DOI: https://doi.org/10.15407/techned2018.04.047

REACTIVE POWER COMPENSATION APPROACH WITH DYNAMIC MODE OF LOAD CURRENT

V.J.Zhuikov*, I.V. Verbytskyi, A.G.Kyselova*****
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institue",
pr. Peremohy, 37, Kyiv, 03056, Ukraine, e-mail: verbitskiy@bigmir.net.

The actuality of the compensation of the residual reactive power that arises with the non-stationary current of the power grid is shown. On the example of the computer power supply unit, the amount of residual reactive power is calculated by using a compensator with one period lag of the power grid voltage. In parallel with the general reactive power compensator, it is proposed to use an auxiliary one, which eliminates distortion of the grid current based on its predicting. It is shown that the use of the additional compensator allows reaching power factor value closed to one with a non-significant increase in the total installed capacity of the compensation system. The proposed compensation method is adapted to the presence of current pulsation of the general compensator. References 10, figures 9.

Keywords: reactive power compensation, dynamical grid current, least squares method, power factor.

Introduction. Implementation of energy-efficient technologies in electrical devices, for instance, electric drives or "sleep" mode in household electric appliances etc. [1, 2] can cause the dynamic change of consumed current from a power grid. As the result, the total grid current shape is always changed.

In consequence of the time lag of reactive power compensation devices, their efficiency at the dynamic current mode is decreased [3]. Therefore, the amount of consumed energy increases, the shape of the supply voltage is distorted, and stress on the transmission line is increased [4, 5]. Because of this, the actual task is the problem of compensation of residual reactive power in power grids with non-stationary current, theoretical principles of which is proposed in [6], calculation of excess energy which is generated as a result of its availability and suggestions for the possibility of its compensation is relevant.

In the paper, on the basis of the consumed current of a personal computer power supply, which is one of the possible consumers with dynamically changing current, the structure of a reactive power compensation system with general and additional compensators is proposed, effectiveness of a reactive power compensation algorithm in transient mode is analyzed, installed power of the additional compensator is estimated, the compensation algorithm is adopted to the general compensator pulsation.

Analysis of the consumed power from the power grid. As mentioned above, electronic devices with the input capacitor filter and rectifier are loads with dynamically changing current, for instance, personal computer power supplies. Thus, in the paper, as an object of study is used 500 W Frontier atx-500f power supply of the computer based on a dual-core AMD Athlon 64x2 4400+ processor. The analysis is performed based on the measured data during 320 seconds which corresponds to 16 thousand periods of the power grid voltage. In the Fig. 1 is shown the timing diagram of 3 periods of instantaneous current values $i_g(t)$ and voltage $u_g(t)$ of the power grid and illustrating the typical dynamics of the consumed power. As can be seen from the figure, in the half-period of the grid voltage t=0.20..0.21 sec. the maximum value of current is 3 A, while in the neighboring half-period t=0.22..0.23 sec - the current value increases to 3.8 A. Such dynamics of the current is explained by increasing of the computer processor energy consumption. The same behavior is observed throughout the time interval of current measurement.

Since the current of the power grid has a dynamic character due to the parametric nature of the load, values of the total power S, active power P, reactive power Q and the power of distortion D are varied in time [7]. In Fig. 2 is shown the diagrams of the total $S_{(k)}$, active power $P_{(k)}$ and power factor $\chi_{(k)}$ depending on the period number k.

The total and active power fluctuate in the range of ± 17 % and change mainly synchronously, therefore the power factor fluctuates within a narrower range of ± 8 % with an average value of χ_{cp} = 0.546. If compensation of reactive power is performed by the compensator with output current $i_c(t)$

$$i_c(t) = i_g(t-T) - I_{m(-1)} \sin(\omega t - \varphi_{(-1)}), \tag{1}$$

ORCID ID: * https://orcid.org/0000-0002-3338-2426 , ** https://orcid.org/0000-0001-7275-5152 ,
*** https://orcid.org/0000-0002-7228-3594

where i_g is the grid current, $I_{m(-1)}$ is the amplitude of the first harmonic of the grid current in the previous period of the grid voltage, $\varphi_{(-1)}$ is phase of the first harmonic of the grid current at the previous period of the grid voltage, the average value of the power factor of the system increases to the value of $\chi_{cp} = 0.978$.

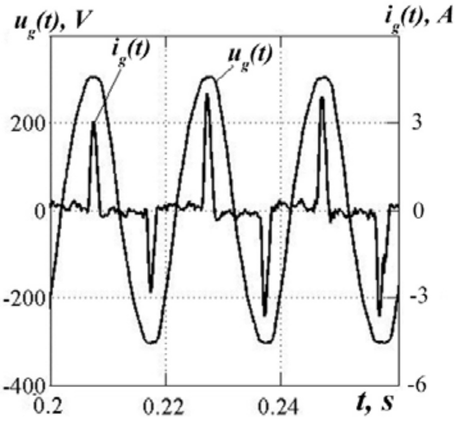

Fig. 1

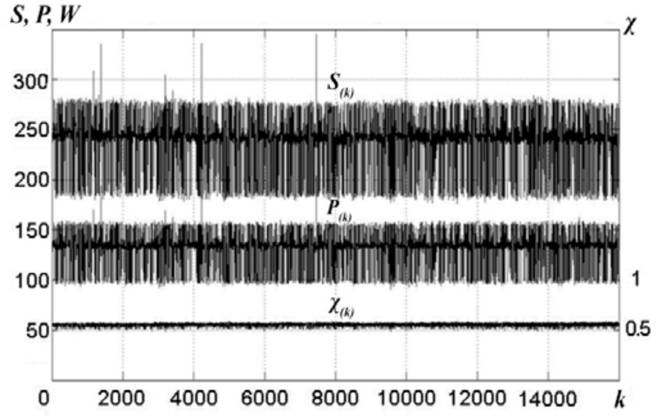

Fig. 2

The timing diagrams of the parameters, depending on the period k is shown in Fig. 3. In this case the shape of the grid current has a distortion as shown in Fig. 4, whose values are significant during the dynamic current change, for example, at the time interval $t = 0.2..0.22$ sec in Fig. 4.

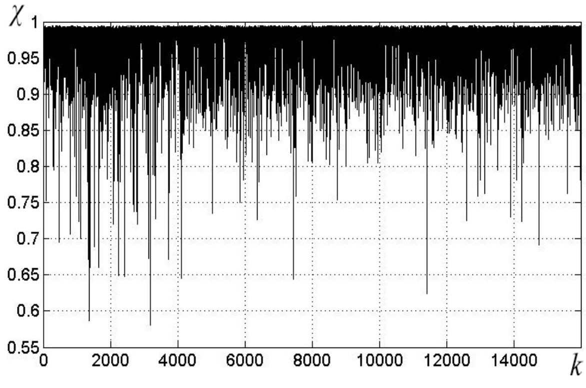

Fig. 3

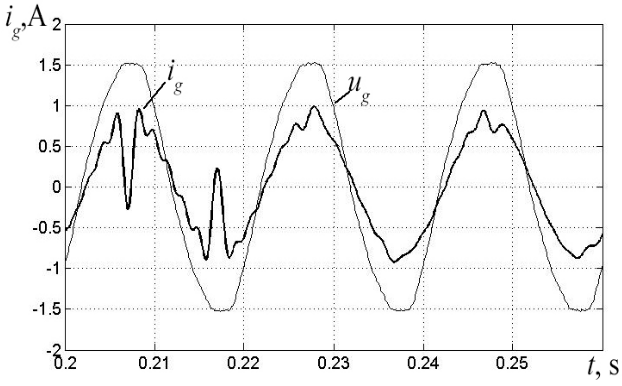

Fig. 4

The average power of the compensator over the entire compensation interval of P_c is P_c=197.7 Watts. The calculated power factor χ_{cp}=0.978 corresponds to the current standards for electricity consumption, however, in such modes an additional stress on the power supply system is created with 2.2% of the nominal value. The stress may be eliminated as result of implementation more effective compensation algorithms based on one or two compensators. In the second case, the first (general) compensator operates with the classical algorithm, the second one (additional) operates with the improved algorithm. The system with two compensators has such advantages:

− a majority of installed compensators operates with classical compensation algorithm with one period lag. One compensator realization of the proposed algorithm requires full replacement of the previous compensator. If two compensators are used, it will enough to install the second compensator with one order less power and improved algorithm. The second variant has a better economic effect.

− the improved algorithm is used for high-frequency current distortions compensation that arise in transient modes. Therefore, the compensator based on the improved algorithm has to operate at a higher frequency that increases it's the dynamical losses and price. Separation of compensation functions allows decreasing frequency of the general compensator. Therefore, the relation effectiveness-price is higher for the system with two compensators, the general compensator and the additional one.

Thus, in the paper are developed the system with two compensators. The compensators connection scheme is shown in Fig. 5. Since the additional reactive power compensator reacts to distortion of the current shape, its control loop must contain a prediction link, this will allow compensating the current deviation from a sinusoidal shape with minimal error.

Let consider the method of predicting the grid current and compensation of its reactive component.

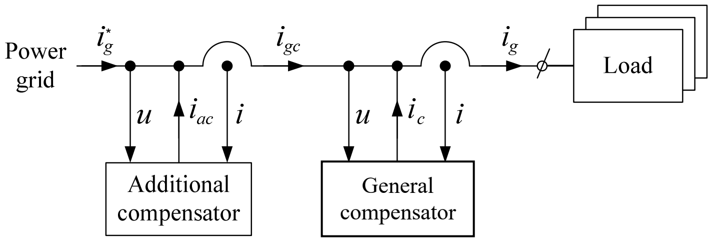

Fig. 5

Predicting approach of the grid current and compensation of the reactive power. In order to compensate reactive power after the general compensator, the additional reactive power compensator has to generate current i_{ac}, which is determined in the same way as in formula (1), and takes into account the current distortion after the general compensator

$$i_{ac(i)}(t) = i_{g\tilde{n}}(t) - I_{g\tilde{n}(1)}\cos(\varphi)\sin(\omega t), \tag{2}$$

where $i_{gc}(t)$ is grid current after the general compensator, $I_{gc(1)}$ is first harmonic amplitude of the grid current, φ is a phase difference between first harmonics of voltage and current.

According to formula (2), the additional compensator eliminates the distortion of the grid current and the residual reactive power, which allows reaching the maximum value of the power factor χ, $\chi = 1$. To realize the proposed principle of reactive power compensation in dynamic modes, it is necessary to identify the value of the grid current first harmonic and its phase based on the grid current.

First harmonic value identification may be realized on the grid current measuring at the beginning of each period. Before the identification process is finishing, distortion compensation is carried out approximately. An identification technique has to identify the current parameters with a minimum amount of measurings. The least squares method (LSM) [8] is one of the effective approximation methods for measured noisy data. Since the criterion for the approximation of LSM is a minimization of the mean square error δ, the additional compensator has a minimum output power.

Let define a grid current approximation function as $F(x)$. Then the mean square error δ of the approximation calculated as follows:

$$\delta(i_{gc},F) = \sqrt{\sum_{k=0}^{N-1}(i_{gc}(k\Delta t) - F(k\Delta t))^2} = \sqrt{\sum_{k=0}^{N-1}(i_{gc}(k\Delta\alpha) - F(k\Delta\alpha))^2}, \tag{3}$$

where Δt is the measuring period of the grid current, $\Delta\alpha$ is the angle which corresponds to the period Δt, N is a number of grid current measurements.

Function F is expedient to define as

$$F(\alpha) = A\sin(\alpha + \varphi), \tag{4}$$

where A, φ are unknown parameters which are identified at the beginning of the grid voltage half-period.

At least two measurements of the grid current are necessary for function F parameter identification. Current distortions increase of the identification error, therefore additional measurements are made. Their amount depends on distortions value and frequency.

Function F parameters A and φ are calculated according to the error δ^2

$$\begin{cases} \sum_{k=0}^{N-1}(i_{gc}(k\Delta\alpha) - F(k\Delta\alpha))\partial F/\partial A = 0; \\ \sum_{k=0}^{N-1}(i_{gc}(k\Delta\alpha) - F(k\Delta\alpha))\partial F/\partial\varphi = 0. \end{cases} \tag{5}$$

After substitution of function F (4) into the system (5) we obtain

$$\begin{cases} \sum_{k=0}^{N-1}(i_{gc}(k\Delta\alpha) - A\sin(k\Delta\alpha + \varphi))\sin(k\Delta\alpha + \varphi) = 0; \\ \sum_{k=0}^{N-1}(i_{gc}(k\Delta\alpha) - A\sin(k\Delta\alpha + \varphi))A\cos(k\Delta\alpha + \varphi) = 0. \end{cases} \tag{6}$$

After a series of simplifications, the system (6) is transformed to

$$\begin{cases} a_1\cos(\varphi) + a_2\sin(\varphi) + a_3A\cos(2\varphi) - a_4A\sin(2\varphi) - a_5A = 0; \\ -a_1\sin(\varphi) + a_2\cos(\varphi) - a_3A\sin(2\varphi) - a_4A\cos(2\varphi) = 0, \end{cases} \tag{7}$$

where
$$a_1=\sum_{k=0}^{N-1} i_{gc}(k\Delta\alpha)\sin(k\Delta\alpha);\quad a_2=\sum_{k=0}^{N-1} i_{gc}(k\Delta\alpha)\cos(k\Delta\alpha);\quad a_3=0.5\sum_{k=0}^{N-1}\cos(2k\Delta\alpha)=0.5\frac{\sin(N\Delta\alpha)\cos(\Delta\alpha(1-N))}{\sin(\Delta\alpha)};$$
$$a_4=0.5\sum_{k=0}^{N-1}\sin(2k\Delta\alpha)=-0.5\frac{\sin(N\Delta\alpha)\sin(\Delta\alpha(1-N))}{\sin(\Delta\alpha)};\qquad a_5=N/2.$$

A solution of the system (7) is given below

$$A=\frac{-a_1\sin(\varphi)+a_2\cos(\varphi)}{a_3\sin(2\varphi)+a_4\cos(2\varphi)};\quad \varphi=\begin{cases}\arcsin\left(C_1/\sqrt{C_1^2+C_2^2}\right), C_1\geq 0, C_2\geq 0;\\ \pi-\arcsin\left(C_1/\sqrt{C_1^2+C_2^2}\right), C_1<0, C_2\geq 0;\\ -\arcsin\left(C_1/\sqrt{C_1^2+C_2^2}\right), C_1\geq 0, C_2<0;\\ \pi+\arcsin\left(C_1/\sqrt{C_1^2+C_2^2}\right), C_1<0, C_2<0,\end{cases}\tag{8}$$

where $C_1=a_1a_4+a_2a_3-a_5a_2$; $C_2=a_1a_3-a_2a_4+a_5a_1$.

First harmonic identification error $\delta_{(1)}$ depends on a number of measurements k. It is calculated as

$$\delta_{(1)}=\sqrt{2}A^{-1}\sqrt{\frac{1}{\pi}\int_0^{\pi}(A\sin(\alpha-\varphi)-A_k\sin(\alpha-\varphi_k))^2\,d\varphi}=\sqrt{2}A^{-1}\sqrt{A^2/2+A_k^2/2-AA_k\cos(\varphi-\varphi_k)},\tag{9}$$

where A_k, φ_k are the identified parameters with k measurements, A, φ are the identified values with minimal error in formula (3) among A_k, φ_k.

The error $\delta_{(1)}$ is calculated for each registered period and average value $\delta_{c(1)}$ is obtained. The relation between error $\delta_{c(1)}$ value and a number of measurements k are shown in Fig. 6.

The average error is less than 1 % already at 20 measurements which corresponds to angle $\pi/6$, that enough for distortion current compensation based on formula (2) at interval $[\alpha_c..\pi]$. At the initial interval $[0..\alpha_c]$ the compensation is performed approximately. According to the possibility of $\sin(\alpha)$ function approximation in the range $[-\pi/4..\pi/4]$ by the linear function $\sin(\alpha)\approx\alpha$, the grid current first harmonic in the range $[0..\alpha_c]$ is approximated as follows:

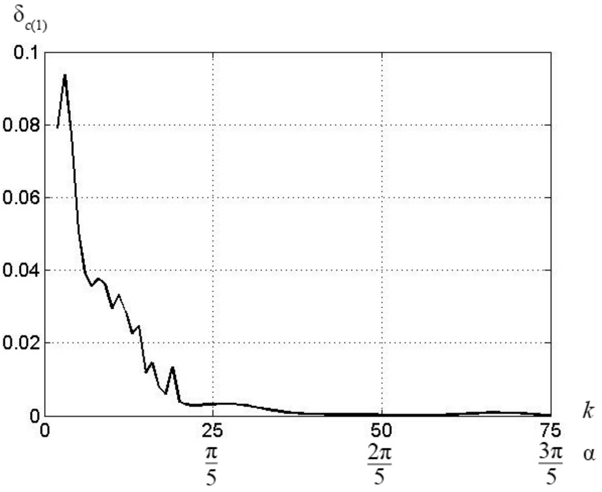

Fig. 6

$$i_{gc(1)}(\varphi)=b\varphi+a,\tag{10}$$

where b and a are the constant coefficients that are calculated based on LSM

$$\begin{cases} b\sum_{k=0}^{N-1}(k\Delta\varphi)^2+a\sum_{k=0}^{N-1}(k\Delta\varphi)=\sum_{k=0}^{N-1}(k\Delta\varphi)\,i_{gc}(k\Delta\varphi);\\ b\sum_{k=0}^{N-1}(k\Delta\varphi)+aN=\sum_{k=0}^{N-1}i_{gc}(k\Delta\varphi).\end{cases}\tag{11}$$

After calculation b and a parameters, the compensation current $i_{ac}(\varphi)$ of the additional compensator in the range $[0..\alpha_c]$ is chosen according to the law $i_{ac}(\varphi)=b\varphi$. The current timing diagram after compensation of general and additional compensators is shown in Fig. 7: *1* – grid voltage shape, *2* – grid current after compensation of the general compensator, *3* – grid current after compensation of the additional compensator.

The current has mostly sinusoidal shape, therefore power factor values are near to ideal, $\chi_{cp}=0.998$. Power factor χ relation with period number k is shown in Fig. 8. Hence, proposed approach of reactive power compensation with the additional compensator allows to increase power factor on 2 % and reach it to 100 % without significant increasing of the compensation system power. But for implementation the system it is necessary to take to account the current pulsation created by the general compensator because it sophisticates the grid current prediction and decreases power factor. Adaptation of the proposed reactive power compensation approach to the current pulsation is given in the next chapter.

Adaptation of the proposed approach to the compensator current pulsation. The current pulsation may be considered as an additional current distortion which has to be compensated with the additional compensator.

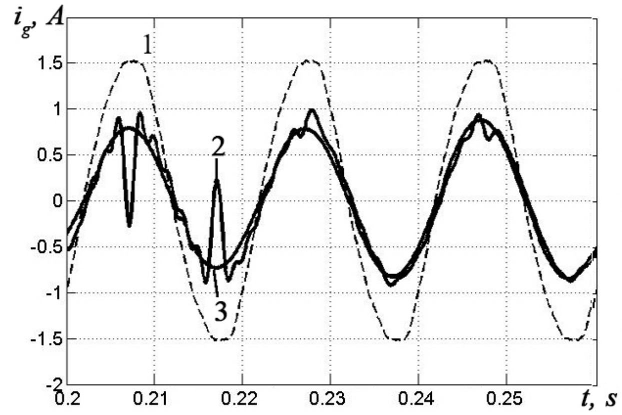

Fig. 7

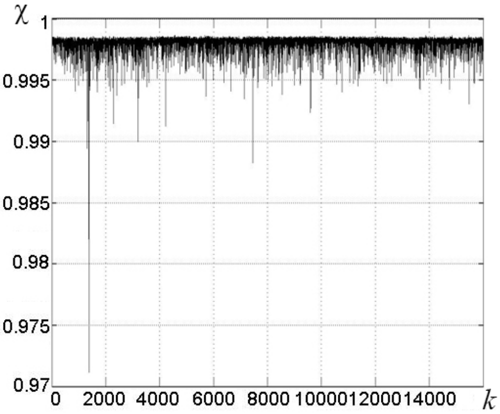

Fig. 8

In this case, the additional compensator has to have a high-speed reaction that increases its technical requirements and price. Therefore, due to not significant current distortions caused by the pulsation, its compensation isn't expedient, but it should be eliminated at the input of the additional compensator control loop. Then, the additional compensator is compensated only current distortions caused by the electrical loads.

For reactive power compensators, usually, is used relay control [9] due to minimization of its time lag [10], therefore the current pulsation frequency is changed. If low pass filter is used for pulsation eliminating, its cutoff frequency will depend on the grid current shape. Therefore, it has to be calculated for border case that increases control loop time lag. Software-apparatus realization of the filter allows reducing control loop time lag. As usual, the pulsation has a triangle shape. Therefore, after double differentiation of the current with pulsation delta-pulses are created. Their positions correspond to minimum $I_{\min}$ and maximum $I_{\max}$ grid current pulsation values. The average current values $i_{gs\_av}(\varphi)$

$$i_{gc\_av}(\varphi) = 0,5(I_{\max}(\varphi) + I_{\min}(\varphi)), \tag{12}$$

doesn't contain the pulsation created with the general compensator. The proposed adaptation needs an additional synchronization unit with two differentiators connected to additional compensator that shown in Fig. 9.

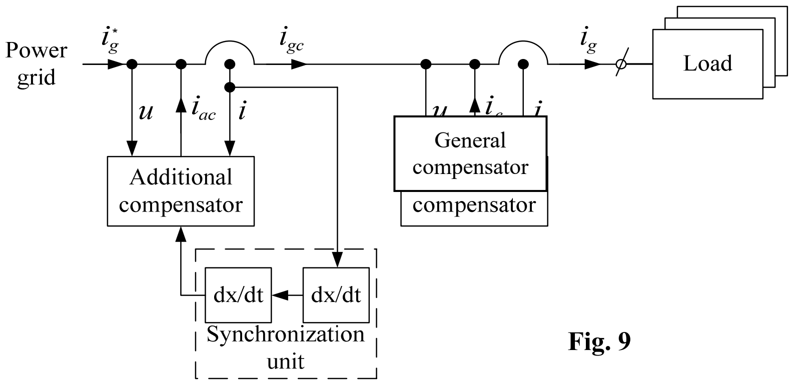

Fig. 9

The compensators' current pulsation decreases power factor. For power factor estimation with pulsation χ_{cp_p} let separate the grid current i_g^* into a pulsation current of the general compensator i_{pc}, a pulsation current of the additional compensator i_{pa} and an ideal grid current without pulsation i_{gi}^*

$$i_g^* = i_{pc} + i_{pa} + i_{gi}^*. \tag{13}$$

If the relation of the general compensator pulsation current RMS value I_{pm} and RMS value of the grid current without pulsation I_{gc}, $\delta_{ic} = I_{pc} / I_{gi}^*$, and the same relation for the additional compensator $\delta_{ia} = I_{pa} / I_{gi}^*$ are known, the power factor value with the current pulsation calculated as follows:

$$\chi_{cp\_p} = \frac{P_{cp}}{S_{cp}} = \frac{U_g I_{ga}^*}{U_g I_g^*} = \frac{U_g I_{ga}^*}{U_g\sqrt{I_{gi}^2 + I_{pc}^2 + I_{pa}^2}} = \frac{U_g I_{ga}^*}{U_g I_{gi}\sqrt{1+\delta_{pc}^2+\delta_{pa}^2}} = \frac{\chi_{cp}}{\sqrt{1+\delta_{pc}^2+\delta_{pa}^2}}, \tag{14}$$

where χ_{cp} is the power factor without the current pulsation, I_{ga} is the active component of the grid current I_g^*.

Let calculate power factor with pulsation χ_{cp_p} when power factor without pulsation is χ_{cp} = 0.998 and compensator current pulsation is 5 %, δ_{ic}=δ_{ia}=0.05

$$\chi_{cp\_p} = \frac{\chi_{cp}}{\sqrt{1+\delta_{pc}^2+\delta_{pa}^2}} = \frac{0.998}{\sqrt{1+0.0025+0.0025}} = 0.996. \tag{15}$$

As we can see the power factor value with the pulsation is slightly decreased to 0.996.

Conclusions. Hence, the grid current shape analysis with dynamical load namely a computer power supply allows to make such conclusions.

1. Reactive power compensation by a compensator with one grid voltage period lag allows to reach power factor value χ=0.978 that corresponds with actual electrical energy quality requirements, but it causes additional stress on power grid namely 2.2 %.
2. The additional compensator with one order less output power eliminates current distortions created during dynamical current consumption and allows to reach power factor χ closed to ideal, χ=0.998.
3. It is necessary to develop the adaptation of the proposed approach to the general compensator current pulsation. In this case power factor χ slightly decreased to value 0.996.

1. Ion Boldea and S.A. Nasar. Electric drives. CRC Press, 2006. 518 p.

2. Wong S.W., Valcarenghi L., Yen S.H., Campelo D.R., Yamashita S., Kazovsky L. Sleep mode for energy saving PONs: Advantages and drawbacks. Globecom Workshops, IEEE, 2009. P. 1-6. DOI: http://doi.org/10.1109/GLOCOMW.2009.5360736 .

3. Bezhenar V., Mykolaets D., Mykytyuk V., Tereshchenko T. Multilevel inverter as var-compensator. IEEE XXXIII International Scientific Conference *Electronics and Nanotechnology* (ELNANO), Kyiv, 2013. Pp. 370-372.
DOI: http://doi.org/10.1109/ELNANO.2013.6552076

4. Gyugyi Laszlo. Unified power-flow control concept for flexible AC transmission systems. IEE proceedings C (*generation, transmission and distribution*). IET Digital Library, 1992. Pp. 323-331. DOI: http://doi.org/10.1049/ip-c.1992.0048

5. Kyselova A.G., Verbitskyi I.V., Kyselov G.D. Context-aware framework for energy management system. 2nd International Conference on Intelligent *Energy and Power Systems* (IEPS), Kyiv, 2016. P. 1-4. DOI: http://doi.org/10.1109/IEPS.2016.7521890

6. Zhuikov V., Verbytskyi I., Bondarenko O. Features of compensation of a reactive power at the transient mode. *Electric Power Networks* (EPNet), 2016. P. 1-4. DOI: http://doi.org/10.1109/EPNET.2016.7999362

7. Tonkal V.E., Novoseltsev A.V., Denisyuk S.P. An energy balance in elecrical circuits. Kyiv: Naukova Dumka, 1992. 312 p. (Rus.).

8. Marquardt Donald W. An algorithm for least-squares estimation of nonlinear parameters. *Journal of the society for Industrial and Applied Mathematics.* 1963. 11.2: 431-441.

9. Fridman E., Fridman L., Shustin E. Steady modes in relay control systems with time delay and periodic disturbances. *Journal of Dynamic Systems, Measurement, and Control.* 2000. 122.4: 732-737. DOI: http://doi.org/10.1115/1.1320443

10. Tsypkin Y.Z. Relay automatic systems. Moskva: Nauka, 1974. 576 p. (Rus)

УДК 621.314

МЕТОД КОМПЕНСАЦИИ РЕАКТИВНОЙ МОЩНОСТИ ПРИ ДИНАМИЧЕСКОМ ТОКЕ НАГРУЗКИ

Жуйков В.Я., Вербицкий Е.В, Киселева А.Г.
Национальный технический университет Украины «КПУ им. Игоря Сикорского”,
пр. Победы, 37, Киев, 03056, Украина, verbitskiy@bigmir.net.

Показана актуальность компенсации остаточной реактивной мощности, возникающей при нестационарном токе сети. На примере блока питания персонального компьютера рассчитан объем остаточной реактивной мощности при использовании компенсатора с инерционностью работы в один период напряжения сети. Предложено параллельно с основным компенсатором реактивной мощности использовать вспомогательный, который устраняет искажения тока сети на основе его прогнозирования. Показано, что использование дополнительного компенсатора позволяет приблизить значение коэффициента мощности к единице при незначительном увеличении суммарной установленной мощности системы компенсации. Адаптировано предложенную методику компенсации в наличии пульсации тока основного компенсатора. Библ. 10, рис. 9.

Ключевые слова: компенсация реактивной мощности, динамический ток сети, метод наименьших квадратов, коэффициент мощности.

УДК 621.314

МЕТОД КОМПЕНСАЦІЇ РЕАКТИВНОЇ ПОТУЖНОСТІ ПРИ ДИНАМІЧНОМУ СТРУМІ НАВАНТАЖЕННЯ

Жуйков В.Я., Вербицький Є.В, Кисельова А.Г.
Національний технічний університет України «Київський політехнічний університет ім. Ігоря Сікорського”,
пр. Перемоги, 37, Київ, 03056, Україна, verbitskiy@bigmir.net.

Показано актуальність компенсації залишкової реактивної потужності, що виникає при нестаціонарному струмі мережі. Проаналізовано форму струму блока живлення персонального комп'ютера. Показано наявність перехідних процесів, які викликають наявність залишкової реактивної потужності при використанні компенсатора з інерційністю роботи в один період напруги мережі. Запропоновано паралельно з основним компенсатором реактивної потужності використовувати допоміжний. Розраховано форму струму додаткового компенсатора для усунення спотворень струму. Показано, що використання додаткового компенсатора дозволяє наблизити значення коефіцієнта потужності до одиниці при незначному збільшенні сумарної встановленої потужності системи компенсації. Запропоновано методику усунення пульсації на вході контуру керування усередненням струму мережі. Бібл. 10, рис. 9.

Ключові слова*:* компенсація реактивної потужності, динамічний струм мережі, метод найменших квадратів, коефіцієнт потужності.

Надійшла 05.12.2017
Остаточний варіант 16.01.2018