*Отримав розвиток метод компенсації неактивних складових струмів навантаження в трифазній трьопровідній системі електропостачання шляхом симетрування сигналів напруги мережі живлення, що викликані несиметрією мережі живлення. Це дозволяє покращити енергетичні показники системи електропостачання, зменшити значення реактивної потужності, падіння напруги на опорах мережі, коефіцієнт несиметрії і коефіцієнт спотворення синусоїдності струмів і напруг мережі живлення*

*Ключові слова: активна компенсація, крос-векторна теорія, блок симетрування, несиметрія, частотна область*

*Получил развитие метод компенсации неактивных составляющих токов нагрузки в трехфазной трехпроводной системе электроснабжения путем симметрирования сигналов напряжения питающей сети, вызванных несимметрией питающей сети. Это позволяет улучшить энергетические показатели системы электроснабжения, уменьшить значение реактивной мощности, падения напряжения на сопротивлениях сети, коэффициент несимметрии и коэффициент искажения синусоидальности токов и напряжений питающей сети*

*Ключевые слова: активная компенсация, кросс-векторная теория, блок симметрирования, несимметрия, частотная область*

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# IMPROVEMENT OF COMPENSATION METHOD FOR NON-ACTIVE CURRENT COMPONENTS AT MAINS SUPPLY VOLTAGE UNBALANC

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## 1. Introduction

Nowadays the share of power-consuming loads of low-voltage power supply systems defined by nonlinearity of their characteristics and unbalance of parameters in phases has greatly increased. Such types of loads include welding apparatuses, controlled electric drives, electric-chemical plants, etc. Operation of such equipment results in occurrence of higher harmonics in currents and voltages and also in unbalance of voltages and currents in the power supply system. Consequently, non-active components appear in the load currents. According to the papers [1, 2], only the basic harmonic component being of a sinusoidal form and existing in the phase with the mains voltage is understood as active current. All the other load current components caused by the availability of nonlinear and asymmetric load are considered non-active [3].

The flow of current non-active components in power supply systems results in increase of losses in transformers, transmission lines, reactive power compensator capacitors, etc. and, consequently, in reduction of the efficiency of operation of low-voltage power supply systems [2–4]. Active power filters (APF) [4] are used to compensate for them in the frequency-domain as the most up-to-date, flexible and efficient devices [5, 6].

The present economic situation, in particular, the rise of the cost of electric power for industrial enterprises, causes the necessity and topicality of the problem of improvement of the efficiency of compensation for nonlinear and asymmetric power-consuming equipment negative influence on low-voltage supply mains.

## 2. Literature review and problem statement

It is known that calculations of compensation currents for APF in three- and four-wire power supply systems are done on the basis of the known theories of instantaneous power (IP) [7, 10]: p-q [4], cross-vector [5] and p-q-r ones [5, 6]. It is known from these theories that all three-phase power components consumed by the load, apart from IP constant component, are undesirable [9–11].

However, the author of the papers [10, 11] demonstrates that under the condition of supply voltage distortion the efficient compensation for variable components of active and reactive power is impossible. It is caused by the fact that even when the sinusoidal character of the load currents is provided, but there is voltage distortion, the spectra of power variable components will contain higher harmonics and asymmetric components [11]. The presence of these components is analytically demonstrated in the papers [10, 11]. As in APF operating with the use of IP p-q theory only distortions caused by the load are compensated for [12, 13], compensation for variable power components under the conditions of distorted supply voltage will only deteriorate the shape of the load current signals [2, 11]. It can be explained by the fact that interpretation of power components according to the IP p-q theory as well as other theories, does not answer the question what nonsinusoidality or unbalance is caused by: the load or the mains [11, 14, 15]. The above said explains the urgent interest of contemporary scientists [9, 12, 14] in the problem of research in the frequency-domain and the time-domain of compensation processes in power supply systems to improve the method of compensation for current non-active components when the supply mains voltages are asymmetric [11, 14, 15].

## 3. The purpose and tasks of the research

The purpose of the paper consists in improvement of the method of compensation for current non-active components, when the supply mains voltage is asymmetric, via research in the frequency-domain and the time-domain of compensation processes in power supply systems.

To achieve the stated purpose the following tasks were formulated:

– analysis in the frequency-domain and in the time-domain of the compensation processes for power non-active components with the use of IP cross-vector theory in the analytical form;

– revealing the ways to improve operation of the system of compensation for current non-active components in the presence of harmonic distortions and supply voltage unbalance with the use of research on mathematical models;

– improvement of the efficiency of operation of power supply system when asymmetric equipment is connected under the condition of power supply voltage unbalance.

## 4. Research of compensation processes in an analytical and numerical form in the frequency- and time-domains

### 4. 1. Research of compensation processes in an analytical form in the frequency-domain

The critical literature review demonstrates that analytical research in the frequency domain, i. e. analysis with the use of harmonic components [16, 17], provides better opportunities for the analysis of supply mains operating modes and nonlinear load. It allows one to properly research both simple nonlinear electric circuits [18–20], and more complicated electrotechnical complexes [21] and power supply systems [14, 15].

That is why an analytical calculation of processes in the frequency-domain with compensation for three-phase asymmetric load was performed in the paper. In this case the IP cross-vector theory was used as the problem posed in the paper consisted in research of the quality of operation of APF, built based on the IP p-q theory, in the frequency-domain and in the time-domain under the conditions of unbalance of supply mains voltage. This choice was caused by the fact that cross-vector theory is analogous to the IP p-q theory and all drawbacks described for the IP p-q theory are inherent in it. Moreover, there is no necessity for transition to α, β, 0 coordinate system. This essentially simplifies the process of analytical research and determination of compensation currents.

During the research in an analytical form it was assumed that there was no currents influence on the mains voltage distortion, i. e. power supply system was believed to have unlimited power. Orthogonal cosine and sine frequency components were written down in the form:

$$U_{A\,a1} = \frac{1}{2} U_{1m},$$

$$U_{A\,b1} = 0,$$

$$U_{B\,a1} = -\frac{1}{4} U_{1m},$$

$$U_{B\,b1} = \frac{\sqrt{3}}{4} U_{1m},$$

$$U_{C\,a1} = -\frac{1}{4} U_{1m},$$

$$U_{C\,b1} = -\frac{\sqrt{3}}{4} U_{1m}.$$

Substitution of numerical values into the analytical expressions was used for visualization of the initial and obtained data and also for control of the analytical results correctness. In this case the following was assumed: maximum amplitude value of phase voltage $U_{1m}$=311 V, shift angle of the first harmonic component of voltage $\phi_{U1}$=0 el. deg., shift angle of the first harmonic component of current $\phi_{I1}$=–30 el. deg.

Orthogonal cosine and sine frequency components of three-phase current:

$$I_{A\,a1} = \frac{\sqrt{3}}{4} I_{1m},$$

$$I_{A\,b1} = -\frac{1}{4} I_{1m},$$

$$I_{B\,a1} = 0,$$

$$I_{B\,b1} = \frac{1}{2} \varepsilon_B I_{1m},$$

$$I_{C\,a1} = -\frac{\sqrt{3}}{4} \varepsilon_C I_{1m},$$

$$I_{C\,b1} = -\frac{1}{4} \varepsilon_C I_{1m},$$

where $\varepsilon_B$, $\varepsilon_C$ – unbalance coefficients of phase B and phase C, respectively. Numerical values of unbalance coefficients were assumed $\varepsilon_B$=0.8, $\varepsilon_C$=1.2. Three-phase asymmetrical current curves are shown in (Fig. 1).

In case of asymmetrical load, causing amplitude unbalance of the mains currents, there occur variable components of instantaneous active and reactive IP. When they are written in the frequency-domain in accordance with IP cross-vector theory, the following expressions are obtained:

– constant component of instantaneous reactive power:

$$P_0 = \frac{1}{2} U_{1m} I_{1m} \cos(\varphi_{I1}) [1 + \varepsilon_B + \varepsilon_C]; \quad (1)$$

– cosine orthogonal component of the second harmonic of instantaneous reactive power:

$$P_{2a} = \frac{1}{8} U_{1m} I_{1m} \cos\varphi_{I1} [2 - \varepsilon_B - \varepsilon_C] + \\ + \frac{\sqrt{3}}{8} U_{1m} I_{1m} \sin(\varphi_{I1}) [\varepsilon_B - \varepsilon_C]; \quad (2)$$

– sine orthogonal component of the second harmonic of instantaneous reactive power:

$$P_{2b} = \frac{1}{8} U_{1m} I_{1m} \sin(\varphi_{I1}) [2 - \varepsilon_B - \varepsilon_C] + \\ \frac{\sqrt{3}}{8} U_{1m} I_{1m} \cos(\varphi_{I1}) [\varepsilon_C - \varepsilon_B]; \quad (3)$$

– root-mean-square (RMS) value of the second harmonic of instantaneous active power:

$$P_{2rms} = \sqrt{P_{2a}^2 + P_{2b}^2} = \\ = \frac{1}{4} U_{1m} I_{1m} \sqrt{[1 + \varepsilon_B{}^2 + \varepsilon_C{}^2 - \varepsilon_C \varepsilon_B - \varepsilon_C - \varepsilon_B]}; \quad (4)$$

– constant component of reactive power:

$$Q_0 = -\frac{\sqrt{3}}{2} U_{1m} I_{1m} \sin(\varphi_{I1}) [1 + \varepsilon_B + \varepsilon_C]; \quad (5)$$

– cosine orthogonal component of the second harmonic of instantaneous reactive power:

$$Q_{2a} = \frac{3}{8} U_{1m} I_{1m} \cos(\varphi_{I1}) [\varepsilon_C - \varepsilon_B] + \\ + \frac{\sqrt{3}}{8} U_{1m} I_{1m} \sin(\varphi_{I1}) [2 - \varepsilon_B - \varepsilon_C]; \quad (6)$$

– sine orthogonal component of the second harmonic of instantaneous reactive power:

$$Q_{2b} = -\frac{3}{8} U_{1m} I_{1m} \sin(\varphi_{I1}) [\varepsilon_B - \varepsilon_C] - \\ - \frac{\sqrt{3}}{8} U_{1m} I_{1m} \cos(\varphi_{I1}) [2 - \varepsilon_B - \varepsilon_C]; \quad (7)$$

– RMS value of the second harmonic of instantaneous reactive power:

$$Q_{2rms} = \sqrt{Q_{2a}^2 + Q_{2b}^2} = \\ = \frac{\sqrt{3}}{4} U_{1m} I_{1m} \sqrt{[1 + \varepsilon_B{}^2 + \varepsilon_C{}^2 - \varepsilon_C \varepsilon_B - \varepsilon_C - \varepsilon_B]}. \quad (8)$$

The study of the obtained expressions in an analytical form revealed that the level of variable power components nonlinearly depends on the level of unbalance, and RMS values of the second harmonic of instantaneous active $P_{2rms}$ and reactive $Q_{2rms}$ powers do not depend on the shift angle of the current phases in relation to voltage. Also, expressions (1)–(8) showed that unbalance of supply voltage caused appearance of variable components of instantaneous active power but does not cause appearance of variable components of reactive power. Moreover, asymmetrical load results in appearance of variable components of both active and reactive power.

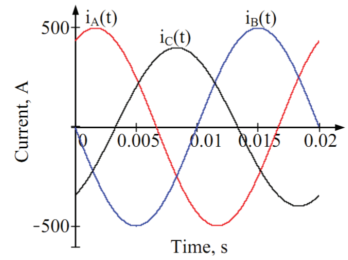


Fig. 1. Three-phase amplitude-asymmetrical load current

According to the cross-vector theory compensation currents in the frequency-domain were calculated:
– for phase A

$$I_{A\,a1} = -\frac{\sqrt{3}}{12} I_{1m} [-2 + \varepsilon_B + \varepsilon_C]; \quad I_{A\,b1} = -\frac{1}{4} I_{1m};$$

– for phase B

$$I_{B\,a1} = \frac{\sqrt{3}}{24} I_{1m} [1 + \varepsilon_B + \varepsilon_C]; \quad I_{B\,b1} = \frac{\sqrt{3}}{4} I_{1m} \left[\frac{1 + \varepsilon_B + \varepsilon_C}{3}\right];$$

– for phase C

$$I_{C\,a1} = \frac{\sqrt{3}}{24} I_{1m} [1 + \varepsilon_B - 5\varepsilon_C]; \quad I_{C\,b1} = \frac{1}{8} I_{1m} [1 + \varepsilon_B - \varepsilon_C].$$

Correctness of the obtained orthogonal frequency components of compensation current was confirmed by the fact that when condition $\varepsilon_B = \varepsilon_C = 1$ was substituted into them, expressions (1)–(8) take a form, describing the operation of the system with symmetrical load, i. e.: $P_{2a}=0$; $P_{2b}=0$; $Q_{2a}=0$; $Q_{2b}=0$; $P_{2rms}=0$; $Q_{2rms}=0$; $P_0 = \frac{3}{2} U_m I_m \cos(\varphi_{I1})$. The high-quality process of compensation results in achievement of amplitude symmetry of currents, which is illustrated in Fig. 2.

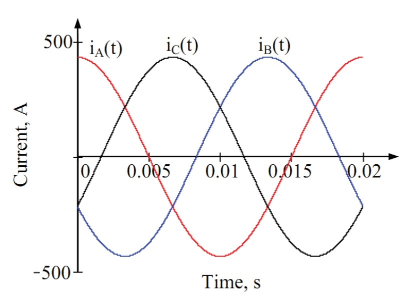


Fig. 2. Compensated currents in mains with asymmetric load

The obtained analytical dependences will allow research for both small deviations of resistances in phases and for cases of limit conditions: open-phase fault (ε=0) and short circuit (1/ε=0).

Analysis of IP components depending on the change of coefficient ε of current amplitude unbalance (Fig. 3, 4) and coefficient $1/\varepsilon$ of the change of load resistance in one of phases (Fig. 5, 6) will enable determination of integral parameters of power processes. They can also be used for calculation of parameters and adjustment of power of APF.

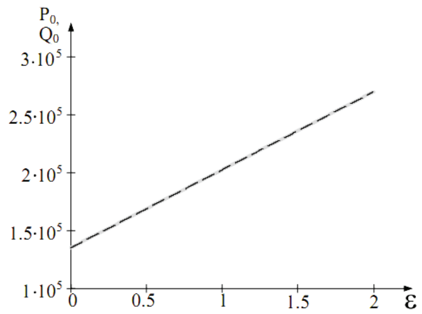


Fig. 3. Constant components of active $P_0$ (——) and reactive $Q_0$ (— — —) powers dependence on the coefficients of current unbalance

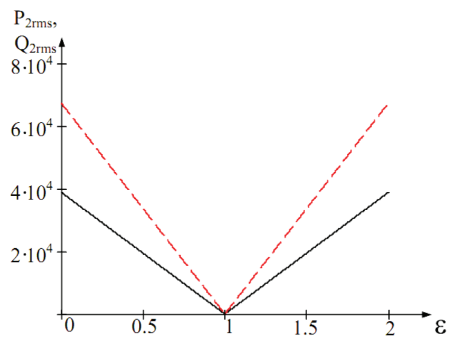


Fig. 4. RMS values of components of active $P_{2rms}$ (——) and reactive $Q_{2rms}$ (— — —) powers dependence on the coefficients of current unbalance

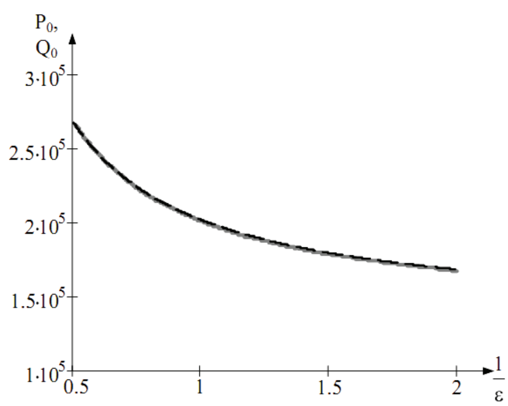


Fig. 5. Constant components of active $P_0$ (——) and reactive $Q_0$ (— — —) powers dependence on the coefficients of change of load resistance $1/\varepsilon$ in one of the phases

To find out the mechanism of currents amplitudes distribution and to determine their dependence on the unbalance coefficient a study in an analytical form was performed in the frequency-domain of generation of compensation currents with elimination of unbalance of active load. Initial harmonic components of current are given below:

$$I_{A\,a1}=\frac{1}{2}I_{1m},$$

$$I_{A\,b1}=0,$$

$$I_{B\,a1}=-\frac{1}{4}I_{1m}\varepsilon_B,$$

$$I_{B\,b1}=\frac{\sqrt{3}}{4}I_{1m}\varepsilon_B,$$

$$I_{C\,a1}=-\frac{1}{4}I_{1m}\varepsilon_C,$$

$$I_{C\,b1}=-\frac{\sqrt{3}}{4}I_{1m}\varepsilon_C.$$

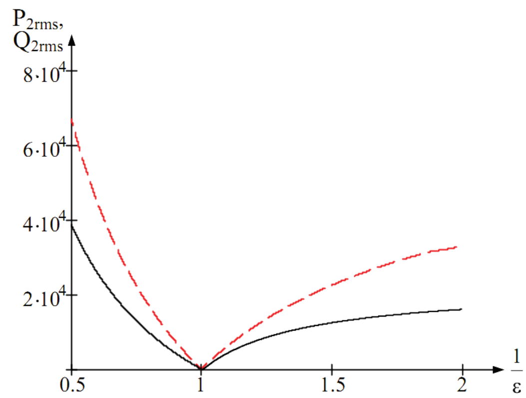


Fig. 6. RMS values of components of active $P_{2rms}$ (——) and reactive $Q_{2rms}$ (— — —) powers dependence on the coefficients of change of load resistance $1/\varepsilon$ in one of the phases

After compensation for undesirable IP components the following analytical expressions of compensation currents are obtained:

– for phase A

$$I_{A\,a1}=\frac{1}{2}I_{1m}\left[\frac{1+\varepsilon_B+\varepsilon_C}{3}\right];\ \ I_{A\,b1}=0;$$

– for phase B

$$I_{B\,a1}=-\frac{1}{4}I_{1m}\left[\frac{1+\varepsilon_B+\varepsilon_C}{3}\right];\ \ I_{B\,b1}=\frac{\sqrt{3}}{4}I_{1m}\left[\frac{1+\varepsilon_B+\varepsilon_C}{3}\right];$$

– for phase C

$$I_{C\,a1}=-\frac{1}{4}I_{1m}\left[\frac{1+\varepsilon_B+\varepsilon_C}{3}\right];\ \ I_{C\,b1}=-\frac{\sqrt{3}}{4}I_{1m}\left[\frac{1+\varepsilon_B+\varepsilon_C}{3}\right].$$

On the basis of the obtained expressions it is possible to come to the conclusion that expression $\left[\frac{1+\varepsilon_B+\varepsilon_C}{3}\right]$, is introduced into the composition of orthogonal components of current of every phase, which allows balancing of current signals amplitudes. That is, currents amplitudes are averaged.

This conclusion and obtained analytical dependences of compensation currents will make it possible to determine the charge of power switches of APF phases and make its correct choice according to the current of the most overcharged switch of the inverter.

It should be mentioned that the analysis of the obtained expressions for compensation for non-active components of current in the frequency-domain demonstrated that the APF correct operation is possible without taking into account asymmetrical components of supply voltage and harmonic distortions [14, 15], caused by load impact on current signals curves. It means that independently of the cause of current unbalance: load or supply mains, the use of harmonic components of voltage, without taking into account their asymmetric components, in generation of compensation currents will enable high-quality compensation. It provides certain possibilities for improvement of compensation methods.

**4. 2. Research of compensation processes in the time-domain with the use of numerical mathematical modeling**

The following stage of the research consisted in assessment of voltage unbalance influence on compensation processes with the use of numerical modeling methods. In this case a hypothesis was suggested that it is necessary to supply signals of the supply mains to APF control system (CS) into the algorithm of compensation currents generation without taking into account asymmetrical components caused by unbalance of supply voltage.

A mathematical model of a section of power supply was worked out for research of modes of compensation for non-active components of load currents in the presence of unbalance of supply mains voltages (Fig. 7). It consists of linear active-inductive load, active-inductive resistances of the mains, current and voltage measuring blocks, a compensator, a CS compensator, a voltage signal balancing block (VSBB), and also a separation block (SB) [14, 15]. For performance of preliminary research during mathematical modeling APF was represented as a controlled current source. That is, the influence of pulse-width modulation was not taken into consideration during the analysis of compensation processes.

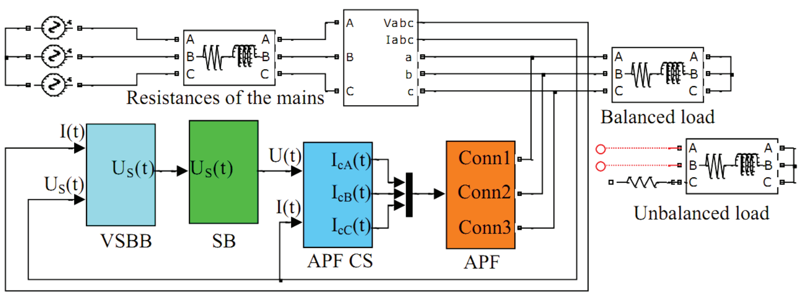


Fig. 7. The mathematical model of power supply mains with a system of compensation at unbalance

Relation of short circuit (SC) power $P_{SC}$ to load power $P_L$ equal to five and twenty was chosen during the analysis of APF operation under the conditions of voltage unbalance. This corresponds to cases of "weak" and "strong" mains, i. e. when supply voltages are distorted under the impact of load currents significantly and insignificantly, respectively.

During the modeling process two configurations of the researched section of the power supply mains were analyzed: a source with asymmetric supply voltage – linear symmetric load, a source with asymmetric supply voltage – linear asymmetric load.

The following values of the parameters of the mains section SC were assumed for modeling $P_{SC}=1.64\cdot10^6$ W. The linear load parameters: for $P_{SC}/P_L=5$ – $L_L=1\cdot10^{-3}$ Hn, $R_L=0.04$ Ohm, for $P_{SC}/P_L=20$ – $L_L=3.8\cdot10^{-3}$ Hn, $R_L=1.8$ Ohm. A throttle with parameters $L_r=0.3\cdot10^{-3}$ Hn, $R_r=0.01$ Ohm was inserted in series into the compensator circuit. The level of unbalance of supply voltage was assessed by the coefficient of reverse sequence and was assumed equal to 3.98 % for the case when $P_{SC}/P_L=5$, and 4.03 % for – $P_{SC}/P_L=20$. VSBB was used for realization of the method proposed by the authors (Fig. 8).

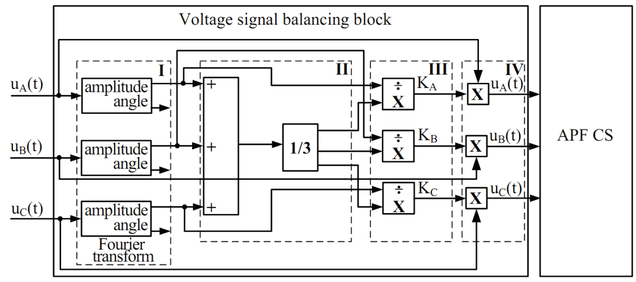


Fig. 8. Voltage signal balancing block

It is designed for balancing signals of supply voltage before their transfer to compensator CS. Amplitude values of voltage in every phase are determined in VSBB with the help of block "Fourier transform" (Fig. 8, I). The obtained numerical values are added, then averaged (Fig. 8, II), coefficients $K_A$, $K_B$, $K_C$ are determined by division of the obtained values by the initial amplitude (Fig. 8, III); these coefficients are necessary for balancing the voltage amplitudes of every phase (Fig. 8, IV). Thus, thereafter, a voltage signal without components caused by supply voltage unbalance is transferred to compensator CS.

## 5. Results of the research of analyzing the proposed compensation system operation in the time-domain

**5. 1. At asymmetric supply voltage and linear symmetric load**

A case of operation of a section of power supply mains with supply voltage unbalance and linear load was considered. During the research unbalance was introduced into phase A by the value of coefficient $\varepsilon_A=0.885$ (Fig. 9). In this case the level of unbalance by coefficient $K_{2U}$ of reverse sequence of voltage was equal to 3.98 %. In such a system supply voltage unbalance (Fig. 9) causes amplitude unbalance of currents at the point of charge connection (Fig. 10). In this case a known compensator (Fig. 9, 10) operated rather efficiently – enabling achievement of current unbalance level according to coefficient $K_{2U}$ equal to 1.76 %, which is within the admissible norms [22, 23]. It is necessary to point out that APF with CS created with the use of IP cross-vector theory was used as a known compensator [6, 7].

However, as the author of the papers [9–11] pointed out, at section II (Fig. 9, 10), where operation of the known compensator is demonstrated, significant harmonic distortion of voltage and current signal form was observed [14, 15]. They were assessed by the coefficient of total harmonic distortions of voltages $THD_U$ and currents $THD_I$ [23]. For the considered case (Fig. 9, II) and (Fig. 10, II) they made $THD_U$=9 % and $THD_I$=11 %. It was caused by the fact that a signal of asymmetric supply voltage was supplied to CS by the compensator.

To eliminate harmonic distortions of current and voltage signals, it was proposed to use a separation block (SB) to separate supply voltage harmonics caused by mains distortion (Fig. 11) [14, 15].

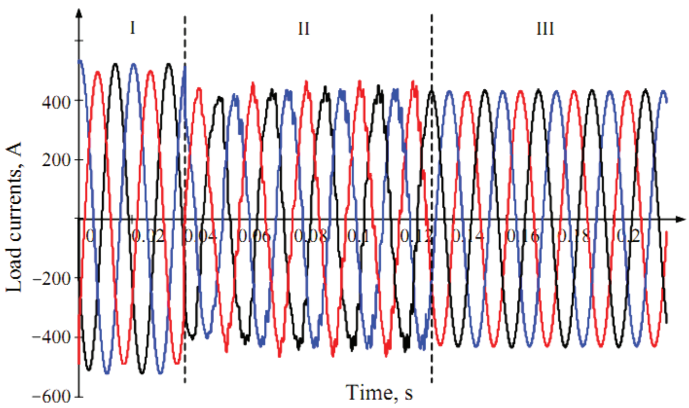


Fig. 9. Mains voltages (I), after (II) connection of a known compensator and after connection of a compensator with VSBB and SB (III)

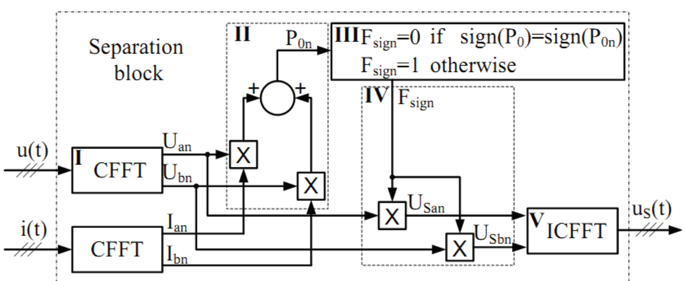


Fig. 10. Mains currents (I), after (II) connection of a known compensator and after connection of a compensator with VSBB and SB (III)

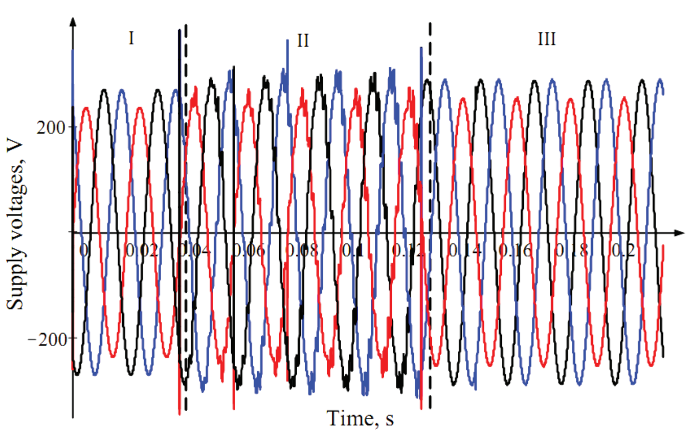


Fig. 11. SB for voltage signals of supply mains

It is intended for elimination from the algorithm of formation of compensation currents [14, 15] of those voltage higher harmonics at the point of compensator connection that are caused not by flowing currents of the load but by power supply distortion. Under real conditions these voltage harmonics can be caused by powerful nonlinear consumers connected closer to the power supply.

In SB with the use of fast Fourier transform (CFFT) transition into the frequency-domain is performed (Fig. 11, I), which makes it possible to determine voltage harmonic composition at the point of compensator connection. Determination of voltage harmonics caused by harmonic distortion in the mains is performed in SB due to the analysis of the sign of the corresponding frequency component of active power [20]:

$$P_0 = P_{01} + P_{02} + \ldots + P_{0n}, \tag{9}$$

where $P_{01}=I_{an}U_{an}+I_{bn}U_{bn}$ (Fig. 11, II), n – harmonic number, $I_{an}$, $I_{bn}$ – cosine and sine harmonic components of current of the n-th harmonic, respectively, $U_{an}$, $U_{bn}$ – cosine and sine harmonic components of voltage of the n-th harmonic, respectively.

According to [14, 15, 21], if the sign of the corresponding component coincides with the sign (Fig. 11, III), it means that the corresponding voltage harmonic is caused by mains distortions. If the signs do not coincide, it means that the corresponding voltage harmonic is caused by flow of nonsinusoidal currents of nonlinear load. Harmonics caused by mains distortion are eliminated from the obtained harmonic composition of voltage (Fig. 11, IV). After that, using inverse Fourier transform (ICFFT), transition to the time-domain is performed (Fig. 8, V). After these operations voltage without harmonic components caused by distortion of supply mains voltage is supplied to CS by the compensator.

The following parameters (Table 1) were calculated for quantitative assessment of compensation modes: $THD_I$ and $THD_U$, voltage drop $\Delta U$ at supply mains resistances, RMS values of variable components of active $\tilde{p}_{rms}$ and reactive $\tilde{q}_{rms}$ powers, constant component Q of reactive power, coefficients of unbalance of current $K_{2I}$ and voltage $K_{2U}$ according to reverse sequence. Also, correspondingly, power $\Delta P$ of losses at active resistances of supply mains and efficiency $\eta$ of the supply mains [24] without taking into account and taking into account ($\Delta P_k$, $\eta_k$) current displacement were calculated. Current displacement was taken into account by increase of active resitance $R_k$ at the k-th harmonic by $\sqrt{k}$ times. The data are given for operation modes at $P_{SC}/P_L$=5 and $P_{SC}/P_L$=20.

The obtained data (Table 1) demonstrated that compensation with the use of VSBB and SB, in comparison with known compensation, made it possible to achieve better balancing of current signals with coefficient $K_{2I}$=0.176 %. Also, it made possible to reach practically zero value of $THD_I$ and $THD_U$, reduction of voltage drop at mains resistances $\Delta U$; decrease of reactive power, variable components of active $\tilde{p}_{rms}$ and reactive $\tilde{q}_{rms}$ powers, decrease of losses and, consequently, increased efficiency. Such results are observed at operation modes with both significant ($P_{SC}/P_L$=5), and insignificant ($P_{SC}/P_L$=20) distortion of currents and voltages signals.

Table 1

Indices of APF operation in mains with symmetrical supply voltage and symmetrical linear load

| Parameter/ Mode | $\Delta U$, V | $THD_U$, % | $THD_I$, % | $\tilde{q}_{rms}$, VA | $\tilde{p}_{rms}$, VA | Q, var | $\Delta P$, W | $\Delta P_k$, W | $\eta$, % | $\eta_k$, % | $K_{2U}$, % | $K_{2I}$, % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_{SC}/P_L$=5 | | | | | | | | | | | | |
| Before compensation | 27.84 | 0 | 0 | $1.05 \cdot 10^3$ | $1.15 \cdot 10^4$ | $1.22 \cdot 10^5$ | $1.96 \cdot 10^4$ | $1.965 \cdot 10^4$ | 92.5 | 92.45 | 3.98 | 3.98 |
| After compensation | 31.4 | 11 | 9 | $1.99 \cdot 10^4$ | $1.14 \cdot 10^4$ | 100 | $1.386 \cdot 10^4$ | $1.386 \cdot 10^4$ | 94.7 | 94.69 | 4.1 | 1.76 |
| After comp. with VSBB and SB | 24.25 | 0.2 | 0.005 | 1031 | 3465 | –85 | $1.383 \cdot 10^4$ | $1.383 \cdot 10^4$ | 94.72 | 97.72 | 4.25 | 0.176 |
| $P_{SC}/P_L$=20 | | | | | | | | | | | | |
| Before compensation | 7.38 | 0 | 0 | 400 | $1 \cdot 10^4$ | $3.19 \cdot 10^4$ | 1374 | 1377 | 92.85 | 91.9 | 3.99 | 3.985 |
| After compensation | 6.55 | 0.5 | 5.06 | 1000 | 235 | 40 | 997 | 998 | 94.7 | 94.69 | 4.022 | 1.499 |
| After comp. with VSBB and SB | 6.52 | 0.3 | 2.1 | 500 | 928 | –9 | 994 | 994 | 94.73 | 94.73 | 4.068 | 0.092 |

**5. 2. At asymmetric supply voltage and asymmetric linear load**

A case of operation of power supply mains section with supply voltage unbalance and asymmetrical linear load was considered. During the research unbalance was introduced into phase A of supply voltage by the value of coefficient $\varepsilon_A$=0.885 and into phase C of the load by reduction of its active resistance by 10 % (Fig. 11, 12). In this case the unbalance according to coefficient $K_{2U}$ of reverse sequence voltage made 4.03 %.

Under such operation conditions (Fig. 11, 12) variation of operation indices similar to those in the previous case can be observed. Compensator with VSBB and SB enabled reduction of load current unbalance to $K_{2U}$=1.72 % and support of $THD_I$ and $THD_U$ at practically zero level (Table 2).

Table 2

Indices of APF operation in mains with symmetrical supply voltage and asymmetrical linear load

| Parameter/ Mode | $\Delta U$, V | $THD_U$, % | $THD_I$, % | $\tilde{q}_{rms}$, VA | $\tilde{p}_{rms}$, VA | Q, var | $\Delta P$, W | $\Delta P_k$, W | $\eta$, % | $\eta_k$, % | $K_{2U}$, % | $K_{2I}$, % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_{SC}/P_L$=5 | | | | | | | | | | | | |
| Before compensation | 27.25 | 0 | 0 | 3500 | $1.2 \cdot 10^4$ | $1.18 \cdot 10^5$ | $1.89 \cdot 10^4$ | $1.9 \cdot 10^4$ | 92.8 | 92.05 | 4.03 | 4.87 |
| After compensation | 27.2 | 7.3 | 7.35 | $1.3 \cdot 10^4$ | 7700 | 450 | $1.36 \cdot 10^4$ | $1.362 \cdot 10^4$ | 94.71 | 94.7 | 4.15 | 1.72 |
| After comp. with VSBB and SB | 24.15 | 0.002 | 0.005 | 5510 | 5294 | –93.5 | $1.35 \cdot 10^4$ | $1.35 \cdot 10^4$ | 94.72 | 94.72 | 4.32 | 0.17 |
| $P_{SC}/P_L$=20 | | | | | | | | | | | | |
| Before compensation | 7.2 | 0 | 0 | 1002 | 3600 | $-3.07 \cdot 10^4$ | 1316 | 1316.4 | 94.4 | 94.4 | 4.01 | 4.9 |
| After compensation | 6.43 | 0.5 | 5.05 | 929 | 236.4 | 30 | 968.4 | 968.8 | 94.71 | 94.705 | 4.023 | 1.46 |
| After comp. with VSBB and SB | 6.42 | 0.05 | 0.4 | 1584 | 1566 | –7 | 966.3 | 996.3 | 94.72 | 94.72 | 4.067 | 0.09 |

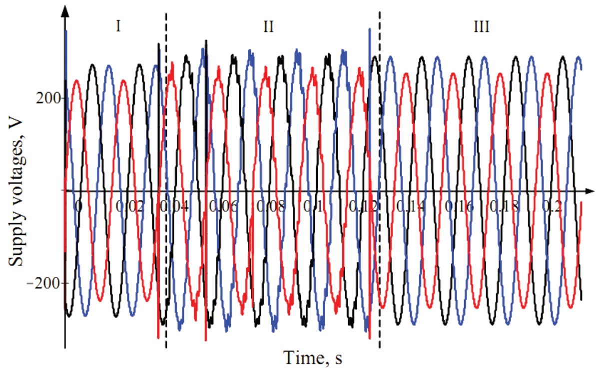


Fig. 12. Mains voltages (I), after (II) connection of a known compensator and after connection of a compensator with VSBB and SB (III)

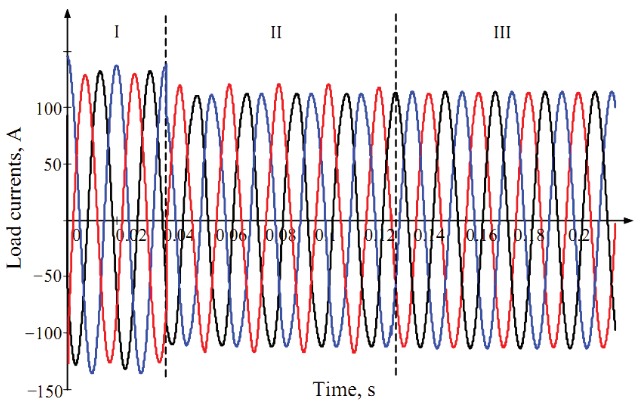


Fig. 13. Mains currents (I), after (II) connection of a known compensator and after connection of a compensator with VSBB and SB (III)

## 6. Discussion of the research results of analyzing the proposed compensation system operation in the time-domain

The subsystem of balancing the supply mains voltage signals, proposed in the paper, made it possible to improve the method of compensation for currents non-active components under the conditions of the supply mains voltages unbalance. The performed mathematical modeling of the researched system and analysis of the obtained numerical data revealed the efficiency and feasibility of the use of the proposed method of compensation for currents non-active components in power supply systems.

Improvement of the method consists in exclusion of voltage asymmetric components, caused by the mains distortions, from the algorithm of compensation currents generation. The latter enabled improvement of the efficiency of power supply systems operation and the speed of compensation system operation.

In the future, the proposed method can be applied to compensation for currents non-active components in the industrial power supply systems to which nonlinear and asymmetric equipment with sharply changing operation mode is connected.

## 7. Conclusions

1. The analysis in the frequency-domain of the processes of compensation for current non-active components in power supply systems with asymmetric load made it possible to obtain analytical expressions for compensation currents. It provided the possibility to determine the ways of improvement of currents non-active components compensation methods under the conditions of operation with supply mains asymmetric voltage. The obtained compensation currents analytical dependences will also enable determination of the charge of APF phases power keys and provide its correct choice according to the current of the most overloaded key of the inverter.

2. The research of the processes of compensation for load currents non-active components of a supply mains section at supply voltage unbalance was carried out in the time-domain on a mathematical model. On their basis, it was shown that the use of the developed method with balancing and separation of supply voltage signals harmonics, as compared with the known compensation system, makes it possible to:

– decrease the level of currents signals unbalance with reverse sequence coefficient by 1.3..1.5 %;

– achieve practically zero value of the currents nonsinusoidality coefficient;

– reduce the value of reactive power after compensation by 15..23 % and voltage drop at the mains resistances by 0.5..23 %.

3. The use of the proposed method made it possible to improve the effectiveness of the power supply system, in particular, to reduce losses in transmission lines by 0.5 % and to increase the efficiency of the power supply system by 0.3..2.5 %.

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