Analysis of the effect of exceeding the allowable values of selected parameters of the receivers on operating conditions of a low voltage network

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Minimum value of the power factor of an electric power network is constrained and its value is determined by the regulations. Customer of electric power is responsible for maintenance of proper value of the power factor. On the other hand, minor electric power customers are not charged with any financial consequences for disregarding proper value of the parameter, in spite of the fact that the distribution companies are charged with the cost of increased power losses. Moreover, the degree of voltage asymmetry of electric power network is constrained and its value is defined by the regulations too. Asymmetry of output voltage of power transformer is caused chiefly by asymmetric loads. The paper presents a proposal of estimating additional power losses caused by reduced value of the power factor and analyzes the effect of various types of load asymmetry on the value of the asymmetry factor. The proposals and analyzes are carried out with the help of Mathcad software.

KEYWORDS: low voltage network, electric power system, degree voltage asymmetry, transformer load asymmetry, synchronous generator

1. Introduction

Based on the Law of April 10, 1997, the Energetic Law (the uniform contents with ensuing changes) with executory acts and, particularly, in accordance with the Decree of the Minister of Economy of May 4, 2007 related to detailed conditions of operation of electric power system (the Law Gazette of 2007, No 93, pos. 623, with ensuing changes), among the quality parameters of electric energy is reckoned a statement requiring that 95 percent of the segments drawn within a week from a set of 10-minutes duration rms. values of symmetric negative-sequence supply voltage should be contained in the range from 0 to 2 percent of positive-sequence supply voltage. The requirement not only is commonly ignored but usually disregarded, since it is related only to the circuits supplied with three-phase voltage, i.e. to the networks supplying the three-phase receivers, particularly the motors. It should be noticed that the standards related to synchronous machines require the ratio of negative to positive-sequence voltage not to exceed 1 percent. It means that the standard requirement is more severe than that of the ministerial decree. In operational practice of electric power networks the synchronous machines are rather rarely directly connected to low-voltage network of relatively high degree of voltage asymmetry. The degree of voltage asymmetry of high-voltage network, where the synchronous machines are usually connected, is in general lower than in low-voltage networks. High degree of voltage asymmetry in a high-voltage network occurs, if high power single - or two-phase receivers are connected thereto. Such situation arises usually in case of supplying the inductive furnaces (ore exceptionally the arc ones). High asymmetric load arises in railway traction supplied from AC 25 kV, when the traction network is supplied directly from the electric power network. In these cases the degree of voltage asymmetry is relatively high even in the 110 kV network serving for supplying the traction network. Voltage asymmetry is transmitted from the network through the transformers to another networks, particularly to the ones of lower voltage. As for now, construction of AC 25 kV railway traction network is not planned in the nearest future.

In MV/LV transformers even in case of symmetric primary voltage (i.e. medium voltage) any asymmetric load is conducive to asymmetry of secondary voltage, with asymmetry coefficient usually exceeding the level admitted by the regulations. The three-phase motors are particularly sensitive to voltage asymmetry, since at higher voltage asymmetry they cannot be loaded with rated power due to possible overheating. Rotational speed of these motors is also below the rated speed and, in consequence, efficiency of the devices driven by these motors is worsened.

In order to fulfill the quality parameters of the electric energy the customer is required to restrain the absorbed power below the contractual level and, in no circumstance, with the $\tan\varphi$ coefficient exceeding 0.4. In engineering practice the term “$\tan\varphi$ coefficient” is rather avoided and replaced with $\cos\varphi$. For $\tan\varphi = 0.4$ the angle $\varphi = 38°$, and the value of the power factor $\cos\varphi = 0.929$. It is a relatively high value, exceeding the level 0.8 used before.

The value of the power factor is related to other parameters determining the quality of electric energy, namely the absorbed voltage and power. A common opinion states at present that protection of the environment consists, to large degree, in reduction of electric power consumption, since extensive power production leads to additional environment pollution. Lower consumption of the energy may be attained not only by reduced absorption of the power or energy but, to large degree, by reduction of the losses related to energy production and transmission. The power losses in an electro-power system are estimated about to 10 percent of the produced power. In case of a high power system the losses are large and, therefore, any action aimed at reducing the losses should be necessary. Such an action includes, among others, restraining production and transmission of reactive power, reflected by the value of the power factor. It should be noticed that the inductive and capacitive reactive power should be discerned. In the electric low voltage networks the inductive reactive power is in practice always transmitted and absorbed. The reactive power is delivered from a medium-voltage distribution network. The network, in turn, is supplied from a 220 kV or 400 kV transmission network, directly connected to the power stations. The power station generators are fitted for generation of inductive reactive power. Their rated power factor must be in the range from 0.8 to 1 in overexcitation mode. At present in the Polish electro-power system only the generators of the Żarnowiec power station, cooperating with a 400kV transmission line, usually operate in underexcitation mode, which means that they do not generate the inductive reactive power.

The Law of April 15, 2011, on "power effectiveness" defines the home goal in economic power management. The Law recommends, among others, auditing power effectiveness of various units, with a view to undertaking the actions aimed at energy saving. The savings should be obtained, among others, by purchase of a new device, or exchange or modernization of the device not fulfilling the requirements related to energy saving. In order to improve the energetic effectiveness, among others, the following undertakings are mentioned in the Law: constraining reactive power fiux, constraining the network losses in the transmission lines and power losses in transformers. The use of new types of transformer plates designed for use in the energetic transformers caused not only reduction of power losses in the transformer cores but significantly constrained intensity of magnetizing current (the no-load current) or absorption of reactive power in no-load state of the transformer. Unfortunately, the power losses in the windings, i.e. the so-called load losses, cannot be practically constrained. The energetic transformers, particularly the ones with adjusted coil number in voltage-less state, are the units distinguished by the highest durability and reliability. Therefore, they are only rarely exchanged for new devices of improved operational parameters. High durability of actually used transformers, significantly exceeding 30 years assumed at the designing stage, does not encourage to exchanging them for new ones, with better parameters ensuring electric energy savings. Desistance from exchanging the transformers is usually justified by the lack of financial means and low market supply. Even the new standard „Normalized IEC voltages" introduced in 1999, that changed rated voltage values of the networks and AC devices from 220/380 V to 230/400 V, did not intensify replacement of the transformers for the new ones. The change of rated voltage of the AC network induced the change of rated voltage values of power transformers from 230/400 V to 242/420 V. Admissible deviation equal to ±10% defined by the standard, appeared to be insufficient reason for replacing the transformers of former values of rated voltages and former parameters with new ones. Transformer manufacturers often still offer at present a large number of the units that do not comply with the standard requirements. It should be noticed that AC motors and generators designed for use in the generating sets are also manufactured incompatibly with the standard defining the rated voltage values. Finally, irrespective of the lack of financial means, the requirements of the "Law of energetic effectiveness" related to replacing the devices with the units of lower energy consumption, are uneasy to be fulfilled.

2. Analysis of the effect of reactive power on operation of an electric power system

Current intensity I flowing in an electric power network in case of absorption of effective power P depends on the power factor cosφ, according to the formula (1):

$$I = \frac{P}{\sqrt{3} U \cos\theta} \tag{1}$$

where U is the phase-to-phase voltage. The effect of power factor on current intensity for the power P is shown in Fig. 1. Product of the current and voltage is equal to apparent power S. The apparent power S = P + jQ, where Q is the reactive power.

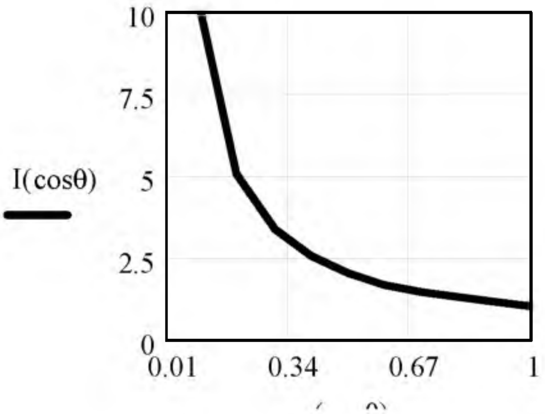

Fig. 1. Relationship between current intensity and power factor

The values shown in Fig. 1 are presented in relative units, referred to current intensity for cosφ = 1. The figure gives evidence that for constant value of reactive power the current intensity grows together with decreasing factor, i.e. with growing transmission of the reactive power. When cosφ = 1, the reactive power is equal to 0 and the current intensity takes its minimum value. The above leads to a conclusion that any power conversion should undergo at maximum value of the power factor. Taking into account that for proper operation of electromagnetic equipment, as electric machines and transformers, the inductive reactive power is necessary, on spot generating of such a power should be always considered, in order to relieve the generators from it and relieve the network from its transmission. As such an option is not always feasible and economically justified, reactive power management should be so arranged as to minimize the loss of power or energy. At the same time one should pay attention to the fact that while generating the inductive reactive power the generator operates at overexcitation mode. It means high excitation current, inducing high maximum torque and increased over-current factor. Hence, in order to improve stability of the electric power system, the generators should produce the inductive reactive power. In the case occurring in the Żarnowiec power plant, where the generators operate at underexcitation mode, i.e. with low excitation current, the generators may work unstably.

For example, a 37.5 MVA, 6.3 kV generator operating in rated conditions, i.e. with inductive power factor equal to 0.8, rated excitation current 310A, and power (load) angle 37.4°, delivering 22.5 MVAr inductive reactive power to the network, has the over-current factor equal to 1.64. On the other hand, while operating with slight underexcitation, with excitation current equal to 0.7 of the rated current (217 A), power angle 87.7°, and power factor 0.9, thus delivering 16.35 MVAr capacitive reactive power to the network, the generator has the over-current factor equal only to 1.0008. Characteristics of the generator torque vs. the load angle β is shown in Fig. 2. In both load cases of the generator, the power loss in the armature winding are equal, since armature current is in these cases equal to its rated value. In underxcitation mode the power loss in the excitation winding is lower, since the excitation current is lower too. In Figure 2 are shown the load angles β = 37.4° (0.653) for rated operation condition and β = 87.7° (1.529) for underexcitation mode. It may be noticed that in underxcitation mode the operation point approximates the maximum torque, i.e. the over-current factor of the generator is minimal.

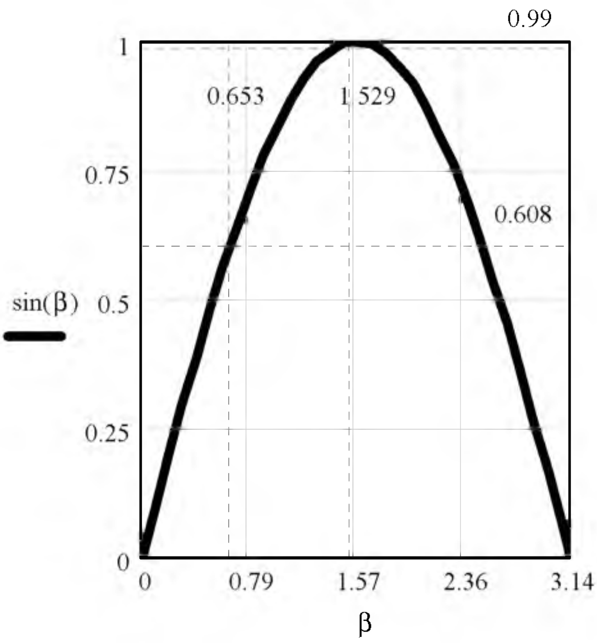

Fig. 2. Characteristics of the torque of a synchronous machine

3. Basic equations for analysis of the effect of transformer load asymmetry on the degree of voltage asymmetry

The analysis was carried out with the help of the method of symmetrical components, using the Mathcad calculation software. The coefficients of voltage asymmetry at transformer output, i.e. the ratios of negative to positive-sequence voltage or zero to positive-sequence voltage, were determined based on previously calculated output voltage of the transformers for assumed impedance of the load (the receivers). For the assumed load impedance values of particular phases in the form (2):

$$Z_{odb}u, v, w = k_{1,2,3} Z_{odn} \exp j0.107 \cdot \frac{2\pi}{3} \tag{2}$$

where u, v, w, denote particular phases.

Impedance values of particular phases serve as a basis for calculating impedance values of symmetric components given by the equations (3) in the following order:

positive-sequence $$Z_1(k_1, k_2, k_3) = \frac{(Z_u(k_1) + aZ_v(k_2) + a^2 Z_w(k_3))}{3} \tag{3a}$$

negative-sequence $$Z_2(k_1, k_2, k_3) = \frac{(Z_u(k_1) + a^2 Z_v(k_2) + aZ_w(k_3))}{3} \tag{3b}$$

zero-sequence $$Z_0(k_1, k_2, k_3) = \frac{(Z_u(k_1) + Z_v(k_2) + Z_w(k_3))}{3} \tag{3c}$$

In the matrix form the impedances take a form (4):

$$\begin{pmatrix} Z_1 \\ Z_2 \\ Z_0 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{pmatrix} \cdot \frac{1}{3} \begin{pmatrix} Z_u \\ Z_v \\ Z_w \end{pmatrix} \tag{4}$$

Decomposition of the supply voltages and currents, and receiver impedance into symmetric components and transformation of the equations of the type $U=I \cdot Z$ to inverse form of the type $I = Y \cdot U$, allow to formulate the equations of current symmetric components in the form (5):

$$\begin{pmatrix} I_1 \\ I_2 \\ I_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{10} \\ M_{21} & M_{22} & M_{20} \\ M_{01} & M_{02} & M_{00} \end{pmatrix} \cdot \frac{1}{D} \begin{pmatrix} U_1 \\ U_2 \\ U_0 \end{pmatrix} \tag{5}$$

where:

$$D_1(k_1,k_2,k_3)=(Z_0(k_1,k_2,k_3)+Z_z)(Z_0(k_1,k_2,k_3)+Z_z)(Z_0(k_1,k_2,k_3)+Z_{\mu0})$$
$$D_2(k_1,k_2,k_3)=-Z_1(k_1,k_2,k_3)Z_2(k_1,k_2,k_3)[3Z_0(k_1,k_2,k_3)+(Z_z+Z_z+Z_{\mu0})]$$
$$D_3(k_1,k_2,k_3)=Z_1(k_1,k_2,k_3)^3+Z_2(k_1,k_2,k_3)^3$$
$$D(k_1,k_2,k_3)=D_1(k_1,k_2,k_3)+D_2(k_1,k_2,k_3)+D_3(k_1,k_2,k_3)$$
$$M_{11}(k_1,k_2,k_3)=(Z_z+Z_0(k_1,k_2,k_3))(Z_0(k_1,k_2,k_3)+Z_{\mu0})-Z_1(k_1,k_2,k_3)Z_2(k_1,k_2,k_3)$$
$$M_{12}(k_1,k_2,k_3)=Z_1(k_1,k_2,k_3)^2-Z_2(k_1,k_2,k_3)(Z_{\mu0}+Z_0(k_1,k_2,k_3))$$
$$M_{10}(k_1,k_2,k_3)=Z_2(k_1,k_2,k_3)^2-Z_1(k_1,k_2,k_3)(Z_0(k_1,k_2,k_3)+Z_z)$$
$$M_{20}(k_1,k_2,k_3)=Z_1(k_1,k_2,k_3)^2-Z_2(k_1,k_2,k_3)(Z_0(k_1,k_2,k_3)+Z_z)$$
$$M_{21}(k_1,k_2,k_3)=(Z_2(k_1,k_2,k_3))^2-(Z_1(k_1,k_2,k_3))(Z_0(k_1,k_2,k_3)+Z_{\mu0})$$
$$M_{01}(k_1,k_2,k_3)=Z_1(k_1,k_2,k_3)^2-Z_2(k_1,k_2,k_3)(Z_0(k_1,k_2,k_3)+Z_z)$$
$$M_{02}(k_1,k_2,k_3)=Z_2(k_1,k_2,k_3)^2-Z_1(k_1,k_2,k_3)(Z_0(k_1,k_2,k_3)+Z_z)$$
$$M_{00}(k_1,k_2,k_3)=(Z_z+Z_0(k_1,k_2,k_3))^2-Z_1(k_1,k_2,k_3)Z_2(k_1,k_2,k_3)$$
$$M_{22}(k_1,k_2,k_3)=(Z_0(k_1,k_2,k_3)+Z_z)(Z_0(k_1,k_2,k_3)+Z_{\mu0})+$$
$$-Z_1(k_1,k_2,k_3)Z_2(k_1,k_2,k_3)$$

Assuming that in the supply voltage only the positive-sequence component is taken into account, the symmetric components of the currents at secondary side of thetransformer are given by the equations (6):

– positive-sequence current component

$$I_1(k_1,k_2,k_3)=M_{11}(k_1,k_2,k_3)U_{ntf}\frac{1}{D(k_1,k_2,k_3)} \tag{6a}$$

– negative -sequence current component

$$I_2(k_1,k_2,k_3)=M_{21}(k_1,k_2,k_3)U_{ntf}\frac{1}{D(k_1,k_2,k_3)} \tag{6b}$$

– zero-sequence current component

$$I_0(k_1,k_2,k_3)=M_{01}(k_1,k_2,k_3)U_{ntf}\frac{1}{D(k_1,k_2,k_3)} \tag{6c}$$

Phase currents are calculated according to the formula (7)

$$\begin{pmatrix} I_a(k_1,k_2,k_3) \\ I_b(k_1,k_2,k_3) \\ I_c(k_1,k_2,k_3 \end{pmatrix}=\begin{pmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{pmatrix}\begin{pmatrix} I_1(k_1,k_2,k_3) \\ I_2(k_1,k_2,k_3) \\ I_0(k_1,k_2,k_3) \end{pmatrix} \tag{7}$$

The current flowing in neutral wire is given by the formula

$$I_{po}(k_1,k_2,k_3) = I_a(k_1,k_2,k_3) + I_b(k_1,k_2,k_3) + I_c(k_1,k_2,k_3) \qquad (8)$$

Phase voltage values are given by the relationships (9):

$$\begin{aligned} U_a(k_1,k_2,k_3) &= I_a(k_1,k_2,k_3)Z_{zu}(k_1) \\ U_b(k_1,k_2,k_3) &= I_b(k_1,k_2,k_3)Z_{zv}(k_2) \\ U_c(k_1,k_2,k_3) &= I_c(k_1,k_2,k_3)Z_{zw}(k_3) \end{aligned} \qquad (9)$$

On the other hand, the symmetric components of the voltages at secondary side of the transformer may be calculated from the formulas (10)

$$U_1(k_1,k_2,k_3) = \frac{(U_a(k_1,k_2,k_3) + aU_b(k_1,k_2,k_3) + a^2U_c(k_1,k_2,k_3))}{3} \qquad (10a)$$

$$U_2(k_1,k_2,k_3) = \frac{(U_a(k_1,k_2,k_3) + a^2U_b(k_1,k_2,k_3) + aU_c(k_1,k_2,k_3))}{3} \qquad (10b)$$

$$U_0(k_1,k_2,k_3) = \frac{(U_a(k_1,k_2,k_3) + U_b(k_1,k_2,k_3) + U_c(k_1,k_2,k_3))}{3} \qquad (10c)$$

The coefficients of voltage asymmetry at secondary side of the transformer are given by the relationships (11):

$$K_u(k_1,k_2,k_3) = \frac{|U_2(k_1,k_2,k_3)|}{|U_1(k_1,k_2,k_3)|} \qquad (11a)$$

$$K_{u0}(k_1,k_2,k_3) = \frac{|U_0(k_1,k_2,k_3)|}{|U_1(k_1,k_2,k_3)|} \qquad (11b)$$

4. Example calculation

Based on the parameters of a transformer of the power 800kVA, voltage values 15000V/420–242.5V, and short-circuit voltage 5.6% the characteristic input values were calculated that are meaningful from the point of view of the present paper. Figures in graphical form present some of the calculation results. The calculation was carried out on the example of an asymmetric receiver of the parameters defined by the equations (12):

$$\begin{aligned} Z_{zu}(k_1) &= (k_1 Z_{odn} e^{j\cdot 0.107\cdot 2\frac{\pi}{3}}) \\ Z_{zv}(k_2) &= (Z_{odn} \cdot 1.2e^{j\cdot 0.307\cdot 2\frac{\pi}{3}}) \\ Z_{zw}(k_3) &= (k_3 \cdot 0.8 Z_{odn} e^{j\cdot 0.207\cdot 2\frac{\pi}{3}}) \end{aligned} \qquad (12)$$

In this case of asymmetric load and various values of k_1, k_2, k_3 the voltage asymmetry factors are equal to:

$$K_u(1,1,1)1 = 0{,}022$$

$$K_u(0.9,1,1)1 = 0{,}025$$

$$K_u(1,0.85,0.9)1 = 0{,}025$$

It may be easily noticed that the asymmetry factors exceed in this case the allowable value. The pattern of the asymmetry factors vs. the k_1, k_2, k_3 values is illustrated in Figures 3 – 7.

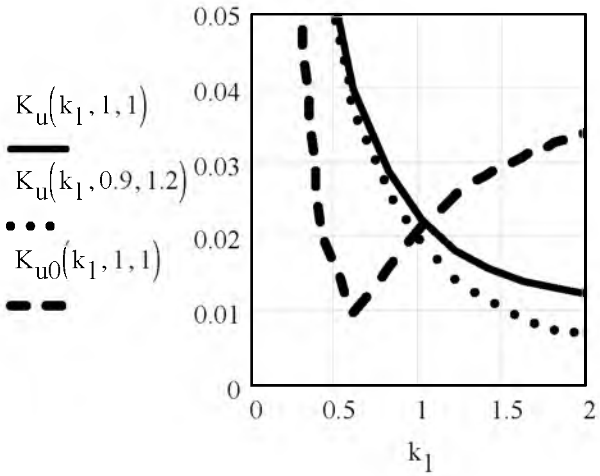

Fig. 3. Relationship between the asymmetry factors and k_1 index

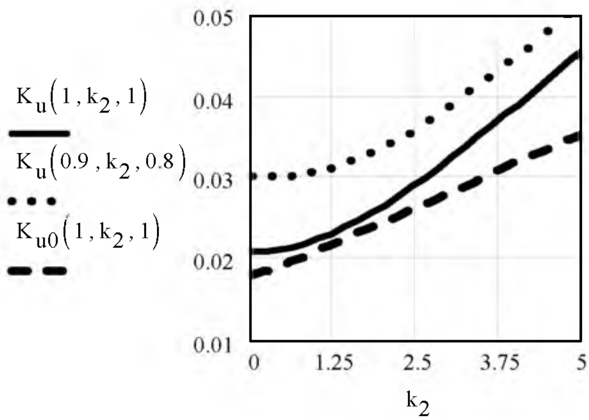

Fig. 4. Relationship between the asymmetry factors and k_2 index

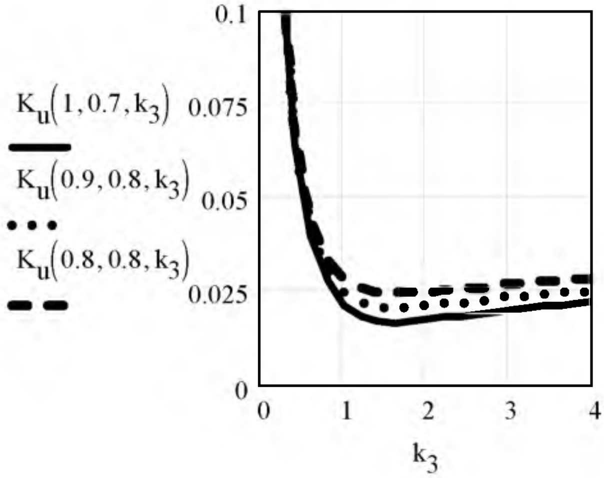

Fig. 5. Relationship between the asymmetry factors and k_3 index

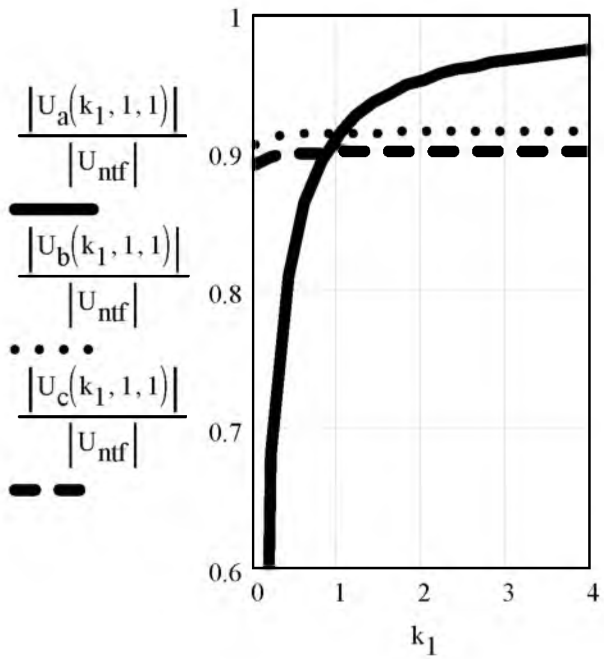

Fig. 6. Relationship between the phase voltage values and k_1 index

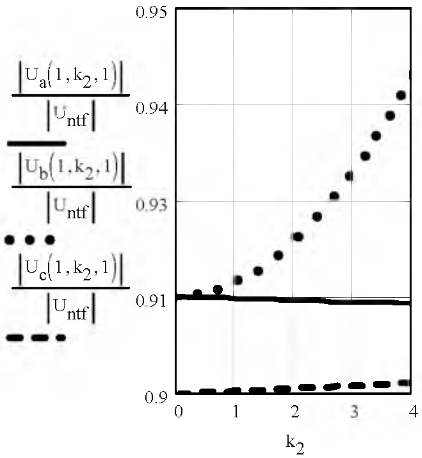

Fig. 7. Relationship between the phase voltage values and k_2 index

The output (secondary) voltage of the transformer is lower than the input (primary) one by the voltage drop, i.e. $U_2 = U_1 - \Delta U$. Te rated output voltage of the transformer is equal to the voltage of the secondary side of an unloaded transformer In case of a MV/LV transformer it is 15575/420 – 242.5 V, where 242.5 V is the rated phase voltage. It should be noticed that such rated voltages of the transformer are related to the rated voltage of the low voltage network 400/231 V. In case of the transformer loaded with rated current for cosφ = 0.8 the output voltage U_2 = 230.9 V, while for cosφ = 0.929 (i.e. tanφ = 0.4) the output voltage grows to 233.3 V. Figure 8 shows the effect of the current intensity on the output transformer voltage for constant value of the load power factor. On the other hand, Figure 9 presents the effect the power factor on the value of output voltage.

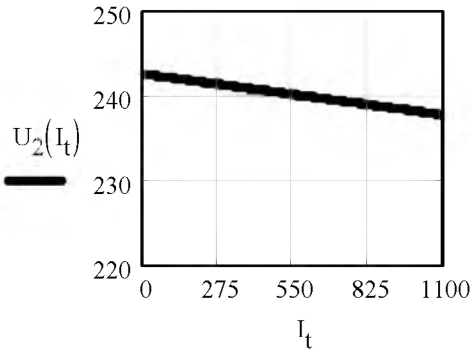

Fig. 8. Dependence between the output transformer voltage and current intensity, for constant power factor

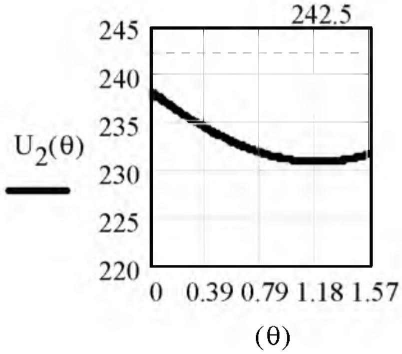

Fig. 9. Dependence between the output transformer voltage and power factor, for rated load current

As it was mentioned above, in case of voltage asymmetry, when the voltage asymmetry factor is below unity, characteristics of the torque of an asynchronous machine varies, which is shown in Fig. 10.

The maximum and initial starting torque decrease, similarly as the torque corresponding to the rated rotational speed.

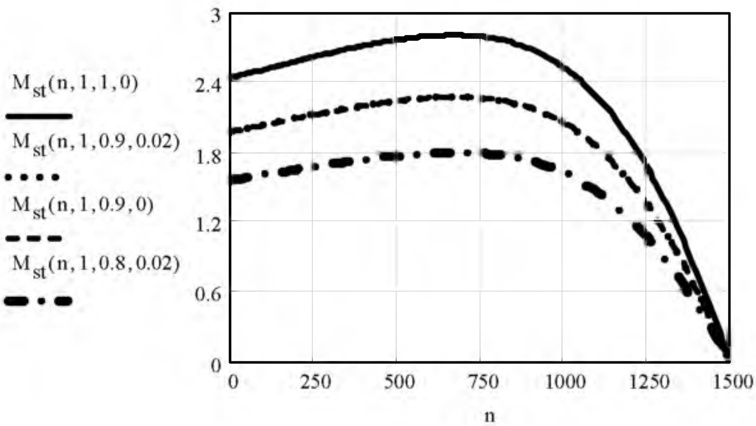

Fig. 10. Characteristics of the torque of an asynchronous motor for various values of the voltage asymmetry factors

5. Summary and conclusions

In the electric network supplying three-phase receivers, particularly the inductive motors, the voltage values, especially the phase-to-phase ones, should be checked with a view to avoid exceeding the voltage asymmetry degree admitted by the regulations. In case of large voltage asymmetry not only the current intensities in particular phases are asymmetric but, first of all, the value of positive-sequence voltage component is reduced, due to high level of the negative-sequence component. This results in reduction of available effective power of the motor. Moreover, taking into account the electric energy transmission, also in low voltage networks the principle of transmission of reactive power of possibly the lowest value should be observed. Transmission of reactive power not only results in higher power loss but also increases the voltage drops. High value of the transmitted reactive power forces the use of the equipment of higher parameters than those required from the point of view of necessary effective power.

References

[1] Stein Z. Eksploatacja maszyn elektrycznych. Rozdz. 5.6 w Poradniku Inżyniera Elektryka, WNT, Warszawa 2007.
[2] Stein Z. Zielińska M. Wykorzystanie programu MCAD do badania wykorzystania mocy znamionowej silników indukcyjnych w warunkach niesymetrii 3-fazowego układu napięć. Materiały ZKwE, Poznań. 2008
[3] Stein Z. Zielińska M. Zagadnienia kompensacji mocy biernej w zakładach przemysłowych. Materiały ZKwE, Poznań, 2008.