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IMPROVEMENT OF THE METHOD FOR ASSESSING LOAD REACTIVITY BASED ON ENERGY FLOWS WITHIN A SINGLE VOLTAGE PERIOD

The object of this research is the process of assessing reactance and compensating for reactive power in single-phase electrical networks containing both linear and nonlinear loads.

The problem addressed is the limited applicability of classical reactive power definitions based on the fundamental harmonic when current waveforms are distorted by nonlinear loads, which complicates correct reactive power assessment and compensation control.

An energy-based approach for estimating load reactance is proposed. The method introduces a dimensionless reactance coefficient determined from the ratio between the energy value over one voltage period and the total area of instantaneous energy flow components associated with the bidirectional energy exchange between the source and the load. For sinusoidal conditions, an analytical relationship between this coefficient and the phase shift angle between voltage and current is obtained. This relationship allows reconstruction of the phase shift angle from discrete voltage and current measurements using Newton's iterative method.

To validate the method, a simulation model of a single-phase electrical network with linear and nonlinear loads was developed in the Simulink environment. Simulations were performed for linear, nonlinear, and mixed operating modes with different ratios of active and reactive power.

The results show that when the nonlinear load dominates or when the capacitive reactive component of the linear load is small, compensation based on the proposed criterion provides higher power factor values than the classical reactive power approach. For loads with a significant inductive component the classical method remains more effective. The proposed improved method can be applied in power quality monitoring systems and adaptive reactive power compensation devices for networks with nonlinear loads.

Keywords: *reactive power, power factor, harmonic, energy flows, electrical network, power system.*

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1. Introduction

Modern power systems are characterized by a significant proportion of nonlinear loads – frequency converters, rectifiers, pulse power supplies, PWM-controlled electric drives, etc. Such consumers generate non-sinusoidal currents and voltages in the network, which leads to increased losses, deterioration of power quality indicators, and complicates the correct distribution of responsibility between the supplier and the consumer. Under these conditions, traditional approaches to determining reactive power, based on the analysis of only the fundamental harmonics of voltage and current, can give conflicting results and not reflect the actual energy exchange mode between the source and the load.

A separate practical problem is the choice of the target indicator by which reactive power compensators are adjusted. In traditional schemes, compensation is mainly focused on minimizing the reactive power of the fundamental harmonic or on achieving a specified power factor. In the presence of a strong harmonic component, such criteria can lead to undercompensation or, conversely, to excessive (in particular, capacitive) compensation, which worsens the operating mode of the network. Therefore, it is important to identify dimensionless energy indicators that are directly related to energy flows over a period of time and can be used as a universal criterion for comparing different modes.

The research focuses on a single-phase network with linear and nonlinear loads. Additionally, the corresponding equivalent reactive power is compared with the classical first-harmonic definition.

The problem of correctly determining active, reactive, and inactive power in networks with non-sinusoidal voltages and currents has been discussed for more than a decade. The adopted IEEE Std 1459–2010 standard systematizes the definition of electrical power for single- and three-phase systems in sinusoidal and non-sinusoidal modes [1]. It proposes new expressions for total, active, and reactive power, as well as for the power factor. A detailed summary of these definitions confirms their suitability for implementation in modern measuring devices [2]. This standard is the result of the long-term work of a special IEEE committee created to review the classical definitions of reactive power in distorted modes.

The classical approaches of Budeanu and Fryze are based on the decomposition of instantaneous power. They introduce the concept of reactive power. These methods are mathematically correct. However, they give ambiguous results in the presence of significant harmonics. Different power theories interpret energy processes in a circuit differently. The physical fundamentals of electrical systems demonstrate these theoretical discrepancies [3]. Furthermore, geometric algebra analysis reveals limitations in traditional non-sinusoidal power definitions [4]. Consequently, comprehensive surveys confirm that these classical theories do not always provide unambiguous recommendations for compensation [5]. One of the most influential modern approaches is L. Czarnecki's currents' physical components (CPC) theory. This framework decomposes current into physically meaningful active, reactive, and deformation components [6]. Furthermore, the corresponding power elements are directly associated with these specific current components to interpret reactive power [7]. These works also critically examine the popular interpretation of reactive power as simply "energy oscillating between the source and load during a period" and emphasize the need for a more cautious interpretation in complex non-sinusoidal modes.

Other energy-oriented power theories are being developed in parallel. In [8], a new definition of reactive power for non-sinusoidal multiphase systems is proposed based on the minimization of "non-reactive" components of the load current. Several studies review the classical definitions of non-active power and their modern adaptations [5]. Other works specifically extend Fryze's approach to assess waveform distortion [9]. Together, these methods help estimate the contribution of individual consumers to the formation of reactive power. In [4], geometric algebra is used to describe the interaction of voltage and current in non-sinusoidal modes, and it is shown that traditional approaches (Budeanu, Fryze, IEEE 1459) may be insufficient for the correct separation of reactive power by individual physical mechanisms.

Another research area focuses on methods for detecting and identifying sources of harmonics and power quality disturbances. The review [10] classifies methods for detecting harmonic sources by active power direction, reactive power, and voltage-current ratio, and analyzes their advantages and limitations. In [11], the experience of using various indices (THD, Euclidean norm, node harmonic current modulus) to identify multiple sources of distortion in electrical networks is summarized. In [12], techniques for localizing sources of power quality disturbances using spectral analysis, harmonic flows, and various disturbance source indicators are considered. In [13], a time-domain approach to localizing harmonic sources and evaluating their contribution under complex network conditions is proposed.

In recent years, significant attention has been devoted to analyzing energy flows over a single oscillation period. Specifically, dissipating energy flow methods are used to localize sources of forced oscillations [14]. These approaches evaluate the energy increment over one period to identify the disturbance source by its sign and magnitude. However, under certain conditions, these methods can falsely indicate untrue sources [14]. This issue has stimulated further improvements, such as adapting localization techniques for networks with harmonic interference [15]. Additionally, practical measurement instruments now use math channels for analyzing such power variations [16]. Other enhancements include the use of empirical mode decomposition algorithms, which have been implemented for shunt active filters [17]. Finally, similar empirical mode operators are successfully applied in broader power system stability studies [18]. Similar ideas of the energy approach are also used in the tasks of localizing sources of harmonics and voltage quality disturbances, where the analysis of harmonic and energy flows is discussed in detail in the review [12].

In practical power quality monitoring instruments, there is also a tendency to estimate power and power factor based on the integration of instantaneous power over separate periods. In modern digital meters, reactive power is often determined as the average of a set of values calculated "per period" – thus, by integrating instantaneous power within one voltage cycle and then averaging [16]. At the same time, technical and educational literature continues to provide an intuitive interpretation of reactive power [19]. It is often described as energy alternately accumulated and returned by inductive and capacitive elements during a period. However, recent works note that this interpretation is not always sufficient to describe complex non-sinusoidal modes.

In this context, the proposed approach belongs to the class of energy-oriented methods. It introduces a reactance coefficient determined by energy flows within a single voltage period to estimate the equivalent reactive power. Specifically, this method focuses on the compensation and isolation of the linear load component in mixed modes.

The approach proposed in this work belongs to the class of energy-oriented methods. It links load reactance to the energy exchange between the source and consumer within a single instantaneous power period. Similar ideas exist that integrate instantaneous power separately during positive and negative intervals. For example, one method introduces "positive" and "negative" energies per half-period [20]. Based on these values, active and reactive energies, as well as the phase shift angle, are determined from single-period characteristics. Another time-domain method evaluates reactive energy by directly summing instantaneous power readings to measure this energy exchange [21]. In [21], reactive energy is interpreted as a measure of energy exchange between the generator and the reactive component of the load within one period of instantaneous power, and the evaluation is performed directly in the time domain by summing the instantaneous power readings.

However, despite the diversity of existing approaches, there is still no universal indicator that ensures high efficiency of reactive power compensation under conditions of waveform distortion caused by nonlinear loads. This highlights the need to improve load reactance estimation approaches and substantiates the development of alternative criteria based on the analysis of energy processes in the time domain.

The relevance of the research is driven by the rapid growth of nonlinear loads, which distort power system waveforms. In these non-sinusoidal modes, traditional first-harmonic methods become inaccurate, causing inefficient reactive power compensation. Therefore, improving load reactance estimation based on single-period energy flows is a highly relevant task. It ensures the accurate isolation of the reactive component and optimizes the power factor.

The object of the research is the process of assessing reactance and compensating for reactive power in single-phase electrical networks containing both linear and nonlinear loads.

The aim of this research is to improve the load reactance estimation method to increase compensation efficiency in non-sinusoidal modes by using a dimensionless coefficient determined from energy flows within a single voltage period.

To achieve this aim, the following tasks were defined:

1. To propose a concept for improving the load reactance estimation method based on energy flows within a single voltage period.
2. To validate the proposed indicator in purely linear and purely nonlinear modes.
3. To analyze the compensation effectiveness for mixed loads compared to the classical method.

2. Materials and Methods

The methodology of this research is based on a combination of theoretical and empirical approaches, incorporating the following scientific methods:

- the mathematical modeling method is used to formalize the relationship between energy flows and load parameters. Specifically, it is applied to derive the integral of instantaneous power $p(t)$ over a single period. By analyzing the areas of positive and negative energy flows. This method enables the analytical separation of the active and reactive components without relying on the traditional vector representation of power;
- numerical analysis methods, specifically the iterative Newton-Raphson algorithm, are utilized for the practical implementation of the proposed modeling approach. These methods are employed to numerically solve the transcendental relationships between the energy ratios and the phase shift angle φ. This ensures high precision in calculating equivalent reactive power using discrete measurement samples within the time domain;

– the computer simulation method is applied to study the operating modes of a single-phase electrical network under complex conditions. Using the MATLAB/Simulink, a detailed simulation model was developed. It includes a sinusoidal voltage source, controllable linear RLC loads, and a nonlinear bridge rectifier with capacitive filtering. This method is essential for generating high-fidelity current and voltage waveforms, providing the raw data for testing the algorithm's sensitivity to harmonic distortions;

– the comparative analysis method serves as the final verification tool to evaluate the effectiveness of the proposed criteria. It is used to contrast the power factor achieved through the proposed reactance coefficient against the results obtained from the classical first-harmonic reactive power definition. By analyzing the compensation error across various mixed-load scenarios, this method identifies the boundaries of applicability for each approach.

3. Results and Discussion

3.1. Proposed concept of the improved load reactance estimation method

Unlike the methods analyzed in the introduction, the proposed approach introduces a dimensionless reactance coefficient K defined as

$$K=1-\left(\frac{A_t}{A_{sm}}\right)^2, \qquad (1)$$

where A_t – the energy value per period, and $A_{sm} = A_{ps} - A_{ng}$ – the total area of the energy flow components. For the sinusoidal mode, an explicit analytical dependence is obtained $K(\varphi)$, which allows the phase shift angle φ to be numerically restored based on experimental values K^* without spectral analysis. Additionally, it is shown that such a coefficient can be used as a tool for isolating the reactive component of the linear part of the load in mixed linear-nonlinear mode, which is not directly considered in the cited works.

Let the voltage and current be purely sinusoidal and described as:

$$u(t)=U_m\sin(\omega t), \qquad (2)$$

$$i(t)=I_m\sin(\omega t+\varphi). \qquad (3)$$

Instantaneous power

$$p(t)=U_mI_m\sin(\omega t+\varphi)\sin(\omega t)= \\ =\frac{U_mI_m}{2}\big(\cos\varphi-\cos(2\omega t+\varphi)\big). \qquad (4)$$

Moments when the power changes sign:

$$p(t)=0\Rightarrow\sin(\omega t)=0 \text{ or } \sin(\omega t+\varphi)=0, \qquad (5)$$

that is:

$$t=0\pm\frac{\pi k}{\omega}, \\ t=-\frac{\varphi}{\omega}\pm\frac{\pi k}{\omega}, \\ k\in\mathbb{Z}. \qquad (6)$$

Positive part of energy per period

$$A_{ps}=\int_0^{\frac{\pi-\varphi}{\omega}}p(t)\mathrm{d}t= \\ =\int_0^{\frac{\pi-\varphi}{\omega}}\frac{U_mI_m}{2}\big(\cos\varphi-\cos(2\omega t+\varphi)\big)\mathrm{d}t. \qquad (7)$$

Considering:

$$\int\frac{U_mI_m}{2}\big(\cos\varphi-\cos(2\omega t+\varphi)\big)\mathrm{d}t= \\ =\frac{U_mI_m}{4\omega}\big(2\omega t\cos\varphi-\sin(2\omega t+\varphi)\big), \qquad (8)$$

it is obtained that

$$A_{ps}=\frac{U_mI_m}{4\omega}\big(2\omega t\cos\varphi-\sin(2\omega t+\varphi)\big)\Big|_0^{\frac{\pi-\varphi}{\omega}}= \\ =\frac{U_mI_m}{2\omega}\big(\sin\varphi+\pi\cos\varphi-\varphi\cos\varphi\big). \qquad (9)$$

Total energy for the period

$$A_t=\frac{\pi}{2\omega}U_mI_m\cos\varphi. \qquad (10)$$

Total area of energy components (total back-and-forth flow)

$$A_{sm}=A_{ps}-A_{ng}=\frac{U_mI_m}{2\omega}\big(2\sin\varphi+\pi\cos\varphi-2\varphi\cos\varphi\big). \qquad (11)$$

The reactance coefficient is defined as the ratio

$$K=1-\left(\frac{A_t}{A_{sm}}\right)^2= \\ =\frac{4\big(\sin\varphi-\varphi\cos\varphi\big)\big(\sin\varphi+\pi\cos\varphi-\varphi\cos\varphi\big)}{\big(2\sin\varphi+\pi\cos\varphi-2\varphi\cos\varphi\big)^2}. \qquad (12)$$

Expression (12) shows that the values of voltage and current amplitudes, as well as the frequency value, are reduced, i. e., the reactance coefficient depends solely on the phase difference between voltage and current. The graph of the dependence of $K(\varphi)$ at $\varphi \geq 0$ is shown in Fig. 1. When the shift direction is negative, the curve is mirrored relative to the axis $\varphi = 0$. This ratio forms the basis for subsequent analysis.

Indicators for comparing the proposed method.

The power factor is used to evaluate the effectiveness of compensation

$$PF=\frac{P}{S}=\frac{P}{I_{RMS}U_{RMS}}, \qquad (13)$$

where P – the active power; S – the total power; I_{RMS} – the effective current value; U_{RMS} – the effective voltage value.

Two approaches to reactive power assessment:

– "Classic" reactive power according to the first harmonic

$$Q_c=Q_1=V_1I_1\sin\theta_1, \qquad (14)$$

where V_1 – the effective value of the first harmonic voltage; I_1 – the effective value of the first harmonic current; θ_1 – the phase shift between them.

– Equivalent reactive power according to the reactance coefficient

$$Q_r=I_{RMS}U_{RMS}\sin(\varphi), \qquad (15)$$

where the angle φ is obtained from relation (12). In turn, $K(\varphi)$ is determined from experimental data (discrete energy flows), as described below.

Computer modeling was used to verify the effectiveness of the proposed approach. Fig. 2 shows a model implemented in the Simulink/Simscape Power Systems environment. The model is designed to study the operating modes of a single-phase AC network with linear and nonlinear loads.

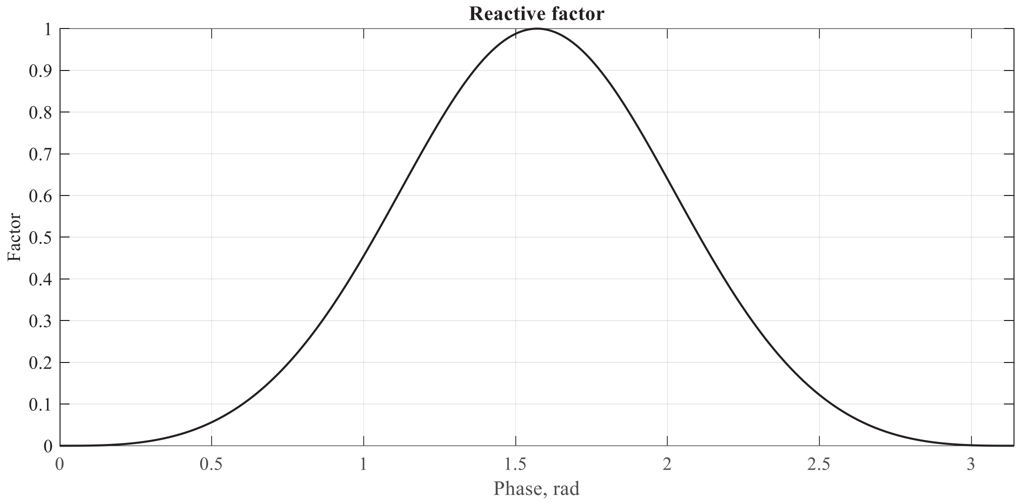

Fig. 1. Curve of the K ratio at $\varphi \geq 0$

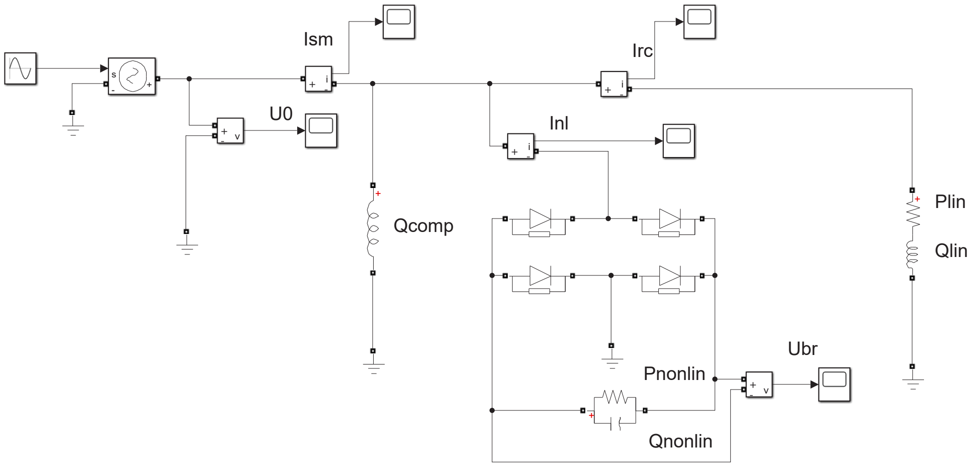

Fig. 2. Model of a single-phase network with linear and nonlinear loads in the Simulink environment

The circuit includes:
- a controlled sinusoidal voltage source (Controlled Voltage Source block with a control signal from the Sine Wave block);
- linear loads of the series RLC type (Plin and Qlin blocks);
- a nonlinear load based on diodes and a parallel RLC circuit Pnonlin Qnonlin;
- current and voltage measurement devices (Voltage Measurement, Current Measurement);
- oscilloscopes for visualization (Scope, Scope1–Scope4).

A nonlinear load formed by a diode bridge and a parallel RLC circuit (Pnonlin, Qnonlin) is modeled as a consumer with an active power of 1 kW and a significant reactive (capacitive) component of 5 kVar. This leads to a pronounced non-sinusoidal current mode, allowing analysis of its effect on the source current waveform and overall circuit performance. Even with a sinusoidal voltage at the input, the current of a nonlinear consumer is significantly distorted.

Fig. 3 shows typical oscillograms, where: U_0 – power supply voltage; U_{br} – voltage after the rectifier; I_{sm} – total current of the mixed load (source current); I_{nl} – current of the nonlinear load; I_{rc} – current of the linear active-reactive load.

Subsequently, based on the obtained time-domain signals of current and voltage, the calculation K^* and the restoration of the angle φ from discrete data are performed.

Based on the simulation results, the voltage and current are represented by arrays of readings over the analysis interval (one period)

$$u[n],\ i[n],\ n=1,2,\ldots,N. \tag{16}$$

Discrete instantaneous power

$$p[n]=u[n]\cdot i[n]. \tag{17}$$

The sums of the "positive" and "negative" parts of the power are calculated:

$$ps=\sum_{n=1}^{N}\max(p[n],0),$$
$$ng=\sum_{n=1}^{N}\min(p[n],0). \tag{18}$$

The formulas given correspond to numerical integration using the rectangle method. For a sufficiently large N, the error is small and has practically no effect on the result. The model uses a sampling frequency of 12800 Hz, which corresponds to (N = 256) readings per period. This is sufficient to ensure that the error in calculating the areas is negligible.

If necessary, physical energies can be estimated as:

$$A_{ps}\approx T_s\cdot ps,$$
$$A_{ng}\approx T_s\cdot ng, \tag{19}$$

but in further relations, the factor T_s is reduced, so in the actual algorithm, it is advisable to operate with the sums (20) without explicit multiplication by T_s.

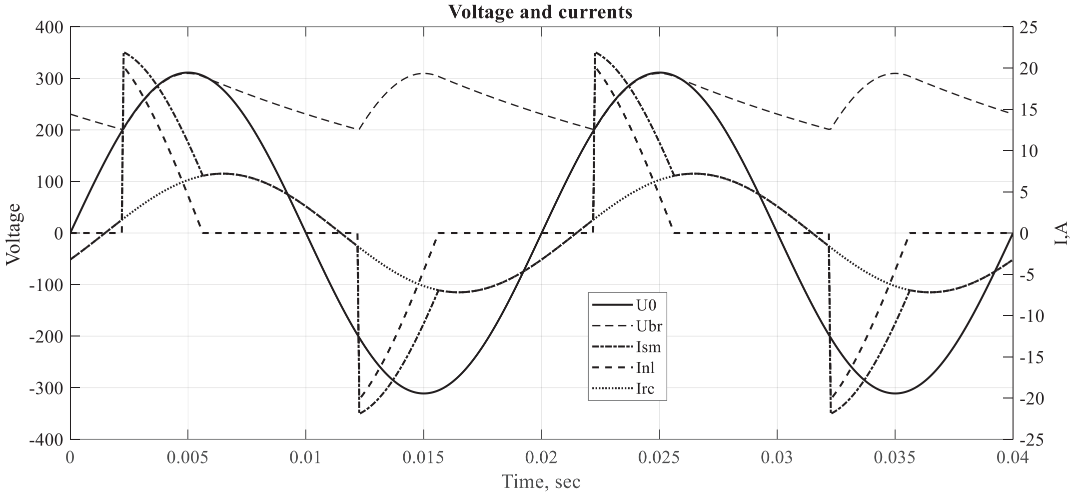

Fig. 3. Oscillograms of currents and voltages in the model

Similarly to (10)–(12), the following estimates are formed:

$$A_t=A_{ps}+A_{ng},\\ A_{sm}=A_{ps}-A_{ng}, \tag{20}$$

which is consistent with the definition in (11).

Then the discrete estimate of the reactance coefficient is

$$K^*=1-\left(\frac{A_t}{A_{sm}}\right)^2=1-\left(\frac{ps+ng}{ps-ng}\right)^2. \tag{21}$$

Next, φ is calculated using Newton's method

$$K(\varphi)=K^*. \tag{22}$$

The following constraint is introduced

$$F(\varphi)=K(\varphi)-K^*. \tag{23}$$

Newton's iteration formula

$$\varphi_{n+1}=\varphi_n-\frac{F(\varphi_n)}{F'(\varphi_n)}=\varphi_n-\frac{K(\varphi_n)-K^*}{K'(\varphi_n)}. \tag{24}$$

Initial approximation

$$\varphi_0=\frac{\pi}{4}. \tag{25}$$

Stopping criterion:

$$\left|\Delta\varphi_n\right|\leq\varepsilon,\ \varepsilon=10^{-4}, \tag{26}$$

where $\Delta\varphi_n$ is

$$\Delta\varphi_n=\frac{K(\varphi_n)-K^*}{K'(\varphi_n)}. \tag{27}$$

To calculate the derivative $K'(\varphi)$, auxiliary functions are introduced:

$$a(\varphi)=\sin\varphi-\varphi\cos\varphi,\\ b(\varphi)=\sin\varphi+\pi\cos\varphi-\varphi\cos\varphi,\\ c(\varphi)=2\sin\varphi+\pi\cos\varphi-2\varphi\cos\varphi. \tag{28}$$

Their derivatives:

$$a'(\varphi)=\varphi\sin\varphi,\\ b'(\varphi)=(\varphi-\pi)\sin\varphi,\\ c'(\varphi)=(2\varphi-\pi)\sin\varphi. \tag{29}$$

The logarithmic derivative gives

$$K'(\varphi)=K(\varphi)\left(\frac{a'(\varphi)}{a(\varphi)}+\frac{b'(\varphi)}{b(\varphi)}-2\frac{c'(\varphi)}{c(\varphi)}\right). \tag{30}$$

Substituting (29), the explicit form follows as:

$$K'(\varphi)=K(\varphi),\\ \sin\varphi\left(\begin{array}{l}\dfrac{\varphi}{\sin\varphi-\varphi\cos\varphi}+\dfrac{\varphi-\pi}{\sin\varphi+\pi\cos\varphi-\varphi\cos\varphi}-2,\\ \dfrac{2\varphi-\pi}{2\sin\varphi+\pi\cos\varphi-2\varphi\cos\varphi}\end{array}\right). \tag{31}$$

Thus, the inverse transformation is calculated $K^*\rightarrow\varphi$, where φ is found iteratively according to (24)–(31) until condition (27) is satisfied.

3.2. Validation of the proposed indicator in purely linear and purely nonlinear modes

In order to compare the efficiency of reactive power compensation using the traditional approach via Q_c and the proposed reactance coefficient via Q_r, a series of simulations were performed with different values of active and reactive load components.

During the modeling process, the value of Q_{comp} – the power of the reactive power compensator, was varied in the range from –2000 var to +2000 var (transition from capacitive to inductive compensation). The effectiveness of compensation was assessed by the power factor PF.

Fig. 4 shows the simulation results in the absence of a nonlinear load (case 1), i. e., the following parameters are used: P_{lin} = 1000 W, Q_{lin} = 1000 var, P_{nonlin} = 1 W, Q_{nonlin} = 1 var. Both indicators Q_c and Q_r – correctly reflect the presence of a reactive component and acquire a zero value at the point of full compensation. Over a significant part of the range, the curves practically coincide, which indicates the adequacy of the proposed model in the case of a linear load.

Case 2 – exclusively nonlinear load.

Modeling parameters: P_{lin} = 1 W, Q_{lin} = 1 var, P_{nonlin} = 1000 W, Q_{nonlin} = 5000 var (Fig. 5). In this case, the maximum power factor is $PF \approx 0.63$. Compensation based on Q_r results in $PF \approx 0.618$, and for Q_c – only $PF \approx 0.587$. Therefore, in the absence of a linear component, the method based on Q_r demonstrates higher effectiveness.

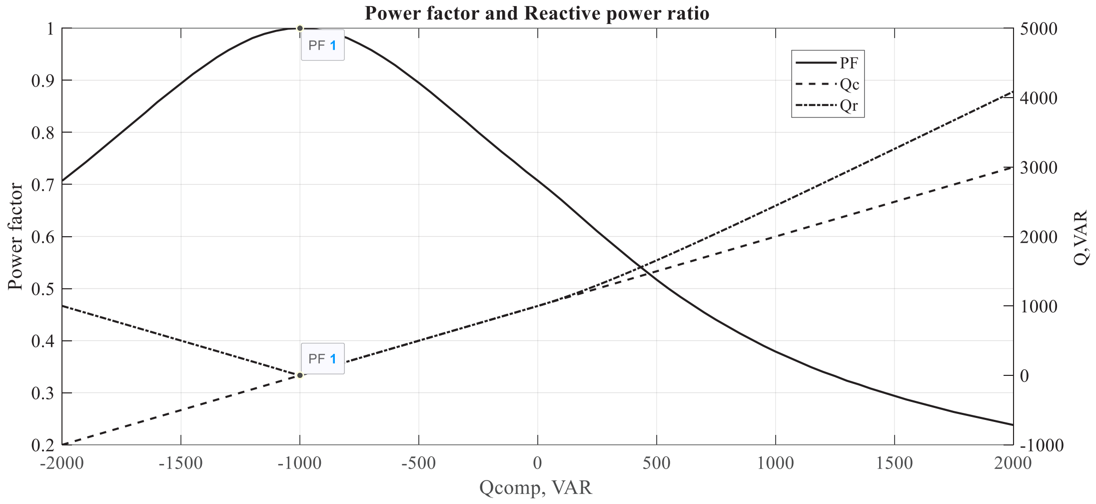

Fig. 4. Simulation results in the absence of nonlinear load

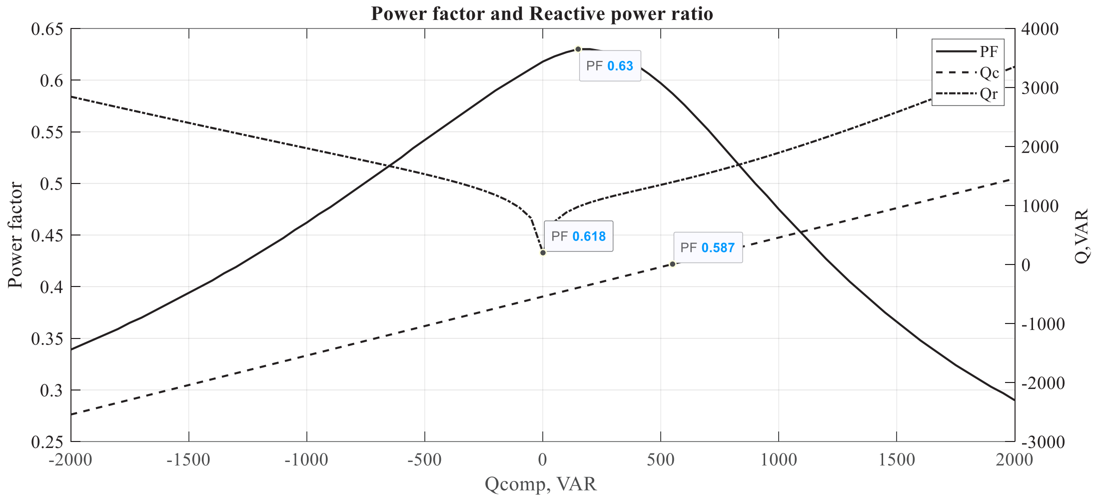

Fig. 5. Simulation results in the absence of linear load

3.3. Analysis of the compensation effectiveness for mixed loads compared to the classical method

In the third case, a dominant nonlinear load is considered in the absence of a reactive component of the linear part.

Model parameters: $P_{lin} = 1000$ W, $Q_{lin} = 1$ var, $P_{nonlin} = 1000$ W, $Q_{nonlin} = 5000$ var (Fig. 6). There is a discrepancy between the curves Q_c and Q_r. The minimum value of Q_r is zero and is observed at the point of no compensation ($Q_{comp} = 0$), while $PF \approx 0.844$. The minimum value is $Q_c = 0$ achieved at $Q_{comp} \approx 550$ var, where $PF \approx 0.821$. Based on PF as the compensation effectiveness criterion, compensation based on Q_r is better. The maximum value of is $PF \approx 0.851$ achieved at $Q_{comp} \approx 175$ var, i. e., none of the methods in this mode gives a strictly optimal PF value, but the maximum is closer to the criterion based on Q_r.

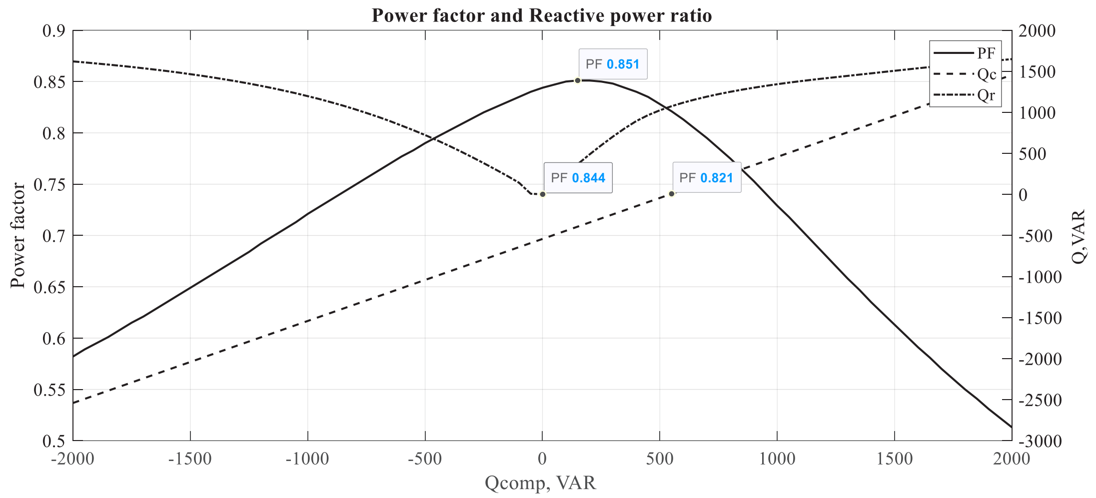

Fig. 6. Simulation results when nonlinear load is included

The following steps (Fig. 7–10) show the simulation results for a mixed load with different values of the reactive component of the linear part.

Mixed load, small reactive component of the linear part. Thus, the model parameters are: P_{lin} = 1000 W, Q_{lin} = 100 var, P_{nonlin} = 1000 W, Q_{nonlin} = 5000 var (Fig. 7). The maximum power factor is $PF \approx 0.855$. Compensation for Q_r gives $PF \approx 0.842$, while for Q_c – $PF \approx 0.835$. The conclusion is similar to the previous case: the criterion based on Q_r provides slightly better compensation.

Case 5 – mixed load, significant inductive component.

Parameters: P_{lin} = 1000 W, Q_{lin} = 500 var, P_{nonlin} = 1000 W, Q_{nonlin} = 5000 var (Fig. 8). Compensation for "classical" reactive power Q_c is more effective: $PF \approx 0.866$ is achieved, which coincides with the maximum. Compensation for Q_r provides only $PF \approx 0.842$.

Case 6 – mixed load, largest inductive component.

Specified model parameters: P_{lin} = 1000 W, Q_{lin} = 1000 var, P_{nonlin} = 1000 W, Q_{nonlin} = 5000 var (Fig. 9). Again, compensation for Q_c proves to be more effective: $PF \approx 0.866$ is achieved, while compensation for Q_r yields $PF \approx 0.842$.

In this case, a mixed load with a capacitive component of the linear part was considered. Parameter values: P_{lin} = 1000 W, Q_{lin} = –300 var, P_{nonlin} = 1000 W, Q_{nonlin} = 5000 var (Fig. 10). The maximum power factor value is $PF \approx 0.829$. Compensation for Q_r yields $PF \approx 0.825$, while for Q_c – only $PF \approx 0.77$. In this mode, the method based on the reactance coefficient K also demonstrates a noticeable advantage.

3.4. Discussion

Empirical evidence demonstrates that the effectiveness of reactive power compensation is contingent upon the load profile and the selected performance indicator. In all simulated states, the proposed enhanced approach, based on the K coefficient, yielded a stable response. For instance, the proposed improved method achieves power factor performance comparable or superior to first-harmonic methods in scenarios involving non-linear or hybrid loads. This advantage stems from the time-domain parameterization of energy over the full voltage cycle, which allows the final calculation to account for waveform distortion inherently.

While traditional methods remain efficient in systems dominated by linear inductive loads, the lack of a universal advantage for either strategy implies that the selection of a specific method must be dictated by the operational configuration of the electrical plant. A distinguishing feature of the proposed technique is the high predictability of the Q_r response. It is minimum value corresponds precisely to the reactive component of the linear load segment, indicating a robust capability to track the principal energy behavior of the system even within multi-type load environments.

From an engineering perspective, this technique serves as a practical tool for power quality estimation and the development of adaptive compensation logic, particularly for networks with a high density of non-linear elements.

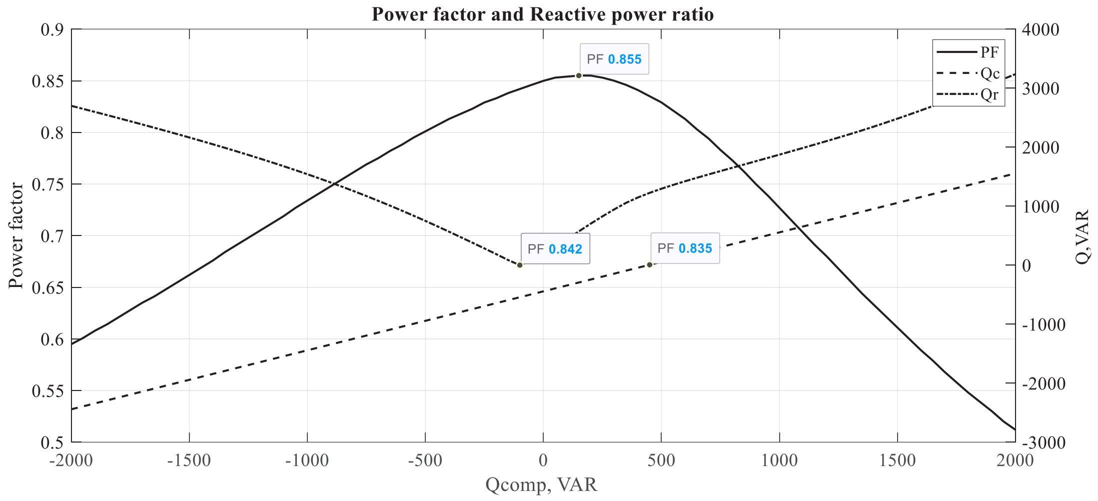

Fig. 7. Simulation results for mixed load (Q_{lin} = 100)

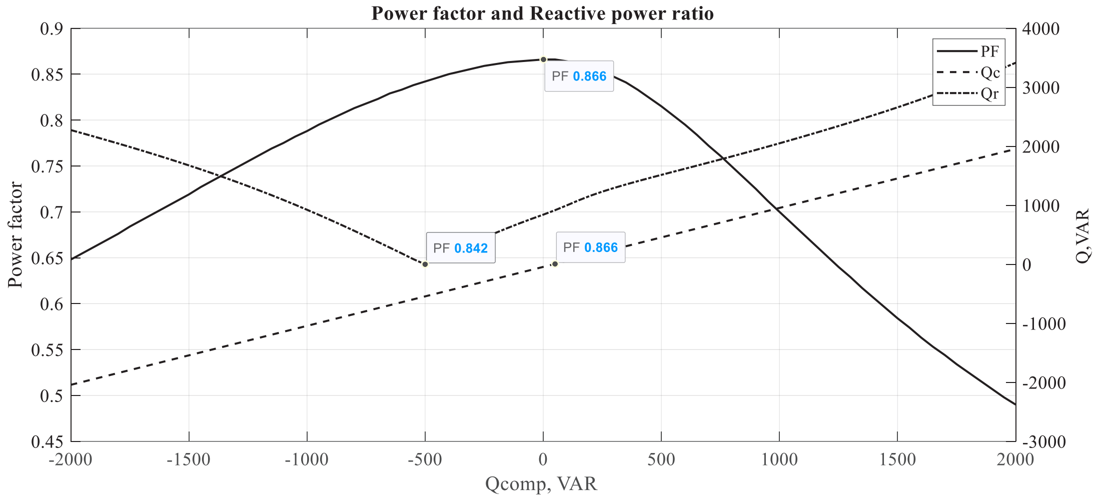

Fig. 8. Simulation results for mixed load (Q_{lin} = 500)

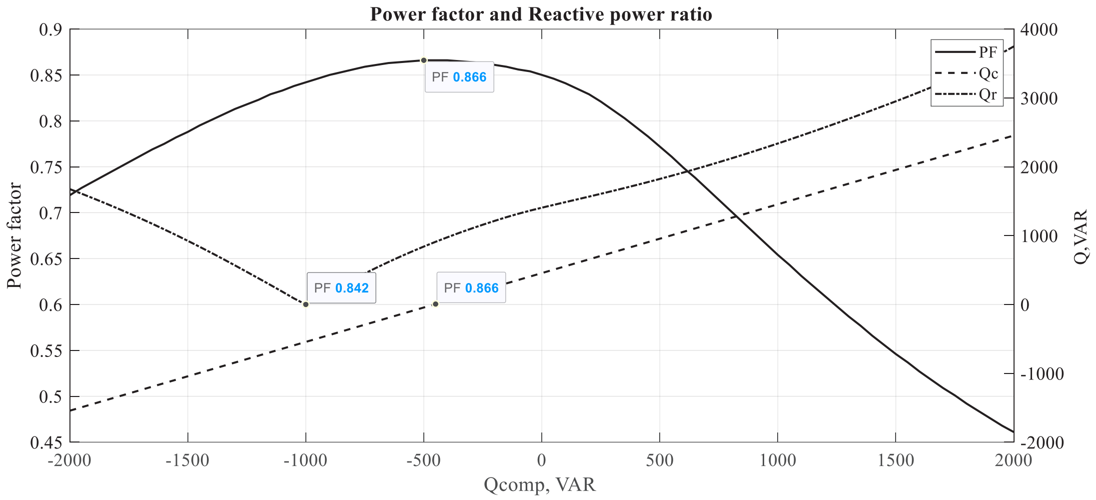

Fig. 9. Simulation results for mixed load (Q_{lin} = 1000)

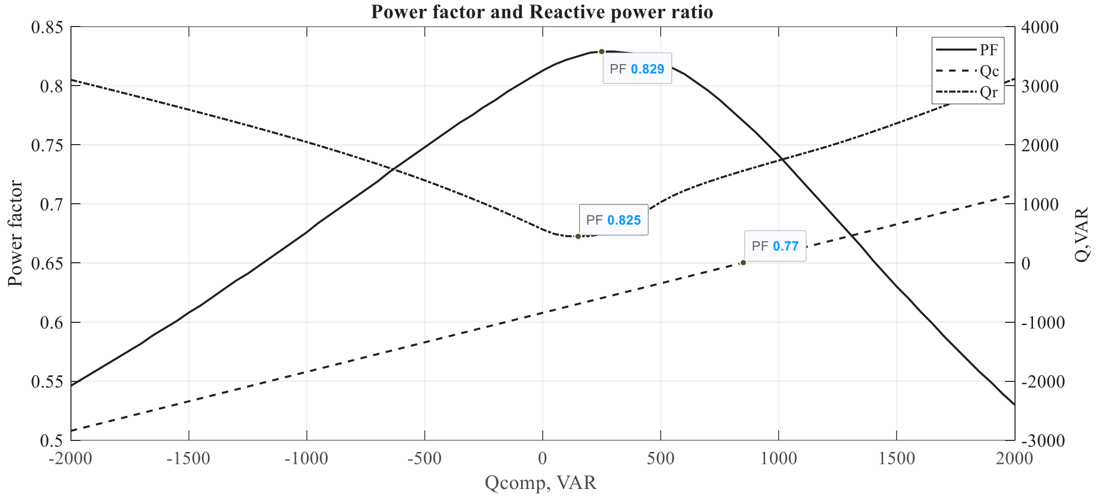

Fig. 10. Simulation results under mixed loading (Q_{lin} = –300)

More generally, the improved method represents an advanced extension of existing analytical tools designed to optimize compensation under non-sinusoidal conditions. However, certain technical restrictions persist. The mathematical method utilizing integration is limited to stable grid frequencies, and high-fidelity results necessitate close synchronization across multiple measurement channels to prevent the introduction of phase-change errors.

Furthermore, while the current optimization focuses on passive and non-linear loads, the implementation of this method within networks containing active power sources warrants further exploration.

Areas for further research: the results reported here point to several areas where the proposed improved method can be meaningfully extended.

First, a detailed comparative analysis between the reactance coefficient K, the corresponding parameter Q_r, and other energy-based methods that rely on period-averaged instantaneous power – particularly the approaches proposed by Nikolov [20] and Spasoevich [21] – would be highly valuable. Conducting such an analysis using consistent models of mixed linear and nonlinear loads, including diode rectifiers in combination with active or passive filters, would enable a more rigorous assessment of the agreement between different energy-based criteria. It would also help identify the operating conditions under which each method demonstrates greater sensitivity or, conversely, improved robustness in the presence of harmonic distortion.

Second, extending the method to multiphase systems remains an important task. Generalizing the coefficient K for three-phase networks, including unbalanced conditions, while accounting for phase shifts as well as zero- and negative-sequence components, would enable its application in real industrial environments. Particular attention should be given to comparisons with power definitions according to the IEEE 1459 standard and the theory of physical current components.

Another promising direction involves using the coefficient K as a basis for adaptive compensation algorithms. Combining this indicator with conventional power quality metrics (such as THD, power factor, and spectral characteristics) could support the development of hybrid control systems capable of automatically adjusting compensation parameters based on the relative contribution of linear and nonlinear load components.

4. Conclusions

1. An improved concept to load reactance estimation has been proposed. It is based on introducing a dimensionless reactance coefficient K, defined as the ratio of net energy over a voltage period to the total area of instantaneous energy exchange associated with bidirectional power flow between the source and the load. For sinusoidal conditions, an analytical relationship between this coefficient and the phase angle has been established, making it possible to reconstruct the equivalent reactive power from discrete time-domain measurements using Newton's iterative method, without relying on spectral decomposition.

2. The research confirms the validity of the dimensionless coefficient K and the corresponding equivalent power Q_r across a wide range of load types. In purely linear circuits, the proposed indicator is mathematically equivalent to the classical reactive power Q_c, ensuring consistency

between the approaches. In strongly nonlinear operating modes, particularly those involving harmonic distortion from rectifier circuits, the proposed method demonstrates improved algorithmic robustness.

Specifically, the Q_r criterion achieved a power factor $PF = 0.618$, representing a 5.3% improvement over the traditional first-harmonic approach, $PF = 0.587$. This proves the effectiveness of utilizing integral energy flows over a voltage period instead of spectral decomposition.

3. The comparative analysis identified the specific boundaries of applicability for the energy-based and vector-based compensation criteria. It was determined that the Q_r method provides significantly higher compensation efficiency in scenarios with dominant nonlinear components or capacitive linear loads, yielding a power factor increase of up to 7%. Conversely, for mixed loads with a substantial inductive linear component, the classical Q_c approach maintains higher accuracy in maximizing the PF. A key scientific finding is the invariance of the Q_r minimum point: in all simulated scenarios, the minimum value of the proposed indicator consistently coincided with the actual reactive component of the linear part of the load. This property confirms that the method effectively isolates the fundamental linear reactivity from nonlinear interference.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, that could influence the research and its results presented in this article.

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The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the submitted work.

Authors' contributions

Dmytro Gapon: Writing – original draft, Methodology, Data curation, Validation, Supervision; ***Roman Demianenko***: Conceptualization, Writing – review and editing, Resources; ***Andriy Solodovnik***: Data curation, Validation; ***Oleksandr Svetelik***: Data curation, Writing – review and editing.

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