Intelligent Control of Industrial Compensating Devices Based on the Application of Fuzzy Logic

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Abstract
The process of reactive power compensation has been formalized using the example of daily electricity consumption by the power substation of the enterprise. The choice of the fuzzy control principle for the operation of compensating devices is justified. Results of computer modeling of the reactive power compensation process based on actual electricity consumption data from powerful substations of the mining and beneficiation plant are presented. The effectiveness of using the fuzzy control principle for compensating devices has been analyzed. The experimental data from January and June 2019 for one of the main substations of the enterprise were used by the authors for testing. The proposed algorithm for controlling the compensation process is implemented based on fuzzy control.

Keywords
Mining and beneficiation plants, fuzzy logic, power networks, energy efficiency, filter-compensating devices, synchronous motors, algorithm.

1. Introduction

Modern electricity consumers at the mining and metallurgical complex stations often have non-linear load characteristics. The presence of semiconductor converters in them and other areas of the enterprise leads to a deterioration in the quality of power supply due to the emergence of higher harmonic components of voltage and current, as well as other indicators [7]. As a result, the equipment wears out faster, and electricity costs may increase due to additional payment for reactive power [21]. Thus, the network operator is forced to implement measures to compensate for reactive power [5, 6]. However, due to the uncertainty of the load and disturbances, compensating systems require more complex approaches to implementation at the design stage. A system based on fuzzy logic can implement such control.

This paper focuses on the substations of the mining and beneficiation complex as the object of research. The subject of the research is the system of control with compensating devices based on fuzzy logic. The main feature and, at the same time, advantage of this system is:

1. Fuzzy control allows working with fuzzy input data, which is useful when dealing with complex systems. For example, as in our case, substations with a large number of electricity consumers.
2. The use and configuration of controllers based on fuzzy logic is more intuitive and simple to set up based on expert rules.

However, we need to consider certain factors to determine such rules. Therefore, the article solves the problem of choosing rational scientific approaches to creating a rational control system for the reactive power compensation process [6].

As an example, an analysis of reactive power consumption during the summer and winter months is presented. The effectiveness of the operation of compensating devices (CDs) using arbitrary daily

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reactive power consumption is investigated. Numerous studies by the authors [1-2] have convincingly shown that improving energy efficiency and reducing the cost of the enterprise is possible through the implementation of an automatic control algorithm. The implementation of a process for determining energy-efficient control with parallel use of CDs and synchronous motors (SMs) is proposed. Despite the considerable amount of research in this field, a number of issues require constant clarification and adaptation to the conditions of a specific enterprise [16-17]. This applies to the preliminary analysis of reactive power consumption levels and the possibility of including SMs in the compensation process. Thus, this work will consider a method of controlling compensating devices based on fuzzy control and mathematical models based on real energy consumption data.

2. Control algorithm for compensating devices and its implementation based on fuzzy

An effective solution in the case of powerful consumers with non-linear loads on the network is the installation of filter-compensation devices (FCDs). The main goal of FCD implementation is to reduce the harmonic composition and control the load tangent of the object at a level of $tg\varphi<0.25$ [21]. Typically, powerful enterprises have SMs in their assets, which can also be involved in the reactive power compensation process [10]. The level of reactive power generation is determined by changing the excitation current. However, a significant increase in the excitation current may lead to overheating and premature failure of the motor. Therefore, to ensure rational control of the excitation current, it is advisable to develop a set of rules for monitoring the temperature of the windings.

Figure 1 shows the structure of an automated control system for the excitation of SMs and the switching of FCDs for reactive power compensation within the enterprise network to balance its flows between consumers (AM, transformers) and from FCDs and SMs. The directions of the reactive power flows are also indicated in Figure 1.

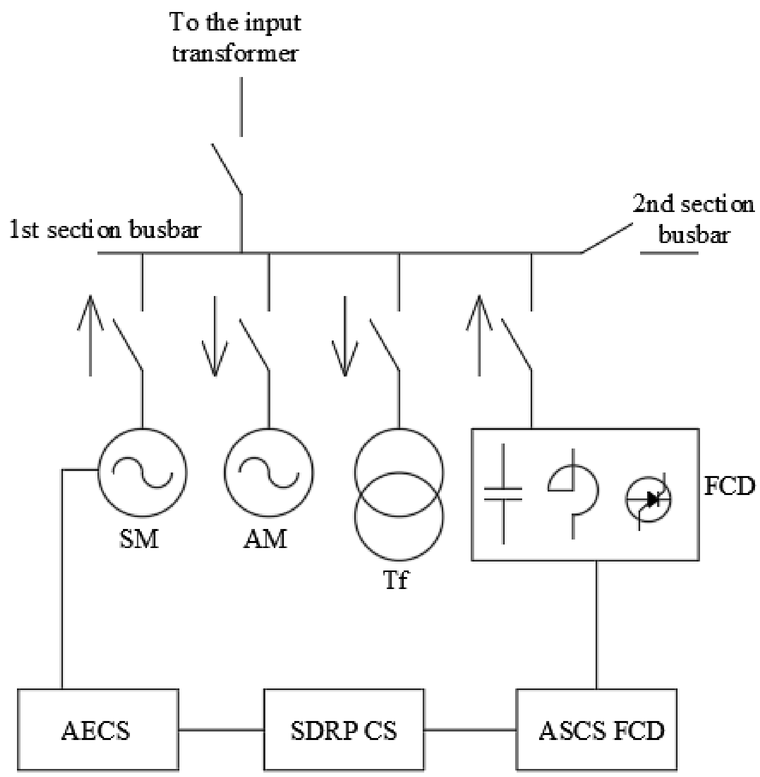

Figure 1: Structural diagram of the reactive power control system

On Figure 1: AECS - Automatic excitation control system; SDRP CS - Systems of automatic control of reactive power; ASCS FCD - Automatic system of automatic control of stages of the FCD.

To reduce the impact of reactive power on the power grid, an algorithm for compensating reactive power is proposed. This algorithm involves the installation of reactive power compensators. The use of the reactive power compensation algorithm allows for a reduction in energy consumption costs, increased efficiency and reliability of the power grid, reduced risk of overvoltage and equipment overload, as well as a decrease in energy losses in the network.

The process control scheme for reactive power compensation can be implemented using the algorithm shown in Figure 2. It should be noted that the algorithm first analyzes the compensating powers of capacitor installations, as losses in kW/kVAR for capacitor banks typically range from 0.002-0.0045, whereas for synchronous motors, this value is 0.013 kW/kVAR for our conditions and existing parameters, consistent with overall evaluation trends. Therefore, the most favorable compensation process is the involvement of capacitor installations in the first place.

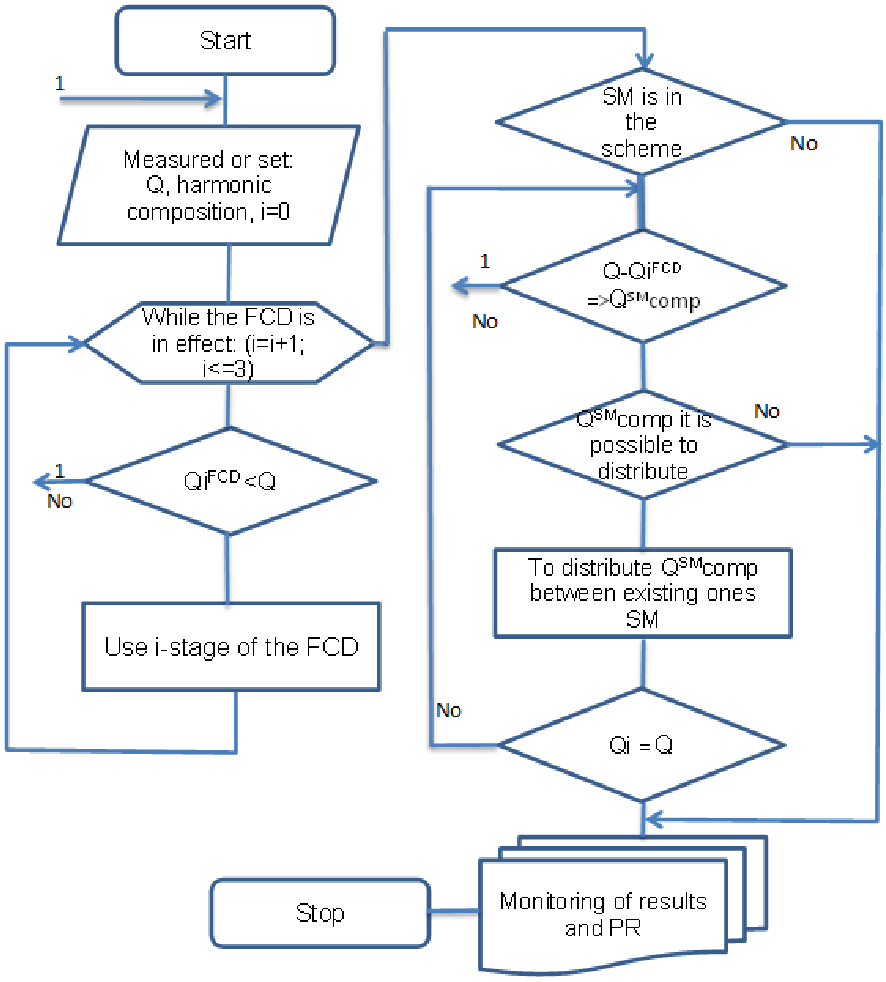

Figure 2: Algorithm of operation of filter-compensating devices

Algorithm operation description:

1. Q and harmonic composition are measured or set.
2. Check if there is a fundamental reactive power (FRP). If yes, one stage is used to compensate for the harmonic components of voltage and current. If there is a need for a second stage, the reactive power module (RPM) is used. The condition is checked:

$$Q_{2FCD} < Q \tag{1}$$

if so, the second stage of FCD is introduced, then it is checked

$$Q_{2FCD} + Q_{3FCD} < Q \tag{2}$$

the third degree is introduced, etc.

if Q_{2FCD}>Q or Q_{iFCD}<Q< Q_{i+1FCD} , then there is an adjustment of the residual reactive power from the compensation of the synchronous motor:

$$Q - Q_{iFCD} \rightarrow Q_{SMCOMP} \tag{3}$$

3. The availability and possibility of SM for compensation is checked Q_{SM}. It is distributed between the synchronous motors involved in the compensation.
4. There is a constant check:

$$Q > Q_{i+1FCD} + Q_{iFCD} \tag{4}$$

if so, an i+1 step of FCD is introduced, with the setpoint of the regulating SM directed to the next value:

$$Q - Q_{FCD} + Q_{i+1FCD} = Q_{SM} \tag{5}$$

$Q`_{SM}$ distributed between SM, providing S_i^*=const. If the FKP capabilities are exhausted, then the process is implemented exclusively with the help of synchronous motors.

ACRP devices (automatic control reactive power) and controllers based on fuzzy logic can be used for controlling the reactive power compensation process. However, they have some differences in usage and operating principles.

The main difference between ACRP and fuzzy logic controllers is that ACRP use precise (crisp) algorithms for controlling the reactive power compensation process, whereas fuzzy controllers use fuzzy algorithms. ACRP have built-in precise algorithms that provide automatic switching on and off of capacitors depending on the level of reactive power in the electrical network. ACRP can also switch capacitors on and off depending on the voltage and current levels in the network to ensure optimal reactive power compensation.

Fuzzy controllers use fuzzy logic to control the process of reactive power compensation. These controllers allow for a wider range of factors that affect the compensation process to be taken into account, such as the state of the network, the level of harmonics, the instability of the power supply, and so on. This provides a more flexible and effective management of reactive power compensation. Figure 3 shows the main advantages and disadvantages of conventional ACRPs and fuzzy logic-based controllers.

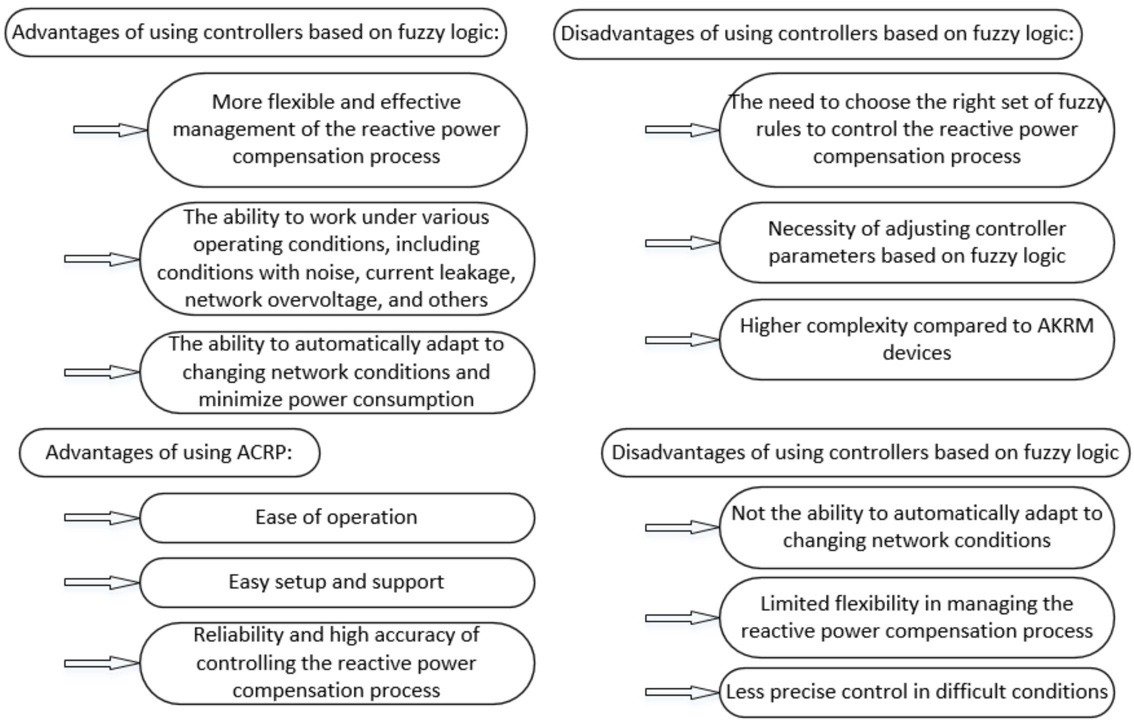

Figure 3: Comparison of reactive power compensation using ACRP and CP based on fuzzy logic

Significant development of controllers allows easy monitoring of all necessary parameters. The complexity of the setup can become an advantage in the form of a more accurate process for controlling compensation. Therefore, the principles of fuzzy control can be used for automatic regulation of reactive power compensation with capacitor banks, which will provide more precise and efficient compensation.

After analyzing the data for the winter and summer months, the necessary "base level" of compensating ability was determined to be 7500 kVAr·h. Since the level of reactive power consumption below this value is not normal, this only occurs in the case of disconnecting powerful consumers (for example, one or two lines of consumption of the OBF1). After that, the consumption of reactive power was calculated taking into account the base level. To determine the rational capacities of capacitor banks, a law of normal distribution was compiled (see Figure 4). On the graph, it can be seen that the maximum for January corresponds to 750 kVAr·h, the highest common point is 1500 kVAr·h, and the third is 2250 kVAr·h. Thus, three levels of reactive power consumption can be determined as input parameters for the fuzzy controller.

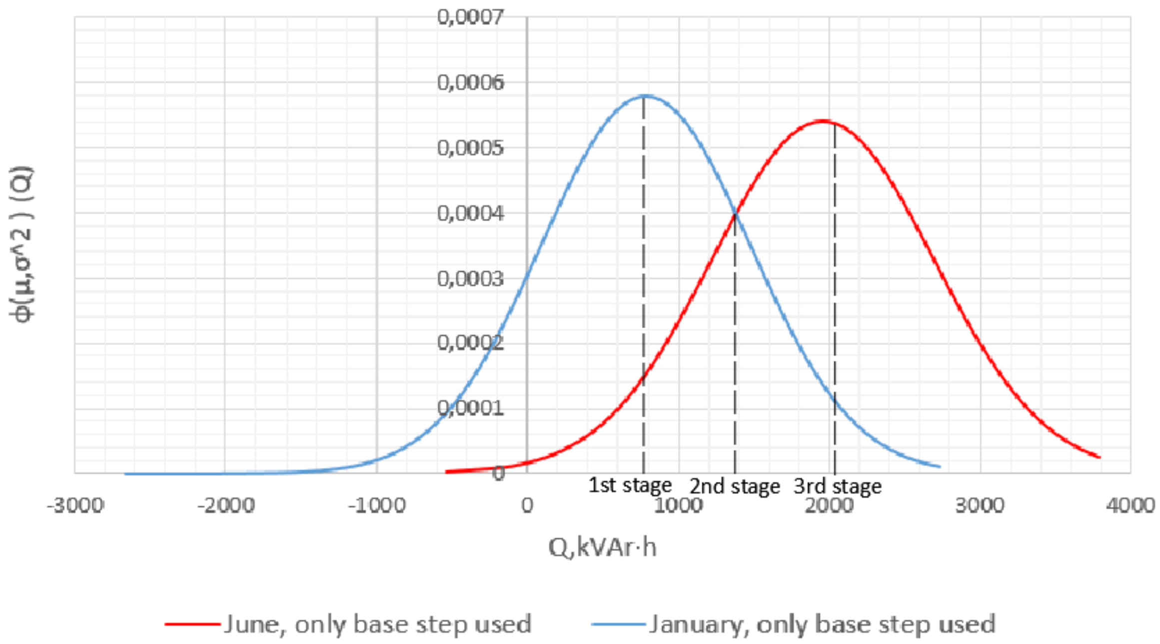

Figure 4: Normal distribution of the reactive power balance of the substation after the introduction of the "base stage"

Similarly, using fuzzy logic, SM can be included in the compensation process. Excitation current control is one of the methods for controlling the power of synchronous motors and is used to provide the necessary power factor and efficient operation of the motor.

According to [16, 17], the maximum value of the total power of motors participating in reactive power compensation mode can be determined:

$$S_{crit} = \sqrt{\left(\frac{U_n}{U}\right)^2 S_n^2 \left(1 + \frac{t_{cr}^{\circ} - t_r^{\circ}}{\Delta t_{cr}^{\circ}}\right)}, \tag{6}$$

where t_{cr}° is the maximum permissible temperature of the cooling air. U_n is rated voltage of the motor. Δt_{cr}° is the maximum allowable temperature exceedance of the stator windings.

The temperature of a synchronous motor can be used as an additional parameter for controlling the excitation current. An increase in temperature can indicate motor overload or other issues that require controller action. The use of fuzzy control allows for a system that can automatically adjust excitation current based on motor temperature.

Considering the load on the synchronous motor is also an important factor in reactive power compensation, as it can affect its operation and compensation efficiency. In particular, a change in load on the synchronous motor leads to a change in power consumed, and therefore, a change in reactive power. If load changes are not taken into account during reactive power compensation, overcompensation or undercompensation of reactive power may occur.

One can express the loading of a synchronous motor as a percentage of its rated power because the rated power is the fundamental value used to determine the motor's maximum efficiency. Therefore, information about the loading of a synchronous motor is an important parameter for determining its efficiency and monitoring its operation.

It is also necessary to consider the number of motors that can participate in the compensation process and their loading. In particular, when the active load SM changes, its compensating ability for reactive power also changes, which should be taken into account. If several SMs of different or the same rated power are involved in the regulation of reactive power, it is necessary to ensure their equal relative loading in terms of full power.

$$S_i = \sqrt{P_i^2 + Q_i^2} = const \qquad (7)$$

It is also important to consider the number of motors that can participate in the compensation process and their load. This, in turn, can affect the overall ability to compensate reactive power using SM. The presence of a large number of motors allows for smoother distribution of compensation levels by including motors with low loads and/or no overheating in the compensation process.

3. Research on the effectiveness of proposed methods

To investigate the effectiveness of fuzzy control compensating devices, the following steps will be taken:

1. Create and configure a fuzzy controller that will make decisions about compensating reactive power based on input data about the state of the electrical network.
2. Evaluate the effectiveness of the reactive power compensator with fuzzy control based on experimental data on daily power consumption.

The calculation of the fuzzy regulator will be carried out using the FuzzyLogicToolbox Matlab package.

To do this, we will select input parameters that affect the compensating ability of the fuzzy controller, as shown in Figure 5. First, there is the parameter of reactive power consumption (Qcons), with levels of consumption being low, medium, and high. The second parameter is tgφ. The next parameter is the number of SMs in the network, as well as the temperature and load of the motors. These three parameters have a significant impact on the amount that we can compensate using SMs. However, when a synchronous motor is highly loaded, its temperature is usually higher than nominal. This is because as the load on the motor increases, its power loss from resistances caused by losses in the stator and rotor, as well as losses due to magnetization, increases. This leads to an increase in the motor's temperature. If the motor's temperature remains low under high load, this may be a sign of ineffective operation or an emergency state. Therefore, it is advisable to combine the load and temperature parameters.

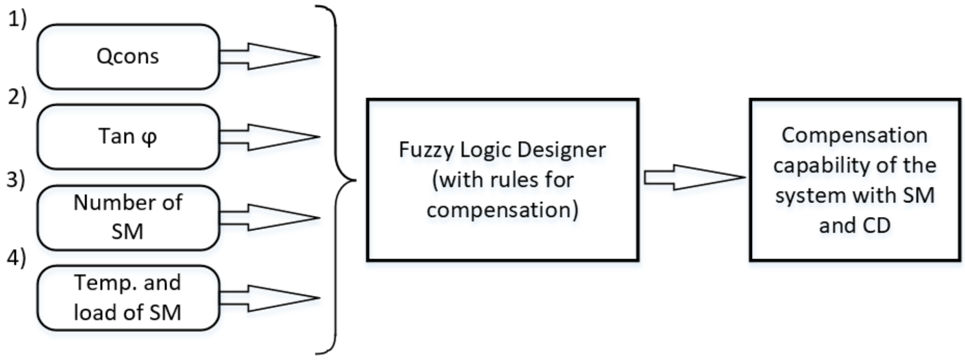

Figure 5: Parameters for the fuzzy controller

All important conditions were taken into account during construction. For example, synchronous motors cannot fully participate in reactive power compensation at high temperature and high load. This is done to prevent emergencies. It is important to monitor the temperature of the synchronous motor during operation to avoid overheating and equipment damage. Temperature sensors can be used to monitor the motor temperature and take measures to reduce it if necessary. For example, with higher values of SM quantity in the network, we can use their share of compensating capacity. This is done by distributing the necessary reactive power that needs to be compensated among all the motors.

Figure 6 shows membership functions that were chosen for input parameters (a, b, c, d) and output compensation capability value (e). The membership functions correspond to the following parameters: a - input reactive power consumption value; b - tanφ value in the network; c - number of synchronous motors; d - motors' temperature and load; e - output value of the function. Taking into account all the aforementioned factors, the following dependencies were obtained (Figure 7, 8).

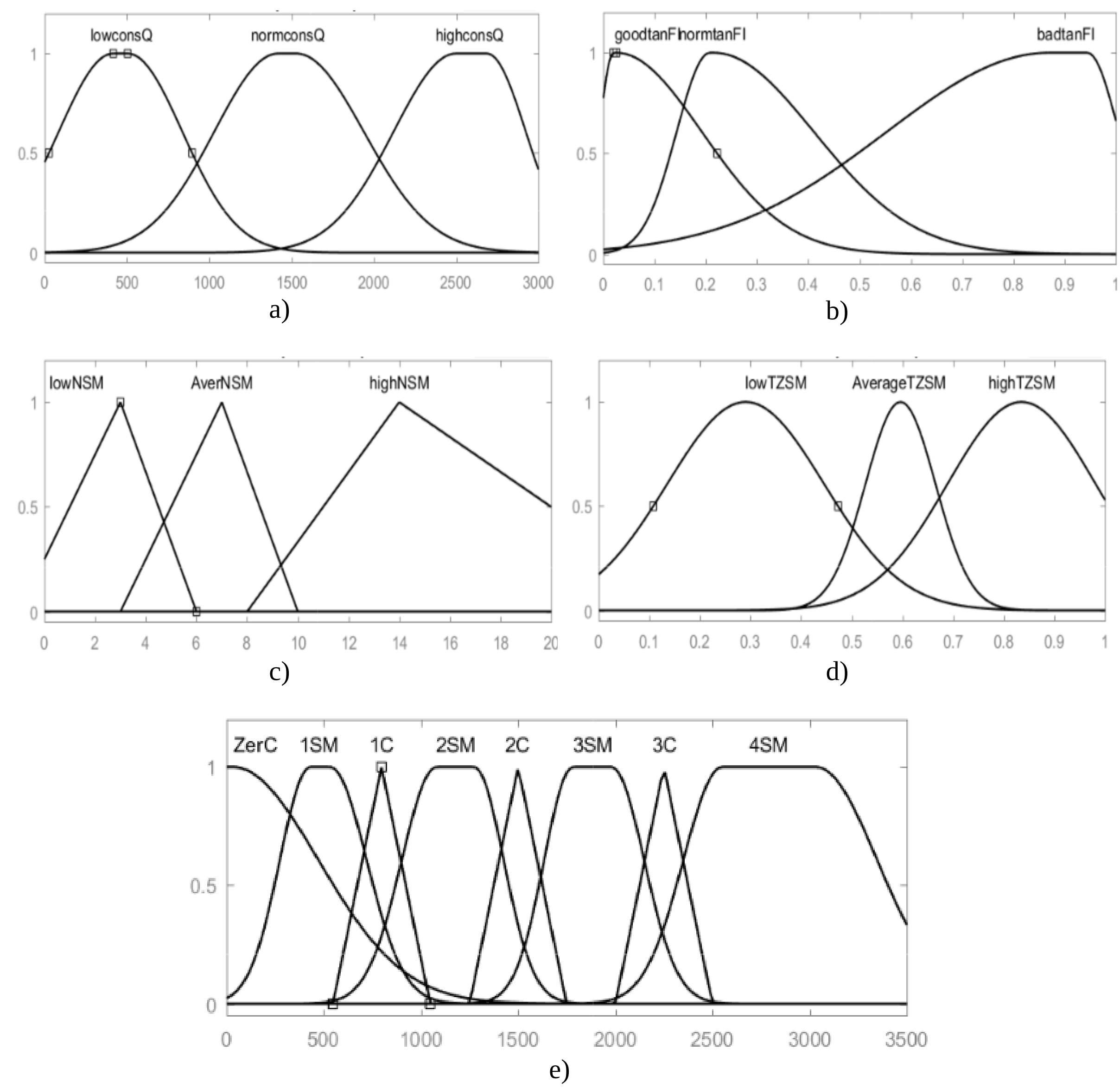

Figure 6: Membership functions

On Figure 7, one can observe relatively low compensation values within the range Q_{cons} from 0 to 1500kVAr·h and tanφ from 0 to 1. This can be explained by the fact that there is no need for significant levels of compensation in this zone. Accordingly, starting from 1500kVAr·h, the need for compensation increases. This is also important to prevent the activation of higher compensation levels until such a need arises. Such a decision helps to avoid excessive reactive power generation.

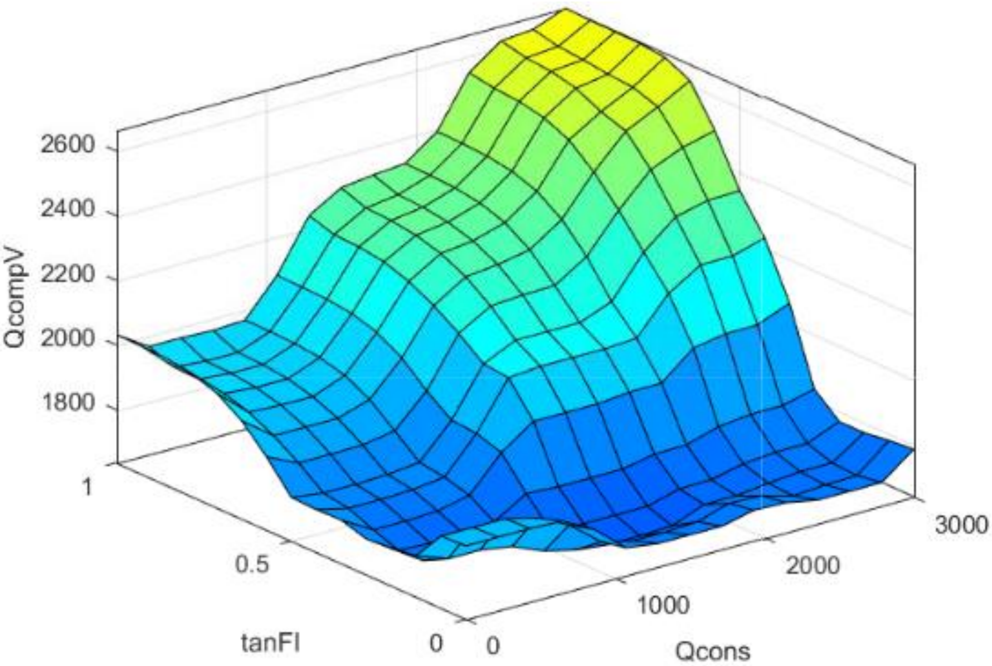

Figure 7: Compensatory capacity of the system from Q_{cons} and tan φ

Figure 8 shows that for low values of the number of motors, high values of temperature (relative to the nominal value), and high loading, the values of compensation possibilities are low. This can be explained by the fact that further increase in reactive power generation from these motors can lead to overheating. Therefore, in the presence of a larger number of synchronous motors, we can distribute higher values of generation even at higher temperatures and loading.

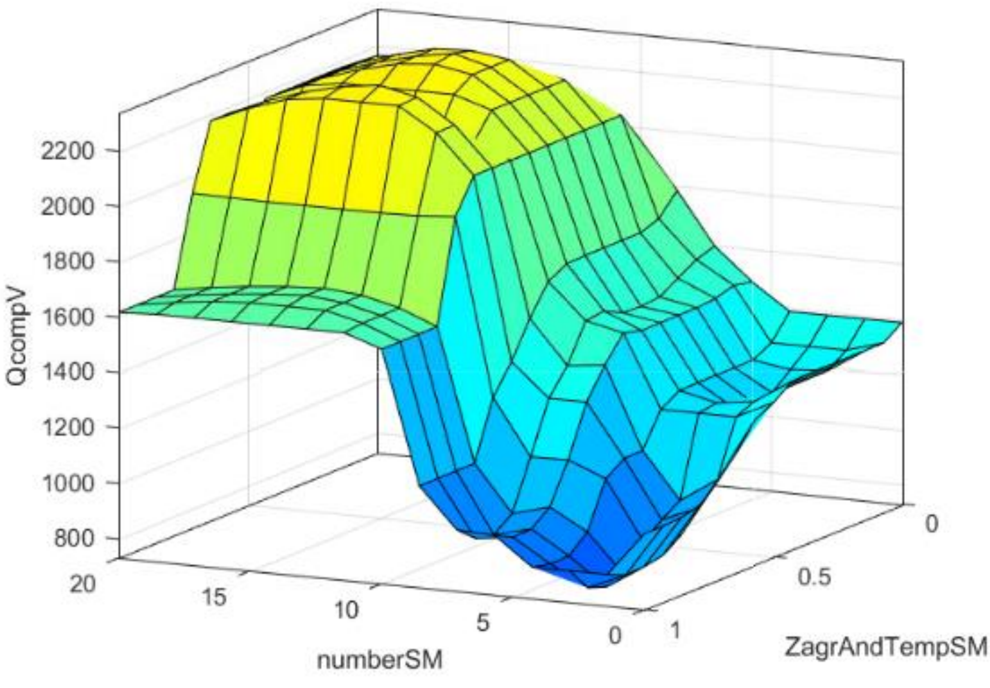

Figure 8: Compensatory capacity of the system: number and load with temperature SM

Figure 9 shows the result of fuzzy logic calculation for certain input parameters. A total of 149 rules were developed. The Rule Viewer enables visual evaluation of the results of fuzzy control. In this case, it allows us to see how various input values correspond to certain output values. We use logical rules to determine the latter. One can use this tool to efficiently tune the parameters of the fuzzy controller and ensure its optimal performance [5]. In this case, we can see that regardless of the reactive power consumption, tanφ, the number of SMs, and their loading, we are able to fully compensate for this quantity. Thus, the composed set of rules allows for effective compensation of reactive power.

Figure 10 and Figure 11 depict the results of the reactive power compensation algorithm using CD and SM for a day in January and June, respectively.

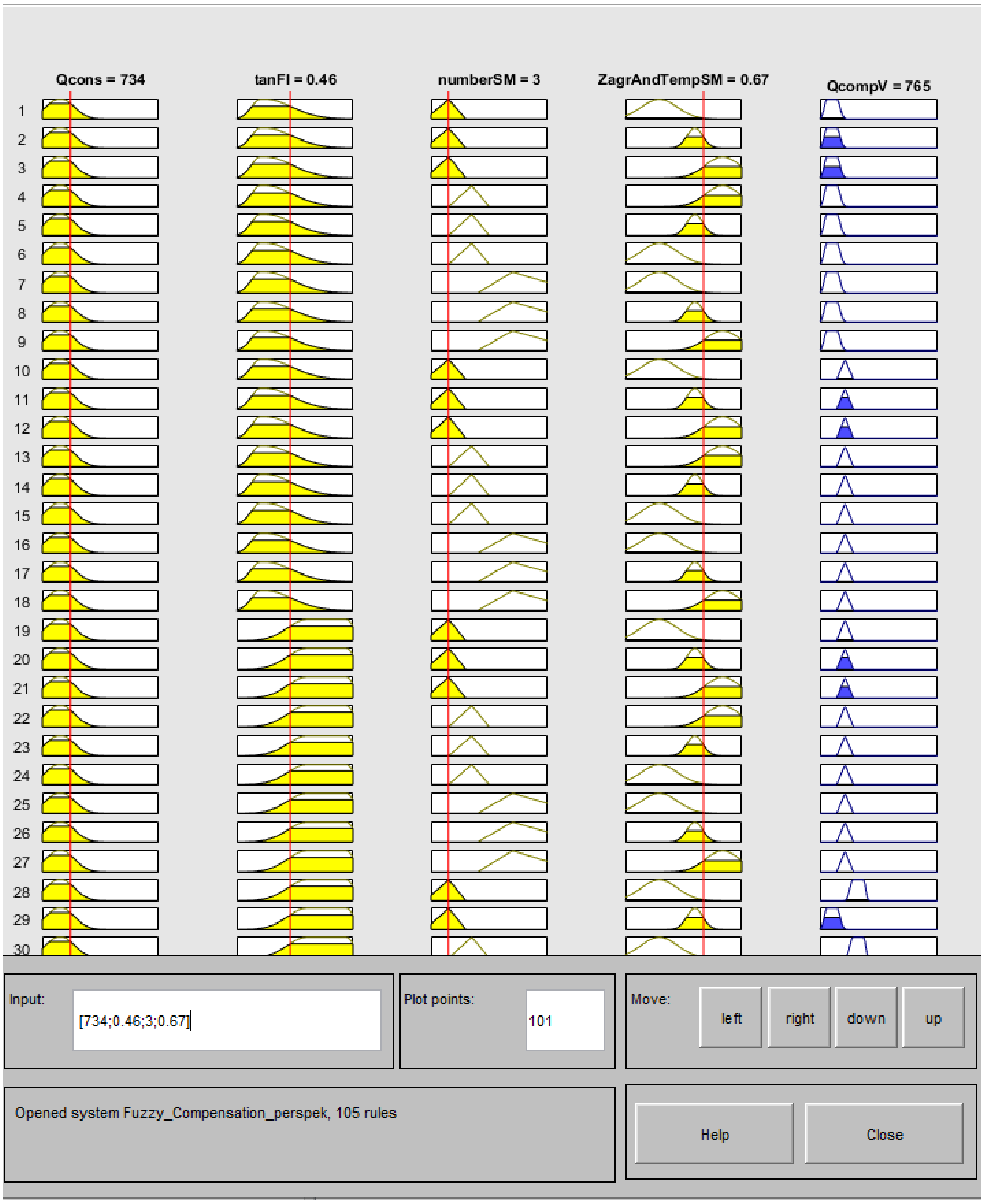

Figure 9: Fuzzy logic calculation results

As seen in Figure 10 and 11, according to the algorithm, the generated power using capacitor banks does not exceed the consumption power. Three levels were used during the day in January (a constant compensation level at 7500 kVAr·h and one level at 750 kVAr·h). During summer days, three levels at

750 kVAr·h and a constant level at 7500 kVAr·h were used. The remaining reactive power is compensated by synchronous motors.

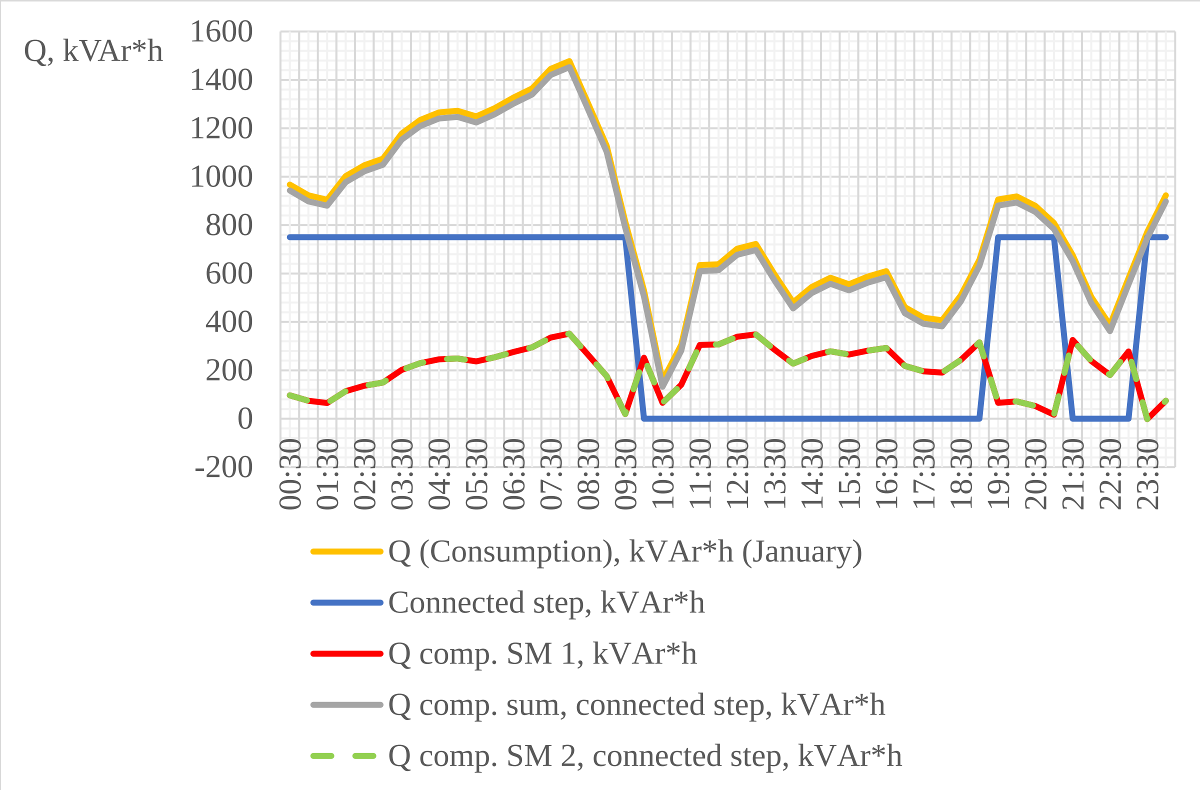

Figure 10: Reactive power compensation using capacitor banks and synchronous motors. January.

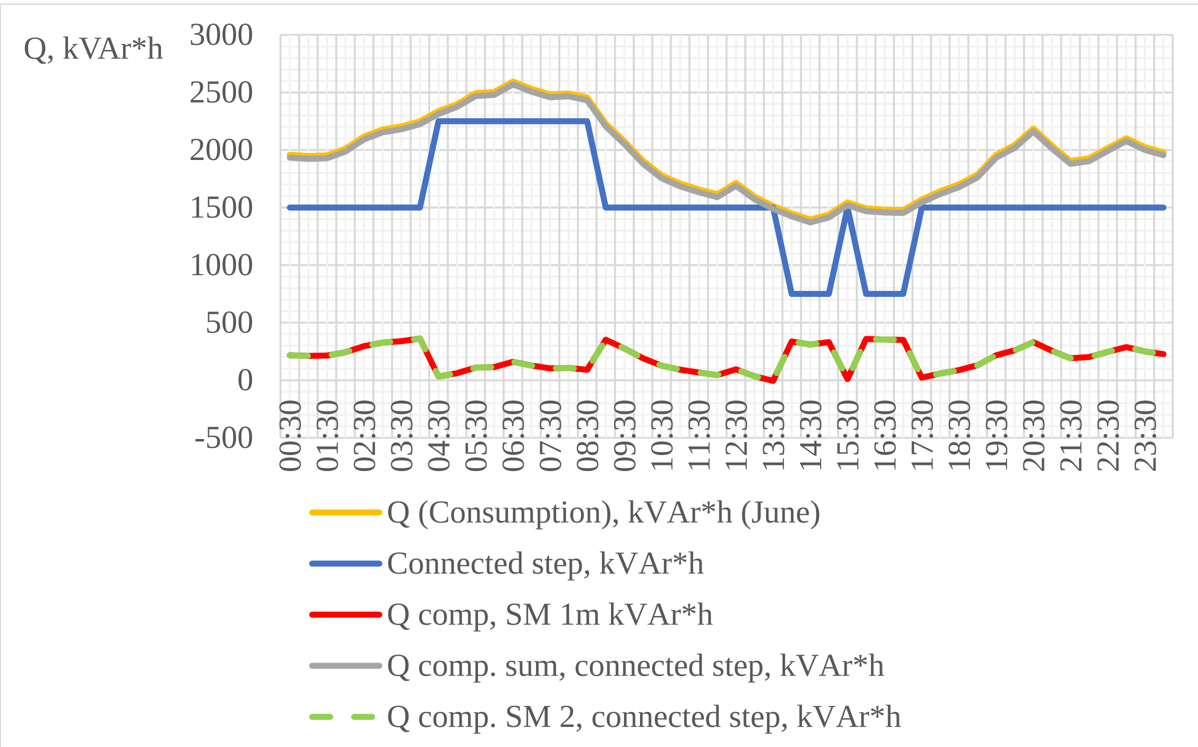

Figure 11: Reactive power compensation using capacitor banks and synchronous motors. June.

However, the process of transient phenomena when using SMs and FCDs for reactive power compensation is also important. The article explores their compensation potential specifically from the perspective of reactive power generation levels. Transient processes when using synchronous motors and capacitor banks for reactive power compensation depend on several factors [17].

Firstly, they depend on the parameters of the synchronous motor itself, such as its capacitance, resistance, and inductance. These parameters affect the motor's response time to load changes and the effectiveness of reactive power compensation. Secondly, transient processes depend on the properties of capacitor banks, such as their capacitance, voltage, and frequency. These parameters affect the effectiveness of reactive power compensation and the stability of the network [18]. Thirdly, transient processes depend on the characteristics of switching devices, such as switching time and resistance. These parameters affect the speed of current and voltage changes.

Therefore, studying transient processes is important for evaluating the effectiveness of reactive power compensation and the stability of the network, but depends on many factors, including the parameters of synchronous motors and capacitor banks, as well as the characteristics of switching devices [13]. Therefore, the use of compensation devices with the specified values in the control system requires further research.

Analyzing the obtained data, it can be stated that the implementation of the compensation algorithm using the proposed method will allow the company with a total installed active power of 283 MW to reduce the payment for reactive power from approximately 400,000 hryvnias per month to one thousand hryvnias per month. Of course, the proposed method only takes into account payment for reactive power according to the tariff. If the payback period of implementation is taken into account, it will depend on many factors, where one of the main ones will be the method of implementation of this method. Therefore, the payback period of implementation of the KP control algorithm should be calculated on an individual basis.

4. Conclusion

Based on statistical data on reactive power consumption of the power substations at PJSC "NorthMEP", a method for selecting the power of compensating devices to ensure minimum payment for reactive power by the enterprise has been proposed. The proposed system of automatic control of compensating devices (by switching FCDs) and regulation of excitation of synchronous motors (for reactive power compensation) balances the flow of reactive power between consumers (asynchronous motors, transformers, etc.), with control of technological parameters of synchronous motors [12]. The developed algorithm is implemented based on fuzzy logic with the consideration of important technological parameters. The obtained level of compensating possibilities depends on all the considered parameters. According to the results of graphical representations, the required level of compensation ensures high energy efficiency.

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