# ASPECTS OF THE STUDY OF THE INCREASE OF THE ENERGY EFFICIENCY IN THE OPERATION OF THE INDUCTION MOTORS WITHIN THE ANCILLARY SERVICES OF A THERMOELECTRIC POWER PLANT

# *ASPECTE ALE STUDIULUI CREŞTERII EFICIENŢEI ENERGETICE ÎN FUNCŢIONAREA MOTOARELOR ASINCRONE DIN CADRUL SERVICIILOR AUXILIARE ALE UNEI CENTRALE TERMOELECTRICE*

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***Abstract:*** *In this paper, the authors systematized and interpreted the results obtained by running their own design computing programs, developed using the facilities offered by the Mathcad mathematical software package combined with facilities offered by appropriate custom chart wizard, provided by Excel. These programs were developed based on the algorithms for calculating the parameters of the equivalent scheme, the electrical balance components and the energy efficiency indicators (efficiency, power factor) for a three-phase induction motor with squirrel cage rotor with deep rectangular bars within the ancillary services of a thermoelectric power plant, using a complete mathematical model for different degrees of loading.*

**Keywords**: energetic efficiency; induction motors with squirrel cage rotor; ancillary services of thermoelectric power plants; loading degree; equivalent scheme parameters; charts of active and reactive powers balance; calculation programs Mathcad, Excel.

***Rezumat:*** *În această lucrare, autorii au sistematizat şi interpretat rezultatele obţinute în urma rulării unor programe de calcul de concepţie proprie, dezvoltate folosind facilităţile oferite de pachetul de programe matematice Mathcad combinat cu facilităţi oferite de asistări grafice personalizate adecvate, oferite de Excel. Aceste programe au fost elaborate pe baza algoritmilor de calcul al parametrilor schemei echivalente, componentelor de bilanţ electric şi indicatorilor de eficienţă energetică (randament, factor de putere) pentru un motor asincron trifazat cu rotor în colivie cu bare înalte dreptunghiulare din cadrul serviciilor auxiliare ale unei centrale electrice de termoficare (CET), folosindu-se un model matematic complet pentru diferite grade de încărcare.*

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**Cuvinte cheie:** eficienţă energetică; motoare asincrone cu rotorul în scurtcircuit; servicii auxiliare ale centralelor termoelectrice; grad de încărcare; parametri schemă echivalentă; diagrame de bilanţ puteri active şi reactive; programe de calcul Mathcad, Excel.

## 1. Introduction

The electric drive systems (pump - drive electromotor) are frequently encountered in the thermoelectric power plants, the supply being made to both medium voltage and low voltage.

Thus it is found from Table 1 that there are induction motors powered at medium voltage (6 kV) within the own services of the district heating power plants (CET) with groups of 60 MW using heavy fuel oil, which drives the boiler starter mineral oil pumps or the withdrawal pumps (transfer from one tank to another) of the black fuel oil.

Such a squirrel cage induction motor is the subject to computer-aided design optimization. In the design process of induction motors, it is frequently required to know the variation of the motor parameters depending on the load evaluated by the load degree $\beta_P = P/P_n$, in order to estimate the energy efficiency in their operation.

*Table 1.* **The characteristics of 6 kV motors within the ancillary services of a district heating power plants (CET) with 60 MW groups using black fuel oil**

| **Aggregate name** | **$P_n$ [kW]** | **Total units** | **In conti-nuous operation** | **$I_n$ [A]** | **$n_n$ [ rpm]** | **$\eta_n$ [%]** | **cos $\varphi_n$** | $\frac{I_p}{I_n}$ |
|---|---|---|---|---|---|---|---|---|
| Power pump | 4000 | 2 | 1 | 419.2 | 2985 | 96.2 | 0.91 | 6.3 |
| Circulation pump | 320 | 2 | 2 | 40.8 | 370 | 91.0 | 0.83 | 6 |
| *Boiler starter mineral oil pump* | **200** | **2** | **-** | **26.0** | **1480** | **90.0** | **0.82** | **5.8** |
| Winter heating pump | 1600 | 1 | 1 | 188.3 | 1480 | 94.0 | 0.87 | 5.6 |
| *Transfer pump* | **200** | **1** | **-** | **26.0** | **1480** | **90.0** | **0.82** | **5.8** |
| Acid wash pump | 400 | 1 | - | 49.8 | 1480 | 92.0 | 0.84 | 5.7 |
| Summer heating pump | 800 | 1 | - | 97.4 | 1480 | 93.0 | 0.85 | 6.0 |

Thus, it may appear appropriate from an *energetical point of view*, the replacement of the motors underloaded with others of a rated power closer to the one required by the work machine, having as main positive effects: reduction of the absorbed power and improvement of the power factor [1].

Obviously, the replacement is possible only if the starting conditions and those related to maintaining the operating stability of the respective drive (pump - drive electromotor) are ensured.

The paper highlights the role of computer-aided scientific research in increasing the energy efficiency of induction motors for driving specific aggregates in the energy industry. This gives the possibility to analyze the different operating scenarios of the electric drive systems (pump - drive electromotor) existing on the market of ancillary services.

## 2. Evaluation of the parameters of the equivalent scheme from the catalog data of the induction motor with squirrel cage rotor with deep rectangular bars

The utility of the induction machine equations is conditioned by the knowledge of the parameters of the equivalent scheme. The designer of an electric drive system does not have the machine and therefore cannot obtain its parameters by acquiring the data obtained by the measurements made in the laboratory and processing them *off* or *online* [2].

For the study with the help of mathematical modelling of the different operating regimes of the induction motors, it is necessary to know the parameters of their equivalent scheme. In order to choose the type and the calculation of the parameters of this scheme, several important details are required regarding the determination of the reduced height of the rotor bar ($h'$).

Thus it was taken into account that in the case of induction motors with squirrel rotor cage with deep bars, particular relations of type (1), (2), (3), (4) must be used in order to separate the components of the rotor resistance and reactance.

In these motors, the rotor resistance and reactance depend on the slip, according to the relations (1):

$$R_R^{'} = R_{RV}^{'} k_R + R_{RC}^{'}\,;\; X_{\sigma R}^{'} = X_{\sigma RV}^{'} k_X + X_{\sigma RC}^{'}\,. \tag{1}$$

Considering that the notations have been made: $X_R^{'} = X_{\sigma R}^{'} + X_{\mu}$ and that $X_{\mu}$ it does not depend on slip, the relations (2) can be written:

$$X_R^{'} = X_{RV}^{'} k_X + X_{RC}^{'} \text{ with } X_{RV}^{'} = X_{\sigma RV}^{'}\,;\; X_{RC}^{'} = X_{\sigma RC}^{'} + X_{\mu}\,. \tag{2}$$

where:
$R'_{RV}, X'_{\sigma RV}$ - the phase leakage resistance, respectively reactance corresponding to the portions of the rotor winding contained within the magnetic core of the rotor, relative to the stator;
$R'_{RC}, X'_{\sigma RC}$ - the phase leakage resistance, respectively reactance corresponding to the portions of the rotor winding located outside the rotor core;
$k_R, k_X$ - two functions depending on the slip which for the motors with rectangular section bars have the expressions (3), (4):

$$k_R = \xi \frac{\mathrm{sh}\,2\xi + \sin 2\xi}{\mathrm{ch}2\xi - \cos 2\xi}\,;\; k_X = \frac{1.5}{\xi}\frac{\mathrm{sh}\,2\xi - \sin 2\xi}{\mathrm{ch}\,2\xi - \cos 2\xi} \tag{3}$$

$$\xi = h'\sqrt{s}\,;\; h' = h\sqrt{\frac{\pi f \mu_0}{\rho}\frac{b_b}{b_c}} \tag{4}$$

where:
ξ - a dimensionless size called conventionally, the reduced height of the bar;
$\mu_0$ - the vacuum magnetic permeability;
ρ - the resistivity of the bar material;
$b_b$, $b_c$ - the width of the section of the rotor bar, respectively that of the rotor slot;
*h* - the height of the section of the rotor bar, expressed in cm.

Taking into account the characteristics of the materials used usuallz, at the frequency of 50 Hz was obtained for *copper* $h' = 6h\sqrt{b_b / b_c}$ [1].

From the equivalent schemes of the induction machine (T [1], Π [2]), the equivalent scheme in Π, shown in Figure 1, was chosen for modelling.

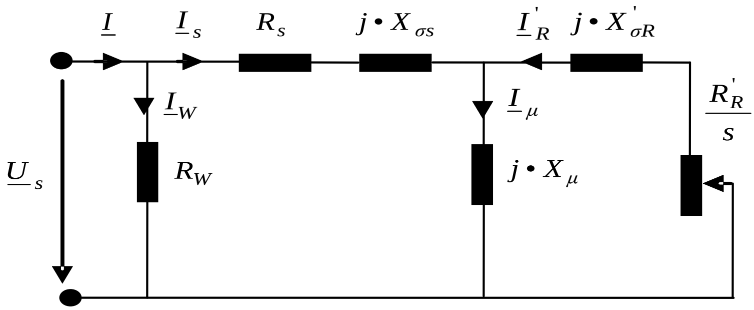


**Figure 1.** The calculation equivalent scheme for the induction motor.

Generally, induction motor parameters are not given in the catalogs of machines manufacturers. However, there is the possibility that, from the catalog data and some additional data that can normally be obtained from the manufacturer, the parameters necessary for mathematical modelling can be determined with sufficient precision.

In order to evaluate the parameters of the equivalent scheme, the authors systematized and completed *the calculation algorithms* existing in the specialized literature [3], [4], which require a minimum of input data, which are used with satisfactory results.

This methodology is based on the mathematical model of the induction motor and its principle consists in imposing the condition that the parameters of the machine are calculated so as to ensure that the values of the state sizes corresponding to the rated regime (absorbed current, power factor, electromagnetic torque) and the principal ones sizes related to the mechanical characteristic (maximum torque and corresponding slip, starting torque) are respected.

Supposedly known: rated power ($P_n$); rated line voltage ($U_n$); rated phase current ($I_n$); rated power factor ($\cos \varphi_n$); rated slip ($s_n$); number of pairs of poles ($p$); maximum torque ($m_m$); starting torque ($m_p$) and starting current ($i_p$); reduced height of rotor bar ($h^{'}$) and iron losses ($P_{Fe}$).

In order to perform the calculations according to these laborious calculation algorithms, **the authors have designed computing programs developed in the Mathcad programming environment version 7.0** [5], which also allow validation of the values calculated by accessible checks.

These programs were supplemented with Excel subprograms thus allowing to obtain additional customized graphical representations like column, line - column in the same system of coordinate axes or line - column on two axes, of the active and reactive powers in absolute and percentage values.

## 3. Case study. Calculation of the components of the electric balance and of the energy indicators for different degrees of load of the induction drive motor, using a complete mathematical model.

The authors analyzed in this study, a motor intended to work within the ancillary (internal) services of a thermal power plant (CET) with 60 MW groups using black fuel oil, which drives the starter boiler mineral oil pumps or the black fuel oil transfer pumps (moving from one tank to another). This induction motor with squirrel cage rotor with deep rectangular copper bars, in the studied construction version, has the following catalogue data, according to Table 2.

This construction variant **MIB2 425M 65-2** of a three-phase induction electric motor (**M**) in closed construction **I** (protection degree IP 44) with deep bar short-circuit rotor (**B**), construction variant **2**, **425M** gauge, has the height of the axis of rotation 425 mm and is a horizontal motor with housing fixing (welded, steel) with soles, two portgear shields, a single shaft end with a diameter of **65** mm and **2** poles.

The motor cooling of closed construction (**MI**) is done by self-ventilation in the closed circuit, with the help of an air-to-air type heat exchanger. The winding insulation is in the insulation class **F**. The motor is coupled directly to the driven mechanism and is intended for continuous operation regime, corresponding to the type **S1** service. The motor with the rotor in short-circuit can be started by direct coupling to the network.

*Table 2.* **The technical characteristics of the drive induction motor**

| Parameter name | Construction variant |
|---|---|
| | MIB2 425M 65-2 |
| Power, $P_n$ [kW] | 225 |
| Rated voltage, $U_n$ [kV] | 6 |
| Rated current, $I_n$ [A] | 24.850 |
| Rated speed, $n_n$ [rpm] | 2974 |
| Power factor, $\cos\varphi_n$ | 0.907 |
| Efficiency, $\eta$ [%] | 96 |
| Rated slip, $s_n = (n_s - n_n) / n_s$ | $0.86136 \cdot 10^{-2}$ |
| Number of poles pairs, $p$ | 1 |
| Starting current reported, $i_p = I_p / I_n$ at $U = U_n$ | 5.4519 |
| Starting torque reported, $m_p = M_p / M_n$ at $U = U_n$ | 0.61360 |
| Maximum torque reported, $m_m = M_{max} / M_n$ at $U = U_n$ | 2.2267 |
| Iron losses, $P_{Fe}$ [kW] | 2.0139 |
| Reduced height of rotor bar, $h'$ [cm] | 2.324 |

*Determination of the parameters of the induction motor with squirrel cage rotor with deep rectangular bars studied.*

Thus, numerical values resulted are synthesized in Table 3, in the order in which they are calculated by the program.

*Electrical balance of the studied drive induction motor, with a complete mathematical model for different load degrees.*

In Table 4 were centralised the components of electrical balance of the studied drive induction motor for *the six analysed operating regimes*: **No load regime** (with the motor mechanically disconnected from the working machine), **Load degree regime** $\beta_P$ = 0.25; 0.5; 0.75; 1 (**Rated regime**); 1.25.

*Table 3.* **The computed parameters of the calculation equivalent scheme for the drive induction motor studied**

| **Parameter name** | **Construction variant** |
|---|---|
| | **MIB2 425M 65-2** |
| Current corresponding to the iron losses, $I_W$ [A] | 0.194 |
| Resistance corresponding to the iron losses, $R_W$ [Ω] | 17880 |
| Phase stator current, $I_{sn}$ [A] | 24.674 |
| Phase resistance of the stator winding at the regime temperature, $R_s$ [Ω] | 1.259 |
| Magnetisation reactance, $X_\mu$ [Ω] | 619.783 |
| Rotor winding resistance reported to stator, $R_R'$ [Ω] | 1.187 |
| Leakage reactance on the stator phase, $X_{\sigma s}$ [Ω] | 18.593 |
| Leakage reactance on the rotor phase, reported to stator, $X_{\sigma R}'$ [Ω] | 13.878 |

*Table 4.* **Electrical balance components of the studied drive induction motor**

| **Component name** | **Construction variant** | | | | | |
|---|---|---|---|---|---|---|
| | **MIB2 425M 65-2** | | | | | |
| | **No load** | $\boldsymbol{\beta_P}$ **= 0.25** | $\boldsymbol{\beta_P}$ **= 0.5** | $\boldsymbol{\beta_P}$ **= 0.75** | $\boldsymbol{\beta_P}$ **= 1** | $\boldsymbol{\beta_P}$ **= 1.25** |
| Joule losses in the stator winding, , $P_s$ [kW] | 0.112 | 0.234 | 0.628 | 1.307 | 2.3 | 3.659 |
| Iron losses, $P_{Fe}$ [kW] | 2.0139 | | | | | |
| Joule losses in the rotor winding, $P_R$ [kW] | 0.0003 | 0.112 | 0.468 | 1.082 | 1.98 | 3.209 |
| Mechanical losses through friction and self ventilation, , $P_{mv}$ [kW] | 2.934 | | | | | |
| Active power absorbed from the network, $P_A$ [kW] | 5.059 | 58.557 | 117.114 | 175.671 | 234.228 | 292.785 |
| Output power available at the shaft, , $P_a$ [kW] | 0 | 53.264 | 111.071 | 168.335 | 225 | 280.969 |
| Efficiency, , $\eta$ [%] | | 90.96 | 94.84 | 95.824 | 96.1 | 95.964 |
| Reactive power covering stator dispersion, , $Q_{\sigma s}$ [kVAr] | 1.647 | 3.46 | 9.267 | 19.29 | 33.959 | 54.02 |
| Reactive power covering rotor dispersion, , $Q_{\sigma R}$ [kVAr] | 0.003 | 1.306 | 5.468 | 12.648 | 23.153 | 37.519 |
| Reactive power needed magnetization machine, $Q_\mu$ [kVAr] | 54.739 | 54.409 | 53.785 | 52.872 | 51.639 | 50.037 |
| Absorbed reactive power, $Q_a$ [kVAr] | 56.389 | 59.174 | 68.52 | 84.81 | 108.752 | 141.576 |

| **Component name** | **Construction variant** | | | | | |
|---|---|---|---|---|---|---|
| | **MIB2 425M 65-2** | | | | | |
| | **No load** | $\beta_P$ **= 0.25** | $\beta_P$ **= 0.5** | $\beta_P$ **= 0.75** | $\beta_P$ **= 1** | $\beta_P$ **= 1.25** |
| Apparent power, , $S_a$ [kVA] | 56.616 | 83.25 | 135.686 | 195.072 | 258.243 | 325.218 |
| Power factor, cosφ | 0.089 | 0.703 | 0.863 | 0.901 | 0.907 | 0.9 |

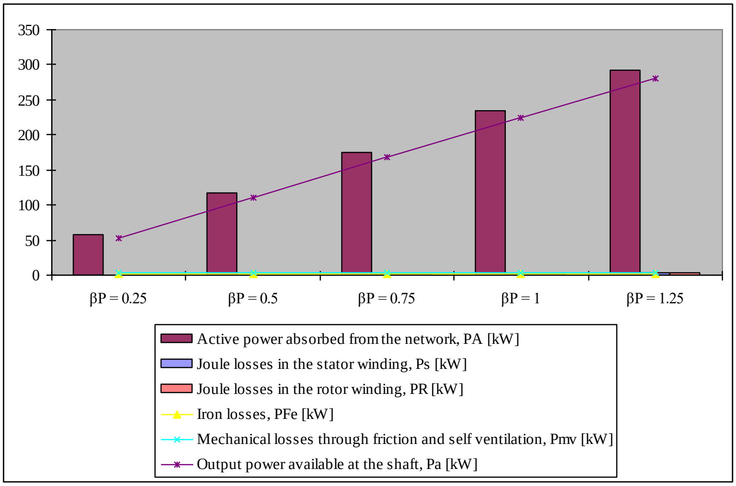


**Figure 2.** Electrical balance diagram of active powers in absolute values [kW] of studied drive induction motor

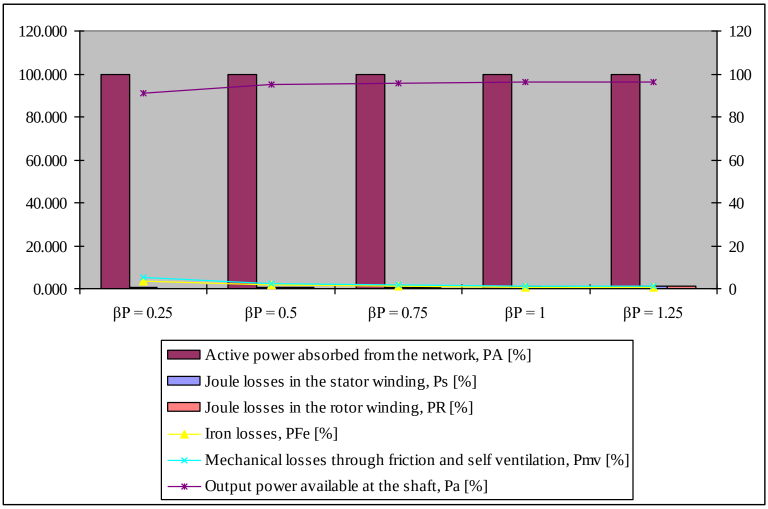


**Figure 3.** Electrical balance diagram of active powers in percentage values [%] of studied drive induction motor

Table 4 shows that:

- The supply voltage being the same, *the iron losses will have the same value* as in the rated regime and for the other studied regimes, $P_{Fe}$ = 2.0139 kW.

- The increase of the speed being insignificant, thus *mechanical losses can be considered as having the value determined for the rated regime*, $P_{mv}$ = 2.934 kW.

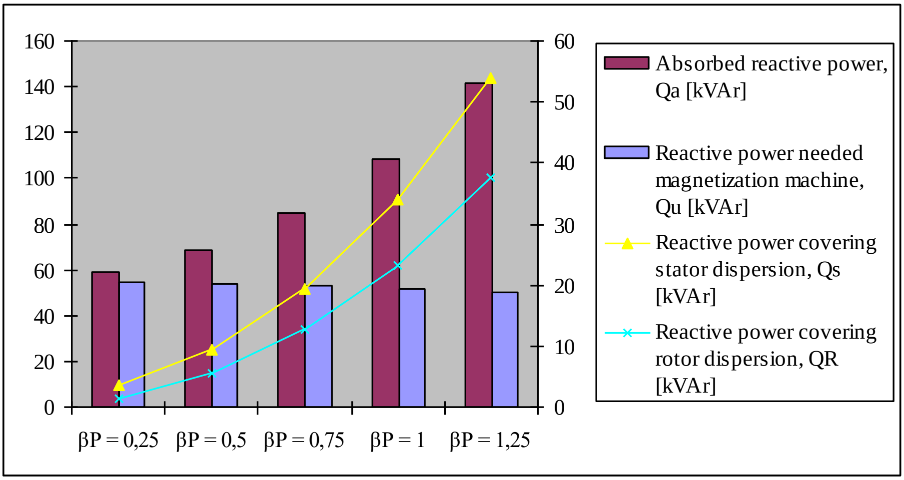


**Figure 4.** Electrical balance diagram of reactive powers in absolute values [kVAr] of studied drive induction motor

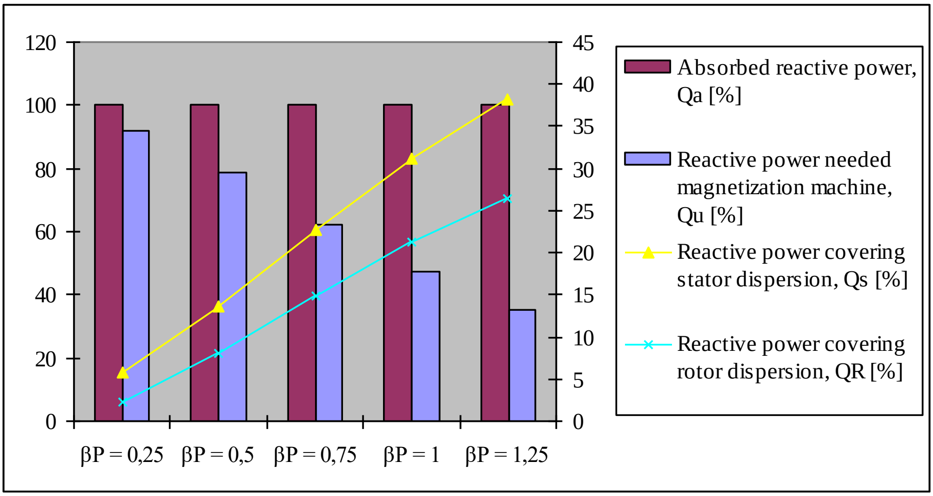


**Figure 5.** Electrical balance diagram of reactive powers in percentage values [%] of studied drive induction motor

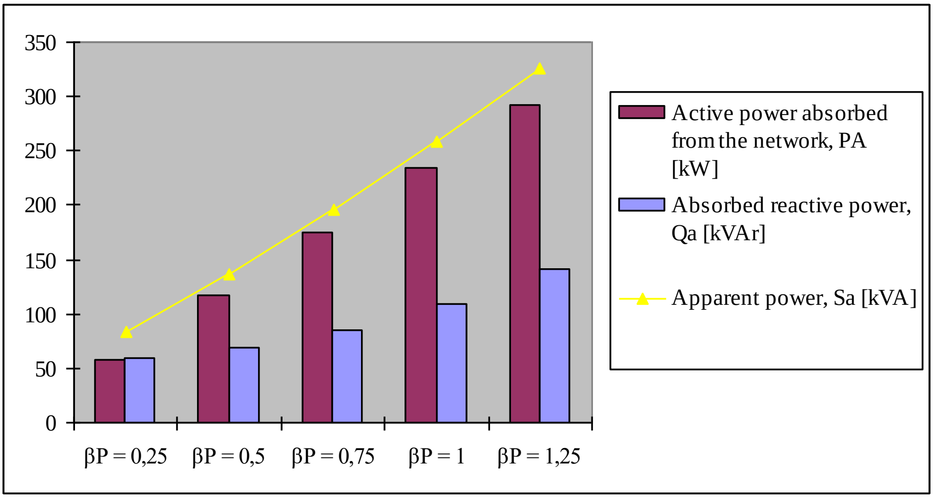


**Figure 6.** Electrical balance diagram of powers in absolute values of studied drive induction motor

**-** The efficiency for **load degree regime** $\beta_P$ = 0.25 will be 94.651% of the rated efficiency and the power factor will be 77.508 % of the rated power factor.

**-** The efficiency for **load degree regime** $\beta_P$ = 1.25 will be 99.858% of the rated efficiency and the power factor will be 99.228 % of the rated power factor.

Also the authors have graphically represented balance Sankey diagrams of active powers in absolute values (Figure 2) and percentage (Figure 3), of reactive powers in absolute values (Figure 4) and percentage (Figure 5) and of powers in absolute values (Figure 6) of the studied drive induction motor.

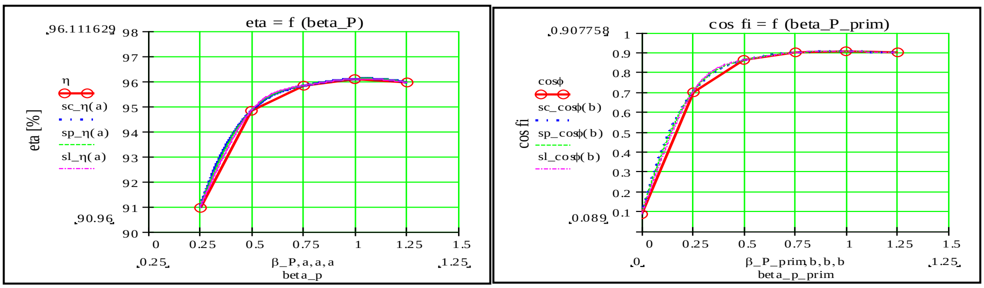


**Figure 7.** The variation of the energy indicators of the studied drive induction motor according to the load degree

To approximate the variation functions of the energy indicators $\eta$ = f ($\beta_P$) and cos$\varphi$ = f ($\beta_P$) *the cubic spline interpolation* was used in three different forms [5] (*cspline* - third order spline function, resulting in a cubic curve between the nodes; *pspline* - second order spline function resulting in parabola segments connected between nodes; *lpline* - first order spline function resulting in a polygonal line between nodes). In Figure 7 were represented in addition to the values of these indicators obtained from the calculation and the curves obtained by these interpolations.

The analysis of the calculated values of the efficiency and the power factor presented in Table 4 and of the corresponding characteristics represented in Figure 7, shows that when operating with loads $\beta_P > 0.75$, the values of these indicators are practically those of the rated regime.

Only if the motor operates on loads $\beta_P < 0.75$, can be taken into consideration the problem of replacing it with a similar motor of lower rated power and whose energy indicators (efficiency, power factor) have to comply with certain conditions [6], [ 7], [8], [9], this solution leading to the reduction of active power losses.

## 4. Conclusions

The comparative study of the variation of the motor parameters according to the load, emphasized the necessity and the opportunity to extend the electric balance analysis of the studied motor, using the complete mathematical model, for different load degrees of motor (no-load regime, rated regime and respectively any load regime).

It is worth pointing out the originality of the solution chosen by the authors (applicable to any other three-phase induction motor of this type), who designed the calculation programs using the facilities offered by the Mathcad mathematical program package (personalized interpolation, providing exact and precise numerical values, of the coordinates of the maximum point of the graphically represented characteristics, etc.) combined with those of the appropriate custom graphic assistance, provided by Excel.

This type of analysis provides the primary data needed to take measures to reduce the different categories of active losses or to compensate the reactive power, allowing the functional-constructive optimization of the studied motor and implicitly improving its energy efficiency.

## ACKNOWLEDGMENT

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