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Diagnostics Algorithms for Analysis and Assessment of Steady States and Disorders in Electrical Networks

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Abstract: Method of symmetric component is used in analysis of disturbances (short circuits and disturbances) and can be verified by computer simulation and measurement. It is based on possibility of making calculations simple by separating a three-phase asymmetric system into three symmetric systems and three single-phase schemes. It is very important for three-phase electrical networks with linear parameters and the same frequency in the network. The transition of quantities (ems, voltages and currents $F \equiv \{E, V, I\}$) from the asymmetric domain of a three-phase system to the symmetric domain is performed using transformation matrices. Expressions determined in the system of symmetric components are then superimposed on expressions corresponding to conditions of asymmetric system, and superposition is correct if electric quantities are of simple-periodic functions.

The paper presents a new method based on analysis using symmetric component methods and diagnostic algorithms for the assessment of the most common disturbances in power grids. The adapted part of the MATLAB package psb.abc,part.mdl was used for method verification, and the obtained results in the form of diagrams and values of diagnostic functions arranged in the form of tables confirm the applicability of the proposed new diagnostic algorithm for analysis and assessment of steady states and disturbances in electrical networks. The proposed diagnostic algorithm enables the realization of the maximum number of diagnostic functions on the basis of which a scheme for diagnosing disorders with classical diode elements or a more modern scheme with microprocessor components can be realized.

Index Terms: Electrical Network, Steady State, Disorder, Algorithm, Diagnostics.

1. Introducton

When analyzing the condition and operation of three-phase electrical networks during disturbances, it is necessary to [1-4]:

- Form a mathematical model of operation and/or a model of the state of the electrical network, and
- Choose a method for solving differential equations of the state of the network in real time.

Methods based on Ohm's and Kirchhoff's law are applicable, but also complex [5-7]. Other models for modeling and solving using mathematical transformations: Edith Clarck α, β, 0, Kimbark x, y, z, Kogo r, s, t, as well as the method of symmetric components, are based on the introduction of new component.

In the analysis of steady states, a matrix model with its own and mutual immittances (impedances/admittances) in nodes and branches are used for calculation. Model defines the topological structure of the network in relation to the reference voltage phasor. There are several methods for identifying matrices Z among which there are [1], [5]:

- Network analyzer method.
- Block transformation method.
- Step-by-step transformation method.
- Symmetric components method.

For determining the matrix Z in the first method, classicals approaches and network analyzers are used, and computer support in the second and third. Application of network analyzers and classical procedures for determining the matrix Z make it difficult to distribute energy sources and transformers of non-standard transmission relationships. Matrix Z must be determined by measurement or calculation from practically the same network analyzers of three-phase AC network.

In case of asymmetry, a three-phase network with linear element parameters and same frequency is decomposed into three independent symmetric systems and displayed using three single-phase schemes. Three groups of vectors represent symmetric "Foretsque" components. At the place of disturbance, there are impedances and voltages that are determined by transformations, where a scheme is assembled that is often complex and unsuitable for calculations. Impedances of network elements in system of symmetric components do not have to be the same. Assumptions are that symmetrical loading and disturbance are preceded by a state of idling and these are sufficient conditions to use single-phase schemes for the calculation.

The main types of disturbances in electrical network are short circuits and interference. When analyzing the consequences of disturbances, interesting quantities are current and voltage. Current is determined by the fault impedance, i.e. impedance of the element between two points connected across it and ability of the power supply to maintain voltage while a large current is flowing. Disturbances should always be avoided, not only because of the loss of energy and electricity, but also because there is a risk of fire (if electricity flows where it should not, overvoltage will be created).

The goal of protecting electrical machines is to reliably detect a fault when it occurs, interrupt the flow of current to it, and rectify the fault. Fault is detected by magnitude of current and/or voltage, phase asymmetry and other unusual voltage differences between components. The sensitivity of the protection elements is characterized by a voltage-current curve showing the combination of current and duration that will cause the deviation [8-9].

The advent of computers has enabled development of algorithms for calculating and measuring symmetrical components to solve the problem of asymmetry in electrical networks, which is presented in this paper.

The paper is organized as follows: Section 2 provides an overview of literature of related papers in the field of electrical networks in which they occur (failures, disturbances...), which can be solved by methods developed on transformation of symmetric or other components. Section 3 presents the method of symmetric components using Cartesian systems of real and imaginary coordinates. Section 4 presents a new method for estimating the most common disturbances in power networks using symmetric component methods and diagnostic algorithms, while algorithms of diagnostic functions are possible power grid with an inverter scheme for its implementation are given in Section 5. Simulation results of reference three-phase discrete analyzer for short-circuit fault type are given in Section 6. Finally, some concluding remarks are presented in Section 7.

2. Literature Review

The problem of disturbances in electric networks is a problem that dates back to the very appearance of electric power networks. The theory of single-phase and three-phase electric machines was developed in the first half of the 20th century by Steinmetz [10], Richter [11], Kron [12], Veinott [13], Schuisky [14], Bedefeld [15], Alger [16], Fitzgerald *et al* [17], Lyon [18], Say [19]-which are just a few names from hundreds of engineers and scientists who have dealt with this topic and published papers in this field. In these works, stationary states and transient performance of electrical machines (disorders: failures, disturbances ...) are analyzed. The problem of using an electric machine in the electric power network is not new, and it mainly comes down to obtaining a sufficient value of reactive energy.

Authors, Akagi [20], Mahfouz [21] and others in their works claim that on the basis of data on phase values, it is much easier to obtain fault characteristics, impedances, phase attitudes, etc ... However, in certain cases; due to the huge number of elements in electrical networks and constant changes in the state (changes in parameters in the windings of electrical machines or their presence or absence due to constant perturbation commutations), this is often not possible in reality. In that sense, by the nature of things, much greater possibilities for fault diagnosis are offered by methods developed on transformations of symmetrical or some other components (for example: Park, Bretford or Edith Clarck transformations for electric networks in which a number of static or rotating electric machine components are alternating electricity).

Although the authors are in references [5], [8] and [22] proposed a procedure similar to the method used in this paper, the method is not referred to in detail and verified. Based on the insight into the mentioned references and other available literature to date, the authors have not found a suitable and sufficiently accurate, theoretical procedure that would adequately determine the problem of disturbances in electrical networks. For this reason, this paper was created, and the simulation results, as well as the algorithm of diagnostic state functions for compensated networks with a neutral point confirmed that the proposed method and the obtained theoretical model are adequate and functional.

3. Symmetric Component Method

The symmetric component method is a vector concept important for three-phase electrical networks presented in the Cartesian system of real and imaginary coordinates [9]. It is used in disturbance analysis and can be verified by computer simulation and measurement. Based on the application of Tevenen's theorem and superposition method in a linear system, it corresponds to reality, because symmetric impedances can be calculated/measured, and symmetrical components of currents and voltages can be determined. Voltage phase A is the sum of three components V_d , V_i and V_0 .

Operator $\hat{a}$, Fig. 1, is the complex value of module 1 inverted by the angle vector $+2\pi/3$: $\hat{a} = e^{j2\pi/3}\angle 120^0$, $a = e^{j120^0}$, $\hat{a}^4 = a\angle 120^0$; a^2 : rotation for $2(2\pi/3) = (4\pi/3)$ ((equivalent to the angle $-2\pi/3$ and $\hat{a}^2 = e^{j4\pi/3}\angle 240^0$); a^3 : rotation for $3(2\pi/3) = 2\pi$ (equivalent to the angle 0 , $\hat{a}^3 = 1\angle 0^0$ and $a^3 = \vec{a}\vec{a}\vec{a} = e^{j360^0} = e^{j2\pi} = 1$) etc... as followed in the Dekart axis system (xy) [23].

Relations for phase components can be written in the form:

$$F_A = F_d + F_i + F_0,\ F_B = a^2 F_d + aF_i + F_0,\ F_C = aF_d + a^2 F_i + F_0 \tag{1}$$

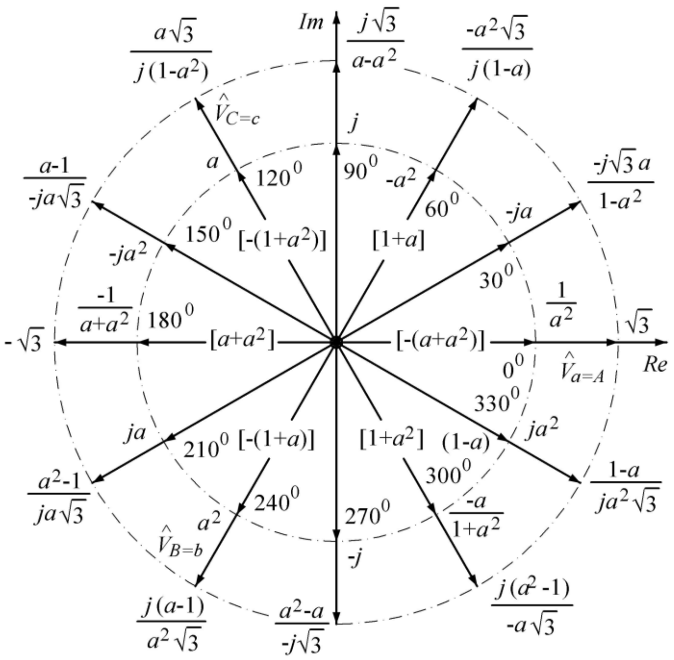

Fig. 1. Diagram of complex values $\hat{a}$

By solving the system of equations (1), symmetric components are obtained:

$$F_d = \frac{1}{3}\left[F_A + aF_B + a^2 F_C\right],\ F_i = \frac{1}{3}\left[F_A + a^2 F_B + aF_C\right],\ F_0 = \frac{1}{3}\left[F_A + F_B + F_C\right] \tag{2}$$

By the method of symmetric components, a three-phase asymmetric system with linear element parameters and the same frequency is decomposed into three independent symmetric vector systems with simple terms and presented with three single-phase schemes (for direct, inverse and zero system) of symmetric "Foretsque" components in matrix form:

$$S = \frac{1}{3}\begin{vmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{vmatrix} \Rightarrow \begin{vmatrix} F_d \\ F_i \\ F_0 \end{vmatrix} = \frac{1}{3}\begin{vmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{vmatrix}\begin{vmatrix} F_A \\ F_B \\ F_C \end{vmatrix}$$

$$S^{-1} = \begin{vmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{vmatrix} \Rightarrow \begin{vmatrix} F_A \\ F_B \\ F_C \end{vmatrix} = \begin{vmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{vmatrix}\begin{vmatrix} F_d \\ F_i \\ F_0 \end{vmatrix} \quad (3)$$

Sizes $F \equiv \{E, V, I\}$ (ems, voltages, currents) from the asymmetric domain to the symmetry domain - a system of symmetric components, they are transformed by transformation matrices.

The solutions determined in the system of symmetric components are superimposed by expressions that correspond to the conditions of the asymmetric system, and the superposition is correct if the electric quantities are simple-periodic functions, Fig. 2, [5]. The impedances of the network elements in the system of symmetric components do not have to be the same $Z_d \neq Z_i \neq Z_0$.

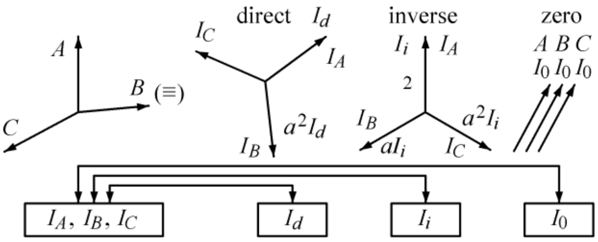

Fig. 2. Asymmetry of a three-phase system and translation into a symmetric

Impedances contain active resistances *R* and reactants *X*. Resistance R_d and R_i are as small as their impact on disorders. Due to different models of networks, zero-order resistance R_0 and grounding systems are different [1], [24-27].

The assumptions are that the load is symmetrical and that the disturbance is preceded by a state of idling, and these are sufficient conditions to use single-phase schemes for the calculation.

4. Development of Disorder Analysis Methods Using Symmetric Component Methods

In the continuation of the paper, a new method based on correct analysis using symmetric component methods and diagnostic algorithms for the assessment of the most common disturbances in electric power networks is presented. The symmetric component method is used in the analysis of disturbances (short circuits and disturbances) [28] and can be verified by computer simulation and measurement [8], [22].

They differ in the three-phase electrical network:

- Simple asymmetry that occurs only in one place.
- Simultaneous asymmetry, which can occur on several partial parts of the electrical network.

Asymmetric regimes occur with collapsed symmetry voltage/current due to disturbances and different impedances of elements by phases [29-30]. Since the system is asymmetric only at the point of disturbance, in addition to the symmetrical power supply, the same load impedances are a condition of symmetry [9].

As mentioned in equation (1), relations for phase components $\{F_A, F_B, F_C\}$ are determined from symmetrical components and impedances: Z_d direct, Z_i inverse and Z_0 zero schedule which depend on the impedance of the network elements in relation to the location of the disturbance. Size transition $F \equiv$ {phase values in the asymmetry domain: E emf, V voltage, I current} in symmetric components in the domain of symmetry is performed using transformation matrices $[S]$ and $\lfloor S^{-1} \rfloor$. If the source creates only a direct component emf $\hat{E}_d \neq 0$, $\hat{E}_i = 0$, $\hat{E}_0 = 0$, voltages $\{V_d, V_i, V_0\}$ and current $\{I_d, I_i, I_0\}$, then the equations for perturbation analysis correspond to a network with multiple sources, emf and internal impedances Z_d, Z_i and Z_0 by Tevenen's theorem on equivalent generators:

$$\begin{array}{lll} V_d = E_d - Z_d I_d & V_d = E_d - Z_d I_d & E_d = V_d + I_d Z_d \\ V_i = E_i - Z_i I_i & V_i = 0 - Z_i I_i & 0 = V_i + I_i Z_i \\ V_0 = E_0 - Z_0 I_0 & V_0 = 0 - Z_0 I_0 & 0 = V_0 + I_0 Z_0 \end{array} \quad (4)$$

$$V_i = -Z_i I_i$$
$$V_0 = -Z_0 I_0$$

where:

E_d , E_i , E_0 are direct, inverse and zero component of emf source,
V_d , V_i , V_0 direct, inverse and zero voltage component at the place of disturbance (according to ground),
Z_d , Z_i , Z_0 direct, inverse and zero impedance component (from source to disturbance location),
I_d , I_i , I_0 direct, inverse and zero current components.

If $I_0 = 0$ current system is balanced. When the network is symmetric (or asymmetric at the point of failure), symmetrical components are independent and can be solved separately. From single-phase schemes of symmetrical components corresponding to the equations from the source to the place of disturbance $m'-m''$ the phase components are determined.

The source creates only emf of direct order $\hat{E}_d \neq 0$, $\hat{E}_i = 0$, $\hat{E}_0 = 0$ and on place $m'-m''$ act $E_A = E_d$, $E_B = a^2 E_d$ and $E_C = aE_d$. Left of $m'-m''$ are values $V_A^{'}$, $V_B^{'}$, $V_C^{'}$, $I_A^{'}$, $I_B^{'}$, $I_C^{'}$ and $z_A^{'}$, $z_B^{'}$, $z_C^{'}$, and right values $V_A^{''}$, $V_B^{''}$, $V_C^{''}$ and $I_A^{''}$, $I_B^{''}$, $I_C^{''}$.

The impedances in the circuit of symmetrical components contain 2 members: left of $m'-m''$ are impedance $z_d^{'}$, $z_i^{'}$ and $z_0^{'}$, and right of $m'-m''$ are impedance $z_d^{''}$, $z_i^{''}$ and $z_0^{''}$. Total values of impedances are:

$$Z_d = z_d^{'} + z_d^{''} ,\ Z_i = z_i^{'} + z_i^{''} ,\ Z_0 = z_0^{'} + z_0^{''} \quad (5)$$

Many previous papers have not listed methods for obtaining schemes of symmetric components after transformations, and the impression is that the schemes were obtained axiomatically, and not as a result of mathematical solutions. A big mistake is to show the sequence diagram of symmetrical components of direct, inverse and zero order currents and voltages, although the connection refers only to the impedance connection of these orders.

The modules and directions of current and voltage are not the same: $I_d \neq I_i \neq I_0$, $V_d \neq V_i \neq V_0$ [5].

5. Disturbance Diagnostic Algorithms in Electrical Networks

The symmetry of phase voltages in electrical network is disturbed by asymmetric loads and characteristics of transmission elements. If the phase voltages and currents are symmetrical, for analysis of a three-phase network, a calculation for one phase and repeating procedure for the other two phases whose voltages have the same modules, but are phase shifted by an angle, is sufficient $2\pi / q$ (q number of phases). Apart from symmetrical stresses, the symmetry condition are the same load impedances.

When analyzing the state and operation of three-phase electrical networks, mathematical models of operation and / or models of the state of electric network must be formed beforehand and methods for solving differential equations of real-time network conditions must be chosen.

Networks with compensated neutral point have the largest number of possible states, so an algorithm for this type of network was written in the paper. According to the IEC standard for this network [31], data on phase quantities are required V_A , V_B , V_C , I_A , I_B , I_C and zero voltage of V_0 and inverse V_i schedule. In compliance with the basic (first) condition that there are voltage and current transformers in each phase of the substation, inverse order filters and sign vector $\vec{W}$ are sufficient to complete the system algorithm which provides network diagnostics and contains eight components:

$$\vec{W} = \{V_A ,\ V_B ,\ V_C ,\ I_A ,\ I_B ,\ I_C ,\ V_0 ,\ V_i\} \quad (6)$$

Binary character is another diagnostic condition for the application of Boolean algebra, and the character of the sign means the presence or absence of a value. The network status set is indicated by $\vec{Y}$, and his components with y_1, y_2,.., y_i,.., y_n that can have two values: 1 for y_i and 0 for $\overline{y_i}$, where $i = 1, 2,.., n$. In Bol's algebra, the order of operations is determined: 1. Conjunction (logical multiplication, Λ [·, "and"]), 2. Disjunction (logical addition, V [+, "or"]), 3. Negation (logical inversion, No [$\overline{X_i}$, "no"]) [30]. The diagnostic algorithm establishes mathematical-logical rules for determining a unique connection between a set of sign vectors $\vec{W}$ the diagnostic algorithm establishes mathematical-logical rules for determining a unique connection between a set of sign vectors $\vec{Y}$. The existence of voltage is indicated, for example, by V_A, and a defect with a line above the symbol $\overline{V_A}$. In the case of branching - separation, the relation is uniquely determined by Boolean diagnostic function "of the sign vector ", $\vec{Y} = F(\vec{W})$ which has only two values: 0 and 1, depending on whether an assessment of the condition is required or not.

In the set of diagnostic functions, the number of components should be equal to the number of estimated network states. If the process of synthesis of diagnostic functions is analogous for all modes, it is sufficient to consider only the process for one mode, for example earth fault.

In the case of a phase A earth fault, the voltmeter shows a voltage close to zero (depending on the position of the earth fault in relation to the busbars of the plant), ie. below the threshold value and therefore the sign component will be $\overline{V_A}$. Voltages V_B and V_C they grow, and it is important that they are higher than given. If currents flow through each phase, there are components in the diagnostic function at ground fault I_A, I_B, I_C.

In phase earthing A, $V_A = 0$, there is no voltage of inverse order $\overline{V_i}$, while zero order voltage V_0 exists, is close to and higher than the threshold voltage threshold. Therefore, the conjunction rule applies to the diagnostic function of phase A earth fault:

$$Y_A = \overline{V_A} V_B V_C I_A I_B I_C V_0 \overline{V_i} \tag{7}$$

By analogy, a phase B earth fault is recognized by function:

$$Y_B = V_A \overline{V_B} V_C I_A I_B I_C V_0 \overline{V_i} \tag{8}$$

while the phase C earth fault is recognized by function:

$$Y_C = V_A V_B \overline{V_C} I_A I_B I_C V_0 \overline{V_i} \tag{9}$$

By connecting relations (7-9), the Boolean diagnostic function of the network mode can be obtained:

$$Y_{033} = \left(\overline{V_A} V_B \overline{V_C} + V_A \overline{V_B} V_C + V_A V_B \overline{V_C}\right) I_A I_B I_C V_0 \overline{V_i} \tag{10}$$

whose value is equal to 1 in the case of an earth fault of any phase (A, B or C).

Relations (7-9) carry more data than relations (10) because they allow to recognize both the earth fault and the phase in which the earth fault occurred. Therefore, it is more important to determine the diagnostic function of the condition than the network mode.

Table 1 shows the diagnostic functions of the state of the compensated electrical network.

Algorithms of diagnostic functions in the electric power network are obtained with the help of diagnostic functions. Not all two-phase and three-phase short circuits with simultaneous phase interruption were taken into account, which is a lack of diagnostic conjunction functions. The character of the conjunction shape function enabled the construction of 2 types of circuits: with diodes and with microprocessors. The value of this analysis and method is reflected in the fact that all functions can be performed with the same scheme with 8 inputs and 1 output, Fig. 3.a,b, where: 1 – input to the standard marked inverter that implements the logic function `NO`, encoder blocks: 2 – phase voltages, 3 – phase currents in the conductor, 4 – zero order voltages, 5 – inverse order voltages, 6 – AC voltage converters to unified DC signal. The inverter diode array is an easier way to get the circuit in Fig. 3.a with the specified diagnostic functions from the Table 1.

Table 1. Diagnostic functions of possible electrical network conditions

Electrical condition networks 033	Diagnostic function $*V_0$, V_i	Electrical condition networks 033	Diagnostic function $*V_0$, V_i
Normal regime	$Y_1 = V_A V_B V_C I_A I_B I_C \overline{V_0}\,\overline{V_i}$	phase B and phase break A, B and C	$Y_{21} = V_A \overline{V_B} V_C \overline{I_A}\,\overline{I_B}\,\overline{I_C} V_0 V_i$
phase A - earth fault	$Y_2 = \overline{V_A} V_B V_C I_A I_B I_C V_0 \overline{V_i}$	phase C and phase break A and B	$Y_{22} = V_A V_B \overline{V_C}\,\overline{I_A}\,\overline{I_B} I_C V_0 V_i$
phase B - earth fault	$Y_3 = V_A \overline{V_B} V_C I_A I_B I_C V_0 \overline{V_i}$	phase C and phase break B and C	$Y_{23} = V_A V_B \overline{V_C} I_A \overline{I_B}\,\overline{I_C} V_0 V_i$
phase C - earth fault	$Y_4 = V_A V_B \overline{V_C} I_A I_B I_C V_0 \overline{V_i}$	phase C and phase break A and C	$Y_{24} = V_A V_B \overline{V_C}\,\overline{I_A} I_B \overline{I_C} V_0 V_i$
phase A and its termination	$Y_5 = \overline{V_A} V_B V_C \overline{I_A} I_B I_C V_0 V_i$	phase C and phase break A, B and C	$Y_{25} = V_A V_B \overline{V_C}\,\overline{I_A}\,\overline{I_B}\,\overline{I_C} V_0 V_i$
phase B and its termination	$Y_6 = V_A \overline{V_B} V_C I_A \overline{I_B} I_C V_0 V_i$	Connection of phase A and B directly and/or to ground	$Y_{26} = \overline{V_A}\,\overline{V_B} V_C I_A I_B I_C V_0 V_i$
phase C and its termination	$Y_7 = V_A V_B \overline{V_C} I_A I_B \overline{I_C} V_0 V_i$	Connection of phase A and C directly and/or to ground	$Y_{27} = \overline{V_A} V_B \overline{V_C} I_A I_B I_C V_0 V_i$
phase A and interruption of phase B	$Y_8 = \overline{V_A} V_B V_C I_A \overline{I_B} I_C V_0 V_i$	Connection of phase B and C directly and/or to ground	$Y_{28} = V_A \overline{V_B}\,\overline{V_C} I_A I_B I_C V_0 V_i$
phase A and interruption of phase C	$Y_9 = \overline{V_A} V_B V_C I_A I_B \overline{I_C} V_0 V_i$	Connection of phase A, B and C directly and/or to ground	$Y_{29} = \overline{V_A}\,\overline{V_B}\,\overline{V_C} I_A I_B I_C V_0 V_i$
phase B and interruption of phase A	$Y_{10} = V_A \overline{V_B} V_C \overline{I_A} I_B I_C V_0 V_i$	Connection of phase A and B and termination of phase C	$Y_{30} = \overline{V_A}\,\overline{V_B} V_C I_A I_B \overline{I_C} V_0 V_i$
phase B and interruption of phase C	$Y_{11} = V_A \overline{V_B} V_C I_A I_B \overline{I_C} V_0 V_i$	Connection of phase A and C and termination of phase B	$Y_{31} = \overline{V_A} V_B \overline{V_C} I_A \bar{I}_B I_C V_0 V_i$
phase C and interruption of phase A	$Y_{12} = V_A V_B \overline{V_C}\,\overline{A_A} I_B I_C V_0 V_i$	Connection of phase B and C and termination of phase A	$Y_{32} = V_A \overline{V_B}\,\overline{V_C} I_A I_B I_C V_0 V_i$
phase C and interruption of phase B	$Y_{13} = V_A V_B \overline{V_C} I_A \overline{I_B} I_C V_0 V_i$	Connection of phase A, B, C and termination of phase 1 or 2	$Y_{33} = \overline{V_A}\,\overline{V_B}\,\overline{V_C}\,\overline{I_A} I_B I_C V_0 V_i$
phase A and interruption of phase B and C	$Y_{14} = \overline{V_A} V_B V_C I_A \overline{I_B}\,\overline{I_C} V_0 V_i$	Phase interruption A	$Y_{34} = V_A V_B V_C \overline{I_A} I_B I_C \overline{V_0} V_i$
phase A and interruption of phase A and B	$Y_{15} = \overline{V_A} V_B V_C \overline{I_A}\,\overline{I_B} I_C V_0 V_i$	Phase interruption B	$Y_{35} = V_A V_B V_C I_A I_B I_C \overline{V_0} V_i$
phase A and interruption of phase A and C	$Y_{16} = \overline{V_A} V_B V_C \overline{I_A} I_B \overline{I_C} V_0 V_i$	Phase interruption C	$Y_{36} = V_A V_B V_C I_A I_B \overline{I_C}\,\overline{V_0} V_i$
phase and interruption of phase A, B and C	$Y_{17} = \overline{V_A} V_B V_C \overline{I_A}\,\overline{I_B}\,\overline{I_C} V_0 V_i$	Phase interruption A and B	$Y_{37} = V_A V_B V_C \overline{I_A}\,\overline{I_B} I_C \overline{V_0} V_i$
phase B and interruption of phase A and C	$Y_{18} = V_A \overline{V_B} V_C \overline{I_A} I_B \overline{I_C} V_0 V_i$	Phase interruption A and C	$Y_{38} = V_A V_B V_C \overline{I_A} I_B \overline{I_C}\,\overline{V_0} V_i$
phase and interruption of phase A and B	$Y_{19} = V_A \overline{V_B} V_C \overline{I_A}\,\overline{I_B} I_C V_0 V_i$	Phase interruption B and C	$Y_{39} = V_A V_B V_C I_A \overline{I_B}\,\overline{I_C}\,\overline{V_0} V_i$
phase B and interruption of phase B and C	$Y_{20} = V_A \overline{V_B} V_C I_A \overline{I_B}\,\overline{I_C} V_0 V_i$	Phase interruption A, B and C	$Y_{40} = V_A V_B V_C \overline{I_A}\,\overline{I_B}\,\overline{I_C}\,\overline{V_0}\,\overline{V_i}$

The scheme of the diagnostic algorithm is also realized with 3 microprocessors, Fig. 3.b, in which the binary code is converted to decimal according to the principle 1 of 10 and 20 microcircuits for the realization of two elements. Comparing schemes, it is concluded that the scheme in Fig. 3.b more reliable and less sensitive to interference, has smaller dimensions and required power.

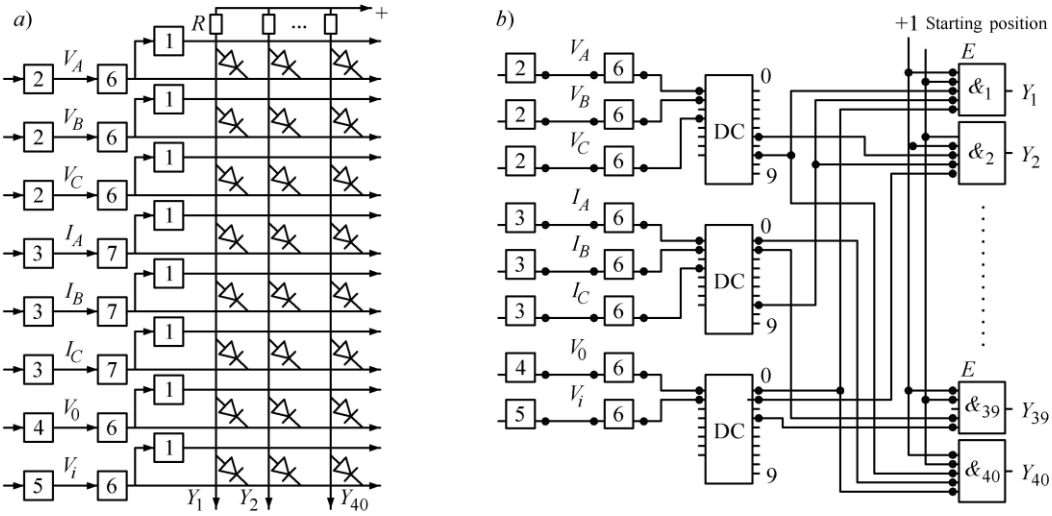

Fig. 3. a) Inverter circuit with diodes for realization of power network diagnostic algorithm, b) circuit with microprocessors

The threshold (lower level) of diagnostic parameters is important for the realization of algorithm V_A, V_B, V_C, I_A, I_B, I_C and V_0, V_i. The lower voltage level of inverse order must beand $V_i^P = 0.2V_f$ if it is in a network with higher single-phase loads, the degree of asymmetry is less than 10-15%, because when one phase is interrupted, the level is much higher than 20%.

In cable networks, the lower level of the zero-order voltage value V_0^P should be selected at 5% of the phase $V_0^P = 0.05 \cdot V_f$, because the natural displacement of the constellation does not exceed 3%. In overhead networks (35 kV) the natural displacement of the star point can reach 30%, therefore for V_0^P you need to choose a higher level, i.e. $V_0^P = 0.4 \cdot V_f$.

Threshold values of important currents I^P is easy to choose because when their value is zero, the interruption of the phases is confirmed, and in the idle mode they are not equal to zero because they are caused by the no-load currents of the transformer. However, those currents are small, so the level I^P should be selected at a value of 1% of the nominal phase current $I^P = 0.01 I_{A,B,C}$.

There is a problem when choosing the voltage threshold because the voltages depend on the position of the fault location. Earth faults with high transient resistances can be treated as phase overloads. According to IEC [31], these post-fault voltages cannot be less than 20% of the rated voltage, although initially the fault voltage is not more than 70% of the rated voltage. In a network whose diagnostic functions are needed, it is good to adopt it as a threshold value $V_p = 0.75 \cdot V_n$.

6. Simulation Scheme and Results

If the voltages are symmetric, for the analysis of a three-phase network, a calculation for one phase and repeating the procedure for the other two phases whose voltages have the same modules and are phase shifted by an angle is sufficient $2\pi / q$ (q-number of phases).

The simulation method, which relies on artificial intelligence and computer assistance through "playback", can replace the classic procedure of calculation and measurement and provide an objective picture of the state of the network. In MATLAB there is a program for simulating electrical quantities according to the algorithm of transient process models and a program for generating quantities [32]. Programs are used to check the generated and processed values and to recognize the generated and processed values after signal simulation [33]. The programs have two parts: front (SCOPE) and block diagrams.

The block diagram is used for writing programs, and the front diagram for displaying user correspondence. The generating program has built-in "simulate signal" functions that are used to generate various signals, but it is the best sine wave choice. The sampling frequency and the number of simulation samples are set at the input. Variables at the input are: frequency, amplitudes and phase attitudes. The "simulate signal" function is located in the Dot product loop (3 loops, for 3 phase voltages and 3 loops for symmetrical components) and has a number of iterations equal to the first harmonic $f = 50$ Hz which is generated, ie. represents the number of rows of each "cluster" field. The input for the Dot product loop is in "cluster" format. The program has 2 "cluster" of 3 fields: voltages for each phase individually and for voltages $V_{d,i,0}$.

By entering the value in the "cluster", the voltage level is selected and 3 parameters are entered on the Scope separately for each phase. The loop in each iteration reads the values of all "cluster" fields at the field location equal to the current iteration. The first iteration contains data on initial values $V_{d,i,0}$. In the next iteration, the values of the current iteration with the initial iteration are added to the loop and the value is obtained at the desired time. After completing the iteration and adding up all the previous iterations, the final values are entered in the output.txt doc. 2-pole file: in the first sampling time, and in the second voltage.

For the verification of the model and algorithm of transient transformer processes, a special program was written in MATLAB for which two schemes were compiled, Fig. 4.a and 4.b, for simulation of processes with given parameters of phase voltage levels and display of diagrams on only two Scopes: 1. for phase voltages and 2. for symmetric voltage components [32].

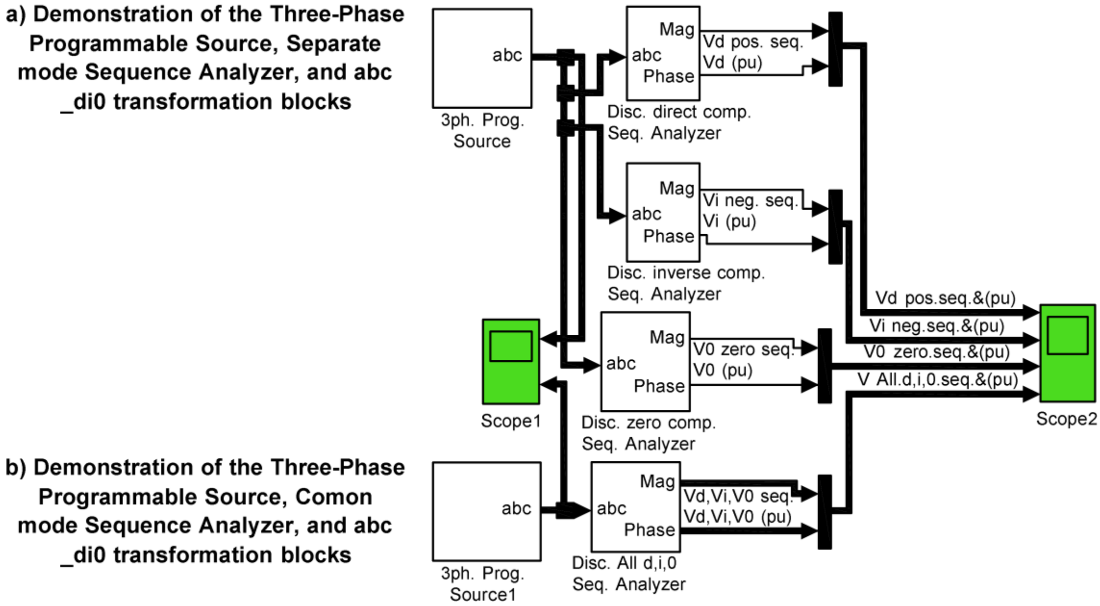

Fig. 4. Model scheme for simulation of a reference discrete three-phase analyzer using Fourier analysis of a moving window of one frequency cycle 50 Hz

Diagram blocks presented on Fig. 4.a and 4.b, serve to simulate the operation of a reference discrete three-phase analyzer using Fourier analysis of a single-cycle moving window. Certain frequencies are first used to define three phase voltage input signals V_a, V_b and V_c with the frequency of the first harmonic, $f = 50$ Hz. Then the phase values are rotated by po 120^0 to obtain direct V_d, inverse V_i and zero V_0 component. The filter block is used in the control system for measuring voltage and current of a given order, and the filter block introduces a delay. Filter block response to step change V_1 is only a monocyclic linear change. Discrete three-phase block analyzer produces components of direct, inverse and zero order in particular: Fig. 4.a or components of all three orders together, or the scheme in Fig. 4.b (amplitude and phase shifts) three (symmetric - balanced or unbalanced - asymmetric) sets of signals containing the fundamental voltage harmonic $f = 50$ Hz [34]. The input contains a signal - vector 3 sinusoidal signals $V_{a,b,c}$. Outputs 1 and 2 respectively give the magnitude (amplitude) and phase position of the components of the appropriate order. For the first simulation cycle, the outputs are constant values in the specified parameters, and V_a, V_b and V_c are input phasors of a certain frequency.

In the adapted part of the MATLAB package psb.abc,part.mdl [32], the operation of the Sequence analyzer for short-circuit fault type disturbance, if the overvoltage levels are simulated on the model scheme [p.u.] [1].

On the Scope 1 voltage phasor diagrams are given V_a (yellow), V_b (blue), V_c (pink), Fig. 5.a. Normal network operation and amplitude level in all three phases a, b, c is $V_m = \sqrt{2}V_n = 1.41 \cdot V_n \Leftrightarrow V_m[p.u.] = 1.41$ and is suitable to interval $0.0 < t < 0.05$ s, and then overvoltage with amplitude levels occur $V_m \approx 2 \cdot V_n \Leftrightarrow V_m[p.u.] \approx 2$ in interval $0.05 < t < 0.15$ s, Fig. 5.b. The voltage level is assumed in the simulation, but realistically, the voltage level is determined by the dynamic impedances of the circuit and the switch-off current, while the overvoltage level is determined by the source (generator or line) and the impedance ratio Z_0 / Z_d [1], [5].

From the Scope 2, Fig. 6.a, we can conclude:

- (a. Scheme, Diagram V_d positive sequence) it is clear that the direct component is not important for overvoltage detection because there is no discrete response in the signal V_d (pink) and V_d [p.u.] (yelow).
- (a. Scheme, Diagram V_i negative sequence) in the inverse component the response is delayed due to the influence of the filter.
- (a. Scheme, Diagram V_0 zero sequence) there is a response in the zero-order component, but with a delay due to the influence of the filter.

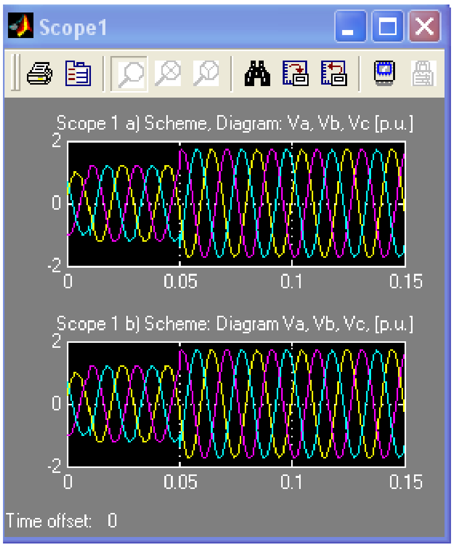

Fig. 5. Voltage (for steady state) and overvoltage (disturbance) diagrams: demonstration of a programmed a, b, c three-phase source in which three phases are analyzed separately

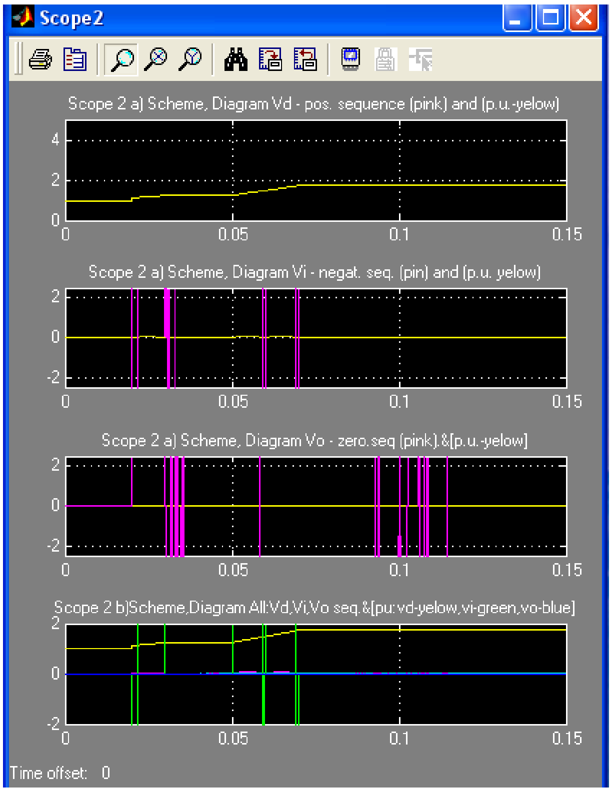

Fig. 6. Voltage (for steady state) and overvoltage (disturbance) diagrams: demonstration of a programmed a, b, c three-phase source in which three phases are analyzed together

All of the above also applies to discrete values for Fig. 6.b where V_d is [p.u.] response (yellow), V_i [p.u.] response (green), and V_0 [p.u.] is not even detected.

Simulation results - simulation diagrams corresponding to surge values when switching off short circuits of levels 1.5–2.0 [p.u.] show that three known methods for analysis of steady states are not correct and reliable for analysis and assessment of surges (disturbances of the type of disturbances - longitudinal asymmetries according to the IEC standard [31]).

Further steps in future research should relate to introduction of obtained formulas in algorithms of protection systems and local automation systems.

7. Conclusion

Based on the previous considerations, we can conclude the following:

- Diagnostic devices that basically contain controllers (or universal microprocessor relays) can be installed to increase the efficiency and quality of control of the state of electrical networks and reduce the time of restoration of normal states after disturbances in plants).
- Synthesis of the algorithm for diagnosing the state of the electrical network was achieved using Boolean algebra.
- Applying the conjunctive form of the Boolean diagnostic function, the diagnostic algorithm can be realized with the help of selected microprocessor components in the set according to the table shown 1.
- Scheme in Fig. 3.b, achieved with microprocessors is better, because it takes less time for automatic reconnection (APU) and normal network operation - thus significantly shortening the time to establish normal network operation and increased reliability of power supply to consumers.

The method of computer-assisted simulation through "playback" replaced classical procedure of calculating and measuring electrical quantities and provided an objective picture of the state of network. In MATLAB Simulink there is a program for simulating electrical quantities according to algorithm of transient process models and a program for generating quantities. Programs are used to check the generated and processed values and to recognize the size of generated and processed signals.

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