# MEANS AND METHODS TO IMPROVE THE POWER FACTOR

## 1. Generalities

Electric equipments are designed for a certain apparent power *S* which is proportional to the product between the r.m.s values of the voltage *U* and the current *I*. The circulation of this power in the electrical system is accompanied, depending on the structure of the consumer of electric energy, by the circulation of the active power *P*, reactive power *Q*, and the deforming power *D*. The useful power is the active one and the determination of the percent of the apparent power it represents is being done with the *power factor k* defined by the relation:

$$k = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}}$$

The percentage of the reactive power and the deforming power are estimated through the *reactive factor ρ* and the *deforming factor τ* of the non sinusoidal permanent regime, according to the following formulas:

$$\rho = \frac{Q}{P} = \mathrm{tg}\varphi; \qquad \tau = \frac{D}{\sqrt{P^2 + Q^2}} = \mathrm{tg}\psi;$$

where the phasors P, Q, D form a three-orthogonal reference system, and the phase shifts *Ψ* and *φ* have the meanings from fig. 12.1. Thus a new formula for the power factor is obtained:

$$k = \cos\varphi \cdot \cos\psi$$

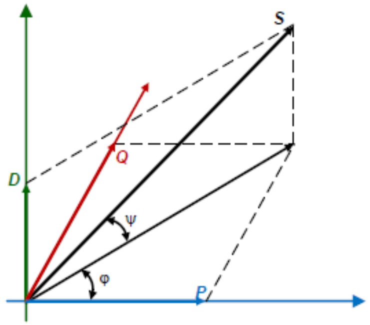


Fig 12.1 Explanatory for the reactive factor ρ and the deforming factor τ

If we consider a single phase circuit in a sinusoidal permanent regime then:

$$D = 0 \ (\psi = 0) \ \Rightarrow \ k = \cos\varphi,$$

so the power factor is numerically equal to the cosine of the phase displacement angle between the voltage and the current.

In the balanced linear three-phase circuits, supplied in sinusoidal voltages, the power factor has the same mathematical expression and meaning as in single-phase circuits. If the electric receivers are slightly asymmetrical, then the voltage-current phase displacement are different for every phase $\varphi_1 \neq \varphi_2 \neq \varphi_3$

and the power factor will be:

$$k = \frac{P_1 + P_2 + P_3}{\sqrt{(P_1 + P_2 + P_3)^2 + (Q_1 + Q_2 + Q_3)^2}}$$

where $P_j$ and $Q_j$ are the active and reactive powers for every phase (j=1,2,3).

The previous formulas define the *instantaneous power factor* that corresponds to a certain moment in the functioning of the consumer's installations. Because the electric load has fluctuations, the standards recommend that determining the *weighted average power factor* should be done considering the consumption of active energy $E_a$ and reactive energy $E_r$ from a certain period of time, and also considering that the consumer's receivers are behaving like a three-phased linear and balanced load, which is working in a sinusoidal permanent regime.

$$\cos\varphi = \frac{E_a}{\sqrt{E_a^2 + E_r^2}}$$

Weighted average power factor can be natural when it is being determined without considering the reactive power compensation plants, and generally, when at its evaluation the powers supplied by these installations are also considered. The value of the overall weighted average power from which the reactive energy consumption is no longer being charged is called *neutral power factor* with value $cos\varphi_n$= 0.92.

For the electrical installations inside the consumer, the study and analysis of the reactive power receivers are considering several aspects: the causes of the power factor decrease, the effects of a low power factor, means and methods of improving the power factor, the technical and economical calculation for placing the reactive power sources etc.

## 2. The causes for the power factor's decrease

From the point of view of reactive power we distinguish inductive receivers which take reactive power from the system to produce their magnetic field (asynchronous motors, transformers etc) and capacitive receivers which give reactive power to the system (static capacitors, overexcited synchronous machines etc.). In calculations, the power absorbed from the supply network is considered positive ($P_c$>0 and $Q_c$>0), and the given to the network is considered negative (P<0 and Q<0).

The required reactive power $Q_c$ of these receivers comprises: the magnetization reactive power $Q_o$ (the main component of reactive power) which depends directly proportional to the amount of iron $V_{FE}$ and the amount of the air gap $V_\delta$ and to the dispersion reactive power $Q_d$, which varies proportionally to the square of the loading factor (coefficient, degree) β.

Thus: $Q_c = Q_0 + Q_d$

In asynchronous machines the magnetization reactive power is determined with the formula:

$$Q_0 = 0{,}25 f B^2 \left( \frac{V_{Fe}}{\mu} + \frac{V_\delta}{\mu_0} \right) \cong \sqrt{3} U_n I_0 \quad [\text{VAr}]$$

where: $f$ – frequency of the supply voltage, [Hz]; $B$ – main induction in the magnetic circuit, [T]; $m = m_0 m_r$ – magnetic permeability, [H/m]; $U_n$ – the rated main voltage, [V]; $I_o$ – the no load current of the motor, [A].

From the first expression it results that the increase of this power is due by:

- *fabrication causes*, like: higher air gap volume, required for safe operation and construction requirements; magnetic materials with modest performances ($m_r$ – low); reduced nominal speed involving a large volume of iron etc.;
- *operating causes*, the most common being improper repairs; asymmetry of the magnetic circuit; displacements of the lamination packets etc.

For asynchronous motors the dispersion reactive power is determined with:

$$Q_d = \beta^2 (Q_n - Q_0) \ \ [\text{VAr}];$$

where: $\beta = \frac{P_s}{P_n} = \frac{P_c}{P_{en}}$ – load ceoficient or the loading coeficient given by the ratio between the power in technological load $P_s$ and the rated mechanical power $P_n$ or between the power requested from the network $P_c$ and the electric rated power $P_{en} = P_n / \eta_n$, with $\eta_n$ being the rated efficiency of the electric motor.

$Q_n = P_{en} \cdot tg\varphi_n$ – rated reactive power, and $\varphi_n$ – the rated phase shift.

$$Q_c = Q_0 + Q_d = Q_0 + \beta^2 (Q_n - Q_0) = = Q_n \left[ a + (1-a) \cdot \beta^2 \right]$$

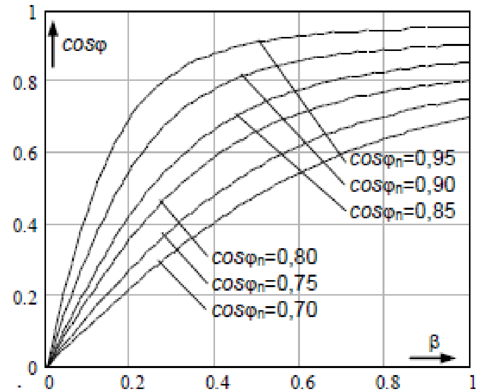



**Fig. 12.2** Characteristics for *cos*φ=f(β,*cos*φn)

where: a = $Q_0/Q_n$.

Finally, the power factor for the asynchonous motor can be represented as such:

$$\cos\varphi = \frac{P_c}{\sqrt{P_c^2+Q_c^2}} = \frac{\beta}{\sqrt{\beta^2+\left(a+\beta^2(1-a)\right)^2 tg^2\varphi_n}} = f(\beta,\cos\varphi_n)$$

And from the graphical representation (fig. 12.2) it results:

- the power factor decreases rapidly with the reduction of the loading factor β, regardles of the rated power factor $\cos\varphi_n$ of the asynchronous motor;
- at the same variation Δβ, the power factor is modified more for the motors that have a smaller rated power factor
- if β≤0,5 then $Qc \approx Qo$ and the reactive consumed power is practically independent from the load on the shaft and can be considered $Qo \approx 0{,}8Qn$. This frequent situation in practice, is generated by the reduces range of rated powers $P_n$ and by the functioning of the aggregates at loads much smaller than the designed ones.

## 3. The effects of a low power factor

The operation of the consumer's electrical installations with a low power factor presents a series of disadvantages for the national power system, from which we mention: an increase in active power losses in the transmission and distribution line, the majority of voltage losses in the electrical networks, extra investments for the system etc.

a) The power losses in the transmission and distribution lines are given by:

$$\Delta P = 3RI^2 = \frac{RS^2}{U^2} = \frac{RP^2}{U^2}\frac{1}{\cos^2\varphi}$$

and it can be observed that they vary in inverse ratio to the square of the power factor for P=ct and U=ct. Thus, if the same active power P is transported under different power factors $\cos\varphi_1 < \cos\varphi_2$, then the power losses $\Delta P_1$ and $\Delta P_2$ are interdependent according to the relation:

$$\Delta P_2 = \Delta P_1\left(\frac{\cos\varphi_1}{\cos\varphi_2}\right)^2$$

from where it results that through the improvement of the power factor we can obtain the reduction of power losses.

The power losses $\Delta P_a$ and $\Delta P_{rd}$ caused by the transportation of the active, reactive and deformed powers respectively, result from:

$$\Delta P = \frac{RP^2}{U^2}\frac{1}{\cos^2\varphi} = \frac{RP^2}{U^2} + \frac{RQ^2}{U^2} = \Delta P_a + \Delta P_{rd}$$

$$\Delta P_{rd} = \Delta P - \Delta P_a = \frac{RP^2}{U^2}\left(\frac{1}{\cos^2\varphi} - 1\right)$$

so $\Delta P_{rd}$ increases fast with the decrease of the power factor.

b) Voltage losses in the transmission networks vary directly proportional with the reactive power for the same transported active power because:

$$\Delta U = \sqrt{3}RI\cos\varphi + \sqrt{3}XI\sin\varphi = \frac{R}{U}P + \frac{X}{U}Q = \Delta U_a + \Delta U_{rd}$$

where: $\Delta U_a$, $\Delta U_{rd}$ are the active, reactive and deforming voltage drops respectively.

For the under-loaded overhead electric lines or for the lines with voltages of over 110kV, the voltage losses are transformed in voltage increasing because $\Delta Q_L < \Delta Q_C$, which leads to $\Delta U = \Delta U_a - \Delta U_{rd} < 0$.

c) The active power loading capacity of the electric networks is decreased by a low power factor. Thus, according to the value of the power factor, more active powers $P_1 = S\cos\varphi_1$, $P_2 = S\cos\varphi_2$ correspond to the same apparent power S. If $\cos\varphi_1 > \cos\varphi_2$ we'll get:

$$P_2 = \frac{\cos\varphi_2}{\cos\varphi_1}P_1$$

from where it results the increase in active power $P_2 > P_1$ by reducing the reactive power consumption.

d) Increasing the investments for the transmission and distribution lines which operate with a low power factor can be explained by the fact that the line is sized for the admissible voltage loss and its heating is calculated for a rated regime.

If we consider the expression for the admissible power losses $\Delta U_{ad} = \Delta U_a + \Delta U_{rd}$, which have normalized values, then for given P and Q it results $\Delta U_{rd} = X \cdot Q/Un = ct$, which leads to:

$$\Delta U_a = \Delta U_{ad} - \Delta U_{rd} = \rho \frac{L}{s} \frac{P}{U_n} = ct. \quad \text{sau} \quad s = \rho \frac{L}{\Delta U_a} \frac{P}{U_n};$$

where: L – length of the line; s – cross section of the phase conductor; r - the resistivity of the conducting material; P – the circulating active power.

For a given active power, investments in power plants are in inverse ratio to the square of the power factor, and the installed apparent power varies inversely proportional to the power factor.

e) The deforming regime generated by the consumer's receivers contributes not only to the decrease of the power factor (D appears in the composition of S) but also to a series of negative effects, like: the amplification of the voltage and current harmonics, extra voltage and power losses ($\Delta U_{rd}$ and $\Delta P_{rd}$ increase), harmonic resonance phenomenons, parasitic braking couplings in electric motors etc.

The current resonance's effect, among others, is overloading or the destruction of capacitor batteries when the harmonics of rank 5, 7, 11 or 13 are important. The voltage resonance, associated in general with the current one, overstresses the cable insulation and the capacitor's dielectric. In case of energy cables, the harmonics of superior ranks increase the losses through Joule-Lenz effect and accelerate the corrosion effects.

The disadvantages of the deforming regime can be eliminated if the resonance effects and their amplification are estimated in the designing stage, which will allow a proper dimensioning of the harmonics filters.

## 4. Natural means of improving the power factor

The need for power factor improvement (compensating) by reducing the reactive and deforming powers is imposed by the fact that the majority of electric receivers, even though they operate at nominal load, have a power factor much below the neutral one. Because of that the means of power factor improving should cover two aspects, namely:

- bringing the power factors of the receivers in service to values as close to the nominal one;
- increasing the power factor at least to the value of the neutral power factor.

Corresponding to these criteria, the power factor compensation methods are grouped into: *natural means* which consist of technical and organizational measures and *special means* involving the installation of reactive power sources, usually static capacitors.

Natural means of improving the power factor relates to the selection and correct operation of the machines in the consumer installations, namely:

- charging as close to the rated load of induction motors;
- reduced supply voltage to the low load induction motors by transition from delta connection to star connection winding;
- replacing oversized receivers (motors, transformers) with other of smaller power
- replacing induction motors with synchronous motors if the technological process allows and the installed power is greater than 100 kW;
- operation of three-phase transformers accordingly with the minimal loss graph;
- optimal use of compensation capacity of synchronous motors
- improvement of technological process (loading, maintenance, repair) and avoiding no load operation to improve energy regime;
- configuration of supply and distribution networks lead to minimal loses and a high power factor.

### 4.1 Natural means of improvement in induction motors

a) Replacing oversized motors is recommended if: there are no long-term overloads during the operation, reducing the power does not affect the energy efficiency of the machine by increasing excessive losses new motor and mounting conditions are suitable.

In practice, $\beta \leq 0,45$ motors are replaced without any economic consideration, those with $\beta \geq 0,7$ or those operating less than 1500 hours / year are not replaced, and for those with $\beta = 0,45..0,7$ a technical-economic calculation is required based on which the replacement decision is taken or not.

Replacing induction motors with synchronous motors is based on a technical-economic study both in the design phase and in the case of operating installations only if the process allows this (no shocks load, constant speed, adequate starts etc.). The advantage of this method is the ability to operate overexcited synchronous motor at a capacitive power factor of 0.8.

b) Supplying motors with low voltage consists in switching stator winding delta connections of (Δ) in star (Y) only if the structure of the machine permits (for motors with manual or automatic star-delta starter) . By this method the voltage applied to the winding is reduced by $\sqrt{3}$ times leading to the decrease of the magnetizing current, and thus, the reactive power.

Operating in star connection will be stable if the resistant torque on the shaft is at most 0,44$M_{n\Delta}$, otherwise the installation overheats. If we consider the proportionality between critical torque *Mk* and nominal torque *Mn* for the two connections:

$$M_{k\Delta} \cong 2M_{n\Delta} \qquad M_{k\,Y} \cong 2M_{n\,Y} = \frac{2}{3}M_{n\Delta}$$

then, for maximum torque on the shaft in star connection the following value results:

$$M_{\max} \le \frac{M_{k\,Y}}{1{,}5} = \frac{2}{1{,}5 \cdot 3}M_{n\Delta} \cong 0{,}44M_{n\Delta}$$

for a safety coefficient of 1,5.

The electric efficiency η for a loading β of the drive motor will be:

$$\eta = \frac{P_s}{P_c} = \frac{P_s}{P_s + p_0 + \beta^2 p_{vn}} = \frac{\beta \cdot P_n}{\beta \cdot P_n + p_{vn}\left(\gamma + \beta^2\right)} = \frac{\beta}{\beta + \chi\left(\gamma + \beta^2\right)}$$

with:

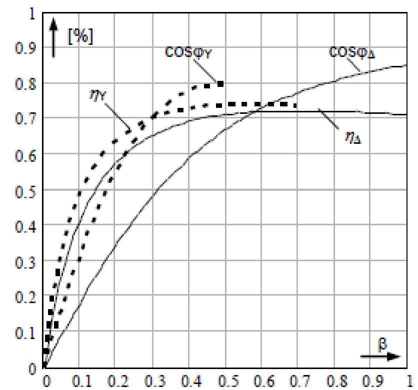
$P_0$-no load loses, constant for a given connection ;

$P_{vn}$ - *variable motor losses at rated load*

$p_n = p_0 + p_{vn} = (1-\eta_n)P_n / \eta_n$ nominal power loses

$\gamma = p_0 / p_{vn}$ loss constant and variable ratio;

$\chi = \dfrac{1-\eta_n}{(1+\gamma)\cdot\eta_n}$ a constant for a given winding connection




Curves η= *f*(β) and cos(φ) = f (β) for star and delta connections of the stator winding

### 5. Special means of improving the power factor

Power factor compensation is achieved at low and medium reactive power, by connecting capacitors, and for high values of power by means of synchronous compensators.In the line systems that supply for the energy consumers, some receivers (converters, induction motors, discharging lamps installations, etc. ) absorb an inductive current from the network, lagged because of the voltage.A method for improving the power factor of a single-phase inductive receiver is to use a capacitor, connected across its terminals.

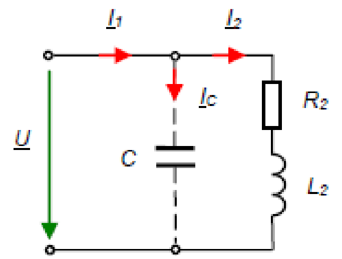



Fig 12.6 The improvement of the power factor of a single-phase receiver

In figure 12.6 an induction receiver is presented with R2 and L2 parameters, which absorbs reactive power.

The load current, when the capacitor C is not connected, is:

$$\underline{I}_2 = \underline{I}_1 = \frac{\underline{U}}{R_2 + j\omega L_2} = \frac{\underline{U}}{Z_2} e^{-j\varphi_2},$$

where

$$\underline{Z}_2 = R_2 + j\omega L_2 = Z \cdot e^{j\varphi_2}$$

The current absorbed from the source, which runs through the distribution line, is lagged from the voltage of $\varphi = \varphi_2$ angle. This angle is closer of π/2 radians, as L2's value is higher and R2's smaller.

In practice, the R2 and L2 parameters are usually unknown. In this case, the P2 active power, absorbed by the source, must be measured, as well as U and I2.

From $P_2 = U \cdot I_2 \cdot \cos\varphi_2$, results the value of $\cos\varphi_2$, then $\varphi_2$.

If the electric capacitor is connected at the terminals of the receiver:

$$\underline{I}_1 = \underline{I}_2 + \underline{I}_C = \frac{\underline{U}}{\underline{Z}_2} + \frac{\underline{U}_2}{\frac{1}{j\omega \cdot C}} = \underline{U} \cdot \left( \frac{1}{R_2 + j\omega \cdot L_2} + j\omega \cdot C \right) =$$

$$= \underline{U} \cdot \left[ \frac{R_2}{R_2^2 + (\omega \cdot L_2)^2} + j\omega \cdot \left( C - \frac{L_2}{R_2^2 + (\omega \cdot L_2)^2} \right) \right]$$

$$C = \frac{L_2}{R_2^2 + \omega^2 \cdot L_2^2}$$

The current I1 has the same argument as U, so that the phase shift angle of these two electrical signals is null. If a capacitor is being use, with a value as close as posible of the one resulted from relation (2), the phaze diagram of the line is represented in figure 12.7.

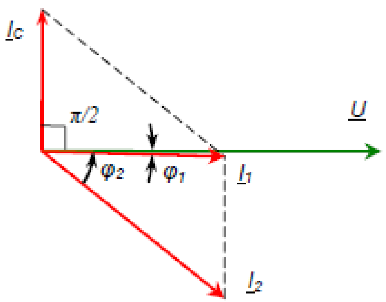



Fig. 12.7 Phase diagram

After connecting the capacitor , the active power absorbed remains the same, because the capacitor doesn't absorb active power, and the power factor raises to the imposed value $\cos\varphi_1$. Usualy, it is required that $\cos\varphi_1 \geq 0{,}92$.

Therefore: $P_2 = U \cdot I_1 \cdot \cos\varphi_1$

After considering relations (1) and(3) we can conclude that:

$$I_1 = I_2 \frac{\cos\varphi_2}{\cos\varphi_1},$$

Consequently, by increasing the power pactor from value $\cos\varphi_2$, to value $\cos\varphi_1$, the absorbed current decreases from value I2 to I1

In order to determine the capacity of the capacitor, we can notice that:

$$I_C = I_2 \cdot \sin\varphi_2 - I_1 \cdot \sin\varphi_1$$

$$I_C = \omega \cdot C \cdot U$$

By using relations (1), (2), (5) and (6) we obtain:

$$C = \frac{P_2}{\omega \cdot U^2} (\mathrm{tg}\varphi_2 - \mathrm{tg}\varphi_1)$$

The ractive power supplied by the capacitor is:

$$Q_c = U \cdot I_c = \omega C U^2 = P_2 (\mathrm{tg}\varphi_2 - \mathrm{tg}\varphi_1)$$

In case of a three phased inductive receiver, the improvement of the power factor is obtained by connecting at the terminals of the receiver a group of capacitors, arranged in star or delta configuration (fig. 12.8)

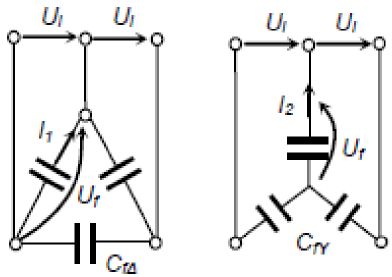



Fig 12.8 Capacitor connections

In case of delta configuration:

$$Q_\Delta = 3U_f \cdot I_1 = 3U_l \omega C_\Delta U_l = 3\omega C_\Delta U_l^2$$

In case of star configuration:

$$Q_Y = 3U_f \cdot I_2 = 3U_f \omega C_Y U_f = 3\omega C_Y U_f^2 = \omega C_Y U_l^2$$

It can be pointed that if the same kind of capacitors are being used ($C_Y=C_\Delta$), the delta configuration is more advantageous,providing a reactive power three times higher than the star configuration.

The electric voltage at which each capacitor is being subjected to is $\sqrt{3}$ times higher than the delta configuation, therefore it is preffered the star type in the case of high voltages.

If $Q_{nc}$ represents the reactive nominal power of the capacitor, the number of capacitors which form the battery of capacitors is:

$$n = \frac{Q_c}{Q_{nc}},$$

where Qc is the reactive power required by the inductive receiver(which follows the relation 8), in which P2 represents the three phased active power).

If the grid voltage $U_r$ is different from the nominal voltage of the capacitors, $U_{nc}$, their power will be adjusted according to the relation:

$$Q_{nc}^* = Q_{nc}\left(\frac{U_r}{U_{nc}}\right)^2$$

Other methods of improvement of the power factor:

-connecting at the busbar the significant inductive consumers of the synchronous overloaded motors, functioning without resisting torque of the shaft (no-load running motor)- the so called synchronous compensator, which produces reactive power. The sollution is being used in the case of electric lines of medium or high voltages, in the situation when the reactive power consumption is very high(more than 50 MVAr),if the consumer has deformed receivers and needs to compensate powers over 10…20MVAr or if there are highly rapid variations of the reactive charge(as in the case of heating arc furnace).

## 6. Conducting the application

### 6.1. The structure of the laboratory application will be studied

The test bench is realised with two asynchronous motors $MA_1$, $MA_2$, of the same type, connected axle to axle and loaded by means of a Prony brake. The motors can function in star or delta configuration.

The stand is equiped with measuring devices for determining the following: the phase and line voltages of the line, the electric line current intensity, the phase current intensity, the three phased active electrical power, the direct current intensity supplying the Prony brake, the power factor.

The installation allows the control of the supply voltage for the asynchronous motors in star and delta configuration, the motors loading at different values of the load factor β, the realization of two types of power factor compensation by connecting the capacitors at the terminals of the receivers with reactive power consume. The signaling process of distinct functioning modes is realized by lamps.

**6.2.** Characteristics to be drawn: $\eta_Y$ ,$\eta_\Delta$, $\cos\varphi_Y$, $\cos\varphi_\Delta$, $A, B = f(\beta)$

The determination of the experimental data will be done in the following order:

- nominal data are being read form machine's nameplate: $P_n$, $U_n$, $I_n$, $n_n$, $cos\varphi_n$, corresponding to the delta configuration of the stator windings;
- it is determined from the no load test, the quantities $p_{0Y}$ , $I_{0Y}$ , $p_{0\Delta}$ şi $I_{0\Delta}$;
- it is determined, for various loading factors $\beta$, the voltage and currents: $P_{cY}$, $I_{cY}$ , $P_{c\Delta}$ and $I_{c\Delta}$ ;
- the power losses in normal regime are calculated: $p_n = p_0 + p_{vn} = (1 - \eta_n)\, P_n / \eta_n$, $p_{vnY} = p_n - p_{0y}$, $p_{vn\Delta} = p_n - p_{0\Delta}$ and the ratios $\gamma_Y = p_{0Y} / p_{vnY}$, $\gamma_\Delta = p_{0\Delta} / p_{vn\Delta}$;
- the loading factor is evaluated: $\beta = P_c /(2P_{cn})$, $P_{cn} = \sqrt{3}\, U_n I_n \cos\varphi_n$
- it is calculated the electrical efficiency and the power factor for various loading factors: $\eta_\beta = \beta/(\beta+\chi\ (\gamma+\beta^2))$ and $\cos\varphi_\beta = P_c/(\sqrt{3} U_s I_c)$, where γ - depends on the winding connection.