Analysis of arc surges in electric networks of the Arctic region

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Abstract. This work is devoted to the urgent issue of the analysis of arc surges in electric networks of the Arctic region of the Russian Federation, using the electric power system of the Kola Peninsula as an example. The article presents an approach to the development of a computational model of a power system in the Matlab software environment, the Simulink simulation application. When compiling the calculation model, the following points were taken into account: the model was in a three-phase formulation; the inductances of overhead power lines were taken into account; non-linear arc resistance was taken into account; grounding resistance was taken into account; the magnetic coupling between the phases and interphase capacitances were taken into account. Based on the results of the model, graphs of transients in the system were obtained for various operating modes. The correctness of the calculation model was checked on the following points: on the voltage, it is necessary that the phase voltages on the buses of the substation ПС-24 correspond to the phase voltages at all points of the model and be shifted relative to each other by an angle of 120 °; current, current at all points of the system, the current must be symmetrical; according to the current of a single-phase short circuit, it is necessary that the value of the short circuit current obtained using the calculation model corresponds to the current value obtained in the analytical calculations. In the study of arc surges, more than 60 calculations were performed. The performed calculations showed the dependence of the overvoltage ratio on the fault location and the uneven distribution of overvoltages in the considered sections. An analysis of the results obtained in the work allows us to conclude that it is advisable to apply this approach to other electric power systems of the regions of the Russian Federation and other countries.

1. Relevance

The main factors determining the maximum overvoltage during single-phase earth faults are: voltage at the emergency phase at the time of primary ignition of the arc, the moment of extinction of the arc and voltage of re-ignition of the arc [1], [2], [3].

It is also necessary to take into account the peculiarities of the development of arc overvoltages in an electric network with long sections of overhead power lines, i.e. in the presence of elements with a relatively large inductance and resistance. Therefore, it is necessary to draw up a calculation model that takes into account these parameters.

2. Requirements for the design model of arc overvoltages
When compiling a calculation model, the following requirements are imposed on it [1], [2], [3], [4], [5]:

- for the model of arc overvoltages, it is necessary that the model be in a three-phase formulation;
- since if there are overhead power lines (the presence of elements with a relatively large inductance), then the inductance of these air inserts must be taken into account;
- account must be taken of the nonlinear resistance of the arc, i.e. the model must be on positive and negative polarity;
- transients and overvoltages are affected by grounding resistance at the location of insulation damage. First of all, this refers to the support of overhead lines. Therefore, the model must take into account the grounding resistance;
- since the section is connected to the supply transformer, therefore, there is a connection with the system, it is advisable to take into account the magnetic coupling between the phases, therefore a three-phase model of the transformer with galvanic isolation and with a grounded high side winding is required;
- transient processes during an arc fault to earth can be affected by interphase capacitances of the network, therefore it is necessary to take into account interphase capacitances in the model of air inserts. However, the presence of a load at the connection points of transformer substations has a shunting effect on the interphase capacitance, therefore, it is necessary to take into account the load resistance between the phases [6], [7], [8], [9], [10], [11].

3. Design model development

To develop the calculation model, the Matlab software environment, the Simulink application, was used. The power system of the Kola Peninsula was chosen as the object of study.

Figure 1 shows the design model diagram for a 10 kV network section connected to the first bus system of the substation ПС-24 power substation. The model performed the replacement of cable and overhead lines with elements with distributed parameters.

At node 0, capacities of the Φ-5 feeder are included, and partially the capacities of the remaining feeders. We turned up the Φ-4 feeder and presented it in the form of a single П - cell (line capacities are assigned to node 6).

In the diagram, the 110 kV network and the energy source at the supply substation are represented by a block of branches 1-23 (nodes 1-12). The resistance of the branch 4 - corresponds to the grounding resistance of the substation ПС-24.

The model diagram of a 10 kV network section connected to the first substation ПС-24 bus system includes 61 nodes and 163 branches.
Figure 1. Calculation model for a 10 kV network section connected to first bus system substation ПС-24

4. Model check
The correctness of the calculation model is checked on the following points:
1. in terms of voltage, it is necessary that the phase voltages on the buses of the substation ПС-24 correspond to the phase voltages at all points of the model and be offset relative to each other by an angle of 120 °;
2. by current, the current at all points of the system, the current must be symmetrical;
3. by the current of a single-phase short circuit, it is necessary that the value of the short circuit current obtained using the calculation model corresponds to the current value obtained in analytical calculations [9-11].

The implementation of this test is confirmed by the voltage and current waveforms for the Φ-10 feeder, shown in Figure 2
Figure 2. Oscillograms of voltage and currents on the first bus system substation ПС-24
a) voltage at the F-10 feeder, b) current at the F-10 feeder, c) single-phase short circuit current

From the current waveform (graph c) it was found that the amplitude value of the short circuit current on the first bus system is = 19.78 A.

In the study of arc surges, more than 60 calculations were performed. Including in phase A in nodes No. 16, 20, 27, 30, 36 and 43 of the calculation model shown in Figure 1. These nodes in the calculation model correspond to specific points on the working diagram of sections of the 10 kV electric network connected to substation ПИС- 24.

5. Characteristic of arc overvoltages on the first bus system of distribution point ПИ-7
Consider the case of modeling a short circuit in phase A on the first bus system of the distribution point ПИ-7 (in node 16 of the calculation model). The characteristic oscillograms of voltages and currents obtained for this case, as well as the arising overvoltages, are shown in Figs. 3 and 4.
Figure 3. Oscillograms of voltages and currents during a single-phase short circuit on the F-10 feeder line (in node 16 of the model of a 10 kV section of the electric network connected to the first substation bus system ПС-24): a) bus voltage in the 10 kV network of the substation ПС-24; b) voltage at the point of short circuit and neutral bias voltage; c) arc current at the point of short circuit; d) voltage drop on the insulation of the line in the place of its damage.

The graph c) shows the arc current at the place of damage, the following time points are indicated here:

- \( t_1 \) - the arc ignition moment;
- \( t_2 \) - the moment of possible arc extinction;
- \( t_3 \) - moment of absence of extinction of the secondary arc due to the fact that the extinction peak exceeds the phase voltage
- \( t_4 \) - arc extinction time;
- \( t_5 \) - the moment of reignition of the arc.
Figure 4. Oscillograms of overvoltages at substations during a short circuit on the F-10 feeder line (in node 16 of the model of a 10 kV network section connected to the first substation bus system PS-24): a) plot number No. 2; b) plot number No. 3; c) plot number No. 4; d) plot number No. 5.

The multiplicity of overvoltages during the first arc burning is less than during repeated ones. This is explained by the fact that at the time t3 there was a decrease in the neutral bias voltage, but at the moment of re-ignition of the arc t5 the neutral bias voltage increased and this led to an increase in the
overvoltage ratio. If the arc in the time interval $t_1 - t_4$ were ignited and extinguished immediately without re-ignition, then an increase in the overvoltage ratio would not have occurred.

Figure 4 shows that the levels of overvoltage during a short circuit in node 16 reach values from 20.9 kV to 21.92 kV, and the greatest overvoltages occur on the overhead line Л-62, the magnitude of which is 21.92 kV.

Due to the large volume of the obtained voltage and current waveforms, the most characteristic waveforms were given, and the magnitude and calculated values of the overvoltage multiplicity in the 10 kV network section connected to the first substation bus system PS-24 are summarized in Table 1.

**Table 1.** The magnitude and frequency of overvoltages in the first bus system substation ПС-24

| Plot number | The magnitude (kV) and the multiplicity of overvoltage during short circuits |
|-------------|--------------------------------------------------------------------------------|
|             | Φ-10            | Л-62       | Л-48        | Л-52       | Л-62       | Φ-10       | Φ-40       |
| 1           | 20.84           | 23.29      | 22.45       | 22.67      | 23.59      | 22.65      |
|             | 2.55            | 2.85       | 2.75        | 2.78       | 2.80       | 2.77       |
| 2           | 21.92           | 23.33      | 22.48       | 22.72      | 23.63      | 22.77      |
|             | 2.68            | 2.86       | 2.75        | 2.78       | 2.80       | 2.79       |
| 3           | 21.88           | 23.38      | 22.54       | 22.79      | 23.73      | 22.89      |
|             | 2.68            | 2.86       | 2.76        | 2.8        | 2.9        | 2.8        |
| 4           | 21.87           | 23.23      | 22.47       | 22.68      | 22.56      | 22.74      |
|             | 2.68            | 2.84       | 2.75        | 2.78       | 2.76       | 2.78       |
| 5           | 21.47           | 22.98      | 22.86       | 22.22      | 22.56      | 23.64      |
|             | 2.63            | 2.81       | 2.8         | 2.72       | 2.76       | 2.80       |
| 6           | 21.25           | 23.48      | 22.44       | 22.52      | 23.25      | 21.68      |
|             | 2.60            | 2.87       | 2.75        | 2.76       | 2.85       | 2.65       |

The performed calculations showed the dependence of the overvoltage ratio on the fault location and the uneven distribution of overvoltages in the considered sections.

The specific number of thunderstorm ceilings of the insulation of overhead lines of 10 kV per 1 km was determined taking into account direct lightning strikes in a line, including reverse ceilings and induced overvoltages.

The performed calculations of arc overvoltages and estimation of the number of overlapping insulation lines showed the need for measures to limit arc overvoltages on sections of the 10 kV network of substation ПС-24.

The developed model showed the reliability of the calculations, which, in turn, will allow it to be used to analyze the electrical networks of the entire Arctic region.

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