Determination of the capacity of capacitor banks for the improvement the power factor of electric drives through interval assessments

Zlatin ZLATEV, Antoaneta DIMITROVA
Trakia university, faculty of "Technics and technologies",
38 Graf Ignatiev str., 8602, Yambol, Bulgaria
e-mail: zlatin.zlatev@trakia-uni.bg

Abstract: *The article presented a study on the possibility of using interval assessments in determining the optimal capacity of capacitor banks for improvement of the power factor of electric drives. For this purpose has been developed simulation test bench and the results are validated using real electric motor. Proven is the possibility of using interval evaluation criteria by area under the curve and Akaike information criterion in determining the optimal capacity of capacitor banks for improvement of the power factor of electric drives. The results obtained confirm those from other authors in the study of methods to improve the power factor of electric drives as a complement with the proposed methods for interval assessment, which is a prerequisite for their successful use in practice.*

Key words: *Power factor improvement, Electric drives, Capacitor banks, Interval assessments*

1. Introduction

The electrical drives consume about 70% of the electricity in industry. Therefore, effective use of that electricity is of great economic and technological matters. Continually doing research and developing methods aimed at improving the energy efficiency of asynchronous motors, as even the smallest increase lead to substantially reduce the cost of electricity [1].

Efforts to reduce electricity consumption in the world are focused on three-phase asynchronous motors, one of the largest consumers. Accepted normative documents establish mandatory requirements for minimum levels of efficiency for electric motors, concluded voluntary agreements to reduce the use of electric motors of low energy class [2].

Thein and Cho [3] review methods to improve power factor (cosφ) through capacitor installed on the motor in operation; by capacitor banks with fixed KVAr, located in one or several locations in the supply systems of the plants. It should be observed load of motors if less than nominal can occur big resonance current, potentially dangerous to the system through automatic capacitor battery that maintains the preset value of the power factor. This is achieved by using a programmable logic controller (PLC) that provides a foot switch in according to the reactive power. The fourth method is a combination of the preceding, on the basis of careful analysis in order to reach the best solution depending on the load.

In the article of Sapna and Garg [4] is made simulation study of induction motors using Simulink Toolbox and its appropriate library. The simulation model is discussed without included capacitors at different loads and then adding them in the simulation at constant load. Has been achieved increase cosφ of 0,17 in unloaded induction motor to 0,95 at full load.

Chingale at al [5] consider switching capacitor cells by PLC controller. In this study are used three-phase asynchronous motor with short-circuited winding with a rated voltage of 250/440V, rated current 3,9/2,25 and rated power 2,5kW. For smooth change of the power factor from 0,35 to 0,85 were selected set of three capacitor banks. Each bank is connected between each phase and neutral star. Each capacitor bank has three capacitors from 2,5μF, 4μF and 10μF and rated voltage of 250V line to neutral.

In the article of Sujit et al [6] is given the opportunity to correct the the power factor for single phase induction motor using the PLC controller for switching capacitor banks of different capacities. The capacitor bank contains capacitors with a capacity of 2,5, 4, 8 and 10 μF. A system has been developed that switched capacitor bank when power factor drops below a certain value. PLC is used to control the on/off mode of the capacitor bank for improvement of the power factor.

From the analysis of the publications in the area of improving the the power factor of electric motors and drives with capacitor banks can be summarized that:

➢ For more precise control of operation of the electric motor using several capacitor banks that are sequentially included in the power circuit to the motor via a programmable controller;

➢ In the popular publications are used complex algorithms to determine the optimal capacity of capacitor banks as neural networks, genetic algorithms;

➢ The studies in recent years have been aimed at the use of simulation models to determine the optimal parameters of capacitor banks;

➤ The extraction of relevant information from measured data for electric motors needed for analysis is difficult.
➤ The development of mathematical modeling and computer technology enables the development of effective methods of processing and analysis of data.
➤ There is a need in-depth analyzes of previously known methods and applied approaches that lead to improve and facilitate the process of determining the optimum parameters of the capacitor banks and electric drives as a whole with a view to integration into automated systems.

The aim of the article is to propose approaches, algorithms and appropriate procedures for determining of the capacity of capacitor banks for improvement of the power factor of electric drives.

The paper is organized in the following order: presented are the materials used and methods;

research was conducted in two stages – investigation with simulation test bench and test procedures developed on a real electric motor; discussion is made and the results were compared with those known from the literature; Finally are presented summaries and conclusions.

2. Material and methods

Used electric motors. Parameters of used in the study electric motors are presented in Table 1. Energy-efficient and energy-inefficient electric motors are used in the simulation study to determine the required capacity of capacitor banks for improvement of the power factor. The test electric motor is used to validate the results of the study and did not participate in the drafting of the methodology of work.

Table 1.
Parameters of electric motors used in the study

Electric motor	U, V Y/Δ	I, A Y/Δ	P, W	rpm, min⁻¹	cosϕ	L, mH	R, Ω
Energy-efficient	400/ 230	0,93/ 1,6	370	1440	0,72	118,3	12,4
Energy-inefficient	400/ 230	1,2/ 2,1	370	1380	0,76	102,5	20,8
Test	400/ 230	0,76/ 1,32	250	1350	0,79	146,1	40,8

Determination of the capacity of the capacitor from capacitor bank. Figure 1 presents the relationship between active, efficient and reactive power and the angle of dephasing, cosine from which determines the power factor. If adding the capacitor in parallel to the load the reactive power will decrease. The difference between the initial reactive power Q_1 and after this

binding of the the capacitor Q_2 is denoted by Q_c. The capacity of the connected capacitor depends on the reactive power Q_c, VAr, the frequency f, Hz and the voltage drop across the load V_{rms}, kV. Figure 2 shows the resulting new capacity when the capacitor is connected in the circuit.
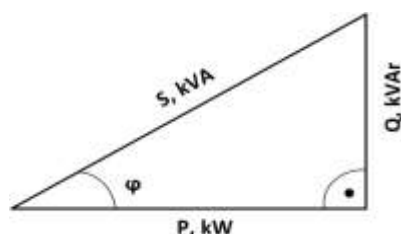

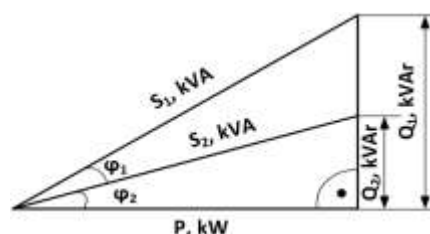Fig.1. Relationship between active, efficient and reactive power

Fig.2. Relationship between active, efficient and reactive power at amending the power factor

Determination of power factor:

$$PF_1 = cos\varphi = \frac{P}{S} \qquad (1)$$

where f, Hz is the frequency of voltage; P, W - Active Power; S, VA - full power.

The requested power factor is:

$$PF_2 = cos\varphi_2 \qquad (2)$$

The total reactive power is determined by:

$$Q_c = Q_1 - Q_2, kVAr \qquad (3)$$

where Q_1, VAr is the initial reactive power; Q_2, VAr - reactive power for searched power factor.

The capacity of capacitor from the capacitor bank is defined by:

$$C = \frac{Q_c}{\omega V_{rms}^2}, F \qquad (4)$$

where:

$$\omega = 2\pi f, \frac{rad}{s} \qquad (5)$$

Area under curve. The criterion area under the curve (AUC) is used in the identification of processes for their comparison. For the calculation of the criterion function *trapz* in Matlab is used [7], where the calculation is the trapezium rule and is defined in the interval [a, b] as:

$$AUC = \int_{a}^{b} f(x)dx \approx \frac{1}{2}\sum_{n=1}^{N}(x_{n+1} - x_n)[f(x_n) + f(x_{n+1})] \quad (6)$$

where $(x_{n+1} - x_n)$ is the distance between any two points on the resulting curve; N – the number of the measured values.

Akaike information criterion. The criterion of Akaike (AIC) is a criterion for the evaluation of the model. After calculating the number of different models, they can be compared with this criterion. Suitable is the model, in which the criterion has the least value. To determine the values of this criterion is used *aic* command in Matlab [9], where AIC is defined as:

$$AIC = N.\log\left(det\left(\frac{1}{N}\sum_{1}^{N}\varepsilon(t,\hat{\theta}_N)\left(\varepsilon(t,\hat{\theta}_N)\right)^T\right)\right) + 2n_p$$
$$+ N.\left((n_y.(\log(2\pi) + 1)\right) \quad (7)$$

where N is the number of measured values; $\varepsilon(t)$ – vector size n_yx1 of prediction errors; θ_N – calculated parameters; n_p – number of estimated parameters; n_y – number of outputs of the model. The coefficients of the models used to estimate the output data with AIC were determined by autoregression model in Matlab [9].

Description of the experimental test bench. The examination of the results obtained was made on a real test bench to which is plugged the test electric motor.

The experimental test bench is operated with multimedia interactive environment LabSoft [10]. In this software (Figure 3) are provided virtual instruments for measurements in real time and generating output signals.
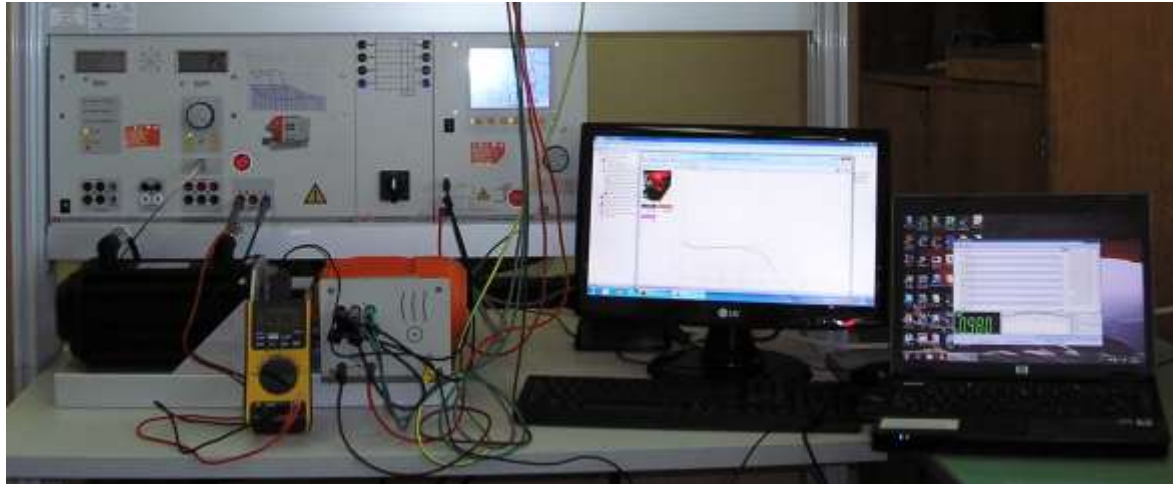

Fig. 3. Experienced test bench – general view

The module for control and testing of servomotors is used for testing of electrical machines and drives. It consists of a device for digital control, brake, automatic and manual synchronization. The connection of this module to a personal computer by means of USB interface. For managed machine is provided thermal protection. Its program assurance is the product "Active Servo" in which it is possible to obtain performance of the tested electric motor: speed; mechanical, complete, active, reactive power; voltage and current per phase; power factor (cosφ); efficiency. Through the software product can be simulated electromechanical systems such as pump, fan, compressor, lifting machine, machine for metal sheets, inertial wheel. Can be determined regime parameters of electromechanical system with various types and value of motor loads.

3. Results and discussion
On the first stage of the study was used a simulation model of energy efficient and energy inefficient motors.

It is developed simulation model in Matlab / Simulink for the Study of electric motors. In figure 4 is a developed model in a general form. The motor is powered by block for three phase power supply. Used is simulation block for measuring current and voltage in three-phase circuit. Since the output of this block is output current and voltage of three phases is necessary the output signal to be demultiplexed. In the block of three-phase asynchronous electric motor are entered

its parameters including nominal supply voltage, power, connection of stator winding rated current, rated speed, inductance and resistance for the rotor and stator windings.
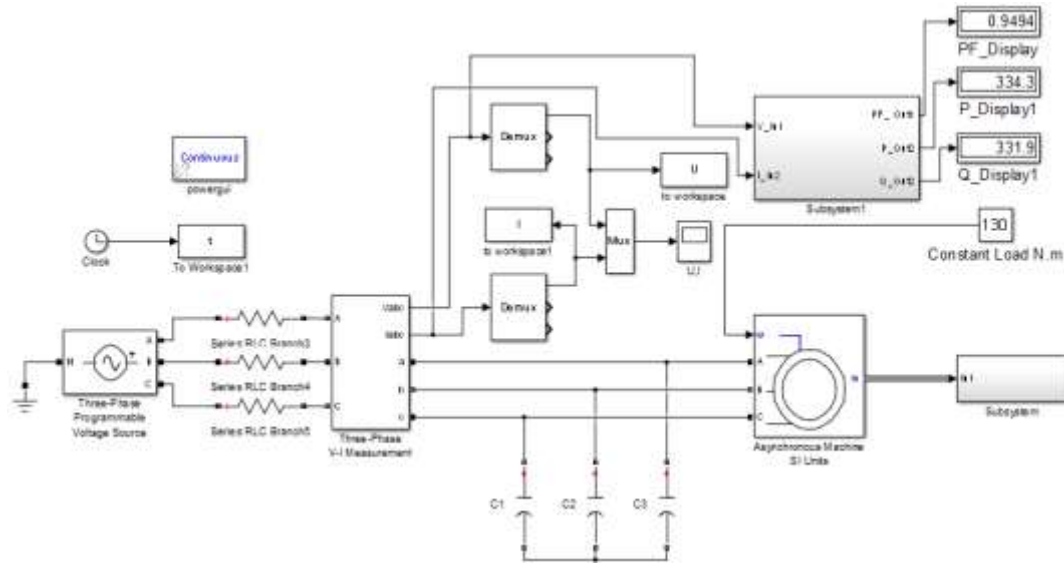

Fig.4. Simulation test bench to determine the power factor of the three-phase asynchronous electric motor

In figure 5 is a model for determining the the power factor, active and full power of electric motor. the demultiplexed signal of voltage and current for one phase is fed to the block for determining reactive, active power and the power factor. In the development is used methodology presented in [11].
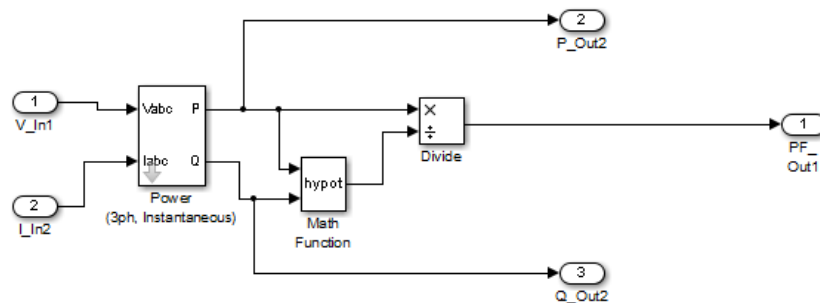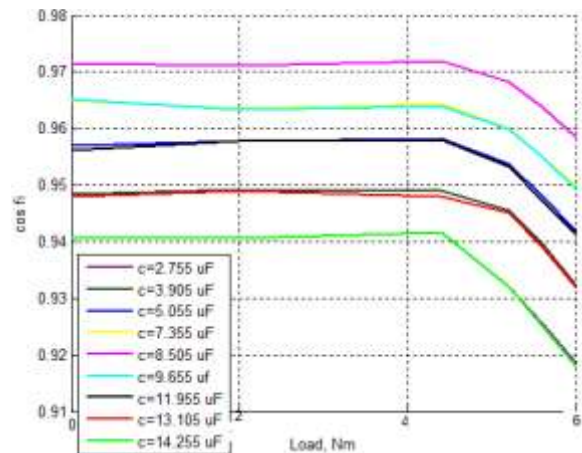

Fig. 5. Block to determine the the power factor (Subsystem1)

Figure 6 presents in graphical form obtained values for power factor for energy efficient and energy inefficient electric motor at different capacitance of a capacitor bank.
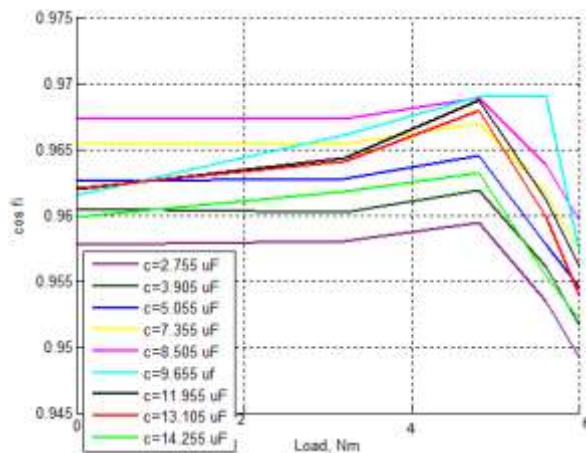
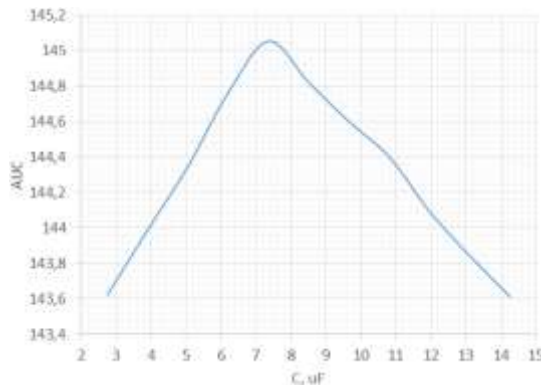a) Energy efficient electrical motor

b) energy inefficient electrical motor

Fig. 6. Power factor of simulated electric motors in a different capacity capacitor bank

By increasing of the capacity of capacitor bank increases and power factor. This improvement is at the expense of increased power consumption from the electric motor reaching current values 1,5A.

In Figure 7 are presented in graphical form results obtained values of area under the curve (AUC) for the power factor of electric motors in a different capacity of capacitor bank. Through second derivative is determined point of change of direction of the resulting characteristics. For energy efficient electric motor it is at C=7,31uF, and for energy inefficient at C=7,47uF.
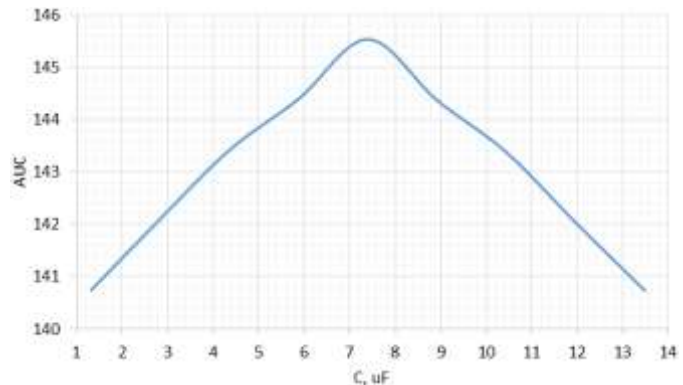
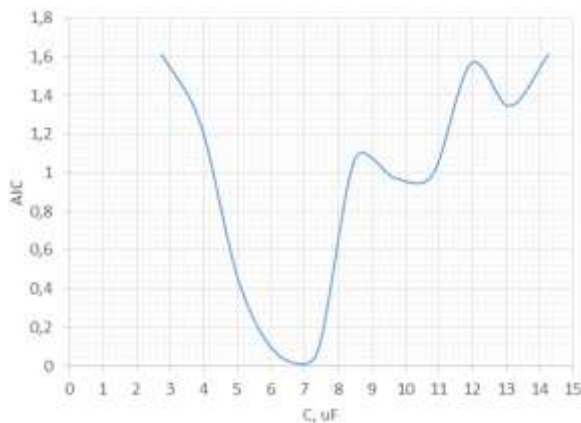a) Energy efficient electrical motor   b) energy inefficient electrical motor
Fig.7. Area under curve for power factor depending on capacity of the capacitor bank

In Figure 8 are presented in graphical form results obtained values of Akaike criterion (AIC) for the power factor of electric motors in a different capacity of capacitor bank. Through the second derivative is determined point of change of direction of the resulting characteristics. For energy efficient electric motor it is at C=7,21uF, and for energy inefficient at C=7,42uF.

The results obtained show that in the energy efficient electric motor requires less capacity of the capacitor battery, which will lead to less power consumption.
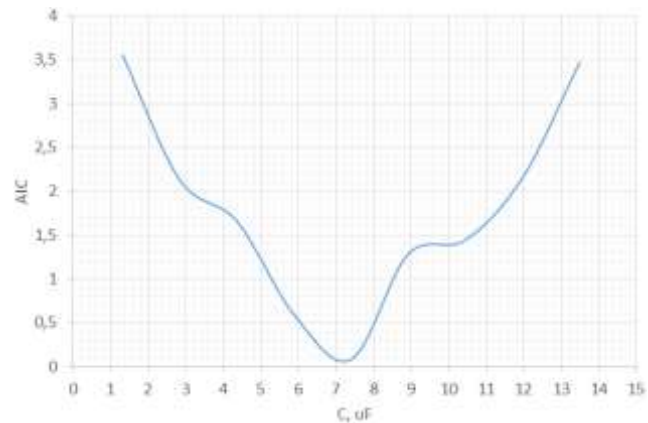
a) Energy efficient electrical motor   b) energy inefficient electrical motor
Fig.8. Akaike information criterion for power factor depending on capacity of the capacitor bank

The second stage of the work is related to the validation of the results and verify the methodology of work. The validation of the results was done by measuring the parameters of the electric motor on a real experimental bench. In a different load in the range L=0-150N.m are determined effective values of current and voltage of one of the phases of the motor, the active and reactive power and power factor. For the same motor by entering parameters in the simulation test bench were obtained data on the same parameters set of the real bench.

Figure 9 shows the change of the power factor for real and simulated motor and the necessary capacity of a capacitor from the capacitor bank to its compensation.
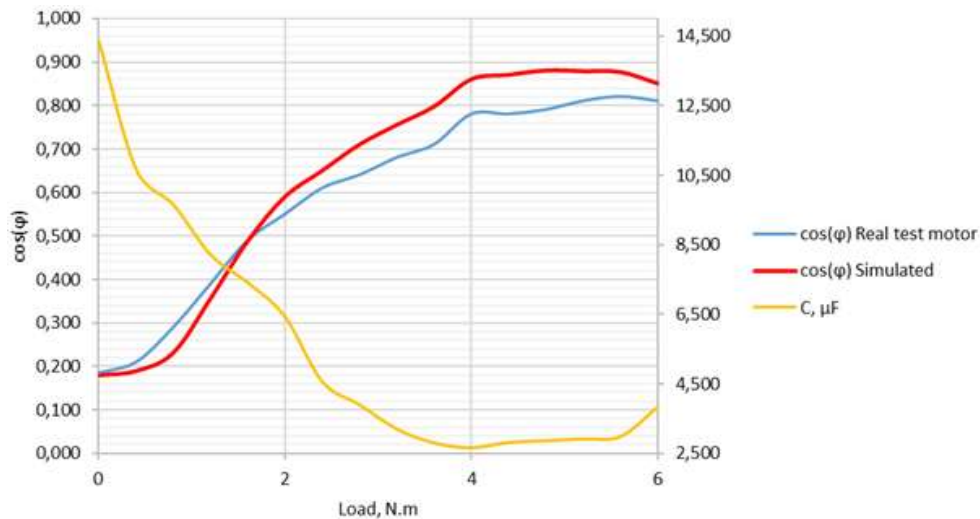
Fig.9. Power factor and capacitance of a capacitor bank for real and simulated electric motor

Studied is the change of the power factor depending on the capacity of the used capacitor banks. Four variation range of capacities are defined and found their influence. In Figure 10 is presented method provided for selecting of the capacity of capacitor bank via the second derivative of the resulting characteristic.
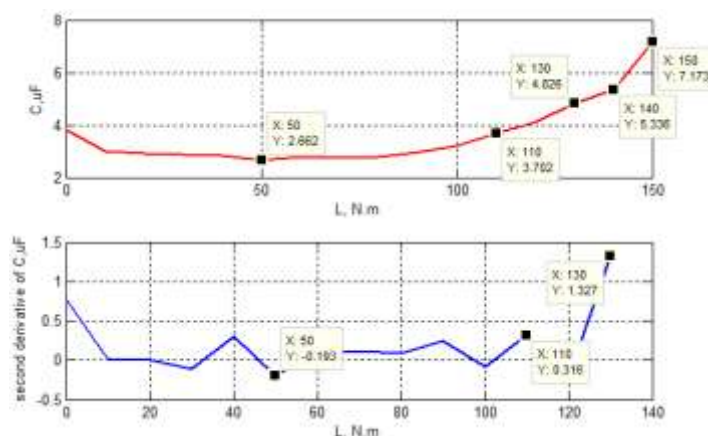

Fig.10. Determining the capacitance of a capacitor bank by second derivative

Figure 11 illustrates the change of the power factor depending on the capacity of the capacitor bank. Visualized is the change of the power factor with the inclusion of capacitor bank. By increasing of the capacity of capacitor bank increases power factor.
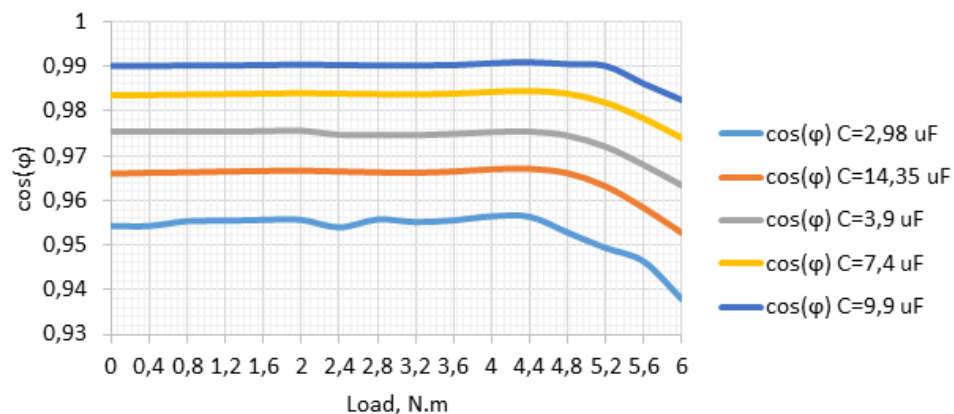

Fig.11. Power factor of real and simulated electric motor in a different capacity of capacitor bank

Figure 12 shows the results in determining the area under the curve (AUC) and Akaike criterion (AIC) for the capacitance of a capacitor bank that obtains optimal power factor over studies real electric motor.
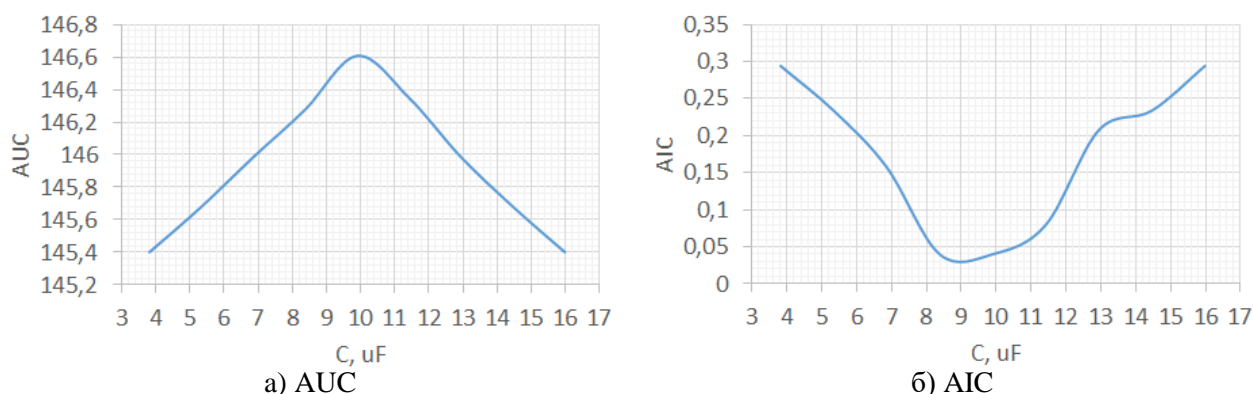

a) AUC   б) AIC

Figure 12. Area under the curve and the criterion of Akaike for the studied real electric motor

Through second derivative is determined point of change of direction of the resulting characteristics. Using area under the curve it is at C=9,91uF, and for AIC at C=8,89uF.

An comparison of results for real motor it has been verified by the correlation coefficient between the values of the power factor generated by the bench and the real electric motor. An examination of the possibility of using this criterion having verified the homogeneity of the data and the distribution, which is normal. The results showed a correlation coefficient R=0,89 between data on real and simulated electric motor.

The results of the research show that for determining of the capacity of capacitor banks by which to improve the the power factor of the electric motor included in the electric drives system can be used the proposed simulation bench.

The proposed procedures using interval assessments - area under the curve and Akaike criterion can be used to determine the optimal capacity of capacitor bank.

From the results it is clear that increasing the value of the capacitance of a capacitor bank than optimal results in a deterioration of the power factor. This is due to the phase shift of current and voltage, which increases with increasing the capacity of the capacitor bank. The larger capacity of capacitor banks leads to increase of current consumed from the motor.

The results of these studies confirm the literature [5, 12], wherein the authors indicate that the use of a capacitor banks improves the power factor of the motor by 43%.

The results are confirmed by research of [4, 13] where is indicated that a precise determination of the capacity of the capacitor bank to ensure optimal performance of the motor.

The studied electric motors are low power and improvement of the power factor requires single capacitor bank. If necessary, several capacitor banks which to be switched depending on the load of the motor can be used in programmable logic controller (PLC), as used in [5, 6, 14].

The use of capacitor banks directly connected to the motor, based on the simulation test reduces the use of reactive energy. The realized savings are within 15%. The capacitors are small and the return on investment is up to one year. Their lives are usually over 20 years, and the savings made accumulate for decades.

4. Conclusion

In the article is presented a study on the possibility of using interval assessments in determining the optimal capacity of capacitor banks for improvement of the power factor of electric drives. For this purpose is used a simulation test bench, and the results have been validated using a real electric motor.

The proposed simulation test bench facilitates and improves the work in determining the necessary capacity of capacitor banks because they do not require the use of a real electric motor and allows conducting research under conditions that are unfavorable for the studied electric drive. The use of the developed test bench requires basic parameters of the motor and information about driven electromechanical system.

Proven is the possibility of using interval evaluation criteria by area under the curve and Akaike criterion in determining the optimal capacity of capacitor banks for improvement of the power factor of electric drives. The effectiveness of the use of these methods is proven by the study results.

The criterion area under the curve is more suitable for practical application of the procedures developed since the resulting graphic results visually better vary the operating modes and the electric motor and facilitate the determination of the optimum capacity of the capacitor bank.

The results obtained confirm those from other authors in the study of methods to improve the the

power factor of electric drives as a complement with the proposed methods for interval assessment, which is a prerequisite for their successful use in practice.

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