THE PRACTICAL IMPLEMENTATION OF RELAY CONTROL OF CURRENT AS MAIN PART IN SYSTEM OF ACTIVE FILTER OF ELECTRIC POWER

V.N. Mescheryakov, *Lipetsk State Technical University, Lipetsk, Russian Federation, mesherek@stu.lipetsk.ru*
M.M. Habibullin, *Lipetsk State Technical University, Lipetsk, Russian Federation, maximum@rambler.ru*
I.S. Pavlov, *Lipetsk State Technical University, Lipetsk, Russian Federation, impredator@yandex.ru*

Here is a simple and effective control system of parallel active power filter. This parallel active power filter can improve the quality of the mains voltage when using non-linear loads. This is achieved by a significant reduction in the parallel active power filter harmonic current load and load power factor correction, while avoiding the risk of resonance phenomena typical of passive filters. This control system is a parallel active power filter may be used either in single phase mains or in three phase mains. We offer method of applying developed control system of parallel active filter. Mathematic model of parallel active power filter has been developed in Matlab 7.11, and its modeled results have been shown as obtained from filter performing for active-inductive load. In order to verify the obtained mathematic results of modeling process Matlab 7.11 set up has been designed in order to do research of current relay controller (RCC). On this installation has been confirmed by practical ability to use the RCC as a key element for the creation of the proposed control system is a parallel active power filter.

Keywords: valve converter, current harmonics, current relay controller, electromagnetic compatibility, active filter, control system of active filter.

Though energy-saving technologies and energy efficient solutions are introduced now in all field of technique, energy consumption increases in world from year to year. Energy consumption in world will increase by 49 % [1] during 2007–2035 years based on results of international researches executed by Bloomberg BusinessWeek Research Services and ABB company in August, 2011. It's necessary to place in operation one 1GW power electrostation a week for next 20 years in order to satisfy the increasing electric power requirements. However, it's not sufficient only to increase power to be generated so that the problem of electric power deficiency would be decided. It's also necessary to provide high quality of energy supplied for consumers.

Nowadays part of nonlinear electric loads is 60 % of all loads [2], so the problem to provide required quality of supplied electric power is one of main problems for energy industries, and as level of energy consumption will be increase in future, this problem will become critical increasingly [3].

Increasing part of nonlinear loads relates to employment of electric arc steel-smelting induction furnaces, transformers, discharge lamps [4, 5] and as well that semiconductor devices and devices based on ones (such as static converters, welders, domestic and office equipment etc.) are quickly developed and distributed in world [6].

Adverse influence of nonlinear loads is that it yields nonsinusoidal current in mains. Nonsinusoidal harmonics of current fly through elements of electric scheme and call voltage drops having nonsinusoidal form. Harmonics of current, full impedances of scheme and as result voltages of harmonics, supplied from mains, are quantities changing in time, that's why there are some distortions in mains [7]. There is a harmonic part of current, and as result there are some perceptible economic damages. It follows substantially from decay of efficiency of equipment performance, arise of higher losses of hysteresis, and arise of extra losses from eddy currents in iron and losses in windings of transformers. As well it's reason for there can be single-phase short circuits on the ground in cable lines, electro punctures, oscillations in electric machines, hence breakdowns and reducing lifetime of machines are. Also, lifetime of electric systems reduces because of there are increasing intension of electric and thermal wearing of insolation in electric systems, reducing reliability of electric circuits performance and reliability of technology processes performance, troubles in performance and earlier failing high exact devices, increasing additional losses in networks and devices themselves, distortions in telecommunication and other communication networks, troubles in performance of protect devices and worsening their characteristics, reducing lifetime of main electric equipment of energy systems, reducing reliability and having fault in automatic and microprocessor-based systems performance [4–9]. In addition, nonlinear load has high level of react energy consumption; hence losses in energy system rise, overload of generators, transformers and transmission lines begin to happen. Oscillations of system voltage arise. In generally quality of supplied energy reduces [10, 11].

From 1 January 2013 on the territory of the Russian Federation and the performance standards of power quality regulates GOST R 54149-2010. According to GOST R 54149-2010, all indicators of the quality of electric power can be divided into two categories – long-lasting changes and random events. For lasting changes include: the frequency deviation, slow voltage changes, voltage fluctuations and flicker, voltage unbalance of non-sinusoidal voltages in three-phase systems. As the random events considered interruptions, voltage sags, surges and voltage pulse [12].

It should be to note that nonlinear distortions in mains on hand of consumers are nearly reasoned by own actions of consumers in their areas, and seldom they are brought with mains [4, 11, 13]. So consumers must control influence their equipment to mains by themselves. And, if it's needed, they must provide compensation of nonlinear distortions and generate reactive power in the direct way on places where it's consumed. So far the hardware to correct one or more rate of electric power quality and implicated parameters of consumed reactive power has been passive power filters of harmonics, compensating capacitor batteries and synchronous compensators. However, as in past decades there are new achievements to develop new high efficiency power semiconductor devices that are full controlled, such as IGBT transistors; so it's become possible to decide this issue by means of active filters of electric energy (AFE) [14, 15]. Nowadays AFE are the newest and the most perspective devices to correct distortions in mains. These devices allow the most effectively enhancing quality of electric energy in distributing networks. The active filters are quick-operating devices, and so they allow compensating full range of harmonics and providing reactive power to mains only when it's required, comparatively with passive harmonics filters have a restricted range of harmonics to compensate. Besides, passive filters supply reactive power to mains continuously [16, 17].

To provide protective for mains from negative influence of semiconductor converters, mainly parallel active filters (PAEF) are used. They allow very much reducing quantity of harmonic part of inverter current and, in fact, provide compensating full reactive power consumed by them [18–24]. All PAEF, produced in industry, have similar structure of power part and sufficient efficiency, and universality. However, they have a high cost of technical implementation, and they have a complicated system of control, based on high-performance microprocessor, executing control of PAEF by means of sophisticated algorithms; that makes them worse as reliable.

By the way, researches to develop high-performance reliable control systems of active filters are quite prospective now.

Let's discuss facility to develop simple system, based on relay control of current (RC), to control PAEF.

Performance for active-inductive load has been modeled in software environment, called Matlab in 7.11 version, in order to analyze influence of nonlinear load to mains. Active-inductive load is represented by uncontrolled single-phase semiconductor bridge rectifier. That has been chosen as the most widely used type of nonlinear load.

Current of single-phase bridge rectifier, fed from mains, and its current harmonic range are shown as result of computer modeling in Fig. 1.

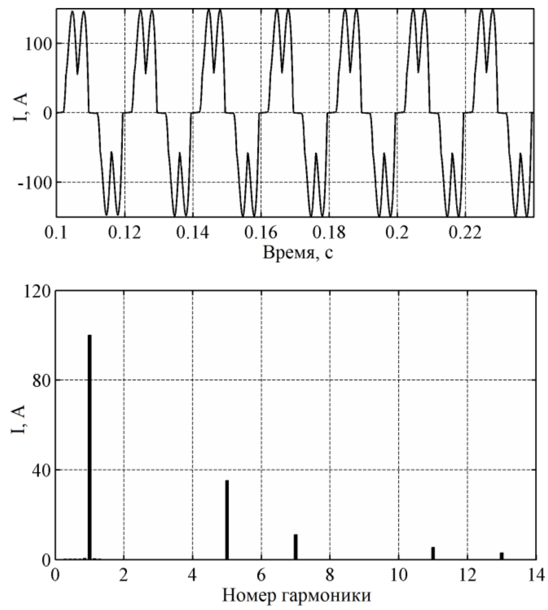

Fig. 1. Slope of instantaneous current, supplied from mains through single-phase bridge rectifier, and his range of harmonics

According to the analysis of the harmonic content of the current in Fig. 1, the value of the total harmonic distortion is 34.27 %, which is several times the normable GOST R 54149-2010 coefficient of harmonic distortion in 8 % [12].

In order to eliminate harmonic distortions, authors suggest PAEF, based on new method to get «ideal» current and to form control impulses for PAEF implemented by relay current control.

Scheme PAEF is connected to mains by, is shown in Fig. 2.

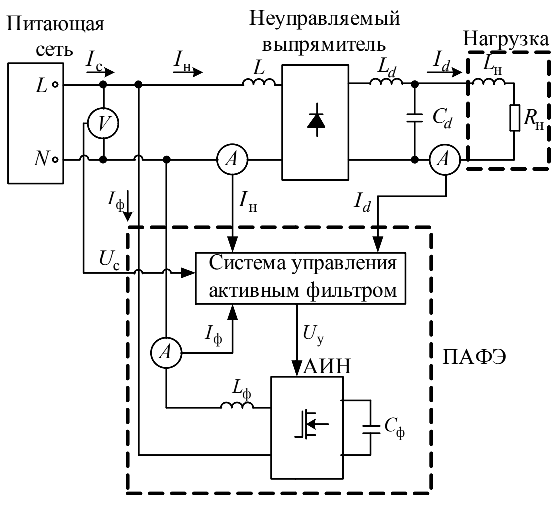

Fig. 2. Connection scheme PAEF to mains

The operation principle of suggested PAEF control system is to compensate difference between real and «ideal» load currents flying through active filter at any moment of time.

«Ideal» current, fed from mains, is defined by equation of balance of power, conveyed through d.c. scheme into load:

$$P_{\text{const}} = U_{\text{cap}} \cdot I_{\text{n}} , \quad (1)$$

where U_{cap} is voltage between condenser armature,

I_n is current consumed by load through bridge rectifier.

Assume power, consumed by load, is equal full power, shown as S, that is supplied from mains:

$$S = U_C \cdot I_C , \quad (2)$$

where I_c is root-mean-square current,

U_c is root-mean-square voltage of mains.

Hence let's count magnitude of «ideal» current, fed from mains:

$$i = \frac{I_d}{k_{sc}} , \quad (3)$$

where k_{sc} is rate of the bridge circuit,

I_d is load d.c. current.

Instantaneous ideal current is:

$$i^*(t) = \frac{I_d}{k_{sc}} \cdot \sin(\omega t + \varphi) , \quad (4)$$

where φ is set phase shift between fed current and mains voltage.

Then make a compare for calculated «ideal» current with measured real load current:

$$\Delta i(t) = i^*(t) - i_н(t) . \quad (5)$$

By the way, PAEF control system is formed by equations (1)–(5).

Value of difference between «ideal» and real currents is entered into block of relay current control (RCC) together with PAEF current feedback. At first, RCC is configured by hysteresis value that determines precision to process the reference signal of current. By way of RCC performance there is continues comparing difference of instantaneous «ideal» load current and real load current, flying through uncontrolled rectifier, with instantaneous current through PAEF. As result of this compare, output signal to control autonomous inverter of voltage is formed so that instantaneous PAEF current value should be as close as possible to value of difference between «ideal» load current and real one. The difference of these values are tried to be in hysteresis area by RCC. Then the formed output signals are conducted to input of autonomous inverter of current (ACI) that then forms instantaneous PAEF current as outcome. That current compensates possible nonlinear distortions of load current. By the way, as result, a form of current, fed from mains through «uncontrolled rectifier – PAEF» system, becomes sinusoidal as approximate as possible.

In point of view of physics, current forming is implemented by means energy storing or energy returning through capacitor of filter via autonomous inverter of current.

Basing on data, derived by way of theoretical calculations, the computer model of PAEF, connected between uncontrolled bridge rectifier with active-inductive load and single-phase mains and in parallel way with ones, has been developed in mathematics software Matlab 7.11.

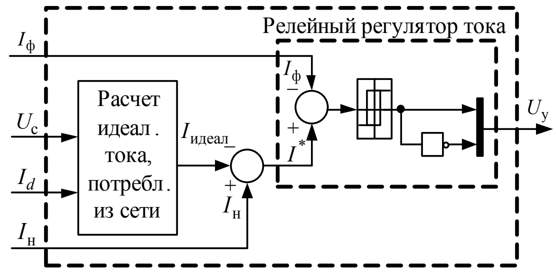

Fig. 3. PAEF control system

The slope of instantaneous PAEF current, obtained by way of modeling, is shown in Fig. 4.

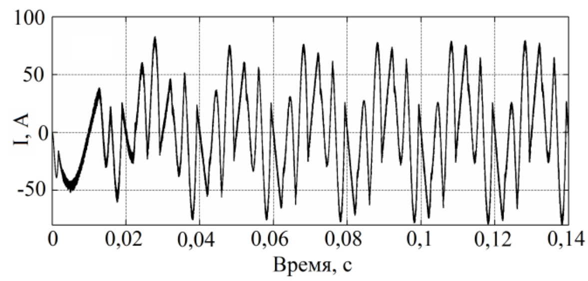

Fig. 4. Slope of instantaneous current « I_f » PAEF

The current, supplied from mains to load, «I» and the mains voltage «U», obtained by way of modeling, are shown in Fig. 5.

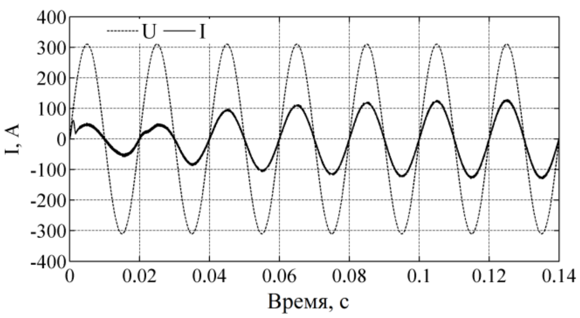

Fig. 5. Slope of instantaneous current «I» and instantaneous voltage «U», supplied from mains to «uncontrolled rectifier-PAEF» system

As it's seen from Fig. 5, current, supplied to «uncontrolled rectifier-PAEF» system, doesn't only have a sinusoidal form, but coincide with mains voltage in phase.

Harmonics analysis of «uncontrolled rectifier-PAEF» system current, obtained by way of modeling, are shown in Fig. 6.

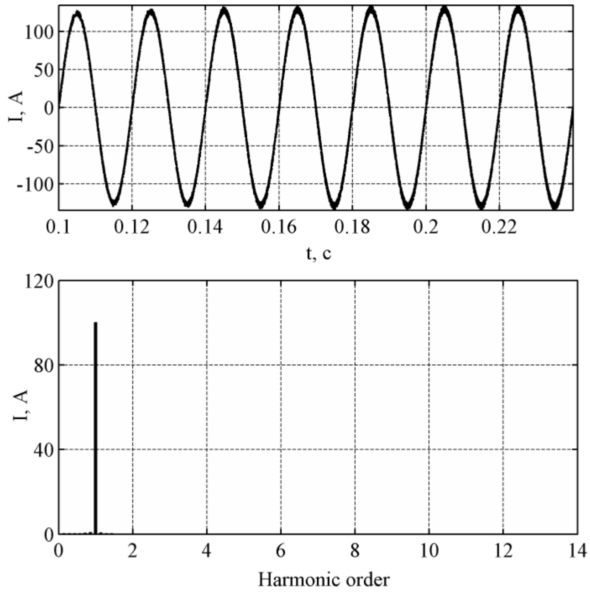

Fig. 6. Slope of instantaneous current, consumed by «uncontrolled rectifier-PAEF» system from mains, and diagram of harmonic range of current

From the results of the study of the harmonic composition of the current drawn by the «uncontrolled rectifier-PAEF» system follows that the level of total harmonic distortion is 0.89 %, which meets the requirements of GOST R 54149-2010 [12].

In order to confirm results, obtained by modeling in Matlab 7.11, practically, set up to research RCC has been made. In fig. 7 general view of set up is revealed.

Represented set up has follow part: «Mitsubishi PS22054» power module and «Mitsubishi 1200V DIP IPM (PS2205X) EVALUATION BOARD» debug board module. Those modules are used as autonomous inverter of current. 24 V regulated power supply is connected to ACI input. Single-phase load is connected, as combination of resistor and inductive coil, to ACI output. RCC functions are implemented by program logic controller «Arduino MEGA 2560» based on «Atmel Atmega 2560» chip. The magnitude and frequency current references and current feedback, obtained from current sensor in load circuit, are entered to inputs of controller. Control signals of pulse width modulation (PWM) for power gates are given from MEGA 2560 outputs. Measuring of set up output values are provided by oscilloscope «HANTEK DSO8060» and multimeter «MASTECH M890F».

Principle of operation of set up is to form and maintain load current in set frequency and magnitude values by relay current control.

The results of RCC operation, obtained by way of the set up performance, are represented in Fig. 8.

As it follows from the slope in Fig. 8 and multimeter readings, load current is formed as sinusoid of set magnitude and frequency. By way of examination of slope in detail it can be possible to observe high-frequency rippling in relate to carrying signal of main frequency. That is result of RRC operates to form required output current curve. Besides, level of these rippling will be so low how narrow value of hysteresis area is. That’s in its turn depends on maximum of frequency generated by power gates of ACI. In other words, the higher frequency of PWM, the narrower hysteresis area, the lower level of current ripping.

So as PWM frequency increases, accuracy of RCC performance increases, too. For the being discussed set up, PWM frequency is quite low about 500 Hz, because of it’s the highest frequency Atmega 2560 can attain via discrete outputs. However, other up-to-date controllers can provide PWM in frequency up to 20 KHz. That does it possible to increase accuracy of similar set up very much.

Conclusions

By the way, during exercised theoretical inquiries and mathematical modeling PAEF, principle to compose control system for PAEF in single-phase mains has been developed. It’s been based on using of relay current control (KCC0 and the revealed way to calculate ideal load current. That allows to obtain steady operation of PAEF and to compensate harmonics range in current, supplied from mains to uncontrolled bridge rectifier that operates for active-inductive load. Also, it allows compensating dynamic reactive power of load.

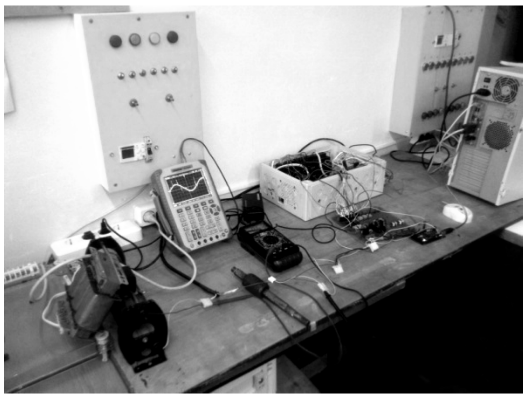

Fig. 7. General view of set up to research RCC

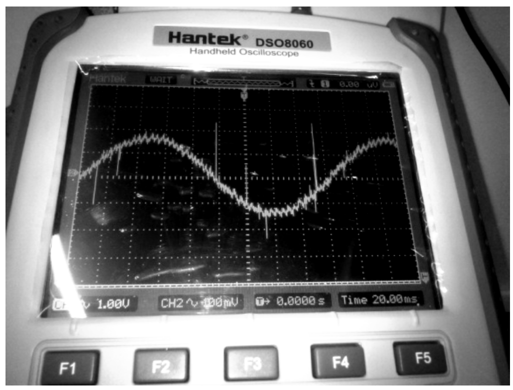

Fig. 8. The load current, displayed via oscilloscope during set up works

As practical evidence of verity of results, has being modeled for PAEF in mathematic software

MATLAB 7.11, has been developed set up to research relay current control. Facility to use RCC as main part for construction PAEF is been verified in practical way.

Also, during analyzing PAEF operation, it's been established as well that developed PAEF control system on RCC has many advantages as simplicity of implementation, reduced cost of manufacture, easy to exploit, reliability and high-operation to performance, high quality of compensating harmonic range of current and voltage in network, and also, facility to compensate reactive power of load. Those all together with facility to regulate regimes of PAEF operation by changing hysteresis area width, provide high accommodation efficiency and universality of PAEF performance.

Hence, using PAEF, based on developed control system, for nonlinear devices, connected to single-phase mains, allows enhancing electromagnetic compatibility of nonlinear devices with mains. That would influence positively as on whole mains, so on its consumers in particularly, and so it'd provide enhancing reliability and efficiency of power supply.

References

1. *ABB Insider*, 2011, no.5, p. 5.

2. Kachanov A.N., Kukoba V.L. Features of Microprocessor Control Systems in Electrical Complexes with a Continuous Process, *Keep Universities Black Earth. Electric Power Industry*, 2009, № 2 (16), pp. 26–29.

3. Nejdawi I.M., Emanuel A.E., Pileggi D.J., Corridori M.J., Archambeault R.D. Harmonic Trend in the USA: A Preliminary Survey, *IEEE Transactions on Power Delivery*, 1999, Vol. 14, no. 4, pp. 1488–1494.

4. Zhezhelenko I.V. *Higher Harmonics in Power Systems of Industrial Enterprises. 2nd ed. rev. and add*, Moscow, 1984, 160 p.

5. Curtarelli F., Deifino V., Denero G.B. Current Harmonic in Industrial Power Systems Arisen from AC / DC converters, *GRES83 Transaction*, Tokyo, 1983, pp. 1016–1024.

6. Klimov V.P., Moskalev A.D. The Problem of Higher Harmonics in Modern Power Systems, *Applied Power Electronics: Scientific and Engineering Sat*, 2002, Issue. 5, pp. 121–135.

7. Arrillaga J., Bradley D., Bodzher P. *Harmonics in Electrical Systems,* Moscow, 1990, 320 p.

8. Gurenko V.V. Effect of Harmonics on the Accuracy of Static Measurements in Networks, *Voltage Regulation in Electrical Networks*, Moscow, 1968, pp. 183–185.

9. Boyar N.P., Dovgun V.P. The Influence of the Harmonic Content of the Currents and Voltages on Energy Efficiency, *Herald KrasGAU,* 2010, no 4, pp. 130–134.

10. Kraychik Yu.S., Contact Honey Reactive Power and Voltage Distortion Text, *Electrical Technology Russia,* 1998, no. 5, pp. 71–73.

11. Zhelezko Yu.S. *Power Factor Correction and Power Quality Improvement*, Moscow, 1985, 224 p.

12. GOST R 54149-2010. *Quality standards for electrical energy in power systems for general use*, Moscow, 2012, 16 p.

13. Victor A., Ramos J.R. , Treating Harmonics in Electrical Distribution System, *Computer Power & Consulting*, 1999.

14. Rozanov J.K., Ryabchitsky M.B. Modern Methods of Improving Power Quality (Analytical Review), *Russian Electrical Engineering,* 1998, no. 3, pp. 42–47.

15. Moran L., Dixon J., Espinoza J., Wallace R. Using Active Power Filters to Improve Power Quality, *5th Brazilian Power Electronics Conference, COBEP'1999*.

16. Moran L., Joos G. Principles of Active Power Filters, *IEEE Industry applications Society Annual Meeting*, 1998.

17. Alekseev B.A. Active Harmonic Filters, *Electronics*, 2007, no. 3, pp. 28–32.

18. IEEE Recommended Practices and Requirements for Harmonic Control in Electrical. Power Systems, *IEEE Std 519-1992,* New York.

19. Mescheryakov V.N., Koval A. *Active Filter-Compensating Devices for Systems Controlled Electric DC*, Lipetsk, 2008, 164 p.

20. Krutikov K.K., Rozhkov V.V. The Use of Multi-function Active Power Filter Consisting of a Powerful Frequency Controlled Electric, *Electrical Technology Russia*, 2011, no. 2, pp. 32–38.

21. Labuntsov V.A., Dayzhun Zhang. Single-phase Solid-state Joints Passive Component of the Instantaneous Power, *Electrical Technology Russia,* 1993, no. 12, pp. 20–32.

22. Volkov A.V., Bondarenko V.I., Wolves V.A. Relay Current Regulation in Active Filter Voltage, Vestnik Kremenchutskogo Derjavnogo Politehnichnogo Universitetu, 2007, no. 4 (45), pp. 70–74.

23. Boyar N.P., Derbenyov A.M., Dovgun V.P. Adaptive System Generating Control Signals for Active Harmonic Filters, *Polzunovskii Vestnik*, 2011, no. 2/1, pp. 25–29.

24. Volkov A.V., Wolves V.A. Compensation Distortion Power and Reactive Power Through the Active Filter with a Projected Relay Control, *Russian Electrical Engineering,* 2008, no. 3, pp. 2–10.

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ПРАКТИЧЕСКАЯ РЕАЛИЗАЦИЯ РЕЛЕЙНОГО РЕГУЛЯТОРА ТОКА КАК ОСНОВНОГО ЭЛЕМЕНТА АКТИВНОГО ФИЛЬТРА ЭЛЕКТРОЭНЕРГИИ

В.Н. Мещеряков, М.М. Хабибуллин, И.С. Павлов

Разработана простая и эффективная система управления параллельным активным фильтром электроэнергии. Такой параллельный активный фильтр электроэнергии позволяет повысить качество напряжения в электросети при работе нелинейной нагрузки. Это достигается за счет существенного снижения параллельным активным фильтром электроэнергии гармонических составляющих тока нагрузки и компенсации реактивной мощности нагрузки, при этом исключается вероятность возникновения резонансных явлений свойственных пассивным фильтрам. Данная система управления параллельным активным фильтром электроэнергии может быть использована как в однофазных, так и в трехфазных электрических сетях. Предложен способ реализации разработанной системы управления параллельным активным фильтром электроэнергии. Построена компьютерная модель активного фильтра электроэнергии в программной среде Matlab 7.11 и приведены результаты моделирования ее работы на активно-индуктивную нагрузку. Для практического подтверждения результатов математического моделирования в программной среде Matlab 7.11 создана установка по исследованию релейного регулятора тока (РРТ). На этой установке практическим путем была подтверждена возможность использования РРТ как основного элемента для создания предложенной системы управления ПАФЭ.

Ключевые слова: вентильный преобразователь, гармоники тока, релейный регулятор тока, электромагнитная совместимость, активный фильтр, система управления активным фильтром.

Литература

1. ABB insider. – 2011. – № 5. – S. 5.
2. Качанов, А.Н. Особенности работы микропроцессорных систем управления в электротехнических комплексах с непрерывным технологическим процессом / А.Н. Качанов, В.Л. Кукоба // Вести высших учебных заведений Черноземья. Электроэнергетика. – 2009. – № 2(16). – С. 26–29.
3. Harmonic Trend in the USA: A Preliminary Survey / I.M. Nejdawi, A.E. Emanuel, D.J. Pileggi et al. // IEEE Transactions on Power Delivery. – 1999. – Vol. 14. – № 4. – P. 1488–1494.
4. Жежеленко, И.В. Высшие гармоники в системах электроснабжения промпредприятий / И.В. Жежеленко. – 2-е изд. перераб. и доп. – М.: Энергоатомиздат, 1984. – 160 с.
5. Curtarelli, F. Current harmonic in industrial power systems arisen from AC/DC converters / F. Curtarelli, B. Deifino, G.B. Denero // ГРЕС83 Transaction-Tokyo. – 1983. – P. 1016–1024.
6. Климов, В.П. Проблемы высших гармоник в современных системах электропитания / В.П. Климов, А.Д. Москалев // Практическая силовая электроника: науч.-техн. сб. – 2002. – Вып. 5. – С. 121–135.
7. Гармоники в электрических системах: пер. с англ. / Дж. Арриллага, Д. Брэдли, П. Боджер. – М.: Энергоатомиздат, 1990. – 320 с.
8. Гуренко, В.В. Влияние высших гармоник на точность статических измерений в электрических сетях / В.В. Гуренко // Регулирование напряжения в электрических сетях. – М.: Энергия, 1968. – С. 183–185.
9. Боярская, Н.П. Влияние гармонического состава токов и напряжений на эффективность энергосбережения / Н.П. Боярская, В.П. Довгун // Вестник КрасГАУ. – 2010. – № 4. – С. 130–134.
10. Крайчик, Ю.С. Связь между реактивной мощностью и искажениями напряжений / Ю.С Крайчик // Электричество. – 1998. – № 5. – С. 71–73.
11. Железко, Ю.С. Компенсация реактивной мощности и повышение качества электроэнергии / Ю.С. Железко. – М.: Энергоатомиздат, 1985. – 224 с.

12. ГОСТ Р 54149-2010. Нормы качества электрической энергии в системах электроснабжения общего назначения. – М.: Стандартинформ, 2012. – 16 с.

13 Victor, A. Treating harmonics in electrical distribution system / A. Victor, J.R. Ramos // Computer Power & Consulting. – 1999. – January.

14. Розанов, Ю.К. Современные методы улучшения качества электроэнергии (аналитический обзор) / Ю.К. Розанов, М.В. Рябчицкий // Электротехника. – 1998. – № 3. – С. 42–47.

15. Using active power filters to improve power quality / L. Moran, J. Dixon, J. Espinoza, and R. Wallace // 5th Brazilian Power Electronics Conference, COBEP'1999.

16. Moran, L. Principles of active power filters, (tutorial course notes) / L. Moran, G. Joos // IEEE Industry applications Society Annual Meeting. – 1998. – October.

17. Алексеев, Б.А. Активные фильтры высших гармоник / Б.А. Алексеев // Электрооборудование. – 2007. – № 3. – С. 28–32.

18. IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical. Power Systems, New York, NY: IEEE.

19. Мещеряков, В.Н. Активные фильтро-компенсирующие устройства для систем регулируемого электропривода постоянного тока: моногр. / В.Н. Мещеряков, А.А. Коваль. – Липецк: ЛГТУ. – 2008. – 164 с.

20. Крутиков, К.К. Применение многофункциональных силовых активных фильтров в составе мощного частотно регулируемого электропривода / К.К. Крутиков, В.В. Рожков // Электричество. – 2011. – № 2. – С. 32–38.

21. Лабунцов, В.А. Однофазные полупроводниковые компенсаторы пассивной составляющей мгновенной мощности / В.А. Лабунцов, Чжан Дайжун // Электричество. – 1993. – № 12. – С. 20–32.

22. Волков, А.В. Релейное регулирование тока в активном фильтре напряжения / А.В. Волков, В.И. Бондаренко, В.А. Волков // Вісник Кременчуцького державного політехнічного університету. – 2007. – Вип. 4 (45). – С. 70–74.

23. Боярская, Н.П. Адаптивная система формирования управляющих сигналов для активных фильтров гармоник / Н.П. Боярская, А.М. Дербенев, В.П. Довгун // Ползуновский вестник. – 2011. – № 2/1. – С. 25–29.

24. Волков, А.В. Компенсация мощности искажений и реактивной мощности посредством активного фильтра с прогнозируемым релейным управлением / А.В. Волков, В.А. Волков // Электротехника. – 2008. – № 3. – С. 2–10.

Мещеряков Виктор Николаевич, доктор технических наук, профессор, заведующий кафедрой электропривода, Липецкий государственный технический университет, г. Липецк, Российская Федерация, тел.:8-910-742-94-75, mesherek@stu.lipetsk.ru.

Хабибуллин Максим Маратович, аспирант второго года обучения, Липецкий государственный технический университет, г. Липецк, Российская Федерация, тел.: 8-906-592-06-07, maximum@rambler.ru.

Павлов Игорь Сергеевич, аспирант второго года обучения, Липецкий государственный технический университет, г. Липецк, Российская Федерация, тел.: 8-952-590-76-22, impredator@yandex.ru

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