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STUDY OF THE REASONS AND PARAMETERS OF COMMON-MODE POWER OSCILLATIONS IN AUTONOMOUS ELECTRICAL COMPLEXES

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Abstract: *The problem of the existence of common-mode and exchange power oscillations at the parallel operation of synchronous generators in autonomous electrical systems is considered. The methods of mathematical modeling were used to obtain the amplitude and period of common-mode oscillations in the whole possible range of settings of the object under study. A method has been developed for mapping the relationships between amplitude and period of common-mode power oscillations and transfer coefficients and rotation frequency setpoints of speed controllers of diesel generators. The use of such maps allows one to apply the method of eliminating exchange power oscillations, taking into account the possible occurrence of common-mode oscillations. Mapping the amplitude settings and the period of common-mode power oscillations makes it possible to understand the trends of amplitude and period of the common-mode power oscillations. It also helps to carry out an in-depth analysis of operation of an autonomous electrotechnical complex.*

Keywords: *exchange power oscillations, common-mode power oscillations, parallel operation, autonomous electric power equipment, generating unit, experimental research.*

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Introduction

The parallel operation of diesel generator units based on synchronous generators is the most commonly used mode of generating electrical energy in autonomous electrical engineering complexes [1, 2]. The advantages of such a layout are well known, which include the rational use of the generated electricity; ensuring the reliability of the power plant; operation of units with the highest efficiency; the ability to repair individual units, economy of fuel and the unit service life [3, 4]. To study the exchange power oscillations during parallel operation of diesel generator units, experimental studies were carried out at the ship-ferry Yeisk of the Kerch ferry [5, 6]. At the same time, common mode power oscillations were detected.

Figs. 1–4 show oscillograms of the generator currents for the running rowing engines, which receive power through the thyristor converters. These oscillograms show self-oscillatory processes of various amplitudes and periods. The form of these oscillations also has a different character. The oscillation amplitude reaches 100 %, and the period is 150–800 ms [6].

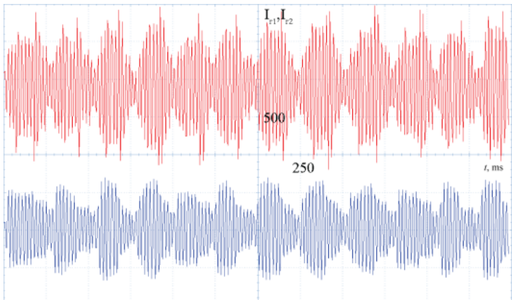

Fig. 1. Currents of parallel-running generators with rowing engines running (mode 1)

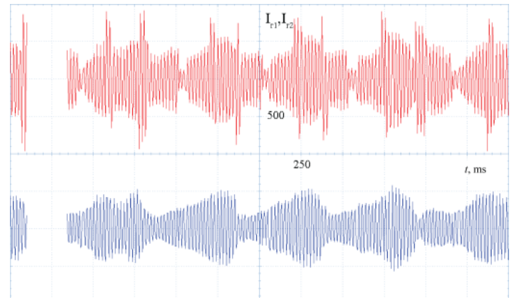

Fig. 2. Currents of parallel-running generators with rowing engines running (mode 2)

Fig. 3. Currents of parallel-running generators with rowing engines running (mode 3)

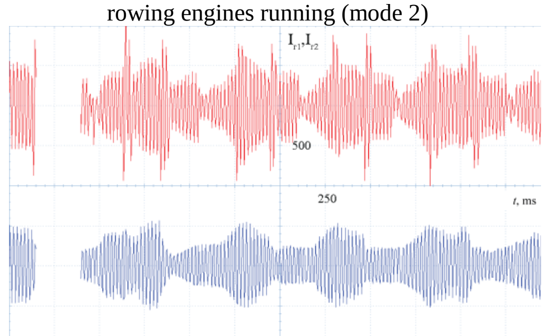

Fig. 4. Currents of parallel-running generators with rowing engines running (mode 4)

The results of the research revealed that the amplitude of the exchange power oscillations of the parallel-running diesel generator depends on the backlash clearances in the rotational speed control loops [6, 7]. A method has been developed for constructing maps of relationship between amplitude of exchange power oscillations and the backlash clearance [8]. It is necessary to carry out similar work with respect to common-mode oscillations.

Methods

To study the causes and nature of common-mode power oscillations during operation of a power plant of an autonomous electrotechnical complex, a mathematical model is used [9, 10], which allows one to construct graphs of instantaneous values of the main parameters of the parallel-running diesel generators.

The mathematical model uses the equation of a diesel engine, which is the driving engine of a generating unit, in a simplified form:

$$J_m \frac{d\omega_r}{d\tau} = M_d - M_g;$$

$$M_d = K_m h; \; M_g = \psi_{sq} i_{sd} - \psi_{sd} i_{sq},$$

where J_m is the reduced moment of inertia of the diesel engine shaft and the generator rotor; M_d is mechanical torque of a diesel engine; M_g is electromagnetic moment of resistance gained by the generator; h is the position of the fuel rail; K_m is diesel engine amplification frequency.

A separate equation describes the diesel engine speed controller, which is represented by an aperiodic link of the first order:

$$T_\omega \frac{dh}{dt} = K_\omega U_\varepsilon - h,$$

where T_ω is the time constant of the actuator; K_ω is transmission coefficient (gain) of the controller; U_ε is the error signal between the set ω_{r0} and the actual ω_r rotation frequencies of the diesel engine.

For mathematical description of the backlash with a gap in the control circuit of rotation frequency of a diesel engine, we use the following expression:

$$U_\varepsilon = \left\{ \begin{matrix} U_\varepsilon = \text{const for } \left| U_\varepsilon - k\varepsilon \right| \le D_n \\ k\left(\varepsilon - D_n \operatorname{sign}\left(\frac{dU_\varepsilon}{dt} \right) \right) \text{for } \frac{dU_\varepsilon}{dt} \ne 0 \end{matrix} \right\},$$

where k is transmission coefficient; D_n is backlash gap; ε is mismatch between the set ω_{r0} and the actual ω_r rotation speeds of the diesel engine.

Thus, each diesel generator unit involved in parallel operation has an automatic rotation speed controller with two main variable parameters: transmission coefficient K_ω and rotation speed setpoint [11] ω_{r0}, as well as backlash with a gap D_n.

The main objective of the study is to find an answer to the question: is there a connection between the setpoints and parameters of the rotational speed control loops of diesel generator units and common-mode power oscillations during parallel operation. It is also important to understand that the amplitude and period of common-mode oscillations depend on and to systematize the obtained results since the results of field experiments prove their variability.

The mathematical model makes it possible to analyze the common-mode power oscillations that occur when two synchronous generators of an autonomous electrotechnical complex are operating in parallel in quasi-steady-state modes.

When conducting research, we will take the range of change for the controller transmission coefficient K_ω from 10 to 200, for the setpoints for the controllers rotation frequency ω_{r0} from 0,9 to 1,1, which correspond to a stable parallel operation of the generating units. It is necessary to take into account the backlash, as, during experimental studies on the ferry Yeisk, the connection between exchange and common-mode power fluctuations became clear, and this is important when implementing measures and means to eliminate the exchange fluctuations to ensure high-quality stable parallel operation of generators. We introduce into the mathematical model the gaps of backlashes of the rotation speed controlling contours of diesel generators, respectively D_{n1} = 0,002 and D_{n2} = 0,01. To eliminate the influence of transients on the results, we choose a time range from 12 to 15 seconds, which obviously corresponds to a quasi-established mode of operation.

The simulation results confirm the existence of common-mode power oscillations and allow us to determine their amplitude and period. For this purpose, we will use the currents IA1, IA2 of parallel-running generators.

Results

Mathematical modeling of parallel operation of diesel generator units, the transmission coefficients of which are not equal, confirmed the assumption on occurrence of common-mode oscillations for this operation mode (Fig. 5).

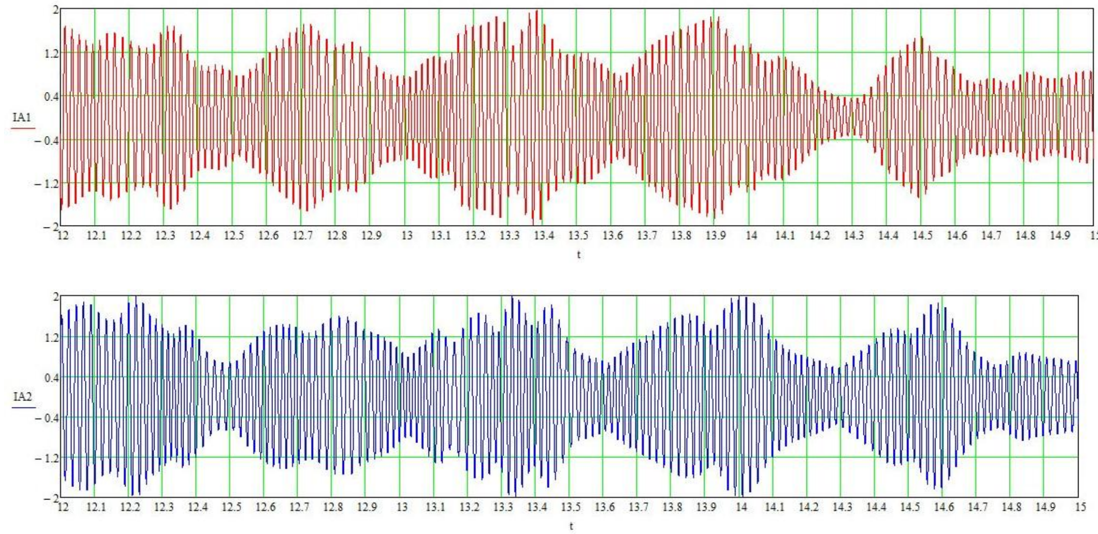

Fig. 5. Modeling results D_{n1}=0,002; D_{n2}=0,01; $K_{\omega 1}$=40; $K_{\omega 2}$=80; ω_{r01}=1; ω_{r02}=1. *I*A1, *I*A2 are currents of parallel-running generators

Moreover, the selective modeling made it possible to think that the amplitude of oscillations increases with the increase in the difference between controllers transmission coefficients of the parallel-running diesel generator units. The clarity of nature of the relationship between common-mode oscillations and the ratio of transmission coefficients of frequency controllers appeared after modeling the entire field of possible setpoint ratios (Tables 1, 2) and construction of graphical visualization of the obtained results in the form of a setpoint map (Fig. 6, 7). It should be noted that for equal gain factors, there are no common-mode oscillations, and the results obtained in the tables correspond to the amplitudes of the exchange power oscillations. This is the main diagonal of the tables from left to right from top to bottom.

Also, during mathematical modeling, we detected the impact of difference in rotation frequency setpoints of the rotation frequency controllers of parallel-running generating units on the occurrence of common-mode power oscillations (Fig. 8).

Table 1

The relationship between amplitude of common-mode power oscillations of the first diesel generator and the frequency controller gain

$K_{\omega 1}/K_{\omega 2}$	10	20	40	60	80	100	120	140	160	180	200
10	**0,01**	**1,1**	**1**	**0,9**	**0,75**	**1,1**	**0,3**	**0,25**	**0,25**	**0,25**	**0,25**
20	0,95	0,01	1,1	1	1,1	0,85	1,1	1,1	0,8	0,85	0,85
40	0,9	0,85	0,05	0,9	1,05	1,5	1,1	1,25	1,05	1,1	1,05
60	1,1	0,85	1,1	0,05	0,3	0,9	0,7	0,95	1	0,95	1,05
80	0,95	1	0,8	0,2	0,05	0,2	0,9	1,2	0,9	1,2	1,1
100	0,7	0,9	1,2	1	0,25	0,05	0,16	0,8	1,05	0,8	1,25
120	0,55	0,75	1,1	0,9	0,9	0,15	0,06	0,13	1,25	0,8	1,3
140	0,75	1,2	1,1	0,9	0,9	0,22	0,15	0,06	0,13	0,7	1,1
160	1,1	1,2	1,2	0,9	0,9	0,75	0,3	0,12	0,06	0,11	0,65
180	1,1	1,2	1,2	1,05	1,05	0,75	0,7	0,23	0,14	0,06	0,1
200	1,1	1	0,9	1,05	1,1	0,75	0,7	0,6	0,2	0,13	0,07

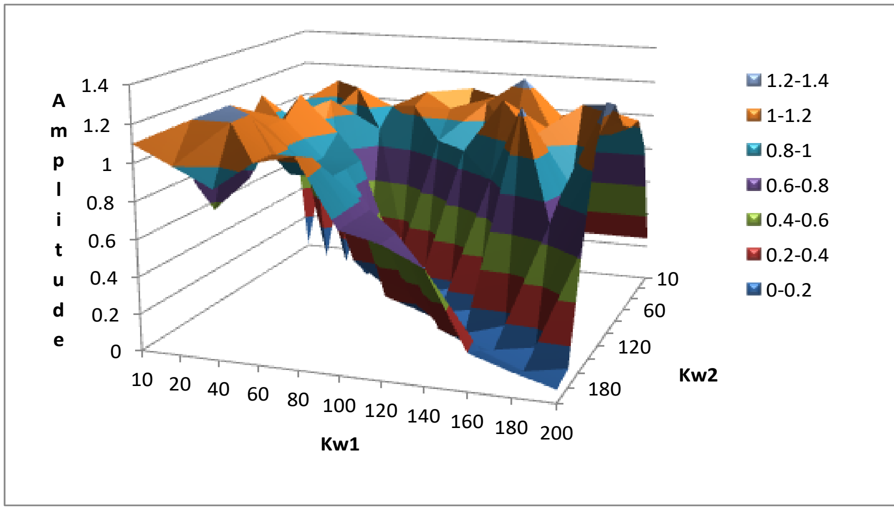

Fig. 6. Map of relationship between the amplitude of common-mode oscillations of the first diesel generator and gain coefficients of frequency controller, $K_{\omega 1}$ and $K_{\omega 2}$ are controller gain coefficients of the first and the second parallel-running diesel generators, respectively

Table 2

Relationship between amplitude of the common-mode power oscillations of the second diesel generator and frequency controller gain

$K_{\omega 1}/K_{\omega 2}$	10	20	40	60	80	100	120	140	160	180	200
10	0,01	1,2	1	0,9	0,9	1,2	0,5	0,45	0,4	0,3	0,3
20	1	0,01	0,9	1	1	1	1,1	0,95	0,8	0,75	0,9
40	0,8	0,65	0,05	1	1,1	0,9	1,2	1,2	1,35	1	1,2
60	1,1	0,95	0,95	0,05	0,3	0,9	0,7	0,95	0,95	1,05	1,1
80	1	1	0,8	0,25	0,05	0,25	0,7	1,1	0,9	1	1,3
100	0,6	0,7	1,1	1,1	0,2	0,05	0,22	0,8	0,8	0,6	1,1
120	0,4	1	1,2	1	1,1	0,1	0,06	0,17	1,1	0,8	1,2
140	0,6	1,1	1,2	0,9	0,95	0,22	0,08	0,06	0,17	0,7	1,05
160	1,2	1	1,2	0,7	0,8	0,6	0,25	0,09	0,06	0,17	0.6
180	1,1	1,2	1,05	1,1	1,2	0,75	0,7	0,2	0,07	0,06	0,14
200	1	1,05	0,95	1,05	1,05	0,75	0,7	0,6	0,15	0,06	0,07

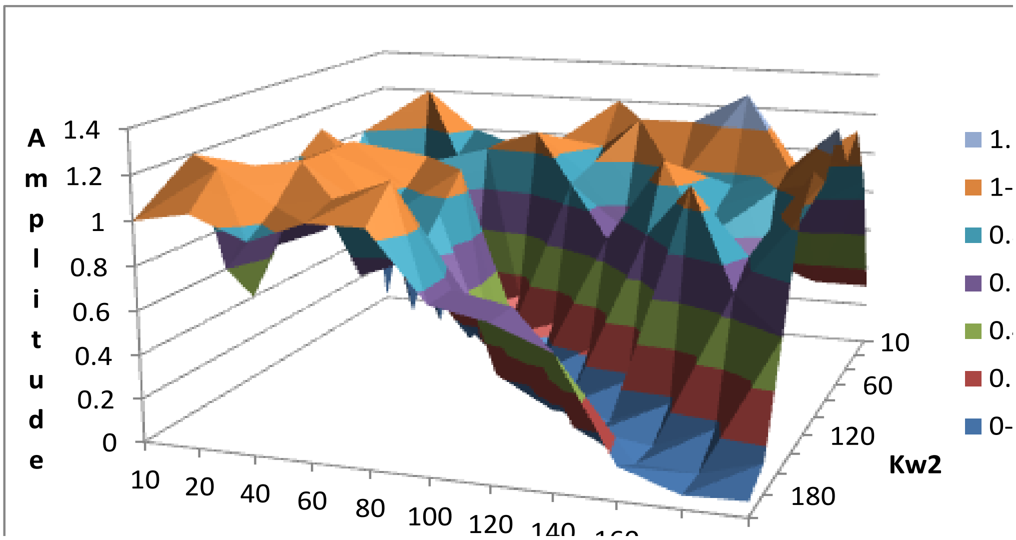

Fig. 7. Map of relationship between the amplitude of common-mode oscillations of the second diesel generator and the gain coefficients of frequency controller, $K_{\omega 1}$ and $K_{\omega 2}$ are controller gain coefficients of the first and the second parallel-running diesel generators, respectively

Fig. 8. Results of modeling: D_{n1}=0,002; D_{n2}=0,01; $K_{\omega 1}$=50; $K_{\omega 2}$=50; ω_{r01}=1,04; ω_{r02}=0,94. *I*A1, *I*A2 are currents of the parallel-running generators

Moreover, the selective modeling gave reason to think that the period of common-mode oscillations decreases with an increase in the difference in speed settings. Clarity of the nature of dependence of common-mode oscillation parameters on the ratio of setpoints for the frequency of rotation of frequency controllers appeared after modeling the entire field of possible setpoints ratios (table 3) and construction of graphical visualization of the results in the form of a setpoint map (Fig. 9). It should be noted that at equal rotation frequency setpoints there are no common-mode oscillations, and the results in the table correspond to the period of exchange power oscillations. This is also the main diagonal of the table from left to right from top to bottom. According to the modeling results, the common-mode power oscillations periods can be considered identical for both generating sets.

Table 3

Relationship between period of common-mode power oscillations and setpoint of frequency controller speed

$\omega_{r01}/\omega_{r02}$	0,9	0,92	0,94	0,96	0,98	1	1,02	1,04	1,06	1,08	1,1
0,9	0,55	0,4	0,5	0,4	0,5	0,4	0,15	0,1	0,1	0,1	0,1
0,92	0,4	0,55	0,4	0,5	0,4	0,5	0,4	0,15	0,15	0,15	0,1
0,94	0,45	0,4	0,55	0,4	0,5	0,4	0,5	0,4	0,15	0,15	0,15
0,96	0,4	0,5	0,4	0,55	0,4	0,5	0,4	0,5	0,4	0,15	0,15
0,98	0,5	0,4	0,5	0,45	0,55	0,4	0,5	0,4	0,5	0,4	0,15
1	0,45	0,5	0,4	0,5	0,4	0,55	0,4	0,5	0,4	0,5	0,4
1,02	0,15	0,4	0,5	0,4	0,5	0,4	0,55	0,4	0,5	0,4	0,5
1,04	0,1	0,15	0,4	0,5	0,4	0,5	0,4	0,55	0,45	0,5	0,4
1,06	0,1	0,15	0,15	0,4	0,5	0,4	0,5	0,45	0,55	0,4	0,5
1,08	0,1	0,15	0,15	0,15	0,4	0,5	0,4	0,5	0,4	0,55	0,4
1,1	0,1	0,1	0,15	0,15	0,15	0,4	0,5	0,4	0,5	0,4	0,55

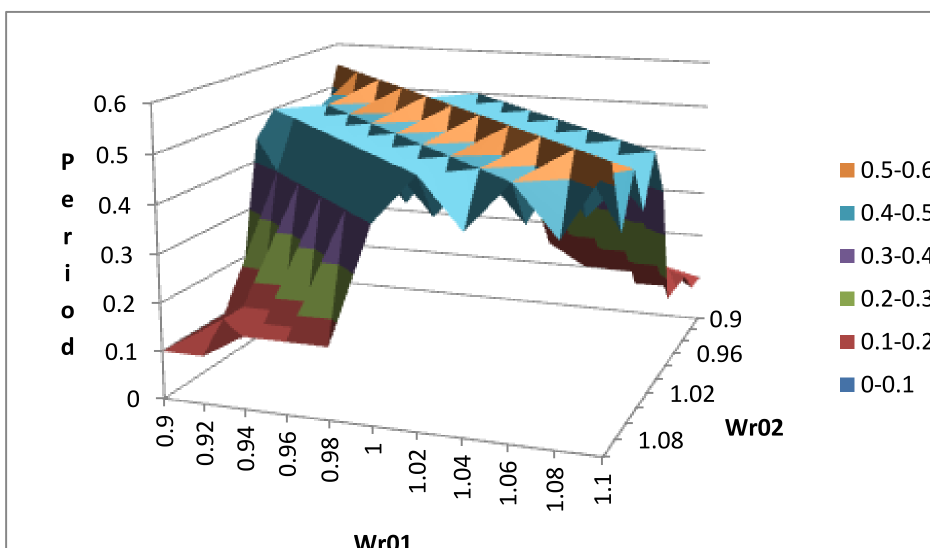

Fig. 9. Map of relationship between common-mode power oscillations period of diesel-generators and setpoints of frequency controller speed. ω_{r01} and ω_{r02} are setpoints of controller frequency of the first and second parallel-running diesel generators, respectively

Discussion

The research showed that common-mode power oscillations at parallel operation of diesel generator units can appear as a result of unequal settings of transmission coefficients and setpoints of controller rotation frequency. At the beginning of deviation of the transfer coefficients from equal values, an increase in the amplitude of common-mode oscillations is observed. When certain limit values are reached, the amplitude begins to oscillate around these values (see Fig. 6, 7). The amplitude of common-mode oscillations significantly exceeds the amplitude of the exchange power oscillations with the same backlash gaps. It should be noted that the amplitude of common-mode oscillations of the parallel-running generator, for which the controller transmission coefficient is more, is also greater. This is due to the fact that this generator will take on more load. However, the difference in load cannot be significant in terms of parallel operation of generating units of equal power, and, consequently, the amplitudes of common-mode oscillations do not differ much, usually the difference is no more than 10–15%.

When the frequency setpoints deviate from equal values, common-mode oscillations are observed, whose amplitude does not change, and the period decreases slightly in some limits, and then there is a rapid decrease and stabilization at values several times smaller (see Fig. 9).

The obtained maps, in addition to general information, describe in detail the common-mode power oscillations for 6VD26/20-AL-2 diesel generators with S450MG 800 kVA generators and can be useful to specialists who operate and set up such units. Similar studies aimed at construction of maps of dependence of the common-mode power oscillations parameters on the transmission coefficient settings and the setpoints for the controllers rotation frequency can be performed for any diesel generator units.

Conclusions

The obtained results are the evolution of work [6], aimed at the study of power oscillations during the parallel-running of diesel generator units as part of autonomous electrical systems. The developed method for construction maps of dependence of amplitude and period of common-mode power oscillations on transfer coefficients and setpoints for the controller rotation frequency can significantly improve the quality of parallel operation of diesel generator units. The algorithm for eliminating the exchange power oscillations is based on the change of the transfer coefficients and setpoints for the controller rotation frequency. Taking into account the obtained results, in order to preserve the stable operation of the autonomous electrotechnical complex, the change in settings of the frequency controllers for parallel operating units must be performed synchronously. The time for changing the settings of the driven units must be an order of magnitude shorter than that for the driving diesel generator [12]. Mapping the amplitude and period of common-mode power oscillations together with the amplitude settings of the exchange power oscillations depending on the backlash clearances allows obtaining an in-depth analysis of the operation of the autonomous electrical complex.

References

1. Lezhnyuk PD, Nikitorovich OV, Netrebskiy VV. Optimization of partition of load between the dispersed energy sources in the in-plant electric system. *Tekhnichna elektrodinamika*. 2012; 2:38-39. (In Ukraine).

2. Gracheva EI, Sadykov RR. The study of probabilistic characteristics of power supply systems. *Proceedings of the higher educational institutions. Energy sector problems*. 2014; 3–4:109-114. (In Russ).

3. Gracheva EI, Ilyasov II, Alimova AN. The comparative analysis and research of methods of calculation of losses of the electric power in the systems of electrical power supply of the industrial enterprises. *Power engineering: research, equipment, technology*. 2018; 20(3-4):62-71. DOI: doi.org/10.30724/1998-9903-2018-20-3-4-62-71. (In Russ.)

4. Nizamiev M.F., Ivshin I.V., Vladimirov O.V., et al. Izmeritel'no-diagnosticheskiy kompleks dlya diagnostiki energeticheskikh ustanovok. *Proceedings of the higher educational institutions. Energy sector problems.* 2014; 3-4:109-114. (In Russ).

5. Khvatov OS, Dar'Enkov AB. Power plant based on variable-speed diesel generator. *Russian Electrical*

Литература

1. Лежнюк П.Д., Никиторович А.В., Нетребский В.В. Оптимизация распределения нагрузки между рассредоточенными источниками энергии в локальной электрической системе // Технічна електродинаміка. 2012. № 2. С. 38-39.

2. Грачева Е.И., Садыков Р.Р. Исследование вероятностных характеристик систем электроснабжения // Известия высших учебных заведений. Проблемы энергетики. 2017. Т.19, № 1-2. С. 95-101.

3. Грачева Е.И., Ильясов И.И., Алимова А.Н. Сравнительный анализ и исследование методов расчета потерь электроэнергии в системах электроснабжения промышленных предприятий // Известия высших учебных заведений. Проблемы энергетики. 2018. Т.20, № 3-4. С. 62-71.

4. Низамиев М.Ф., Ившин И.В., Владимиров О.В., и др. Измерительно-диагностический комплекс для диагностики энергетических установок // Известия высших учебных заведений. Проблемы энергетики. 2014. № 3–4. С. 109-114.

5. Хватов О.С., Дарьенков А.Б. Электростанция на

Engineering. 2014; 85(3):145-149.

6. Savenko AE, Golubev AN. *Obmennye kolebaniya moshchnosti v sudovykh elektrotekhnicheskikh kompleksakh*. Ivanovo: Ivanovskiy gosudarstvennyy energeticheskiy universitet imeni V.I. Lenina, 2016. (In Russ).

7. Pyrhonen J, Jokinen T, Hrabovcov´a V. *Design of Rotating Electrical Machines*. John Wiley & Sons, Inc., Witshire; 2008.

8. Savenko A.E., Savenko P.S. Influence of backlash on amplitude of exchange power fluctuations in autonomous electric power equipment. *Power engineering: research, equipment, technology*. 2018; 20(5-6):46-54. DOI: doi.org/10.30724/1998-9903-2018-20-5-6-46-54. (In Russ.)

9. Savenko A.E. Matematicheskaya model' sudovogo elektrotekhnicheskogo kompleksa. *Vestnik IGEU*. 2015; 5:54-59. (In Russ.)

10. Golubev AN, Martynov VA, Alejnikov AV. Matematicheskaya model' dlya rascheta elektromagnitnykh sil v sinkhronnom elektroprivode s postoyannymi magnitami. *Vestnik IGEU*. 2015; 1:10-13. (In Russ.)

11. Reimert D. *Protective relaying for power generation systems.* Taylor and Francis Group, LLC. 2006.

12. Voronin AI, Tyutikov VV. Procedure for the synthesis of controllers for independent formation of static and dynamic parameters of nonlinear objects. *Izvestiya sfedu. Engineering sciences*. 2015; 3(164):154–164. (In Russ).

базе дизель-генератора переменной частоты вращения // Электротехника. 2014. № 3. С. 28-32.

6. Савенко А.Е., Голубев А.Н. Обменные колебания мощности в судовых электротехнических комплексах. Иваново: Ивановский государственный энергетический университет имени В.И. Ленина, 2016. 172 с.

7. Pyrhonen J., Jokinen T., Hrabovcov´a V. Design of Rotating Electrical Machines. John Wiley & Sons, Inc., Witshire; 2008. 531 p.

8. Савенко А.Е., Савенко П.С. Влияние люфта на амплитуду обменных колебаний мощности в автономных электротехнических комплексах // Известия высших учебных заведений. Проблемы энергетики. 2018. Т. 20, № 5-6. С. 46-54.

9. Савенко А.Е. Математическая модель судового электротехнического комплекса // Вестник ИГЭУ. 2015. № 5. С. 54-59.

10. Голубев А.Н., Мартынов В.А., Алейников А.В. Математическая модель для расчета электромагнитных сил в синхронном электроприводе с постоянными магнитами // Вестник ИГЭУ. 2015. № 1. С. 10-13.

11. Reimert D. Protective relaying for power generation systems. Taylor and Francis Group, LLC. 2006. 545 p.

12. Воронин А.И., Тютиков В.В. Методика синтеза регуляторов для независимого формирования статических и динамических показателей нелинейных объектов // Известия ЮФУ. Технические науки. 2015. № 3(164). С. 154-164.

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