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MANAGEMENT MODES OF REACTIVE POWER COMPENSATION FACILITIES IN NETWORKS WITH RENEWABLE ENERGY SOURCES WITH DISTORTING LOADS

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Abstract- Modern electrical networks are characterized by the integration of renewable energy sources and at the same time the loads are distorting (non-sinusoidal and asymmetrical). In such conditions, as is known, the choice of compensating devices in electrical networks to compensate for reactive power is carried out according to the complex of the first harmonic of voltage and positive sequence current. Currently, the application of the existing methodology in distributed generation networks based on renewable energy sources (RES) and when sinusoidal distortion by nonlinear loads creates significant difficulties. This is due to the fact that RES requires a large amount of reactive power from the system, and the higher harmonic components of asymmetrical current and voltage created by distorting loads overload the reactive power compensation means. In distribution networks, these devices are mainly static cosine capacitors, which do not operate effectively under these conditions. The article presents a method for the rational selection of compensating sources of reactive power in distributed generation networks based on renewable energy sources and in conditions where the loads are distorting and control based on the theory of fuzzy logic in conditions of uncertain changes in the network mode. It is shown that using the theory of fuzzy logic when controlling means of reactive power compensation in a network with renewable energy sources, under the influence of uncertainty factors, the corresponding compensation characteristics are improved. Reactive power compensation devices operate efficiently and reliably, and at the same time, switching devices perform small switching's, which increases their reliability and also increases their service life.

Keywords: Electrical Network with Distributed Generation, Renewable Energy Source, Reactive Power Compensation, Fuzzy Logic Theory, Distorting Load, Voltage Asymmetry, Non-Sinusoidal.

1. INTRODUCTION

Quantitative and qualitative changes in industrial sectors, as well as the integration of renewable energy sources in recent years, have given the issues of reactive power compensation in distributed generation networks special significance. In this regard, the current period of growth in demand for reactive power significantly exceeds the growth in demand for active power. As is known, in this case, the transfer of reactive power from the place of generation to the place of consumption leads to a deterioration in the technical and economic indicators of the electric grid enterprise [1, 2].

The 22% of 100% of the reactive power generated in the power system is lost in step-up transformers of the power plant and autotransformers 110-500 kV, 6.5% in regional networks, 13.5% in step-down transformers and only 58% of the generated reactive power -i enters the consumer buses 6 -10kV [3]. It should be noted that practically all indicators of the quality of electrical energy depend on the voltage of the reactive power requirement. Therefore, the question of electricity quality should be considered in direct connection with the question of reactive power compensation. The problem can be solved by the synthesis and application of high-speed multifunctional compensation of reactive power, which improves the quality of electric energy simultaneously in several parameters. It is known that the most convenient means of compensating reactive power in distribution networks is the use of static capacitor banks (SCB) [4]. This is due to their following advantages compared to other means of compensation: the ability to use both at low and high voltages; low active power losses (0.0025-0.005 kW/kVar); lowest specific cost (per 1 kVar) compared to other compensating devices; ease of operation (no rotating or moving parts); ease of installation work (low weight, no foundation required), etc. In addition, the use of traditional means of reactive power compensation (RPC), designed for sinusoidal voltage and current, in networks with high harmonic components of voltage and current generated by nonlinear loads is associated with certain technical difficulties.

Because the value of the power factor corresponding to this value of the phase shift is effective for the case of non-distorting and unchanging system modes. In the case of distorting systems and the integration of RES, such a power factor can lead to unsustainable power consumption patterns. Since in a network with RES and for a large number of modern consumers in higher

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harmonic modes, the power factor is less than, defined as the phase angle of the first harmonic. In this regard, at present, according to international standards, stringent requirements are imposed on the level of reactive power.

For this purpose, the range of the harmonic composition of current and voltage has been expanded up to the 40th harmonic [5, 6]. To take into account this factor, an integral indicator of the harmonic composition of voltage and current is taken [3]:

$$K_{THD,U} = \sqrt{\sum_{n=2}^{40} U_n^2 / U_1} \quad (1)$$

$$K_{THD,I} = \sqrt{\sum_{n=2}^{40} I_n^2 / I_1} \quad (2)$$

where, I_n is the effective value of the higher harmonics of current; and I_1 is value of the first harmonic of current.

Some settings because both unbalance and higher harmonics at the same time. Such installations include, for example, powerful arc furnaces, AC electric locomotives with valve installations. The presence of asymmetric sources of higher harmonics leads to the emergence of asymmetric systems of currents and voltages of different frequencies:

$$U_n = \begin{bmatrix} U_{1,n,j} \\ U_{2,n,j} \\ U_{0,n,j} \end{bmatrix}; \; I_n = \begin{bmatrix} I_{1,n,i} \\ I_{2,n,i} \\ I_{0,n,i} \end{bmatrix} \quad (3)$$

where, $U_{k,n,j}$ are voltages, respectively, of direct, reverse and zero sequence of individual harmonic components for the jth node; $I_{k,n,i}$ is currents, respectively, of the direct, reverse and zero sequence of individual harmonic components for passing through the ith transmission line, respectively $j = \overline{1,n}$; $i = \overline{1,m}$; and k= 1,2,0.

As can be seen from expression (3), the problem becomes more complicated in asymmetrical and non-sinusoidal modes taking into account the uncertainty of the initial information about the mode and topology of the network circuit, therefore the selection of a compensating device for the first harmonic of positive sequence current and voltage cannot ensure its effective operation in a network with a distributed generation with renewable energy sources. Thus, taking into account the uncertainty of the initial information, a qualitatively new approach to the selection of compensation devices and their control in non-sinusoidal and asymmetrical voltage and current conditions is required. For this purpose, along with traditional methods, a method and algorithm using the latest mathematical technologies, such as the theory of fuzzy logic and fuzzy sets, are proposed.

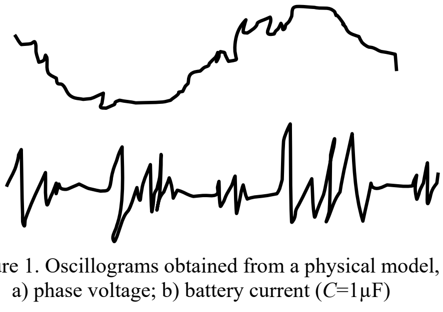

Figure 1. Oscillograms obtained from a physical model, a) phase voltage; b) battery current (C=1μF)

2. DETERMINING RATIONAL POWER OF COMPENSATING DEVICES IN A DISTRIBUTED NETWORK BASED ON RES

Before moving on to reactive power mode control, let's look at the expression of apparent power in single-ended and non-sinusoidal modes. Let an asymmetric polyharmonic voltage system are U_{AB}, U_{BC}, U_{CA} be connected in a system with distributed generation based on RES at the input of a three-phase load. The consumed active power at the input in this case will be:

$$P = P_1 + \Delta P_L + \Delta P_H \quad (4)$$

where, $P_1 = 3U_{11}I_{11}\cos\phi_{11}$ is the active power of the symmetrical components of the fundamental frequency; $\Delta P_L = 3U_{12}I_{12}\cos\phi_{12}$ is loss of active power due to asymmetric components of the fundamental frequency; $\Delta P_H = \sum_{n=2}^{n_m}\left(P_{A,n} + P_{B,n} + P_{C,n}\right)$ is active power losses due to higher harmonics.

In accordance with the above losses, the total power factor of a three-phase load in a distributed network based on RES is determined by:

$$\lambda = \frac{P}{S} = \frac{P_1}{S} + \frac{\Delta P_H}{S} + \frac{\Delta P_\Gamma}{S} = \lambda_C + \lambda_H + \lambda_\Gamma \quad (5)$$

where, λ_C, λ_H, λ_Γ are the components of the total power factor, due to the symmetrical and asymmetric components of the fundamental frequency, higher harmonics; and S is total power at the output of the consumer:

$$S = \sqrt{\left(P_1 + P_H + \sum_{n=2}^{n_m} P_n\right)^2 + \left(Q_1 + P_H + \sum_{n=2}^{n_m} Q_n\right)^2} \quad (6)$$

where, Q_1 is the reactive power of the fundamental harmonic; and $\sum_{n=2}^{n_m} P_n$, $\sum_{n=2}^{n_m} Q_n$ are active and reactive power due to higher harmonics.

From Equations (5) and (6) it can be seen that in order to increase the power factor in a distributed network based on RES, it is necessary to reduce the value of the total power at the input of the three-terminal network. Currently, to solve this problem in the power supply systems of industrial enterprises connected to the RES network, capacitor banks are used. Since, with asymmetric polyharmonic systems of voltages and currents, the installation of capacitors causes a change in the asymmetry coefficients in the reverse sequence and distortions of the sinusoidality of the voltage curve, it is necessary to select the values of compensating powers based on minimizing the values of the total power at the consumer input.

This paper proposes a method and algorithm for estimating the optimal value of the compensating power of static reactive power compensators and controlling the power of these compensators in a network with RES using fuzzy logic theory, which ensures a minimum loss of active power in a network with RES and, accordingly, a minimum of total power at the input of electricity consumers. Description of the method is given in the following:

1. According to the measurement data of the symmetrical components of linear voltages and currents of the direct sequence of the fundamental frequency, the reactive power consumed by the loads and RES is determined:

$$Q_1 = 3U_{11}I_{11}\sin\phi_{11} \quad (7)$$

2. Based on the values of this reactive power, the nominal value of the capacitance of the capacitor bank is calculated:

$$C_H = Q_1 / \left(3U_\varphi^2\omega\right) \quad (8)$$

3. To determine the capacitance value that provides a minimum loss of active power and a minimum of apparent power at the input of consumers in a network with RES, the dependence $\lambda\left(C_H\right)$ is calculated. For this purpose, a series of values from 0 to C_H is set and the corresponding values of the total power are calculated according to (6).

4. The optimal value of the compensating capacitance and the minimum losses in the network with RES will correspond to $S = S_{\min}$, which, in turn, corresponds to the maximum value of the power factor $\lambda = \lambda_{\max}$.

A SCB is connected to the installation, the capacity of which is closest to the optimal one. In this case, it is necessary to fulfill the conditions that exclude overloads of cosine capacitors in terms of voltage and current:

$$I_C = \sqrt{\sum_{n=1}^{40} I_{c,n}^2} \le 1.3 I_{nom,k} \quad (9)$$

$$U_C = \sqrt{\sum_{n=1}^{40} U_{c,n}^2} \le 1.3 U_{nom,k} \quad (10)$$

where, $I_{c,n}, I_{c,n}$ are the harmonic components of the current and voltage of the network; $I_{nom,k}, U_{nom,k}$ are the nominal values of the current and voltage of the capacitor bank.

Currents of groups of harmonics, generated by nonlinear loads in the network, increase significantly, and it can be noted that the voltage of these harmonics is directly applied to the capacitor batteries. In addition, it is known that the capacitive resistance of the battery decreases with the increase in the number of harmonics. This leads to the fact that resonance currents of the same magnitude as the first harmonic flow through the batteries, and sometimes even more.

Capacitors can be recharged up to 30% in current and up to 10% in voltage. In fact, the current overload due to resonance can reach 400-500%, so that the current of the resonance frequency can significantly exceed the current of the first harmonic. When choosing the capacity of capacitor batteries and the place of installation, it is necessary to take into account the possibility of the occurrence of a resonance phenomenon at one of the harmonic frequencies of voltage and current generated by non-linear loads.

In accordance with the described methodology, an algorithm was compiled in relation to the MATLAB software systems.

3.CONTROL ALGORITHM FOR REACTIVE POWER COMPENSATION IN A DISTRIBUTED NETWORK BASED ON RES AND WITH DISTORTING LOADS

To compensate for RP in a power supply network with RES and non-linear distorting loads, a fuzzy logic controller circuit has been developed that allows voltage stabilization in the electrical network, taking into account the compensation of the harmonic components of the reactive power of each harmonic (Figure 2).

In the case of a power supply scheme with distorting non-linear loads, a model for the formation of fuzzy logic using Mamdani algorithms was also used. The membership function (FP) of fuzzy sets of terms for input and output variables has a triangular, trapezoidal, bell-shaped, S and Z-shaped form [7].

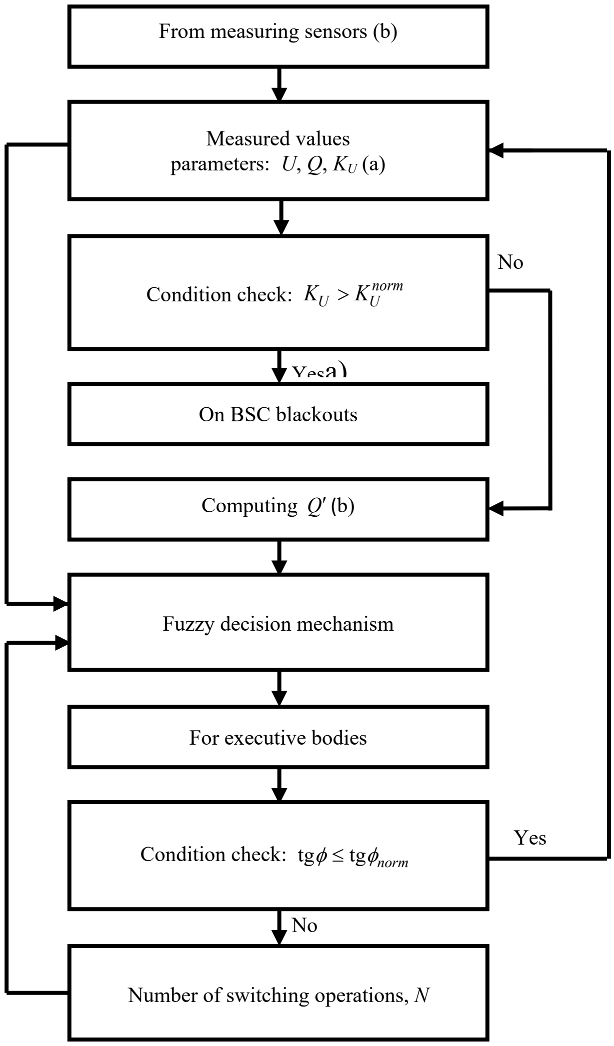

Figure 2. Fuzzy control algorithm taking nonlinear voltage distortion into account

During the operation of a fuzzy controller (FC) in distribution networks, the calculated or measured value of reactive power, the rate of change (change dynamics) of reactive power, the calculated or measured voltage value and the amount of switching's per day performed by the installation were fed to the FC input. Output linguistic variables of the FS are switch switching and controller action delay time.

The value of the input linguistic variables of the FS comes from the information-measuring systems, and the output parameters are determined using the fuzzy decision mechanism. After the FK decision is made, the output linguistic variables are converted into clear numbers with the help of a defuzzifier.

The following output and input linguistic variables were used to operate the reactive power FC: fuzzy values at the controller input (input variables), FP and parameters of input linguistic variables are shown in Table 1.

Table 1. Linguistic variables of FK, their domains of definition in the form of terms and numerical values of parameters

Terms	Membership function	Numerical values of term parameters
Reactive power		
Very small	Z–figurative	(0 0.045)
Small	Trapezoidal	(0 0.045 0.145 0.22)
Medium	Trapezoidal	(0.145 0.22 0.42 0.46)
Big	Trapezoidal	(0.42 0.46 0.86 0.97)
Very big	S- figurative	(0.82 0.93 1.0)
Dynamics		
Negative	Z- figurative	(-0.45 0)
Zero	Triangular	(-0.82 0 0.82)
Positive	S- figurative	(0 0.45)
Voltage		
Low	Trapezoidal	(0.7 0.75 0.9 0.96)
Normal	Trapezoidal	(0.9 0.95 1.05 1.12)
High	S- figurative	(1.06 1.12)
Emergency	Z- figurative	(0.9 0.75)
Harmonic distortion		
Normal	Z- figurative	(2.6 6.1)
Little big	Triangular	(2.6 6.1 9.2)
Big	S- figurative	(6.1 9.2)
Quantity		
Small	Z- figurative	(0 8 11)
Not Small	S- figurative	(8 11 13)
Directions		
Up	Trapezoidal	(0.5 0.75 1.25 1.5)
Down	Trapezoidal	(-1.5 -1.25 -0.75 -0.5)
Stop	Trapezoidal	(-0.5 -0.25 0.25 0.5)
Delay		
Very Small	Z- figurative	(0 0.045)
Short	Trapezoidal	(0 0.045 0.16 0.22)
Medium	Trapezoidal	(0.16 0.22 0.42 0.47)
Long	Trapezoidal	(0.42 0.47 0.86 0.96)
Very long	S- figurative	(0.82 0.92 1.12)

After determining the fuzzy values of the term-sets $T_{E_{ij}}(\cdot)$ of variables (input parameters) and controlled parameters (output parameters) $T_{E_{1j}}(Q)$ with $j=\overline{1.5}$, $T_{E_{2j}}(Q')$ with $j=\overline{1.3}$, $T_{E_{3j}}(U)$ with $j=\overline{1.4}$, $T_{E_{4j}}(K_U)$ with $j=\overline{1.3}$, $T_{E_{5j}}(D_L)$ with $j=\overline{1.2}$, $T_{E_{6j}}(D_r)$ with $j=\overline{1.3}$, $T_{E_{7j}}(D_y)$ with $j=\overline{1.5}$, a system of fuzzy control rules RM (fuzzy modeling) is compiled.

For many FCs, fuzzy rules are used, which have the following form [8]:

$$\left.\begin{array}{l} \text{if } x_1 \text{ is } A_{11}, \ldots, \text{ and } x_n \text{ is } A_{1n} \text{ then } y \text{ is } B_1 \\ \text{if } x_1 \text{ is } A_{21}, \ldots, \text{ and } x_n \text{ is } A_{2n} \text{ then } y \text{ is } B_2 \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \text{if } x_1 \text{ is } A_{n1}, \ldots, \text{ and } x_n \text{ is } A_{mn} \text{ then } y \text{ is } B_m \end{array}\right\} \tag{11}$$

Based on the above state and control variables, 67 fuzzy decision and control rules were compiled for this FC in the form (10).

4. RESULTS OF THE STUDY OF HIGHER VOLTAGE HARMONICS ACCORDING TO THE SCHEMES OF IEEE AND AZERENERGY WITH INTEGRATED RES

To test the developed model and algorithm for controlling the flow of reactive power over a distributed network based on renewable energy sources with non-linear consumers, computational experiments were carried out for the standard test circuit IEEE scheme and in the scheme of the electrical network of the Azerenergy system [9]. In Figures 3a, 3b shows the pattern of change in the coefficient of total harmonic voltage distortion across K_U the nodes of the IEEE test circuit and the real electrical network of power systems with renewable energy sources. As can be seen, in all cases $K_U > 2\%$ and exceeds the established standards for tires with a voltage of 110 kV [3].

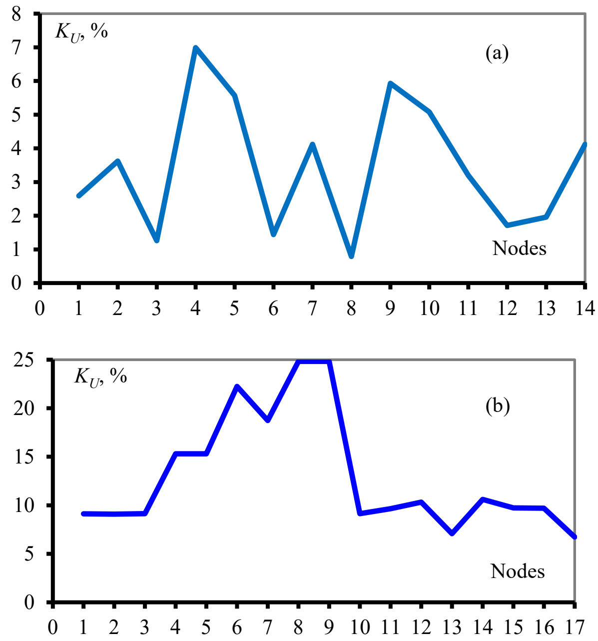

Figure 3. profiles of the total coefficient of harmonic components (K_U) of the voltage at maximum load conditions of the network; a) for 14 node IEEE scheme; b) for a real scheme of power systems

For example, on the 110 kV bus of the substation No. 4 of the IEEE scheme $K_U = 7\%$, and on the bus of the substation No. 9, $K_U = 6\%$ (Figure 4a), for a real electrical network on the bus of the substation No. 12, 15 and 16, $K_U = 10\%$, and on the bus of the substation No. 1-3 and No. 9, $K_U = 9\%$.

Similar results are obtained on 35 kV and 10 kV buses. On these tires, the coefficient values K_U significantly exceed the established norms for these voltage classes. So, on 35 kV buses, Substation No. 8 K_U is within 15% ($K_U^{nom} = 4\%$), and on 10 kV buses 20-25% ($K_U^{nom} = 5\%$). On 10 kV buses, the effective voltage value decreases, respectively, to 7.9% and 8.05%.

So, based on the computational experiments carried out using the ETAP complex, the results were obtained, from which it was found that under conditions of a non-sinusoidal supply voltage, it is necessary to take into account the value of the total factor of harmonic components in the fuzzy reactive power control algorithm to prevent partial overloads of the SCB [10].

5. RESULTS OF SIMULATION OF THE FC CONTROL ALGORITHM

To represent the efficiency of using the fuzzy algorithm proposed above in the form (10) FC of reactive power in electrical networks of power systems under conditions of non-sinusoidality and voltage asymmetry, numerous calculations have been made by computer simulation in the MATLAB software package using the Fuzzy Logic Toolbox module [11-14]. When modeling the algorithm, typical graphs of active and reactive loads were used, which are shown in Figure 4.

Based on the computer implementation of the FC algorithm and the knowledge base in the form (10), two pairs of surface controls $Y = f(U', K_U)$ and $Y = f(Q, K_U)$ are obtained.

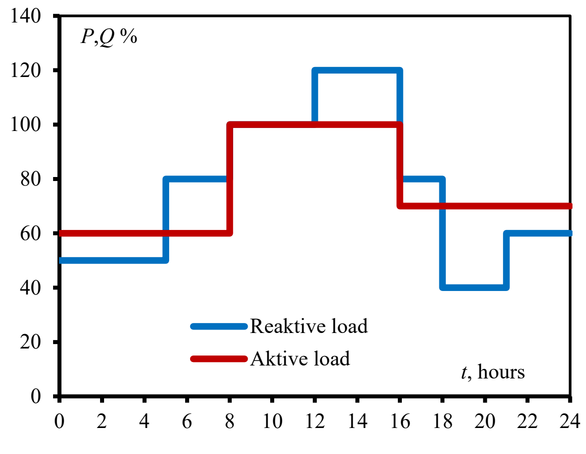

Figure 4. Typical daily schedules of active and reactive loads

When K_U = Normal, to reduce the voltage and reactive power factor tgϕ, FC decides to turn on the SCB section, and if the voltage corresponds to the terms above the rated voltages, the FC generates control actions to turn off the SCB sections. When K_U = Large, FC decides to turn off the SCB instantly, regardless of the voltage values and tgϕ. When K_U =Slightly large, depending on the voltage value and tgϕ, the controller makes one or another decision in accordance with the HP PM control algorithm.

The delay time of the controller operation is generated depending on the number of switching sections of the SCB per day and on the value of the input variable "Dynamics". If the number of switching's is Few per day and the "Dynamics" is negative, then the delay will be medium, or if the number of switching's is Few per day and the "Dynamics" is positive, then the delay will be short, etc.

Figures 5a, 5b show the obtained diagrams of fuzzy control reactive power (a) and tgϕ (b), respectively, in the initial mode, with and without taking into account the values of the coefficient K_U.

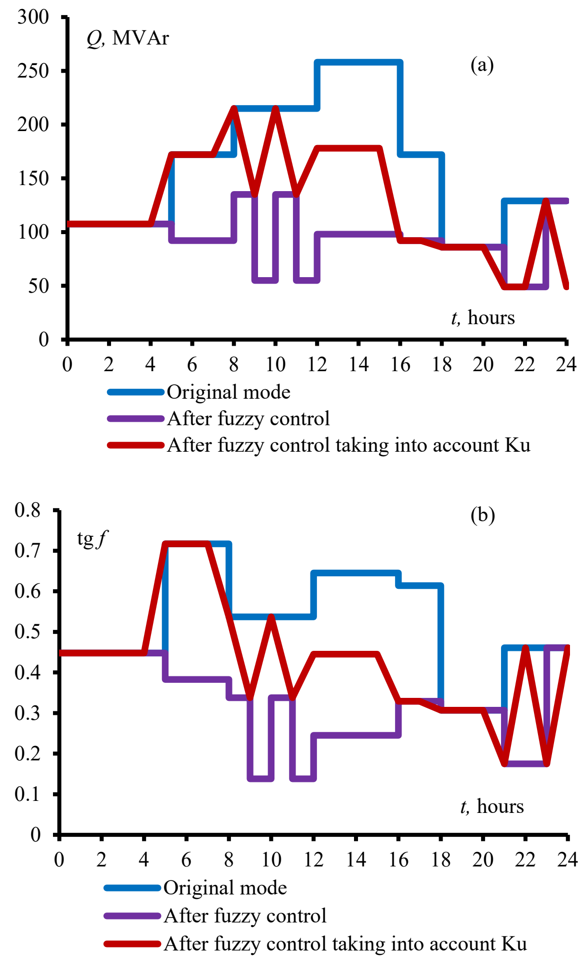

Figure 5. Reactive power control diagrams (a) and tgϕ (b) in a system with distributed generation based on RES

As can be seen from the figure, in accordance with the surface control, taking into account the value of K_U, FC generates control signals only at its small values and values that are within the normal range (K_U^{norm}) set in [3].

When controlled, the values at certain hours (for example, 4-7 hours $\text{tg}\phi = 0.71$) are obtained above the norm, but, despite this, under conditions $K_U > K_U^{norm}$ overloads of the SCB capacitors are prevented, as well as their premature failure.

6. CONCLUSION

1) The method of rational choice of compensators for compensating reactive power under RES conditions and uncertain circuit-mode changes in the distributed generation system based on RES, asymmetry and non-sinusoidality created by distorting loads is given. The method makes it possible to take into account the effect of asymmetric higher harmonics of currents on the SCB.
2) In a distributed generation system based on the IEEE standard 14-node scheme and the real Azerenerji network scheme with integrated RES, the values and changes in the coefficient of the n-th harmonic components and the total coefficient of harmonic components for current and voltage were determined. In the case under consideration, it was found that the values of some harmonic components and the total coefficient of the harmonic component of the voltage exceed the established standards, which must be taken into account when compensating for reactive power.
3) Based on the fuzzy logic model, an algorithm FC of reactive power in a system with distributed generation based on RES with distorting loads is proposed, which allows stabilizing the variability of the reactive power factor within the limits established by the operating conditions for consumers, as well as to ensure the normal operational technical condition of the SCB. As a result of taking into account the harmonic distortion of sinusoidal voltage and current in the algorithm, overloads of the SCB with higher harmonic currents are prevented. This leads to an increase in the functional reliability of switching devices, as well as SCB as a whole.

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