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ASSESSMENT OF ELECTRICAL NETWORK POWER COMPONENTS DURING OPERATION OF AN ACTIVE POWER FILTER ACCORDING TO IEEE 1459-2010 STANDARD

Summary. The paper deals with assessment of power components according to IEEE 1459-2010 standard during operation of a three-phase active power filter in complex with a nonlinear unbalanced load under the conditions of balanced and unbalanced network voltage. Correction of the algorithm of Fryze theory taking into consideration the cases of load currents' and network voltage unbalance has been proposed. Fryze algorithm correction is performed with determination of power and currents values according to IEEE 1459-2010 standard. A comparative assessment of the quality of operation of the active power filter has been carried out with the use of algorithms based on different power theories (*pq*-theory, Fryze theory).

Keywords: active power filter, Fryze theory, *pq*-theory, IEEE 1459-2010 standard

OCENA KOMPONENTÓW MOCY SIECI ELEKTRYCZNEJ PODCZAS PRACY AKTYWNEGO FILTRA WEDŁUG IEEE 1459-2010 STANDARD

Streszczenie. Praca dotyczy oceny składników energetycznych, zgodnie z normą IEEE 1459-2010 podczas działania trójfazowego filtru aktywnego w kompleksie z nieliniowym o obciążeniu niesymetrycznym w warunkach zrównoważonego i niezrównoważonego napięcia sieci. Autorzy zaproponowali algorytm korekcji oparty na teorii Fryzego. Algorytm ten został opracowany z określeniem wartości mocy i prądów ,zgodnie z normą IEEE 1459-2010. Porównawcze oceny jakości działania filtru aktywnego zostały przeprowadzone z wykorzystaniem algorytmu na podstawie teorii mocy (pq-teorii, teoria Fryzego).

Słowa kluczowe: aktywny filtr mocy, teoria Fryzego, *pq*-teoria, standard IEEE 1459-2010

1. INTRODUCTION

Continuous growth of installed power of nonlinear, unbalanced and jumping loads is not always accompanied by timely introduction of engineering solutions directed to provision of the quality of electric power even in developed countries of Western Europe [1].

Unbalance and nonsinusoidality influence on the elements of the systems of electric power supply and consumption is well-known [2]. Most often long-term asymmetric and unbalanced modes are accompanied by considerable voltages deviations and variations caused by overflows of reactive power, presence of higher harmonics currents and voltages. At present in practice there is no difference between the assessment of balanced and unbalanced power consumption. Usually only data about active and reactive powers are used, at best positive and negative phase-sequence voltages are taken into account [2], but these data not sufficient for rational operation of electric power consumption system.

To improve indices of quality of electric power various ways and methods are used, they are based on current sinusoidalization, correction of the power coefficient and balancing of load currents. Active power filters (APF) are an efficient engineering solution for compensation of reactive power and reduction of higher harmonics [4]. APF represents a combination of: 1) a reactive power compensator; 2) a higher harmonics filter; 3) a balancing device. The quality of APF functioning is evaluated according to certain indices.

Conventional measuring devices do not take into account new requirements to methods of assessment of electric power quality; they use out-dated methods based on the assumption that current and voltage are sinusoidal. It results in considerable errors in calculation of power. Important changes in electrical power engineering that have taken place during the recent 50 years are caused by the following factors [3]: 1) widespread adoption of achievements of electronics in power equipment in the form of power semiconductor devices; 2) discussion in technical literature and further development of the system of terms, definitions, notions, electrical values; 3) operated measuring equipment meant for lines with sinusoidal signals with the frequency of 50/60 Hz; 4) microprocessors and computers enabling performance of complex calculation algorithms, and more and more often being used by manufacturers of measuring instruments to create new, accurate and multifunctional measuring equipment.

The mentioned components are also typical of APF. Generation of an adequate control algorithm is only possible on condition of corresponding assessment of processes in electric power system, i.e. on condition of determination of components of electric power in case of nonlinear, unbalanced load or/and network.

2. RESEARCH MATERIALS

A functional diagram of a three-phase APF in the structure of electric consumption system is given in Fig. 1. APF power part includes a transistor converter *VT1-b*, capacitors *C1*, *C2* and a buffer reactor *L1-3*. Reactor *L1-3* in APF diagram is a current-restricting element that, due to self-induction, provides generation of the assigned current in the process of capacitor charge and discharge. APF assigned current generation block provides calculation and generation of current according to the algorithm. Algorithm of the block operation is based on existing theoretical notions of energy exchange processes in electric circuits. APF control pulse shaping block generates converter switch control voltage corresponding to determined APF assigned current for the present moment in time.

Two basic methods: pulse-width modulation (PWM) and current relay control (CRC) can be distinguished among methods of generation of control impulses for APF converter transistors. Realization of control by PWM method conditions comparison of modulating voltage according to the reference signal of fixed amplitude and frequency. In this case the error is corrected by PI regulator whose parameters are determined according to the optimum operating mode.

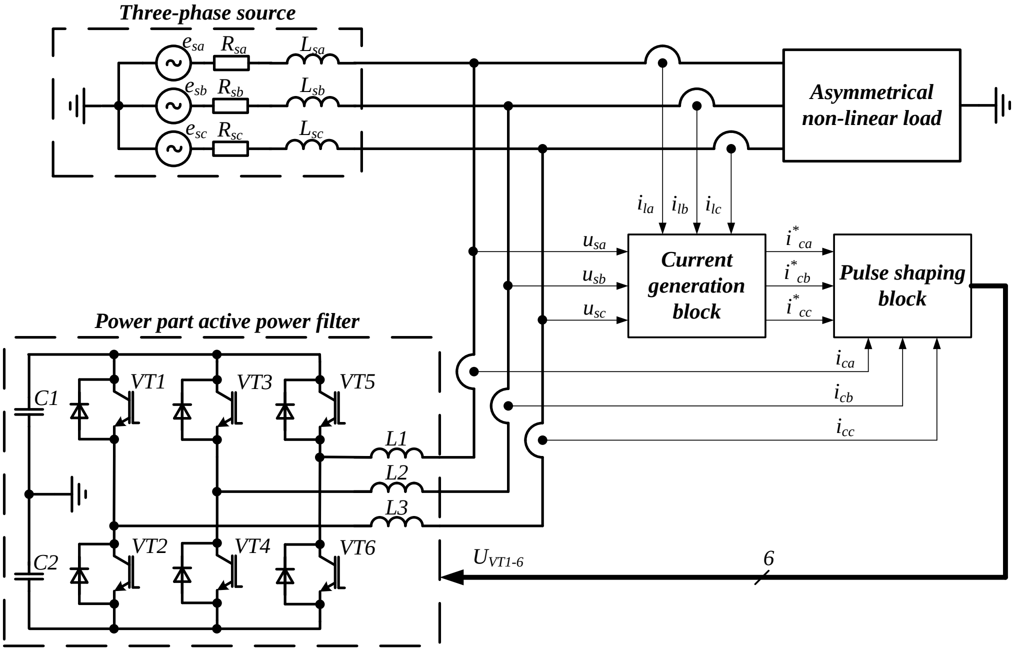

Fig. 1. Functional diagram of a three-phase APF
Rys. 1. Schemat działania trójfazowej APF

As stated in [5], PWM with a PI regulator requires a determined mathematical model of the control object, which is difficult to obtain. Change of the load mode requires recalculation of the coefficients and time constants of the regulator. CRC is characterized by stability, quick response, accuracy, which is caused purely by the power circuit parameters and the values in the hysteresis band of the relay element. The basic fault of CRC consists in variable frequency of commutation caused by constant value of the hysteresis band of the relay element and results in appearance of subharmonics. To eliminate this fault an adaptive current relay control (ACRC) was created [6]. By introduction of current values of capacitor voltages U_{dc1}, U_{dc2} and network voltage u_a, u_b, u_c into the control pulse shaping block generation of the upper and the lower limits of the relay control hysteresis band is provided [6].

Quality of APF operation depends on the applied method of generation of the assigned currents. Methods for determination of the assigned current i^*_c, that are based on *pq*-theory [7, 8] and Fryze theory are commonly used [7, 9].

Using *pq*-theory of power [8], the network instantaneous voltage and the load instantaneous current are transformed into coordinates $\alpha\beta$ by means of Clark transformation:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_{Sa} \\ u_{Sb} \\ u_{Sc} \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{2}$$

where u_{Sa}, u_{Sb}, u_{Sc} – values of the network instantaneous voltage; i_{la}, i_{lb}, i_{lc} – values of the load instantaneous current in coordinates *abc*.

Instantaneous active and reactive power:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

where u_α, u_β – the network instantaneous voltage in coordinates $\alpha\beta$; i_α, i_β – the load instantaneous current in coordinates $\alpha\beta$.

Instantaneous active and reactive powers are presented by two components [8]: constant (average) P, Q and variable $\tilde{p}$, $\tilde{q}$:

$$\begin{gathered} p = P + \tilde{p} \\ q = Q + \tilde{q} \end{gathered} \tag{4}$$

Average active power is determined by integration:

$$P = \frac{1}{T}\int_0^T p\,dt \tag{5}$$

where $p=u_a i_a+u_b i_b+u_b i_c$ –instantaneous active power; T –period of the network voltage.

In general case APF is given functions of compensation for the components of variable active power $\tilde{p}$ and reactive power q. Assigned current of APF in coordinates $\alpha\beta$ [8]:

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{\left(u_\alpha^2 + u_\beta^2\right)} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ q \end{bmatrix} \tag{6}$$

Assigned current of APF in coordinates *abc* is determined by means of Clark inverse transformation [8].

In Fryze theory of power current is resolved into two orthogonal components in the time domain [9]: active i_A and passive i_P:

$$i = i_A + i_P \, , \tag{7}$$

Active power and value of mean-square voltage during period T of the network voltage are determined [9]:

$$P = \frac{1}{T}\int_0^T u \cdot i dt \, , \tag{8}$$

$$U^2 = \frac{1}{T}\int_0^T u^2 dt \, . \tag{9}$$

Then active current according to Fryze [9]:

$$i_A = \frac{P}{U^2} u \, . \tag{10}$$

Current passive component is separated from the load current [9]:

$$i_P = i_{ld} - i_A = i_c^* \, . \tag{11}$$

Determination of electrical values in Fryze theory is demonstrated for a monophasic network; analogous calculations are performed for other phases.

However, the data of the theory are efficient under the condition that the network and the load connected to it are balanced. When the problem of currents balancing occurs in case of unbalance, correction of APF mode is required.

The authors posed a task of singling out current components that reflect unbalance taking into account current distortion. This problem was solved with the help of statements of IEEE 1459-2010 standard [3].

The standard concept [3] consists in separation of the basic component of voltage U_1 and current I_1, from higher harmonics U_h, I_h and singling out the direct sequence components U^+_1, I^+_1 in the fundamental harmonic. In this case active power:

$$\begin{gathered} P = \sum_{a,b,c} \left(P_1 + P_H \right) \\ P = \sum_{a,b,c} \left[U_1 I_1 \cos\theta_1 + \left(U_0 I_0 + \sum_{h \neq 1} U_h I_h \cos\theta_h \right) \right] \end{gathered} \, . \tag{12}$$

where P_1 – active power according to fundamental harmonic; P_H – active power determined by higher harmonics; U_1, I_1 – effective values of voltage and current according to fundamental harmonic; $\theta_1=\alpha_1–\beta_1$, $\theta_h=\alpha_h–\beta_h$ –phase shift of current harmonic in relation to voltage harmonic.

For unbalanced modes an effective voltage is introduced; it is determined by effective values of inter-phase voltages U_{ab}, U_{bc}, U_{ca}, and is presented as effective voltage according to fundamental harmonic U_{e1} and effective voltage of higher harmonics U_{eH}:

$$U_e = \sqrt{\left(U_{ab}^2 + U_{bc}^2 + U_{ca}^2\right)/9} = \sqrt{U_{e1}^2 + U_{eH}^2}\,; \tag{13}$$

$$U_{e1} = \sqrt{\left(U_{ab1}^2 + U_{bc1}^2 + U_{ca1}^2\right)/9}\,;\ U_{eH} = \sqrt{U_e^2 - U_{e1}^2}\,. \tag{14}$$

Effective current is determined in an analogous way by effective values of phases currents I_a, I_b, I_c, and is presented as effective current according to fundamental harmonic I_{e1} and effective current of higher harmonics I_{eH}:

$$I_e = \sqrt{\left(I_a^2 + I_b^2 + I_c^2\right)/3} = \sqrt{I_{e1}^2 + I_{eH}^2}\,; \tag{15}$$

$$I_{e1} = \sqrt{\left(I_{a1}^2 + I_{b1}^2 + I_{c1}^2\right)/3}\,; \tag{16}$$

$$I_{eH} = \sqrt{I_e^2 - I_{e1}^2}\,. \tag{17}$$

Effective total power is divided into effective total power according to fundamental harmonic and inactive total power:

$$S_e = 3U_e I_e = \sqrt{S_{e1}^2 + S_{eN}^2} = \sqrt{\left(3U_{e1}I_{e1}\right)^2 + S_{eN}^2}\,. \tag{18}$$

The latter includes powers caused by distortion of current and voltage respectively D_{eI}, D_{eU} and total power of harmonics S_{eH}:

$$S_{eH} = \sqrt{S_e^2 - S_{e1}^2} = \sqrt{D_{eI}^2 + D_{eU}^2 + S_{eH}^2}\,, \tag{19}$$

$$D_{eI} = 3U_{e1}I_{eH};\ D_{eU} = 3U_{eH}I_{e1};\ S_{eH} = 3U_{eH}I_{eH}\,. \tag{20}$$

To characterize unbalanced mode the total power of imbalance according to fundamental harmonic is used:

$$S_{U1} = \sqrt{S_{e1}^2 - \left(S_1^+\right)^2} = \sqrt{S_{e1}^2 - \left(\left(P_1^+\right)^2 + \left(Q_1^+\right)^2\right)}\,, \tag{21}$$

where S^+_1, P^+_1, Q^+_1 – total, active and reactive powers of direct sequence according to fundamental harmonic:

$$P_1^+ = U_1^+ \cdot I_1^+ \cdot \cos\left(\theta_1^+\right), \tag{22}$$

$$Q_1^+ = U_1^+ \cdot I_1^+ \cdot \sin\left(\theta_1^+\right), \tag{23}$$

where U^+_1, I^+_1 – direct sequence voltage and current; θ^+_1 – angle of phase displacement of voltage and current [3].

Power coefficient is divided and it is determined separately for effective total power and direct sequence total power:

$$PF = P / S_e\,, \tag{24}$$

$$PF_1^+ = P_1^+ / S_1^+\,, \tag{25}$$

Based on the above stated, the authors propose two variants of correction of APF assigned current depending on the causes of unbalance. The algorithm of generation of the assigned current is based on postulates of Fryze theory as it operates separately with phase current. Besides, it is simple to understand, realize, has been approbated for many years, has become popular with scientists and correlates with methods applied by researchers for determination of electrical values without performance of additional vector transformations.

Variant 1, when three-phase unbalanced nonsinusoidal load is connected to a three-phase balanced sinusoidal network. In this case active power is determined according to expression (11), and APF assigned current is determined taking into account:

$$i_c^* = i_{ld} - i_A = i_{ld} - \left[\left(P_1^+ / U_{rms}^2 \right) u_s \right], \tag{26}$$

where i_{ld} – load current; i_A – active current according to Fryze theory; U^2_{rms} – mean-square value of the network voltage; u_s – value of the network instantaneous power.

Variant 2, when three-phase unbalanced nonsinusoidal load is connected to an unbalanced three-phase network. In this case, as previous experiments demonstrate, it is insufficient to balance active power of the network by its determination through direct sequence power according to fundamental harmonic (11). It is proposed to single out direct sequence current from the obtained active current according to Fryze i_A:

$$i_c^{**} = i_{ld} - i_{1A}^+ = i_{ld} - \left[\left(P_1^+ / U_{rms}^2 \right) \cdot u_s \right]_1^+. \tag{27}$$

where i^+_{1A} – fundamental harmonic direct sequence active current according to Fryze theory:

$$i_{1A}^+ = \frac{1}{3}\left(i_{Aa} + a \cdot i_{Aa} + a^2 \cdot i_{Aa} \right), \tag{28}$$

where i_{Aa}, i_{Ab}, i_{Ac} – active current according to Fryze theory for phases a, b, c; a – operator of phase $a=e^{j2\pi/3}$, $a^2=e^{j4\pi/3}$.

To research the proposed solutions when APF operates according to the diagram (Fig. 1), model [6] has been created and it contains additional calculation blocks according to expressions (12-28). The model in visual environment Matlab/Simulink, of a three-phase APF with an ACRC in the electric power system is shown in Fig. 2.

A model of an electric power system with a three-phase active power filter (Fig. 2) includes: a three-phase source (*Three-Phase source*) with equivalent active and inductive supports, three-phase nonlinear load – a three-phase thyristor converter (*Thyristor converter*) with active-inductive load *(RL-load*) connected to three-phase electric network through a three-phase reactor (*Reactor1*), a three-phase transistor converter (*Transistor converter*), a block of generation of the assigned current (*Current generation block*) of the active power filter and a pulse shaping block (*Pulse shaping block*). To obtain power parameters of the system according to IEEE 1459-2010 standard, blocks *Qualitive source*, *Qualitive load* are created.

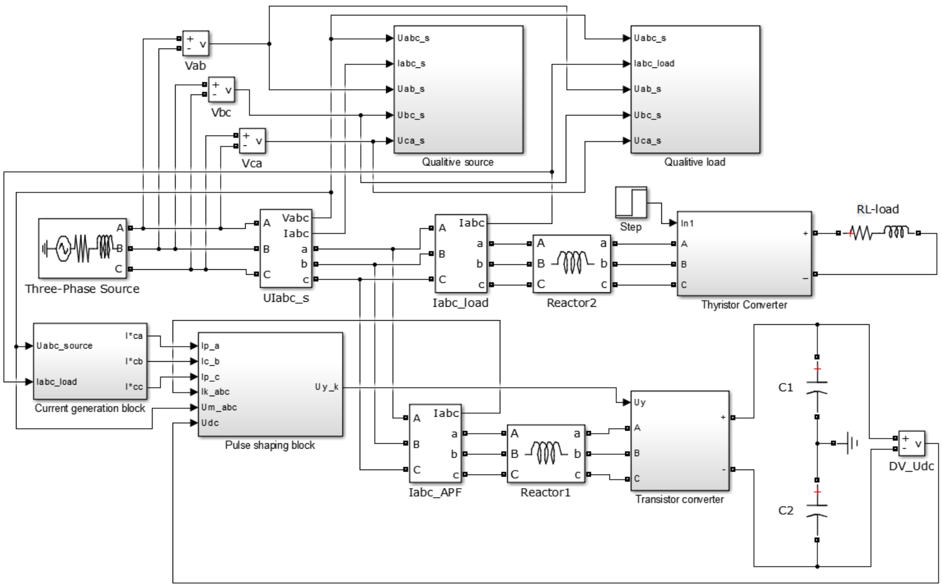

Fig. 2. Mathematical model of a three-phase active power filter with an adaptive current relay control
Rys. 2. Model matematyczny trójfazowego aktywnego filtra z adaptacyjnym sterowaniem przekaźnikowym

The diagram elements parameters are calculated on the following basis: three-phase nonlinear load of calculation power *P=38 kW, Q=66 kVAr* – three-phase thyristor converter with active-inductive load R_{ld}=2 *Ohm*; L_{ld}=0,0116 *H*. Electric power is supplied from a three-phase electric network with nominal voltage U_s=380 *V* and nominal frequency 50 *Hz.* Equivalent active and reactive supports of the network are calculated on the basis of acceptable loss of voltage on them in the amount of 7 %. According to method [5] parameters of the elements of the three-phase active power filter are calculated: frequency of commutation of converter transistors f_c=15000 *Hz*; value of inductance of active power filter reactor *L*=0.0054 *H*; value of capacitors capacity $C1=C2=40\cdot10^{-3}$ *F*; value of capacitors voltage $U_{dc1}= U_{dc2}$=1000 *V*. Common output of two capacitors *C*1 and *C*2 connected in series is grounded (Fig. 1, Fig. 2).

To assess the influence of algorithms of generation of three-phase active power filter assigned current a series of experiments on research of electrical and power parameters of the mode of the system: electric network – three-phase nonlinear load – three-phase active power filter were carried out for variants given in table 1.

Nonlinear load in model [6] is realized by a thyristor rectifier, load unbalance (*NUL*) is provided by means of introduction of active resistance of 4500 *W* into phase *a*. Voltage unbalance of power supply (*LUG, NUG*) is introduced into phase *a* by amplitude of 38 *V*, network voltage nonsinusoidality (*NUG*) is performed by voltage third harmonic of the amplitude of 30 *V*.

3. MODELING RESULTS

During the research the following oscillograms were obtained: an oscillogram of the network unbalanced voltage (Fig. 3, *a*), of the load unbalanced current (Fig. 3, *b*), network current when Fryze theory is used (Fig. 3, *c*) and when Fryze theory algorithm correction is used (Fig. 3, *d*).

The research was carried out at the thyristor converter control angle equal to $\alpha=45^0$

Table 1

A series of experiments on research of electrical and power parameters of the mode of the system: network – load – active power filter

No.	Configuration	Algorithm of APF assigned current
1	sinusoidal balanced voltage – nonlinear balanced load (LBG-NBL)	Fr – Fryze theory PQ – pq theory MF – correction of Fryze theory
2	sinusoidal balanced voltage – nonlinear unbalanced load (LBG-NUL)	
3	sinusoidal unbalanced voltage – nonlinear balanced load (LUG-NBL)	
4	sinusoidal unbalanced voltage – nonlinear unbalanced load (LUG-NUL)	
5	nonsinusoidal unbalanced voltage – nonlinear unbalanced load (NUG-NUL)	

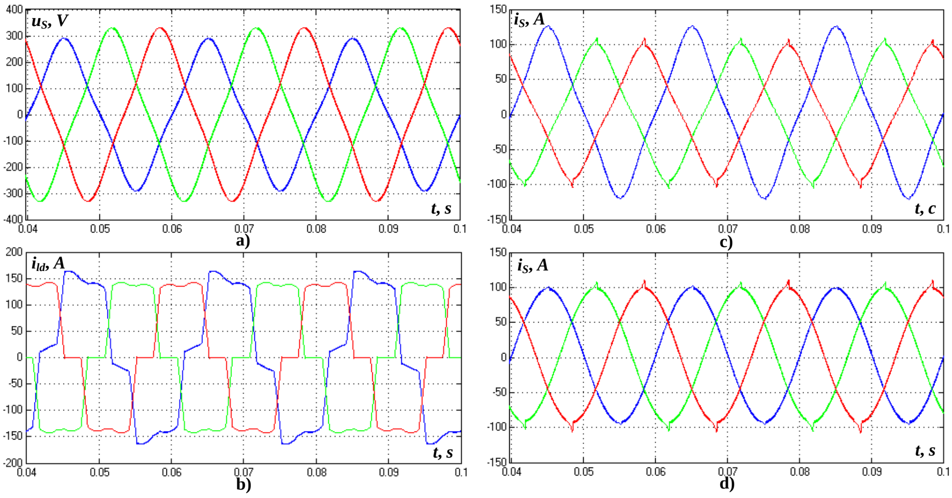

Fig. 3. Oscillograms: a) network unbalanced voltage u_S; b) load unbalanced current i_{ld}; c) network current i_S when Fryze theory is used; d) network current i_S when algorithm correction is used

Rys. 3. Oscylogramy: a) sieci niesymetrycznych napięć u_S; b) prąd i_{ld} biorąc pod uwagę obciążenia niesymetryczne; c) prąd sieciowy i_S, gdy jest używana teoria Fryzego; d) prąd sieciowy i_S, gdy jest używany algorytm korekcji

The obtained oscillograms (Fig. 3) demonstrate that application of Fryze theory, when nonsinusoidality of the network unbalanced voltage and the load unbalanced current appear, is not taken into account and results in deterioration of the electric network operation as the phase in which unbalance occurs is loaded additionally (Fig. 3, *c*). The proposed correction of the algorithm of the Fryze theory of voltage (Fig. 3, *d*) performs balancing of currents in the network. The following indices are chosen for assessment of APF operation (Fig. 4), network parameters are indicated as "*s*", and load – as "*ld*":

- efficiency of reduction of direct sequence reactive voltage according to the fundamental harmonic (Fig. 4, a) $\varepsilon_Q = \left[\left(Q^+_{1ld} - Q^+_{1s}\right)/Q^+_{1ld}\right]\cdot 100\%$;
- decrease of the coefficient of distortion of the current curve sinusoidality (Fig. 4, b) $\varepsilon_{THDi} = \left[\left(THD_{eI\_ld} - THD_{eI\_s}\right)/THD_{eI\_ld}\right]\cdot 100\%$;
- decrease of the power of the network current distortion DeI (Fig. 4, c) $D_{eI} = \left[\left(D_{eI\_ld} - D_{eI\_s}\right)/D_{eI\_ld}\right]\cdot 100\%$;
- decrease of the power of unbalance (Fig. 4, *d*) $S_{U1} = \left[\left(S_{U1\_ld} - S_{U1\_s}\right)/S_{U1\_ld}\right]\cdot 100\%$;
- coefficient of harmonic distortions (Fig. 4, e) $K_{HP} = \left(S_{eN}/S_e\right)\cdot 100\%$;
- coefficient of unbalance (Fig. 4, f) $K_{AL} = \left(S_{U1}/S^+_1\right)\cdot 100\,\%$.

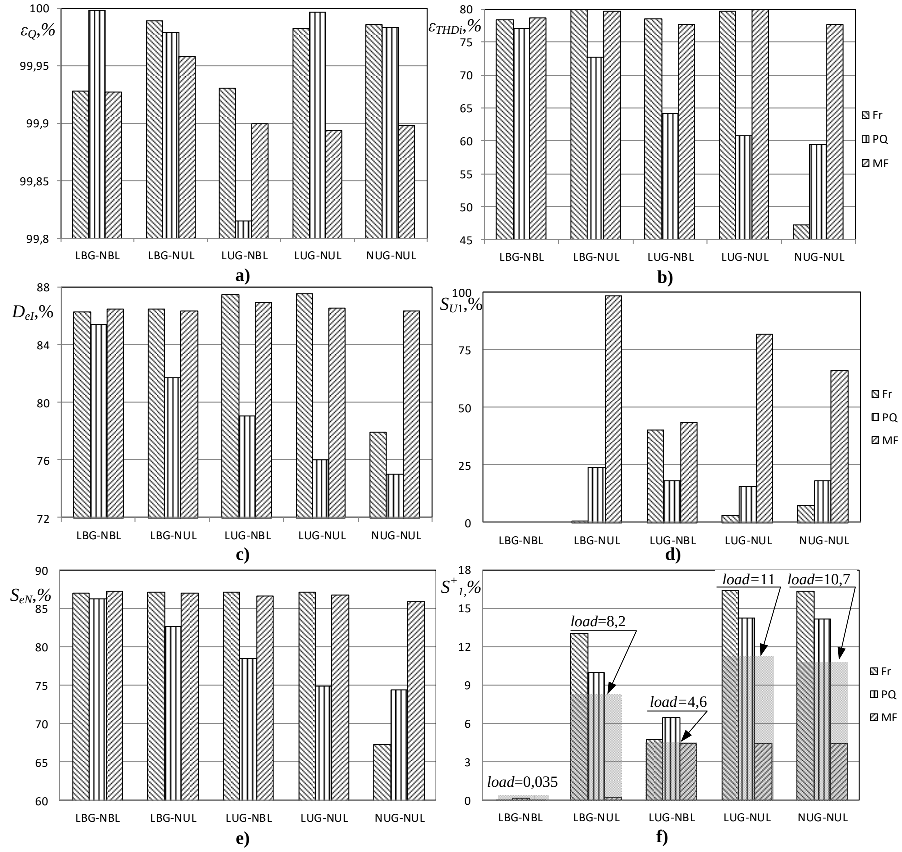

Fig. 4. Diagrams according to IEEE 1459-2010 standard: a) efficiency of reduction of direct sequence reactive voltage; b) reduction of non-sinusoidal components in the current curve; c) decrease of the power of the network current distortion; d) decrease of the power of unbalance; e) coefficient of harmonic distortions; f) coefficient of unbalance

Rys. 4. Diagramy według standardu IEEE 1459-2010: a) efektywności redukcji bezpośredniej sekwencji biernej napięcia; b) redukcja niesinusoidalnych składników bieżącej krzywej; c) spadek mocy sieci prądu zniekształceń; d) zmniejszenie mocy niesymetryczne; e) współczynnik zniekształceń harmonicznych; f) współczynnik niewyważenia

Efficiency of compensation for direct sequence reactive voltage according to the fundamental harmonic (Fig. 4, *a*) makes >99 % for all algorithms of generation of APF assigned current in all load combinations. Presence of higher harmonics, unbalance, as is obvious in Fig. 4, *b*, reduce efficiency of algorithms *Fr* and *PQ* to a level below 60 %, unlike algorithm *MF* (77 %). An analogous tendency can be seen in assessment of the power of distortion of current D_{eI} by harmonics (Fig. 4, *c*). Rather high indices mark the proposed algorithm *MF* (42-94)%, against a background of algorithms *Fr* and *PQ*, when unbalance coefficient is assessed (Fig. 4, *f*). Decrease of total negative influence (Fig. 4, *e*) as compared with indices (Fig. 4, *c*) has the same tendency. It is confirmed by the values of unbalance coefficient (Fig. 4, *f*), for which it increases for practically all configurations and algorithms *Fr* and *PQ* except algorithm *MF*.

4. CONCLUSIONS

Under the conditions of balanced voltage of the network and balanced load the algorithm of generation of APF current realized on the basis of Fryze theory of voltage or *pq* theory, provides a high degree of compensation for reactive power ε_Q>99 %, decrease of harmonics level ε_{THD}>75 %, but in the presence of unbalance these indices are reduced. Methods of determination of power components, in particular, direct sequence power, stated in IEEE 1459-2010 standard, are used for correction of the algorithm of APF assigned current generation under the conditions of unbalance.

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