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GROUP POWER SUPPLY SYSTEMS FOR DRIVES WITH CAPACITIVE DRIVES EQUIPPED WITH PARALLEL ACTIVE FILTERS

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Purpose. *The article aims to improve the control methods for multifunctional parallel active filters (PAFs) to ensure rapid and precise compensation of inactive full-power components in three- and four-wire mixed power systems, particularly for group power supply systems for drives with capacitive energy storage devices.*

Methods. *The paper proposes two methods for PAF control: the instantaneous power method (p-q theory) and the control method in a synchronously rotating coordinate system based on the Park-Gorev transformations. Simulations were conducted to compare the performance of PAFs using these control methods. The article evaluates the effectiveness of these control methods in compensating inactive power components and minimizing reactive power in group power supply systems.*

Results. *The study found that controlling PAFs in a synchronously rotating x-y coordinate system simplifies the selection and control of inactive power components, leading to faster and more accurate compensation. Including zero sequence current in the compensation, reference currents allow PAFs to function in both three- and four-wire systems without additional zero sequence current compensation devices. Simulation results demonstrated the PAF's effectiveness in compensating reactive power, harmonics (5th, 7th, and 49th), and inactive power components in diode rectifiers and in load symmetry correction.*

Originality. *The study introduces an improved control method for multifunctional PAFs, particularly within group power supply systems using capacitive energy storage. This approach provides a novel way to address energy savings and improve power quality in systems with nonlinear and dynamic loads, reducing energy losses and improving equipment lifespan.*

Practicality. *The results offer practical solutions for enhancing the efficiency of power supply systems in industrial settings. Using PAFs with capacitive energy storage reduces energy exchange between motors and the grid, mitigating losses in transformers, converters, and supply lines. Implementing this method improves energy management, enhances equipment longevity, and ensures compliance with power quality standards.*

Key words: *Parallel active filter (PAF), capacitive energy storage, group power supply systems, power quality, energy savings, control methods.*

Колб Андрій, Морозов Ігор. Системи групового живлення приводів з ємнісними накопичувачами, обладнані паралельними активними фільтрами

Мета. *Метою статті є вдосконалення методів керування багатофункціональними паралельними активними фільтрами (ПАФ) для забезпечення швидкої та точної компенсації неактивних компонентів повної потужності в три- і чотирипровідних змішаних системах електроживлення, зокрема для групових систем живлення електроприводів з ємнісними накопичувачами енергії.*

Методи. *У статті запропоновано два методи керування ПАФ: метод миттєвої потужності (p-q теорія) та метод керування в системі координат, що синхронно обертається, на основі перетворень Парка-Горєва. Проведено імітаційне моделювання для порівняння продуктивності ПАФ з використанням цих методів керування. У статті оцінено ефективність цих методів керування для компенсації неактивних складників потужності та мінімізації реактивної потужності в групових системах електропостачання.*

Результати. *Дослідження показало, що керування ПАФ у системі координат x–y, що синхронно обертається, спрощує вибір і контроль неактивних компонентів потужності, що призводить до більш швидкої і точної компенсації. Включення струму нульової послідовності в опорні струми компенсації дозволяє ПАФ працювати як в три-, так і в чотирипровідних системах без додаткових пристроїв компенсації струму нульової послідовності. Результати моделювання продемонстрували ефективність ПАФ для компенсації реактивної потужності, гармонік (5-ї, 7-ї та 49-ї) та неактивних складників потужності в діодних випрямлячах, а також для корекції симетрії навантаження.*

Новизна. *У дослідженні представлено вдосконалений метод керування багатофункціональними ПАФ, зокрема в системах групового електропостачання з використанням ємнісних накопичувачів енергії. Цей підхід забезпечує новий спосіб розв'язання проблеми енергозбереження та покращення якості електроенергії в системах з нелінійними та динамічними навантаженнями, зменшуючи втрати енергії та збільшуючи термін служби обладнання.*

Цінність. *Результати дослідження пропонують практичні рішення для підвищення ефективності систем електропостачання в промислових умовах. Завдяки використанню ПАФ з ємнісним накопичувачем енергії система зменшує обмін енергією між двигунами та мережею, зменшуючи втрати в трансформаторах, перетворювачах та лініях електропередач. Впровадження цього методу покращує управління енергоспоживанням, збільшує термін служби обладнання та забезпечує відповідність стандартам якості електроенергії.*

Ключові слова: *паралельний активний фільтр (ПАФ), ємнісний накопичувач енергії, групові системи електропостачання, якість електроенергії, енергозбереження, методи керування.*

Actuality. Since electric drives consume up to 60% of the generated electric power, and the greatest losses occur at the consumer, electric drives have a huge reserve for saving electric power. One perspective direction of saving energy using industrial electric drive and normalizing traditional indicators of electric power quality is the application of group power supply systems of drives from common DC buses with capacitive accumulators and the application of parallel active filters (PAF) [1]. In the system under consideration, the regenerative braking energy of one or a group of motors is accumulated by a capacitive accumulator and, bypassing the network, is transferred to the motor mode drives. This eliminates the energy exchange between the motors and the grid and thus eliminates additional losses in the transformer, input converter, and supply lines. The stored energy is also used for power quality management in mixed power systems, where, in addition to DC busbars, there are non-linear and asymmetrical consumers with dynamic loads that significantly degrade conventional power quality indicators.

In case of deviations of power quality indicators exceeding the standardized standard values, normal operation of electrical equipment is either impossible at all or can be ensured at the cost of load reduction, leading to technological disruption.

The presence of higher harmonics in asynchronous drive systems causes vibrations and noise. Also, it serves as an additional source of thermal effect on the motor insulation due to polarization processes, which leads to leakage currents and bias currents. This significantly reduces the service life of the motor.

Consequently, the issues of energy saving using industrial drive and the development of effective technical means, criteria, and their control algorithms to improve the energy efficiency of electric drive, transmission, and electric power consumption are relevant and important.

Literature review. There are several economic and power quality directions: improvement of power supply systems, improvement of consumers (nominal load), application of multiphase-controlled rectifiers and frequency converters with PWM, use of passive FCU, etc. However, the wide application of FCU has revealed many disadvantages that cause additional generation of harmonics, such as resonance phenomena. However, the wide application of FCU has revealed several disadvantages, which cause additional generation of harmonics, for example, due to resonance phenomena. The complex spectrum of network currents and voltages makes using FCU inefficient [2–7].

In the case of nonlinear and asymmetrical dynamic loads, fast-acting compensating devices are required to quickly and accurately unload the network from the negative influence of inactive components of full power. The most effective in this direction are PAFs [8–14].

The purpose of the work is to improve the control methods of multifunctional PAFs for fast and accurate compensation of inactive full power components in both three and four-wire mixed power systems adapted to group power supply systems for drives with capacitive energy storage devices.

Results of the study. The PAF (Fig. 1) contains a three-phase AVI with double-sided conductivity connected to the network through a reactor L_{fi}, designed to suppress high frequencies caused by switching the inverter keys. The signals to set the current to be compensated are generated by the control unit using instantaneous reactive power values (first harmonic shift power, distortion, and asymmetry). The current loops are closed through relay regulators (RCRs) with frequency limiting switching frequency of the inverter keys. The RCRs are a simple and reliable in-operation circuit, having a limiting speed at given energy constraints in the DC link represented by capacitor C_i of the required capacitance. The inductance of the output filter L_{fi} is determined by a compromise solution between suppression of high-frequency (modulation) current pulsations and the possibility of providing a high value of the current derivative, which is necessary to form a compensation current of the required frequency.

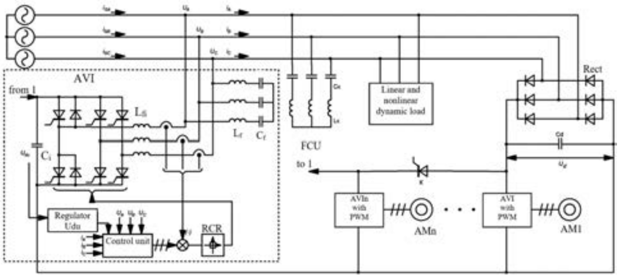

Fig. 1. Functional scheme of the parallel active filter (PAF) adapted to the system of group power supply of drives with capacitive storage Cd of electric power

In practice, two methods of PAF control are most commonly used. The instantaneous power method (p-q theory) and the control method in a synchronously rotating coordinate system oriented along the generalized (resultant) vector of the grid voltage, based on the direct and inverse Park-Gorev transformations.

In the first case, the constant $p_{\ddot{\imath}}, q_{\ddot{\imath}}$ and variable p_v, q_v components of the instantaneous power are determined according to the dependence

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} p_{\ddot{\imath}} \\ q_{\ddot{\imath}} \\ p_{0\ddot{\imath}} \end{bmatrix} + \begin{bmatrix} p_v \\ q_v \\ p_{0v} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} u_\alpha & u_\beta & 0 \\ -u_\beta & u_\alpha & 0 \\ 0 & 0 & u_0 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}. \qquad (1)$$

In the above expression, the orthogonal components in the fixed coordinate system $\alpha - \beta$, for example, of the generalized network voltage vector are defined as

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} 1 & -0{,}5 & -0{,}5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}. \qquad (2)$$

In the limiting case, the PAF should generate all inactive components of the total power into the load. However, in combined systems, capacitor banks and LCFs (e.g. 5th and/or 7th harmonics) can be used to compensate part of the reactive power (Fig. 1). Therefore, different tasks can be solved with the PAF: compensation of all inactive components; individual components or their different combinations. For the instantaneous power signals, *p* and *q* are subjected to filtering with the help of ELF in order to divide them into components to form the required control parameter of compensation p^* and q^* (Fig. 2, 3). The compensator reference currents in $\alpha - \beta$ axes are calculated based on p^* and q^* and the components u_α, u_β of the mains voltage at the point of connection of the PAF

$$\begin{bmatrix} i_{\hat{e}\alpha} \\ i_{\hat{e}\beta} \end{bmatrix} = \frac{2}{3(u_\alpha^2 + u_\beta^2)} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix}. \qquad (3)$$

In the three-phase coordinate system the setting of compensation currents are defined as [6]

$$\begin{bmatrix} i^*_{\hat{e}a} \\ i^*_{\hat{e}b} \\ i^*_{\hat{e}c} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -0{,}5 & \sqrt{3}/2 \\ -0{,}5 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{\hat{e}\alpha} \\ i_{\hat{e}\beta} \end{bmatrix}. \qquad (4)$$

In case of distortion of the mains voltage waveform by higher harmonics and load asymmetry to improve the accuracy of compensation of inactive power components, filter F1 is introduced into the control system to isolate the main harmonic of the direct sequence (Fig. 1).

The functional scheme of PAF control by the method of *p-q* instantaneous power theory is shown in Fig. 2. The required active power consumed by the PAF to compensate losses and maintain the voltage in the DC link at a given level is formed in the form of two signals. The first one corresponds to the variable component p_v, and the second one corresponds to the output signal of the voltage regulator (VR) in the DC link.

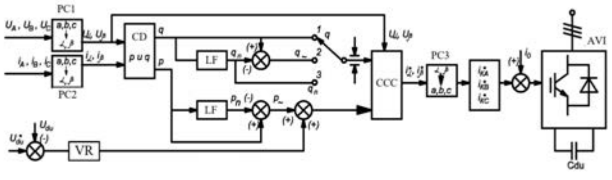

Fig. 2. Functional scheme of PAF control in the stationary coordinate system α, β (CCC – compensation current calculator according to (4); CD – computing device)

The circuit provides several modes of reactive power compensation: full compensation; compensation of individual components or their combination. The use of a narrow-band filter to isolate variable components of double frequency allows symmetrizing the load.

The general disadvantage of the *p-q* method of instantaneous power theory is the use of harmonic variables $u_\alpha, u_\beta, i_\alpha, i_\beta$ when calculating the setting compensation currents according to (3) and (4), which reduces the noise immunity of the system and complicates the calculation algorithm. Computer simulation of PAF operation modes (Fig. 3) has shown that its control in a synchronously rotating *x-y* coordinate system, oriented along the generalized vector of grid voltage, allows to simplify the procedure of selection and continuous control of inactive components of full power, to increase the speed and accuracy of compensation. This method is based on the direct and inverse Park-Gorev transformations. The direct transformation consists in determining the projections of the resulting current vector on the *x-y* axes [6–8]

$$\begin{bmatrix} i_x \\ i_y \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}, \qquad (5)$$

where $\theta = \omega t$ is the spatial position of the rotating coordinate system, defined as

$$\cos\theta = u_\alpha / U, \sin\theta = u_\beta / U, U = \sqrt{u_\alpha^2 + u_\beta^2}\ . \quad (6)$$

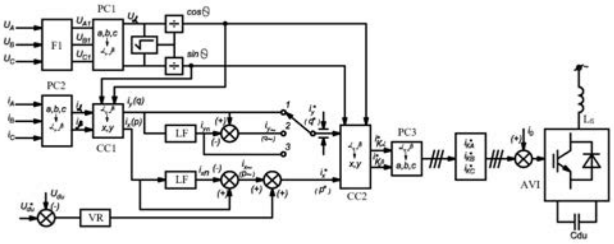

Fig. 3. Functional scheme of PAF control using synchronously rotating coordinate system (x, y method of instantaneous power theory)

It is essential that the component i_y and the variable i_x correspond to the inactive components of the currents to be compensated. As in the scheme of Fig. 2, a VLF is used to separate i_x, i_y into constant and variable components.

Inverse transformation from a rotating coordinate system to a stationary one [8]

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_x \\ i_y \end{bmatrix}. \qquad (7)$$

The assignment of compensation currents is formed by switching from two-phase coordinate system to three-phase coordinate system and adding zero sequence current i_0

$$\begin{aligned} i_a &= i_\alpha + i_0, \\ i_b &= -\frac{i_a}{2} + \frac{\sqrt{3}}{2} i_\beta + i_0, \\ i_c &= -\frac{i_a}{2} - \frac{\sqrt{3}}{2} i_\beta + i_0 \end{aligned} \qquad (8)$$

Thus, if we apply first the direct Clark transformation and then the Park-Gorev transformation to the three-phase system of variables, then the projection of the generalized current vector on the *y-axis* and the variable component of the projection on the *x-axis* correspond to the inactive components of the currents to be compensated to minimize the reactive power consumption. In this case, too, using the LFD, it is possible to realize different compensation modes.

Compensator control can be realized both by calculating the required output voltage of the PAF

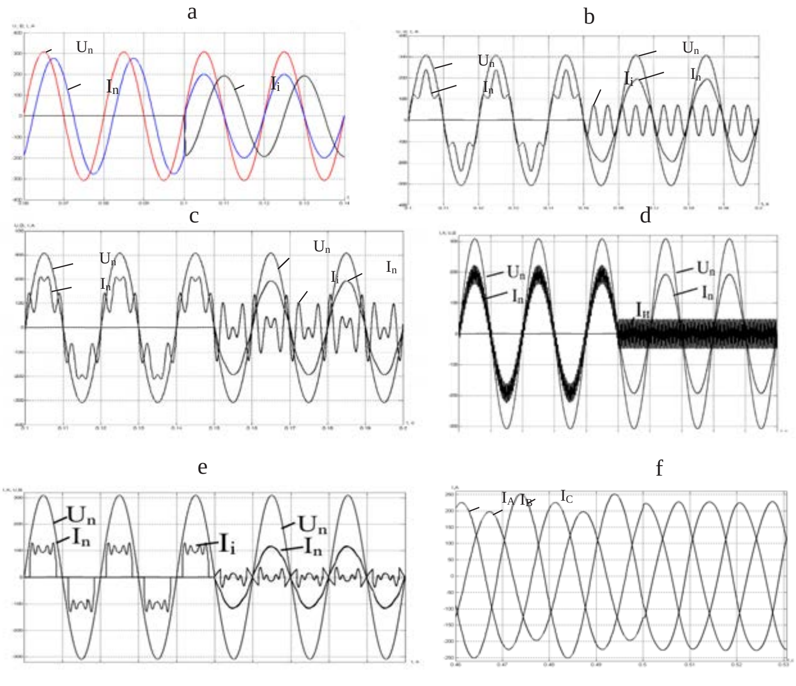

Fig. 4. Compensation of reactive power (a); 5th harmonic (b); 5th and 7th harmonics (c); 49th harmonic (d); inactive power components of diode rectifier in group power supply systems of drives (e); load symmetry (f)

using various modulation principles and regulators, and relay control by the compensation current deviation from the set value. Various methods can be used to reduce the switching frequency of the inverter keys. The PAF with RRT, covered by current feedback, acquires the properties of a current source, which significantly increases the accuracy and speed of the system to the maximum possible.

The PAF control circuits (Fig. 2, 3) provide a limitation of the maximum value of compensated reactive power to protect it from overloads and possible capacitor discharge.

It should be emphasized that the formation of the PAF control parameter according to (8) does not require the use of additional devices for zero sequence current compensation in four-wire systems.

The simulation results of some modes of PAF operation are shown in Fig. 4.

Conclusions:

1. In a synchronously rotating coordinate system oriented along the generalized vector of the network voltage, the procedure of PAF control parameter formation is considerably simplified, and the application of relay control increases the compensator performance to the maximum possible under the available energy constraints.

2. The addition of zero sequence current to the compensation reference currents allows the PAF to be used in both three and four wire systems without additional zero sequence current compensation devices.

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