ON-LINE MONITORING SYSTEM OF ICE-COVERED OVERHEAD TRANSMISSION LINE BASED ON MECHANICAL AND INCLINATION ANGLE MEASUREMENT

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Abstract**—In this study, mechanical analysis was conducted on the icing load of transmission lines, and the calculation method for the icing thickness was discussed. The icing monitoring system has been developed, based on the measurement of some meteorological information, including wind speed and direction, temperature and humidity, etc and axial tension of overhead transmission line, two-dimensional obliquity. By using GSM/GPRS network, data transmission was achieved between conductor monitoring terminal and central master station. The icing status was analyzed by the expert system software of master station, using relevant theoretical models, so that the deicing information could be provided promptly and the ice harm accidents could also be prevented effectively.**

Keywords-overhead transmission line; icing; on-line monitoring; tension measurement; mechanical model

I. INTRODUCTION

Affected by macroclimate, microtopography and microclimate condition, transmission line icing is fairly common in China. The accidents, including conductor breakage, tower collapse, flashover, occur frequently[1][2]. The glaze rarely seen before in parts of the southern China, in January, 2008, caused large area icing for transmission lines, and the icing thickness on some towers was evidently beyond current mechanical bearing ability of transmission lines, leading to severe tower collapse and the seriously affected operation of power grid.

A lot of research work on transmission line icing has been carried out by the design, research and operation institutes[3]. Of these research work, the main collected data[4-6] concerning icing monitoring system of transmission lines include on-site image, microclimate and temperature, conductor displacement and acceleration, obliquity of suspension point and tension at suspension point of the transmission lines.

The on-site image of transmission lines was visual, as a result, the icing condition could be judged by artificial or image identification, but the camera lens might be covered with snow and ice or frozen in adverse weather. Microclimate and the temperature of transmission lines are the main indirect parameters for judging the icing status. The obliquity of suspension point could reflect the effects of wind on transmission lines and the changes of the line state. The displacement and acceleration of transmission lines are important parameters to monitor the waving track of iced transmission lines. The steady state icing of lines was monitored by measuring axial tension in strain section and obliquity of suspension point with this system.

In this study, an icing monitoring system of transmission lines was designed based on the measurement of axial tension in strain section and obliquity of suspension point, and the design methods were expounded for the collection of tension signals on a basis of the mechanical analysis on the icing load of transmission lines. In addition, on-site installation and operation confirmed the effectiveness of this system.

II. MECHANICAL ANALYSIS ON ICING LOAD OF TRANSMISSION LINES

Icing is a physical process of latent heat release and solidification of liquid cooling water[7]. The quantity, thickness and density of ice depend on thermal equilibrium state on the icing surface.

The overhead transmission lines are regarded as flexible cables since their rigidity is usually ignored in engineering calculation[8-9], therefore, the inclined parabola formula

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could be used for transmission lines, and the error is within the allowable range of engineering.

The span of this transmission line hanging between A and B is *l*, the elevation difference between A and B is *h,* and the angle of elevation difference is *β.* Considering the influence of wind load on the whole span of transmission line, the stress of transmission line is shown in Fig.1, the inclined span l_{AB} is generally considered as the length of the transmission line, thus the angle contained by wind direction and transmission line is a fixed value in the same span. The load acting on the transmission line could be resolved into vertical specific load r_v and horizontal specific load r_h.

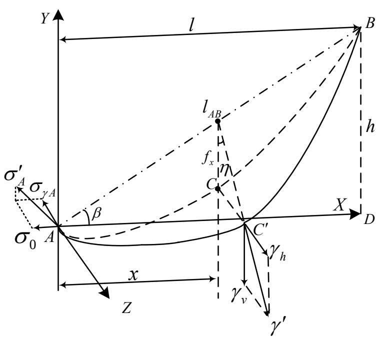

Fig.1 Mechanical analysis on transmission line

In the case of no icing on the transmission line, the self-weight specific load of the transmission line in a static state is:

$$r_1 = \frac{g_n q}{A} \tag{1}$$

Where, g_n is acceleration of gravity, *q* is mass of wire in unit length, and A is sectional area of wire. Meanwhile, considering the influence of specific load of wind pressure, the specific load of unit horizontal wind pressure of the transmission line is:

$$r_4 = \frac{v^2 D\alpha_0 \mu_{sc} \mu_z \mu_\theta \times 10^{-3}}{1.6A} \tag{2}$$

Where *v* is the actual wind speed, D is the external diameter of wire, α_0 is non-uniformity coefficient of wind pressure, μ_{sc} is shape coefficient of wire, μ_z is height variation coefficient of wind pressure, and the variation coefficient of wind pressure varying with wind direction μ_θ is set by referring to the reference[9].

After the icing, the difference in aerodynamic characteristics of ice shape on different sections was ignored[10], the covering ice was equivalent to circular section, and the influence of the change of mechanical load caused by steady-state icing analyzed by this system could be ignored. The abnormal value and change of axial tension could be directly used to judge the waving of iced transmission line.

Wind direction

The ice with different types and sections covering on the transmission line was converted into circular glaze section with the density of 0.9g/cm^3. According to the method of mass conservation, in the case of icing, the specific load of increasing icing is:

$$r_2 = 0.9\pi g_n b\left[\frac{b(b+D)}{A}\right]\times 10^{-3} \tag{3}$$

Where b is the icing thickness, and in the case of icing, the specific load of unit horizontal wind pressure of transmission line is:

$$r_5 = \frac{v^2 (D+2b) a_0 \mu_{sc} \mu_z \mu_\theta \times 10^{-3}}{1.6A} \tag{4}$$

The comprehensive specific load of the transmission line *r* is the combined effects of both horizontal specific load r_h and vertical specific load r_v., $r' = \sqrt{r_h^2 + r_v^2}$

The tension sensor which was placed between strain tower and suspended insulator, could measure the axial tension of transmission line. The axial stress of overhead suspension point A is:

$$\sigma'_A = \frac{\sigma_0}{\cos\beta} + r'\left(\frac{r' l^2}{8\sigma_0 \cos\beta} - \frac{h\cos\eta}{2}\right) \tag{5}$$

Where σ_0 is horizontal stress of transmission line in the vertical plane.

The included angle θ_{vA} between angle of wind deflection of transmission line *η* and the suspension point A in the vertical plane could be measured, when a calibrated two-dimensional angle sensor was fixed on the surface of tension sensor. The following formula is tenable for the included angle θ_{vA} relative to the suspension point A in vertical plane:

$$\tan\theta_{vA} = \tan\beta - \frac{r_v l}{2\sigma_0 \cos\beta} \tag{6}$$

The relation among the angle of wind deflection *η*, comprehensive specific load *r*, and vertical specific load r_v is $r_v = r' \cos\eta$.

According to the axial tension T_A of transmission line at point A measured by tension sensor and the included angle θ_{vA} between angle of wind deflection of transmission line *η* and suspension point A in the vertical plane measured by the angle sensor, and the horizontal stress σ_0 of transmission line in the vertical plane and the comprehensive specific load *r* of transmission line could be solved based on Formula (5)and (6) using the known parameters of transmission line and data of wind speed and direction.

According to the comprehensive specific load *r* obtained, by using the known data of wind speed and direction of transmission line, the icing thickness could be calculated, based on the calculation of specific load in Formula（1-4）.

The sag of a casual point in transmission line between A and B is:

$$f_x = \frac{r_v x(l-x)}{2\sigma_0 \cos\beta} \tag{7}$$

x is the distance between a casual point in transmission line and suspension point A in vertical plane, so that the sag f_x of a casual point in transmission line could be obtained.

As to n split wire, each split wire has similar icing condition. The covering ice is equivalent to circular section, and supposing that the comprehensive specific load of each split wire is r_n, and the vertical specific load is r_{vn}, then the horizontal stress of the split wire in vertical plane is σ_{0n}.

Here, the axial tension at suspension point A is the joint force of axial tension of each split wire, and the axial stress could be expressed as follows for the suspension point A of each split wire:

$$\frac{\sigma_A'}{n} = \frac{\sigma_{0n}}{\cos\beta} + r_n'\left(\frac{r_n' l^2}{8\sigma_{0n}\cos\beta} - \frac{h\cos\eta}{2}\right) \tag{8}$$

The Formula (6-7) are also fit for each split wire, and corresponding parameters should be changed to vertical specific load r_{vn} and the horizontal stress of each split wire in vertical plane σ_{0n}.

The comprehensive specific load of each split wire r_n and the horizontal stress of each split wire in vertical planeσ_{0n} could be calculated by Formula (6), (8), according to the measured tension and obliquity, so that the icing thickness of each split wire and overall icing condition of n split wire could also be calculated.

III. THE COMPOSITION OF THE ICING MONITORING SYSTEM OF TRANSMISSION LINE

The icing monitoring system of transmission line is mainly composed of monitoring terminal of transmission line, central master station and expert system analysis software. Data transmission between monitoring terminal of transmission line and central master station is carried out using GSM/GPRS network[11]. The monitoring terminal of transmission line is composed of tension sensor, obliquity sensor, wind speed and direction sensor, temperature and humidity sensor and solar radiation sensor, which are installed between strain tower and insulator string of the transmission line. The whole collection process and data transmitted by GPRS module are controlled by master control MCU. The power of whole terminal is supplied by solar power system[12]. The topologic structure of the whole system is shown in Fig.2.

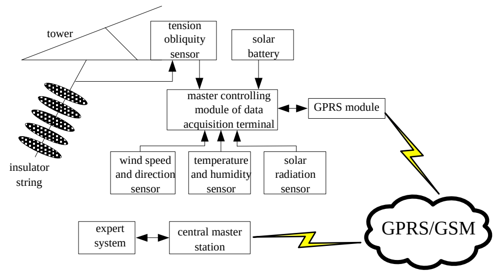

Fig.2 Topologic structure of the whole system

According to the given acquisition strategy, the master control (MCU) of transmission line monitoring terminal would be responsible for controlling the acquisition of axial tension of wire, two-dimensional obliquity of suspended wire, wind speed and direction, temperature and humidity of environment, solar radiation temperature, etc., then the data are packed and transmitted to central master station by using short message service(SMS) of GPRS module or general packet radio service(GPRS). At the same time, according to the actual needs, central mater station could set the parameters of monitoring terminal of transmission line (such as acquisition strategy, real-time data request, data transmission mode).

After receiving collected data of monitoring terminal, according to the expert system analysis software, master station will analyze the icing condition of the monitored transmission line by using icing-related theory model. The whole system could monitor stress, obliquity, sag of transmission line, and analyze the icing development process and severity, and sound the alarm in time, when the tension of the transmission line exceeds the maximum working tension, so that the occurrence of ice harm accident could be prevented. A large quantity of real-time data of transmission line icing could be collected by this system, which is of great significance to the in-depth study on the icing theory.

IV. MECHANICAL SIGNAL ACQUISITION AND PROCESSING

A. Tension obliquity sensor and it's installation

Considering the factors, such as tower construction, differences in insulator types and strength of sensor construction, after mechanical strength and corrosion prevention experiments being conducted, the adopted tension sensors in this system are completely in line with the demand of non-standard hardware. The double-arm bridge in this tension sensor is used to measure equivalent circuit. The tension makes the strain gauge produce strain, so that the resistance value of bridge arm is changed, then corresponding tension signal is produced and the comprehensive output precision is less than 0.05%.

Two-dimensional obliquity sensor is adopted in this system; high-performance integrated sense components are applied in it, and it could accurately give corresponding standardized analog output caused by the obliquity change of orthogonal two direction of X and Y. The resolution is 0.015°. The direction of X and Y is calibrated, so that the change of angle could respectively reflect the obliquity θ_{vA} at suspension point A in vertical plane and angle of wind deflection η of the transmission line.

The both ends of tension sensor are suspended span configuration which attaches between strain tower and insulator string passing through P-shape hanging plate, adjustment plate and U-shape hanging ring. The obliquity sensor is fixed on tension sensor, and the field installation of tension obliquity sensors is shown in Fig.3.

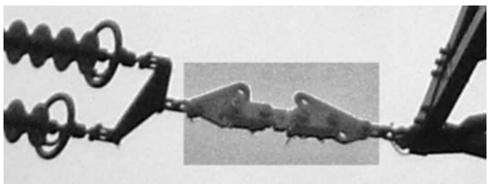

Fig.3 Field installation of tension obliquity sensor

B. Tension sensor measuring circuit

In the whole icing monitoring system, the tension data provided important basis for calculation and analysis, and the measuring precision of the tension data would directly affect analytical accuracy of whole system. The output signal of tension sensors was feeble, (the output sensitivity of tension sensor in this system was 1.24mV/V), and the power was supplied by monitoring terminal of transmission line.

The output precision would be affected by the stability of power supply of tension sensors. The high-precision low temperature shift voltage reference ADR01, manufactured by Analog Devices Company, was adopted in this system, it’s initial precision was 0.1%, and would provide stable reference voltage of 10V to tension sensors in combination with the driving circuit.

Because of the feeble output signal of tension sensors, (the output of full scale tensile force was only 12.4mV), the signal conditioning was necessary to amplify the coordination with circuit, and the configuration of tension signal conditioning circuit is shown in Fig. 4.

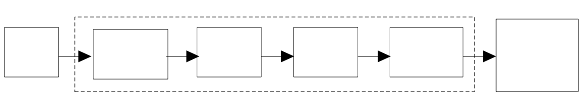

Fig.4 Configuration of tension signal conditioning circuit

The over-voltage protection circuit, using the coordination between gas discharge tubes and transient voltage suppressor, could clamp the over-voltage transmitting to the terminal system through the circuit to a safe voltage level, in order to prevent the post circuit from being affected. The measured tension signal was low frequency signal; the differentiator was low-pass filter, so that the high-frequency noise which affected the measurement should be removed. The instrument operational amplifier AD621 with high common-mode rejection ratio, low power consumption and high precision, was adopted in pre-amplifying circuit, so as to amplify the output signals of tension sensors. To cut off the return circuit of interference signals induced by signal line, a high precision linear optical isolation was adopted in tension signal conditioning circuit, so as to isolate analog signals from digital acquisition. Through tension signal conditioning circuit, the intrinsic feeble signals output by tension sensors were amplified effectively, which made master control (MCU) conduct AD conversion accurately.

To reduce the interference of strong electromagnetic field during the signal transmission, the double-shield cable conductor was adopted for all signal lines to measure sensors, and they were grounded effectively near the tower insulator joint and terminal shielding box.

V. FIELD EXPERIMENTAL DATA AND ANALYSIS

To verify the performance of this system, the monitoring system has been installed on 1110kV transmission line of a certain power grid in South China. The wire of transmission line is steel-cored aluminum strand of LGJ-300/40, its comprehensive sectional area is 338.89mm^2, diameter is 23.94mm, linear expansibility is 19.6×10^{-5}℃$^{-1}$, elasticity coefficient is 73kN/mm^2, the mass in unit length is 1.133kg/m, the maximum working tension is 27464N and fracturing tension is 87609N. The monitored representative span of strain section is 236m, the height of suspension point of installed tower transmission line is 25m, and elevation difference of suspension point is 4m.

According to the tension obliquity and meteorological information obtained by the field measurement, the comparison between maximum sag acquired by calculation and the on-site measured value of transmission line is shown in Table 1.

Tab. 1 Maximum sag of field measurement and calculated values

wind speed(m/s)	3.43	4.21
aligned wind direction(degree)	95	79
tension(N)	14317	14363
obliquity of X-axis(degree)	6.24	6.2
obliquity of Y-axis(degree)	0.73	1.06
measured maximum sag(m)	5.23	5.19
calculated maximum sag(m)	5.41	5.4

By comparison, the error between the maximum sag obtained by measurement and calculation of this system and measured values is small, and it is estimated through the measurement of tension obliquity and meteorological information that the status of strain section, could satisfy the engineering requirements quite well.

Supposing that the wind speed is 5m/s in case of icing, the wind direction is vertical to the transmission line, and the temperature of iced transmission line is fixed, the relationship simulation among icing thickness, axial tension of transmission line and obliquity at suspension point in the vertical plane of wire is shown in Fig.5. The icing load could be calculated with the measured data in the icing state, so that the icing severity could be deduced.

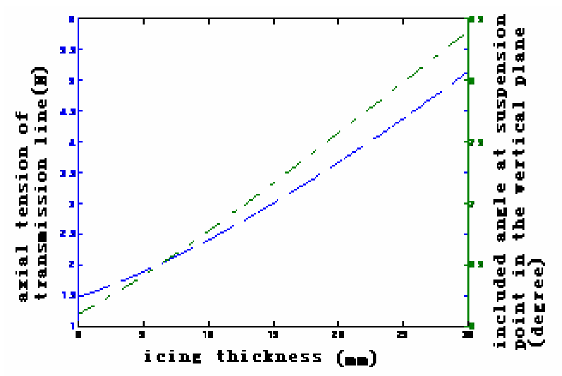

Fig.5 The relations among icing thickness and axial tension of transmission line and obliquity at suspension point in the vertical plane

When severe icing occurs to transmission lines, the tension of transmission lines might exceed its maximum working tension, inducing plastic deformation and even breakage accidents. In case of the transmission line waving caused by icy wind, the abnormal tension value with cyclic variation of transmission line could be reflected by this system effectively.

VI. CONCLUSION

In this study, the mechanical analysis was conducted on the icing load of transmission line, and the icing thickness of it was calculated on the basis of analyzing the icing mechanism. The measures of anti-electromagnetic interference were adopted, and the reliable operation of transmission line monitoring terminal was realized. The central master station obtained the monitoring data through the GSM/GPRS network and analyzed the icing condition of transmission lines using icing theory model according to the expert system analysis software.

The axial tension in strain section directly reflected the mechanical action of transmission line load on the tower, and the obliquity at suspension point was also an important parameter in the mechanical analysis. This system could realize real-time monitoring for the icing condition of transmission lines so that the icing harm accident could be prevented effectively. A large quantity of icing data were collected to provide basic information for the design of transmission lines and study on icing theory. At the same time, this system could also be used to monitor conductor sag, average temperature, and dynamically estimate allowable transmission capability of lines, which could improve the operation and management of transmission lines.

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