ANALYSIS OF THE ERROR OF THE DEVELOPED METHOD OF DETERMINATION THE ACTIVE CONDUCTIVITY REDUCING THE INSULATION LEVEL BETWEEN ONE PHASE OF THE NETWORK AND GROUND, AND INSULATION PARAMETERS IN A NON-SYMMETRIC NETWORK WITH ISOLATED NEUTRAL WITH VOLTAGE ABOVE 1000 V

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Abstract - In the work the study of the developed method was carried out for reliability by analyzing the error in indirect determination of the insulation parameters in an asymmetric network with an isolated neutral voltage above 1000 V. The conducted studies of the random relative mean square errors show that the accuracy of indirect measurements in the developed method can be effectively regulated not only by selecting a capacitive additional conductivity, which are connected between phases of the electrical network and the ground, but also by the selection of measuring instruments according to the accuracy class. When choosing meters with accuracy class of 0.5 with the correct selection of capacitive additional conductivity that are connected between the phases of the electrical network and the ground, the errors in measuring the insulation parameters will not exceed 10%.

Key words: voltage, network, neutral, insulation, conductivity, error.

I. INTRODUCTION

A decrease in the level of insulation resistance of the phases of the electrical network relative to the ground creates the occurrence of emergency operating modes of electrical installations, which may result in electric shock to people.

In order to eliminate the electric shock to people, it is necessary to provide a high level of insulation resistance in a network with an isolated neutral voltage of more than 1000 V by carrying out activities related to systematic and effective monitoring of its condition, which is one of the main directions for providing electrical safety in a 6 kV auxiliaries of power plants.

The practice of operating electric grids with a voltage of 6 kV at thermal power plants shows the absence of a method for measuring insulation resistance at the enterprise. And if it is available, the insulation resistance measurements are made, as a rule, extremely irregularly and, moreover, with large errors. The most widely used method was the measurement of insulation resistance by using a measuring device - megger.

Unsatisfactory installation of preventive inspections and repairs of operating electrical installations, as well as worsening of the insulation of networks and electrical equipment, create the danger of occurrence of emergency operating conditions, which may result in electric shock, equipment damage and long down-time of high-performance mechanisms. In the process of operating the electric power plant, maintenance personnel rely mainly on protection against single-phase earth faults, which may be faulty.

In the organization of works taken at thermal power plants, time is not always allocated for execution and implementation in full the repair, commissioning and preventive testing of electrical installations [1-11]. Meggers used to measure the resistance of phases of electrical installations relative to ground cannot be considered a reliable means of prevention.

The other side of this issue is the lack of clear recommendations on the method of measuring the insulation resistance in a 6 kV network of auxiliary needs of power plants in accordance with the requirements of the Uniform Rules of Safety. Numerous proposals on methods for measuring the insulation parameters of electrical installations with voltages above 1000 V have hitherto not led to the creation of a universal control method suitable for both research and practical purposes.

In connection with the foregoing, the urgency of the task of further improving the means for continuous and periodic monitoring of the insulation parameters of a network with voltages above 1000 V of industrial and mining enterprises in the process of their operation continues to be relevant. Operation of a network with a voltage above 1000 V in industrial and mining enterprises with low insulation resistance is very dangerous, and therefore the issue of controlling insulation resistance and maintaining it at a high level should be given constant attention.

II. Analysis of the Error of the Developed Method for Determining the Insulation Parameters in a Network with a Voltage above 1000 V

In three-phase electrical networks with an isolated neutral voltage above 1000 V, there is a lack of symmetry of phase voltages. Non-symmetry in high voltage networks is formed with three factors: unbalanced load on the phases of the electrical network; incorrect execution of transposition of high-voltage wires; when one phase of the network is broken under load; if any phase relative to the ground is damaged.

One of the important priorities of the developed indirect methods of determining the insulation parameters in a network with an isolated neutral voltage above 1000 V is the accuracy of determining the unknown quantities. In the indirect determination of the isolation parameters in a network with an isolated neutral, strict requirements are put in place to ensure the reliability of the values of the unknown quantities.

Carried out analysis of the error of the developed method for determining the active conductivity, which reduces the isolation level between one of the phases of the network and ground, and of the insulation parameters in an asymmetric network with an isolated neutral voltage above 1000 V, which is based on the measurement of the values of the line voltage and the residual voltage, as well as was carried out the analysis of the angle of lag between the vectors of the line voltage and the residual voltage before and after connecting additional capacitive conductivity between the phases of the network and ground, and determine:

– the conductivity value, which reduces the insulation resistance of one of the phases of the electrical network relative to the earth

$$\mathrm{g_o} = \frac{U_o U_{o1}}{3U_l (U_o \mathrm{Cos}\alpha_1 - U_{o1}\mathrm{Cos}\alpha)} b_o, \qquad (1)$$

– determination of capacitive conductivity of network isolation

$$\mathrm{b} = \frac{\mathrm{U_{o1}Cos\alpha b_o}}{\mathrm{U_o Cos\alpha_1 - U_{o1}Cos\alpha}}. \qquad (2)$$

– active conductivity of network isolation

$$\mathrm{g} = \frac{(U_l \mathrm{Sin}\alpha - U_o) U_{o1} b_o}{1{,}73 U_l (U_o \mathrm{Cos}\alpha_1 - U_{o1}\mathrm{Cos}\alpha)}, \qquad (3)$$

– full conductivity of network isolation

$$y = \frac{U_{pho} U_{o1} b_o}{1{,}73 U_l (U_o Sin\alpha_1 - U_{o1} Sin\alpha)}., \qquad (4)$$

where U_l - line voltage of the network;

$\mathrm{U_o}$ – zero sequence voltage in case of insulation failure of one of the phases of the network relative to the ground;

$\mathrm{Cos\alpha}$ – angle of lag between the vectors of the voltage of the zero sequence and the line voltage;

$\mathrm{U_{o1}}$ – zero sequence voltage in case of insulation failure of one of the phases of the network relative to the ground after connecting additional capacitive conductivity between the phases of the network and ground;

$\mathrm{Cos\alpha_1}$ – the angle of lag between the zero sequence voltage and line voltage vectors, after connecting additional capacitive conductivity between the phases of the network and ground;

$\mathrm{b_o}$ – additional capacitive conductivity, connected between phases of the network and ground.

In order to analyze the error of the developed method for determining the insulation parameters in an asymmetric network, it is necessary to fulfill the replacement conditions U_l - linear voltage to U_{ph} - the phase voltage relative to the ground before the insulation of the network is damaged, since $U_l = 1{,}73\mathrm{U}_{ph}$ it is also assumed that when unbalance appears, the line voltages remain unchanged. The zero sequence voltage on the open triangle of the voltage transformer is characterized as $3\,\mathrm{U_o}$, with taking into account the above described equations, the parameters describing the insulation will take the form:

– the conductivity value, which reduces the insulation resistance of one of the phases of the electrical network relative to the ground

$$\mathrm{g_o} = \frac{U_o U_{o1}}{U_{ph} (U_o \mathrm{Cos}\alpha_1 - U_{o1}\mathrm{Cos}\alpha)} b_o, \qquad (5)$$

– active conductivity of network isolation

$$\mathrm{g} = \frac{(U_{ph} \mathrm{Sin}\alpha - U_o) U_{o1} b_o}{U_{ph} (U_o \mathrm{Cos}\alpha_1 - U_{o1}\mathrm{Cos}\alpha)}. \qquad (6)$$

– full conductivity of network isolation

$$y = \frac{U_{pho} U_{o1} b_o}{U_{ph} (U_o Sin\alpha_1 - U_{o1} Sin\alpha)}. \qquad (7)$$

It should be noted that when determining the insulation parameters in a network with an isolated neutral, based on the measurement of the magnitude of the residual voltage modules and the phase voltage relative to the ground, and the angle of lag between the residual voltage and linear voltage vectors when connecting the capacitive additional conductances between the phases of the network and ground , it becomes necessary to establish the methodological error of the obtained mathematical dependences.

Based on the analysis of error, practical recommendations are developed that ensure:

– normal operation of electric receivers in the production of measurements;

– the satisfactory accuracy of the developed method for determining the insulation parameters in a network with an isolated neutral voltage above 1000 V, with the achievement of safety in the production of works in electrical installations, and also with the provision of simplicity and convenience of measurements.

When analyzing the error of the developed method for determining the insulation parameters of the phases of the electrical network relative to the ground in a network with an isolated neutral voltage above 1000 V, the determined ratio of the relative method error to the error of the measuring devices measuring the magnitude of the voltage modules and the value of the capacitive conductivity is used as additional conductivity.

The error analysis of the developed method for determining the insulation parameters of an asymmetric network with a voltage above 1000 V is made using the basic provisions of the theory of errors and the theoretical foundations of electrical engineering.

The relative rms error for conductivity reduces the insulation resistance between one of the phases of the network and ground in networks with an isolated neutral voltage above 1000 V is determined from the mathematical dependence (5):

$$\mathrm{g_o} = \frac{U_o U_{o1} b_o}{U_{ph}(U_o Sin\alpha_1 - U_{o1} Sin\alpha)},$$

where U_{ph}, $\mathrm{U_o}$, $\mathrm{U_{o1}}$, $\mathrm{Sin\alpha}$, $\mathrm{Sin\alpha_1}$, $\mathrm{b_o}$ are the values that determine the conductivity that reduces the insulation resistance between one of the phases of the network and ground in networks with an isolated neutral with voltage above 1000 V, obtained by direct measurement.

The relative root-mean-square error of the method for determining the conductivity of a resistance-reducing insulation between one of the phases of the network and ground in networks with an isolated neutral voltage higher than 1000 V is determined from the expression [6-9]:

$$\varepsilon_{g_o} = \frac{1}{g_o}\sqrt{\begin{gathered}\left(\frac{\partial \mathrm{g_o}}{\partial U_{ph}}\right)^2 (\Delta U_{ph})^2 + \left(\frac{\partial g_o}{\partial U_\mathrm{o}}\right)^2 (\Delta U_\mathrm{o})^2 + \left(\frac{\partial g_o}{\partial U_\mathrm{o1}}\right)^2 (\Delta U_\mathrm{o1})^2 + \\ + \left(\frac{\partial \mathrm{g}_o}{\partial \mathrm{Sin}\alpha}\right)^2 (\Delta Sin\alpha)^2 + \left(\frac{\partial \mathrm{g}_o}{\partial \mathrm{Sin}\alpha_1}\right)^2 (\Delta Sin\alpha_1)^2 + \left(\frac{\partial \mathrm{g}_o}{\partial \mathrm{b_o}}\right)^2 (\Delta \mathrm{b_o})^2\end{gathered}}, \quad (8)$$

where $\frac{\partial g_o}{\partial U_\mathrm{ph}}$; $\frac{\partial \mathrm{g_o}}{\partial \mathrm{U_o}}$; $\frac{\partial \mathrm{g_o}}{\partial \mathrm{U_{o1}}}$; $\frac{\partial \mathrm{g_o}}{\partial \mathrm{Sin\alpha}}$; $\frac{\partial \mathrm{g_o}}{\partial \mathrm{Sin\alpha_1}}$; $\frac{\partial \mathrm{g_o}}{\partial \mathrm{b_o}}$; – partial derivatives of the function

$\mathrm{g_o} = \mathrm{f}\ (U_{ph}, \mathrm{U_o}, \mathrm{U_{o1}}, \mathrm{Sin\alpha}, \mathrm{Sin\alpha_1}, \mathrm{b_o})$.

Define the partial derivatives of the function $\mathrm{g_o} = \mathrm{f}\ (U_{ph}, \mathrm{U_o}, \mathrm{U_{o1}}, \mathrm{Sin\alpha}, \mathrm{Sin\alpha_1}, \mathrm{b_o})$ by variables U_{ph}, $\mathrm{U_o}$, $\mathrm{U_{o1}}$, $\mathrm{Sin\alpha}$, $\mathrm{Sin\alpha_1}$, $\mathrm{b_o}$:

$$\begin{gathered}
\frac{\partial g_o}{\partial U_\mathrm{ph}} = -\frac{\mathrm{U_o U_{o1} b_o}}{U_{ph}^2 (U_o \mathrm{Sin}\alpha_1 \text{-} U_{o1} Sin\alpha)}; \\
\frac{\partial g_o}{\partial U_\mathrm{o}} = -\frac{\mathrm{U_{o1}^2 Sin\alpha b_o}}{U_{ph} (U_o \mathrm{Sin}\alpha_1 \text{-} U_{o1} Sin\alpha)^2}; \\
\frac{\partial g_o}{\partial U_\mathrm{o1}} = \frac{\mathrm{U_o^2 Sin\alpha_1 b_o}}{U_{ph} (U_o \mathrm{Sin}\alpha_1 \text{-} U_{o1} Sin\alpha)}; \\
\frac{\partial g_o}{\partial \mathrm{Sin}\alpha} = \frac{\mathrm{U_o U_{o1}^2 b_o}}{U_{ph} (U_o \mathrm{Sin}\alpha_1 \text{-} U_{o1} Sin\alpha)^2}; \\
\frac{\partial g_o}{\partial \mathrm{Sin}\alpha_1} = -\frac{\mathrm{U_o^2 U_{o1} b_o}}{U_{ph} (U_o \mathrm{Sin}\alpha_1 \text{-} U_{o1} Sin\alpha)^2}; \\
\frac{\partial g_o}{\partial \mathrm{b_o}} = -\frac{\mathrm{U_o U_{o1}}}{U_{ph} (U_o \mathrm{Sin}\alpha_1 \text{-} U_{o1} Sin\alpha)}.
\end{gathered} \quad (9)$$

Here ΔU_{ph}; $\Delta \mathrm{U_o}$; $\Delta \mathrm{U_{o1}}$; $\Delta \mathrm{Sin\alpha}$; $\Delta \mathrm{Sin\alpha_1}$; $\Delta \mathrm{b_o}$ – absolute errors of direct measurements of quantities U_{ph}; $\mathrm{U_o}$; $\mathrm{U_{o1}}$; $\mathrm{Sin\alpha}$; $\mathrm{Sin\alpha_1}$; $\mathrm{b_o}$, which are defined by the following expressions:

$$\begin{gathered}
\Delta U_{ph} = U_{ph} \Delta U_{ph*}; \\
\Delta \mathrm{U_o} = \mathrm{U_o} \Delta \mathrm{U_{o*}}; \\
\Delta \mathrm{U_{o1}} = \mathrm{U_{o1}} \Delta \mathrm{U_{o1*}}; \\
\Delta \mathrm{Sin\alpha} = \mathrm{Sin\alpha} \Delta \mathrm{Sin\alpha_*}; \\
\Delta \mathrm{Sin\alpha_1} = \mathrm{Sin\alpha_1} \Delta \mathrm{Sin\alpha_{1*}}; \\
\Delta \mathrm{b_o} = \mathrm{b_o} \Delta \mathrm{b_{o*}}.
\end{gathered} \quad (10)$$

To determine the error of measuring devices, we assume that

$\Delta U_{ph*} = \Delta \mathrm{U_{0*}} = \Delta \mathrm{U_{01*}} = \Delta \mathrm{Sin\alpha_*} = \Delta \mathrm{Sin\alpha_{1*}} = \Delta \mathrm{b_{o*}} = \Delta$,

Where ΔU_{ph*}; $\Delta \mathrm{U_{0*}}$; $\Delta \mathrm{U_{10*}}$ - the relative error of measuring voltage circuits;

$\Delta \mathrm{Sin\alpha_*}$; $\Delta \mathrm{Sin\alpha_{1*}}$ – the relative error of the measuring circuits of the angle of lag between the voltage vector of the damaged phase of the electrical network and the line voltage formed by the potentials of the other two phases;

$\Delta \mathrm{b_{o*}}$ – the relative error of the measuring device, which measures the value of additional capacitive conductances that are connected between the phases of the network and the ground.

Solving the equation (8), substituting in it the values of the partial derivatives of the equation (9) and the values of the partial absolute errors (10), assuming that $\Delta \mathrm{U_*} = \Delta \mathrm{b_{o*}} = \Delta$, we obtain the mathematical dependence of the determination of the random relative mean square error for the method of determining the conductivity, which reduces the insulation resistance between one of the phases of the network and ground in networks with an isolated neutral voltage of more than 1000 V:

$$\varepsilon_{g_o} = \Delta\sqrt{2 + \frac{2(U_{o1}^2 Sin^2\alpha + U_o Sin^2\alpha_1}{(U_o Sin\alpha_1 + U_{o1} Sin\alpha)^2}} \qquad (11)$$

or

$$\varepsilon_{g_o} = \Delta\sqrt{2 + \frac{2}{1 - \frac{2U_o U_{o1} Sin\alpha Sin\alpha_1}{U_{o1}^2 Sin^2\alpha + U_{o1}^2 Sin^2\alpha_1}}}. \qquad (12)$$

We express the resulting equation (12) in relative units and perform its investigation in the Mathcad environment:

$$\varepsilon_{g_o} = \Delta\sqrt{2 + \frac{2(Sin^2\alpha_* + U_{o*})}{(U_{o*} + Sin\alpha_*)^2}}, \qquad (13)$$

where $U_{o*} = \frac{U_o}{U_{o1}}$, $Sin\alpha_* = \frac{Sin\alpha}{Sin\alpha_1}$.

The relative rms error for capacitive conductivity of insulation in an asymmetric network with an isolated neutral with voltage above 1000 V is determined from the mathematical dependence (2):

$$b = \frac{U_{o1} b_o Sin\alpha}{U_o Sin\alpha_1 - U_{o1} Sin\alpha},$$

where U_o, U_{o1}, $Sin\alpha$, $Sin\alpha_1$, b_o are the quantities that determine the capacitive conductivity of the insulation in an asymmetric network with an isolated neutral with voltage above 1000 V, obtained by direct measurement.

The relative root-mean-square error in the method for determining the capacitive conductivity of an insulation in an asymmetric network with an isolated neutral with voltage above 1000 V is determined from the expression:

$$\varepsilon_b = \frac{1}{b}\sqrt{\begin{array}{l}\left(\frac{\partial b}{\partial U_o}\right)^2 (\Delta U_o)^2 + \left(\frac{\partial b}{\partial U_{o1}}\right)^2 (\Delta U_{o1})^2 + \left(\frac{\partial b}{\partial Sin\alpha}\right)^2 (\Delta Sin\alpha)^2 + \\ + \left(\frac{\partial b}{\partial Sin\alpha_1}\right)^2 (\Delta Sin\alpha_1)^2 + \left(\frac{\partial b}{\partial b_o}\right)^2 (\Delta b_o)^2\end{array}} \qquad (14)$$

where $\frac{\partial b}{\partial U_o}$; $\frac{\partial b}{\partial U_{o1}}$; $\frac{\partial b}{\partial Sin\alpha}$; $\frac{\partial b}{\partial Sin\alpha_1}$; $\frac{\partial b}{\partial b_o}$; – are partial derivatives of the function $b = f\,(U_o, U_{o1}, Sin\alpha, Sin\alpha_1, b_o)$.

Define the partial derivatives of the function $b = f\,(U_o, U_{o1}, Sin\alpha, Sin\alpha_1, b_o)$ by variables U_o, U_{o1}, $Sin\alpha$, $Sin\alpha_1$, b_o:

$$\frac{\partial b}{\partial U_o} = -\frac{U_{o1} Sin\alpha Sin\alpha_1 b_o}{(U_o Sin\alpha_1 - U_{o1} Sin\alpha)^2};$$
$$\frac{\partial b}{\partial U_{o1}} = \frac{U_o Sin\alpha Sin\alpha_1 b_o}{(U_o Sin\alpha_1 - U_{o1} Sin\alpha)^2};$$
$$\frac{\partial b}{\partial Sin\alpha} = \frac{U_o U_{o1} Sin\alpha_1 b_o}{(U_o Sin\alpha_1 - U_{o1} Sin\alpha)^2}; \qquad (15)$$
$$\frac{\partial b}{\partial Sin\alpha_1} = -\frac{U_o U_{o1} Sin\alpha b_o}{(U_o Sin\alpha_1 - U_{o1} Sin\alpha)^2};$$

$$\frac{\partial b}{\partial b_o} = \frac{U_{o1} Sin\alpha}{U_o Sin\alpha_1 - U_{o1} Sin\alpha}.$$

Here ΔU_o; ΔU_{o1}; $\Delta Sin\alpha$; $\Delta Sin\alpha_1$; Δb_o – absolute errors of direct measurements of quantities U_o; U_{o1}; $Sin\alpha$; $Sin\alpha_1$; b_o,which are defined by the following expressions:

$$\Delta U_o = U_o \Delta U_{o*};$$
$$\Delta U_{o1} = U_{o1} \Delta U_{o1*};$$
$$\Delta Sin\alpha = Sin\alpha \Delta Sin\alpha_*; \qquad (16)$$
$$\Delta Sin\alpha_1 = Sin\alpha_1 \Delta Sin\alpha_{1*};$$
$$\Delta b_o = b_o \Delta b_{o*}.$$

To determine the error of measuring instruments, we assume that $\Delta U_{o*} = \Delta U_{o1*} = \Delta Sin\alpha_* = \Delta Sin\alpha_{1*} = \Delta b_{o*} = \Delta$,

where ΔU_{o*}; ΔU_{1o*} – relative error of measuring voltage circuits;

$\Delta Sin\alpha_*$; $\Delta Sin\alpha_{1*}$ – relative error of the measuring circuits of the phase angle between the voltage vector of the damaged phase of the electrical network and the line voltage formed by the potentials of the other two phases;

Δb_{o*} – the relative error of the measuring device, which measures the value of additional capacitive conductances, which are connected between the phases of the network and the ground.

Solving the equation (14), substituting in it the values of the partial derivatives of equation (15) and the values of the partial absolute errors (16), assuming that $\Delta U_* = \Delta b_{o*} = \Delta$, we obtain the mathematical dependence of the determination of the random relative mean square error for the method for determining the capacitive conductivity of insulation in an asymmetric network with an isolated neutral with voltage above 1000 V:

$$\varepsilon_b = \Delta\sqrt{1 + \frac{4U_o^2 Sin^2\alpha_1}{(U_o Sin\alpha_1 + U_{o1} Sin\alpha)^2}}. \qquad (17)$$

We express the resulting equation (17) in relative units and perform its investigation in the MathCAD environment:

$$\varepsilon_b = \Delta\sqrt{1+\frac{4U_*^2}{(U_* + \mathrm{Sin}\alpha_*)^2}}. \qquad (18)$$

where $U_{o*} = \frac{U_o}{U_{o1}}$, $\mathrm{Sin}\alpha_* = \frac{\mathrm{Sin}\alpha}{\mathrm{Sin}\alpha_1}$.

The relative rms error for the total conductivity of the insulation in an asymmetric network with an isolated neutral with voltage above 1000 V is determined from the mathematical dependence (6):

$$y = \frac{U_{pho}U_{o1}b_o}{U_{ph}(U_o Sin\alpha_1 - U_{o1}Sin\alpha)},$$

where U_{ph}, U_o, U_{o1}, $\mathrm{Sin}\alpha$, $\mathrm{Sin}\alpha_1$, b_o – are the values that determine the total conductivity of the insulation in an asymmetric network with an isolated neutral with voltage above 1000 V, obtained by direct measurement.

The relative root-mean-square error of the method for determining the total conductivity of an insulation in an asymmetric network with an isolated neutral with voltage higher than 1000 V is determined from the expression:

$$\varepsilon_y = \frac{1}{y}\sqrt{\begin{aligned}&\left(\frac{\partial y}{\partial U_{ph}}\right)^2(\Delta U_{ph})^2 + \left(\frac{\partial y}{\partial U_{pho}}\right)^2(\Delta U_{pho})^2 + \left(\frac{\partial y}{\partial U_o}\right)^2(\Delta U_o)^2 + \\ &+\left(\frac{\partial y}{\partial U_{o1}}\right)^2(\Delta U_{o1})^2 + \left(\frac{\partial y}{\partial \mathrm{Sin}\alpha}\right)^2(\Delta Sin\alpha)^2 + \left(\frac{\partial y}{\partial \mathrm{Sin}\alpha_1}\right)^2(\Delta Sin \\ &+\left(\frac{\partial y}{\partial b_o}\right)^2(\Delta b_o)^2\end{aligned}} \qquad (19)$$

где $\frac{\partial y}{\partial U_{ph}}$; $\frac{\partial y}{\partial U_{pho}}$; $\frac{\partial y}{\partial U_o}$; $\frac{\partial y}{\partial U_{o1}}$; $\frac{\partial y}{\partial \mathrm{Sin}\alpha}$; $\frac{\partial y}{\partial \mathrm{Sin}\alpha_1}$; $\frac{\partial y}{\partial b_o}$; – partial derivatives of the function $y =$ f (U_{ph}, U_o, U_{o1}, $\mathrm{Sin}\alpha$, $\mathrm{Sin}\alpha_1$, b_o).

Define the partial derivatives of the function $y =$ f (U_{ph}, U_o, U_{o1}, $\mathrm{Sin}\alpha$, $\mathrm{Sin}\alpha_1$, b_o) by variables U_{ph}, U_o, U_{o1}, $\mathrm{Sin}\alpha$, $\mathrm{Sin}\alpha_1$, b_o:

$$\frac{\partial y}{\partial U_{ph}} = -\frac{U_{pho}U_{o1}b_o}{U_{ph}^2(U_o \mathrm{Sin}\alpha_1 - U_{o1}Sin\alpha)};$$
$$\frac{\partial y}{\partial U_{pho}} = -\frac{U_{o1}b_o}{U_{ph}(U_o \mathrm{Sin}\alpha_1 - U_{o1}Sin\alpha)};$$
$$\frac{\partial y}{\partial U_o} = -\frac{U_{pho}U_{o1}\mathrm{Sin}\alpha_1 b_o}{U_{ph}(U_o \mathrm{Sin}\alpha_1 - U_{o1}Sin\alpha)^2}; \qquad (20)$$
$$\frac{\partial g_o}{\partial U_{o1}} = \frac{U_{pho}U_o\mathrm{Sin}\alpha_1 b_o}{U_{ph}(U_o \mathrm{Sin}\alpha_1 - U_{o1}Sin\alpha)^2};$$
$$\frac{\partial y}{\partial \mathrm{Sin}\alpha} = \frac{U_{pho}U_{o1}^2 b_o}{U_{ph}(U_o \mathrm{Sin}\alpha_1 - U_{o1}Sin\alpha)^2};$$
$$\frac{\partial y}{\partial \mathrm{Sin}\alpha_1} = -\frac{U_{pho}U_o U_{o1} b_o}{U_{ph}(U_o \mathrm{Sin}\alpha_1 - U_{o1}Sin\alpha)^2};$$
$$\frac{\partial y}{\partial b_o} = -\frac{U_{pho}U_{o1}}{U_{ph}(U_o \mathrm{Sin}\alpha_1 - U_{o1}Sin\alpha)}.$$

Here ΔU_{ph}; ΔU_o; ΔU_{o1}; $\Delta\mathrm{Sin}\alpha$; $\Delta\mathrm{Sin}\alpha_1$; Δb_o – absolute errors of direct measurements of quantities U_{ph}; U_o; U_{o1}; $\mathrm{Sin}\alpha$; $\mathrm{Sin}\alpha_1$; b_o, which are defined by the following expressions:

$$\begin{gathered}\Delta U_{ph} = U_{ph}\Delta U_{ph*};\ \Delta U_o = U_o \Delta U_{o*}; \\ \Delta U_{o1} = U_{o1}\Delta U_{o1*}; \\ \Delta \mathrm{Sin}\alpha = \mathrm{Sin}\alpha \Delta \mathrm{Sin}\alpha_*; \\ \Delta \mathrm{Sin}\alpha_1 = \mathrm{Sin}\alpha_1 \Delta \mathrm{Sin}\alpha_{1*}; \\ \Delta b_o = b_o \Delta b_{o*}.\end{gathered} \qquad (21)$$

To determine the error of measuring devices, we assume that $\Delta U_{ph*} = \Delta U_{o*} = \Delta U_{o1*} = \Delta \mathrm{Sin}\alpha_* = \Delta \mathrm{Sin}\alpha_{1*} = \Delta b_{o*} = \Delta$,

where ΔU_{ph*}; ΔU_{o*}; ΔU_{1o*} – relative error of measuring voltage circuits;

$\Delta \mathrm{Sin}\alpha_*$; $\Delta \mathrm{Sin}\alpha_{1*}$ – the relative error of the measurement circuits of the phase angle between the voltage vector of the damaged phase of the electrical network and the line voltage formed by the potentials of the other two phases;

Δb_{o*} – the relative error of the measuring device, which measures the value of additional capacitive conductances that are connected between the phases of the network and the ground.

Solving equation (19) by substituting in it the values of the partial derivatives of equation (20) and the values of the partial absolute errors (21), assuming that $\Delta U_* = \Delta b_{o*} = \Delta$, we obtain the mathematical dependence of the determination of the random relative mean square error for the method for determining the total conductivity of insulation in an asymmetric network with isolated neutral voltage above 1000 V:

$$\varepsilon_y = \Delta\sqrt{3+\frac{3U_o^2\mathrm{Sin}^2\alpha_1 + U_{o1}^2\mathrm{Sin}^2\alpha}{(U_o\mathrm{Sin}\alpha_1 + U_{o1}\mathrm{Sin}\alpha)^2}}. \qquad (22)$$

The resulting equation (22) is expressed in relative units and we perform its investigation in the MathCAD environment:

$$\varepsilon_y = \Delta \sqrt{3 + \frac{3U_{o*}^2 + Sin^2\alpha_*}{(U_{o*} + Sin\alpha_*)^2}}, \qquad (23)$$

where $U_{o*} = \dfrac{U_o}{U_{o1}}$, $Cos\alpha_* = \dfrac{Cos\alpha}{Cos\alpha_1}$.

On the basis of the obtained results of random relative mean square errors of determining the active conductivity, which reduces the isolation level between one of the phases of the network and ground, and the capacitive, active and complete conductivities of insulation in a symmetrical network with an isolated neutral voltage above 1000 V, under operating voltage, construct the dependencies:

$$\varepsilon_{g_o} = \frac{\Delta b}{\Delta} = f(U_{o*};\ Cos\alpha_*);$$

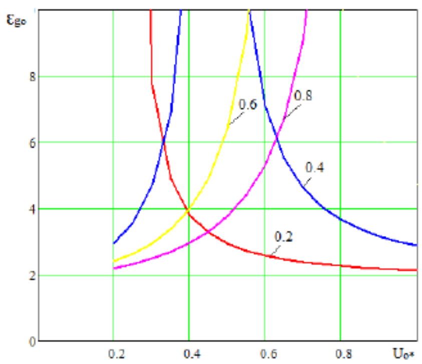
$$\varepsilon_b = \frac{\Delta b}{\Delta} = f(U_{o*};\ Cos\alpha_*);$$

$$\varepsilon_y = \frac{\Delta b}{\Delta} = f(U_{o*};\ Cos\alpha_*),$$

presented in Fig. 1, Fig. 2, Fig. 3.

The obtained mathematical dependences of the relative mean square errors, active conductivity, which reduces the isolation level between one of the phases of the network and the ground ε_{g_o}, capacitive ε_b, full ε_y conductivity of phase isolation of an electrical network with an isolated neutral, presented in a graphical design (Figure 1. - Figure 3) , Show that the value of the capacitive additional conductivity b_o, which is introduced between the phases of the electrical network and the ground, affects the variation of the error, depending on the reliability of the sought values.

An error analysis shows that in order to provide the required accuracy for each particular network, the value of the capacitive additional conductivity is selected.



$Cos\alpha_*$ =0,2; 0,4; 0,6; 0,8

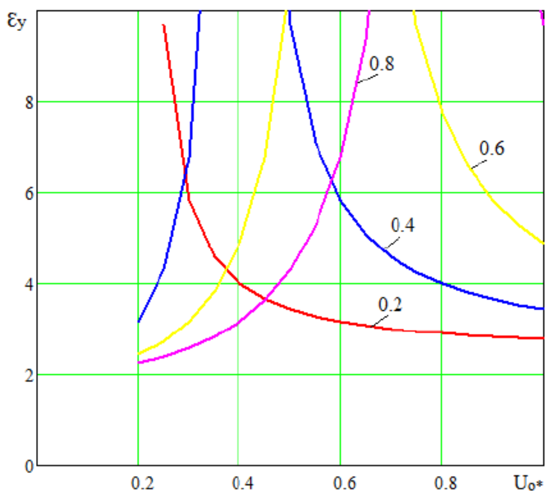
Fig. 1. Relative mean-square errors of determining the active conductivity, reducing the level of insulation between one of the phases of the network and the earth

When determining the active conductivity that reduces the level of isolation between one of the phases of the network and the ground, based on the obtained graphs (Fig. 1) relative rms error, capacitances forming capacitive conductivity are selected that are connected between phases of the electrical network and ground so that when: $Cos\alpha_*$ = 0.2 the zero sequence voltage in relative units was in the range of U_{o*} =0.3-0.9; $Cos\alpha_*$ = 0.4, the zero sequence voltage in relative units was in the range of U_{o*} =0.2 to 0.35 or U_{o*} =0.6 to 0.9; $Cos\alpha_*$ = 0,6 the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.5; $Cos\alpha_*$ = 0,8 the zero sequence voltage in relative units was within the range of U_{o*} =0.2-0.65.

Then the error does not exceed 10% when using measuring instruments with accuracy of 1.0, and 5% when using measuring instruments with accuracy class of 0.5, and when using measuring instruments with accuracy class of 0.2, an error of not more than 2% is provided.

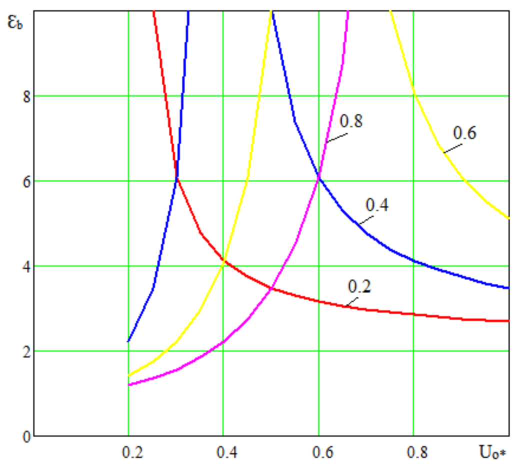
When determining the capacitive conductivity of the insulation of the phases of the electrical network relative to the ground, based on the error-correction curves shown in Fig. 2, such capacitances forming capacitive conductivity are selected, which are connected between the phases of the electrical network and the ground, so that at: $Cos\alpha_*$ = 0.2 the zero sequence voltage in relative units is within the range of U_{o*} =0.2-0.9; $Cos\alpha_*$ = 0.4, the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.3 or U_{o*} =0.5-0.9; $Cos\alpha_*$ = 0,6 the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.5 or U_{o*} =0.7-0.9; $Cos\alpha_*$ = 0,8 the zero sequence voltage in relative units was within the range of U_{o*} =0.2-0.65. Then the error does not exceed 10% when using measuring instruments with accuracy class of 1.0, and 5% when using measuring instruments with accuracy class of 0.5, and when using measuring instruments with accuracy class of 0.2 an error of not more than 2% is provided.

When determining the total conductivity of the insulation of the phases of the electrical network relative to the ground, based on the error-correction curves shown in Fig. 3, capacitances that form capacitive conductivity are selected, which are connected between phases of the electrical network and ground, so that at: $Cos\alpha_*$ =0.2 the zero sequence voltage in relative units is within the range of U_{o*} =0.3-0.9; $Cos\alpha_*$ = 0.4, the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.3 or U_{o*} =0.5-0.9; $Cos\alpha_*$ = 0,6 the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.5 or U_{o*} =0.75-0.9; $Cos\alpha_*$ = 0,8 the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.3 or 0.5-0.9. Then the error does not exceed 10% when using measuring instruments with accuracy class of 1.0, and 5% when using measuring instruments with accuracy class of 0.5, and when using measuring instruments with accuracy class of 0.2, an error of not more than 2% is provided.



$\mathrm{Cos}\alpha_*$ =0,2; 0,4; 0,6; 0,8

Fig. 2. Relative mean-square errors in determining the capacitive conductivity of a network isolation with an isolated neutral with voltage above 1000 V



$\mathrm{Cos}\alpha_*$ =0,2; 0,4; 0,6; 0,8

Fig. 3 Relative root-mean-square errors in determining the total conductivity of a network isolation with an isolated neutral with voltage above 1000 V

Since the random relative mean square error of the method for determining the active conductivity of insulation in an asymmetric network with a voltage higher than 1000 V is determined by the Pythagoras formula and can be represented as:

$$\varepsilon_g = \frac{g_*}{\Delta} = \frac{1}{g}\sqrt{\left(\frac{\partial y}{\partial g}\right)^2 \Delta y^2 + \left(\frac{\partial b}{\partial g}\right)^2 \Delta b^2} \quad (24)$$

,

then it follows that the error in the correct selection of capacitive additional conductivity that are connected between the phases of the electrical network and the ground in determining for capacitive and complete conductivities of network isolation will be legitimate and for the active conductivity of network isolation. Therefore, the error in the active conductivity of the network isolation will represent both the geometric sum of the capacitive and total conductivities of the network isolation. On the basis of the foregoing it follows that the error in determining the active conductivity does not exceed 10% when using measuring instruments with an accuracy class of 0.5.

The conducted studies of the random relative mean square errors show that the accuracy of indirect measurements in the developed method can be effectively regulated not only by selection of capacitive additional conductivity, which are connected between phases of the electric network and ground, but also by the selection of measuring devices according to the accuracy class. When choosing meters with an accuracy class of 0.5 with the correct selection of capacitive additional conductivity that are connected between the phases of the electrical network and the ground, the errors in measuring the active conductivity of the insulation of the network will not exceed 10%.

On the basis of the foregoing, it follows that the method developed provides satisfactory accuracy in determining the insulation parameters in a three-phase unbalanced electrical network with an isolated neutral, as well as the simplicity and safety of operating in existing electrical installations with voltages above 1000 V in industrial and mining enterprises.

III. Conclusion

When introducing a method for determining the active conductivity that reduces the level of isolation between one of the phases of the network and the ground and the insulation parameters in an asymmetric network with a voltage above 1000 V based on the analysis of the random relative mean square error, it is found that in order to ensure the required accuracy for each particular network should be selected its own value of additional conductivity that is included between the phases of the electrical network and the earth, so as to provide the required satisfactory accuracy at definition for:

– active conductivity reducing the level of isolation between one of the phases of the network and the ground, based on the obtained graphs of the relative rms errors, capacitances forming capacitive conductivity are selected that are connected between phases of the electrical network and ground so that at: $\mathrm{Cos}\alpha_*$ = 0.2, the zero sequence voltage in relative Units was within the range of U_{o*} =0.3-0.95; $\mathrm{Cos}\alpha_*$ = 0.4, the zero sequence voltage in relative units was in the range of U_{o*} =0.2 to 0.35 or U_{o*} =0.6 to 0.95; $\mathrm{Cos}\alpha_*$ = 0,6 the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.5; $\mathrm{Cos}\alpha_*$ = 0,8 the zero sequence voltage in relative units was in the range of U_{o*} =0.2 to 0.65, then the error does not exceed 10% when using measuring instruments with accuracy class of 1.0, and 5% when using measuring instruments with accuracy class of 0.5, and when using measuring instruments with accuracy class of 0.2, an error of not more than 2% is provided;

–capacitive conductivity of the insulation of the phases of the electrical network with respect to the ground, such capacitors forming capacitive conductivity are selected which are connected between the phases of the electrical network and the ground so that at: $Cos\alpha_* = 0.2$ the zero sequence voltage in relative units is within the range of U_{o*} =0.2-0.9 ; $Cos\alpha_* = 0.4$, the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.3 or U_{o*} =0.5-0.9; $Cos\alpha_* = 0,6$ the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.5 or U_{o*} =0.7-0.9; $Cos\alpha_* =$ 0,8 the zero sequence voltage in relative units was within the range of U_{o*} =0.2-0.65. Then the error does not exceed 10% when using measuring instruments with accuracy class of 1.0, and 5% when using measuring instruments with accuracy class of 0.5, and when using measuring instruments with accuracy class of 0.2, an error of not more than 2% is provided;

–the total conductivity of the insulation of the phases of the electrical network relative to the ground, such capacitances forming capacitive conductivity are selected that are connected between the phases of the electrical network and the ground so that at: $Cos\alpha_* = 0.2$ the zero sequence voltage in relative units is within the range U_{o*} =0.3-0.9 ; $Cos\alpha_* = 0.4$, the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.3 or U_{o*} =0.5-0.9; $Cos\alpha_* = 0,6$ the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.5 or U_{o*} =0.75-0.9; $Cos\alpha_* = 0,8$ the zero sequence voltage in relative units was in the range of U_{o*} =0.2-0.3 or U_{o*} =0.5-0.9. Then the error does not exceed 10% when using measuring instruments with accuracy class of 1.0, and 5% when using measuring instruments with accuracy of 0.5, and when using measuring instruments with accuracy class of 0.2, an error of not more than 2% is provided;

–the active conductivity of network isolation the error will represent both the geometric sum of the capacitive and total conductivities of the network isolation. On the basis of the foregoing it follows that the error in determining the active conductivity does not exceed 10% when using measuring instruments with an accuracy class of 0.5.

On the basis of the foregoing, it follows that the method developed provides satisfactory accuracy in determining the insulation parameters in an asymmetric network with an isolated neutral with voltages above 1000 V in industrial and mining enterprises.

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