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ANALYSIS OF EXCHANGE PROCESSES DURING PARALLEL OPERATION OF WIND ELECTRIC UNITS

Розглянуто можливості використання гібридних електростанцій на базі поновлюваних джерел електроенергії. Проаналізовано обмінні потоки енергії між різнотипними джерелами електроенергії. Побудовані залежності обмінної потужності від основних параметрів електричного сигналу. Визначено точки мінімуму обмінної потужності між генераторами, що дозволило зробити висновки про оптимальні режими роботи генераторів з різною природою генерації незалежно від внутрішньої будови і принципу їх дії

Ключові слова: електромагнітна сумісність генераторів, поновлювані джерела електроенергії, неактивна потужність Фризе, обмінні процеси, обмінна потужність

Рассмотрены возможности использования гибридных электростанций на базе возобновляемых источников электроэнергии. Проанализированы обменные потоки энергии между разнотипными источниками электроэнергии. Построены зависимости обменной мощности от основных параметров электрического сигнала. Определены точки минимума обменной мощности между генераторами, что позволило сделать выводы об оптимальных режимах работы генераторов с разной природой генерации независимо от внутреннего строения и принципа их действия

Ключевые слова: электромагнитная совместимость генераторов, возобновляемые источники электроэнергии, неактивная мощность Фризе, обменные процессы, обменная мощность

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1. Introduction

The growth of number of electric plants and autonomous power systems is observed in the global energy sector using non-traditional sources of electric energy (NSE). This primarily applies to wind, solar, small hydro power plants, etc. [1–3]. When operating any power plants, it is necessary to increase reliability and sustainability of their work, reduction of energy losses in the transmission, adjustments in the schedule of load, provision of efficient work on the energy market. The problems of instability in the work of NSE, usually caused by their irregularity and natural factors (unstable wind, nighttime, drought, etc.), are solved by using hybrid power sources – virtual power plants (VPP) (Table 1).

But while solving the problem of stability of provision of resources, there occurs a new, more global problem – electromagnetic compatibility (EMC) of diverse power generating units.

The problem of EMC now is one of the most important in the electricity sector, both in theoretical and applied sense. The significance of this problem is as big as the known problems of ecology, energy security and energy resourse saving. Its economic nature manifests in the enormous losses that occur as a result of failure to comply with the requirements of EMC. Thus, annual economic loss due to unsatisfactory levels of EMC in the industry and in everyday life amounts (by various estimates) to EUR 100 to 500 billion in the CIS countries [5].

Table 1

Variants of combination of hybrid power generating units

№	Wind power plants	Solar power plants	Bio power plant	Small hydro power plants	Small hydro accumulating power plants
1	+	+	–	–	–
2	+	–	–	+	–
3	–	+	–	+	–
4	+	+	–	+	–
5	+	–	–	+	+
6	–	+	–	+	+
7	+	+	–	+	+
8	+	+	+	–	–
9	+	+	+	+	–
10	+	+	+	+	+

EMC of technical means considers devices and processes that are usually considered under conditionsof generating electromagnetic disturbances, their influence on electrical equipment, the degree of automation and correction of the negative influence of the environment. Electromagnetic compatibility is a global problem, within which a number of separate problems is considered [5]. Under conditions of operation of various systems (for example, substations) and subsystems (e. g., transformers), the specified problems can interweave and partially duplicate each other. In this case, analysis of parallel operation of wind energy units (WEU) in VPP is a relevant issue and requires a deeper analysis. This analysis should be enlarged and adequate. But because of the changing nature of the work of the WEU, the use of integral characteristics is inefficient. Therefore, it is actual to use Instantaneous characteristics for analysis of parallel operation of WEU.

2. Analysis of scientific literature and the problem statement

Modern development of dispersed electric power systems, in particular based on WEU, is based on the provisions of the concept of Smart Grid [2, 3]. In the beginning of the 21st century the Smart Grid technologies are regarded as the foundation of modernization and innovative development of centralized and decentralized systems of electric power industry.

The growth in interest to exploring the questions related to no sinusoidal modes is predetermined by the increased proportion of higher harmonic components in currents of nonlinear loads [4, 5]. Increase in the number and level of higher harmonic components of currents and voltages is linked to a wide distribution of systems of dispersal generation, electrical and electromechanical devices that are sources of harmonics: WEU, static converters, electric arc furnaces, welding machines, controlled drives of electrical machines, devices with saturated magnetic elements, etc. As a result, the losses in lines grow; the obstacles in the electrical equipment increase, the electromagnetic situation and the quality of electric power deteriorate [5–7].

The problem of increasing efficiency in the systems with WEU, which is key at solving the problems of development of electroenergy, is directly connected with the assessment of the quality of electricity, provision of specified levels of electromagnetic compatibility (EMC) [7–9].

To assess energy efficiency of energy processes, reactive power and the indicators on its basis are widely used [3, 10–12]. However, the dissemination of mathematical methods and definitions of power, designed for sinusoidal processes, on no sinusoidal and asymmetrical multi-phase processes usually leads to the loss of connection with the physical essence of processes in the system and to difficulties in interpretation of results [3, 11–13] and sometimes even to false conclusions.

The known definitions of reactive power in non-sinusoidal currents and voltages often contradict each other, and their use is dictated by solving a certain narrow range of tasks. In this case, for each range of tasks they often offer own understanding of these processes, own terminology and own decomposition of parameters describing these processes [3, 11, 14].

Difficulties also occur when setting up evaluation system of energy efficiency based on the known methods. The criteria of efficiency of processes, obtained by the known classic methods of calculation based on harmonic analysis, do not always reflect the essence of processes [3, 10, 12–16]. For example, all methods of equivalentiation are only calculation techniques and do not reflect real physical processes. Therefore, energy processes in nonsinusoidal asymmetrical systems are appropriate to evaluate on the curve of instantaneous power, which makes it possible to identify the components of the flows of energy and their ratio in arbitrary form of the curve of voltage and current.

To assess the effectiveness of energy saving measures, ensure the quality of energy supply and EMC with regard to electric power quality and its concentration in energy flow, there are problems of adequate summing of the balance of energy components [3, 11, 12]. In this case, the balance of energy is appropriate to consider not only as the expression of quantitative ratio between the costs and the use of energy, that is, reflection of the principles of equilibrium and balance, but also take into account a broader definition of balance – building up a system of indicators, which characterize the ratio of balance in any phenomenon that changes [3, 11].

At present, in the framework of development of the theory of exchange processes, certain tasks are successfully resolved in electric power systems. In particular, in the analysis of processes of energy conversion in electromechanical systems [12, 13], the analysis of electric power quality in electrical traction systems [16], vector control of electric machines of alternating current [10], the equipment for electric drives of great power was created with improved undicators due to application of compensating capacities, when the advanced introduced modules with the properties to generate reactive power are additionally introduced, compensation of higher harmonic by generating harmonics of reverse polarity [15]. Worth noting are some studies to optimize the levels of reactive power in the electricity supply systems with the sources of dispersed generation [8, 17].

In January 2000 the IEEE (Institute of Electrical and Electronics Engineers) announced the creation of the IEEE Standard 1459–2000 to calculate the full power of three-phase electrical networks with asymmetrical nonlinear loads under balanced or unbalanced conditions. In March 2010, the IEEE Standard 1459–2010 was published with important changes and amendments [18]. The IEEE Standard 1459–2010 for implementation of the algorithm of determining components of power requires transmission of maximum power from the source to the consumer, in particular, direct sequence of main harmonic [19].

At present there is no doubt that the problem of efficient power supply is directly connected with the assessment of the quality and balance of power in the devices and systems and is integral to the analysis of components of the full power of their electrical circuits and, above all, to determining inactive power.

The conducted analysis revealed that it is important to solve many problems, such as, first of all, design and construction of systems with dispersed sources of generation, enhancing efficiency, improving the quality of electricity, providing specified levels of EMC, monitoring the state of the elements of the system, maintaining the modes of electricity supply. Solving these problems is based on building up adequate models, conducting a comprehensive analysis of energy processes.

This predetermines the need for comprehensive consideration of the problems of evaluation of exchange processes, components of the losses of electricity, adequacy of formation and calculation of the components of the balance (both instantaneous and integral).

It also must be taken into account during research that during the transition to a market system of interrelations, the concept of "electrical energy" passes from a purely scientific and technical sphere into economic, becoming the object of buying and selling. This circumstance imposes additional requirements on electricity as a commodity, including ensuring compliance with existing regulations, the breach of which entails not only technical problems but also punitive economic sanctions.

As a result, the search for new approaches is promising to ensure the quality of electric power in the systems of generators of electricity based on exchange processes, and in a broader context – the quality of power supply in the systems with the sources of dispersal generation. First of all, it is important to analyze exchange processes at joint (parallel) work of such complicated sources as WEU, which can work as part of wind power stations (farms), virtual power plants and active consumers (prosumer).

3. The purpose and objectives of the study

The purpose of this study is analysis of exchange processes in the systems with regard to external conductive obstacles.

To achieve the set goal, the following tasks were defined:

– to carry out calculation for analysis of the impact of load on the exchange processes in the system "two generators – one load";

– to carry out calculation and analysis for determining similarities in the characteristics of exchange processes;

– to identify opportunities to minimize exchange capacity when optimizing operation modes of power systems.

4. Materials and methods of the study of electromagnetic compatibility of non-traditional sources of electric power

The concept of K. Budana is based on frequency representation of currents and voltages, with the active and full power defined by [20]:

$$P=\frac{1}{T}\int_0^T p(t)dt=\sum_{k=l\in G} U_k I_l \cos(\beta_l+\alpha_k), \quad (1)$$

$$S=UI=\sqrt{\sum_{k\in N} U_k^2}\sqrt{\sum_{l\in M} I_l^2}, \quad (2)$$

a component of total power was also introduced – reactive power:

$$Q=\sum_{k=l\in G} U_k I_l \sin(\beta_l+\alpha_k). \quad (3)$$

Determining reactive power by the formula (3) does not provide equality, necessitating the introduction of additional component – power distortion, which is defined as the discrepancy between the square of full and the sum of squares of active and reactive powers:

$$D=\sqrt{S^2-(P^2+Q^2)}. \quad (4)$$

Similarly, C. Frieze proposed to carry out decomposition of current and voltage into two components and to represent the square of total power as the sum of the squares of active (efficient) and passive (fictitious) capacities:

$$Q_F=\sqrt{S^2-P^2}=\sqrt{D^2+Q^2}. \quad (5)$$

For the systems with no sinusoidal signals they use reactive power Kvade (6), whic is the discrepancy between the inactive power of Frieze and the first harmonic component of reactive power:

$$Q_{kv}=\sqrt{Q_F^2-Q_1^2}. \quad (6)$$

As can be seen in Table 2 [4], the classic approach only captures the presence of reactive power in the presence of reactive power (points 3 and 11–13 in Table 2). However, classic approach does not allow analyzing exchange processes at various intersections of the circle with different modes of operation between generators of various types and performing their assessment at the effect of heteronymic harmonic components of current and voltage.

The example of reactive power, defined by the means of exchange processes, is reactive power based on determining the exchange capacity Q_{ex} (7) under condition of constant intensity of conversion of electricity to other kinds during the period T.

$$Q_{ex}=\frac{1}{T}\int_0^{t^*} u(t)i_p(t)\,dt, \quad (7)$$

where $i_p(t)=i(t)-i_a(t)$ is the reactive component of current; $i_a(t)=u(t)P/U_d^2$ is the active component of current; i(t) is the total current in the circuit; P is the active power; U_d is the valid value of voltage.

For conducting an analysis of mutual influence of the elements in the system of two generators – one load, the scheme of which is depicted in Fig. 1, and determining the parameters that execute the largest influence, let us assign initial parameters.

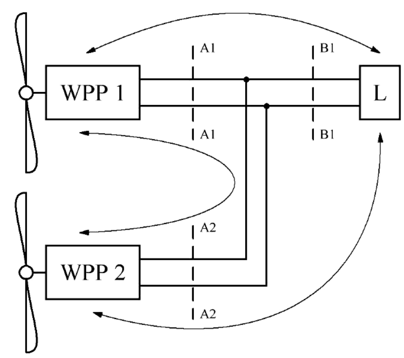


Fig. 1. Power scheme of one load by two wind generators

Assign that parameters of the generators:

$$e_1(t)=E_{1.0}+\sum_{k=1}^{n} E_{1k}\sin(k\omega t+\varphi_{1k}),$$

$$e_2(t)=E_{2.0}+\sum_{k=1}^{n} E_{2k}\sin(k\omega t+\varphi_{2k})$$

are the no-sinusoidal different-type EMP of generators and r_1, r_2 are the internal resistances of generators. Let us also assign actively-inductive load $Z_i=R+X_L$. The scheme of substitution of the described system is depicted in Fig. 2.

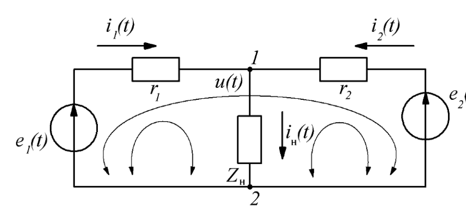


Fig. 2. Scheme of substitution of the system of two generators that feed one load

To determine the currents that pass through each generator and the load, one can use any method of calculation (method of contour currents, host potentials, imposition method, etc.) from the known theoretical bases of electrical engineering [20]. For the scheme of substitution shown in Fig. 2, the easiest way is to use the imposition method. With this purpose let us conditionally consider the influence of each generator on the load (Table 3). The share of influence of each generator in the power circuit by the Ohm's law is determined for each scheme and in the load by the method of foreign resistance.

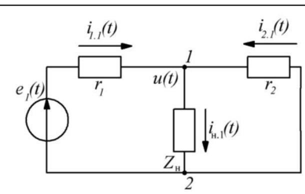
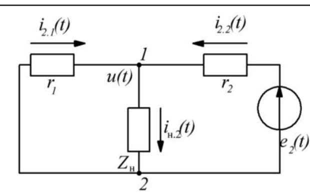
Table 2

Ratio of capability to reflect different sides of energy processes by reactive and exchange capacities

Characteristic of various aspects of the course of energy process	Reactive capacity	Exchange capacity
1. Unambiguous reflection of exchange processes (indication of the condition $W^{-} \neq 0$)	–	+
2. Accumulation of energy in reactive elements (characteristic of energy capacity and extreme operating modes of reactive elements)	–	+
3. Availability of mutual compensation of reactive capacities of different harmonics (possibility of existence of condition of equality to zero of reactive characteristic at $i_p(t) \neq 0$)	+	–
4. Reflection of energy exchange in the presence of heteronymic harmonics of current and voltage at the intersection of the circle	–	+
5. Reflection of exchange processes between generators of current and voltage	–	+
6. Assessment of exchange processes in transient modes	–	+
7. Comparison of exchange processes in the various intersections of the circle	–	+
8. Assessment of mutual influence of the elements of the circle, which are characterized by different harmonic composition of the voltage u(t) and the current i(t)	–	+
9. Assessment of stability of operating modes by introducing limit values of the magnitude of characteristics	–	+
10. Taking into account the values of angle of the current ψ_k^i and the voltage ψ_k^u (k>1) for higher harmonics	–	+
11. Indication of the presence of reactive capacity in the circle with nonlinear non-stationary resistance in the absence of reactive elements	+	–
12. Reflection of generation of reactive capacity in the circles with key elements	+	–
13. Reflection of harmonic $p_h(t)$ and inter harmonic $p_{ih}(t)$ components of the instantaneous power p(t)	+	–
14. Unambiguous elimination of reverse energy flows while compensation for relative characteristic	–	+

Table 3

Distribution of currents in the scheme of substitution

Scheme of substitution under the action of one generator		
Current that passes through the resistance r_1	$i_{1.1}(t) = \dfrac{e_1(t)}{\dfrac{Z_i \cdot r_2}{Z_i + r_2} + r_1}$	$i_{1.2}(t) = i_{2.2}(t)\dfrac{Z_i}{Z_i + r_1}$
Current that passes through the resistance r_2	$i_{2.1}(t) = i_{1.1}(t)\dfrac{Z_i}{Z_i + r_2}$	$i_{2.2}(t) = \dfrac{e_2(t)}{\dfrac{Z_i \cdot r_1}{Z_i + r_1} + r_2}$
Current that passes through the load	$i_{i.1}(t) = i_{1.1}(t)\dfrac{r_2}{Z_i + r_2}$	$i_{i.2}(t) = i_{2.2}(t)\dfrac{r_1}{Z_i + r_1}$
General scheme of substitution of the system of two generators-load		
Current that passes through the resistance r_1	$i_1(t) = i_{1.1}(t) - i_{1.2}(t) = I_{1.0} + \sum_{k=1}^{n} I_{m1k} \sin(k\omega t + \psi_{1k})$	
Current that passes through the resistance r_2	$i_2(t) = i_{2.2}(t) - i_{2.1}(t) = I_{2.0} + \sum_{k=1}^{n} I_{m2k} \sin(k\omega t + \psi_{2k})$	
Current that passes through the load	$i_i(t) = i_{i.1}(t) + i_{i.2}(t) = I_{i.0} + \sum_{k=1}^{n} I_{mik} \sin(k\omega t + \psi_{ik})$	

Consider energy flows through the intersection A1–A1 – the energy flows that pass through the first generator, A2–A2 – the energy flows that pass through the second generator, B1–B1 – the energy flows that are accumulated and given by load.

The voltage between the nodes 1–2 of the scheme of substitution:

$$u(t)=e_1(t)-i_1(t)\cdot r_1=e_2(t)-i_2(t)\cdot r_2$$

or, one can write down in a general form (8):

$$u(t)=U_0+\sum\nolimits_{k=1}^{n}U_{mk}\sin(k\omega t+\varphi_{uk}). \quad (8)$$

Therefore, the exchange capacity through the intersections A1–A1, A2–A2 and B1–B1 according to the formula (7) will have the form:

$$Q_{ex.1}=\frac{1}{T}\int_0^{t^+}u(t)i_{1p}(t)\,dt, \quad (9)$$

$$Q_{ex.2}=\frac{1}{T}\int_0^{t^+}u(t)i_{2p}(t)\,dt, \quad (10)$$

$$Q_{ex.н}=\frac{1}{T}\int_0^{t^+}u(t)i_{1н}(t)\,dt. \quad (11)$$

It follows from the formulas (9)–(11) that a different value of the exchange capacity $Q_{ex.1}\neq Q_{ex.2}\neq Q_{ex.н}$ will pass through each intersection in a period of time.

5. Results of research into exchange processes in the systems with power sources of various types

The voltage that will be created in the intersection A–A (Fig. 3) changes periodically by sinusoidal law, which can be written down as follows: $u(t)=1000\sin(\omega t)$ whereas the law of change in current, generated by the source of obstacle J(t), may change accidentally. Let us consider three variants of periodic functions of change in current, such as [4, 20]:

– rectangular periodic signal:

$$i(t)=\frac{4\cdot I_m}{\pi}\sum_{k=1}^{\infty}\frac{\sin(2k-1)(\omega t+\varphi)}{2k-1}, \quad (12)$$

– triangular periodic signal:

$$i(t)=\frac{8\cdot I_m}{\pi^2}\sum_{k=1}^{\infty}\frac{(-1)^{k+1}\sin(2k-1)(\omega t+\varphi)}{(2k-1)^2}, \quad (13)$$

– sinusoidal periodic signal:

$$i(t)=I_m\sin(\omega t+\varphi). \quad (14)$$

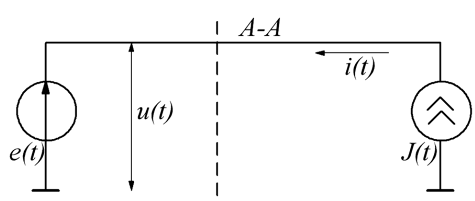


Fig. 3. Main directions of energy flows through the intersections of the circle

Since the probability of equality to zero of the phase shift between voltage and current in the intersection is almost zero, there is a need to determine exchange capacity depending on the shift phase at various forms of action of the signal. As an example, we present the calculation of the exchange capacity during the action of the third harmonic of a rectangular form of the signal at a phase shift between the voltage and the current $\varphi=\pi/2$ (Fig. 4), for which:

$$u(t)=1000\sin(\omega t),$$

$$i(t)=\frac{4\cdot 10}{\pi}\sum_{k=1}^{\infty}\frac{\sin(2k-1)(3\omega t+\varphi)}{2k-1},$$

$$Q_{ex}=\frac{2}{T}\int_0^{t^+}u(t)i_p(t)dt,$$

$$Q_{ex}=\frac{2}{T}\left(\int_0^{T/12}u(t)i_p(t)dt+\int_{T/4}^{5T/12}u(t)i_p(t)dt\right)=3{,}138\ \text{kVar}.$$

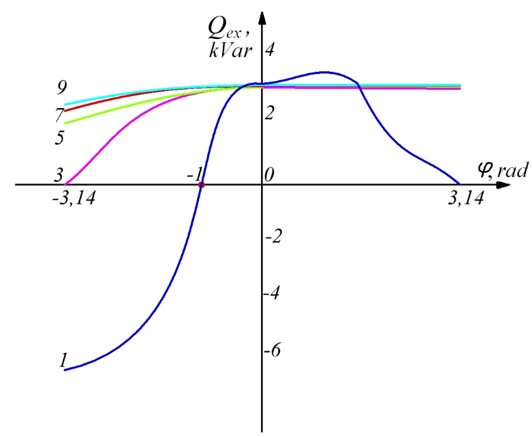


Fig. 4. Dependency of the exchange capacity on the angle of phase shift under the action of primary and higher harmonic components of current: — is the main harmonic; — is the third harmonic; — is the fifth harmonic; — is the seventh harmonic; — is the ninth harmonic

Fig. 4 shows how exchange capacity changes for different harmonic components of perturbing currents. Under the influence of harmonics 5, 7 and 9, the exchange capacity does not practically change, necessitating their compensation, because in any mode of operation of such a system, the exchange processes will be present. Under the influence of the third harmonic component, there occurs a point, at the phase shift equal to $-\pi$, when exchange capacity equals zero. And under the action of the first harmonic component of perturbing signal, the graph displays that in the range of the phase shift angle $-\pi<\varphi<-1$, the generator will assume the role of consumer, this follows from a negative sign of the exchange capacity, and with other values of the angle it will act as a generator. Also in the graph are the two points that will characterize optimal mode of operation (points $\varphi=-1$ and $\varphi=\pi$).

6. Discussion of the results of research into exchange processes in the circles with non-traditional sources of electric power

Based on the results of the calculations, we constructed the graphs (Fig. 5), from which the points of equality to zero of exchange capacity are derived, i. e. the values of the phase shift angle, at which the exchange power by primary and higher harmonics equals zero. These calculations also allowed us to conduct a study of the influence of a single periodic pulse signal with varying frequency and of varying duration and to determine optimal points. The dependency of the phase shift angle on the duration of the pulse when $Q_{ex}\to\min$ is presented in Fig. 6, from which it is evident that for each value of a phase shift angle there is a set of two values of optimal angle and this dependency is rectilinear.

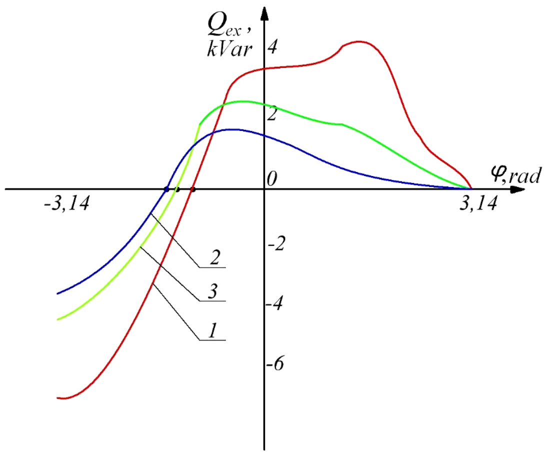


Fig. 5. Dependency of the exchange capacity on the phase shift angle under the action of the main harmonic component of the source of obstacles: 1 — is the rectangular pulse signal; 2 — is the triangular pulse signal; 3 — is the sinusoidal signal

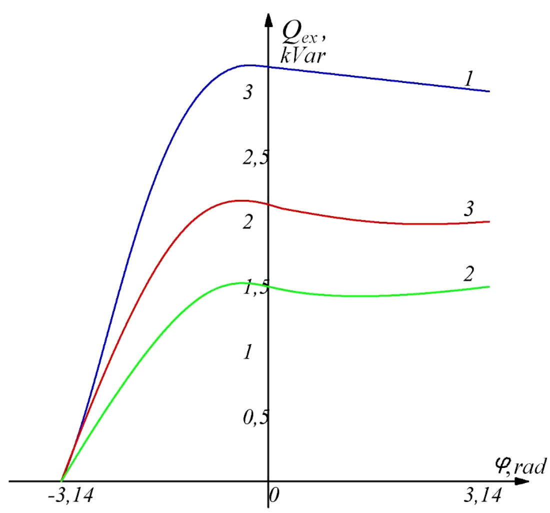


Fig. 6. Dependency of the exchange capacity on the phase shift angle under the action of the third harmonic component of the source of obstacles: 1 — is the rectangular pulse signal; 2 — is the triangular pulse signal; 3 — is the sinusoidal signal

As can be seen from Fig. 4–6, graphic dependencies of the exchange capacity on the phase shift angle are similar in character. For the first harmonic component of the perturbing action, the one, exact for all types of periodic signal, is common $-\varphi=\pi$ and the other zero point ranges within $\varphi=-1{,}26$ at a triangular periodic pulse signal to $\varphi=-1$ at a rectangular periodic pulse signal.

The obtained data made it possible to analyze uniform periodic perturbing signals, different in form, and provided the basis for the analysis of periodic uneven pulse perturbing signals to the generator. Fig. 7, 8 present graphic dependencies of the exchange capacity on the shift phase angle under the action of pulse perturbing signals of different duration.

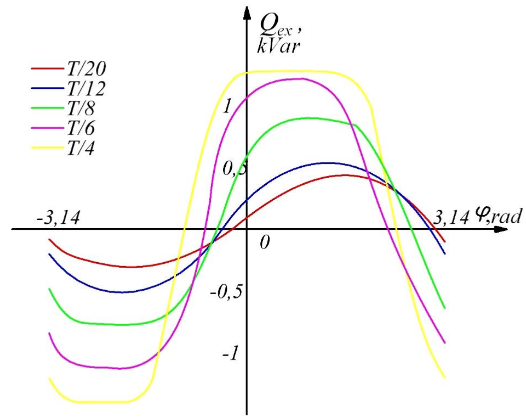


Fig. 7. Dependency of the exchange capacity on the phase shift angle $Q_{ex}=f(\varphi)$ at different duration of the pulse: — $\tau=T/20$; — $\tau=T/12$; — $\tau=T/8$; — $\tau=T/6$; — $\tau=T/20$

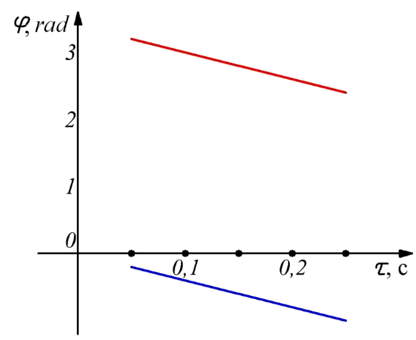


Fig. 8. Angular characteristic of exchange capacity minimum: — the first set of optimal values; — the second set of optimal values

When analyzing the graphs depicted in Fig. 7, one can see that the points of equality to zero of the exchange capacity at different phase shift angles and the duration of pulse have a certain dependency. On building up these dependencies in Fig. 8, it turned out that they are linear and parallel. With the help of this characteristic, it is possible to determine optimal mode of operation of a particular generator, aware of the character of perturbing action and the duration of pulses.

7. Conclusions

1. With an active load, all the power generated by generators is consumed by active load while the overflows between generators are mutually compensated. At occurrence of reactive resistance in the load, power overflows occur. Nonsinusoidality of voltage, generated by one and/or two generators, also causes electromagnetic energy exchange between the elements of the circle.

2. The calculations of comparison between the graphs with perturbing signal of various types revealed that no

matter which signals were compared, the dependencies of exchange capacity on the phase shift angle are correlated, i. e., to simplify the calculations, one can perform replacement of sinusoidal signal of obstacles by a rectangular or triangular signals with the same amplitudes and frequencies. Also, as can be seen from the figures, for the higher and the main harmonic components of currents, the exchange capacity grows and reaches a certain peak value, after which, under the action of higher harmonics, the exchange capacity does not change or changes insignificantly while under the influence of the main harmonic, it continues to grow to its maximum, after which coincides into zero. This tendency is observed for all periodic signals of error, different in form.

3. The conducted studies make it possible to carry out analysis and optimization of energy processes in dispersed electric power systems with different energy sources, to identify and minimize unwanted energy flows between the elements of the system, as well as to compensate for the mutual influence of various-type sources of electric power, both traditional and non-traditional.

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