UDC 621.316.761.2

FUZZY-PID CONTROLLER IN THE PULSE WIDTH MODULATION SYSTEM FOR CONTROLLING OF THREE-PHASE PARALLEL ACTIVE POWER FILTER CONVERTER

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Purpose. The development of the fuzzy-pid controller in the method of pulse with modulation for control converter active power filter. **Methodology.** Using the known method of calculating of the regulators in the loop current of the power active filter, it is showed that regulator coefficients depend on current. It is proposed to use the fuzzy controller for correcting the control loop parameters when the current changes with respect to the target value. Based on a technique known in electrical engineering as a method of symmetrical components, as well as taking into account the provisions of the existing standards, the procedure of formation of given current in accordance with the Fryze theory is distinguished. **Results**. In the formula for determining of the active power in accordance with Fryze theory the power and the positive sequence voltage were input, which significantly reduced the components of the feedback network current sequence. By applying the fuzzy controller in the control loop of the APF power current has lead to the lower current waveform distortion ratio at 25,22 %. **Originality.** The Fryze theory is used to select and to compensate the load inactive components, but since the theory is not applied for polyphase circuits, it is not used for current and voltage asymmetry, and the procedure determining the given APF current is adjusted and proposed. This procedure allows to control three-phase APF in three-phase AC loop current at asymmetry of load current, asymmetry of supply voltage and non-sinusoidal supply voltage. **Practical value.** The proposed procedure for the formation of given APF current can be used in the development of information systems management by compensation process.

Key words: active power filter, Fryze power theory, direct sequence, fuzzy control, pulse width modulation.

СИСТЕМА РЕГУЛЮВАННЯ ТРИФАЗНОГО ПАРАЛЕЛЬНОГО СИЛОВОГО АКТИВНОГО ФІЛЬТРА З НЕЧІТКИМ РЕГУЛЯТОРОМ В КОНТУРІ СТРУМУ

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Методи управління силовими активними фільтрами будуються на сучасних уявленнях про складові потужності. Для визначення заданого струму силового активного фільтра можуть бути реалізовані різні теорії визначення неактивних складових потужності, серед яких застосовується теорія повної потужності за С. Фрізе. В той же час, вагомою частиною якості роботи пристрою в цілому є процес регулювання струму. На підставі аналізу відомих робот встановлено, що параметри регулятора замкнутого контуру струму компенсатора зумовлюються режимом навантаження, яке змінюється. Таким чином виникає необхідність корегування параметрів регулятора. За попередніми дослідами встановлено, що для корекції коефіцієнтів регулятора може бути використаний апарат нечіткої логіки. Запропоновано нечіткий регулятор з відповідним порядком перерахунку коефіцієнтів регулятора. В пакеті візуального програмування розроблено модель пропонованої системи. Ефективність застосування пропонованого рішення підтверджено порівнянням часових діаграм струму вузлів системи для двох варіантів: з фіксованими параметрами регулятора та нечіткого регулятора. За результатами сформульовано висновки про раціональність застосування пропонованого рішення.

Ключові слова: силовий активний фільтр, теорія потужності Фрізе, пряма послідовність, нечіткий регулятор, широтно-імпульсна модуляція.

PROBLEM STATEMENT. The increased usage of semiconductor technology, led to increasing of nonlinear loads, which exacerbated the problem of power quality [1]. The negative impact of non-linear load leads to a high total harmonic distortion (THD), which is taken from transmitter network. This load current is characterized by high level of harmonic components, the effect of which causes economic losses. They are caused by the deterioration of the energy index. It is also characterized by the reduction of the reliability of the power supply networks and technological processes, the growth in additional losses in the networks and in components of electric equipment, the reduction of the service term of the main electric equipment in power systems, reduction of reliability and malfunction of relay protection systems, automation, microprocessor systems and networking.

Non-linear load has high reactive power consumption, increasing losses in the electric power system, overload of generators, transformers, power transmission lines, and voltage fluctuations.

The latest achievement of power converter technology and the most effective technical solutions in the field of inactive components compensation of power loads in three-phase means of AC voltage is the controlled filter-compensating device or active power filter (APF) [2].

Analysis of previous studies. APF management methods are based on the actual understanding of the power components [3], but the most important component in the device operation is the method control pulses formation in the conversion keys. [4]. Among the methods of the control pulses the pulse with modulation and relay current control (RCC) are also distinguished. The RCC method attracts the researchers' attention due to such features as ease of implementation, fast transient response, high accuracy and limitations of peak current, but the variable switching frequency of converter valves, which leads to the generation of high-frequency components in the network is considered as a significant disadvantage [4].

Pulse width modulation provides for comparison of the modulating signal with the reference signal of fixed amplitude and frequency. Modulating signal in case of APF is current error in the loop current. The current error is regulated wit the appropriate controller, which parameters are calculated in accordance with the optimal settings [1, 4].

The use of pulse modulation leads to the formation pulses controlling the switching valves of APF with constant frequency, which provides the opportunity to filter corresponding harmonics with the passive filter [4].

According to the work [1] it is proposed the specific APF current regulator synthesis sequence. Assuming that the filter output voltage U_0 is constant and equal to its average value (U_{0av}) during the carrier waveform, U_0 is expressed as a function of the resistance voltage in the Laplace domain

$$U_0(s)=U_{0av}(s)=\frac{U_c}{2U_{t\max}}\cdot U_m(s),$$

where U_c and $U_{t\max}$ are voltage on the DC bus and the amplitude of the triangular carrier signal.

Taking into consideration that the coordinate basic origin corresponds to the moment when the phase voltage A, $u_A=U_A\sin(\omega_1 t)$, passes through zero and becomes positive, the active filter transfer functions for current is defined using Kirchhoff's laws in the Laplace domain ,

$$G_{Fi}(s)=\frac{I_F(s)}{U_m(s)}=\frac{U_c}{2L\cdot U_{t\max}\cdot s}=\frac{1}{K_{Fi}\cdot s},$$

where $K_{Fi}=\frac{2L\cdot U_{t\max}}{U_c}$ is factor; L – is throttle inductance in the AC circuit.

In the current loop flowchart (Figure 1) it is assumed that the current sensor dynamics is reflected with the transfer function:

$$G_{Ti}(\mathrm{s})=\frac{K_{Ti}}{1+T_{Ti}\cdot s},$$

where K_{Ti} – the current sensor transfer ratio; T_{Ti} – time constant of the current sensor.

We can use the classical proportional-integral structure of current controller. Thus, the controller parameters depend on the APF current and the capacitor voltage, which causes controller error while the load duty and current form are changed. The correspondent regulator controls the current accuracy, the parameters controller structure:

$$G_{Ci}(\mathrm{s})=\frac{1+\theta_{1i}\cdot s}{\theta_i\cdot s}.$$

Using the classical approach to the synthesis of regulators when setting up an open loop for transfer function:

$$G_{di}(\mathrm{s})=G_{Ci}(\mathrm{s})\cdot G_{Fi}(\mathrm{s})\cdot G_{Ti}(\mathrm{s})=\frac{1+\theta_{1i}\cdot s}{T^2\cdot s^2\cdot(1+\mathrm{T}_{Ti}\cdot s)},$$

where $T^2=\frac{\theta_i\cdot K_{Fi}}{K_{Ti}}$, the current controller parameters are obtained:

$$\theta_{1i}=4T_i\,;\ \theta_i=8K_{Ti}\cdot T_{Ti}^2/K_{Fi}.$$

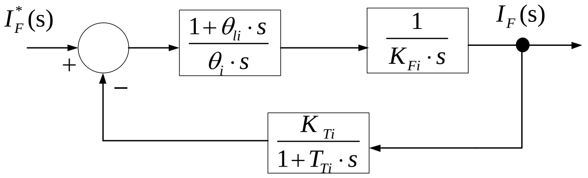


Figure 1 – Current loop flowchart

Thus, the transmission function of the current controller is defined as

$$G_{Ci}(\mathrm{s})=\frac{K_{Fi}}{2K_{Ti}\cdot T_{Ti}}\left(1+\frac{1}{4T_{Ti}\cdot s}\right).$$

Thus, the controller parameters depend on the APF current and the capacitor voltage, which causes controller error while the load duty and current form are changed. It sets the task of adjusting the regulator coefficients at change of the loading regime with using the elements of fuzzy logic theory [5–7].

PURPOSE. The development of the fuzzy-pid controller in the pulse width modulation system for controlling of three-phase parallel active power filter converter and this model survey.

EXPERIMENTAL PART AND RESULTS OBTAINED. Fuzzy-pid control is used when there is insufficient knowledge of the control object and the control experience in nonlinear systems is available, but the identification of these systems is rather time-consuming [4–6].

In 1974, Mamdani [5] demonstrated the possibility of the application of the ideas of fuzzy logic for building dynamic object management system. Since then the scope of the fuzzy controller has been constantly expanding and the diversity of their structures and functions have been increasing.

Fuzzy logic control is used mainly in two ways: the construction of the regulator and the organization of adjustment coefficients of the existing regulator. Both ways can be used simultaneously.

One of the most common structures of fuzzy controller is shown in Fig. 2.

In general, the the controller input receives the error *e* and its time derivative *de*/*dt* is calculated. Then, both values at first are subject of fuzzification (transformation into fuzzy variables), the obtained fuzzy variables are used in a block of logic operations for the control action on the object, which after performing defuzzification (inverse transform of fuzzy variables) is supplied to the regulator output as the manipulated variable *u*.

In order to perform the regulatory functions of fuzzy variables the operations formulated in the form of fuzzy rules must be fulfilled.

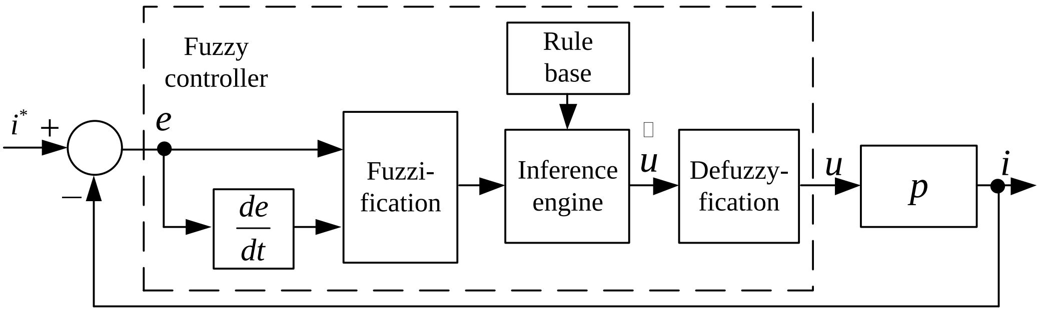


Figure 2 – Example of fuzzy controller structure

APF control algorithm. In proposed solution the determining of current compensator is given by using the S. Fryze method of full power, in which the current (voltage) into two orthogonal components in the time domain is set out.

S. Fryze proposed to decompose the current i in the active i_A (replicates the form of mains voltage and receives the same energy as all current for the reviewed interval) and passive i_{Π} (residual current, not consumed energy or orthogonal with the mains voltage and active current) components:

$$i_{ld} = i_A + i_{\ddot{I}} \ .$$

Active current by Fryze:

$$i_A = \frac{P}{U^2} \cdot u \, ,$$

active power and the current value of the RMS voltage of the reviewed interval T:

$$P = \frac{1}{T}\int_0^T u \cdot idt \, ; \; U^2 = \frac{1}{T}\int_0^T u^2 dt \, .$$

The passive current component is recovered from the current load:

$$i_{\ddot{I}} = i_{ld} - i_A \, .$$

Since the passive components don't consume energy they should be compensated according to the Fryse theory. Fryze theory is used to isolate and compensate load's inactive components, but because the theory is not intended for polyphase circuits, and does not take into account the current and voltage asymmetry, then procedure for determining the given APF current is proposed.This procedure allows to control the three-phase APF in the three-phase AC current at asymmetry of load currents, asymmetry of supply voltage and the supply voltage anhormonicity.

The mains phase voltages u_{abc} and load phase currents ii_{ld_abc} are controlled, and the phase currents of the power active filter $i_{c.abc}$ are controlled.

For the realization of fundamental harmonic voltage and load current the expansion in Fourier series is used.

Determination of the cosine and sine components of the primary voltage harmonics for three phases:

$$U_{a1\cos} = \frac{2}{T}\int_0^T u_a \cdot \cos\omega t \cdot dt \, ;$$

$$U_{a1\sin} = \frac{2}{T}\int_0^T u_a \cdot \sin\omega t \cdot dt \, ,$$

The same is similarly for the phases b and c. For further calculations, we consider that the calculations for mains phase a are accompanied by similar calculations for phases b and c.

Determination of the cosine and sine components of the primary current harmonics for three phases:

$$I_{a1\cos} = \frac{2}{T}\int_0^T i_{ld.a} \cdot \cos\omega t \cdot dt \, ;$$

$$I_{a1\sin} = \frac{2}{T}\int_0^T i_{ld.a} \cdot \sin\omega t \cdot dt \, ,$$

Is similar for the phases b and c.

The components of the primary voltage harmonics are determined in a complex form:

$$\dot{U}_{1\grave{a}} = U_{a1} \cdot e^{j\varphi_{a1}} = \sqrt{U_{a1\cos}^2 + U_{a1\sin}^2} \cdot e^{jarctg\frac{U_{a1\sin}}{U_{a1\cos}}} \, .$$

The components of the primary current harmonics are determined:

$$\dot{I}_{1\grave{a}} = I_{a1} \cdot e^{j\psi_{a1}} = \sqrt{I_{a1\cos}^2 + I_{a1\sin}^2} \cdot e^{jarctg\frac{I_{a1\sin}}{I_{a1\cos}}} \, .$$

On the basis of the main components of the harmonic voltage and phase currents the components of the line voltage sequence are determined:

$$\dot{U}_{1\grave{a}}^{+} = \frac{1}{3}\left(\dot{U}_{1\grave{a}} + a \cdot \dot{U}_{1b} + a^2 \cdot \dot{U}_{1c}\right) = U_{1a}^{+} \cdot e^{j\varphi_{1a}^{+}} \, ;$$

$$\dot{U}_{1b}^{+} = \frac{1}{3}\left(a^2 \cdot \dot{U}_{1a} + \dot{U}_{1b} + a \cdot \dot{U}_{1c}\right) = U_{1b}^{+} \cdot e^{j\varphi_{1b}^{+}} \, ;$$

$$\dot{U}_{1c}^{+} = \frac{1}{3}\left(a \cdot \dot{U}_{1a} + a^2 \cdot \dot{U}_{1b} + \dot{U}_{1c}\right) = U_{1c}^{+} \cdot e^{j\varphi_{1c}^{+}} \, ,$$

where a – phase and current operator:

$$\dot{I}_{1a}^{+} = \frac{1}{3}\left(\dot{I}_{1a} + a \cdot \dot{I}_{1b} + a^2 \cdot \dot{I}_{1c}\right) = I_{1a}^{+} \cdot e^{j\varphi_{1a}^{+}} \, ;$$

$$\dot{I}_{1b}^{+} = \frac{1}{3}\left(a^2 \cdot \dot{I}_{1a} + \dot{I}_{1b} + a \cdot \dot{I}_{1c}\right) = I_{1b}^{+} \cdot e^{j\varphi_{1b}^{+}} \, ;$$

$$\dot{I}_{1c}^{+} = \frac{1}{3}\left(a \cdot \dot{I}_{1a} + a^2 \cdot \dot{I}_{1b} + \dot{I}_{1c}\right) = I_{1c}^{+} \cdot e^{j\varphi_{1c}^{+}} \, .$$

The instantaneous voltage u of the component of the fundamental harmonic u_1:

$$u_{a1}^{+} = U_{a1}^{+} \cdot \sin\left(\omega t + \varphi_{1a}^{+}\right) .$$

The active power for the positive sequence for fundamental harmonic is found:

$$P_{a1}^{+} = U_{a1}^{+} \cdot I_{a1}^{+} \cdot \cos\left(\varphi_{a1}^{+} - \psi_{a1}^{+}\right).$$

The effective value of voltage of the basic positive sequence harmonic is determined for each phase:

$$U_{RMSa}^{+} = \sqrt{\frac{1}{T}\int_{0}^{T}\left(u_{a1}^{+}\right)^{2} dt}\ .$$

Additionally the square of the average current values of voltage of the basic positive sequence harmonic is calculated:

$$U_{RMS+}^{2} = \left(\frac{U_{RMSa}^{+} + U_{RMSb}^{+} + U_{RMSc}^{+}}{3}\right)^{2}.$$

The active current by Fryze for phase *a* is determined:

$$i_{AF.a} = \frac{P_{a1}^{+} \cdot u_{a1}^{+}}{\left(U_{RMS}^{+}\right)^{2}},$$

and similarly for the phases *b* and *c*.

The passive component current loads corresponding to the given current APF is determined:

$$i_{P.a} = i_{c.a}^{*} = i_{ld.a} - i_{AF.a},$$

and similarly for the phases *b* and *c*.

The current error, i.e. the difference between the target $i_{c\_abc}^{*}$ and the current i_{c_abc} three-phase current APF is found:

$$\Delta i_{a} = i_{c\_a}^{*} - i_{c\_a}.$$

Despite the fact that the fuzzy controller is implemented in a discrete form, the derivative with respect to time is calculated using the *Z*-transformation:

$$\Delta i_{a}^{'} = \frac{K_{d}\left(z-1\right)}{T_{s} z}\Delta i_{a}.$$

where K_{d} – coefficient of differential component intensification, which is determined according to known methods; T_{s} – time constant, 10^{-5} c; z –- the operator of the discrete Laplace transformation.

The fuzzification is performed:

$$\Delta i_{a.1} = G_{ce}\Delta i_{a};$$

$$\Delta i_{a.2} = G_{e}\Delta i_{a};$$

$$\Delta i_{a.3} = G_{ce}\Delta i_{a}^{'}.$$

G_{e} and G_{ce} factors are determined from the intensification of proportional component K_{p} and from intensification of the proportional component K_{i}, which is determined according to known methods:

$$G_{e} = 1;$$

$$G_{ce} = \frac{G_{e} \cdot (K_{p} - \sqrt{K_{p}^{2} - 4 \cdot K_{i} \cdot K_{d}})}{2 \cdot K_{i}};$$

The initial parameter f_a is determined according to the rules:

– if $\Delta i_{a.2}$ is negative and $\Delta i_{a.3}$ is negative, then $f_a = -1$;

– if $\Delta i_{a.2}$ is negative and $\Delta i_{a.3}$ is equal to 0, then $f_a = -0{,}5$;

– if $\Delta i_{a.2}$ is negative and $\Delta i_{a.3}$ is positive, then $f_a = 0$;

– if $\Delta i_{a.2}$ is equal to 0 and $\Delta i_{a.3}$ is negative, then $f_a = -1$;

– if $\Delta i_{a.2}$ is equal to 0 and $\Delta i_{a.3}$ is equal to 0, then $f_a = 0$;

– if $\Delta i_{a.2}$ is equal to 0 and $\Delta i_{a.3}$ is positive, then $f_a = 0{,}5$;

– if $\Delta i_{a.2}$ is positive and $\Delta i_{a.3}$ is negative, then $f_a = 0$;

– if $\Delta i_{a.2}$ is positive and $\Delta i_{a.3}$ is equal to 0, then $f_a = 0{,}5$;

– if $\Delta i_{a.2}$ is positive and $\Delta i_{a.3}$ is positive, then $f_a = 1$.

The defuzzification is performed:

$$uf_{a} = G_{cu}\Delta i_{a.1} + f_{a}\left(G_{cu}\frac{K_{i}T_{s}z}{\left(z-1\right)} + G_{u}\right).$$

where $G_{cu} = \frac{K_{i}}{G_{e}}$; $G_{u} = \frac{K_{d}}{G_{ce}}$.

By the method of pulse-with modulation with sawtooth voltage u_{ref}, pulses are generated:

$$U_{VT1-2} = \begin{cases} U_{VT1} = 1; U_{VT2} = 0,\ \text{ÿêù î}\ uf_{a} \geq u_{ref}; \\ U_{VT1} = 0; U_{VT2} = 1,\ \text{ÿêù î}\ uf_{a} < u_{ref}. \end{cases}$$

Similarly the voltages for the voltage phase transistors *b* and *c* are formed. The diagram, implementing the operations above is shown in Fig. 3.

The diagram (Fig. 3): 1 – three-phase electric power supply; 2 – asymmetrical nonlinear load; 3 – three-phase transistor converter; 4 – three-phase reactor; 5 – storage capacitor; 6 – sensors block of mains phase voltage; 7 – sensors block of the voltage; 8 – sensors block of current for actual APF; 9 – block of determining of cosine and sine of fundamental harmonic component; 10 – the block of determining of fundamental harmonic voltage and load current in complex form; 11 – block of determining of mains voltage and direct sequence voltage for fundamental harmonic; 12 – block of determining of active power by direct sequence fundamental harmonic; 13 –block basic harmonic voltage formation; 14 – block f determining of operating voltage in direct sequence basic harmonic; 15 – block of determining of square of average values of direct sequence basic harmonic voltage; 16 – block of determining of active current by Fryze; 17 – block of determining of passive component of the current; 18 – adder block; 19 – block of time derivative; 20 – fuzzification block; 21 – inference; 22 – defuzzification block; 23 – pulses formation block.

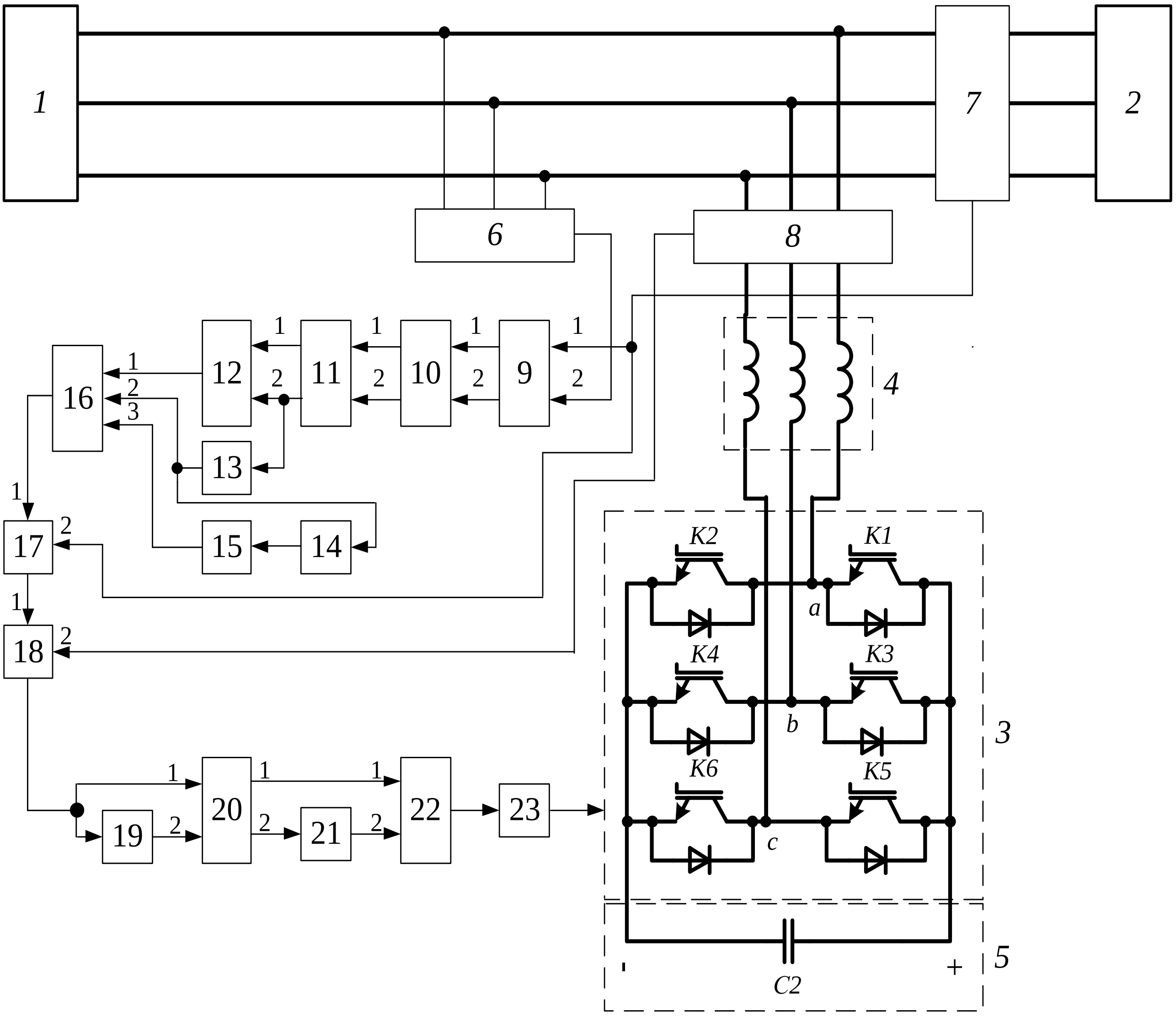


Figure 3 – Diagram of the control device of the three-phase parallel power active filter with fuzzy controller

The model of the control device of the three-phase parallel APF [14] with fuzzy controller was developed in the MATLAB/Simulink package. The nonlinear load in the model is presented in the form of a thyristor converter with RL-load R_{TC}=2 Ohms, L_{TC}=0.0116 H connected to the mains through the reactor *(Reactor2)* L_{RC} =0.0015 H. To the mains are also connected:

1) a single-phase inductive load with the power Q =6 *kvar*, connected to phase c;

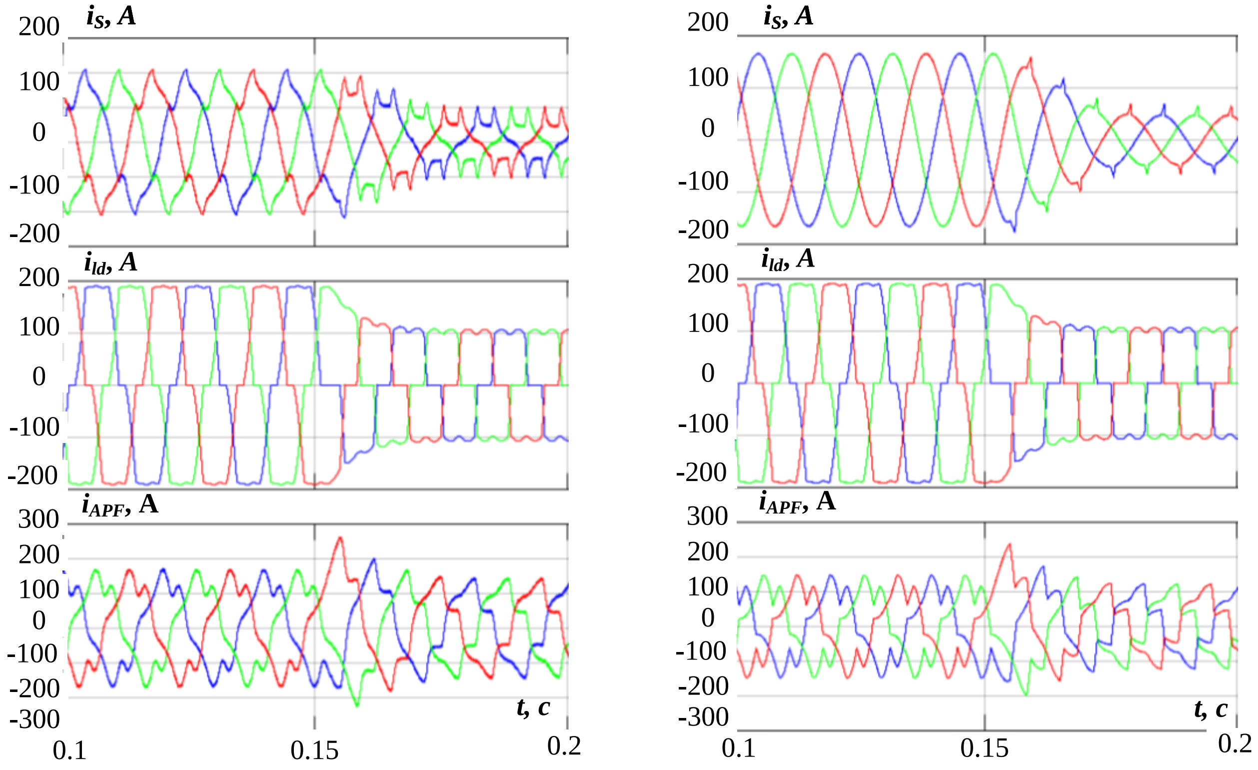
2) two-phase active load with the power P=6 kW, connected to the phases *a-c*;

3) three-phase RL-load with the power P = 33 kW, Q = 66 kvar.

The means parameters are calculated according to [10]: three-phase power supply with nominal voltage of the interphase voltage of 380 V, frequency of 50 Hz and with RL resistance R_S=0.1 Ohms, $L_S=1.3\cdot10^{-5}$ H.

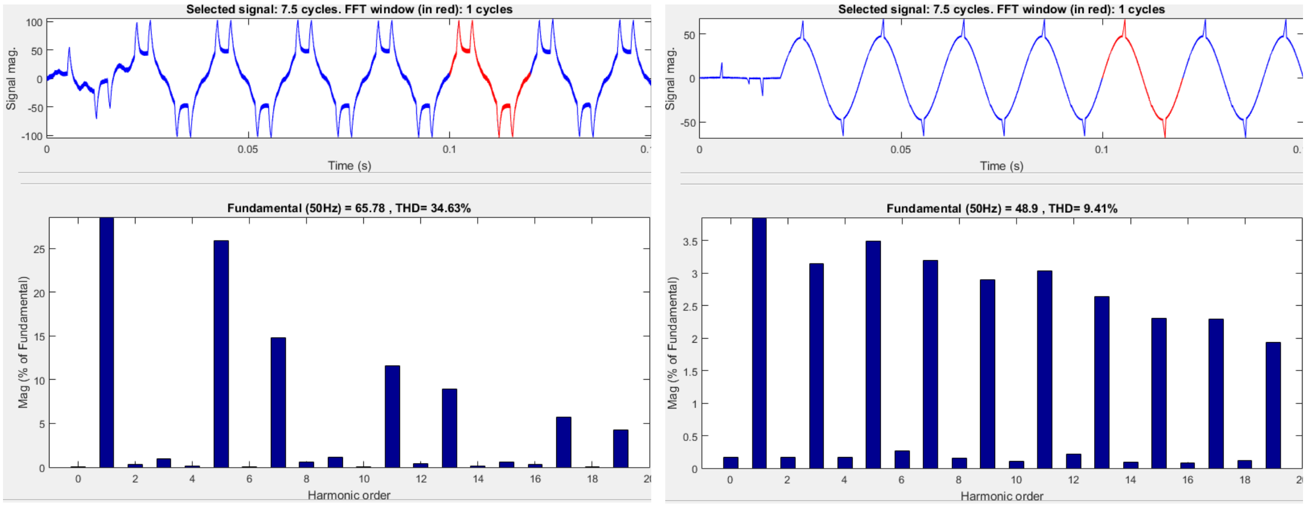
To create the voltage asymmetry, the voltage source is input in the phase *«b»* with amplitude of 35 V, 50 Hz and 120^0 phase shift. To create the voltage, in the *abc* phase the voltage source with amplitude 10 V, frequency 150 Hz, the 0^0 phase shift are input.

Three-phase APF is represented by: transistor inverter, which is connected to the mains through the reactor, DC link capacitors, which are connected to the capacity $C_1=40\cdot10^{-6}$ F. APF parameters were calculated as described by methods [11, 12]. The system of the given APF current determining is represented by the algorithm, which takes into account the asymmetry of voltage and current and is based on the Fryze power theory [14]. The method of pulses formation uses *PWM* [4]. The controller parameters are calculated in method [1].



a) b)

Figure 4 – Results of device operation with:
a) fixed controller parameters; b) with fuzzy controller implementation



a) b)

Figure 5 – Harmonious composition of the means phase current with compensator implementation with:
a) fixed controller parameters; b) fuzzy controller implementation

CONCLUSIONS. The usage of APF controllers to improve its performance and operational quality requires the solution of additional tasks related with correction of the controller parameters under the conditions of load current change and its forms.

It is noted that the effectiveness of the Fryze power theory can be significantly increased by using of capacities and voltages of the positive sequence in the well-known algorithm.

The possibility of using of the Mamdani fuzzy control algorithm in the structure of the current control system APF was shown, and according to the experiments results it was found that such usage leads to lower current distortion index at 25,22 %.

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СИСТЕМА РЕГУЛИРОВАНИЯ ТРЕХФАЗНОГО СИЛОВОГО АКТИВНОГО ФИЛЬТРА С НЕЧЕТКИМ РЕГУЛЯТОРОМ В КОНТУРЕ ТОКА

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Методы управления силовыми активными фильтрами строятся на современных представлениях о составляющих мощности. Для определения заданного тока силового активного фильтра могут быть реализованы различные теории определения неактивных составляющих мощности, среди которых применяется теория полной мощности С. Фризе. В то же время, весомой частью качества работы устройства в целом является процесс регулирования тока. На основании анализа известных работ установлено, что параметры регулятора замкнутого контура тока компенсатора обусловливаются режимом нагрузки, которое изменяется. Таким образом, возникает необходимость корректировки параметров регулятора. За предварительными опытами установлено, что для коррекции коэффициентов регулятора может быть использован аппарат нечеткой логики. Предложен нечеткий регулятор с соответствующим порядком пересчета коэффициентов регулятора. В пакете визуального программирования разработана модель предлагаемой системы. Эффективность применения предлагаемого решения подтверждена сравнением временных диаграмм тока узлов системы для двух вариантов: с фиксированными параметрами регулятора и нечеткого регулятора. По результатам сформулированы выводы о рациональности применения предлагаемого решения.

Ключевые слова: силовой активный фильтр, теория мощности Фризе, прямая последовательность, нечеткий регулятор, широтно-импульсная модуляция.

Стаття надійшла 14.11.2016.