A novel sensing system for monitoring power lines

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In this work, we use a capacitance sensing technology to design an online monitoring system for power lines. By the theoretical analysis and simulation of a plurality of coplanar metal line electrode fields and capacitors, as well as the freezing tests of the system in low temperature, the system could be powerful for monitoring the ice thickness of power lines. We found out that the capacitance can be formed due to the metal electrode changes if the sensor is merged into ice coatings of analog conductors. Especially, the system possesses a simple structure, high accuracy, readily installation, and low costs.

1. Introduction

In recent years, due to the sped-up progress in construction of high voltage and extra-high voltage state power grids, people are giving higher and higher concern on safety and reliability of the transmission lines. Wire icing is a widespread natural phenomenon, especially in heavy ice area, where wire icing is the core concern in the design of overhead lines. The infrequent ice-snow calamity gave the most severe damage to the state power grid unprecedented in history, and caused tremendous impact upon public lives [1-2]. This simulated numerous studies on automated wire icing detecting instruments [2-4], and some achievements have been achieved.

Currently, methods of overhead transmission line ice thickness detection mainly comprise compact meteorological method, image method, sag measuring method, weighing method and simulating method, etc. The air temperature, humidity, wind speed, wind direction, snowing and other meteorological conditions are on a real-time basis monitored in the compact meteorological method [5-6], and the ice coating is forecasted on the basis of ice coating model and continuous duration of ice coating climate and weather. This requires quantities of historical data, and models in different circumstances and geographic shapes also vary from each other. The detected circuit is discontinuously or continuously photographed in the image monitoring method [7], in which images are transmitted to the control center by various remote transmission methods, and treated and analyzed by the control center. Though this method is simple and straightforward, but the camera can easily be covered by ice and snow under severe conditions, failing in providing rational ice thickness. In the sag measuring method [8], the wire angles are measured through the angle sensor installed around the tower. We can do so by referring to microclimate parameter, solving the overhead line status equation by using Newton-Raphson method, introducing the horizontal tension, and finally calculating the equivalent ice thickness out. The tension on the line is measured in weighing method [9], and the ice thickness is calculated out by calculation matrix, which is maturely applied by far, but the electronic tension sensor is usually used for tension measurement, which has the defects of zero drift and nonlinearity. The investigating station or ice investigating station are set around the overhead line for analog method [10], analog conductors or grounding wires having similar type or material with transmission conductors or grounding wires are set around the investigating station, to check the ice thickness on analog conductors. Due to along distance between hypothetic analog conductors and overhead transmission line, and big difference from real transmission line circumstance (e.g., wind speed and temperature, etc.), measurements of this method are hard to be accurate.

The designed monitoring system in the paper basically belongs to analog method, while differences are the analog conductors and monitoring instruments are hung on the transmission line tower, which is close to the transmission line, and the monitoring instrument are in the approximate same circumstance as the transmission line, thus more accurately achieving the real-time monitoring of overhead line ice thickness.

2. Principle of capacitance sensing type transmission line ice thickness monitoring system

2.1. Principle of capacitance sensing

In 1969, Noltingk [10] first suggested the high-accuracy measuring system based on coplanar capacitor edge effects, and two sensor design structures - giant coplanar capacitance sensor and circular coplanar capacitance sensor, which both use capacitance edge

effects for micro distance measurements. By far, there are lots of application researches into capacitance sensing technology, such as touch screen and touch switch etc. [11-14]. Also, more and more achievements are reported. For example, He et al. researched into the principle of single planar capacitance sensor, and obtained the relational expression between the dielectric constant and capacitance of the planar capacitor [15]; Zhang et al. measured and researched the water ratio of building enclosure through coplanar multi-electrode scattering field capacitance sensor, and conducted the capacitance calculating formula of single coplanar capacitance sensor, and optimally designed the electrode structure, which forms the capacitance by simulation [16]; Liu et al. researched into the cereal water ratio measurements through planar multi-electrode fringing electric field [17], simulated multi-electrode electric field, and found the relation between capacitance and cereal water ratio. Dong et al. from Tsinghua University simulated and researched the electric field distribution and sensitivity characteristic of coplanar multi-electrode scattering field capacitance sensor [18, 19], and found the coplanar eight-electrode capacitance field distribution and sensitivity field distribution. Liu et al. analyzed and researched the principle and mathematical model of the capacitance sensor in random geometric shape, and measured the timber water ratio through planar capacitance [20]. Li et al. used the coplanar scattering-field capacitance sensor, and measured the sand water ratio with this sensor [21].
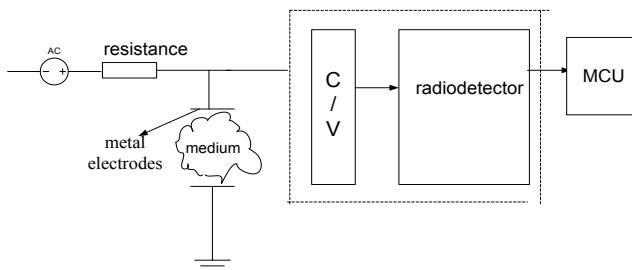

Fig. 1. The principle of capacitance sensing base unit.

Fig. 1 illustrates the capacitance sensing principle of capacitance sensing base unit. The signal source charges one terminal of plate electrode (fixed charging current and time), and capacitance of the capacitor changes when the objects with different dielectric constants approach the plate electrode, which causes the change of terminal voltages. Attributes of detected objects can be verified by detecting the capacitor terminal voltages.

2.2. Structure of capacitance sensing type ice thickness sensor

Based on the theory of the dielectric constant difference [22, 23] between the ice and air, a monitoring system for measuring the transmission line ice thickness is designed in this paper. The system comprises analog conductors, capacitance sensing type ice thickness sensor, inspection and control instrument, bracket, fasteners,

antenna, solar cell, battery and other components. In them, the capacitance sensing type ice thickness sensor is the key equipment to the system. Fig. 2 is the sensor external view, in which *1* is 25 sets of metal electrodes, 10 is insulating bracket, 11 is capacitance measuring electrode plate, and 12 is insulating shell. Fig. 3 is the front cross-section of ice thickness sensor, in which *1* is the connector between one terminal of 25 metal conductor electrodes and the insulating bracket, 2 is the cross-section of simulating transmission line, and 13 is the transmission line ice coating on sensor cross-section. Distances from 25 electrodes to the wire are different, which is 2mm, 4mm, 6mm, 8mm... up to 50mm, and the capacitance is formed separately between every metal electrode and the analog conductor.
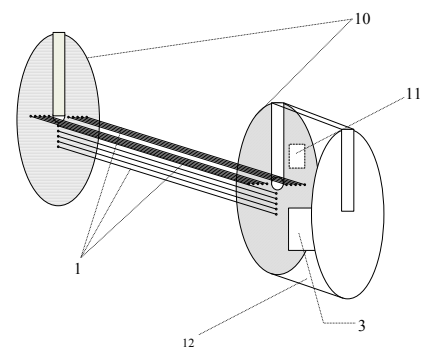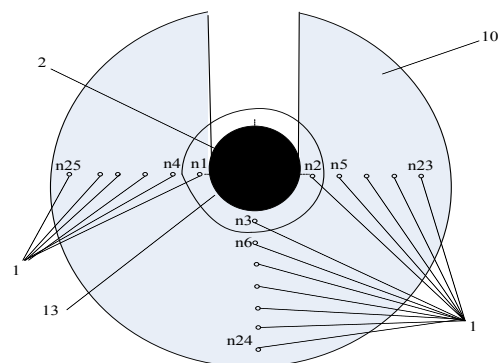

Fig. 2. Sensor external view.

Fig. 3. Sensor cross-section view.

3. Installation method of detection instruments and detection principle of transmission line ice thickness

An appropriate tower is chosen as monitoring spot, a section of analog conductor fully the same as circuit wire is installed on the transmission line tower, the capacitance sensing type ice thickness sensor is installed on the analog conductor, and the detecting control module, battery and solar cell are fixed on the tower.

Due to the difference in dielectric constant between air and ice, once there is ice coating on analog conductor, part of metal electrode close to the analog conductor will be coated by ice (i.e., the metal electrode will be jointed and frozen with analog conductor). Capacitances of 25 electrodes will be detected individually by the capacitance measuring circuit, the measured capacitance will be verified by microprocessor, and n, the number of metal electrodes frozen and jointed with analog conductor, will be calculated out. By this, the ice thickness can be calculated: $H=2*n+2$mm.

Hereinafter, analysis is done based on the mathematical model when the capacitance and the medium between metal wire electrode and analog conductor changes: assuming the radius of each metal conductor is R, if the metal conductor is energized, the electric field strength in the radius of r can be conducted with Gauss theorem:

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0 r} \qquad (r>R) \qquad (1)$$

Perform an integral from the formula, and set the potential at $r = r_0$ as zero to get:

$$\varphi(r) = \frac{\lambda}{2\pi\varepsilon} \ln\frac{r_0}{r} \qquad (r > R) \qquad (2)$$

Assuming there is no other electric charge in the space formed by metal electrode and analog conductor, and the analog conductor radius is $R2$, according to electromagnetics, superposition theorem should be satisfied as below:

$$\varphi = \varphi_1 + \varphi_2 = \frac{\lambda}{2\pi\varepsilon}\ln\frac{a}{r_1} - \frac{\lambda}{2\pi\varepsilon}\ln\frac{a}{r_2} = \frac{\lambda}{4\pi\varepsilon}\ln\frac{r_2^2}{r_1^2} \qquad (3)$$

According to the research done by Zhang et al. [22], the final capacitance deriving formula of the two cylinder-shape straight conductors is:

$$C = \frac{Q}{U} = \frac{2\pi\varepsilon_x}{\ln[\frac{d^2 - R_1^2 - R_2^2}{2R_1 R_2} + \sqrt{(\frac{d^2 - R_1^2 - R_2^2}{2R_1 R_2}) - 1}]} \qquad (4)$$

In the formula above, d is the central distance between two conductors, ε_x is the dielectric constant of the medium between electrodes, and the R_1 and R_2 are respectively the radiuses of each metal conductor. From the formula above, it can be seen that when the radius of

metal electrode and analog conductors, and the distance d between them, are fixed, the variance of capacitance C is only related with ε_x. If the ice thickness is greater than or equal to the distance d between two electrodes, the capacitance keeps basically unchanged.

4. Simulation analysis

The Maxwell electromagnetic field simulating and analyzing software from Ansoft is used to simulate the voltage and the electric field strength, as shown in Figs. 4 and 5. Fig. 4 shows the cross-section views of two conductors in different diameters, where the broken line is the equipotential line. Fig. 5 shows the 25 spots in the cross-section view of capacitance sensing type ice thickness sensor are the metal electrode.
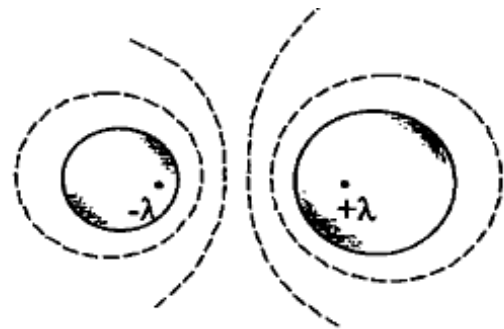

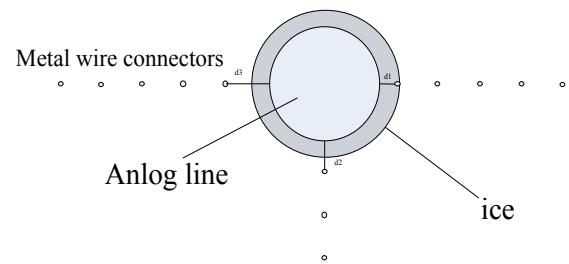*Fig. 4. Model of two cylinder-shaped conductor.*

Fig. 5. Cross-section view of transmission line.

The electrode which is closest to analog conductor is set as the DC excitation source of amplitude 5v, analog conductor as 0v (grounding), with automatic mesh generation for each segment, while the boundary condition is set as the boundary condition of air, and the relative dielectric constant of ice coating is set as 4 for obtaining results. The illustrations (b) and (d) are obtained under the condition of ice coating, and the illustrations (a) and (c) are obtained without ice coating.
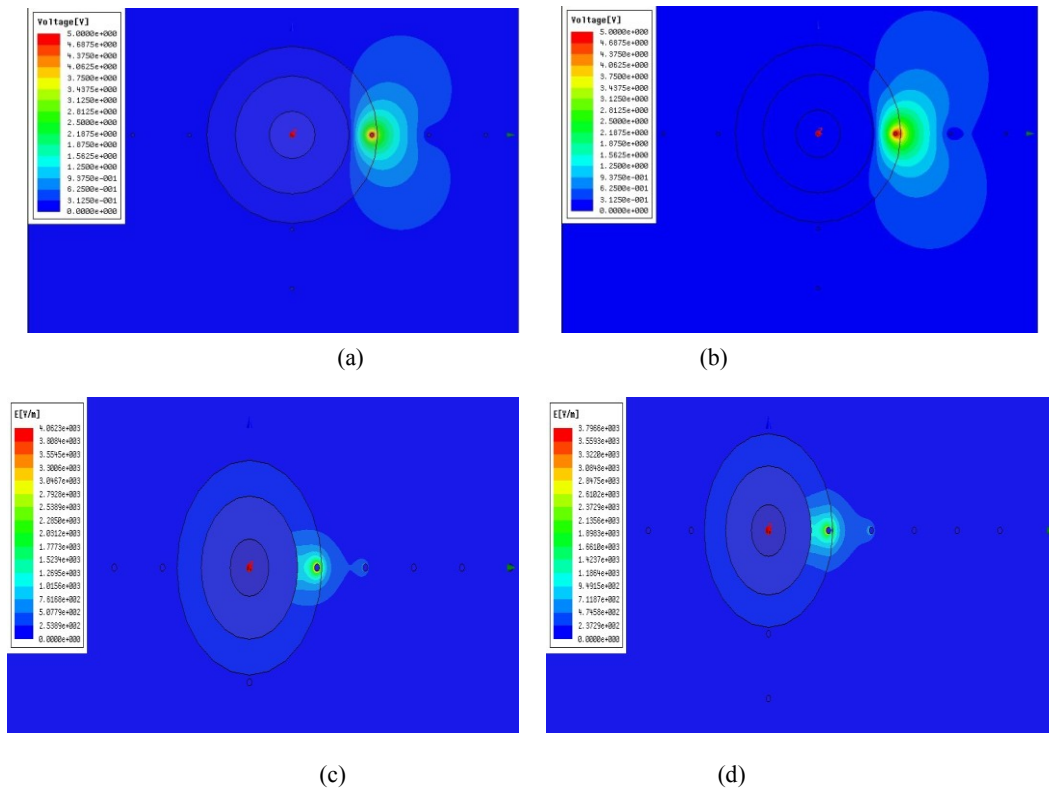
(a)   (b)

(c)   (d)

Fig. 6. Simulating illustration of electric field voltage and electric field strength.

Fig. 6 shows 4 illustrations: voltage simulation illustration without ice coating (a), voltage simulation illustration with ice coating (b), electric field strength simulation illustration without ice coating (c), and electric field strength simulation illustration with ice coating (d). It can be clearly observed from the comparison between illustrations (a) and (b): the ice coating influences the voltage shape in the space, and makes the voltage distribution spread out; and from illustrations (c) and (d): ice coating severely influences the distribution of space electric field. Especially be noted that the boundary between ice and air becomes rough. Combining with Formula 5, it can be concluded that the capacitance between the electrode and conductor changes (getting higher); according to the change of direct digital (which can be converted into voltage) measured by capacitance measuring circuit, we can find if the ice thickness reaches the distance between electrode and conductor according to the change of direct digital quantity.

5. Practical tests and results

Based on the principle and analysis above, we have built a set of simplified sensors and its system in the lab for the frozen tests in a low-temperature box, as shown in Fig. 7. The temperature is set at -15℃, humidity at 95%, and a steel cord with a diameter of 22mm is used as the analog conductor in the test. The tiny drops are sprayed every two hours to simulate the snowing process. A set of capacitance digital volume on all metal electrodes of analog wires is selected without icing (Fig. 8, curve B), a set of data on analog wire during the initial phase of icing (Fig. 8, curve C), and a set of data on analog wires if the final icing thickness reaches a certain level (Fig. 8, curve D). In Fig. 8, X-axis is the metal electrode number, and Y-axis represents the capacitance digital volume on each of the metal electrodes. It can be seen from curve C that the capacitance digital volume from the first electrode to the seventh electrode is relatively low, at about 500 or less, while that from the eighth to the fifteenth is relatively large, ranging from 700 to 900. Therefore, all metal electrodes before the 8th one are congealed with the thin ice on analog wires, and ice thickness can be considered as $H = 7 \times 2mm = 14mm$.

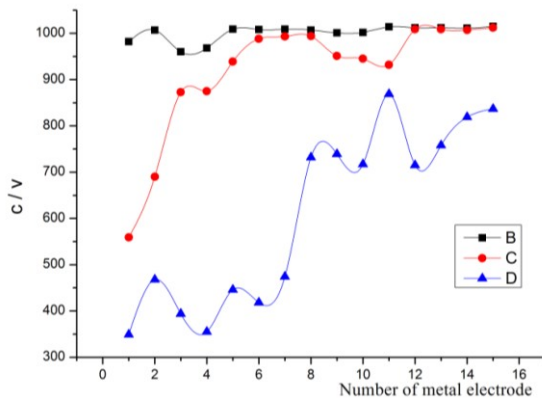*Fig. 7. Field test in low-temperature ice coating.*

Fig. 8. Direct digital number of 15 electrodes.

6. Conclusions

Capacitance formed between the metal electrodes changes if the sensor metal electrode is merged into the ice coating. Based on such principle, the designed sensor can be used to monitor the ice thickness on analog conductors. Moreover, such a sensor shows a simple structure, high accuracy, ease of installation, and low cost. It is also noted that such system is only validated using the low-temperature frozen test in the lab, and further investigations are still required for the capacitance change of metal electrode caused by the ice-snow compound on the transmission lines under the field environment.

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