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THE EFFICIENCY IMPROVEMENT OF A MULTIPHASE POWER SUPPLY SYSTEM BY USING ENERGY-SAVING SHUNT ACTIVE FILTRATION STRATEGIES

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Minimizing energy losses and increasing the efficiency of a multiphase power supply system by increasing the load power factor using an active shunt filter (SAF) is analyzed. Two SAF control strategies are presented, which provide the maximum efficiency at close to the unit value of power factor or at sinusoidal symmetric currents of the power supply system with any number of phases for non-sinusoidal and asymmetric sources, nonlinear and asymmetric load, and the arbitrary ratio of the resistance of linear and neutral wires. It is shown that the use of direct information about the EMF of a multiphase source as a reference vector of the desired transmission line current does not improve the achieved result of efficiency maximization. A virtual experiment obtained and verified the formula for calculating the efficiency of a multiphase power supply system with an arbitrary load in the form of dependence on load factor and power factor. The power supply system's power factor was determined and experimentally confirmed when applying the SAF strategy to form sinusoidal symmetric currents of a multiphase source. References 10, figures 5.
Keywords: power loss, control strategy of parallel active filter, increase of power supply system efficiency.

Introduction. The increase in the number and increase in the power of nonlinear consumers leads to a deterioration in the quality and increase in energy losses of power supply systems and a corresponding decrease in their efficiency. The problem of accounting and compensating for electric energy losses is reflected in power theories, the latest achievements of which are systematized in [1]. More and more such theories, including standardized ones [2-5], determine the square of apparent power proportional to the power losses; in this case, the power factor is equal to the unit if energy losses are minimized in the transmission line [5]. The papers [6, 7] consider methods for determining the minimum possible losses and the maximum achievable efficiency of a single-phase DC power supply system and a three-phase AC system under sufficiently strict conditions of voltage symmetry of a three-phase source and load and zero current in a neutral wire.

The goal of the work is the creation and analysis of strategies to minimize energy losses and increase the efficiency of a multiphase power system by increasing the load power factor using a shunt active filter (SAF).

Energy-saving capabilities of the active filtration strategy with unity power factor. Electromagnetic processes of the n-phase power supply system with neutral wire (Fig. 1) and shunt active filter are entirely determined by n-coordinate vectors of phase EMF $\mathbf{e}(t)=\|e_1 \quad e_2 \quad \ldots \quad e_n\|^\wedge$, phase voltages $\mathbf{u}(t)=\|u_1 \quad u_2 \quad \ldots \quad u_n\|^\wedge$, deducted relative to the zero wire, and current vectors of the source $\mathbf{i}_S(t)$, load $\mathbf{i}_L(t)$, and active filter $\mathbf{i}_F(t)$ of similar dimensions that form a matrix-vector system of equations:

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$$\mathbf{u}(t) = \mathbf{e}(t) - \mathbf{R}\mathbf{i}_S(t);$$
$$\mathbf{i}_S(t) + \mathbf{i}_F(t) = \mathbf{i}_L(t); \qquad (1)$$
$$T^{-1}\int_T \mathbf{u}^\wedge(t)\mathbf{i}_S(t)dt = T^{-1}\int_T \mathbf{u}^\wedge(t)\mathbf{i}_L(t)dt = P,$$

where ^ is the transpose sign; T is the period of phase voltages; P is the load power. The last equation (1) ensures the equality of load power and power of multiphase source currents, which eliminates the energy consumption of the SAF. Subject to the same resistances of line wires r and a different value of neutral resistance r_N, the matrix of transmission line resistances $\mathbf{R} = (r\mathbf{I} + r_N\mathbf{j}\mathbf{j}^\wedge) = \mathbf{R}^\wedge$ contains the unit matrix $\mathbf{I}$ with dimension $n\times n$ and a vector $\mathbf{j} = \|1 \;\; 1 \;\; ... \;\; 1\|^\wedge$ of dimension n, consisting of units.

The task of active filtration in this SAF application is to minimize the power losses in the transmission line:

$$\Delta P = T^{-1}\int_T \mathbf{i}_S^\wedge(t)\mathbf{R}\mathbf{i}_S(t)dt \to \min$$

provided zero SAF active power.

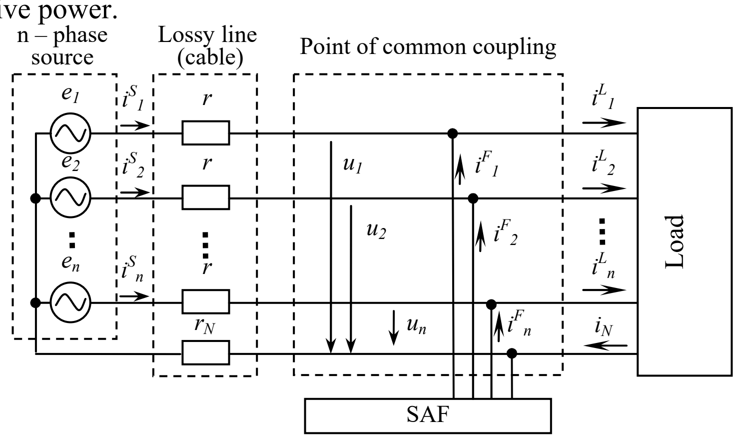

Fig. 1

The paper [8] shows that a unit value of the power factor in a three-phase four-wire power system provides an active current:

$$\mathbf{i}_A(t) = \frac{T^{-1}\int_T \mathbf{u}^\wedge(t)\mathbf{i}_L(t)dt}{T^{-1}\int_T \mathbf{u}^\wedge(t)\mathbf{R}^{-1}\mathbf{u}(t)dt}\mathbf{R}^{-1}\mathbf{u}(t) = \frac{P}{P_U}\mathbf{R}^{-1}\mathbf{u}(t), \qquad (2)$$

formed in the transmission line using the SAF. Due to the matrix-vector form, this expression is valid for a multiphase power system, while the active current reference vector takes the form:

$$\mathbf{R}^{-1}\mathbf{u}(t) = r^{-1}(\mathbf{I} + \frac{r_N}{r}\mathbf{j}\mathbf{j}^\wedge)^{-1}\mathbf{u}(t) = r^{-1}[\mathbf{I} - \frac{r_N}{r(1 + r_N\mathbf{j}^\wedge\mathbf{j}/r)}\mathbf{j}\mathbf{j}^\wedge]\mathbf{u}(t) =$$
$$= r^{-1}\left[\mathbf{u}(t) - \frac{nr_N}{r + nr_N}\times\frac{\mathbf{j}^\wedge\mathbf{u}(t)}{n}\mathbf{j}\right] = r^{-1}[\mathbf{u}(t) - \sigma_n\mathbf{u}_0(t)] = r^{-1}\mathbf{u}_\sigma(t), \qquad (3)$$

where $\mathbf{u}_0(t) = [\mathbf{j}^\wedge\mathbf{u}(t)]\mathbf{j}/n$ is the zero-sequence component of the phase voltage vector; $\sigma_n = nr_N/(r + nr_N)$ is the coefficient of its optimal weakening.

When forming an active current in the transmission line, the power loss reaches a minimum value [8]:

$$\Delta P_{MIN} = \Delta P_A = \frac{1}{T}\int_T \mathbf{i}_A^\wedge(t)\mathbf{R}\mathbf{i}_A(t)dt = \frac{1}{T}\times\frac{P^2}{P_U^2}\int_T [\mathbf{R}^{-1}\mathbf{u}(t)]^\wedge\mathbf{R}\mathbf{R}^{-1}\mathbf{u}(t)dt = \frac{P^2}{P_U}. \qquad (4)$$

Using the first equation in (1) for $\mathbf{i}_S(t) = \mathbf{i}_A(t)$, we convert the expression for P_U to similar to that done in [9] for a three-phase four-wire power supply system:

$$P_U = T^{-1}\int_T \mathbf{u}^\wedge(t)\mathbf{R}^{-1}\mathbf{u}(t)dt = P_0 - 2P - \Delta P_A, \qquad (5)$$

where $P_0 = T^{-1}\int_T \mathbf{e}^\wedge(t)\mathbf{R}^{-1}\mathbf{e}(t)dt = T^{-1}\int_T \mathbf{e}^\wedge(t)\mathbf{i}_0(t)dt = \mathbf{e}\circ\mathbf{i}_0$ is the short circuit power of the multiphase source on the transmission line resistances; $\mathbf{i}_0(t) = \mathbf{R}^{-1}\mathbf{e}(t)$ is short-circuit current vector derived from the first equation in (1) when $\mathbf{u}(t)=0$; $\mathbf{x}\circ\mathbf{y}=T^{-1}\int_T \mathbf{x}^\wedge(t)\mathbf{y}(t)dt$ is the denotation of the integral scalar product of two same arbitrary dimension periodic vectors.

Substituting (5) in (4), we obtain an equation with minimum power losses normalized relative to the load power:

$$\alpha=\frac{\Delta P_A}{P}=\frac{1}{k_L-2-\alpha}, \qquad (6)$$

where $k_L=P_0/P$ is the load factor. The last equation is reduced to the square equation $\alpha^2-(k_L-2)\alpha+1=0$ with a solution in the form of a smaller root:

$$\alpha=\Delta P_A/P=0.5k_L-1-\sqrt{0.25k_L^2-k_L}. \qquad (7)$$

With these minimum relative losses, we have the maximum value of the multiphase power supply system efficiency:

$$\eta_{MAX}=\frac{P}{P+\Delta P_A}=\frac{1}{\alpha+1}=\frac{1}{0.5k_L-\sqrt{0.25k_L^2-k_L}}= \\ =\frac{0.5k_L+\sqrt{0.25k_L^2-k_L}}{k_L}=0.5+\sqrt{0.25-k_L^{-1}}. \qquad (8)$$

The latter expression entirely coincides with the value obtained in [6] for the efficiency of the DC power supply system in the absence of current pulsations in the load.

We will show that even the use for active filtration purposes of direct information about the multiphase source EMF as a transmission line current reference vector does not improve the achieved result to maximize efficiency. In this case, the source current is formed as part of the short-circuit current:

$$\mathbf{i}_{SE}(t)=\beta\mathbf{i}_0(t)=\beta\mathbf{R}^{-1}\mathbf{e}(t),$$

where β is the sustainable coefficient, the value of which is determined from the condition of ensuring zero active power of the SAF. The voltage on the point of common coupling (PCC) with such source currents is determined by the expression:

$$\mathbf{u}(t)=\mathbf{e}(t)-\mathbf{R}\mathbf{i}_{SE}(t)=\mathbf{e}(t)-\beta\mathbf{R}\mathbf{i}_0(t)=(1-\beta)\mathbf{e}(t).$$

The SAF active power takes on a value:

$$P_F=\mathbf{u}\circ\mathbf{i}_F=\mathbf{u}\circ\mathbf{i}_L-\mathbf{u}\circ\mathbf{i}_{SE}=P-(1-\beta)\beta(\mathbf{e}\circ\mathbf{i}_0)=P-(1-\beta)\beta P_0.$$

As a result of equating this value to zero, we obtain a quadratic equation to determine the coefficient β:

$$\beta^2-\beta+k_L^{-1}=0,$$

the smaller root of which is $\beta=0.5-\sqrt{0.25-k_L^{-1}}$.

Power loss in the transmission line with the specified SAF control strategy:

$$\Delta P_E=\frac{1}{T}\int_T \mathbf{i}_{SE}^\wedge(t)\mathbf{R}\mathbf{i}_{SE}(t)dt=\frac{\beta^2}{T}\int_T \mathbf{e}^\wedge(t)\mathbf{R}^{-1}\mathbf{e}(t)dt=\beta^2P_0= \\ =(0.5-k_L^{-1}-\sqrt{0.25-k_L^{-1}})k_LP=(0.5k_L-1-\sqrt{0.25k_L^2-k_L})P=\alpha P=\Delta P_A$$

is exactly equal to the minimum power loss caused by the active current (2).

Thus, the statements suggest that (7) determines the minimum relative losses and (8) determines the maximum efficiency of an arbitrary power system, which can be achieved using active filtration. The behavior of the graph of maximum efficiency vs load factor (Fig. 2) at small values of the latter reflects the known fact from the electric circuit theory that the maximum power that can be transferred to the load in the power supply system with losses is equal to a quarter of the short circuit power at the efficiency of 50%.

The efficiency of the power supply system with arbitrary load and active filtration with the strategy of providing symmetric sinusoidal source currents. The arbitrary load can be characterized by a power factor $\Lambda=P/S$. Suppose the apparent power S satisfies the proportionality condition of its square of power loss in the transmission line. In that case, the square of the power factor represents the ratio between the minimum possible losses and the power losses of this load [4]:

$$\Lambda^2=\Delta P_{MIN}/\Delta P. \qquad (9)$$

In particular, this condition satisfies the determination of apparent power proposed in [8], which allows obtaining the active current (2). Then, considering (7) and (9), the efficiency of a multiphase power system with an arbitrary load is determined by the expression:

$$\eta = (1+\frac{\Delta P}{P})^{-1} = (1+\frac{\Delta P}{\Delta P_{MIN}} \times \frac{\Delta P_{MIN}}{P})^{-1} = (1+\Lambda^{-2}\alpha)^{-1} = [1+\Lambda^{-2}(0.5k_L - 1 - \sqrt{0.25k_L^2 - k_L})]. \tag{10}$$

In Fig. 2 dotted line shows the level of reduction in the efficiency of the power supply system for the load with a power factor $\Lambda = 0.5$ built according to (10).

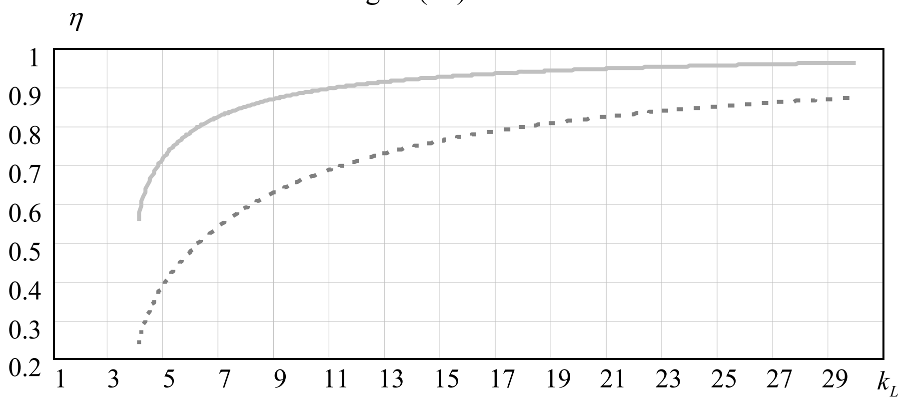

Fig. 2

From (2), it follows that in the case of asymmetric non-sinusoidal voltages at PCC, the formation of the power system active current is accompanied by the energy consumption of the multiphase source higher harmonics and negative and zero sequences symmetric components of the network frequency, which the standard IEEE Std 1459-2010 [2] recommends avoiding. The paper [10] presents algorithms of active filtration, forming the vectors of source currents following the recommended by this standard of apparent power decompositions for permissible quadratic components. In particular, the transfer of energy to the load at the frequency of the main harmonics by the positive sequence component of the phase voltage vector $\mathbf{u}_+(t)$ provides symmetric sinusoidal currents of the source following the expression:

$$\mathbf{i}_+(t) = \frac{P}{\frac{1}{T}\int_0^T [\mathbf{u}_+(t)]^\wedge \mathbf{u}_+(t)dt}\mathbf{u}_+(t) = \frac{P}{U_+^2}\mathbf{u}_+(t). \tag{11}$$

Such a current vector of a multiphase source causes the power loss:

$$\Delta P_+ = \frac{1}{T}\int_T \mathbf{i}_+^\wedge(t)\mathbf{R}\mathbf{i}_+(t)dt = \frac{P^2}{U_+^4 T}\int_T \mathbf{u}_+^\wedge(t)(r\mathbf{I} + r_N \mathbf{jj}^\wedge)\mathbf{u}_+(t)dt = \frac{P^2 r}{U_+^2} \tag{12}$$

and the square of the power factor according to (4), (9), (10):

$$\Lambda_+^2 = \Delta P_{MIN} / \Delta P_+ = \frac{P^2}{P_U} \div \frac{P^2 r}{U_+^2} = \frac{U_+^2}{rP_U}. \tag{13}$$

Substitution (13) in (10) gives the maximum efficiency of the multiphase power system, provided by symmetrical and sinusoidal source currents.

Experimental verification of the results of the study. Fig. 3 shows the scheme of the experiment for modeling the proposed methods of increasing efficiency for the most common three-phase power supply system with neutral wire. The circuit contains three-phase EMF sources (220V, 50Hz), a line with losses, and a load in the form of a rectifier with SAF in parallel at the PCC.

Fig. 4 shows the simulation results in two modes of the SAF operation, which through dependent sources, forms the transmission line currents according to (2) and (11). Analytical waveform "1", shown by dotted lines, is constructed by (8), reflecting the power supply system's theoretical maximum achievable efficiency. With the help of (10), a solid waveform is constructed "2", which corresponds to the SAF operation mode with the reference vector of the first harmonic positive sequence of symmetric phase voltages. The calculation of the parameter Λ_+^{-2} for this waveform is carried out by (13), which, under the conditions implemented in the experiment $U_{1-}/U_{1+} = U_0/U_{1+} = U_H/U_{1+} = 0.3$, acquires a value:

$$\Lambda_+^{-2} = 1 + \frac{U_{1-}^2 + U_H^2 + U_0^2/(1+3r_N/r)}{U_{1+}^2} = 1.2025.$$

During the simulation, the load resistance R (2, 3, 5, 8 Ohms) changed, and thus groups of points with different power factor values k_L were obtained. When applying the SAF control strategy using the apparent voltage reference vector, a family of experimental points is obtained that coincide with waveform "1", i.e., the possibility of obtaining the maximum efficiency in forming active current (2) in the transmission line is confirmed. The experimental points obtained in the SAF mode with the reference vector of the first harmonic symmetrical voltages of the positive sequence also correspond well to the theoretical waveform "2" and illustrate the possibility of maximizing the efficiency of the power supply system while providing symmetric sinusoidal currents.

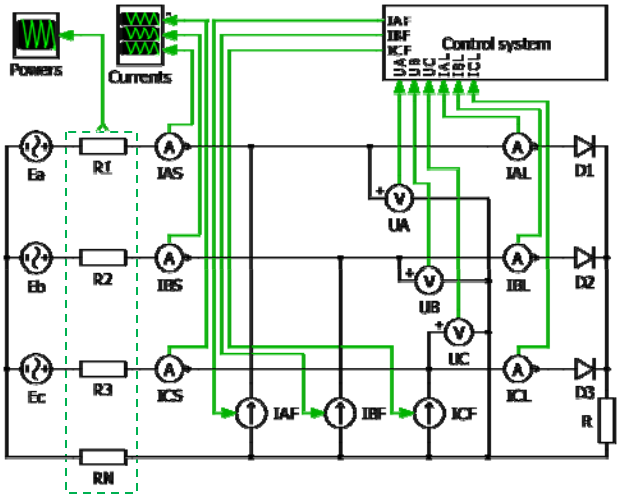

Fig. 3

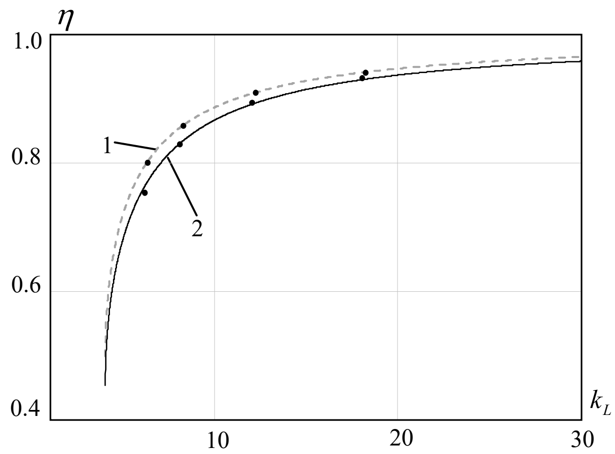

Fig. 4

Fig. 5 shows the simulation results in the time domain for load resistance of 8 Ohms. At the time of 0.1 s, the SAF is turned on using the support-vector apparent voltage, switching at a time of 0.2 s to the control strategy with the formation of symmetric sinusoidal currents of the source.

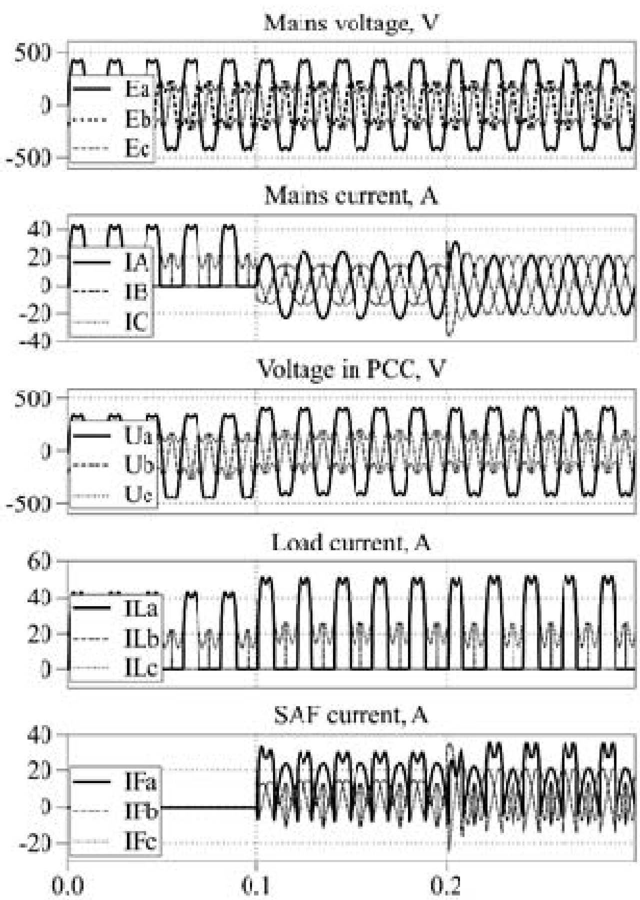

Fig. 5.

Conclusions.

1. The analytical expressions, confirmed by a virtual experiment, for the minimum possible relative losses and the most achievable efficiency of an arbitrary power system were obtained, which can be achieved using shunt active filtration by forming an active current (2) in the transmission line.

2. A comparison of two active current generation strategies first using phase voltages at PCC and second using EMF of a multiphase source showed that the first is not inferior to the second in terms of energy saving effect in the transmission line, but significantly outperforming the second for ease of implementation in the SAF control system.

3. The application of the active filtration strategy with the first harmonic positive sequence phase voltage vector allows for obtaining sinusoidal and symmetric currents of the network at the maximum achievable efficiency for such conditions. The power factor is analytically determined and experimentally confirmed when applying the SAF strategy with the formation of symmetric sinusoidal currents of a multiphase source.

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ПІДВИЩЕННЯ ККД БАГАТОФАЗНОЇ СИСТЕМИ ЖИВЛЕННЯ ІЗ ЗАСТОСУВАННЯМ ЕНЕРГОЕФЕКТИВНИХ СТРАТЕГІЙ ПАРАЛЕЛЬНОЇ АКТИВНОЇ ФІЛЬТРАЦІЇ

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Проаналізовано мінімізацію втрат електроенергії та збільшення ККД багатофазної системи живлення шляхом підвищення коефіцієнта потужності навантаження за допомогою паралельного активного фільтра (ПАФ). Представлено дві стратегії керування ПАФ, які забезпечують максимальний ККД за близького до одиниці значення коефіцієнта потужності або синусоїдних симетричних струмах системи електроживлення з довільною кількістю фаз у разі несинусоїдних та несиметричних джерелах, нелінійному та несиметричному навантаженні, довільному співвідношенні опорів лінійних та нейтрального проводів. Показано, що застосування для цілей активної фільтрації безпосередньої інформації про ЕРС багатофазного джерела як опорного вектора бажаного струму лінії передачі не покращує досягнутого результату максимізації ККД. Отримано та верифіковано віртуальним експериментом формулу для розрахунку ККД багатофазної системи живлення з довільним навантаженням у вигляді залежності від двох параметрів: коефіцієнта навантаження та коефіцієнта потужності. Визначений та експериментально підтверджений коефіцієнт потужності системи живлення у разі застосування стратегії ПАФ з формуванням синусоїдних симетричних струмів багатофазного джерела. Бібл. 10, рис. 5.

Ключові слова: потужність втрат, стратегія керування паралельним активним фільтром, підвищення ККД.

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