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# DETERMINATION OF LIMITING VALUES OF ASYMETRY PARAMETERS OF ELECTRIC MODE FROM THE CONDITION OF ADMISSIBLE HEATING OF ASYNHRONOUS MOTOR

*The technique, intended for determination of admissible level of voltage asymmetry while control process is elaborated. The influence of inverse voltage argument variation on thermal state of stator windings of asynchronous motors is shown.*

***Key words:****voltage asymmetry, asynchronous motor, inverse voltage, angle shift between voltages of direct and inverse sequences, thermal state.*

## Research problem set-up

As practical experience shows, present state of electric networks is characterized by asymmetry mode, that negatively influences both the operation of technological and electric equipment.

Numerous research are performed to study the characteristics of electric equipment, including asynchronous motors (AM) while their coupling to asymmetric voltage. Characteristic feature of these research is that they are aimed at evaluation of damage, caused by asymmetry of operation mode [1, 2] or are aimed at determination of the possibility of operation, of, for instance, asynchronous motors in these conditions [3 - 5]. For the control of electric modes, as a result of which variations of asymmetry (symmetry of voltage or current, reactive power compensation in conditions of voltage asymmetry), the information, regarding admissible values for parameters, used to evaluate asymmetric mode becomes very important. Such admissible values must be provided in the course of control and be determined, proceeding form the conditions of normal operation, most sensitive to voltage asymmetry of electric equipment, asynchronous motors.

Application of static capacitor banks (SCB) of symmetric construction at asymmetric voltages increases the value of voltage asymmetry indices, and, in certain conditions, these indices obtain nonadmissible values. In this connection, there appears the necessity to take into account the given circumstance in the process of control, limiting the value of voltage asymmetry factor by inverse sequence ($k_{2U\,adm}$), directly in the place of SCB coupling for electric equipment, located near this node. As $k_{2U\,adm}$ we will assume its value, to which, together with other parameters, formed at the moment of decision-making and which determine conditions of AM operation, corresponds admissible heating of electric machine. Note, that, a number of parameters, determining AM heating (phase voltage, coefficient of motor loading, temperature indices of ambient environment) usually change, due to various reason, in time, and as a result, $k_{2U\,adm}$ is also time function.

According to ГОСТ 13109-97 (State Standard) the asymmetry of voltage is normalized in the point of consumer connection to electric grid of energy system (further point 1, Fig. 1) [6]. However, the value of asymmetry factor by inverse sequences in point 1 – $k_{2U(1)}$ and in the points of AM connection electric grid of consumer (further point 2, Fig. 1) – $k_{2U(2)}$ may considerably differ. If the asymmetry is caused by single – phase loads, connected to consumers grids, then $k_{2U(2)} > k_{2U(1)}$, and if from the side of the grids of power supply company, then $k_{2U(2)} < k_{2U(1)}$.

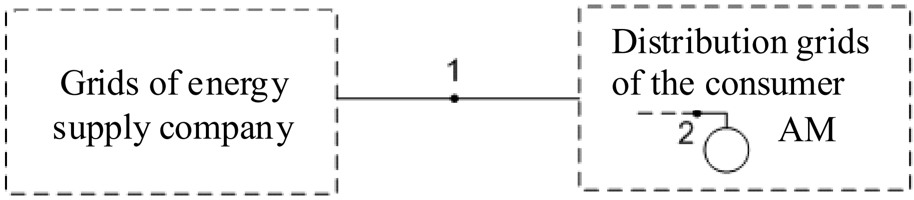


Fig. 1. Generalized diagram of electric grids: 1 – node of connection of consumers grid's; 2 – node of AM connection

It is quite natural, that norms, specified by ГОСТ 13109-97, for online control of electric modes cannot be used. One of the conditions to provide both maximum efficiency of optimizing devices and reliable operation of AM is the possibility of on-line determination of $k_{2U\,adm}$ or admissible (limiting) value of the voltage of inverse sequences $U_{2\,adm}$, corresponded by $k_{2U\,adm}$.

The aim of the given paper is the elaboration of the technique, intended for determination of limiting values of the voltage of inverse sequence in the points of connection of AM to electric grids in order to improve the efficiency of optimizing devices control and reliable operation of AM.

**Elaboration of the technique for on-line determination of $U_{2\,adm}$**

Admissible value of the voltage of inverse sequence in point 2 can be calculated proceeding from the condition of heating of motor windings insulation, applying the method of equivalent heating losses. The given method is based on the principle of superposition (superposition of temperature excess, created by each type of losses) [7]:

$$\Delta t_{m1} = k_{m1} \cdot \Delta P_{m1} + k_{st} \cdot \Delta P_{st} + k_{m2} \cdot \Delta P_{m2} + k_{mec} \cdot \Delta P_{\text{мех}} + k_{adm} \cdot \Delta P_{adm}, \quad (1)$$

where $\Delta t_{m1}$ – is excess of winding temperature over the ambient temperature; $k_{m1}$, $k_{m2}$, $k_{st}$, $k_{mec}$, $k_{ad}$ are coefficient, characterizing the impact of loses in stator windings, rotor windings, losses in steel, mechanical and additional losses on the heating of the stator winding; $\Delta P_{m1}$, $\Delta P_{m2}$ are losses in stator and rotor windings; $\Delta P_{st}$ – are losses in steel; $\Delta P_{mec}$ – are mechanical losses; $\Delta P_{\text{д}}$ – are admissible losses in the motor.

Coefficients $k_{m1}$, $k_{m2}$, $k_{st}$, $k_{mex}$, $k_{ad}$ can be determined either experimentally or as functions from rotation frequency of basic parameters of the core and body of the motor [7].

Losses $\Delta P_{st}$, $\Delta P_{mec}$ – are the constant components of losses. $\Delta P_{\text{д}}$ –are minor values and their variations can be neglected. Voltage $U_2$ in point 2 considerably influences losses in the windings of stator and rotor of AM, since the resistance to the currents of inverse sequence is 5- 8 times less than the resistance to the currents of direct sequence. Minor asymmetry of voltage generates considerable currents of inverse sequence and causes additional heating of windings. We will present asymmetric system of currents by symmetric system, equivalent by thermal effect of winding of the phase, heated most. It enables to apply for investigations, the method of equivalent heating losses. This method is applied in case, when AM is connected to symmetric voltage. We may assume, that for efficient control of electric modes by means of capacitor plants, we must have information not only about the modulus but also about its phase.

Losses in stator and rotor windings of AM depend on currents squares, passing across stator and rotor windings, correspondingly:

$$\Delta P_{m1} = 3 \cdot m_T \cdot I_1^2 \cdot r_1 = 3 \cdot m_T \cdot \left( \left| \dot{I}_1^{(1)} + \dot{I}_1^{(2)} \right| \right)^2 \cdot r_1, \quad (2)$$

$$\Delta P_{m2} = 3 \cdot m_T \cdot I_2^2 \cdot r_2 = 3 \cdot m_T \cdot \left( \left| \dot{I}_2^{(1)} + \dot{I}_2^{(2)} \right| \right)^2 \cdot r_2, \quad (3)$$

where $m_T$ – is the coefficient of operation temperature reduction to calculated temperature, that corresponds to the class of motor windings heat resistance; $I_1$, $I_2$ – are current in stator and rotor windings, correspondingly; $\dot{I}_1^{(1)}$, $\dot{I}_1^{(2)}$, $\dot{I}_2^{(1)}$, $\dot{I}_2^{(2)}$ – are current vectors of direct and inverse sequence of stator and rotor windings, correspondingly, determined by the formula :

$$\dot{I}_1^{(1)} = \frac{\dot{U}_1^{(1)}}{\underline{z}^{(1)}}, \tag{4}$$

$$\dot{I}_1^{(2)} = \frac{\dot{U}_1^{(2)}}{\underline{z}^{(2)}}, \tag{5}$$

$$\dot{I}_2^{(1)} = \frac{\dot{U}_1^{(1)}}{\left(r_1 + \frac{r_2^{(1)}}{s}\right) + j \cdot \left(x_1 + x_2^{(1)}\right)}, \tag{6}$$

$$\dot{I}_2^{(2)} = \frac{\dot{U}_1^{(2)}}{\left(r_1 + \frac{r_2^{(2)}}{2-s}\right) + j \cdot \left(x_1 + x_2^{(2)}\right)}, \tag{7}$$

where $\dot{U}_1^{(1)}$, $\dot{U}_1^{(2)}$ – are vectors of linear voltages of direct and inverse sequences in point 2; $r_1$, $x_1$ – are active and reactive resistances of stator windings, correspondingly; $r_2^{(1)}$, $r_2^{(2)}$, $x_2^{(1)}$, $x_2^{(2)}$ – are active and reactive resistances of rotor windings to currents of direct to currents of direct and inverse sequences, correspondingly; $\underline{z}^{(1)}$, $\underline{z}^{(2)}$ – is the resistance of the motor to currents of direct and inverse sequences, correspondingly; $s$ – is the slip, depending on the coefficient of motor loading.

Values $r_2^{(1)}$ and $x_2^{(1)}$ differ from $r_2^{(2)}$ and as a result of current displacement in the rotor while operation slips $0 < s \le s_н$ [8].

Having substituted formulas (4) – (7) in (2) – (3), and the latter in (1), we obtain the dependence $\Delta t_{m1}\left(\dot{U}_1^{(2)}\right)$:

$$\Delta t_{m1}\left(\dot{U}_1^{(2)}\right) = k_{m1} \cdot \Delta P_{m1}\left(\dot{U}_1^{(2)}\right) + k_{st} \cdot \Delta P_{st} + k_{m2} \cdot \Delta P_{m2}\left(\dot{U}_1^{(2)}\right) + k_{mec} \cdot \Delta P_{mec} + k_a \cdot \Delta P_a . \tag{8}$$

Equating the right part of the dependence (8)to admissible excess temperature over the ambient temperature, we can find both modulus and phase $\dot{U}_{2ad}$.

**Example.** Determine the admissible value of $\dot{U}_1^{(2)}$ in point 2 for AM 160 kW ($\Delta P_{st} = 1573\, W$, $\Delta P_{mec} = 488\, W$, $\Delta P_{ad} = 860\, W$, insulation class F) while coupling its windings to linear voltages. The voltage of direct sequence in point 2 $\dot{U}_1^{(1)} = 381{,}05 \cdot e^{j \cdot 30^o}\ B$, loading coefficient of the motor $\beta = 0{,}9$.

Ambient temperature is $40^0$ C. For insulation of class F excess temperature of the winding over the ambient temperature of the air is $100^0$ C.

Solution. Applying the formulas suggested in [7], we obtained the following value of coefficients $k_{m1} = 0{,}013$, $k_{m2} = 1{,}1 \cdot 10^{-3}$, $k_{st} = 0{,}022$, $k_{mec} = 1{,}1 \cdot 10^{-3}$, $k_{ad} = 1{,}1 \cdot 10^{-3}$. Equation (8) we will be written in the following form:

$$0{,}013 \cdot \Delta P_{m1}\left(\dot{U}_1^{(2)}\right) + 0{,}022 \cdot 1573 + 1{,}1 \cdot 10^{-3} \cdot \Delta P_{m2}\left(\dot{U}_1^{(2)}\right) + 1{,}1 \cdot 10^{-3} \cdot 488 + 1{,}1 \cdot 10^{-3} \cdot 860 = 100 .$$

From the given equation for the cases, when argument $\dot{U}_1^{(2)}$ equals $90^o$, we obtain value of inverse sequence $U_1^{(2)} = 10{,}28\ B$ ($k_{2U} = 2{,}7\%$).

## Study of the dependence of excess temperature on the argument $\dot{U}_1^{(2)}$

We will construct the dependence of excess temperature of AM windings on the argument of the voltage of inverse sequence in polar coordinates.

Fig. 2 shows, that at different values of the argument of inverse sequence voltage, motor windings are not heated equally. The greatest value of excess temperature of AM windings corresponds to the case, when the current in one of the windings will be maximum (arguments of the current of direct and inverse sequences are equal) [2]:

З рис. 2 видно, що за різних значень аргументу напруги зворотної послідовності, обмотки двигуна нагріваються неоднаково. Найбільше значення перевищення температури обмоток АД відповідає такому випадку, коли струм в одній із обмоток буде максимальним (аргументи струмів прямої та зворотної послідовностей однакові) [2]:

$$\arg\left(\dot{I}_1^{(1)}\right) = \arg\left(\dot{I}_1^{(2)}\right). \tag{9}$$

From the expressions (4) – (5), taking into account (9), it follows :

$$\arg\left(\frac{\dot{U}_1^{(1)}}{\underline{z}^{(1)}}\right) = \arg\left(\frac{\dot{U}_1^{(2)}}{\underline{z}^{(2)}}\right), \tag{10}$$

i.e., maximum excess temperature of AM windings we obtain, when the difference of arguments between voltage of direct and inverse sequence equals to difference of motor resistance arguments to currents f direct and inverse sequence:

$$\arg\left(\dot{U}_1^{(1)}\right) - \arg\left(\dot{U}_1^{(2)}\right) = \arg\left(\underline{z}^{(1)}\right) - \arg\left(\underline{z}^{(2)}\right). \tag{11}$$

It should be noted, that the value of the right part of the expression (11) changes depending on the level of motor loading that is, on slip

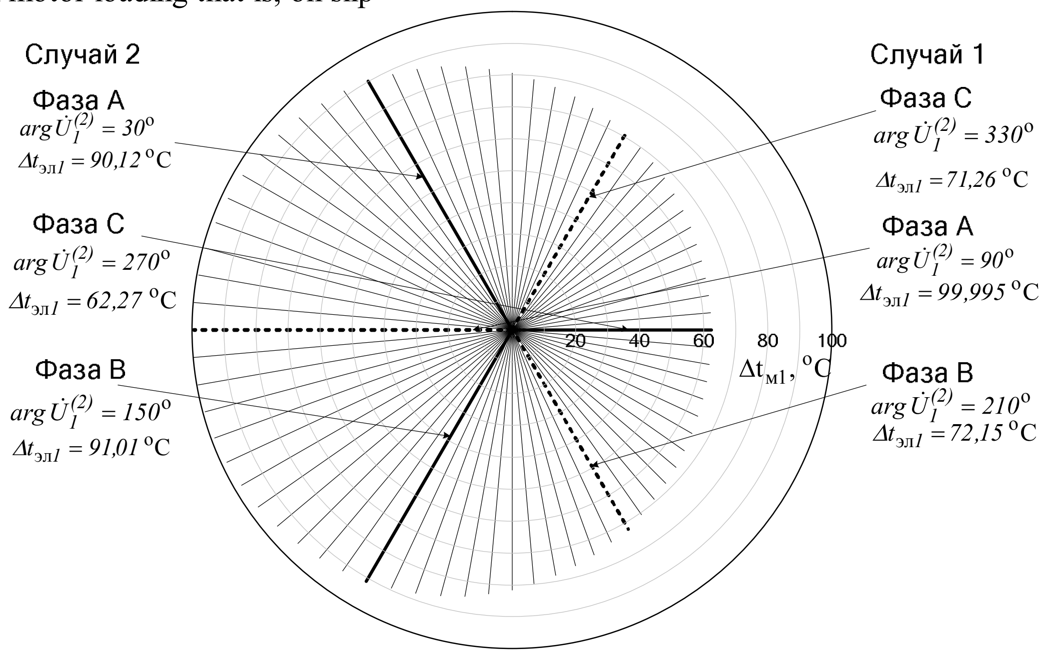


Fig. 2. Dependence of temperature excess of AM windings on the argument of inverse sequence voltage

For the given example, we obtain maximum value of $\Delta t_{m1}$ in one of the phases, when argument $\dot{U}_1^{(2)}$ is $60^o$ greater that argument $\dot{U}_1^{(1)}$. Of all possible cases, shown in Fig. 2, for this example we will underline the following :

а) case 1: $arg\dot{U}_1^{(2)} = 90^o$ temperature excess of phase A winding – 99,995$^o$ C, phase B – 72,15$^o$ C, phase C – 71,26$^o$ C over the temperature of ambient.

б) case 2: $arg\dot{U}_1^{(2)} = 30^o$ temperature excess of phase A winding is – 90,12$^o$ C, phase B – 91,01$^o$

C, phase C – 62,27$^o$ C over the temperature of ambient air.

The example of cases 2 shows that for phase B (since it is the most heated) at $U_1^{(2)} = 10{,}28\ B$ we have additional heating margin. Having performed calculations for $arg\dot{U}_1^{(2)} = 30^o$, we obtain admissible value of inverse sequence voltage, that is $U_1^{(2)} = 17{,}06\ B$ ($k_{2U} = 4{,}48\%$).

Having analyzed the results obtained in the example it should be noted, that the arrangement of inverse sequence voltage considerably influences the value of $\dot{U}_1^{(2)}$, which is determined form the conditions of admissible temperature heating of AM windings insulation.

For the given numerical example $\dot{U}_1^{(2)}$ at different arguments changes within the limits from 10,28 V ($k_{2U} = 2{,}7\%$) to 17,06 V ($k_{2U} = 4{,}48\%$).

## Conclusions

1. One of the conditions to provide both maximum efficiency of optimizing devices and reliable operation of AM is the possibility of on-line determination of $k_{2U\ ad}$ at its preset loading and the temperature of ambient air.
2. Maximum value of inverse sequence voltage can be determined from the conditions of admissible temperature heating of AM windings insulation applying the method of equivalent heating losses.
3. Maximum temperature excess of AM windings we will obtain, when the difference of arguments between the voltage of direct and inverse sequence equals the difference of arguments of motor resistances to the currents of direct and inverse sequences.

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