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Wire Torsion Measurement for the Tasks of Monitoring of the Mechanical State of Overhead Power Transmission Line

D. A. Yaroslavsky
Kazan State Power Engineering University
Kazan, Russia
fbox52@gmail.com

D. A. Ivanov
Kazan State Power Engineering University
Kazan, Russia
ivanov.da@kgeu.ru

Vu Nguyen
Kazan State Power Engineering University
Kazan, Russia
vu2307@gmail.com

***Abstract*—A system of overhead power transmission line monitoring was developed to assess the effect of mechanical loads in a wire/ground wire on its torsion angle. The system allows measuring the torsion angle of the wire, helps to prevent possible overhead power transmission line damage by tracking the tension force, as well as conductor and pendant fitting defects. It includes a control device, a data station, and a dispatch software package. Controllers are installed directly on the wire/ground wire of the overhead power transmission line. The rotation and elevation angles and wire temperature are measured. Input data are processed in the data station with specialized software. The developed system for monitoring the state of overhead power transmission lines, which takes into account the wire rotation, will reduce the costs associated with their maintenance and repair.**

Keywords—overhead power transmission line, wire, ground wire, tension, inclinometry method, monitoring system, wire rotation, wire torsion

I. Introduction

Electric power is transferred from power plants or substations to its consumers via power transmission lines (mainly overhead ones), which are a part of the electric power system. Overhead power transmission line (OHTL) is used for transmitting electric power through wires hanging in the open air and secured with insulators and linear fittings to the supporting structures.

It is difficult to inspect OHTL for all possible failures, because wires are extremely long. For example, the total length of OHTL in the Russian Federation is more than 2.8 million km [1,2]. Another problem with maintaining transmission facilities in a proper operating condition is the high level of equipment wear (up to 70%) [3] aggravated by the ongoing increase in electric power consumption and, therefore, new OHTL sections being commissioned. Thus, OHTL monitoring and timely prevention of possible accidents are desperately needed.

The integral structural elements of OHTL are wire, insulators with line hardware, and supports (towers and footings). These elements experience various mechanical loads and can become destroyed if their ultimate strength is exceeded [4,5]. Notably, OHTL are built in areas with different climatic conditions, which also affects the mechanical strength of their elements.

The load upon the OHTL structural elements is both horizontal (mechanical stresses in a stretched wire) and vertical (produced by their own weight or by the weight of the wire). The wire is an OHTL element, in which changes in the mechanical load on the OHTL are observed. Suspended from the supports of an overhead power line wire/ground wires are subject to internal stresses, which depend on the temperature of the wire/ground wire. The vertical load from the dead weight of the wire/ground wire is evenly distributed along the length of the overhead line.

This is due to changes in the tension force of the wire depending on temperature, ice and rime deposits (IRD), and wire oscillations caused by the wind disturbances. The main mechanical tensions in the OHTL wire are associated with its elongation [6–11].

Mechanical overloading of the OHTL structural elements is caused by IRD, fatigue of an OHTL element, errors in the line construction, and remedial measures. Among the listed factors, IRD have the most serious consequences. They can cause:

- Hauling wires between adjacent spans and rapprochement of wires between themselves.
- Swaying and rapprochement of wires due to a jump because of non-simultaneous dropping of ice deposits.
- Intense wire swinging, causing short circuits between wires/ground wires, burns of its, and in some cases damage to linear fittings and fixtures.
- A significant overload of wires and their breaks.
- Destruction of supports as a result of wire breakage during overload from ice, when unbalanced stresses on supports from remaining whole wires significantly exceed the calculated ones, as well as when ice is combined with strong wind.
- Overlap of the linear insulation of the overhead power line during melting due to a significant decrease in the ice discharge characteristics of insulators compared to moisture discharge characteristics, which usually select the required level of linear insulation.

It is important to first accurately localize the site of accident or defect, because moving along OHTL is often complicated (deep snow, natural barriers, marshlands, terrain, etc.) and the speed of preventing/overcoming an accidental situation is directly related to the financial losses incurred.

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To solve the problems of detecting accidents on long sections of power lines, the current level of technological development allows the creation of automated systems for monitoring and diagnosing the technical condition of overhead power lines. There are several methods for implementing such systems: location, sensor, using robotic or unmanned vehicles and others [5, 10]. The authors of the study used a sensor-based approach to implement a monitoring system.

II. A Model of the Method for Determining the Wire Tension Force with Account of the Torsion Angle

A promising method for evaluating the mechanical load on a wire is that one based on measuring the inclination angle of various objects relative to the gravitational field of the earth [7]. The accuracy of this method can be improved by using data from sensors with higher accuracy in determining the angle of wire torsion and by developing a technique for converting data on the angle of wire torsion into the actual mechanical loads. This is possible, because *the wire/ground wire rotates around its axis when stretched.*

Wires and ground wires for OHTL have a stranded structure, thereby resembling a highly flexible rope made of twisted wires.

When twisted, each wire, except the central one, is located along a helix. Fig. 1 shows the images of wires and ground wires used in OHTL.

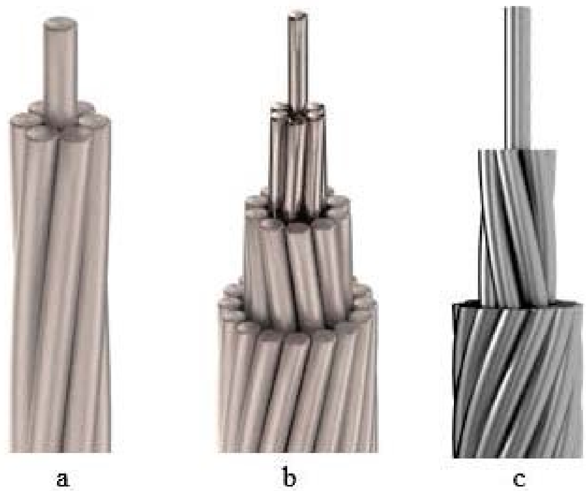

Fig. 1. Wires and ground wires: a is the A-70 wire; b is the AS-120/19 wire; c is the GTK-50 ground wire

Due to residual mechanical deformations after twisting, the wire/ground wire rotates around its axis when stretched [11].

As stranded wires and ground wires are similar in their structure to ropes, the rotation around their axis is assessed based on the theory of strength calculation for steel ropes [12] as applied to the existing inclinometry [13], which takes into account thermal expansion [14] and elastic deformations [16] in the wire. Thus, the dependence of the tension force of the wire/ground wire in a span with anchor support on the angles of its torsion and inclination, as well as its temperature, was obtained:

$$T = \frac{(l+L_0\cdot ch(u)) - \sqrt{(l+L_0\cdot ch(u))^2 - 8L_0(\varphi_1-\varphi_0)\frac{B}{C}}}{2\alpha^* L_0\cdot \cos(\alpha)}, \quad (1)$$

where l is the span length, m;

$$u = ln\,tg(\frac{\pi}{4}+\frac{\alpha}{2}), \quad (2)$$

where α is the angle of wire inclination at the suspension point with respect to the straight line running through the suspension points of the span;

$\alpha^* = (A - C^2/B)^{-1}$ is the specific relative elongation of the wire, N^{-1};

A is the rope stiffness in elongation, N;

B is the rope stiffness in twisting, N•m^2;

C is the wire stiffness coefficient (influence coefficient), N•m;

L_0 is the length of an unstretched wire at the current temperature, m;

φ_1 is the angle of rotation of the wire around its axis at the current mechanical loads on the wire and the ambient temperature until IRD appearance, ºC;

φ_0 is the initial angle of rotation of the wire around its axis until IRD appearance, ºC.

The results of the numerical calculation of the parameters of the ground wire in a span confirm that the physical and mechanical principles in the model for calculating the tension force based on the torsion angle are correct.

However, in reality, this technique can be used only in spans with a single anchor support and at the torsion angles of the wire/ground wire up to 180º, which is due to structural limitations of the wire/ground wire torsion during attachment to the support.

The advantages of the model for determining the tension force of the wire/ground wire based on its torsion angle are as follows:

- Evaluation of elastic interactions in the wire/ground wire.
- Evaluation of the temperature effects on the mechanical loads of wires/ground wires.
- Dependence of the mechanical load parameters on the angle of wire/ground wire torsion around its axis, which is important because of a greater operating range of the control device in terms of the torsion angle, as compared to the inclination angle.

III. Hard- and Software

The system for monitoring the state of overhead power transmission lines consists of special hardware and metrological tools [17] (control devices), as well as specialized software (SW).

Control devices [18] are installed on the wire/ground wire in proximity to the suspension point from the side of the anchor support (Fig. 2) and are used to measure the torsion and inclination angles, as well as the wire/ground wire temperature.

Fig. 2. Control device installed on the 6 kV overhead power transmission line

The developed devices are powered by taking off power with the magnetic component of the wire electromagnetic field. The critical difference between the developed monitoring device from all similar devices (the sensor system for monitoring and control of freezing [17] and the ASTROSE system [19]) is that it contains a module for measuring the angle of wire rotation around its axis, the accuracy of measurement of the torsion angle by which is brought to the level of accuracy measured for the inclination angle of the wire. The flow diagram of the developed controller is shown in Fig. 3.

The controller includes the following sensors:

- STS21, temperature sensor, +-0.2%, I2C, -40 +125.
- HCPD-3V-S2, I2C relative humidity and temperature sensor, 2%.
- ADXL213AE, dual-axis accelerometer, 0.01%.
- ADXL355, three-axis accelerometer, 0.01%.

In our variant of implementation of the device for monitoring the OHTL mechanical parameters, the resolution of the torsion angle of the wire/ground wire equaled the resolution of the inclination angle of the wire/ground wire, i.e., it increased from 0.1º to 0.01º. This made it possible to use data on the rotation angle of the wire/ground wire, thereby increasing the accuracy of measurement of the mechanical loads on OHTL.

The SW of the automated system for monitoring of the mechanical parameters of OHTL performs the following functions:

- Data collection.
- Data storage.
- Processing of data.
- Visualization of the current state of the OHTL under investigation with the ability to view statistical data for the entire period of operation of the system for monitoring of the OHTL mechanical parameters.

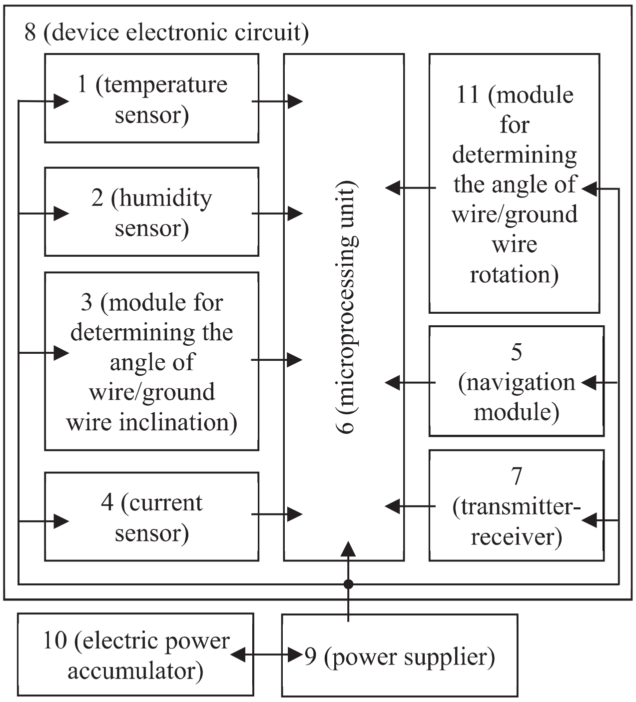

Fig. 3. Structural flow diagram for the control device

Elements of the developed SW are installed on the control devices, data collection station, and data processing station.

The SW installed on the controllers of OHTL mechanical parameters enables development of a self-organizing network based on the protocol of communication channel organization for the IEEE 802.15.4 wireless sensor networks, thereby providing sufficient reliability, low power consumption, and a sensor network of 216 nodes [20].

Data from the control devices go to the data collection station. The data are then transferred to a cloud server and a computer, where they are processed by the developed methodology with the specialized SW. The processed data are available for dispatching and monitoring through the web-interface.

When the mechanical loads on OHTL are determined, the SW processes data on the angle of both inclination and torsion of the wire/ground wire. The mathematical model of the SW calculates values of the tension force in the wire based on its physical and mechanical characteristics, length of the unstretched wire, and parameters measured with the help of the control devices [21].

IV. Practical Application of the Developed System for Monitoring of Overhead Power Transmission Lines

The system for monitoring the state of overhead power transmission lines identifies mechanical loads on their wires/ground wires. The mechanical loads are mainly caused by temperature changes in the geometry of the wire/ground wire and by IRD on it. Tracking of the OHTL mechanical parameters helps to control both IRD and defects on the line.

Comparison with the standard inclinometry method [7] based on the tension force at the suspension point was performed to verify the developed method. The real sag and twisting values of the wire from the controlling devices of the OHTL monitoring system were used as the initial data for calculation.

The tension force of the 6kV OHTL with the A-70 wire was calculated based on the real data for the case with IRD (Fig. 4).

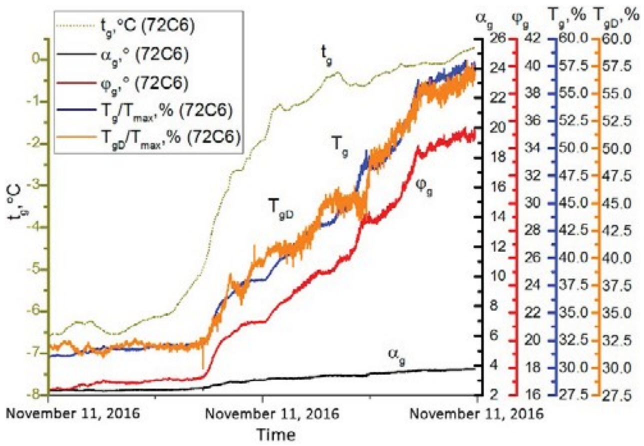

Fig. 4. Behavior of the A-70 wire with IRD: t is the wire temperature; α is the angle of wire inclination, ϕ is the angle of wire torsion; T_{gD} is the wire tension force calculated by the standard method, T_g is the wire tension force calculated by the developed method

Calculation of the OHTL with IRD was carried out for a span of 39.6 m with a single anchor support. The geometrical parameters of the OHTL were determined based on the photogrammetry of the obtained images of the line [22,23]. The coefficients in the formula for calculating the tension force of the wire had the following values: $B = 1.42 \cdot 10^3$ N*m^2; $C = 3.77 \cdot 10^4$ N*m; $\alpha^* = 3.033 \cdot 10^{-7}$ N^{-1}. The wire temperature varied from -6.93 to 0.29 ºC. The length of the unstretched wire at the current temperature changed in the range from 39.596 to 39.602 m. The initial torsion angle was – 5.56 º. The inclination and torsion angles of the wire during the period under consideration changed from 2.22 º to 3.8 º and from 15.64 º to 35.54 º, respectively. The calculation was performed by the standard and developed methods with regard to the angle of both wire inclination and torsion. The resulting tension force varied from 1162 N to 2252 N according to the standard method and from 1161 N to 2254 N according to the new method.

An increase was observed in the ratio of torsion angle variations with respect to the range of variations in the angle of inclination of the wire along with an increase in the tension force acting on the wire. This indicates a greater sensitivity of the torsion angle to changes in the tension force of the wire than in the angle of inclination.

V. Detection of Defects in the Strands of the OHTL Wire

The results of experimental studies of the effect of wire breakage defects on the wire rotation (torsion) are plotted and shown in Fig. 5 (A-70) and Fig. 6 (AS-120/19).

The breakage of the A-70 wire strands caused an almost linear increase in the change of the rotation angle (Fig. 5), indicating the possibility of diagnosing the degree of the defect by changing the rotation angle of the wire as the wire temperature changes in a given range.

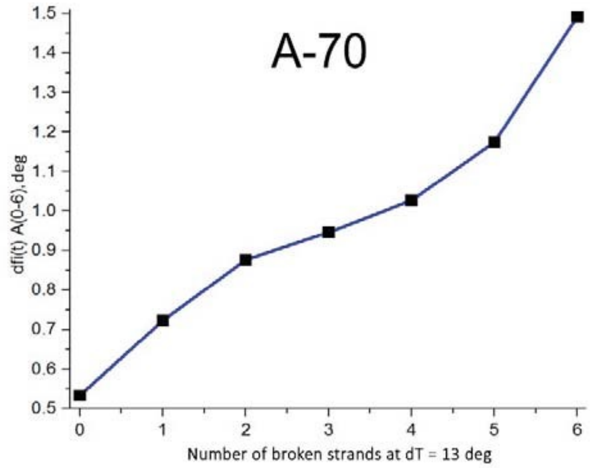

Fig. 5. Dependence of the torsion angle in the A-70 wire on the number of broken strands (from 0 to 6) upon changes in the wire temperature by 13ºC

Therefore, when a breakage-related defect occurs in the wire, the torsion angle changes in a greater range with the same changes in the wire temperature.

VI. Conclusions

Wire/ground wire torsion development upon stretching was described. A model for calculation of the tension force in the wire/ground wire based on its physical, mechanical, and geometric parameters and taking into account the torsion angle was proposed. A hard- and software complex, measuring the key variable parameters of wires during their use, for monitoring the OHTL state was described.

Feasibility of the system for OHTL monitoring based on the method of calculation of the tension force and torsion angle of the wire/ground wire was substantiated. The efficiency of the developed monitoring system for solving the following tasks was proved:

- Identification of the mechanical loads on wires/ground wires of OHTL with and without IRD.
- Timely detection and control of wire defects associated with strand breakage.
- High accuracy of measuring the torsion angle of the wire.
- Software allows us to measure, collect, process and store data on the angle of torsion of the wire.

- Software for final processing and visualization of data allows you to determine the tensile forces of the wire in accordance with a method that takes into account the angle of torsion of the wire.
- Identify areas of overhead lines with wire defects in overhead lines based on statistical data.

The effectiveness of the proposed methodology and automated monitoring system based on the results of laboratory and field tests has been experimentally confirmed. Verification was carried out by direct measurement.

Introduction and further development of the system for automated monitoring of the OHTL technical state will minimize losses during electric power transmission and enable timely repair of wires in order to maintain normal operation of OHTL.

The direction under study has prospects for further scientific development, for example, in the field of determining the degree of development of wire defects, taking into account wind effects, automatic initial calibration of the system, etc.

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