There are eight conductors between the two transmission line towers, divided into four left and four right, with a length of 418.46 m. At the highest point, there are two lightning cables, and below them, there are six four-split conductors. The single point cloud data of the high voltage cables were extracted, and each cable line is numbered as in Figure 2.

3.2 Single Power Line Point Cloud Model

The deformation of high-voltage cables is affected by environmental factors such as weather conditions and topography. The change cycle of terrain and geomorphology factors is relatively long, difficult to predict and control, and its impact on cable deformation is often smaller than weather changes, mainly to analyse the deformation of high-voltage cables affected by different weather conditions and the relationship between the size of the impact.

For better curve fitting and deformation analysis of high voltage cables, each cable needs to be extracted and studied separately. The point cloud after extraction is treated separately as an independent cable point cloud model. The number of point clouds for each cable after segmentation is shown in Table 1.

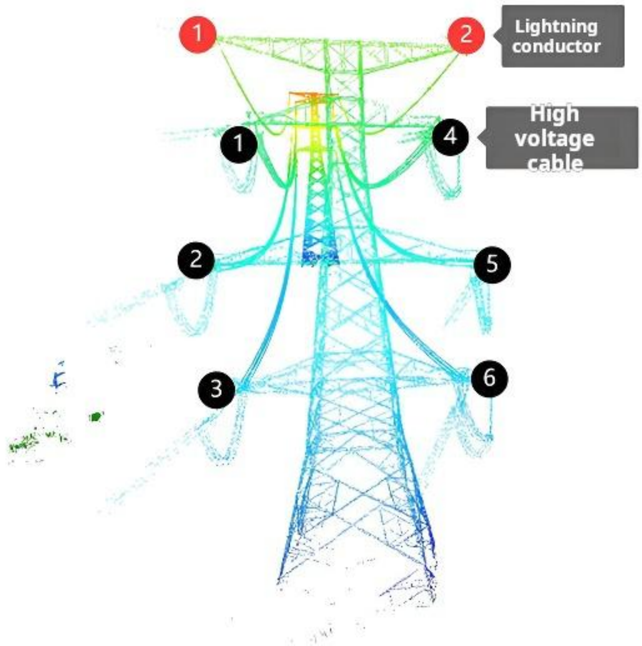


Figure 2. Schematic diagram of the cable line

Table 1. Number of power line point clouds (in units)

guidewire	one point cloud	two point cloud	triple point cloud	quadruple point cloud
Lightning cable 1	1701	1616	1474	1570
Lightning cable 2	2103	2097	1978	1988
High voltage cable 1	7758	7548	6887	7002
High voltage cable 2	7258	7027	6546	6606
High voltage cable 3	7042	7352	6985	7146
High voltage cable 4	8990	8892	8176	8278
High voltage cable 5	9255	9084	8495	8552
High voltage cable 6	8755	9044	8387	8450

Using the high voltage cable point cloud data, the mathematical model of a single conductor is obtained by fitting the spatial points using the least squares method. As the high voltage cables are suspended at both ends of the tower, the use of the plane where the high voltage cables are located is perpendicular to the ground can be chosen to convert the spatial coordinates of the high voltage cables. The X-O-Z plane is used as the mathematical simulation plane so that the 3D point cloud modelling problem is converted into a parabolic problem fitted on the plane.

After the completion of coordinate conversion, the X,Y coordinates of a single point cloud can be extracted and modeled using the least squares method.To improve data processing efficiency, the point cloud data of the high voltage cable is thinned out by reducing the number of points with a 0.5 m interval. This reduction in points significantly reduces the dataset, allowing for mathematical modeling. The number of point clouds is reduced significantly and then mathematically modeled, and the fitted parabolic equations are obtained by the least squares method, as shown in Table 2.

Table 2. Mathematical modelling equations for high voltage cables

power line	Number of original point clouds (pcs)	Number of thinned out point clouds (pcs)	simultaneous equations	R-value
High voltage cable 1	7556	359	$y = 0.0004x^2 + 0.1801x + 22.346$	0.9994

High voltage cable 2	7089	358	$y = 0.0004x^2 + 0.1765x + 21.994$	0.9993
High voltage cable 3	6841	352	$y = 0.0004x^2 + 0.1758x + 21.776$	0.9993
High voltage cable 4	7489	258	$y = 0.0004x^2 + 0.1742x + 20.352$	0.9994
High voltage cable 5	9081	372	$y = 0.0004x^2 + 0.1709x + 21.975$	0.9994
High voltage cable 6	8597	359	$y = 0.0004x^2 + 0.1708x + 20.463$	0.9994

From Table 2, it can be seen that the curve fitting R-value of each cable is at 0.9993, and the fitting effect is better. The curve fitting effect of HV cable 1 is shown in Figure 3, in which the blue points are the scanned HV cable point cloud data, the red curve is the fitting equation, and the horizontal and vertical coordinates indicate the horizontal and vertical coordinate sizes of the point cloud data in the X-O-Z plane respectively. It can be seen in the end point of the high-voltage cable at the error is slightly larger than the middle part of the analysis of the reasons for the error with the distance between the station and the target object, in order to facilitate the collection of data scanning station was set up in the high-voltage transmission towers below the end of the distance between the station and the station is greater than the middle part of the point of the error therefore exists.

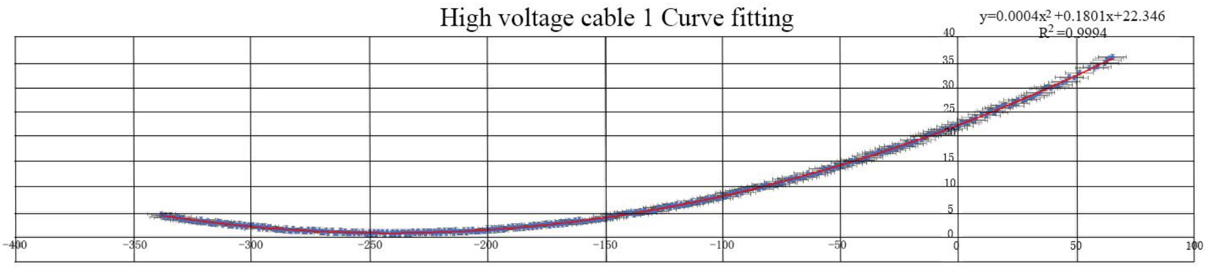
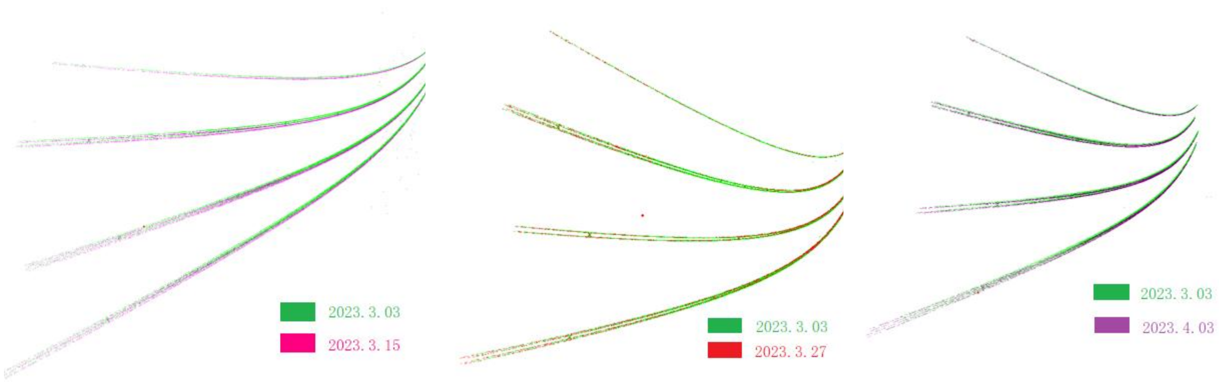


Figure 3. Curve fitting for high voltage cable 1

3.3 Deformation Comparison Analysis

The overall comparative analysis is based on the high voltage cable point cloud of the first period, comparing the deformation of the point cloud model in different periods as shown in Figure 4.



(a) Comparison of phase I and phase II point clouds (b) Comparison of Phase I and III point clouds (c) Comparison of Phase I and Phase IV point clouds

Figure 4. Overall deformation of the cable in all phases

The overall deformation of the high-voltage cable can be obtained by comparison, and the correlation between weather factors and the deformation of the high-voltage cable is further analysed by using the comparison of the characteristic points, recording the temperature, humidity, wind direction and wind power information at the time of scanning, and investigating the influence of different factors on the deformation, as shown in Table 3. Combined with the horizontal displacement of the high-voltage cable and the vertical displacement change of the overhanging point, the effect of different factors on the deformation is studied.

Table 3. Data scanning weather records

Data Acquisition Time	environmental temperature	dew point temperature	air humidity	wind trends	wind power
2023/3/3 14:00	62°F	31°F	31 per cent	SW	2mph
2023/3/15 17:00	75°F	53°F	46%	ESE	2mph
2023/3/27 17:00	59°F	41°F	52 per cent	E	2mph
2023/4/3 17:00	75°F	68°F	80 per cent	SSW	7mph

Since the cable is a four-split conductor, the same cable is seen to consist of two thinner cables in the vertical displacement direction. Measurement of displacement in order to pursue the accuracy of the conductor were measured on the two displacements. Single cable respectively its split conductor on the displacement changes, and finally the two displacement changes can be obtained by taking the average value of its changes in the vertical displacement.

By comparing the deformation of the cable in different periods, the wind force has a greater impact on the horizontal deformation of the high voltage cable. the wind force from 3 March to 27 March is relatively stable, all around 2mph, while the wind force on 3 April increased significantly to 7mph. from the data of the horizontal displacement, we can see that in the case of increased wind force, the horizontal displacement of the cable also increases. The increase in launching wind force will have an adverse effect on the stability of the cables. The horizontal displacement of each cable at different times and recording the raw data is shown in Table 4.

Table 4. Horizontal displacements of cables at different times (in metres)

dates	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
15 March	0.1450	0.0375	0.1169	0.0777	0.0762	0.0347
27 March	0.0099	0.0769	0.0328	0.0304	0.0328	0.0056
3 April	-0.2403	-0.1992	-0.1662	-0.1910	-0.1981	-0.1878

By comparing the deformation of the cable in different periods, the wind force has a greater impact on the horizontal deformation of the High-voltage cables have significant vertical displacement deformation, and the amount of deformation varies greatly between different cables. Under the environment of high temperature and high humidity, the high-voltage cable showed a larger amount of vertical displacement deformation, and the horizontal displacement of the conductor increased accordingly. Comparing the data of different dates, under the same temperature, the change of humidity has a more significant effect on the deformation of the cable in the vertical direction. The lowest overhang point of the HV cable on 3 March was used as the origin of the coordinates in the comparison process, with upwards being positive and downwards being negative in the vertical direction. On 15 March and 27 March, the humidity was 46% and 52% respectively, the vertical displacement deformation of the conductor increased about 0.5m and 0.1m compared with that on 3 March, and the horizontal displacement also increased accordingly. On 3 April, the humidity reached 80%, and the vertical displacement deformation of the conductor increased by about 0.1 m compared with that on 3 March.According to the raw data of water displacement change of the high-voltage cables listed in Table 5, the vertical change of a single cable at different times was integrated and counted.

Table 5. Changes in vertical displacement of cables (in metres)

dates	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
15 March	-0.4275	-0.4990	-0.4465	-0.4883	-0.4883	-0.4808

27 March	0.0556	0.0410	0.0338	0.0797	0.0214	0.1232
3 April	-0.2050	-0.3157	-0.2887	-0.2842	-0.3184	-0.2690

4. Conclusion

The operational safety inspection of overhead transmission lines based on LiDAR technology makes up for the shortcomings of labor intensity and long inspection cycle of manual power inspection. In this paper, we use terrestrial three-dimensional laser scanning technology to obtain high-voltage cable point cloud data, analyze the degree of deformation of high-voltage cables, and extract high-voltage cable point cloud using density clustering method, Deformation analysis of high-voltage cable arc droop was conducted by processing the scanned point cloud data. The results indicate that humidity plays a more significant role in influencing the deformation of the high-voltage cable arc droop compared to wind power. However, this method obtains the data of high-voltage cable at a certain moment, and cannot confirm whether it is in the maximum deformation at this time, which will affect the accuracy of the data. In the future, we can simulate the high-voltage cable trajectory by acquiring point cloud data over a specific time period, enabling precise analysis of its deformation characteristics.

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