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PROBLEMS OF ELECTROMAGNETIC COMPATIBILITY IN PROCESS OF COMPENSATION REACTIVE POWER ABSORBED BY THREE-PHASE INDUCTION MOTORS

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Abstract: *The changes in the standards and regulations pertaining to such parameters affecting electromagnetic compatibility, like voltage harmonic content and the value of tangent j require the need to adapt the power of the condensers necessary for attaining a required value of the power coefficient in the point of power input from the network. Moreover, the operating conditions of the condensers should be analyzed, with consideration of admissible levels of particular harmonics of the power network voltage. The paper presents the values of reactive power that should be ensured in order to satisfy the regulations in force. Variations in the reactive power absorbed by the motors are provided for different values of the THD(U) coefficient and different values of particular harmonic components.*

Key words: electrical machines, induction motors, electromagnetic compatibility, frequency analysis.

1 INTRODUCTION

Technical and economical reasons related to transmission and use of electric power impose introduction of the standards and regulations determining the parameters affecting the quality of electric power delivered to the power network customers. To-day the quality standards of electric power delivered by the power network are defined by the „Regulation of the Minister of Economy and Labour of December 20, 2004, on detailed conditions of connecting the entities to the power network, energy trade, rending the transmission services, network exploitation, and quality standards of clients service". The regulation stipulates the quality standards including, among others, voltage distortion (THD) and its content of particular harmonics, the degree of asymmetry of three-phase voltage system, and the requirement imposed on the recipient of not to exceed the consumption of the contractual power, with tanφ not exceeding 0.4. Such parameters provided by the regulation, as harmonic content of the voltage, the degree of asymmetry of the three-phase voltage system, or voltage or frequency deviations determine electromagnetic compatibility (EMC). Value of the tanφ coefficient provided by the regulation corresponds to the power factor cosφ = 0.928. This is a high level, considerably exceeding the one being formerly in force, i.e. 0.8. Such a solution imposes the need of larger compensation of the reactive power, than for formerly assumed level of the factor, particularly in the systems supplying the induction motors. Taking into account that in low voltage networks, both for communal and industrial needs, compensation of the reactive power is effected with condensers, the harmonics content of the voltage becomes meaningful. The condensers are distinguished, among others, with poor resistance to voltage harmonics, as a result of reduced reactance of the condensers for higher order harmonics. The decreasing reactance leads to the fact that for equal voltages of particular harmonics the currents forced by the harmonics and reaching the condensers are higher for higher harmonic orders. As generally the voltage harmonics content of the power networks can not be effectively reduced, the condensers are designed with such redundancy of thermal strength as to ensure the load current exceeding its rated level up to 30%. The rated current is assumed for the first harmonic component, i.e. 50Hz. In case the harmonic content in a power network point is so high that current intensity reaching the condenser exceeds the admissible level, the condenser must be provided with an additional choke or, alternatively, the circuit should include special filters, possibly of active operation. In particular cases, when reduction of the high harmonics content is not possible, the reactive power should be compensated not by the condensers but by synchronous machines. An important advantage of the synchronous machines consists in easy and stepless control of the reactive power to be compensated and, at the same time, low sensitivity to voltage harmonics content. An additional advantage of the synchronous machines used for purposes of reactive power compensation is the fact that the compensated reactive power in practice does not depend on voltage oscillations. A fault of the condensers is their considerable sensitivity to voltage oscillations resulting from the fact that the reactive power of a battery depends on square of the voltage, according to the formula $Q = 3 \cdot U^2 \cdot \omega \cdot C$. The formula shows that for the voltage smaller by 10% the reactive power of the battery decreases as much as 19%. At the same time, reactive power of a motor drops only by 10% which means that the power factor of the supply circuit, for unchanged battery power, decreases. This is why the condensers subject to remarkable voltage oscillations induce growing amplitude of these oscillations, if capacitance of the condensers connected to the network is not adapted sufficiently quickly. While exploiting the condenser battery used for purposes of reactive power compensation the degree of asymmetry of the three-phase voltage system should be taken into account, as the currents of odd harmonics divisible by three flow even through star or delta connected condensers. This does not occur for symmetric voltage system. It should be noticed that the currents of the third harmonic and its multiples always occur for a condenser connected in a single-phase system. In order to calculate the currents of particular harmonics reaching the condensers the values of voltage harmonics should be known. The voltage harmonics should be determined by measurements. Without such a knowledge the values provided by proper standards or tables of admissible levels of particular harmonic components may be assumed. The currents calculated this way are often considerably underestimated, as real voltage harmonic levels usually exceed the admissible values. This occurs especially for the motors supplied by inverter systems used for controlling the rotating speed or if another receivers generating higher order harmonics are connected to the network. Therefore, not only voltage harmonics should be surveyed in the networks, but also the harmonics of the currents of the receivers generating high harmonic levels should be controlled. The current harmonics affect, in turn, the voltage harmonics content.

2 VOLTAGE HARMONICS OF A POWER NETWORK

An important difficulty arising during analysis of operation conditions of an induction motor supplied from a power network is a result of incompatibility of the standards and regulations pertaining to power networks and electrical machines. This is of special meaning while calculating the currents of particular harmonics reaching the motors and condensers used for compensation of reactive power absorbed by the motors. Therefore, in spite that the harmonics content factor of the network voltage, defined as THD(U), often meets the regulatory requirements, the other harmonics content factor of the same network, referred to as HVF, does not follow the standards binding for electric machines. In consequence, the knowledge of particular voltage harmonics is of greater meaning than the factors defined as THD(U) characterizing total harmonics content. Anyway, knowledge of particular harmonics enables easy calculating of the HVF factor.

To-day, according to standard requirements, the THD(U) value is determined considering 40 harmonics, while available harmonics measures provide usually up to 63 harmonic components. Value of the total coefficient of harmonics distortion THD(U) is calculated omitting so-called interharmonics, according to the formula (1):

$$THD(U)_{\%} = \sqrt{\sum U_{h\%}^2} \qquad (1)$$

where $U_{h\%}$ is the percent value of subsequent voltage harmonic referred to the first one (rated voltage). Such a value of the THD factor is considered as a characteristic parameter of a power network. On the other hand the standard pertaining to electric machines (PN-EN 60034-1/2001) does not require accounting for the THD(U) factor but rather the HVF factor of harmonics content, defined on a quite other way. This factor is calculated from the relationship (2) (according to the standard PN-EN 60034-1/2001)

$$HVF = \sqrt{\sum_{2} \frac{u_{hn}^2}{n}} \qquad (2)$$

where u_{hn} is a value of subsequent voltage harmonic and n is its order. The harmonic order plays here a role of a weight coefficient.

The standard, for purposes of calculation of the factor, recommends considering only the fifth, seventh, eleventh, and thirteenth harmonics, with appropriate weight coefficients. In result the HVF factor may be formulated as (3):

$$HVF = \sqrt{\frac{(u_{h5})^2}{5} + \frac{(u_{h7})^2}{7} + \frac{(u_{h11})^2}{11} + \frac{(u_{h13})^2}{13}} \qquad (3)$$

where u_h is a relative value of a proper voltage harmonic. The use of this formula may be admitted only provided that the motors are supplied in a three-conductor system and symmetric three-phase voltages, when the currents of the third harmonic and its multiples do not reach the motor winding.

The need of consideration of the weight coefficients for purposes of the HVF factor may be justified by the fact that reactance of the motor circuit, having an inductive character, grows for higher order harmonics. Therefore, the higher is the order of the harmonic component, the less its effect on motor operation. In case of three-phase motors consideration of only these four harmonics is fully reasonable, as with assumption of symmetry of the three-phase supply voltages, the third and ninth voltage harmonic components induce no current in the motor circuit. The harmonics of the order exceeding thirteen may be disregarded as inducing no significant currents in the motors of commonly used powers. Taking into account that the regulations admit asymmetry of the three-phase voltage system not exceeding 2 or 3 percent, the currents derived by the third and ninth harmonics should be theoretically considered. Nevertheless, they may be neglected as being very small.

The Standard PN-EN 61000-2-4 provides the levels of electromagnetic compatibility of the disturbances transmitted in the networks of industrial plants. The induction motors provided with condensers for compensation of the reactive power are commonly used in such networks. In consequence, the harmonic components occur there to the highest degree. The standard distinguishes three classes of networks of different admissible compatib ility levels. Table 1 shows the examples of admissible values of total factor of voltage harmonic distortion THD(U) provided by the standard, with their classification into classes, and the values of several the most important harmonics.

In accordance with the Standard PN-EN 60034-1/2001 the HVF factor should not exceed the 0.02 or 0.03 levels, according to the type of the motor.

Table 1 specifies the HVF factors calculated for the fifth, seventh, eleventh, and thirteenth harmonics, according to admissible harmonic values provided by the standard for three classes of the network.

Class	1	2	3
HVF value	0.021	0.035	0.049

Tab. 1: HVF factor values for three classes of the network

The HVF factor values show that for the admissible voltage harmonic content the conditions of motor supply are met only provided that the voltage harmonics content satisfies the requirements of the Class 1. Usually, in the networks of industrial plants the harmonics content does not meet even the conditions determined for the Class 3. In consequence, the motors are then used under the conditions differing from rated ones.

3 HARMONIC COMPONENTS OF CONDENSER CURRENT

The main function of the condensers installed in power networks of industrial plants consists in compensation of reactive power absorbed by the induction motors utilized there. Taking into account that the power network voltage contains a whole spectrum of harmonic components inducing the currents of particular harmonics, harmfully affecting the condensers, prior to installing the condensers it should be checked whether the current harmonic are of admissible level, preventing damage to the condensers.

In order to assess the risk caused by the harmonic components reaching the condensers the current values may be calculated on the grounds of the harmonics. Alternatively, a D_w^2 factor provided by the Standard PN-EN 61000-3-2 may be used for this purpose, calculated with consideration of the voltage harmonics.

The condensers designed for reactive power compensation in industrial networks have star or delta connection without a neutral conductor, similarly like the induction motors. Therefore, in case of a symmetric three-phase voltage system the third harmonic and its multiples may be neglected while calculating the currents absorbed by the condensers, as they are unable to induce currents corresponding to them. In case of asymmetry of the three-phase voltage system not exceeding 3 percent, the currents due to these harmonics are so small that can be readily neglected.

If the hazard to the condensers caused by the harmonics content is assessed based on the current intensity, the currents reaching the condenser and derived from particular harmonics are calculated by the formula (4)

$$I_h = \frac{U_h}{X_{ch}} \qquad (4)$$

where: U_h - voltage of the n-th order harmonic; f_n - voltage frequency; X_{ch} - reactance of the condenser of capacitance C_n

$$X_{ch} = \frac{1}{2\pi n f_n C_n}$$

In any case the number of considered harmonics may be discussed. Exploitation measurements show that maximal voltage values are due to the fifth and seventh harmonics. Moreover, it is commonly known that the THD(U) parameter should be calculated with consideration of 40 harmonics. Table 1 shows that for higher harmonic order the admissible voltage harmonic should decrease. In result, from the point of view of practical accuracy, the number of considered harmonics may be constrained to four, i.e. to the fifth, seventh, eleventh, and thirteenth ones, similarly like in case of calculation of the HVF factor for A.C. three-phase motors.

In case of consideration of odd harmonics up to the 17^{th} order, the currents are calculated from the formula (5):

$$I = \sqrt{I_{h1}^2 + I_{h3}^2 + I_{h5}^2 + I_{h7}^2 + I_{h9}^2 + I_{h11}^2 + I_{h13}^2 + I_{h15}^2 + I_{h17}^2} \qquad (5)$$

Nevertheless, for the condensers connected in three-phase systems the calculation of the third, ninth, and fifteenth harmonics should be made with consideration of the factor of asymmetry of the three-phase voltage system, the level of which should not exceed 0.03.

For practical calculation of the current reaching the condenser the following relationship may be applied:

$$I = \sqrt{I_{h1}^2 + I_{h5}^2 + I_{h7}^2 + I_{h11}^2 + I_{h13}^2} \qquad (6)$$

or

$$I = \sqrt{I_{h1}^2 + I_{h5}^2 + I_{h7}^2 + I_{h11}^2 + I_{h13}^2 + I_{h17}^2} \qquad (7)$$

However, when the three-phase voltage system is asymmetric and, particularly, if the condenser operates in a single-phase system, the current should be calculated also with consideration of the third and ninth harmonics:

$$I = \sqrt{I_{h1}^2 + I_{h3}^2 + I_{h5}^2 + I_{h7}^2 + I_{h9}^2 + I_{h11}^2 + I_{h13}^2} \qquad (8)$$

Taking into account the admissible voltage harmonic values the following relative current values reaching the condenser are obtained for the Class 3, according to the number of considered harmonics: 1.583, 1.43.

In any case, irrespective of the number of considered harmonics, the current exceeds admissible level, i.e. 1.3 I_n.

Table 2 presents relative values of particular harmonics of the condenser current, according to the requirements of the classes 3 and 1.

Class	Harm.1	Harm.3	Harm.5	Harm.7	Harm.9
3	1	0.0054	0.4	0.49	0.0067
1	1	0.0027	0.15	0.21	0.004

Class	Harm.11	Harm.13	Harm.15	Harm.17
3	0.55	0.585	0.009	0.6
1	0.33	0.39	0.001	0.34

Tab. 2: Relative values of particular harmonics of condenser current

If the voltage is determined with consideration of all the above specified harmonics that should be taken into account e.g. for the case of a single-phase condenser, the harmonics content corresponding to the Class 3 gives the phase current exceeding the rated level by 58.3% ($I=1.583\ I_n$), i.e. above admissible level. On the other hand, consideration of admissible voltage harmonics content according to the Class 1 gives the phase current exceeding the rated level only by 20% ($I=1.2\ I_n$), i.e. below the admissible level ($I=1.3\ I_n$).

Consideration of the regulations pertaining to admissible levels of particular voltage harmonics allows to notice that the current of the ninth harmonic exceeds the current of the third one, as condenser reactance is less for the ninth than for the third one. In order to compare the values of the current harmonics the admissible voltage harmonics should be taken into account. According to the regulations being in force admissible levels of the ninth, and especially the fifteenth voltage harmonic are below the level of the third one.

The Standard PN-EN 61000-3-2 provides a principle of assessing the network voltage harmonics content guaranteeing that condenser current does not exceed the rated current by 30%, thus avoiding their overheating. The principle does not require calculation of the current, as being based on the above mentioned D_w^2 factor. It makes allowance only for voltage harmonics with consideration of the weight factor, similarly like the HVF factor. This factor enables checking whether the voltage harmonic content of the network, to which the condensers designed for reactive power compensation are connected, results in excessive current level.

According to the Standard PN-EN 61000-3-2 the factor is calculated from the formula (9):

$$D_w^2 = \sqrt{\sum_{2}^{40} n^2 u_h^2} \qquad (9)$$

where: n – harmonic order, u_h – voltage value of the harmonic.

The formula should consider the harmonics up to 40th order, nevertheless, similarly like in the case of HVF, only the most important or odd harmonics, up to the 13th or 17th one may be accounted for. The third harmonic and its multiples may be also easily neglected. In the following equations only the selected harmonics are considered:

$$D_w^2 = 3^2 u_{h3}^2 + 5^2 u_{h5}^2 + 7^2 u_{h7}^2 + 9^2 u_{h9}^2 + 11^2 u_{h11}^2 + \\ + 13^2 u_{h13}^2 + 15^2 u_{h15}^2 + 17^2 u_{h17}^2 \qquad (10)$$

or

$$D_w^2 = 5^2 u_{h5}^2 + 7^2 u_{h7}^2 + 11^2 u_{h11}^2 + 13^2 u_{h13}^2 \qquad (10a)$$

The relationship (10a) is of the highest practical significance, as four harmonics are considered in it, i.e. the fifth, seventh, eleventh, and thirteenth ones. Restriction to only four above mentioned harmonics may be justified by the provisions of the standard system that for higher order of the voltage harmonics allows for lowering of their levels.

In order to justify such an approach Table 3 specifies example values of the D_w^2 factor, taking into account odd harmonics up to the 17th and 13th, omitting, at the same time, the ones divisible by 3.

According to the standard for admissible condenser current not exceeding 1.3 of the rated level the D_w^2 value must not exceed 0.7 for rated voltage, or 0.3 for 1.1 of the rated voltage.

D_w^2 value			
Class	1	2	3
Harm.5,7,11,13	0.328	0.513	1.045
Harm. 1-13	0.443	0.628	1.507
Harm. 1-17	0.472	0.671	1.68

Tab.34: Values of the D_w^2 factor with classification into the network classes

Table 4 presents the D_w^2 values calculated for the fifth, seventh, eleventh, and thirteenth harmonics for admissible harmonics values consistent with the standard of three network classes.

Class	1	2	3
D_w^2 value	0.328	0.513	1.045

Tab.45: D_w^2 values calculated for 3 network classes for admissible harmonics values

It results from the D_w^2 values specified above that for admissible voltage harmonics content corresponding to the third class the condenser current shall always exceed the admissible value equal to 1.3 of rated current, irrespective of the number of considered harmonics.

Comparison of the values obtained in accordance with the current calculation method and the D_w^2 factor method allows to confirm that the results are similar. Therefore, any of these methods is suitable for practical purposes. Nevertheless, the current calculation method seems to be better as it enables determining the current intensity and, for example, defining the adjustment range of the protection aimed at preventing condenser damage.

4 CALCULATION OF REACTIVE POWER ABSORBED BY THE INDUCTION MOTORS

The active and reactive power absorbed by an induction motor may be readily calculated on the grounds of its impedance determined based on a classical equivalent diagram. Such a diagram provides the formula (11) for impedance of the symmetric positive-sequence voltage as a function of rotating speed n and the k_f coefficient, defined as the rate of the frequency f to rated network frequency f_n of the network voltage. The use of the k_f coefficient is advantageous as it enables calculating the motor impedance, while changing the frequency during frequency control of the rotating speed and while analyzing the effect of harmonics on motor operation.

$$Z_1(n,k_f) = R_s + jXr_s(k_f) + \frac{Z_0(k_f)\left(\frac{R'_w}{s(n,k_f)} + jXr'_w(k_f)\right)}{\frac{R'_w}{s(n,k_f)} + Z_0(k_f) + jXr'_w(k_f)} \quad (11)$$

where

$$Z_0(k_f) = \frac{1jX_\mu(k_f)R_{Fe}}{R_{Fe} + 1jX_\mu(k_f)}$$

where Z_1 – impedance of the symmetric positive-sequence voltage; n – rotational speed, k_f - coefficient of frequency change, R_s stator resistance; X_{rs} - reactance of stator leakage, R_w' –resistance in rotor terms; X_{rw}' – resistance leakage in rotor terms, X_μ - magnetizing reactance, R_{Fe} - equivalent resistance of the losses in iron.

In order to consider the conditions of motor operation, regarding asymmetry of three-phase voltage system, calculation of motor impedance for symmetric negative-sequence voltage component $Z_2(n,k_f)$ is also necessary.

The reactive power necessary for compensation of an induction motor may be calculated, with sufficient practical accuracy, on the grounds of only the basic harmonic of symmetric positive-sequence. Hence, the stator current may be calculated from the equation (12):

$$I_{1s}(n,k_f) = \frac{U_n}{Z_1(n,k_f)} \quad (12)$$

In order to calculate active power absorbed by the motor the following formula may be used:

$$P_1(n,k_f) = 3U_n \,\mathrm{Re}(I_{1s}(n,k_f)) \quad (13)$$

while for reactive power:

$$Q_1(n,k_f) = 3U_n \,\mathrm{Im}(I_{1s}(n,k_f)) \quad (14)$$

The motor power coefficient is defined by the relationship

$$\cos\varphi(n,k_f) = \frac{P_1(n,k_f)}{\sqrt{P_1(n,k_f)^2 + Q_1(n,k_f)^2}} \quad (15)$$

In order to compensate reactive power consumed by the motors the reactive power of a battery of condensers Q_k is usually so adjusted as to meet the requirements of binding regulations (at present cosφ=0.928). As the reactive power consumed by the motor changes together with the load, i.e. with changing speed n, for constant battery power the circuit power coefficient varies too. Constant value of the power coefficient may be maintained during group compensation. While individual compensating of reactive power of a single motor, particularly of small or average power, constant value of the power coefficient can not be maintained. The power of the battery is so adjusted as to achieve the required cos φ for the rated load.

During calculation of power coefficient of the whole circuit supplying a single motor of their group, the formula should include the Q_k parameter, representing the reactive power of the condenser designed for improving the value of the power coefficient.

The power coefficient of the motor circuit with a condenser may be calculated from the relationship (16):

$$\cos\varphi(n,k_f) = \frac{P_1(n,k_f)}{\sqrt{(P_1(n,k_f))^2 + (Q_1(n,k_f) + Q_k)^2}} \quad (16)$$

The dependence between the power coefficient and relative value of the effective power of the motor p_{mu} should be expressed and plotted. The value of rotational speed of the rotor was assumed as an independent variable that contributed to easier presentation of various relationships in terms of the rotational speed n.

Absolute value of reactive power of the motor is calculated on the grounds of the formula (17):

$$p_{mu}(n,k_f,k_{u1},k_{u2}) = \frac{P_{mu}(n,k_f,k_{u1},k_{u2})}{P_n} \quad (17)$$

where:

$$P_{mu}(n,k_f,k_{u1},k_{u2}) = \frac{M_{uz}(n,k_f,k_{u1},k_{u2})}{60} 2pbM_n(n)$$

$$M_{uz}(n,k_f,k_{u1},k_{u2}) = M_{st}(n,k_f,k_{u1},k_{u2}) - D_{pmu}$$

M_{st} is the static moment of the motor, while D_{pmu} is a moment of mechanical losses.

In case of a motor supplied by asymmetric three-phase network voltage, the absorbed reactive power Q_{11} should be calculated from the equation (18):

$$Q_{11}(n,k_f,k_{u1},k_{u2}) = Q_1(n,k_f,k_{u1},k_{u2}) + Q_2(n,k_f,k_{u1},k_{u2}) \quad (18)$$

while the absorbed active power from the equation (19):

$$P_{11}(n,k_f,k_{u1},k_{u2}) = P_1(n,k_f,k_{u1},k_{u2}) + P_2(n,k_f,k_{u1},k_{u2}) \quad (19)$$

P_1 and Q_1 are the power components corresponding to positive-sequence voltages, while P_2 and Q_2 are the components of the negative-sequence. The parameters k_{u1} and k_{u2} represent the factors of network voltage asymmetry for the positive and negative components, respectively.

In asymmetric conditions the coefficient of motor power is calculated from the formula(20):

$$\cos\varphi(n,k_f,k_{u1},k_{u2}) = \frac{P_{11}(n,k_f,k_{u1},k_{u2})}{\sqrt{Q_{11}(n,k_f,k_{u1},k_{u2})^2 + P_{11}(n,k_f,k_{u1},k_{u2})^2}} \quad (20)$$

In the case of asymmetric voltage system, when the asymmetry is within admissible range, i.e. does not exceed 0.03, the factor k_{u2}=0.03 should be substituted to the formulas. In the case of voltage asymmetry a reduction of effective power for conventional value of rotational speed, assuming for example the rated speed, should be considered. This is due to the fact that the static moment includes the positive and negative sequence components, having opposite senses, that may be presented by the equation (21):

$$M_{st}(n,k_f,k_{u1},k_{u2}) = M_{st1}(n,k_f,k_{u1}) - M_{st2}(n,k_f,k_{u2}) \quad (21)$$

For a motor of the power 3.2kW, subject to rated load, i.e. rated speed and symmetric supply voltage, the power coefficient amounts to 0.761. On the other hand, in the case of asymmetric voltage of the degree corresponding to k_{u2}=0.03 imposing the value k_{u1}=0.943, the power coefficient changes to 0.72. For the above degree of voltage asymmetry and rated speed the power coefficient drops to the level 0.87.

5 CALCULATION OF REACTIVE POWER AND POWER COEFFICIENT

The paper provides calculated values of some characteristic parameters for the motors of the powers amounting to 3.2kW - 380V, 15kW - 380V, and 500kW - 6000V.

The motor of small power (3.2kW) subject to its rated load, i.e. operating with rated rotational speed, absorbs the reactive power of Q_n=3390Var and active power P_{1n}=3976W from the network. Rated power coefficient of the motor is relatively small, amounting to $\cos\varphi$ = 0.761. In order to illustrate variations of the absorbed power with respect to the speed, Figure 1 shows relative values of absorbed reactive and active power, in the speed range 1200-1500 r.p.m. Moreover, variations of effective mechanical power as a function of the rotational speed are presented as well.

In order to achieve the value of power coefficient equal to 0.928, that is required by the regulations, a condenser of the power Q_k=1800Var should be connected.

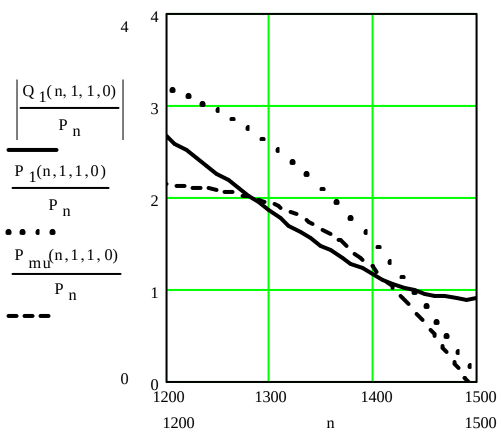

Fig. 1. Reactive, active, and effective mechanical power absorbed by an induction motor of 3.2kW capacity as functions of the rotational speed

Figure 2 presents the variations of power coefficient of the motor as a function of the load (speed) without compensation (the continuous line) and with connected battery of condensers (the dotted line). It shows that in case of underloading of the motor, the power coefficient is smaller than expected value but more advantageous than its natural value.

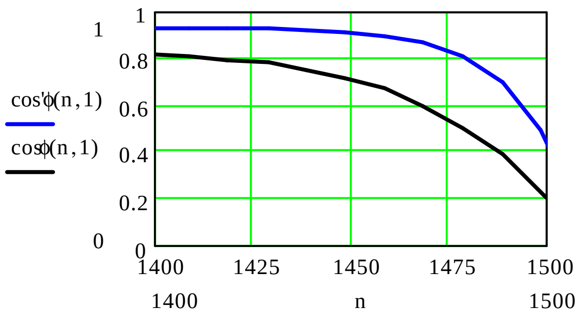

Fig. 2. Variation of power coefficient of the 3.2kW motor as a function of the load, without compensation and in the case of a connected battery of condensers Q_k=1800Var

The motor of middle power (15kW) subject to its rated load operating with rated rotational speed, absorbs the reactive power of Q_n=8736Var and active power P_{1n}=16720W from the network. Rated power coefficient of the motor amounts to $\cos\varphi$ = 0.886 which is better than for the motor of 3.2kW. Figure 3 shows relative values of absorbed reactive and active power in due speed range (1200-1500 r.p.m.). Moreover, variations of effective mechanical power presented as well. In order to achieve, under the rated load, the value of power coefficient equal to 0.928, that is required by the regulations, a condenser of the power Q_k=20800Var should be connected. As the value of the reactive power absorbed by the motor, with respect to its rated power, is smaller in the case of the 3.2kW motor, natural value of the power coefficient is relatively high (0.886). In consequence, power of the battery of condenser necessary for achieving the required power coefficient only slightly exceeds the level corresponding to the one of the 3.2kW motor. Figure 4 presents the variations of power coefficient of the motor as a function of the load (speed) without compensation (the continuous line) and with a connected battery of condensers (the dotted line). It shows that in case of underloading of the motor the power coefficient is smaller than its expected value but more advantageous than its natural value.

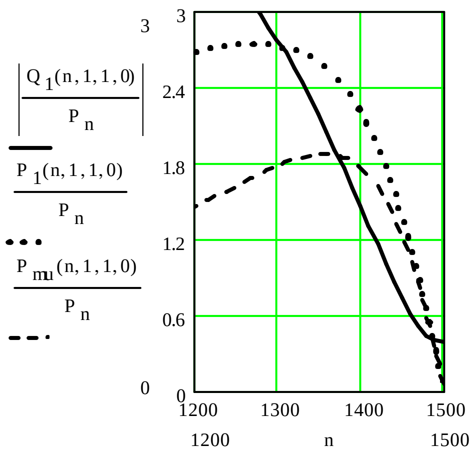

Fig. 3. Reactive, active, and effective mechanical power absorbed by an induction motor of 15kW capacity as functions of the rotational speed

As the value of the reactive power absorbed by the motor, with respect to its rated power, is smaller in the case of the 3.2kW motor, natural value of the power coefficient is relatively high (0.886).

In consequence, power of the battery of condenser necessary for achieving the required power coefficient only slightly exceeds the level corresponding to the one of the 3.2kW motor. Figure 4 presents the variations of power coefficient of the motor as a function of the load (speed) without compensation (the continuous line) and with a connected battery of condensers (the dotted line). It shows that in case of underloading of the motor the power coefficient is smaller than its expected value but more advantageous than its natural value.

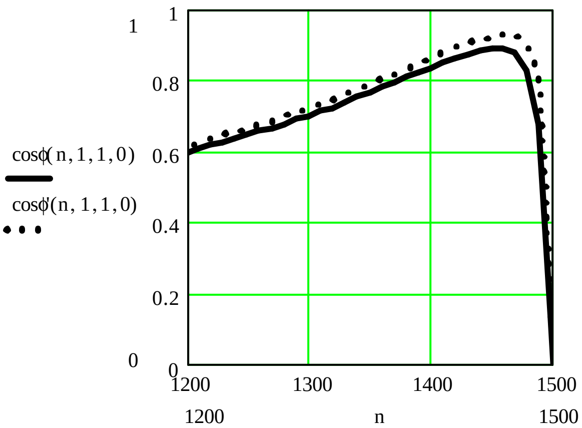

Fig. 4. Variation of power coefficient of the 15kW motor as a function of the load, without compensation and in the case of a connected battery of condensers Q_k=2000Var

Table 5 specifies the values of the power coefficient and relative effective power for some selected values of rotational speed, on the example of the 15kW motor. It may be noticed that, in the case of this motor, small speed variations result in insignificant changes of the power coefficient, but, at the same time, the effective mechanical power varies considerably.

Speed n	1470	1465	n_n	1450	1440
cosφ	0.871	0.882	0.886	0.889	0.884
Effective power	0.805	0.917	1	1.207	1.365

Tab. 5: Values of power coefficient and relative effective power for different rotational speeds of the 15 kW motor

The motor of high power (500 kW) subject to its rated load, absorbs the reactive power of Q_{1n}=281700Var and active power P_{1n}=510500W from the network. Rated power coefficient of the motor amounts to cosφ = 0.876. Figure 5 shows relative values of absorbed reactive and active power in due speed range (1000-950 r.p.m.). Moreover, variations of effective mechanical power are presented as well.

In order to achieve, for the rated load, the value of power coefficient equal to 0.928, that is required by the regulations, a condenser of the power Q_k=775kVar should be connected.

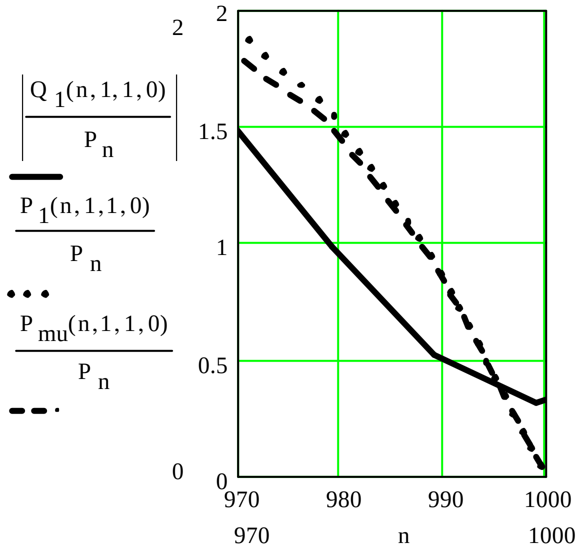

Fig. 5. Reactive, active, and effective mechanical power absorbed by an induction motor of 500kW capacity as functions of the rotational speed

Figure 6 presents the variations of power coefficient of the motor as a function of the load (speed) without compensation (the continuous line) and with connected battery of condensers (the dotted line). It shows that in case of underloading of the motor the power coefficient differs from the expected value but is more advantageous than its natural value.

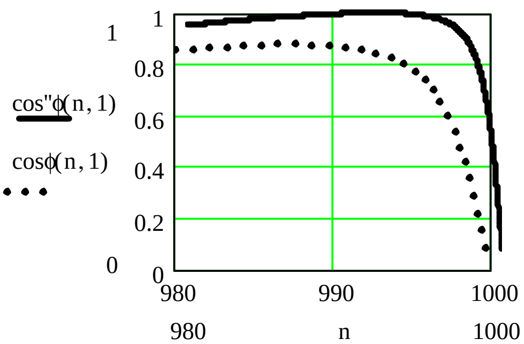

Fig. 6. Variation of power coefficient of the 500kW motor as a function of the load, without compensation and in the case of a connected battery of condensers Q_k= 77500 Var

6 CONCLUSIONS

Consideration of the above results allows to state that the condensers used for purposes of reactive power compensation in public and industrial networks, in which the content of particular harmonics does not exceed admissible levels, are not subject to overload. In consequence, there is no risk of their switching off by the overcurrent protection devices. In order to avoid switching off the condensers of industrial networks of the Class 3 in result of excessive currents of harmonic components the condensers should be protected by special chokes or by means of filters connected to the circuits.

According to rated coefficient and reactive power of the condenser, as for example in the case of the 15kW motor, for smaller loads the power coefficient of the motor supply circuit may be nearly constant and amounts approximately to recommended value equal to 0.928.

REFERENCES

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[3] Praca zbiorowa: „Zasilanie, uzytkowanie i diagnostyka maszyn elektrycznych w przemysle i taborze trakcyjnym. Analiza czestotliwosciowa pradów i napiec w obwodach stojana maszyn trójfazowych pradu przemiennego". Badania w ramach dzialalnosci statutowej IEp. Poznan 2001.

[4] „Rozporzadzenie Ministra Gospodarki i Pracy z dnia 20 grudnia 2004 roku w sprawie szczególowych warunków przylaczenia podmiotów do sieci elektroenergetycznych, obrotu energia elektryczna, swiadczenia uslug przesylowych, ruchu sieciowego i eksploatacji sieci oraz standardów jakosciowych obslugi odbiorców"

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