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MODELING OF ASYMMETRICAL OPERATING MODES OF POWER AUTOTRANSFORMERS

T.U. Shaulemetov[1]

Tashkent State Technical University named of I.A.Karimov

KEYWORDS
autotransformers,
phase operation,
method of symmetrical components,
calculated equivalent circuit,
asymmetrical conditions,
open-phase operating conditions

ABSTRACT

There are cases of change in values during the process of exposure and distribution of electric current when the voltage in the autotransformer changes. Therefore, we study the distribution and characteristics of the current in the lattice homogeneous mode. It is important to study the effect of electric current on autotransformers in the process of studying the losses generated in them, as well as in transient processes. When operating power autotransformers that have become widely used in networks of 220 kV and higher, it is often necessary to deal with open-phase modes caused by disconnections of one or two phases in the case of short circuits or in the ca se of single-phase repairs. This leads to asymmetry of the voltage of autotransformers, which affects the quality of power supply to consumers. For the autotransformer itself, an open phase operation can be dangerous with respect to overloading of individual windings. The presence of an electrical connection between high and medium voltage causes the specifics in the analysis of their operating modes. In addition, while the theoretical analysis and the general approach to the calculation of asymmetrical modes of two-winding transformers are currently considered in sufficient detail, the task of analyzing the asymmetrical operating modes of three-winding autotransformers remains important. An approach to the calculation of autotransformer and combined asymmetrical operating modes of power autotransformers has been developed on the basis of the method of symmetrical components. The proposed model and obtained analytical expressions allow one to determine the currents and voltages of the phase windings of the autotransformer in a variety of asymmetrical modes of operation on the basis of a unified approach.

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[1] Tashkent State Technical University named of I. A. Karimov

INTRODUCTION.

When operating power autotransformers that have become widely used in networks of 220 kV and higher, one often has to deal with asymmetrical modes of operation caused by a short shutdown of one or two phases during short circuits or a longer shutdown during single-phase repairs. Such modes can also occur at open-phase shutdowns of the autotransformers or at their single-phase switching. In some cases, for a group of single-phase autotransformers in the case of emergency disconnection of one phase, it may be permissible to work in two phases. In this case, installation of a backup phase is not required, especially if there are two groups of single-phase autotransformers at the substation [1]. Open-phase modes lead to voltage unbalance of autotransformers, which affects the quality of power supply to consumers. For the autotransformer itself, asymmetrical operation can be dangerous with respect to the overload of individual windings. The presence of an electrical connection between high and medium voltages determines the specificity of the analysis of the modes of their operation. In addition, while the theoretical analysis and the general approach to the calculation of asymmetrical modes of two-winding transformers are considered in sufficient detail, the task of analyzing the asymmetrical modes of operation of three-winding autotransformers remains important.

Most often, power autotransformers are used to connect electrical networks with voltages of 110, 220, 330, and 500 kV on the high- and medium-voltage sides. In this case, in addition to series and common windings with electrical connection, power autotransformers, as a rule, have tertiary windings of low voltage (LV), connected in a triangle. These windings compensate for the harmonic components of voltage and EMF, multiples of three, and can be used to communicate with the power grid of the lower voltage. Rated power of winding LV U_{Lrat} is less than rated power of the autotransformer S_{rat} and cannot exceed the value of common power S_{com}.

Despite the appearance in recent years of effective numerical methods for calculating electromagnetic devices, the analysis of asymmetrical modes of power transformers is usually carried out on the basis of the method of symmetrical components. The main advantage of this approach is the possibility of using equivalent circuit of reduced transformers for currents of different sequences and carrying out calculations using simple analytical formulas. In this case, the analysis of many asymmetrical modes can be carried out using reference parameters of transformers. The main disadvantages of the method of symmetrical components are low accuracy, mainly due to the assumption that the magnetic circuit is linear and that the parameters of the magnetizing branch of the replacement circuit are constant.

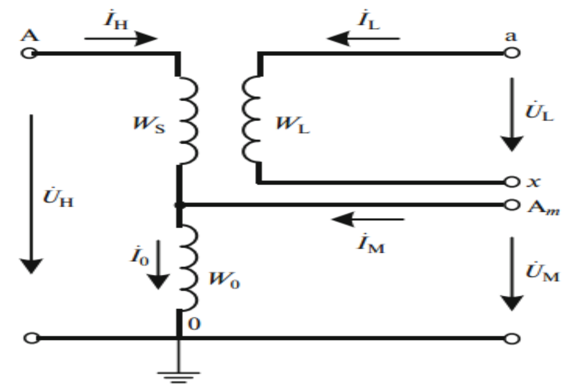


Fig. 1. Wiring diagram of the windings of a single-phase autotransformer.

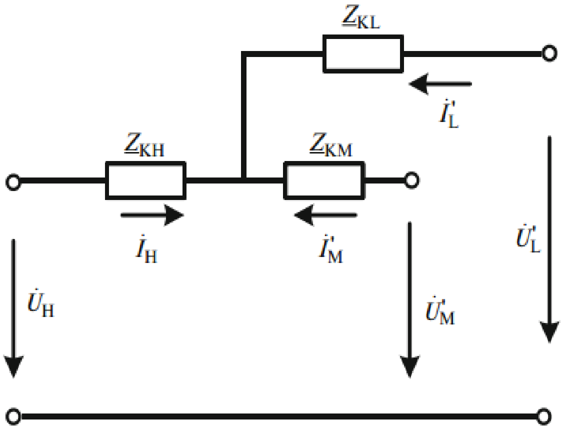


Fig. 2. Equivalent circuit of the autotransformer phase.

As is known [2], the calculation of symmetrical three-phase circuits is carried out "for one phase." The connection diagram of the windings of one phase of a three-winding autotransformer is shown in Fig. 1. Here, as in the general theory of three-winding transformers, the following designations of phase magnitudes are adopted U_H, U_M and U_L are phase voltages of the windings of the highest (HV), medium (MV), and lowest (LV) voltages; I_H, I_M , and I_L are phase currents HV, MV, and LV; $W_H = W_S + W_C$ is the number of turns of the high-voltage winding; $W_M = W_C$ is the number of turns of the MV winding; and W_M is the number of turns of the LV winding.

If we neglect the magnetizing current of the autotransformer, the connection between currents I_H, I_M , and I_L will be determined by the equation

$$W_S I_H + W_C I_C + W_L I_L = 0, \qquad (1)$$

moreover,

$$\dot{I}_C = \dot{I}_H + \dot{I}_M \qquad (2)$$

When analyzing symmetrical modes, the phase of the autotransformer is represented by the equivalent circuit [3], the form of which is no different from the equivalent circuit of the phase of a three-winding transformer (Fig. 2), while the magnetizing current is usually neglected. Since in the equivalent circuit all magnetic (transformer) connections are replaced by electric ones, the voltages and currents from the MV and LV side usually lead to the number of windings (voltage) of HV:

$$U'_M = U_M k_{HM}, U'_L = U'_L k_{HL}, \quad (3)$$

$$I'_M = I_M \frac{1}{k_{HM}}, \dot{I}'_L = \dot{I}_L \frac{1}{k_{HL}},$$

where $k_{HM} = \frac{U_{H.rat}}{U_{M.rat}}$ and $k_{LH} = \frac{U_{H.rat}}{U_{L.rat}}$ is the transformation ratios of a three-winding autotransformer.

Parameters of the equivalent circuit, Z_H, Z_M , and Z_L (Fig. 2) can be easily determined, for example, by the formulas of [4], using reference data [5]. To exclude overloads of the autotransformer windings, the modes, in which the phase currents of series I S=IH, common windings I_C, and LV windings I_L of the autotransformer will not exceed their rated values, are acceptable.

When using relative units,

$$I_{\Pi} = I_{B} \leq 1, I_{C} \leq k_{com}, I_{L}' \leq \alpha, \qquad (4)$$

where $k_{com} = 1 - \frac{1}{k_{HM}}$ is the common power factor;

$$\alpha = \frac{S_{L.rat}}{S_{rat}}, \dot{I}_{C} = \dot{I}_{H} + \dot{I}_{M} = \dot{I}_{H} + k_{HM}\dot{I}_{M}' \quad (5)$$

In expression (5), the direction of currents $\dot{I}_{H}, \dot{I}_{C}$, and $\dot{I}_{M}$corresponds to Fig. 1

In the analysis of asymmetrical modes by the method of symmetrical components, the phases of autotransformers, as well as the phases of transformers, are represented by equivalent circuits of direct, reverse, and zero sequence. Moreover, the equivalent circuit of the autotransformer and its parameters for reverse sequence currents are no different from the direct sequence circuit.

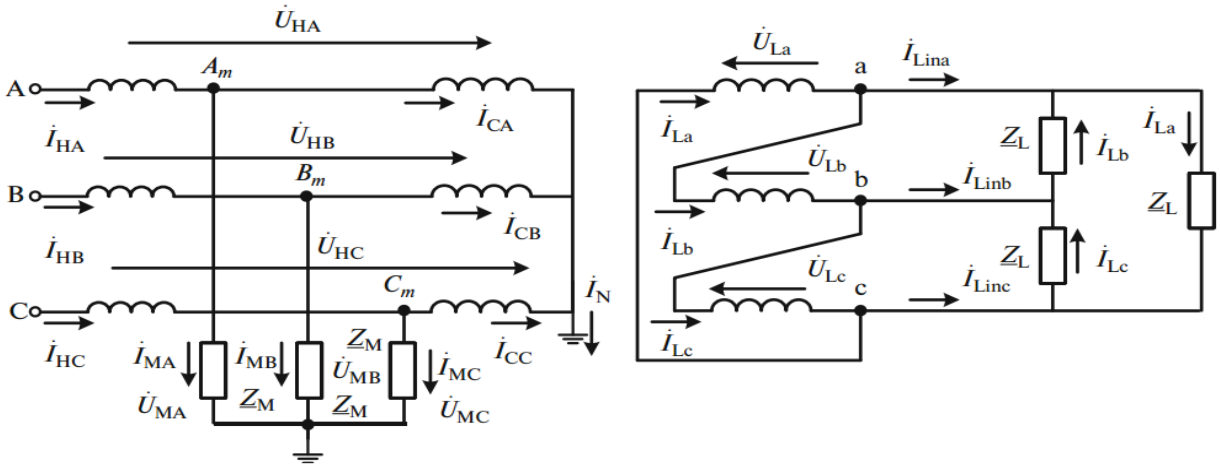


Fig.3. Combined power transfer mode HV→MV and HV → LV.

Zero sequence currents and fluxes in autotransformers appear and act similarly to the third harmonics of the magnetizing current and flux resulting from saturation of the magnetic circuit. The only difference is that the first change with a basic frequency, while the second change with a threefold frequency. Power autotransformers are made in both three- and singlephase forms. In this case, the resistance of the magnetizing branch to the zero sequence currents in group and three-core autotransformers will be different; however, if there is a grounded neutral, zero sequence currents can flow in all windings. In this case, the magnetizing current is a small fraction of the total zero sequence current and can be neglected. Consequently, when analyzing asymmetrical modes, a simplified equivalent circuit of the autotransformer can be used (Fig. 2), the type and parameters of which will be the same for all sequence currents; moreover, for zero sequence currents, the LV winding will be short-circuited.

Thus, when analyzing asymmetrical modes, each phase of the autotransformer can be considered independently of other phases. At the same time, to avoid overloading the windings of expression (4), it is necessary to consider each phase of the autotransformer.

The most common modes of operation of power autotransformers are autotransformer and combined modes in which HV ↔ MV power flows and, at the same time, LV ↔ MV or LV ↔ HV occur. In accordance with the principle of compensation [6], the network to which the complex power from the autotransformer is delivered can be represented as the complex resistances of three phases. In symmetrical modes, these complex resistances are equal; in asymmetrical modes, in the absence of rotating electrical machines in HV, MV, and LV networks, the systems of equivalent circuits of each circuit that take into account mutual induction will be the same for the direct and reverse sequences. However, the complex of equivalent zero sequence resistance in HV and MV networks will have a different value than for the direct and reverse components, since, unlike the latter, zero sequence currents are closed along ground and grounding devices. If there are rotating electrical machines in the networks, the equivalent complex resistances will be different for all symmetrical components.

It follows from the above that, if the phase resistances of the circuit are different and do not change for currents of different sequences, then the calculation of such a circuit can be carried out for each phase separately with respect to total currents and voltages, without decomposing them into symmetrical components.

The normal modes of operation of networks with a voltage of 220 kV and higher are symmetrical modes. Long asymmetrical modes arise when line and phase wires are broken. When this happens, the load phase resistance in the general case will be different for the currents of direct, reverse, and zero sequences.

Consider the combined power transfer mode in autotransformer (HV → MV) and transformer (HV → LV) ways. The connection diagram of the autotransformer windings and load resistances in this mode is shown in Fig. 3. We will assume that a symmetrical system of phase voltages of the direct sequence, U_{HA}, U_{HB} and U_{HC} is connected to the phases of the HV winding. A symmetrical load with corresponding resistances and is connected to the autotransformer on the sides of the MV and LV.

Consider the case in which the parameters of the autotransformer and the load have the following values in relative units:

Operation mode	Values of the currents in the windings of the autotransformer and the neutral (p.u.)									
	I_{HA}	I_{HB}	I_{HC}	I_{CA}	I_{CB}	I_{CC}	I_{La}	I_{Lb}	I_{Lc}	I_N
Symmetrical	0,998	0,998	0,998	0,234	0,234	0,234	0,411	0,411	0,411	0
Disconnection of the line wire of phase A on the MV side	0,591	1,19	1,124	0,591	0,54	0,583	0,591	0,324	0,334	1,375
Disconnection of the line wire of phase A on the LV side	0,772	0,937	1,113	0,793	0,529	0,33	0,343	0,343	0,686	0
Disconnection of the line wire of phase A on the HV side	0	1,353	1,349	0,35	0,576	0,42	0,175	0,467	0,56	1,009

The currents are expressed in fractions of the rated currents of the series $\left(I_{S.rat} = \frac{S_{rat}}{\sqrt{3}U_{H.rat}}\right)$, common $\left(I_{C.rat} = \frac{k_{com}S_{rat}}{\sqrt{3}U_{M.rat}}\right)$, and HH $\left(I_{L.rat} = \frac{S_{L.rat}}{\sqrt{3}U_{L.rat}}\right)$windings, with the rated currents of these windings in relative units: I_S=I_S=1, $I_C = k_{com}, and\ \ I_L$=$\alpha$.

$U_H = U_{HA} = 1, k_{HM} = 2, \alpha = 0.5, Z_{KH} = 0.048 + J0.12, Z_{KM} = 0.048, and\ Z_{KL} = j0.22C$. Load resistance for direct, reverse, and zero sequence currents: $Z_M = 1.2 + J0.8, Z_{M2} = 0.05 + j0.11, Z_{M0} = 0.05 + J0.05, Z_{L1} = Z_L = 1.41 + j1.41, and\ Z_{L1} = 0.06 + j0.2$.

In this case, for the mode in question, we take the directions of the currents $\dot{I}'_M$ and $\dot{I}'_L$ opposite to the corresponding directions in Fig. 2.

SYMMETRICAL MODE

For the symmetric mode, from the calculation of the equivalent circuit (Fig. 2), taking into account the load resistances, we obtain

$$\dot{I}_H = \frac{\dot{U}_H}{Z_{KH} + \frac{(Z_{KM} + Z_M)(Z_{KL} + Z_L)}{Z_{KM} + Z_M + Z_{KL} + Z_L}} = 0{,}998e^{-j43^\circ},$$

$$\dot{I}'_M = \dot{I}_H \frac{(Z_{KL} + Z_L)}{Z_{KM} + Z_M + Z_{KL} + Z_L} = 0{,}597e^{-j36°},$$
$$\dot{I}'_C = \dot{I}_H - \dot{I}'_M = 0{,}411e^{-j53°},$$
$$\dot{I}'_C = \dot{I}_H - k_{HM}\dot{I}'_M = 0{,}234e^{-j53°}.$$

Thus, in the symmetrical mode, the serial winding is loaded with almost rated current ($I_S = I_H = 0.998$), while the LV winding and the common winding are loaded with currents less than rated. The effective values of the currents in the windings of the autotransformer for this mode are given in the Table 1.

RESULTS.

Consider the operating mode of three-circuit autotransformers with HV, MV and LV windings (Fig. 2).

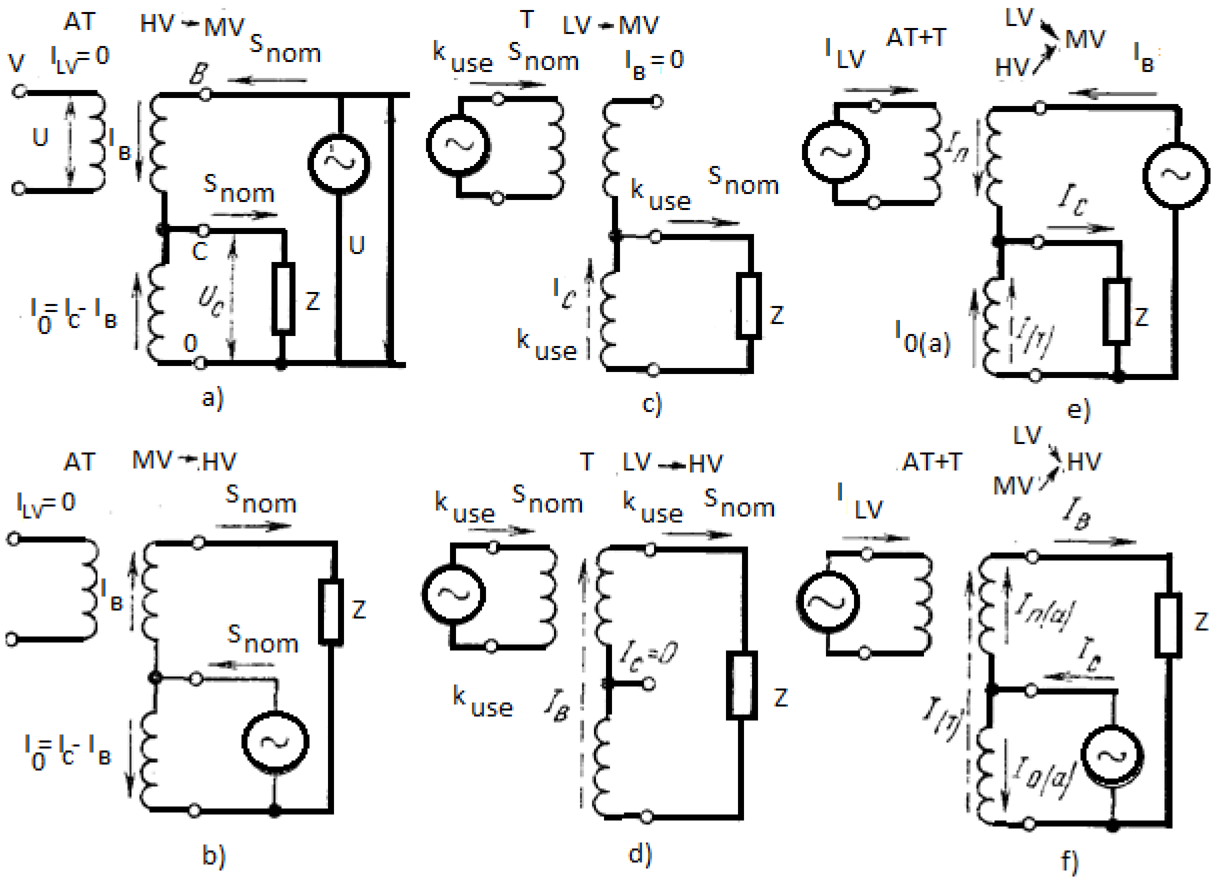


Figure 2. Distribution of currents in autotransformer circuits in different modes: a, b - autotransformer modes; c, d- transformer modes; e, f- combined modes.

In autotransformer modes (Fig. 2, a, b), the rated power can be transmitted from the S_{nom} HV coil to the MV coil and vice versa. In both modes, the difference in currents in the common winding Ic - I_B = k_{useful} Ic passes, so the series and common windings are loaded with typical power, which is allowed.

In transformer modes (Fig. 2 v, g), power can be transferred from the LV coil to the MV coil or to the HV coil. It is not possible to load the LV wrap more than the Sтип. Mode is the term of admission of LV → HV or LV → MV is as following:

$$S_{LV} \leq S_{tip} = k_{useful} S_{nom} \qquad (3)$$

If the S_{tip} is transformed from LV to MV, then it is not possible to transfer additional power from HV to MV even if the total winding is loaded with the same power and the winding is not loaded in series. In transformer mode (Fig. 2, g), the common and series windings are not fully loaded when the stip power is transferred from the LV winding to the HV winding:

$$I_0 = I_{\text{п}} = \frac{k_{useful} \cdot S_{nom}}{U_{\text{в}}} = k_{useful} I_{\text{в}} \qquad (4)$$

therefore, a certain amount of additional power can be transmitted from the MV loop to the HV (see Figure 2, explanation given for e).

In the combined mode, when the power is transmitted by the autotransformer path HV → MV and the transformer path LV → MV (Fig. 2, d), the current in the winding series is as following equation:

$$I_{LV} = I_{\text{в}} = \frac{\sqrt{P_{\text{в}}^2 + Q_{\text{в}}^2}}{U_{\text{в}}},$$

Where $P_{\text{в}}$, $Q_{\text{в}}$ — Active and reactive powers transmitted from HV to MV.

Sequential winding load

$$S_{\text{кк}} = (U_{\text{в}} - U_{\text{с}}) I_{\text{кк}} = \frac{\sqrt{P_{\text{в}}^2 + Q_{\text{в}}^2}}{U_{\text{в}}} (U_{\text{в}} - U_{\text{с}}) = k_{useful} S_{\text{в}}$$

From this, it can be seen that even when the nominal power $S_{\text{в}} = S_{nom}$ is transmitted, the winding series is not overloaded.

The currents in the common circuit are directed in one direction in autotransformer and transformer modes:

$$I_0 = I_{0(\text{а})} + I_{(\text{т})}$$

Total winding load

$$S_{gen} = U_{\text{с}} \left(I_{0(\text{а})} + I_{(\text{т})} \right).$$

After replacing the amount of currents and making the appropriate changes, we get the following result:

$$S_{gen} = \sqrt{\left(k_{useful} P_{\text{в}} + Q_{LV}\right)^2 + \left(k_{useful} Q_{\text{в}} + Q_{LV}\right)^2} \qquad (4)$$

Where, P_{LV}, Q_{LV} — Active and reactive powers transmitted from the LV coil to the MV coil.

Thus, the combined mode LV → MV, HV → MV is limited by the total load and is allowed under the following conditions

$$S_{gen} \leq S_{tip} = k_{useful} S_{nom}$$

The distribution of currents in the combined mode, which transmits power from the LV and MV windings to the HV winding, is shown in Figure 2, e. In the general winding, the direction of current in the autotransformer mode is opposite to the direction of the current in the transformer mode, so the load on the winding can be much smaller than allowed and finally zero. The currents in the winding series are interconnected and as a result can overload it. This mode is limited to serial loading:

$$S_{кк} = k_{useful}\sqrt{(P_c + Q_{LV})^2 + (Q_c + Q_{LV}^2)} \qquad (5)$$

Where, P_c, Q_c — Active and reactive powers in the MV system;

P_{LV} , Q_{LV} is the active and reactive forces on the LV side.

If the following condition is accoplished, the combined mode LV → HV, MV → HV is allowed:

$$S_{кк} \leq S_{tip} = k_{useful}S_{nom} \ (6)$$

There may be other combined modes, i.e., power transfer from MV winding to LV and HV windings, or operation in deceleration mode by transferring power from HV winding to MV and LV windings.

DISCONNECTION (BREAK) OF THE LINE WIRE OF PHASE A ON THE MV SIDE

In accordance with [2], this mode can be modeled by the inclusion of three asymmetrical sources of EMF in the line wires on the MV side. Design schemes for currents of (a) direct, (b) reverse, and (c) zero sequences of the considered mode are shown in Fig. 4. In these circuits, the unknown values are currents and EMF $\dot{E}_{M1,}$ $\dot{E}_{M2,}$ and $\dot{E}_{M0.}$

In accordance with the method of symmetrical components for two sources of EMF in phases B and C, we will have

$$\dot{E}_{MH} = \alpha^2\dot{E}_{M1} + \alpha\dot{E}_{M2} + \dot{E}_{M0} = 0, \qquad (6)$$
$$\dot{E}_{MM} = \alpha\dot{E}_{M1} + \alpha^{\dot{2}}E_{M2} + \dot{E}_{M0} = 0,$$

where $\alpha = e^{j120°}$.

From (6), it follows that

$$\dot{E}_{M1} = \dot{E}_{M2} + \dot{E}_{M0} = 0. \quad (7)$$

When disconnecting the line wire of phase A from the MV side,

$$I'_{MA} = I'_{M1} + I'_{M2} + I'_{M0} = 0. \quad (8)$$

Taking into account expressions (6)–(8), we obtain

$$\dot{E}_{M1} = \dot{E}_{M2} + \dot{E}_{M0} = \frac{\frac{\dot{E}_{ME}}{Z_{ME1}}}{\frac{1}{Z_{ME1}} + \frac{1}{Z_{ME2}} + \frac{1}{Z_{ME0}}}, \quad (9)$$

$$E_{ME} = U_H\frac{Z_{KL} + Z_{L1}}{Z_{KH} + Z_{KL} + Z_{L1}},$$

$$Z_{ME1} = Z_{KM} + Z_{M1} + \frac{Z_{KH}(Z_{KL} + Z_{L1})}{Z_{KH} + Z_{KL} + Z_{L1}},$$

$$Z_{ME2} = Z_{KM} + Z_{M2} + \frac{Z_{KH}(Z_{KL} + Z_{L2})}{Z_{KH} + Z_{KL} + Z_{L2}}.$$

$$Z_{ME0} = Z_{KM} + Z_{MO} + \frac{Z_{KH}Z_{KL}}{Z_{KH} + Z_{KL}}.$$

Having determined the EMF $\dot{E}_{M1} = \dot{E}_{M2} + \dot{E}_{M0}$ by the formula (9), one can find the currents$\dot{I}_{M1},\ \dot{I}_{M2} and\ \dot{I}_{M0}$:

$$\dot{I}_{M1} = \frac{E_{ME} - E_{M1}}{Z_{ME1}},$$
$$\dot{I}_{M2} = \frac{-E_{M2}}{Z_{ME2}},$$
$$\dot{I}_{M0} = \frac{-E_{M0}}{Z_{ME0}},$$

The remaining unknown currents in the diagrams of Fig. 4 are determined by the formulas

$$\dot{I}_{H1} = \frac{\dot{U}_H - \dot{E}_{M1} - \dot{I}'_{M1}(Z_{M1} + Z_{M1})}{Z_{KH}},$$
$$\dot{I}_{H2} = \frac{-\dot{E}_{M0} - \dot{I}'_{M1}(Z_{KM} + Z_{M2})}{Z_{KH}},$$
$$\dot{I}_{H0} = \frac{-\dot{E}_{M0} - \dot{I}'_{M1}(Z_{KM} + Z_{M0})}{Z_{KH}},$$
$$\dot{I}'_{L1} = \dot{I}_{H1} - \dot{I}'_{M1}, \dot{I}'_{L2} = \dot{I}'_{H2} - \dot{I}'_{M2}, \dot{I}'_{L0} = \dot{I}'_{HO} - \dot{I}'_{MO.}$$

Knowing the symmetrical components of the currents, it is easy to find the resulting currents in each winding of the autotransformer. The effective values of these currents determined by the above parameters are given in Table 1. It follows from the calculation results, that, in this mode, the currents exceed the rated values in phases B and C of the series winding, in phases A and B of the common winding, and in phase A of the LV winding.

DISCONNECTION (BREAK) OF THE LINE WIRE OF PHASE A ON THE LV SIDE

In this case, the network operation mode on the LV side will be single phase. In this case, zero sequence currents in the windings of the autotransformer will not leak. This mode can be modeled by the inclusion of three unbalanced sources of EMF in the line wires on the LV side (Fig. 5a). Having performed the transfer of these sources through nodes a, b and c, we obtain the scheme shown in Fig. 5b. Design schemes for currents of the (a) direct and (b) reverse sequences of the considered mode are shown in Fig. 6. In these schemes, the unknown val ues are currents and EMF $\dot{E}_{\alpha1}$ and $\dot{E}_{\alpha2}$.

For two sources of EMF in phases B and C (Fig. 5a),

$$\dot{E}_{Lb} = \alpha^2\dot{E}_{\alpha1} + \alpha\dot{E}_{\alpha2} + \dot{E}_{\alpha0} = 0,$$
$$\dot{E}_{Lc} = \alpha\dot{E}_{\alpha1} + \alpha^2\dot{E}_{\alpha2} + \dot{E}_{\alpha0} = 0,$$

whence it follows that

$$\dot{E}_{\alpha1} + \dot{E}_{\alpha2} + \dot{E}_{\alpha0}. \quad (10)$$

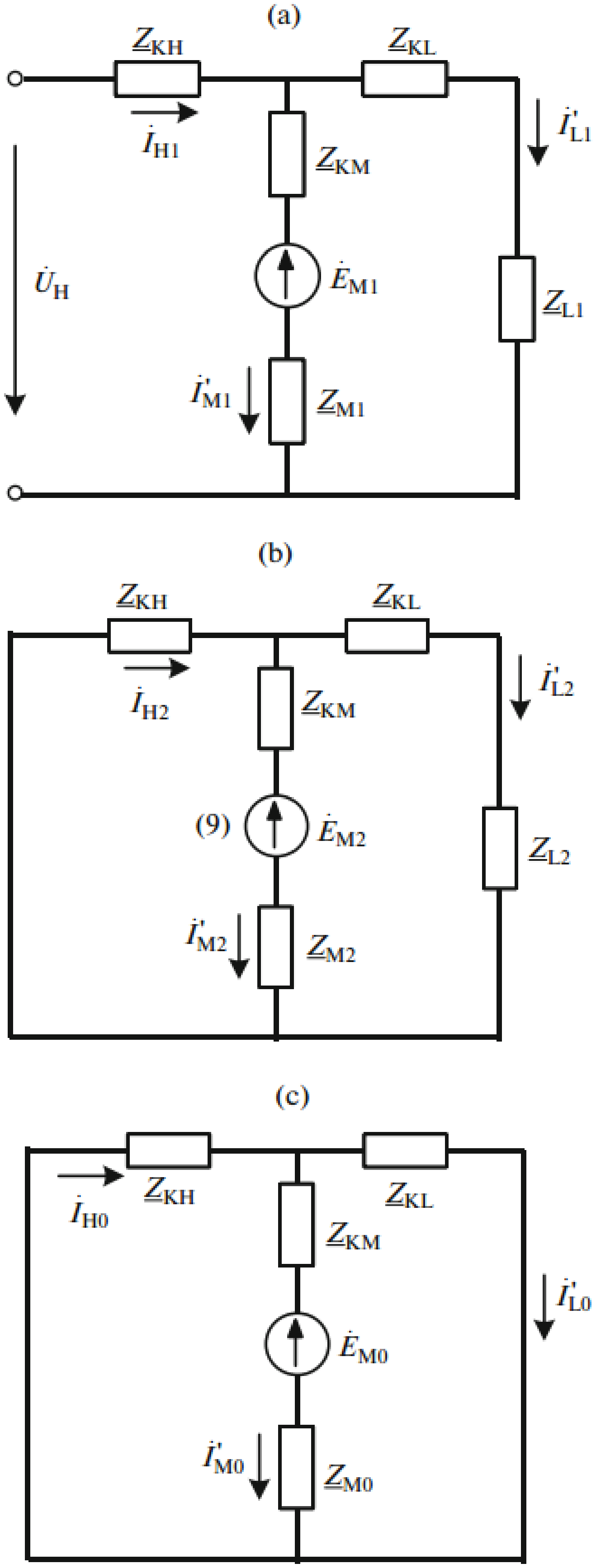


Fig. 4. Design schemes for (a) direct, (b) reverse, and (c) zero sequence currents in the case of wire breakage on the MV side.

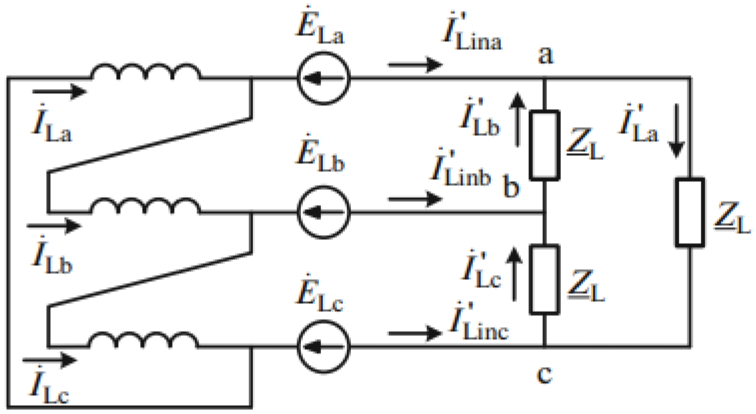
For diagrams in Fig. 6, the following ratios hold:

$$\dot{I}'_{L1} = \frac{\dot{E}_{\alpha E} - \dot{E}_{\alpha 1}(1-\alpha)}{Z_{\alpha E1}}, \dot{I}'_{L2} = \frac{-\dot{E}_{\alpha 2}(1-\alpha^2)}{Z_{\alpha E1}}, (11)$$

where

$$\dot{E}_{\alpha} = \dot{U}_H \frac{Z_{KM} + Z_{M1}}{Z_{KH} + Z_{KM} + Z_{M1}},$$

(a)



(b)

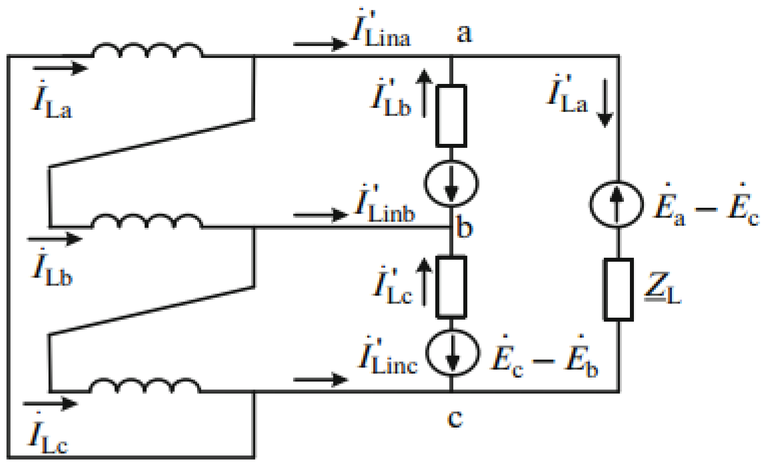


Fig. 5. Simulation of disconnecting the line wire on the LV side.

$$Z_{\alpha E1} = Z_{KL} + Z_{L1} + \frac{Z_{KH}(Z_{KM} + Z_{M1})}{Z_{KH} + Z_{KM} + Z_{M1}},$$
$$Z_{\alpha E2} = Z_{KL} + Z_{L2} + \frac{Z_{KH}(Z_{KM} + Z_{M2})}{Z_{KH} + Z_{KM} + Z_{M2}}.$$

When disconnecting the line wire of phase A on the LV side, the linear current is expressed through the symmetrical components of the phase current:

$$\dot{I}'_{Lin\alpha} = \dot{I}'_{Lin\alpha 1} + \dot{I}'_{Lin\alpha 2} = \sqrt{3} I'_{L1} e^{j30^\circ} + \sqrt{3} I'_{L1} e^{-j30^\circ} = 0.$$

Since

$$(1-\alpha)e^{j30^\circ} = (1-\alpha^2)e^{-j30^\circ} = \sqrt{3},$$

then substituting formulas (11) into the last expression, taking into account (10), we obtain

$$\dot{E}_{\alpha 1} = \dot{E}_{\alpha 2} = \dot{E}_{\alpha 0} = \frac{\dfrac{\dot{E}_{\alpha E} e^{j30°}}{Z_{ME1}}}{\sqrt{3}\left(\dfrac{1}{Z_{\alpha E1}} + \dfrac{1}{\alpha_{E2}}\right)}. \quad (12)$$

Having determined EMF values $\dot{E}_{\alpha 1} = \dot{E}_{\alpha 2}$ by formula (12), currents $\dot{I}'_{L1} and \dot{I}'_{L2}$ can be found using (11).

The remaining unknown currents in the diagrams of Fig. 6 are determined by the formulas

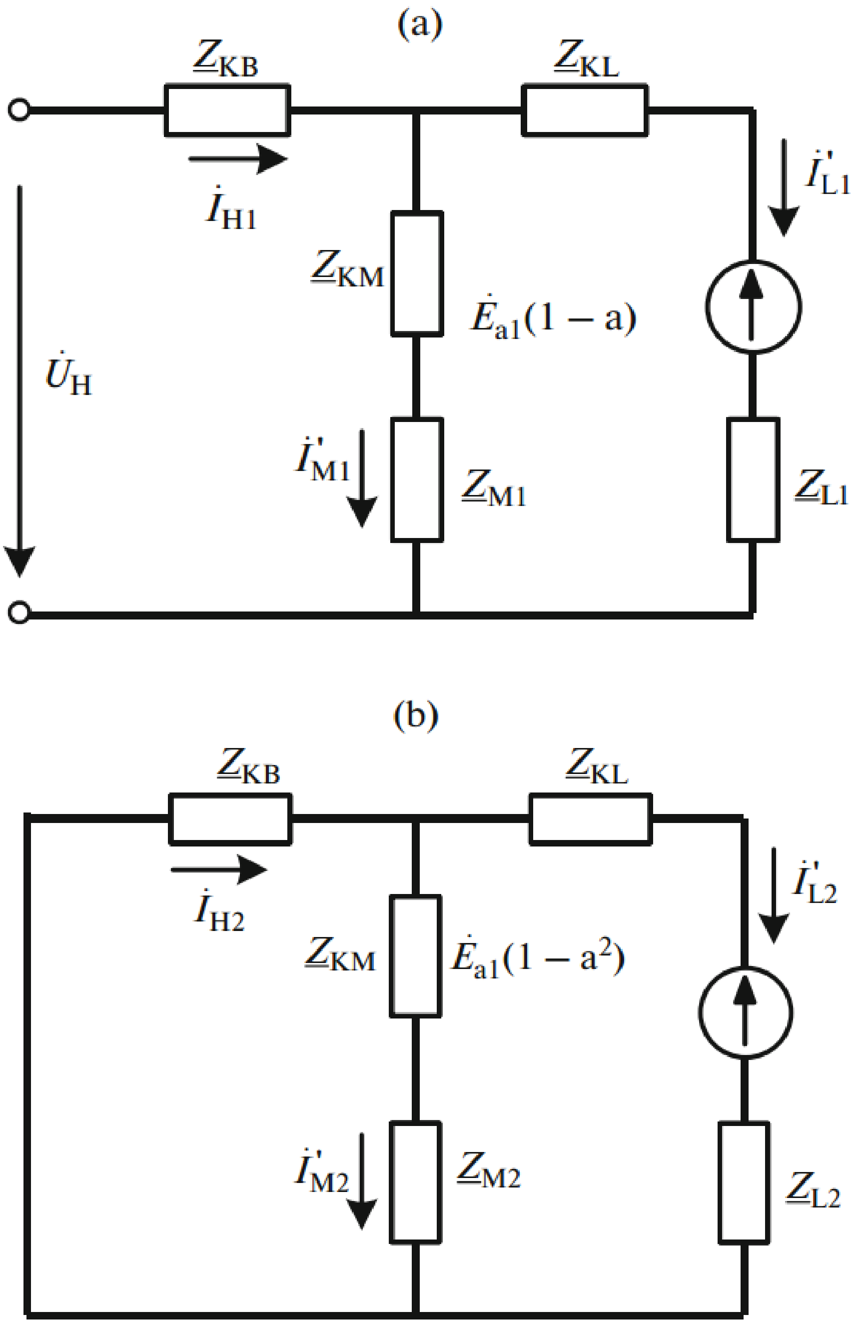


Fig. 6. Design schemes for (a) direct and (b) reverse sequence currents.

$$\dot{I}_{H1} = \frac{\dot{U}_H - \dot{E}_{\alpha 1}(1 - \alpha) - \dot{I}'_{L1}(Z_{KL} + Z_{L1})}{Z_{KH}},$$

$$\dot{\mathrm{I}}_{\mathrm{H2}}=\frac{\dot{\mathrm{E}}_{\alpha 2}(1-\alpha^2)-\dot{\mathrm{I}}'_{\mathrm{L1}}(\mathrm{Z}_{\mathrm{KL}}+\mathrm{Z}_{\mathrm{L2}})}{\mathrm{Z}_{\mathrm{KH}}},$$

$$\dot{\mathrm{I}}_{\mathrm{M1}}=\dot{\mathrm{I}}_{\mathrm{H1}}-\dot{\mathrm{I}}'_{\mathrm{L1}},\dot{\mathrm{I}}'_{\mathrm{M2}}=\dot{\mathrm{I}}_{\mathrm{H2}}-\dot{\mathrm{I}}'_{\mathrm{L2}}.$$

Using the found symmetrical components, it is easy to determine the resulting currents in each of the windings of the autotransformer. The effective values of these currents determined by the above parameters are shown in Table 1. It follows from the calculation results that, in this mode, the currents exceed the rated values in phase C of the series winding, phases A and B of the common winding, and phase C of the LV winding.

DISCONNECTION (BREAK) OF THE LINE WIRE OF PHASE A ON THE HV SIDE

This mode can be analyzed by analogy with the wire disconnection mode on the MV side. Turning on three asymmetrical EMF sources into the line wires on the HV side in accordance with the principle of compensation, we obtain

$$\dot{I}_{H1}=\frac{\dot{U}_H-\dot{E}_{H1}}{Z_{HE2}},$$

$$\dot{I}_{H2}=\frac{-\dot{E}_{H2}}{Z_{HE2}},$$

$$\dot{I}_{H0}=\frac{-\dot{E}_{H0}}{Z_{HE0}},$$

where

$$\dot{E}_{H1}=\dot{E}_{H2}=\dot{E}_{H0}=\frac{\frac{\dot{U}_H}{Z_{HE1}}}{\frac{1}{Z_{HE1}}+\frac{1}{Z_{HE2}}+\frac{1}{Z_{HE0}}},$$

$$Z_{HE1}=Z_{KH}+\frac{(Z_{KM}+Z_{M1})(Z_{KL}+Z_{L1})}{Z_{KM}+Z_{M1}+Z_{KL}+Z_{L1}},$$

$$Z_{HE2}=Z_{KH}+\frac{(Z_{KM}+Z_{M2})(Z_{KL}+Z_{L2})}{Z_{KM}+Z_{M2}+Z_{KL}+Z_{L2}},$$

$$Z_{HE1}=Z_{KH}+\frac{(Z_{KM}+Z_{M0})Z_{KL}}{Z_{KM}+Z_{M0}+Z_{KL}}.$$

Knowing currents $\dot{I}_{H1}$, $\dot{I}_{H2}$ and $\dot{I}_{H0}$, it is easy to
determine the currents in all windings of the autotransformer. The effective values of these currents for the considered mode are given in the Table 1. It follows from the calculation results that, in this mode, the currents exceed the rated values in phases B and C of the series winding, in the common winding of phase B, and in phase C of the LV winding.

The proposed approach and analytical expressions make it possible to determine the currents and voltages of the phase windings of the autotransformer in the most diverse asymmetrical modes of operation using parameters taken from reference data. When using this mathematical model and the results of calculating open-phase modes, one should remember that the method of symmetrical components is based on the principle of superposition, that is, on the assumption that the parameters of the equivalent circuit are constant, which can introduce a certain error into the results of the calculation of some asymmetrical modes of autotransformers.

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