Development and modeling of LED indicator of high voltage insulator status

R N Balobanov\textsuperscript{1}, D I Amirov\textsuperscript{1} and A G Razina\textsuperscript{2}

\textsuperscript{1}Department of Electric Stations named after V. K. Shibanov, Kazan State Power Engineering University, Krasnoselskaya Str., 51, Kazan, Republic of Tatarstan, 420066, Russia
\textsuperscript{2}Department of Applied Physics and Nanoelectronics, Chuvash State University named after I.N. Ulyanov, Moskovsky prospect 45, Cheboksary, Chuvash Republic, 428015, Russia

E-mail: rassel_ipek@mail.ru

Abstract. The article discusses a non-contact method for monitoring the state of high-voltage insulation. The principle of operation of circuits of devices built using various electronic components is described. The results of modeling the operation of the device in the software complex of finite element modeling COMSOL Multiphysics are presented. The modeling was carried out by constructing and analyzing three-dimensional models of insulators of the LK70/35 and LK 70/110 brands with indicators installed on them. The presented method of insulation control will allow, during visual inspection of overhead lines, to additionally receive information about the change in the electric field and the appearance of partial discharges in the insulation. The main results of this article are the determination of the parameters and requirements for the electronic components of the considered circuits of indicators of the state of high-voltage insulators.

Keywords: polymer insulator, indicator, defects, LEDs, power line, insulation condition, assessment, outdoor switchgear, contactless method, dynistor.

1. Introduction

Insulators are one of the most important structural elements of power lines and open switchgears. Improvement and modernization of insulator designs occurs throughout the history of the development of the electric power industry. Insulators are electrical insulating structures designed for fastening and insulating live parts of installations under potentials. Insulators are classified according to voltage, type of installation, purpose and design. The disadvantage of all designs of insulators is the lack of available methods of operational monitoring of the state of internal insulation. An exception is tempered glass suspension insulators. The internal breakdown of such insulators can be easily identified by the breakdown of the glass insulating piece. Due to this, these insulators are widely used in the power industry. However, they have many disadvantages: weak hydrophobicity and tracking resistance in comparison with silicone rubber of polymer insulators, low moisture-discharge characteristics in comparison with polymer insulation, the impossibility of manufacturing large-size support insulation for substations, etc.

Recently, active developments have been carried out in the direction of creating systems for monitoring the state of high-voltage insulating structures. One of the promising directions is the creation of defect indicators installed on an insulating structure. Various options for insulating structures have
been developed, consisting of solid or composite insulators, with additional or built-in elements for assessing their condition [1 - 18]. These elements are called defect indicators.

2. Materials and Methods

During the design, two electrical circuits of the indicator were developed. The first circuit is based on the MCP 65R41 comparator (Fig. 1).

![Comparator indicator circuit](image)

Figure 1. Comparator indicator circuit.

In this circuit, the current induced on the electrode, which serves as a capacitor plate, is rectified by the diode bridge and, flowing through the capacitor C1, charges it. The circuit, consisting of R2 and VD5, creates a reference voltage that is applied to the inverse input of the comparator and thus sets the threshold. The voltage generated by the divider built across R3 and R4 is applied to the direct input of the comparator, which is proportional to the voltage across C1. In the process of operation, the voltage on C1 gradually increases to a certain value. At this moment, the voltage at the direct input, proportional to the voltage on C1, reaches the operating threshold and the comparator switches, opening its output transistor and thereby supplying voltage to the LED HL1. The LED lights up. The current flowing through the LED discharges C1 and the voltage across the capacitor begins to drop rapidly, since the capacitor charge current from the electrode is many times less than the discharge current. The voltage at the direct input of the comparator also drops. As soon as it falls below the trip threshold, the comparator switches, interrupting the current through the LED. The LED goes out. Capacitor C1 starts recharging. Thus, the cycle of charging and discharging (turning the LED off and on) is continuously repeated. Resistor R5 in the circuit serves to set the required hysteresis value at the comparator input and determines the time of the LED on. Resistor R6 limits the current through the LED and also determines the on time of the LED. Resistor R7 shunts the LED, allowing C1 to discharge even if the voltage across the LED is below its turn-on threshold.

The second scheme is based on dinistors (Fig. 2). In Figure 2, the dotted lines indicate the connection of the indicator with the high-voltage and grounded part of the structure. A feature of this scheme is the ability to display discharges that occur in the insulation during damage and / or contamination. The circuit consists of two loops. The first one includes the following elements: capacitance C1, resistances R1 and R2, dinistor VD6 and green LED HL1. The second one consists of the capacitance C2, the resistance R3, the dynistor VD7 and the red LED HL2.

Let's consider the principle of the indicator. The distribution of potentials along an insulating structure changes in violation of the integrity of its individual parts. The potential difference in the damaged area decreases, which causes an increase in voltage on the intact part of the structure. The defective condition of the insulator can be detected, for example, by increasing the intensity or frequency of the pulses of the light emitted by the indicator mounted on the portion of the insulating part of the structure or support, as this increases the voltage on it. One of the electrodes of the radiator can be earthed through the grounded part of the insulator or support, the second electrode can be positioned freely.
To ensure reliable operation of the radiator with a constant installation, it is necessary to connect a discharger in parallel to it. In the event of a surge overvoltage, the discharger shunts the radiator, protecting it from failure.

The scheme works as follows. The current from the diode bridge VD1–VD4 charges the capacitance C1. As charging C1 voltage on it increases. The dynistor VD6 does not pass the current until the voltage on its terminals (on C1) reaches 40 V. As soon as the voltage reaches the desired value, the dynistor opens and the charge from the capacitor C1 is discharged to the LED HL1, as a result of which the LED emits a flash of green light. Simultaneously with the flash, the voltage on the dynistor VD6 drops, and it closes. Next, the capacitance C1 is again charged until the opening voltage of the dynistor and the cycle repeats. Thus, the green LED is pulsed.

If there are no discharges on the insulation, only the green HL1 LED will always be triggered, because due to the voltage drop across the VD5 diode, the dynistor VD7 will always be closed.

At a certain intensity of the discharges on the insulator, the pulses, passing through the second (high-frequency) circuit with a capacitance C2, will increase the voltage on the VD7 dynistor to a level higher than that on the VD6 dynistor. Then VD7 will open first and the red LED HL2 will light up. The value of capacitance C2 is selected in such a way as to react to the appearance of short pulses (≤ 1 μs) caused by discharges on the insulator. More details of the work of the LED indicator are considered in the thesis.

3. Results
The indicator works without using a separate power source on the principle of accumulating electric field energy. For the efficiency of such a device, it is necessary that during the accumulation of energy, as little of it as possible is lost. Therefore, the development of criteria for the selection of elements of the indicator circuit with minimum leakage currents is fundamental. This was the first challenge in the simulation.

The second task in computer calculations was to assess the possibility of visually detecting the appearance of an insulation defect on various types of insulators by changing the voltage on the indicator, and hence changing the LED blinking frequency.

The calculations were carried out in the COMSOL Multiphysics program [23-24] by constructing and analyzing three-dimensional models of insulators LK70/35 and LK70/110 with the same indicator installed on them.

At the beginning of the modeling of the LK70/35 insulator, a three-dimensional model of the insulator was drawn in the COMSOL program.

Figure 3 shows a separate section of the insulator with an indicator installed on the end piece.
Figure 3. Indicator attached to the end cap.

The situation was simulated when the insulator is in air, a phase voltage of 20 kV (35 kV / 1.7) is applied to the ends of the insulator, the amplitude value of which is $U_0 = 28$ kV. A parametric calculation was carried out, where the resistance value of the indicator circuit $R_i$ was used as a parameter. The electronic circuit of the indicator itself was modeled by a strip of semiconducting material, the ends abutting against two electrodes, one of which is fixed to a grounded end cap. The variable parameter $R_i$ was converted into the value of the specific conductivity of the material of the semiconducting strip $G$ from the well-known formula:

$$
R_i = \frac{l}{G \cdot S},
$$

where $l$ is the length of the circuit, m;
$S$ — cross-sectional area of the strip in the middle part, m$^2$.

The equation used by COMSOL Multiphysics to calculate is derived from Ohm's Law, Continuity Equation, and Gauss's Theorem. For a sinusoidal current with an angular frequency $\omega = 2\pi f$ and an isotropic medium, these expressions can be written as:

$$
J = \sigma \cdot E;
\nA \cdot J = \nabla \cdot (\sigma \cdot E) = -j \cdot \omega \cdot \rho;
\n\nA \cdot D = \rho;
\nE = -\nabla \cdot V; D = \varepsilon \cdot \varepsilon_0 \cdot E,
$$

where:
$J$, $E$, $D$ are vectors of current density (A / m$^2$), electric field strength (V / m) and electric displacement (C / m$^2$), respectively;
$\sigma$ - specific conductivity (S / m);
$\rho$ is the volumetric charge density (C / m$^3$);
$\varepsilon$ is the dielectric constant of the material;
$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m — electrical constant; $j$ is the imaginary unit.

After substituting the expressions for $E$ and $\rho$ into the continuity equation, a Poisson equation of the form $\nabla \cdot (-(\sigma + j \cdot \omega \cdot \varepsilon \cdot \varepsilon_0) \cdot \nabla \cdot V) = f$ is obtained from a set of mathematical equations solved by the COMSOL Multiphysics software.

$$
\nabla \cdot (-(\sigma + j \cdot \omega \cdot \varepsilon \cdot \varepsilon_0) \cdot \nabla \cdot V) = 0
$$
Table 1. Initial data for calculation in COMSOL Multiphysics software.

| Name           | Value          | Size       | Description                                      |
|----------------|----------------|------------|--------------------------------------------------|
| l              | 14e-3[m]       | 0.014 m   | Circuit length                                  |
| S              | 1e-5[m^2]      | 1E−5 m²   | Cross-sectional area of the strip (diagram) in the middle |
| R              | 1e6[1/S]       | 1E6 Ω     | Leakage resistance of indicator circuit         |
| r              | R*S/l          | 714.29 Ω·m| Resistivity of the indicator circuit             |
| G              | 1/r            | 0.0014 S/m| Specific conductivity of the indicator circuit   |
| sigma_air      | 0[S/m]         | 0 S/m     | Specific air conductivity                       |
| epsilon_air    | 1              | 1         | Dielectric constant of air                       |
| sigma_copp     | 5.99e7[S/m]    | 5.99E7 S/m| Specific conductivity of copper                  |
| epsilon_copp   | 1              | 1         | Dielectric constant of copper                    |
| sigma_al       | 3.77e7[S/m]    | 3.77E7 S/m| Specific conductivity of aluminum                |
| epsilon_al     | 1              | 1         | Dielectric constant of aluminum                  |
| sigma_sig      | 1e-14[S/m]     | 1E−14 S/m | Specific conductivity of rubber                  |
| epsilon_sig    | 2.09           | 2.09      | Dielectric constant of rubber                    |
| sigma_gla      | G              | 0.0014 S/m| Specific conductivity of the circuit             |
| epsilon_gla    | 1              | 1         | Dielectric constant of the circuit               |
| $U_0$          | 28[kV]         | 28000 V   | Insulator voltage amplitude                      |
| f              | 50[Hz]         | 50 Hz     | Frequency                                        |

Further, the electrical characteristics of materials for each of the areas were established using the example of the isolation area. Also, boundary conditions were set for the potential, "land" and the boundaries of the computational domain.

The parametric calculation was performed for the values of the leakage resistance $R$ of the indicator electrical circuit: $1 \text{ MΩ}$, $10 \text{ MΩ}$, $100 \text{ MΩ}$ and $500 \text{ MΩ}$. The most important result is shown in Figure 4.

Shown here is the potential difference between the electrodes of the circuit as the circuit leakage impedance changes from $1 \text{ MΩ}$ to $500 \text{ MΩ}$. It can be seen from the graph that the developed circuit based on dinistors (figure 2) will not work until the potential difference does not exceed the response voltage of the dinistors (~ 40 V), which can only happen if the total resistance of the indicator exceeds 20 megohms. This important conclusion formed the basis for the choice of components and the design of the indicator.

The constructed model served as the basis for calculating the operation of an insulator for $110 \text{ kV}$ with an indicator, where the capabilities of the indicator were modeled and evaluated in terms of functional purpose.
Figure 4. Dependence of the amplitude value of the circuit voltage on the resistance of the indicator circuit.

**Modeling a 110 kV suspended polymer insulator with a defect.** In the case of a 110 kV suspended polymer insulator with a defect, it is necessary to assess the change in the repetition rate of the indicator light pulses in the presence of a defect in the insulating structure shunting part of its length.

For this, a model of a 110 kV insulator of the LK70 / 110 brand was created. A feature of this insulator, in contrast to LK70 / 35, is the presence of screens at the ends, which serve to equalize the electric field. The presence of screens determines the requirements for optimal fixing of the indicator on the insulator. We considered two possible options for attaching the indicator: on the terminal behind the screen and on the screen itself.

The insulation defect was modeled as a conductive channel 1 mm in diameter located inside the insulator between the rubber sheath and the fiberglass rod, as shown in Figure 5. The defect shunts 30% of the insulating structure.

Figure 5. Section of the insulator with a highlighted defect.

Calculations in the COMSOL Multiphysics program were carried out according to the initial data (table 1) with the changes and additions reflected in table 2 according to the formula (3).
Table 2 Initial data for calculation with changes and additions

| Name     | Value          | Size      | Description               |
|----------|----------------|-----------|---------------------------|
| $R$      | $4.0 \times 10^{-7} [\text{S}]$ | $4 \times 10^{-7} \Omega$ | Indicator circuit resistance |
| $\sigma_D$ | $1 \times 10^{-12} [\text{S/m}]$ | $1 \times 10^{-12} \text{S/m}$ | Defect specific conductivity |
| $\varepsilon_D$ | $1$ | $1$ | Defect dielectric constant |
| $U_0$    | $90 [\text{kV}]$ | $90000 \text{V}$ | Insulator voltage amplitude |

Figure 6 shows the results of a parametric calculation in the form of graphs of the dependence of the amplitude of the potential difference between the indicator electrodes on the conductivity of the defect for cases where the indicator is installed behind the screen and on it, respectively. As expected, in absolute terms, the voltage is higher in the second case. However, the change in voltage as the defect develops is negligible. In the first case (figure 6, 1) the voltage increases from about 64 V to 83 V and the ratio is 1.3, and in the second case (figure 6, 2) from 112 V to 145 V and the ratio is also 1.3.

![Figure 6](image1)

Figure 6. 1 - Change in the potential difference from the conductivity of the defect when the indicator is located behind the screen; 2 - Change in the potential difference from the conductivity of the defect when the indicator is located on the screen.

Figure 7 shows the voltage distribution along the indicator from the free electrode (antenna) to the attachment point for cases without a defect (figure 7, a) and with a defect (figure 7, b) with high conductivity, respectively.

![Figure 7](image2)

Figure 7. Change of potential on the indicator from antenna to ground: a - no defect in insulation ($\sigma_D=1 \times 10^{-12} \text{ S/m}$) b - defect with high conductivity ($\sigma_D=100 \text{ S/m}$).
Further, it is important to find out whether the increase in the voltage on the indicator in the event of a defect will be sufficient to change the repetition rate of light pulses of the indicator LEDs when visually distinguishing between the defective and normal states of the insulator.

The principle of operation of the indicator according to the diagram in Figure 2 is based on the accumulation of energy on a capacitor through an integrating circuit.

![Figure 8. Equivalent circuit of the indicator input circuit.](image)

The voltage on C1 will increase over time according to the law:

$$U_c(t) = U_{in} \cdot (1 - e^{-\frac{t}{\tau}})$$  \hspace{1cm} (4)

In the circuit (figure 2), the voltage $U_c(t)$ can only increase up to the switching voltage of the dynistor. The time to reach this value is the shorter, the higher the input voltage $U_{in}$. As shown by modeling, with a defect in the polymer insulator LK70 / 100, covering 30% of the insulation, the voltage on the indicator increases 1.3 times.

Let $t_1$ and $t_2$ be the time for the voltage on C1 to rise to the turn-on value of the dinistor $U_c(t_1) = U_c(t_2)$ for the case without a defect and with a given defect, respectively. Then, setting $U_c(t_1) = U_c(t_2) = 36$ V, and $U_{in1} = 112$ V and $U_{in2} = 145$ V from formula (4) we get:

$$t_2 = \frac{\ln(1 - \frac{U_c}{U_{in1}})}{\frac{U_c}{U_{in1}}} = 0.736$$

$$t_1 = \frac{\ln(1 - \frac{U_c}{U_{in2}})}{\frac{U_c}{U_{in2}}}$$

Thus, the presence of a defect will cause an increase in the repetition rate of light pulses by $1 / 0.736 = 1.36$ times. As laboratory and field experiments have shown, this increase in the pulse repetition rate on one indicator is difficult to assess. However, when observing simultaneously two or more indicators located on adjacent phases of the same support, the identification of a defective insulator is simplified.

4. Conclusion

Modeling in the COMSOL Multiphysics program formulated the requirements for the electronic components of the developed circuit: the choice of elements should be such that the total resistance of the indicator circuit was at least 20 megohms.

Modeling the operation of the indicator on a polymer insulator in the presence of a defect in the form of a conductive channel showed that an increase in the voltage on the indicator caused by damage to the insulation and, accordingly, an increase in the frequency of light pulses of the indicator is visually detected by the operator when simultaneously observing two or more indicators located on adjacent phases of one and the same support.

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