The application of the technology of sensor networks for the intellectualization of the overhead power transmission lines

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Abstract. The length of overhead power transmission lines in the Russian Federation is over 2.8 million kilometers. Power grids are rapidly becoming obsolete. The level of deterioration of the equipment achieves 70% [1]. This leads to breakdowns on overhead power transmission lines and reduce the quality of electricity supply. One of the focus areas towards improving the situation is a deep modernization of the power grid with an orientation on energy efficiency. The purpose of this work is the creation a system for operative monitoring of the technical condition of high-voltage power-transmission lines based on modular devices. The modular device is configured depending on the issues at hand: control of ice formation; control of ice melting; localization of the place of short circuit, breakage, lightning strike; determination of electrical loads on the wire or control of the load of overhead power transmission lines; determination of mechanical loads at the wire suspension point; determination of conditions for the occurrence of ice formation, determination of defects in insulators. This will equip the overhead line diagnostic systems without serious financial costs by simple installation on the wire of the developed device which design allows to change the configuration of the equipment and solve a wide range of tasks.

1 The system for operative monitoring of the technical condition of high-voltage power transmission lines

Our system for operative monitoring of the technical condition of the overhead line includes the developed modular devices [2, 3], installed on the overhead line wires, transmitting information through each other and powered directly from the line. The topology of the sensor network depends on the tasks that needs to be solved (the location of the sensors on the line is influenced by the task of diagnosing the parameters of the overhead line and the need for data retransmission). The reservation of communication channels is implemented which implies transmission of the data bypassing the defective device, not only within one phase wire, but also through devices on adjacent phase wires. The data acquisition module can be replaced by another, depending on the monitoring tasks, and can be used as an infrastructure for data transmission. Data from modular devices is collected on a "cloud" server where it is processed. The processed data is available for dispatching and monitoring via the web-interface.

The modular device is served as a hub of the sensor network (Fig.1), consisting of the main board with a microcontroller and communication module [4]. The device is installed directly on the phase wire (Fig. 2,3). Modifications are possible with the autonomous power supply module, the electrostatic power supply module – for 110 kV lines and above with power take-off from the overhead line, the electromagnetic power module – for lines up to 110 kV with power take-off from the overhead line. Primarily, they are made with sensors for distribution networks with voltage of 35 kV and lower, since these air lines are the least surveyed, but at the same time the longest. In this type of networks, the radial-trunk (tree) structures are dominating.

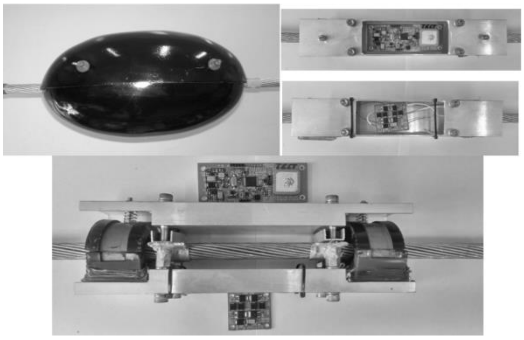

Fig. 1. Modular device.

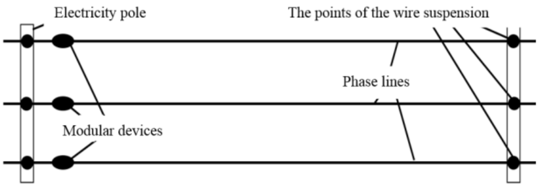

Fig. 2. The points for installation modular devices on overhead lines on each phase line.

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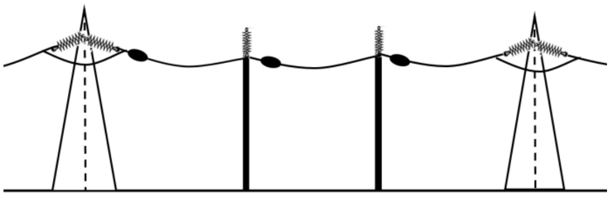

Fig. 3. Section of overhead power line between two adjacent anchor electricity poles, equipped with modular devices.

The modular device is configured depending on the tasks need to be solved (Fig.8): control of ice formation; control of ice melting; localization of the place of short circuit, breakage, lightning strike; determination of electrical loads on the wire or control of the load of transit overhead lines; determination of mechanical loads at the wire suspension point; determination of the conditions of ice formation, determination of defects in insulators.

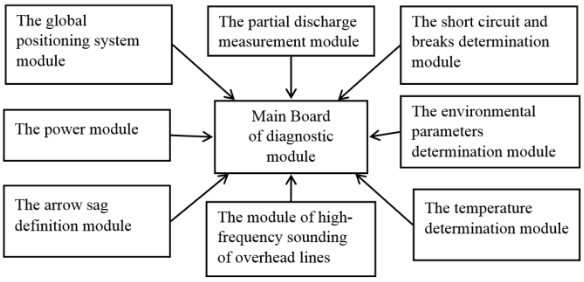

Fig. 4. Flowchart of the modular device.

Control of icings is achieved by installing the arrow sag definition module and/or module of measuring high-frequency parameters of overhead lines. The sag is determined by accelerometers that transmit information about the angle of inclination of the sensor installed directly on the wire. The sag depends the ice load on the wire. However, hauling wires between adjacent spans also should be taken into account.

When high frequency sensing is carried out, we detect of signals reflected from the inhomogeneities of the wave resistance of the line. The appearance of ice on the wires of the line is detected by reducing the amplitude and increasing the delay of the pulse reflected from the end of the line [3].

Localization of the place of short circuit, breakage, lightning strike is realized by installing a current sensor and a module of the global positioning system. The global positioning module is used to define address of a diagnostic device. A more accurate localization will be observed if the devices are installed at the beginning and end of the overhead power transmission lines.

Determination of electrical loads on the wire or load control of transit overhead lines is carried out by installing a temperature determination module of the wire. It allows the optimization of the line load, taking into account current losses and thermal effects on the wire.

Determination of mechanical loads on the wire is carried out thanks to the module for determining the sagging arrow. It is determined the current mechanical effects experienced by the wire, as well as the level of wear of the overhead power transmission lines.

The determination of the conditions of occurrence of icings is achieved through installing the environmental parameters determination module. This module includes a wire temperature sensor, air temperature sensor, and relative humidity sensor. The module allows to identify the point of desublimation [3].

Defect detection in high-voltage insulators is carried out using a partial discharge (PD) detection module. The module consists of electromagnetic sensor, phase sensor, antenna for data transmission, analog-to-digital converter, microcontroller. According to the developed technique, the module determines the triangulation of partial discharges and their number and amplitude. This allows us to draw conclusions about the development of a defect in insulators and determine the residual life.

Wireless data transmission is carried out using modules based on its own protocol "smart wire", which is a modification of the IEEE 802.15.4 standard [6,7]. It allows organize inexpensive and capable of self-recovery network. It increases the reliability of the system as a whole.

The installed deviceson the power line collect pre-processing and accumulation of data on the sagging angle, ambient temperature, wire temperature, ambient humidity and the current value of amperage.

Data from sensors are collected on a "cloud" server, where they are processed according to the developed model. The processed data is available for dispatching and monitoring via web-interface and/or IEC-61850.

The project is creating a system for monitoring the status of overhead lines on the basis of sensor installed directly on the line. The status of the overhead line can be monitored in real time, timely notifying the relevant services. The monitoring system will:

- optimize the capacity (more effectively manage existing overhead lines, which is especially important in conditions of high load density in large cities of the Republic of Tatarstan);
- reduce losses and minimize external impacts on power lines due to early detection of defects on overhead lines and prevention or early elimination of emergency situations due to the rapid localization of the defect site;
- information from the sensor network, as well as information processed by mathematical models can be used by the system of emergency and regime automation, as well as automated systems of electricity metering;
- the sensor network itself can be an automated system of electricity metering;
- make prediction of the status of overhead lines [9].

2 Methods for monitoring ice deposits on overhead lines

On worn-out overhead power lines, the effect of pulling the wire from one span to another (misalignment) is observed, which, over time, leads to the appearance and development of defects in linear fittings. In this regard, a mathematical model is proposed that takes into account the misalignment of linear reinforcement on overhead lines.

Consider the effect of elastic deformation obeying Hooke's law on a wire. We will solve the problem by rigorous methods (within the framework of the absolutely flexible thread model) [8,9,10]. Place the wire as shown in fig. 5.

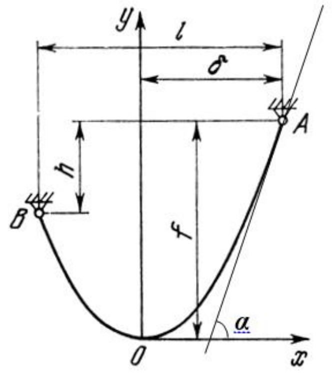

Fig. 5. Kinematic diagram of wire sag with designations of basic geometric parameters.

For a stretched wire, the force of gravity *q*, per unit length of the wire, is a variable value that depends on the tangential tension *T*. Therefore, for a wire subject to linear deformation, in the equation, *q* can be expressed by the following relationship

$$q = \frac{q_0}{f(T)} \tag{1}$$

where q_0 is the force of gravity per unit length of the still unstretched wire, $f(t)$ is the law of elongation.

When stretched according to Hooke's law

$$f(T) = 1 + \beta T \tag{2}$$

where β – specific elongation of the wire, therefore,

$$q = \frac{q_0}{1 + \beta T} \tag{3}$$

Based on the well-known hyperbolic model of the equilibrium of the wire [8] under the condition h = 0, the equilibrium equations for the wire take the form

$$\left\{\begin{array}{l} u = \frac{1}{2}\left(\frac{l}{a} - \beta q_0 L_0\right) \\ \operatorname{sh} u = \frac{L_0}{2a} \end{array}\right\} \tag{4}$$

where $u = \ln \operatorname{tg}(\frac{\pi}{4} + \frac{\alpha}{2})$, L_0 – the length of the wire without stretching, and is the shape factor of the hyperbola.

For h = 0, the expressions for the wire length *L* and the sagging arrow *f* are

$$L = L_0 + \frac{\beta}{2} a q_0 \left[l + L_0(\operatorname{ch} u - \beta a q_0)\right] \tag{5}$$

$$f = a\left(\operatorname{ch} u - 1 + \frac{\beta}{8} q_0 \frac{L_0^{\ 2}}{a}\right) \tag{6}$$

If we exclude a and express L₀, we obtain

$$L_0 = \frac{-u \pm \sqrt{2\beta\, l q_0 \operatorname{sh} u + u^2}}{\beta q_0} \tag{7}$$

The absolute value of the real values of the variable *u* lies in the range $10^{-3} < u < 1$.

The sensor measures the angle of inclination of the tangent to the wire relative to the horizon and the temperature of the wire.

There are three states of the monitoring system:

1. The sensor is in calibration mode. In the absence of conditions for the occurrence of ice (humidity less than 80%, wire temperature above 0°), the length of the unstretched wire is cyclically calculated - using formula (7), L_{0t} is calculated and the corresponding value of the wire temperature t_0 is stored. The readings are statistically averaged.

2. At the moment of icing conditions, the sensor switches from calibration mode to tracking mode. Length L_0 is calculated by the formula

$$L_{0t}\left(1 + \delta(TK - TK_0)\right) \tag{8}$$

The hyperbola shape factor is calculated by the formula [8]:

$$a = \frac{L_0}{2\operatorname{sh} u} \tag{9}$$

calculate the weight of the wire with ice

$$q = \frac{\left(\frac{l}{a} - 2u\right)}{\beta L_0} \tag{10}$$

the force of gravity is found by the formula

$$T = aq \operatorname{ch} u \tag{11}$$

3. When the environmental parameters change and the conditions of ice formation disappear (humidity less than 80%, wire temperature is higher than 0°) and q returns to the value q_0, the sensor again switches to the mode described in p.1.

3 Methodology for determining defective insulators using partial discharge triangulation (PD)

To determine the location of the PD source, the work proposes the use of the method for determining the difference in the time of signal arrival to the receiving devices [11-12]. To compose the equations, it is necessary to know the coordinates of the PD determination module, as well as the difference in the arrival time of the PD pulse to each module. Knowing the difference in the time of receiving the signal, using mathematical processing, the distance from the PD source to the diagnostic module is calculated.

Assuming that the PD wavefront expands spherically from the position of the source at the speed of light, propagation can be described using the formula:

$$D = v \cdot t \tag{12}$$

where D is the distance, v is the propagation speed, and t is the propagation time and, knowing the coordinates of the diagnostic device, represent (12) in the following form:

$$(x - x_i)^2 + (y - y_i)^2 = (V_e \cdot t_i)^2 \tag{13}$$

where (x_i, y_i, z_i) – coordinates of the i-th PD determination module in Cartesian space, (x, y, z) is the coordinates of the partial discharge event, v_e is the speed of the electromagnetic wave, t_i is the “time of flight” of the propagating PD signal from its source to the i-th sensor.

Let the time of flight from the PD source to the 1-st module be equal to T, and the difference in arrival time between the first and other modules is τ_{1n}. For our case, for three modules, a system of equations is obtained [13]:

$$\begin{gathered}(x-x_1)^2+(y-y_1)^2=(V_e{*}T)^2\\(x-x_2)^2+(y-y_2)^2=(V_e{*}(T+\tau_{12}))^2\\(x-x_3)^2+(y-y_3)^2=(V_e{*}(T+\tau_{13}))^2\end{gathered} \tag{14}$$

The system of equations is solved using the iterative least squares method.

After determining the number of PDs, their intensity and location, the obtained distribution is compared with that for serviceable, pre-defective and defective insulators. Using the developed technique, the rate of the aging process and the development of various defects is determined, which makes it possible to predict the residual life of the high-voltage insulator.

4 Conclusion

Implementation and construction of the developed modular devices of an intellectual network gives the following advantages:

- higher speed of data transfer in comparison with standard communication protocols (ZigBee, LoRa, etc.), as the created sensor network already has a fixed structure that allows to load the information channel considerably less, due to minimization in sending information on topology and configuration of network of devices (the real speed can reach 250 kbit/s, instead of 40 kbit/s, thanks to use of the modern data transfer modules working according to the IEEE 802.15.4 standard);

- the possibility of further development of the system due to the openness of the code for developers.

The introduction of the system of operational monitoring of the technical condition of the overhead line based on the developed modular device for monitoring the state of the overhead line will allow in the shortest possible time and with minimal cost to increase the information content of power lines and prevent a significant number of accidents. This will be possible because of various sets of diagnostic modules that allow you to adapt the functionality of the device for specific tasks.

Research, development and implementation of elements of this network will reduce losses on overhead lines, improve the reliability of the power grid and the possible volume of power transmission.

Acknowledgements

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