Objectivation of diagnostic indicator of defective insulating elements of strings by means of electric field intensity detection in inter-insulating intervals

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Abstract. The work describes existing methods of insulating elements diagnostic in strings. Non-traditional methods such as surface conductivity insulating monitoring methods, detection method of insulation current, heat monitoring method etc. were discussed. In the recommended method of heat monitoring with remote measurements temperature difference in insulator between correct and defective insulators is recommended 0.3-0.5°C that doesn’t let to get true-to-fact data because of proximal meaning of uncertainty value to limiting resolution of thermal camera. Monitoring methods of insulation condition of overhead line contained in normative documents require correction and riders because of lack of information. Objectivation of diagnostic indicator for finding of defects in strips by means of electrical intensity detection in inter-insulating intervals was conducted. In the result of experimental research during modeling of the string containing 14 insults the presence of defect elements in different points along the strip with one, two, and three neutral insulators was imitated. 1467 experimental data were received from 16384 possible combinations. During the experiment electric field intensity in the air-gap between insulators and loss in voltage in insulators were measured off. Received electric field intensity curve shapes have equipotential character. On the base of the results calculation was made for each curve and numeric values of hyperbolic tangent at difference positions of neutral isolators in the string. On the received results graphs of change of $\tanh(E/\Delta k)$ at different value and position of saw-shaped neutral isolators were constructed. Comparison of received values of hyperbolic tangent at presence and absence of neutral insulators allows to find out the existence of defect elements in the string.

1. Introduction

Insulators condition on the transmission line and electricity distribution is a paramount important factor for an electric power system reliable functioning [1]. Damaged and inadequate to the standards for electrical characteristics defective isolators may lead to expensive shutdown electric system, serious injuries or fatal accidents [2].

For maintenance of overhead line, it is necessary to control of isolation condition for what different devices, methods and means can be used [3, 4]. Electromagnetic field, recording of optical emission and acoustic signals, temperature, and high-frequency electromagnetic radiation were used in applied methods as diagnostic indicators. Variety of used methods based on different physical features gives
multivalued assessment and decrease in formativeness of the results. That is why, it is necessary to justify a diagnostic feature reacting to the change in electromagnetic fields when defective elements appear in strings at different numbers and position of the defect.

Alternating voltage distributes along insulators of the string irregularly and appearance of defective elements brings additional field distortions to inter-insulating interval may serve as diagnostic features that are not affected to external factors (temperature, illumination, acoustical signals).

2. Experimental
Currently, for overhead line control traditional and non-traditional methods are used.

2.1. The traditional methods. Traditional methods are considered in detail in volumes and norms of electrical equipment examination [5]. Thus, in the work considerable attention is paid to study of non-traditional methods of insulating monitoring.

2.1.1. Surface conductivity insulating monitoring method. This method is used for risk estimation of insulation contaminated layer of overhead line and choice of more effective lap preventive actions [6]. Knowing characteristics of contaminated layer, it is possible to calculate on some precision of flashover by means of numerical methods [7]. In the determination of contaminations characterized only by entrainment of manufacturing plants, it is possible to calculate contaminated layer thickness and conductivity on condition of thorough wetting, also moisture-spark voltage of insulation [8].

2.1.2. Detection method of insulation current. Substantial connection between moisture-spark characteristics and prestrike insulation currents appear due to equal insulator contamination [6]. However, insulation currents are highly correlated to insulator type, unequal contaminated layer and composition. Despite repeated attempts, insulating capability of insulators does not have correlation relationship with insulation currents [9].

2.1.3. Heat monitoring method. The method is based on distant determination of temperature of contact connection of cords and insulation on intensity and spectral content of infrared emission with use of thermal cameras and pyrometers.

When identifying line polymer insulators with rough defects for example with conducting extraneous bodies or wire in fiberglass rods the experience of thermal cameras appliance is rather illustrative [10].

Neutral insulators in strings may be as «colder» so «warmer» than correct insulators [11]. Pointed difference may be if an insulator has very low resistance. In this case heat power that excretes in it will be also very low and it will be colder than juxtaposed insulators. Conversely, if resistance of the insulator is enough high but lower than rejectable level of 3000 mega ohm it will be heated more than if it would be correct.

2.2. Methods of preventive insulation monitoring based on discharge process registry. Principal capability of diagnostic of overhead line condition method realizes on insulation with help of corona discharges intensiveness and surface partial discharge. In according to accepted standards of overhead line design field intensity on overhead conductors is restricted by $E = (0... 0.9)E_n$, where $E_n$ is density of corona origin [12]. Defects, damages and structural breaking that appeared during operational process lead to uprising and reinforcement of intensity of surface partial discharge or corona discharges. Under development quantitative ways of corona discharges and surface partial discharge recording are based on special features of emission of different frequency range [13 –15].

Principally there are three possible detection method of corona discharges and surface partial discharge intensity: acoustic, electromagnetic, optical.
2.2.1. Acoustical way. Acoustic way consists of measuring acoustic noise generated by discharge processes mainly in the ultrasonic spectrum region. This way regarding overhead line insulation monitoring found limited use because of deficient space resolving power capability, low interference protection and sensitivity. Its scope is limited by distribution substations 6-35 kV [16].

2.2.2. Electromagnetic method. For purposes of insulation preventive monitoring some types of recording devices for electromagnetic emissions of corona discharges and surface partial discharge were worked out [17]. However, these inventions didn’t become widespread because of low stability of measurement devices to corona discharges and different exterior interferences.

2.2.3. Optical method. Advantages of optical method of corona charges and surface partial discharge recording is high spatial-temporal ability measure of the resolution and sensitivity in comparison with other methods of detection [18–20]. Disadvantage of the method is the need for conduction of the insulator elements test during darkness hours, difficulty of surface partial discharge signals selection from corona discharge signals, also it is difficult to differ surface partial discharge moving along contaminated surface of correct insulator from motionless surface partial discharge positions connected with insulation faults.

3. Results of Researches

In high-voltage engineering laboratory of the Department of electric supply and technical diagnostics of Federal State Budgetary Educational Institution of Higher Education «Mari State University» experimental data on field-strength variation and insulated elements of strings consisted from 14 insulators with imitation of presence of defect elements in different points along the strip with one, two and three neutral insulators intension were taken off. 1467 experimental data were received from 16384 possible combinations.

Figures 1–3 show voltage distribution and electric field intensity along the string with one, two and three neutral insulators.

![Figure 1](image-url)  
Figure 1. Voltage distribution and electric field intensity along the string with one neutral insulator in the string.
The algorithm for finding defective elements based on the experimental data is as follows:

- since the shape of the electric-field intensity curves has an equipotential character (Figures 1–3), it is possible to carry out a tangent to a curve from any point of the string of insulators (Figure 4);
- to calculate the hyperbolic tangent $\tanh(E/\Delta k)$, from point 12, we draw tangents to the electric field intensity curves.

**Figure 2.** Electric-field voltage and intensity distribution along the string with 2 neutral insulators in the string.

**Figure 3.** Electric-field voltage and intensity distribution along the string with 3 neutral insulators in the string.
As an example, let us take the curve of the electric-field intensity distribution, where the second insulator, counting from the cord, will be the neutral one (Figure 4).

Figure 4 shows that \( \text{th}(E/\Delta k) = \text{th}(21/(12-7)) = 0.999609 \).

Let us consider the cases when there are one, two, three zero insulators in a string (Figure 5, 6, 7). After the tangents to the curves of the electric field, obtain the numerical values of the hyperbolic tangent at different positions of the neutral insulators (Tables 1, 2, 3).

**Table 1.** \( \text{th}(E/\Delta k) \) value, with 1 neutral insulator in a string.

| Number of insulator coupling, counting from the cord | \( \text{th}(E/\Delta k) \) | Number of insulator coupling, counting from the cord | \( \text{th}(E/\Delta k) \) |
|----------------------------------------------------|--------------------------|----------------------------------------------------|--------------------------|
| 1                                                  | -                        | 8                                                  | 0.999295                |
| 2                                                  | 0.999609                 | 9                                                  | 0.978026                |
| 3                                                  | 0.995434                 | 10                                                 | 0.999831                |
| 4                                                  | 0.99972                  | 11                                                 | 0.97627                 |
| 5                                                  | 0.969715                 | 12                                                 | 0.999593                |
| 6                                                  | 0.997644                 | 13                                                 | 0.984921                |
| 7                                                  | 0.950151                 | 14                                                 | -                       |

**Figure 5.** Change of \( \text{th}(E/\Delta k) \) at different positions of neutral insulators (1 neutral insulator).
Table 2. \(th(E/\Delta k)\) values with 2 neutral insulators in a string.

| Number of insulator coupling, counting from the cord | \(th(E/\Delta k)\) | Number of insulator coupling, counting from the cord | \(th(E/\Delta k)\) |
|-------------------------------------------------|-------------------|-------------------------------------------------|-------------------|
| 1                                               | -                 | 8                                               | 0.944155          |
| 2                                               | 0.977587          | 9                                               | 0.998838          |
| 3                                               | 0.99976           | 10                                              | 0.924946          |
| 4                                               | 0.973601          | 11                                              | 0.999393          |
| 5                                               | 0.999139          | 12                                              | 0.948085          |
| 6                                               | 0.949335          | 13                                              | -                 |
| 7                                               | 0.997898          | 14                                              | -                 |

Figure 6. Change of \(th(E/\Delta k)\) at different positions of neutral insulators (2 neutral insulators).

Table 3. \(th(E/\Delta k)\) values with 3 neutral insulators in a string.

| Number of insulator coupling, counting from the cord | \(th(E/\Delta k)\) | Number of insulator coupling, counting from the cord | \(th(E/\Delta k)\) |
|-------------------------------------------------|-------------------|-------------------------------------------------|-------------------|
| 1                                               | 0.980096          | 8                                               | 0.999992          |
| 2                                               | 0.999999          | 9                                               | 0.919121          |
| 3                                               | 0.985508          | 10                                              | 0.99983           |
| 4                                               | 0.999978          | 11                                              | 0.959335          |
| 5                                               | 0.876972          | 12                                              | -                 |
| 6                                               | 0.997434          | 13                                              | -                 |
| 7                                               | 0.992126          | 14                                              | -                 |
As it can be seen from the graphs (Figure 5, 6, 7), the change of \( \text{th}(E/\Delta k) \) at different positions of the neutral insulators has the form of a sawtooth curve. Consequently, if we know \( \text{th}(E/\Delta k) \) without any neutral insulators, we can determine which element of the string has a defect. For example, Figure 5 shows that if the tangent value is higher than the straight \( \text{th}(E/\Delta k) \) without zero insulators, even insulators are defective, if the tangent value is lower than the straight \( \text{th}(E/\Delta k) \) without neutral insulators, odd insulators are defective. Thus, it is possible, by measuring the electric field intensity and changing the position of the measuring points (for example, to carry out measurements at different points of the string insulators) to obtain information about the presence or absence of defective elements.

The analysis of the search algorithm to find the defects in a string consisting of 14 insulators is carried out. According to the conducted analysis, it can be said that the search for defects in a string is possible by measuring the electric field intensity and calculating the hyperbolic tangent \( \text{th}(E/\Delta k) \).

To develop the matter of finding defects in the overhead line strings, a method based on measuring the electric field intensity in the insulating intervals with the help of the PZ-50 device was chosen. The analysis of the experimental data showed that the search for defects in the string is possible by measuring the electric field intensity and, therefore, the calculation of the hyperbolic tangent \( \text{th}(E/\Delta k) \).

4. Conclusion
1. The methods of monitoring the overhead line insulation condition, which are presented in normative documents, need updating and supplementing, as they have insufficient informative value.
2. Considering the proposed control methods, we recommend a remote method (thermal imaging method) that does not require shutdown of the equipment and does not affect its operation, as well as does not cause distortion in the current state of the controlled object. However, thermal imaging control method for remote measurement of the temperature difference on the insulator between serviceable and defective insulators is normalized 0.3–0.5 °C, which does not allow to obtain reliable values due to the close error value to the limit of the resolution of thermal imagers and the effects of climatic factors.
3. The substantiation of the diagnostic feature of defective insulating elements in strings by registration of electric field intensity in the inter-insulating intervals is carried out.

As a result of experimental studies on modeling defects in insulator string, equipotential curves were obtained, which allow determining the value of hyperbolic tangent at different number of neutral insulators in the string. According to the obtained values, a graph of \( \text{th}(E/\Delta k) \) changes at different positions of neutral insulators is constructed. The obtained graphs have a sawtooth shape. Comparison
of the nature of the obtained hyperbolic tangent values in the absence and presence of neutral insulators helps to identify the presence of defective elements in the string.

References

[1] Cimador A et al 1994 Proc of the 32th CIGRE Study Group Committee 3 04
[2] Devine C M and Farquhar J A 1985 Electrical world 199(12) 59–61
[3] Lilien J L and Destine J 2012 US Patent 8184015
[4] Olsen R G and Edwards K S 2002 IEEE transactions on power delivery 17(4) 1142–1152
[5] STO 34.01-23.1-001-2017 Scope and norms of testing electric equipment
[6] Merkhalev S D and Solomonik E A 1983 The selection and operation of isolation in districts with contaminated atmosphere (Energoatomizdat: Leningrad) (in Russian)
[7] Aksenov V A 1981 Development of calculation methods and research of the prestrike characteristics and voltage overlap of polluted insulators PhD Thesis (Sibir Energy Research Institute: Novosibirsk) (in Russian)
[8] Rutskiy V M 1994 Development of a method for the selection of insulation levels in the area of the projected industrial enterprises PhD Thesis (Sibir Energy Research Institute: Novosibirsk) (in Russian)
[9] Bazutkin V V et al 1986 High voltage (Energoatomizdat: Moscow) (in Russian)
[10] CIGRE WG 22.03 1996 Review of “In service diagnostic testing” of composite insulators ELECTRA 169 105–119
[11] Taloverya V L and Chernov V F 1982 Proc the all-Union Scientific and Technical Seminar 38–42 (in Russian)
[12] Aleksandrov G.N. and Peterson L.L (eds) 1983 Design of power transmission lines of ultrahigh voltage (Energoatomizdat: Moscow) (in Russian)
[13] Tourrel D C and Ishivari M 2000 Proc of the 38th CIGRE Study Group Committee 1 04
[14] Privalov E E 2015 Diagnostics and thermal imaging control of electric power equipment: tutorial (Direct-Media: Moscow-Berlin)
[15] Kalicki T et al 1995 Proc of the 9th ISH 5066
[16] Karkkainen S 1974 Physical mechanisms of partial discharges (VTT Technical Research Centre: Finland)
[17] Svi P M 1961 Electric stations 12 34–36 (in Russian)
[18] Zhultz H and Zimmer H 1980 Elektrizittswirtschift 19 704–708
[19] Sibiryakov V G 1985 Development of methods and equipment for remote optical control of high-voltage isolation of overhead line and SWYD PhD Thesis (Sibir Energy Research Institute: Novosibirsk)
[20] Benjamin J et al 1999 IEEE Trans Dielectr Electr Insul 6 896 –899