ISSN 1330-3651
UDC/UDK 621.313.323.013.8:510.64

APPLICATION OF FUZZY LOGIC FOR REACTIVE POWER COMPENSATION BY SYNCHRONOUS MOTORS WITH VARIABLE LOAD

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Original scientific paper
Synchronous motors which are over-excited in the branched radial network, to which a large number of high-voltage asynchronous motors and transformer stations are connected, can operate as synchronous compensators. By adjusting the excitation current on the rotor, synchronous motors can be supplied by appropriate active power $P \approx P_r$ = const. from the network, and send reactive power back to the network $Q = f(I_e)$ and thus improve the power factor. The adjustment of synchronous motor excitation current depends on the load, and it is necessary to analyze the load by measuring electrical quantities of a synchronous motor with variable load. This paper presents an analysis of synchronous motor loads, using fuzzy c-clustering method. A classification of load groups has been designed and the maximum load for certain working conditions has been determined as well as currents of excitation circuit in the given conditions.

Keywords: *synchronous motor, excitation current, fuzzy c-clustering method*

Primjena neizrazite logike za kompenzaciju reaktivne energije sinkronim motorima s promjenjivim opterećenjem

Izvorni znanstveni članak
Sinkroni motori koji su prepobuđeni u razgranatoj radijalnoj mreži, u kojoj je priključen veliki broj asinkronih visokonaponskih motora i transformatorskih postaja, mogu raditi kao sinkroni kompenzatori. Podešavanjem uzbudne struje na rotoru, sinkroni motori mogu iz mreže uzimati odgovarajuću aktivnu snagu $P \approx P_r$=const., a u mrežu vraćati reaktivnu energiju $Q = f(I_e)$ i tako popravljati faktor snage. Podešavanje struje uzbude sinkronog motora ovisi o opterećenju, te je neophodno napraviti analizu opterećenja mjerenjem električnih veličina sinkronog motora s promjenjivim opterećenjem. U radu je prezentirana analiza opterećenja sinkronog motora korištenjem neizrazite logike c-načina grupiranja. Napravljena je klasifikacija opterećenja po skupinama, određeno maksimalno opterećenje za pojedine radne uvjete te određene struje uzbudnoga kruga u zadanim uvjetima.

Ključne riječi*: sinkroni motor, struja uzbude, neizraziti c-način grupiranja*

1 Introduction

Synchronous motors, installed on EŠ-6/45 excavators and over-excited in a highly branched mine radial network, to which a large number of high-voltage asynchronous motors and transformer stations are connected, can operate as synchronous compensators. By adjusting the excitation current on the rotor, synchronous motors can be supplied by appropriate active power $P \approx P_r$ = const. from the network, and send reactive power back to the network $Q = f(I_e)$ and thus improve the power factor in the 6 kV mine network. The adjustment of the synchronous motor excitation current depends on the load, and it is necessary to analyze the loads by measuring electrical quantities of the synchronous motor with variable load. Synchronous motors, due to their structural design, have an advantage over other electric motors because, in addition to their basic application, they can operate as reactive power compensators. This type of compensation is often used in practice and can simply be applied to motors that have the constant and uniform load. In drives with variable load it is not easy to determine the limits because the load is changing at any moment. It is necessary to determine the maximum values of the excitation current and reactive power increase. Each motor has been designed for a certain rated power up to which it can be loaded.

Research has been done on synchronous motor with S = 630 kV·A rated power, installed on the EŠ-6/45 excavator, which drives the main generator group of excavators through which DC motors are powered, which again continue to drive the working mechanisms of excavators. Excavators operate in cycles, repeating the same action – digging – turning - dumping, thereby changing the load depending on the depth of excavation and ground hardness. For determination of the synchronous machine load, it would be necessary to make a large number of complex geological measurements, which is, in such a short time, practically impossible. The measurement of load on the synchronous motor shaft where all loads are added is a far more effective method. Excavators operate 23 hours a day. Work is interrupted once a week due to regular maintenance, so a large number of data is obtained and has to be classified. The data is registered every second, so within a period of one week a huge amount of data is obtained. The cycle duration ranges from 30 to 43 seconds and is variable in terms of load, depending on external influences, ground type and the open pit depth.

2 Compensation of reactive power by synchronous motor with salient poles

A synchronous motor with salient poles can be described by the following equations [1]:

The apparent power formula is: $S = \sqrt{P^2 + Q^2}$. (1)

Active power:

$$P = 3 \cdot \frac{U \cdot E}{X_d} \cdot \sin\delta + 3 \cdot \frac{U^2 \cdot \sin 2\delta}{2} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d} \right). \quad (2)$$

Reactive power:

$$Q = -\frac{3 \cdot U \cdot E}{X_{\mathrm{d}}}\cos\delta + 3 \cdot U^2 \left(\frac{\sin^2\delta}{X_{\mathrm{q}}} + \frac{\cos^2\delta}{X_{\mathrm{d}}} \right). \tag{3}$$

Moment:

$$M = \frac{3 \cdot U \cdot E}{\omega \cdot X_{\mathrm{d}}} \cdot \sin\delta + \frac{3 \cdot U^2 \cdot \sin 2\delta}{2 \cdot \omega} \cdot \left(\frac{1}{X_{\mathrm{q}}} - \frac{1}{X_{\mathrm{d}}} \right). \tag{4}$$

The synchronous motor installed on the EŠ-6/45 excavator has a variable load that is cyclically repeated on the same schedule: digging-turning-dumping. The excavator starts from an operating point that is at the same level with pedestal and can dig up to a depth of 32 m. By increasing the digging depth the loads are increased and thus the active power increases at the same time, but the amount of delivered reactive power is reduced. The reactive power change is performed by changing the excitation current.

The reactive power compensation by using synchronous motors is significant since it does not require any investments. The change of excitation current value is sufficient. It is therefore necessary to make long-term measurements of active and reactive powers and to conduct data analysis. The obtained data should be properly classified. The problem which arises is two-dimensional, where the requirement $S > \sqrt{P^2 + Q^2}$ must be satisfied. The above mentioned task can be resolved by using fuzzy logic or c-clustering method. This is necessary for calculating the demands for active and reactive power and related daily energies, as well as for establishing the sensitive system of the excitation regulation with fast response and pattern recognition.

3 Fuzzy C - Clustering

Fuzzy c-clustering method (FCM) is an algorithm of sample grouping where each point in the set of samples belongs to the group of the next degree determined by the membership degree [2]. FCM divides a group of samples $X = (x_1, x_2, ..., x_n)$, which represent points in p-dimensional Euclidean space, where the number of c-groups is pre-determined and locates group centers in each group. The sample can be determined by the degree of affiliation to one or more groups. This method was developed by Bezděk in 1981. FCM is such that a sample can belong, according to its value, to several groups [3], with the membership degree specified by the membership degree between 0 and 1. Any $\boldsymbol{U}$ matrix represents a single c-partition or a matrix with as many rows as there are groups (c) and as many columns as there are members (n) in the set.

$$\boldsymbol{U} = [\boldsymbol{U}], i = 1,...,c; j = 1,...,n \tag{5}$$

where:
u_{ij} – is a number from 0 to 1 which represents the degree at which element x_j belongs to the i-th group.

The goal of FCM is to determine which $\boldsymbol{U}$ matrix best divides the space of the given set. The objective function is:

$$J = \sum_{i=1}^{c} \sum_{j=1}^{n} u_{ij}^m \left\| x_j - v_i \right\|^2 \tag{6}$$

where:
m – $m \in [1, \infty)$ is the exponential weighting factor which affects the degree of fuzzyfication of the accompanying $\boldsymbol{U}$ matrix,
$\| x_j - v_i \|$ – is Euclidean distance between i-th center and j-th data sample.

Fuzzy distribution of samples ends with achieving the minimum of the function from the relation (6), with actualization of membership matrix,

$$\boldsymbol{u}_{ij} = \frac{1}{\sum_{k=1}^{c} \left(\frac{\left\| x_i - v_i \right\|}{\left\| x_j - v_k \right\|} \right)^{\frac{2}{(m-1)}}}, \tag{7}$$

and clustering of v_i centers

$$v_i = \frac{\sum_{j=1}^{n} u_{ij}^m x_j}{\sum_{j=1}^{n} u_{ij}^m}. \tag{8}$$

The above described system of equations (7) and (8) is solved iteratively with the goal of determining the minimum of established criterion function. Iterative algorithm can be presented as follows:

- Step 1: the number of c groups is determined and it must satisfy the requirement: $2 \leq c \leq n$ and the exponential weighting factor $1 < m < \infty$. The initial partition matrix $\boldsymbol{U}^{(0)}$ and criterion ε are determined as well. The iteration counter i is set to zero,
- Step 2: the centers of groups v_i^l (i = 1,...,c) are calculated, based on the current partition matrix U^l and relation (5),
- Step 3: a new matrix $\boldsymbol{U}^{(l+1)}$ is calculated using the centers of groups from the previous step, based on relation (8),
- Step 4: the value $\Delta = \| \boldsymbol{U}^{(l+1)} - \boldsymbol{U}^l \| = \max_{i,j} | u_{ij}^{(l+1)} - u_{ij}^l |$ is calculated. If $\Delta < \varepsilon$ iterative process returns to step 2; otherwise the algorithm is finished.

The above explained algorithm minimizes the established function by ending in some local minimum depending on the starting point of an iterative procedure. The performance depends on the initial group centers, thus allowing the fast algorithm for determining the group centers, or allowing FCM to run several times, each time by starting with a different set of initial group centers. The choice of the m parameter affects the fuzzyfication of the whole algorithm, so that for $m \to \infty$ the fuzzyfication is such that all elements of the partition matrix $\boldsymbol{U}$ gravitate towards the value $1/c$, which means that all elements with equal credibility are joined to each group. The value of the m parameter at interval 1,5 to 30 is used most frequently. The value of the number of groups is determined based on the research. After the clusterization process [4] the so-called validity indices are calculated, which provide information on whether the assumption of a number of clusters was correct. The maximum value of the reactive power in relation to the active power is sought, where the maximum apparent power of synchronous motor is the limiting factor. This procedure is applied to each group. For greater excavation resistance more power is needed, while reactive power is reduced, and vice versa. The advantage of this method is the ability to classify a large number of data in groups. The experience of employees is a very important factor because it enables the prediction of loads, depending on the ground type and excavation depth, and therefore the prediction of the load as well. In this way it is possible to determine the number of groups according to the loads [5].

4 Determining the number of groups

Electrical measurements of active and reactive power for different values of excitation current were made on the observed synchronous motor. Excitation current was set by the manufacturer to 245 A, and after that the current value was increased to 260 A, at the same time achieving the maximum value of power S = 630 kV·A. This served as the basis for data analysis. Fig. 5 and Tab. 1 illustrate how much reactive power the motor can supply to the network [6].

Table 1 Centers of 6 groups

	Q / kvar	P/ kW	S / kV·A
1	426,5	308,8	527
2	451,4	39,4	453
3	449,4	126,4	467
4	448,8	193,3	489
5	341,4	52,4	345
6	224,3	30,5	226

Table 2 Centers of 10 groups

	Q / kvar	P / kW	S / kV·A
1	352,1	67,1	358,4
2	427,3	315,9	531,4
3	445,9	210,9	493,3
4	451,5	169,3	482,2
5	451,7	110,6	465,0
6	453,7	38,6	455,3
7	419,2	38,9	421,0
8	304,5	42,3	307,4
9	222,1	29,3	224,0
10	130,6	8,9	130,9

For each set of points in 2D space, with pre-selected number of groups, the initial U_{ij} matrix is formed according to relation (5), where the number of rows represents the number of groups i and the number of columns represents the number of samples j. Each matrix member is the degree of element affiliation to one of the specified groups. The task of FCM is to determine which division of points in space to the specified groups is the best one. According to relation (6) the criterion function is established, for which the minimum is determined. The vector of group centers prototypes will change during the iteration process, depending on the $\boldsymbol{U}$ matrix changes [7]. After meeting the criterion $\Delta < \varepsilon$, according to relation (8), the algorithm is completed; otherwise, the iterative process returns to step 2. The diagram in Fig. 9 shows the achievement of the function minimum under the given condition. It can be seen that after 10 iterations the condition is met. The results are presented in Tab. 2.

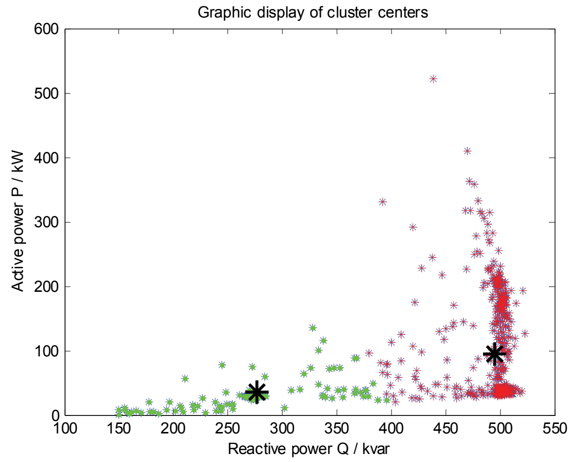

Figure 1 Display of centers for 2 groups

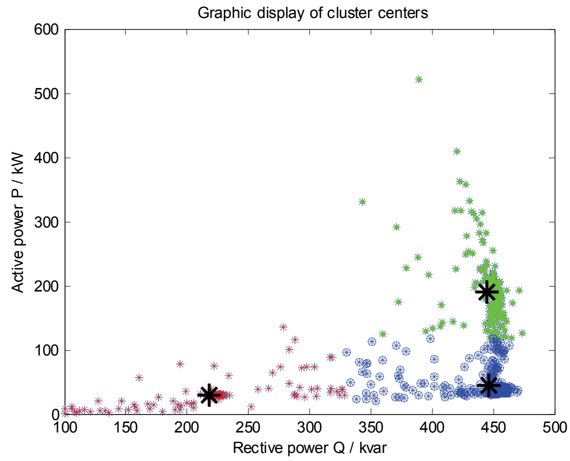

Figure 2 Display of centers for 3 groups

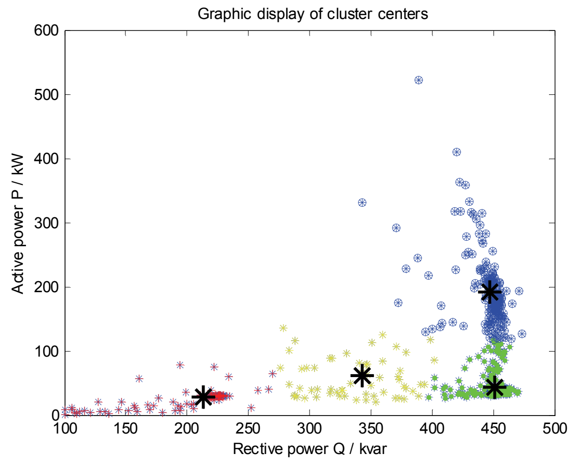

Figure 3 Display of centers for 4 groups

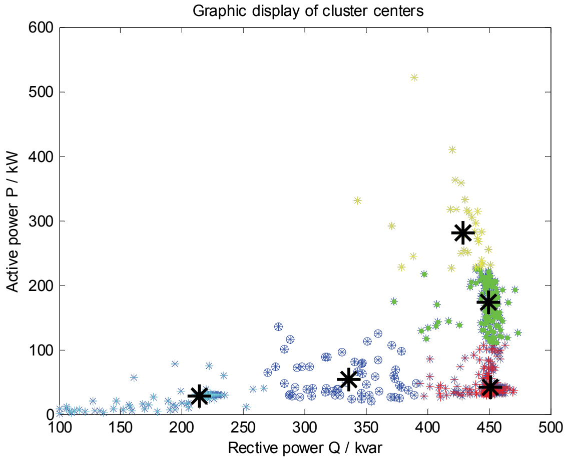

Figure 4 Display of centers for 5 groups

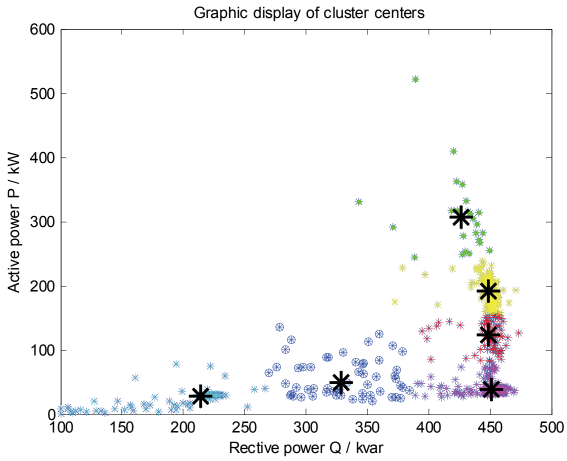

Figure 5 Display of centers for 6 groups

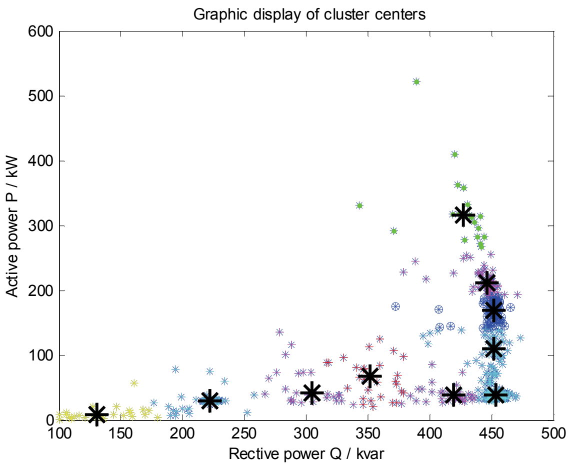

Figure 6 Display of centers for 10 groups

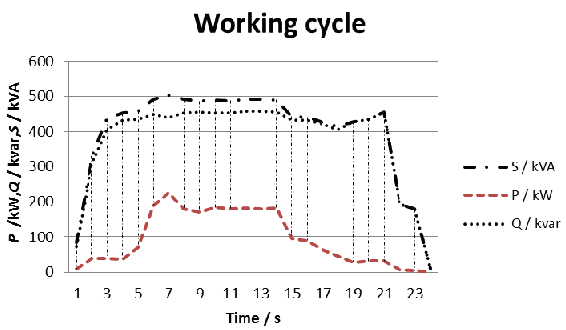

Figure 7 Working cycle for load T_1

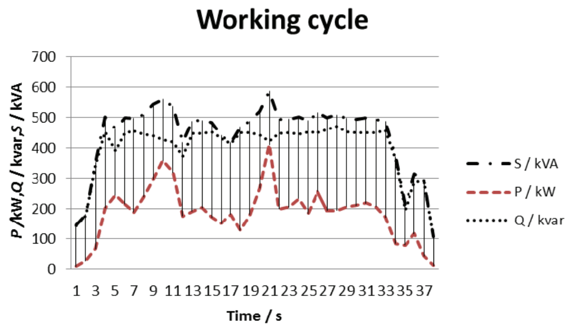

Figure 8 Working cycle for load T_2

The research for cases with 2, 3, 4, 5, 6 and 10 groups was conducted. The number of groups depends on working conditions and the possibility of regulation of synchronous motor excitation current. By comparison of certain conditions for the centers for 6 and 10 groups, from Tables 1 and 2, it was decided to choose the case with 6 groups, i.e. when the excitation current is 260 A. In the mentioned example the case with 6 groups was chosen and the results are presented in Tab. 1. The analysis shows that the synchronous motor was not overloaded, that is, that the value of the maximum power of 630 kV·A was not exceeded. Figs. 7 and 8 show the changes in the synchronous motor power for different loads where $T_1 > T_2$ or digging depth at T_1 is lower. The excavator was digging from the ground surface with shorter working cycle (Fig. 7).

From the conducted analysis it can be concluded that the synchronous motor can compensate reactive power with over 400 kvar and it is justifiable to increase the excitation current from 245 A to 260 A. In the manufacturing process three excavators with identical synchronous motors were installed. Therefore the total reactive power for compensation can range from 1200 kvar to 1300 kvar.

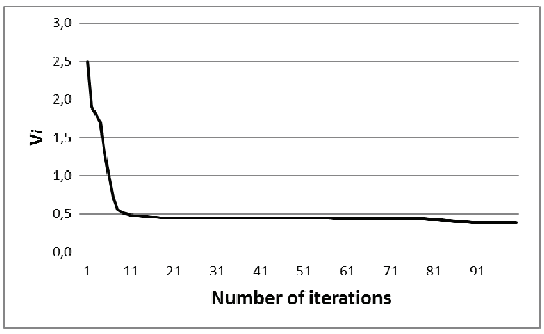

Figure 9 Display of function convergence to the specified minimum

5 Energy consumption

The working cycle of the excavator lasts 20 to 43 seconds, depending on the dumping angle. The longest period is obtained for the dumping angle of 180°. The excavator operates 23 hours a day, therefore making 2025 cycles per day or 13 500 cycles per week. Regular maintenance in duration of 8 working hours is performed once a week. Based on the above mentioned data the total consumed energy is calculated and compared with the data obtained by measuring and computing. The comparison of results of consumed energy for the case with 6 points is made in Tab. 3 and for the case with 10 points in Tab. 4. A slight difference can be detected; therefore, in the future observations the case with 6 points will be used. In the mentioned body of research the synchronous motor was excited by 245 A current [8]. By comparing the results obtained by computing and measuring we can conclude that the application of fuzzy logic provides an appropriate matching of the data obtained by computing and measuring. Tab. 6 presents the results in the case when the synchronous motor was excited by 260 A current. By comparing the results from Tabs. 3 and 5, it is easy to see that by increasing the excitation current from 245 A to 260 A there is a significant increase in reactive power in each synchronous motor by 49,5 kvar or 148,5 kvar for all three motors, as presented in Tab. 6.

Table 3 The results for the case with 6 points I_e = 245 A, Q = 426,5 kvar, P = 308,8 kW

	Cycles	2070	13 860	59 580	714 960
		1 Day	Week	Month	Year
Computing	W_{P1} / kW·h	7102,4	47 555,2	204 425,6	2 453 107
Measurement	W_{P2} / kW·h	7183,6	48 221,3	208 923,4	2 499 721
Error	%	1,14328	1,40069	2,20021	1,90021
Computing	W_{Q1} / kvar·h	9809,5	65 681	282 343	3 388 116
Measurement	W_{Q2} / kvar·h	9723,8	65 089	286 125	33 975 010
Error	%	–0,87364	–0,90133	1,33951	0,27699

Table 4 The results for the case with 10 points I_e = 245 A, Q = 427,3 kvar, P = 315,9 kW

	Cycles	2070	13 860	59 580	714 960
		1 Day	Week	Month	Year
Computing	W_{P1} / kW·h	7265,7	48 648,6	209 125,8	2 509 510
Measurement	W_{P2} / kW·h	7304,3	48 988,6	208 648,8	2 534 025
Error	%	0,53126	0,69889	–0,22809	0,97692
Computing	W_{Q1} / kvar·h	9827,9	65 804,2	282 872,6	3 394 471
Measurement	W_{Q2} / kvar·h	9924,1	66 028,3	284 582,3	3 408 726
Error	%	0,97885	0,34056	0,60441	0,41995

Table 5 The results for the case with 6 points I_e = 260 A, Q = 475,7 kvar, P = 306,7 kW

	Cycles	2070	13 860	59 580	714 960
		1 Day	Week	Month	Year
Computing	W_{P1} / kW·h	7054,1	47 231,8	203 035,4	2 436 425
Measurement	W_{P2} / kW·h	7183,6	48 221,3	208 923,4	2 499 721
Error	%	1,83581	2,09499	2,89999	2,59793
Computing	W_{Q1} / kvar·h	10 941,1	73 257,8	314 913,4	3 778 961
Measurement	W_{Q2} / kvar·h	11 048	74 282	319 431	3 834 621
Error	%	0,97705	1,39808	1,43455	1,4729

Table 6 Reactive energy for excitation current of I_u = 260 A

1 Motor	1 Day	Week	Month	Year
W_{Q2} / kvar·h	1138,5	7623	32 769	393 228
2 Motor	1 Day	Week	Month	Year
W_{Q2} / kvar·h	2277	15 246	65 538	786 456
3 Motor	1 Day	Week	Month	Year
W_{Q2} / kvar·h	3415,5	22 869	98 307	1 179 684

Table 7 Comparison of computed and measured values

Number of points		2	3	4	5	6	7	8	9	10
Computing	W_{P1} / kWh	749119,2	1513332	1520482	2194133	2436425	2445163	2511098	2511353	2509510
Measurement	W_{P2} / kWh	2499721	2499721	2499721	2499721	2499721	2499721	2499721	2499721	2499721
Error	%	233,6881	65,17997	64,40326	13,92753	2,597925	2,231266	-0,45307	-0,46315	-0,39005
Computing	W_{Q1} / kvarh	3931486	3927514	3944196	3807559	3778961	3784522	3781344	3785316	3787699
Measurement	W_{Q2} / kvarh	3834621	3834621	3834621	3834621	3834621	3834621	3834621	3834621	3834621
Error	%	-2,46382	-2,36518	-2,77813	0,710739	1,472897	1,323797	1,408943	1,302533	1,238794

Tab. 7 shows that the difference in error from 6 to 10 points is irrelevant; therefore a further increase in the number of groups would not produce any significant results. By increasing the excitation current to 260 A, the delivered reactive energy is increased by 13 %, compared to its value when the excitation current was 245 A. By applying fuzzy logic it is quite possible to precisely determine the limits up to which the synchronous motor can be adjusted [9, 10, 11].

6 Conclusion

The research investigates the possibility of using reactive energy compensation by 630 kV·A synchronous motors, which are installed on EŠ-6/45 excavators. The mentioned method of reactive energy compensation, although known in theory, has not been sufficiently used in practice, although research shows the necessity of its application. The cause of this is probably the high modeling complexity and problem programming because it is difficult to determine the limits of the excitation current regulation due to variable loads. By increasing the excitation current the synchronous motor increases the reactive power delivered to the power supply, and thus improves the power factor in the 6 kV mine network. In this way, the reliability of reactive power compensation is increased, the application of condenser batteries is reduced and the quality of energy is improved. After the conducted research it can be concluded that the application of c-clustering can help us obtain data on a potential increase of reactive power by increasing the excitation current depending on the load under variable load condition.

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