# Modeling 6(10)-35 kV electrical network for fault location via negative correlation

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**ABSTRACT**

In order to maintain the technical leadership of the economic sector in any nation, there is currently a greater focus on guaranteeing the fail-safe operation of electrical networks and electrical equipment. This paper presents a model for evaluating the fault location procedure based on computer simulation in MATLAB/Simulink of complex 6(10)-35 kV power line systems. The proposed algorithm for preprocessing electrical network signals in normal and emergency modes uses a negative statistical correlation of all possible electrical parameters, while the resulting percentage errors when estimating the location of the fault are within acceptable limits. Algorithms and significant parameters have been determined for effectively carrying out the procedure for searching for the location of a fault through the use of modeling programs, namely: zero-sequence voltage, negative-sequence voltage, initial current value. and the positive sequence voltage is the transition resistance at the accident site. An assessment of the results of preliminary modeling may indicate that devices for finding the location of a fault in the 6(10)-35 kV electrical network will be able to use information obtained about the object using the developed methodology, adjust calculation algorithms and take into account the operating modes of the electrical network.



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## 1. INTRODUCTION

Currently, the majority of Kazakhstan's electrical system's coverage is provided by the 6(10)-35 kV distribution network. The large length of the network leads to frequent damage as well as the occurrence of abnormal operating modes. Damages in 6(10)-35 kV networks are not always of an emergency nature. Thus, a single-phase earth fault, as the most common type of damage, refers to an emergency mode. The three-phase power grid continues to operate in this abnormal mode; however, the resulting overvoltages quickly shorten the service life of the insulation of the serviceable phases [1]. The relevance of the introduction of modern tools and methods for determining the location of damage is characterized by obtaining a significant technical and economic effect by reducing power outages, preventing the transition of unstable damages to stable ones, and reducing logistical and other costs for the maintenance of the electric network. To solve these problems, scientists [2]-[5] present methods for determining single-phase ground faults and offer ways to improve accuracy by reducing the control zone of overhead power lines through the use of special digital signal processing of emergency mode oscillograms. An interesting method was proposed by [6] when determining fault locations in a highly branched electrical network and high complex resistance, taking into account climatic conditions during the measurement.

A high number of modern methods involve the use of information systems for the localization of accidents on power lines. Thus, Deng [7] proposes a method for determining the location of faults in the electrical network by correlating topological structural nodes of the network depending on the degree of emergency events and the accumulation of an accident database. In articles [8], [9], the fault localization technology is summarized from three points of view: selection of the defect line; localization of the site; further damage ranking with subsequent modeling. Special attention should be paid to the method based on the wavelet transform, which has a low error rate and the possibility of computer simulation when fixing the emergency mode [10]. Calculations and simulation of overhead transmission line modes in determining the fault location are an integral part of solving problems, related to the design and operation of relay protection systems and emergency automation [11], [12]. An interesting method for determining the location of faults by matching the waveform of the backward wave with a simulation based on a static model of the system is presented in the article [13].

Methods of managing the transmission of emergency mode data using modern information technologies are presented in scientific papers [14]-[19], which present new concepts in the detection of damage sites. The results of studies of these models and methods can be used in the planning of regimes, operational management, calculation of the distance to the accident site, and serve as the basis for optimization and assessment of the stability and reliability of a power system. The defect detection method using emergency mode parameters (remote) also has significant errors due to the long-term recognition of the fault current and the complexity of processing calculations in the presence of high branching in the 6(10)-35 kV network [20]. Therefore, the parameters of the emergency mode are significant and do not have a strictly functional nature of fixation.

The analyzed methods mainly use certain factors that affect the accuracy of determining the location of damage in networks with a voltage of 6(10)-35 kV with an isolated neutral. For high accuracy, it is important to take into account the features of the network operation mode, load fluctuations in case of an accident, the conditions of branching of the electrical network, as well as the values of transient resistances at the site of the defect. It is also necessary to take into account the statistical relationship of all parameters of the electric network when developing an electric network model, which is an obligatory part of the algorithms of modern microprocessor protection devices and the automation of electric networks. The purpose of this article is to form a computer model of an electric network to determine the emergency mode when searching for a fault location in 6(10)-35 kV networks with relay protection and automation devices, with the inclusion of statistical dependencies of significant parameters of the electric network using the negative correlation method.

## 2. METHOD

The study of the considered electrical network of 6(10)-35 kV to determine the location of damage is proposed to be carried out by the method of negative correlation with indication of emergency mode factors. The method takes into account the statistical dependencies of all possible average values or ranks of electrical parameters and modes of operation of the network with a voltage of 6(10)-35 kV. To implement this research, a formalized description method is used by developing a computer model using a real network as an example, which is partially shown by the author in a scientific article by [21]. At the same time, additional restrictive conditions are observed: the variables of the network parameters (X) and the result of the desired distance (Y) are continuous quantitative data have a normal distribution, and the variance of random variables along the direct regression should be constant.

The levels of implementation of the negative correlation method in determining the location of damage by emergency mode parameters are the requirements of the technical specification for finding the location of damage in 6(10)-35 kV networks, software implementation, a formalized description of the components of the problem solution (mathematical model), and components of the circuit parameters (libraries). The first abstract level of the method forms the technical specification that the method must implement to accurately determine the location of the fault. The goals and objectives of the first level are clear: the composition of the work, materials, a list of regulatory and technical documents, and deadlines are indicated. These are general norms. To create the basic part of the algorithmic model, the initial one-line schematic diagram of the studied electrical network is used. This is shown in Figure 1.

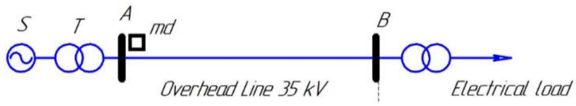


Figure 1. Single-line schematic diagram of the 35 kV network under study, with the installation of a measuring and fixing device

On this electrical circuit diagram, the designations are adopted as:
- A and Б: buses of 35 kV substations;
- C: system, energy source of unlimited power;
- T: power step-down transformer feeding the outgoing line;
- OL 35 kV: investigated overhead line (OL) 35 kV;
- Load: the current load of the line under study;
- MD: measuring devices of the outgoing line, installed at the beginning of the line.

The choice of a software product using the negative correlation method of fault location search in the electrical network is made at the second abstract level of the method. To implement the task of the level, well-known software and information products were analyzed, which perform the functions of correlation analysis and at the same time form a full-fledged model of the electric network. A comparative analysis of MATLAB, PSpice, DesignLab, Labview, MathCAD, and SwitcherCAD applications has shown that currently the MATLAB Multisim program is a leader in the field of scientific and technical software and differs in an acceptable level of design complexity in terms of program volume, number of variables, complexity of program development, complexity of program structure, and transformations (algorithms). Therefore, for network modeling, the MATLAB program is proposed to be used with the connection of Simulink block-object modeling applications.

The third abstract level forms models based on multi-purpose parameters that will meet the terms of the technical specification. All technical and electrical parameters of the power transmission line are set, which have a direct impact on the results of modeling and measurements. With a decrease in the total resistance in the model by no more than 10%, it is allowed to neglect the values of the generated charging reactive power of the line, as well as the same type of line resistances (active or inductive) when modeling emergency mode.

The overhead power line itself is the main object of this study. To correctly simulate its operating modes (normal and emergency overloads), it is necessary to calculate the parameters and compile matrices of equations of the state of the line in different modes. Simulink uses the transmission line parameters tool, which is used to simulate high voltage line parameters to speed up and accurately calculate transmission line parameters. For the correct formation of the algorithm and obtaining the results of the model, it is necessary to set the entire family of probabilistic and physical parameters of the line, as partially indicated by [22], and which are presented in Table 1. The data obtained can be written to the block modeling power lines after calculating the parameters at this abstract level. To do this, select the necessary block in the modeling window that creates the line model.

The fourth abstract level involves the use of a mathematical model in the constructed blocks. To implement the method of negative correlation of fault location search, the most optimal calculation model is to determine the parameters of the symmetrical components of the emergency mode, namely the reverse and zero sequence. The mathematical relationship between the model parameters will determine the distance to the damage site using expression (1) [23]:

$$l = \frac{U'_{ph} - 2 \cdot U'_2}{I'_2 \cdot 2 \cdot Z_2} \tag{1}$$

where $U'_{ph}$ is the instantaneous value of the phase voltage of the damaged phase before damage, B. $U'_2$ is the instantaneous voltage of the reverse sequence, V; $I'_2$ is the instantaneous value of the reverse sequence current, and A; $Z_2$ is the resistance of the reverse sequence, Ohm.

The resistance of the reverse sequence, as a random value, is determined by an array of $dZ_{trt}$ values, and determines the tendency of the effective feature to change as the desired distance to the fault site, when the factorial feature changes as transient resistance:

$$Z_2 = x_{sp2} + dZ_{trt} \quad (2)$$

where $x_{sp2}$ is the specific inductive resistance of the line, Ohm/km and $Z_{trt}$ is the contact (transient) resistance at the site of damage, Ohm.

Table 1. List of editable parameters of the power line parameters tool application

| Comments | User comments window |
|---|---|
| General parameters | Basic parameter setting block |
| Units | The system calculating the parameters of the model |
| Ground resistivity | Earth soil resistivity (Ohm/km) |
| Nominal frequency | Rated frequency of AC mains (Hz) |
| Line geometry | Geometric parameters of the calculated line |
| Phase conductors | Number of phase wires. Default is 3 |
| Ground conductors | Number of grounding conductors (lightning wires) |
| Label | Phase wire identifier |
| Phase number | Phase number to which the conductor belongs to |
| X | The horizontal location of the conductor relative to the one whose position is set to 0 (m) |
| Y tower | Vertical position of the wire on the support at the attachment point relative to the ground (m) |
| Y min | Minimum wire height to ground (m) |
| Conductor type | Conductor type identifier used in wire calculation |
| Conductors | Parameter bloc of wires used in the line |
| Conductor types | The number and characteristics of conductors used in the projected power transmission line are 3 phases |
| Internal conductor inductance from | Method for calculating the internal inductance of conductors by geometric radius |
| Include conductor skin effect | Consideration of the effect of current displacement under the internal inductive action of an alternating electric field |
| D out | Outer radius of conductor (cm) |
| T/D ratio | The ratio of the cross-sectional areas of steel and aluminum parts of the wire core |
| GMR | Geometric average radius of the conductive core (cm) |
| DC res | DC conductor resistance (ohm/km) |
| Nb_cond | Number of conductors in a phase |
| Compute | Parameter calculation block |
| RLC line parameters | Starting the calculation of specific RLC line parameters |
| Computed parameters | Output block of calculated parameters to the program console |

When considering a symmetrical homogeneous p-wire long-distance power transmission line with branches that has damage in the i-th section, the scheme in Figure 1 must be represented as a cascading connection of several elementary four-poles of two types. One type of four-pole corresponds to a section of a power transmission line with distributed parameters, the other to a branch. As a result, for the part of the network circuit to the left and right of the damage site, they will be defined as the product of the passive parameters of elementary four-poles, according to expression (3). Analytical expressions (1)-(3) are the main ones for setting the parameter values of the simulation model blocks.

$$l_i = \frac{1}{\gamma} Arth \frac{U_1'' ch\gamma L_i - U_1' + I_1'' Z_2 sh\gamma L_i}{U_1'' sh\gamma L_i - I_1' Z_B + I_1'' Z_2 ch\gamma L_i} \quad (3)$$

where $U_1'$, $U_1''$, $I_1'$, $I_1''$ are the input currents and voltages of the passive parameters of the four-pole terminals before and after the fault location in the electrical network.

## 3. RESULTS AND DISCUSSIONS

For approbation of the method and computer algorithmic model, initial parameters are set according to the conditions of the first abstract level, taken from information on a particular distribution substation and transmission lines: Operating voltage: the accepted value is 35 kV; line length: the accepted value is 23.8 km; wire grade and cross-section: accepted AS-70 mm$^2$; type of poles: accepted PB35-1 poles with a height of 19.6 meters and 15.2 meters wire chain dimension; system transformer from the higher voltage side: TDTN-2500/100/35 transformer; line load: total load power value of 1800 kVA.

Based on the selection of parameters and initial scheme in Simulink, a three-phase distribution network with power supply, the line under study, measuring and fixing devices and line load is modeled [24]. The network model to realize the second and third abstraction level of the method is shown in Figure 2.

The initial network model is conventionally composed of five blocks:

- Unlimited power supply system by capacity;
- 35 kV power transmission line;

– Current line load (power flow);
– Sensors, measuring current and voltage transformers;
– Devices for recording instantaneous current and voltage values.

The part of the model that simulates the emergency mode (transmission line) in MATLAB also contains two different blocks.

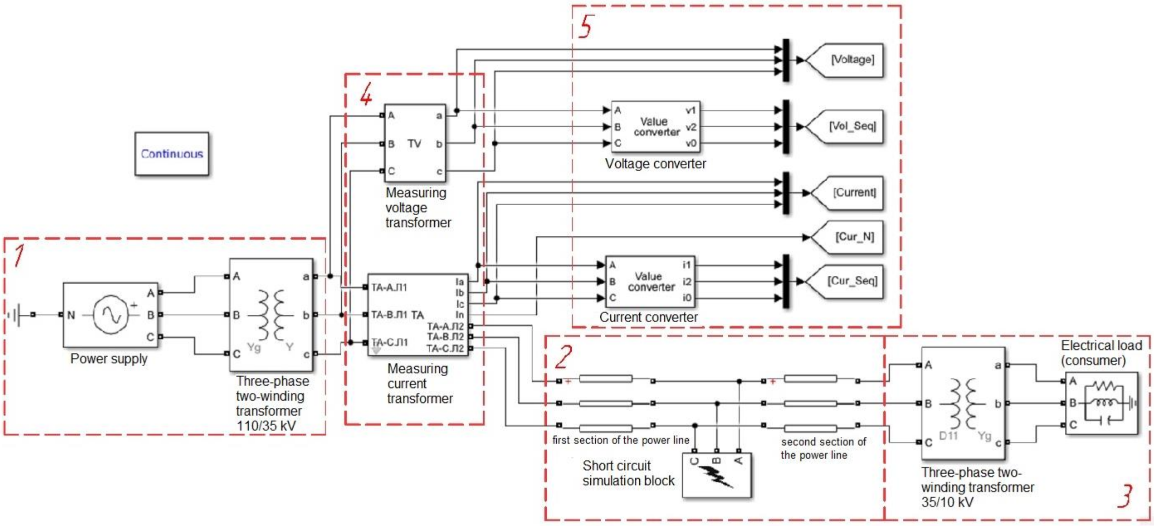


Figure 2. Model of the studied 35 kV network in Simulink

The first of them is a block for modeling the transmission line itself. Two blocks are installed on the model to simulate damage along the entire length of the line, provided that the line lengths are jointly changed in the block parameters. Its parameters are shown in Figure 3:

– Number of phases: the number of phases in the simulated block;
– Line length: length of the simulated line, km;
– Frequency used for RLC specification: nominal frequency of the electrical network for calculating RLC circuits, Hz;
– Resistance per unit length: specific active resistance of the line to direct current. It is set both in matrix form for intrinsic and mutual conductivities, and in vector form, taking into account only the values of the direct and zero sequence, Ohm/km;
– Inductance per unit length: specific inductance of the line. It is also set in matrix or vector form, H/km;
– Capacitance per unit length: line capacity per unit length. Specified as a vector or matrix value, f/km.
– The second block creates situations of various emergency and abnormal modes. The block is called three-phase fault. Consider the main block parameters shown in Figure 4:
– Initial status: the initial state of the block state. 1 – triggered for damage imitation, 0 – not triggered;
– Fault between: a block for selecting points included in the fault. It allows selecting all possible damage types.
– Switching times: time values, upon reaching which the block changes its status of being in the opposite one. It is possible to set several times for various block operation cycles. It is also possible to influence an external signal on the block status. When this item is enabled, the cycle time is invalid, sec;
– Fault resistance is an active resistance at the fault point between the poles of the selected faulty phases. In other words, this is the contact resistance of the short circuit, Ohm;
– Ground resistance: ground resistance of the earth during ground faults, Ohm;
– Snubber resistance is the value of the active resistance of the leakage current path of the simulated switch that commutates a short circuit, Ohm;
– Snubber capacitance is the capacitance of the leakage current path of the simulated switch commutating the short circuit, F.
– In order to understand the correct operation of the short circuit simulation unit, it is necessary to form an algorithmic principle of its operation.

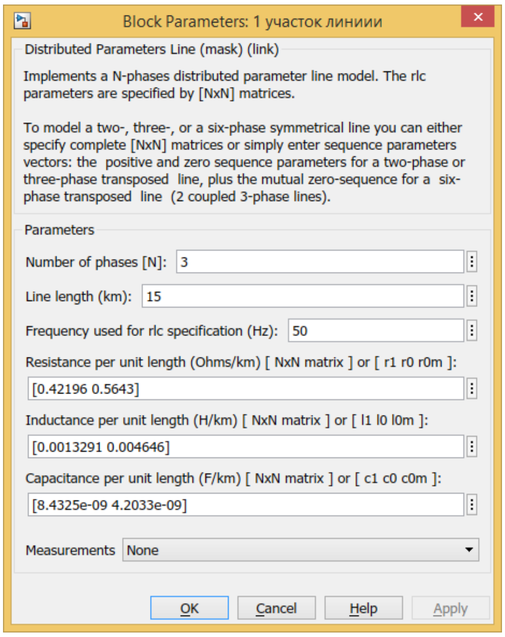


Figure 3. Parameters window of the “distributed parameters line” block

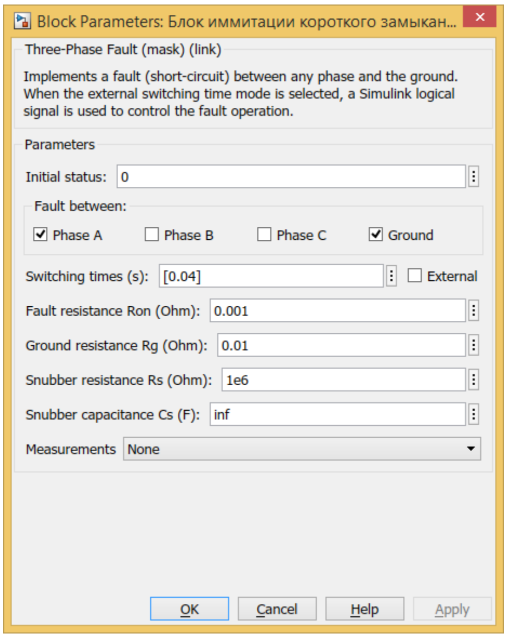


Figure 4. Parameters window of the three-phase fault block

The simulated scheme of this block is shown in Figure 5. This scheme can be divided into logical and executive ones. The logical part is responsible for the signals applied to the closing of the Fault A, Fault B and Fault C switches, which reproduce the pole closures between themselves. The value of the resistance and capacitance of the leakage current in the event of a short circuit just affect the value of the simulated resistance of the parallel branch of these switches.

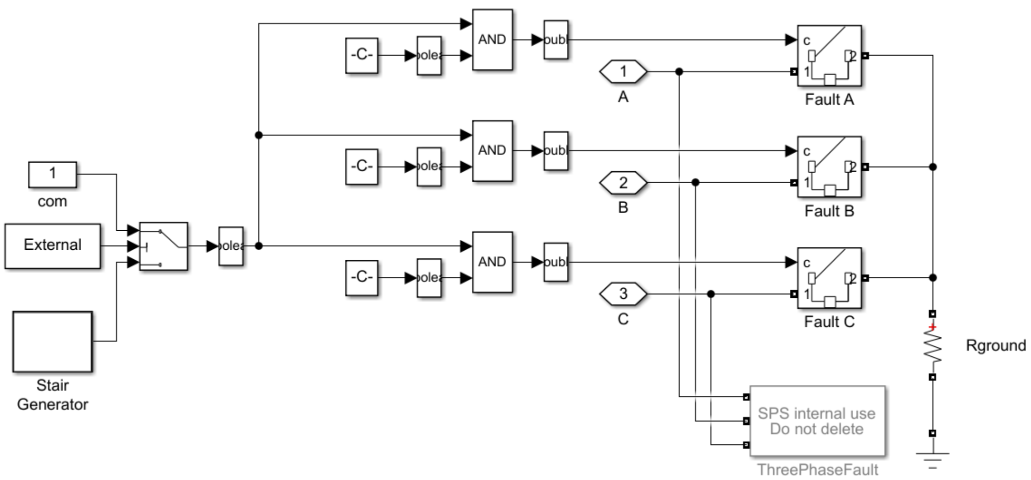


Figure 5. The structure of the short circuit simulation block (three-phase fault)

When starting the model calculation, the logical part surveys the block parameters to get information about the need to turn on one or another switch, depending on the selected poles involved in the fault's formation. Then the “logic” waits for either the trip time or an external signal to send an impulse to turn on the switches that act to turn off the short circuit. “Logic” gives a signal to open the circuit breakers when there is time for the termination of the short circuit or the removal of an external signal. If there is time for the termination of the short circuit or the removal of the external signal, the “logic” gives a signal to open the switches.

The resistor installed in the object's circuit imitates the zero point (grounding). It represents the resistance of the ground to the earth when the earth pole is included in the short circuit. When the key to the influence of the "earth" pole on the short circuit is removed, this resistor is assigned the value of infinity (inf) which actually means a gap between the ground and the short circuit point.

The load in the circuit simulates the line load according to the actual circuit diagram. It also comprises two blocks. One of the three-phase transformers (two-winding) block is already known (three-phase transformer (two windings)). The difference is only in the electrical parameters of the unit itself. The load of the whole system is realized by the block of three-phase parallel RLC load. Its main parameters are given in Figure 6. In addition, the model contains separately modeled groups of current transformers and voltage transformers.

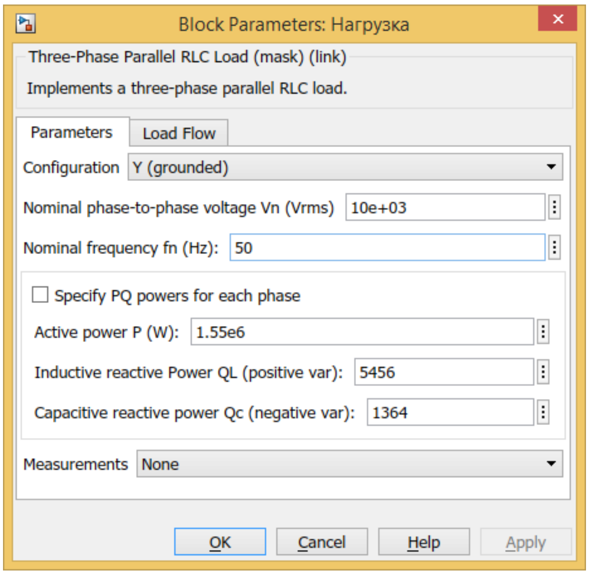


Figure 6. Block of three-phase parallel RLC load

Figure 7 illustrates the block diagram of a current transformer group simulation. The current transformers themselves are modeled using a block that simulates a saturable transformer. This block more accurately repeats the work of a current transformer, simulating its current-voltage characteristic. The main parameters of this block are shown in Figure 8: Nominal power and frequency - rated power of the winding and frequency of the alternating electric field pierced in the transformer windings, VA, Hz; Windings 1(2) parameters – parameters of the transformer primary (secondary) winding. It includes rated line voltage, V; active winding resistance, Ohm; winding inductance, H; Saturation characteristic-magnetization characteristic. It is set by two dependent current parameters on the generated voltage.

The parameters of this block only set the line voltages of the primary and secondary windings, not the phase current values. The current values are measured using current measuring blocks, analogous to a conventional ammeter. The primary voltage value is written as a formula to get a current transformer [11], [25].

$$V_1 = \frac{I_2}{k_{CT}} \tag{4}$$

where $I_2$ is nominal secondary value of current CT.

It is accepted that $I_2 = 5$ A. $k_{CT}$ is the CT transformation ratio depending on the rated value of the primary current. These blocks are installed both in each phase and in the neutral wire, which is formed when the secondary windings of the current transformers are connected to a star with a neutral wire. The neutral wire is a zero sequence filter, which is formed during ground faults. In this circuit and scientific work, the zero sequence current is one of the main signals, warning about the appearance of a phase wire contact with the ground. The primary current value is connected through the analog inputs of the block diagram, designated as L1 and L2. The measured secondary current values are fed to discrete outputs, which are connected to other analyzing and recording devices.

The output data have the names of the measured currents respectively, which is very convenient when connecting to other devices. In the process of determining the fault location, negative or zero sequence values are often applied. The instantaneous values of the measured quantities are usually used in pulse methods. However, instantaneous values can also be appropriate for the determination method with the emergency mode parameters. Simulated voltage and current conversion blocks are used to determine the values of the symmetrical components. The block diagram of these blocks is shown in Figure 9.

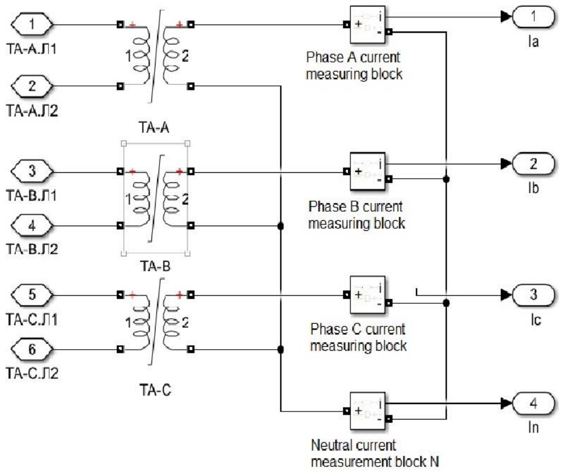


Figure 7. Structural diagram of modeling a group of current transformers

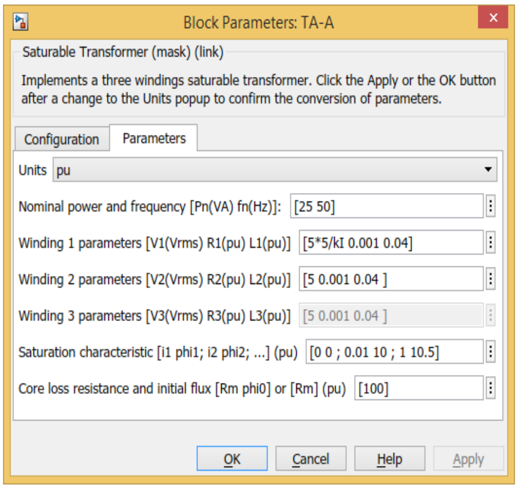


Figure 8. Saturable transformer parameters window

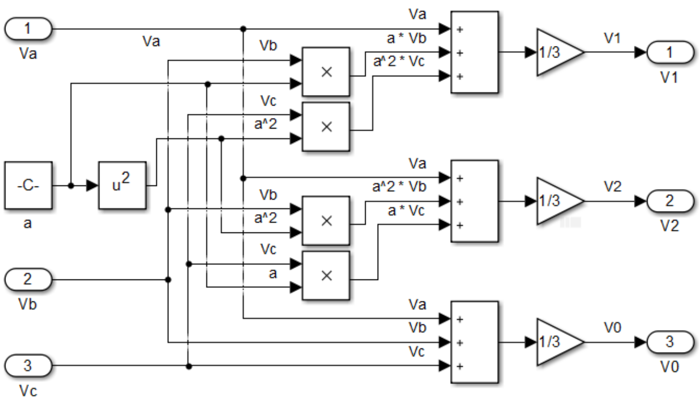


Figure 9. Structural diagram of the symmetrical components filter

The two blocks placed on the model of the network under study are the same, only the names of the block inputs and outputs are different for the best visualization of the model. The operation of this block is based on the theory of symmetrical components [1], [26]. According to this theory, any three-phase system, in normal and emergency modes, can be decomposed into three symmetrical components, such as direct, reverse, zero. This block finds the required values by solving the system of equations of the symmetrical components:

$$\begin{cases} \bar{A}_1 = \frac{1}{3}(\bar{A} + a\bar{B} + a^2\bar{C}) \\ \bar{A}_2 = \frac{1}{3}(\bar{A} + a^2\bar{B} + a\bar{C}) \\ \bar{A}_0 = \frac{1}{3}(\bar{A} + \bar{B} + \bar{C}) \end{cases} \quad (5)$$

where $\bar{A}, \bar{B}, \bar{C}$ is vector quantities of current/voltage measured for conversion. $a = e^{j\frac{2\pi}{3}}$ is the rotation operator according to the method of symmetrical components. $\bar{A}_1, \bar{A}_2, \bar{A}_0$ is the values of direct, reverse and zero sequence, respectively.

The output values of this block are the effective values of the symmetrical components. These data are transmitted to a chain of In-From blocks for further analysis and work. The transmitted data is extracted from the data blocks for two purposes: visual viewing on the oscilloscope and transferring it to the MATLAB workspace for further work. The data transfer scheme is shown in Figure 10.

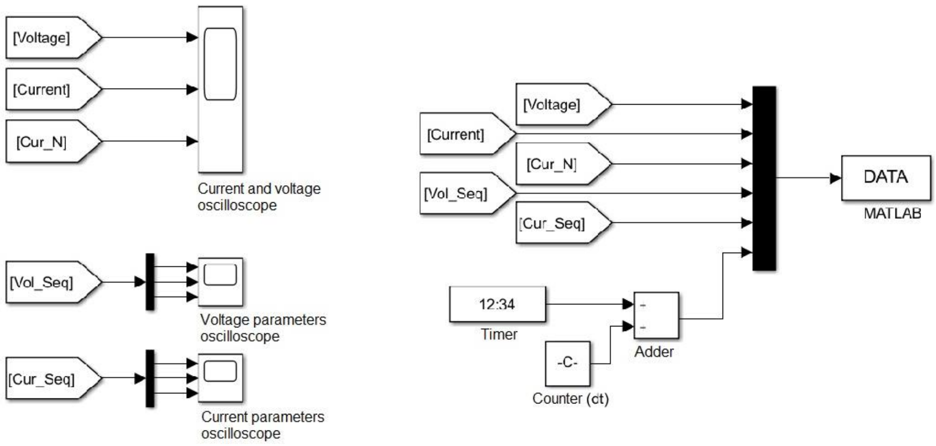


Figure 10. Scheme for fixing and transmitting measured and converted values

A working model of the network under study was formed in the Simulink program (MATLAB software) at this stage of modeling. The oscillograms generated when running the calculation of this model result from this work. The sample rate of the model is set to 10 kHz to check the performance of it. The response time of the short circuit simulation block is 0.04 sec without reset time. The duration of the entire simulation is 0.15 sec. The results of fixing values with oscilloscopes are shown in Figures 11-13.

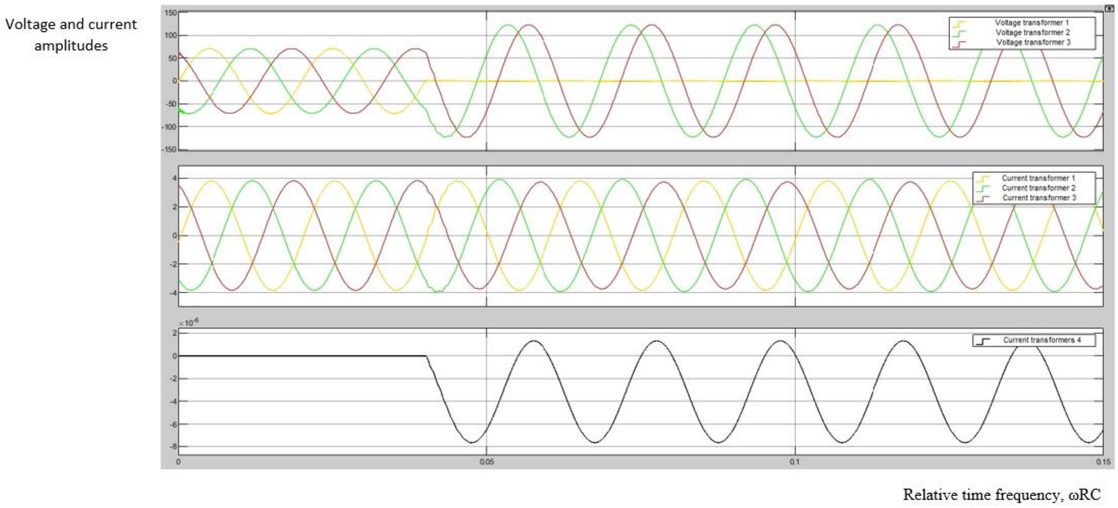


Figure 11. Oscillograms of the measured values of phase voltages, currents and zero sequence current

It can be concluded that the model of the network under study is correct, based on the obtained images. According to the theory [11], at the moment of the occurrence of a single phase-to-ground fault, a zero-sequence current appears. However, its value is minimal, so it is very difficult to detect by using many protections installed on these types of networks. In our case, the phase-to-earth fault current is $15 \times 10^{-7}$ A.

When a single-phase earth fault occurs, the voltage of the damaged phase drops to almost zero, and the voltage value in the intact phases increases to almost linear, as seen in the oscillograms. With such an asymmetric mode, a zero sequence voltage appears. Here, this voltage is 70 V, which means an obvious single-phase short circuit in the line under study. It is also worth paying attention to the behavior of the values in the reverse sequence. When a single-phase earth fault occurs, an oscillatory transient process occurs with a smooth increase in the periodic component. This mode is also repeated when the second wave of a single-phase earth fault impulse arrives.

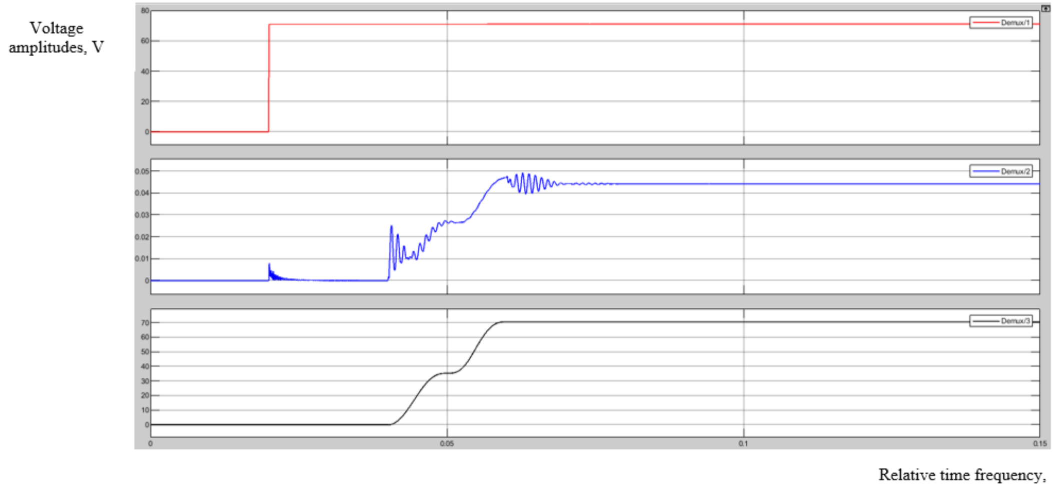


Figure 12. Oscillograms of the measured values of the symmetrical voltage components

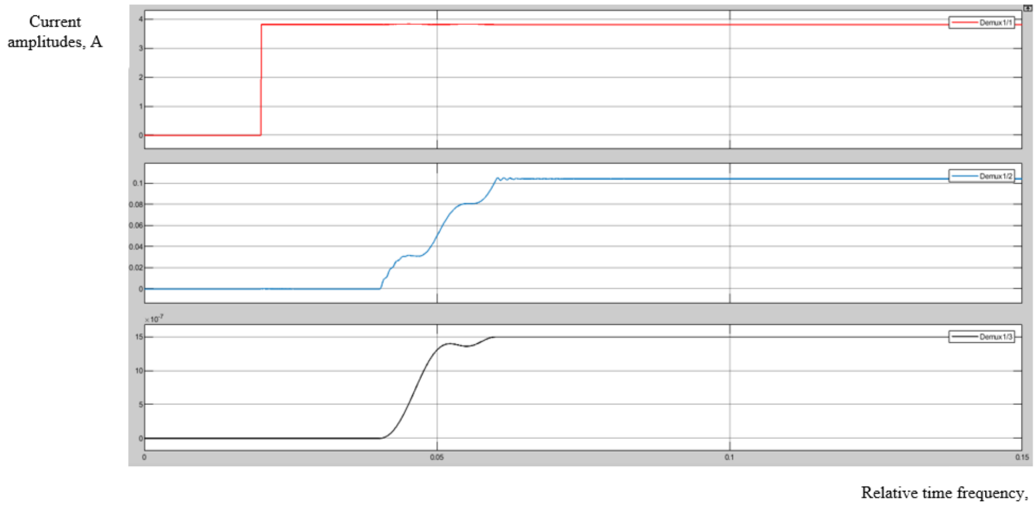


Figure 13. Oscillograms of the measured values of the symmetrical components of the currents

When calculating the average values of the waveforms and standard deviations of the network voltage parameters (Figures 11 and 12), the pearson correlation coefficient $r_p$ calculated by using (6) and (7):

$$r_p = \frac{\overline{X_1} - \overline{X_0}}{S_x} \cdot \sqrt{\frac{n_1}{N(N-1)}}, \tag{6}$$

$$r_p = \frac{85.6 - 70}{9.2} \cdot \sqrt{\frac{10 \cdot 10}{20(20-1)}} = 0.864. \tag{7}$$

where $\overline{X_1}$ is the average value of the variables in which the variable Y is equal to the instantaneous zero-sequence sign; $\overline{X_0}$ is the average value of the variables in which the variable Y is equal to the steady-state value of zero-sequence voltage; $S_x$ is the standard deviation value for the variable X; $n_1$ is the number of variables in which the nominal variable Y is equal to 1; and N is the total number of variables.

The calculated number of degrees-of-freedom k is 18, and the critical value of the correlation coefficient $r_{cr}$ is 0.44. Comparing the actual value of the correlation coefficient $rp$ and its critical value (0.86>0.44) we can conclude that the correlation between instantaneous and steady-state values of earth fault voltage on the constructed model, is statistically significant at $\rho \leq 0.05$. These conditions show the significance of the correlations and the model as a whole. Analysis of the results of test modeling algorithms to determine the location of faults showed that the error of each of (1), (3) is explained by the methodological error of the algorithm to find the fault location of the electrical network, the computational error of Matlab

Simulink and the error of the method of averaging the values of correlation analysis methods. For the proposed model, the maximum error of the negative correlation method in the absence of significant deviations of single-phase earth fault parameters, did not exceed 0.815%, which shows the correctness and accuracy of the method selected for the study of fault location search in the electric network voltage 6(10)-35 kV with insulated neutral.

## 4. CONCLUSION

When studying complex processes occurring during faults on 6(10)-35 kV power lines, not only analytical methods of calculation and forecasting but also computer algorithmic modeling should be used. To determine the fault location, a simulation model of the 6(10)-35 kV electrical network based on the negative correlation method has been developed. The method is designed for successful modeling of the network operation mode when searching for the fault location based on statistical relationships of all possible electrical parameters. The significant parameters identified are zero sequence voltage, reverse sequence currents and voltages; initial value of forward sequence current and voltage. In addition, the model has formed a block that considers the random component - it is the transient resistance at the fault location $Z_{trt}$. It is also worth noting that the initial zero value of the direct sequence of symmetrical components arises because of the state of the voltage converter. For a correct calculation in the component program, it is necessary to know all instantaneous values of the magnitude regarding the sampling frequency, since the first 0.02 seconds of the Simulink simulation do not reproduce the calculation of the magnitudes of the symmetrical components. These results show that the offset of the values from the setpoints in the model is also possible through a fault location search.

The influence of random events on the accuracy of fault location by the parameters of the network mode is not considered in the framework of this research, it is a promising and relevant area for further research by the authors on this model. This developed method and model can be used in the future to analyze the accuracy of determining the location of faults in power lines during complex accidents - double ground faults, metal faults and through transition resistance. Also, further research using a model of the influence of load and branches on the accuracy of fixing emergency mode parameters, analysis of the sensitivity of the fault location to the imposition of non-sinusoidal voltage on the frequency deviation of the supply network, and much more will be relevant. All this will help in the future to establish a clear algorithm for microprocessor flaw detection of protection in an electrical network with an isolated neutral voltage of 6(10)-35 kV.

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