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DEVELOPMENT OF A VALVE GENERATOR WITH A VARIABLE FREQUENCY OF ROTATION

Abstract. The article deals with the maintenance of the required value of the output voltage on an electric generator driven by a variable speed shaft. Schemes for creating such a synchronous generator with the possibility of combining the winding armature connections depending on the frequency of rotation of the rotor shaft are proposed. A test sample was tested without a gear generator, and experimental data were presented.
Key words: electric generator, rotational speed, anchor winding, valve switch, rectifier, inverter.

Introduction. Interruptions in power supply of agricultural production cause significant material damage and disorganise the process. To prevent such consequences on the farming objects of Kazakhstan is quite a difficult task since they do not have network redundancy and are far from large settlements and each other. At the same time, a significant part of agricultural products of Kazakhstan (about 90%) is produced in numerous (more than 250 thousand) peasant, farmer and cooperative farms of relatively small and medium size [1]. At such facilities, the use of traditional (petrol and diesel) or non-traditional (solar, wind, etc.) sources of electricity is uneconomical. In the literary sources [2] for the backup power supply of low-power agricultural facilities tractor driven power generator sets (PGST) are recommended.

It should be noted that the existing PGST is designed to operate from a power shaft (PS) with a specific rotational speed (mostly 1000 rpm) and have different rotational speed conversion mechanisms (gear reducers, massive pulleys, etc.) since they have synchronous generators with speeds of 1500 and 3000 rpm. The used rotational speed conversion mechanisms increase the weight of the PGST, reduce the reliability of the design and require additional maintenance [1, 2].

One of the essential differences between renewable energy is the lack of predictability and lack of control by the consumer. Ensuring reliable power supply can be achieved using a combination of traditional hydrocarbon fuels and renewable energy sources. As a reliable source based on hydrocarbon fuels, a diesel generator has found the full application. Recently, gas-piston and gas-turbine installations have become popular. The advantage of diesel power plants (DPP) is their versatility, low cost and fast payback period. The versatility of internal combustion engines is the ability to use a power shaft for rotating an electric generator and to provide a mobile autonomous power supply system.

The economic efficiency of diesel power plants, including gasoline, is determined by the specific consumption, which is equal to the ratio of energy production to fuel consumption for an hour. Particular use depends on the operating conditions: temperature of the environment, load, speed.

The majority of DPP includes a frequency rotation regulator, output voltage values. This configuration allows connecting a load of AC directly to the generator. As synchronous generator machines and, more rarely, asynchronous tools are more often used. To maintain the frequency constant of the current, the drive motor must rotate at a constant speed, regardless of the load. Maintaining the nominal rate at low pressure increases the specific fuel consumption and reduces the working life, which is reflected in the cost of generated electricity. Resource reduction is associated with *cylinder coking*. It occurs when the load is reduced to less than 20% of the rated, and the rated speed is maintained. In the conditions of remoteness and lack of centralised power supply, the relevance of issues of reducing the cost of electricity and increasing equipment life is very high [3]. In the articles [4, 5], the authors present the results of an experimental study of the efficiency of using variable speeds of diesel generators by the load change. A comprehensive analysis of many operational indicators was carried out: emissions, consumption, power quality. From the study of the results of experiments, it follows that a change in rotational speed with a change in load can *reduce fuel consumption* by 20%. The dependence of the reduction in specific consumption with decreasing pressure with a corresponding decrease in rotational speed is almost straightforward. When reducing the load to 40% of the nominal value, the maximum rate should be reduced to an amount of 50% of the nominal value.

Further reduction of the rotational speed leads to unstable operation of the diesel engine, into the flesh to a complete stop. When loading below 40%, specific consumption is growing. The articles [6, 8, 9] provide an analysis of the effect of loading inverter diesel generators on their specific fuel consumption. The experiments were carried out using diesel power plants of various capacities 10 kW (KDE12 EA3) and 200 kW (8ЧН13 / 14 (ЯМЗ 33-238Н)). The results of the tests showed similar speed optimal modes. In the figure 1, the optimal speeds of diesel power plants are given in the electrical load changes. For ease of analysis, the characteristics are constructed in relative units.

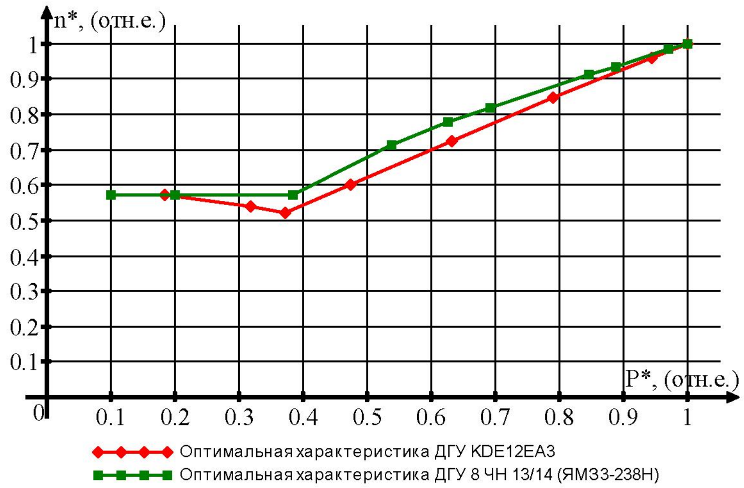


Figure 1 – The optimal speed mode with variable DPP load

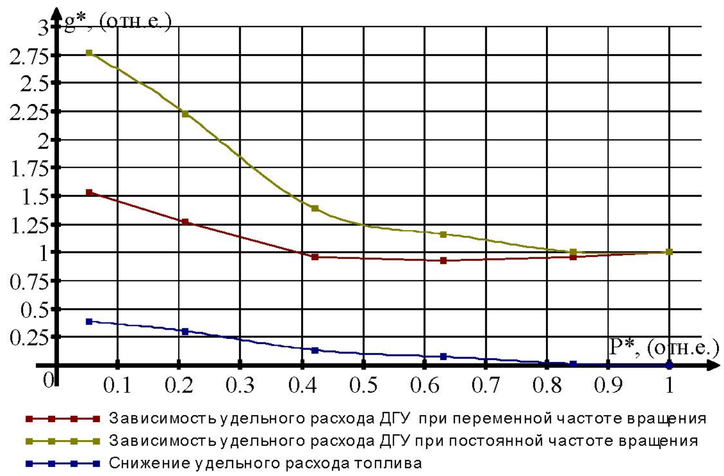


Figure 2 – The specific flow diagram is when the rotational speed is coordinated
with the rotational speed and while maintaining a constant rotational speed of DPP KDE12 EA3

When working on a free load, the typical load change schedule is variable, and there is a probability of pressure occurring less than 15% [5].

The decrease in the specific consumption from the rotational speed matching with the KDE12 EA3 engine load is shown in figure 2. It can be seen from the figure that for autonomous consumers, fuel savings at low pressures can bring savings of up to 30%.

This mode of operation of the drive motor imposes its requirements on an electromechanical converter, which may consist of an electric generator or an electric generator with voltage converters (rectifiers, inverters). It is necessary to analyse the consistency of the characteristics of the engine with the features of the generator. The main requirement for coordinated operation of a generator with a drive engine is to maintain the voltage value and satisfactory efficiency at a variable frequency of rotation and power.

Formulation of the problem. When used as a drive motor, the power take-off shaft of agricultural machinery poses the problem of matching the speed modes of the generator and the power take-off shaft: obtaining the required voltage from the drives at different speeds or obtaining the energy of varying magnitude from one trip. At variable or different rates, the question arises of ensuring the constancy of the frequency of the alternating current and ensuring the required voltage value. There are two leading solutions: the use of synchronised asynchronous generators and the use of valve-type asynchronous and synchronous generators. According to the authors, one of the promising solutions is a variant using a valve-type synchronous generator and an autonomous inverter, which converts direct current from the rectifier into alternating current with a constant frequency. Such installations are recently called inverter diesel generators [6].

Synchronised asynchronous generators is an asynchronous machine with a phase rotor [3-5]. The study of operating modes of devices of this type in diesel plants with variable rotational speeds is considered in the works [10]. The stator winding is connected to the mains or the consumer directly, and the phase winding of the rotor is connected to the frequency converter. The frequency of the stator winding depends on the slip s; therefore, the condition of maintaining a constant rate f_2 is made by smoothly adjusting the frequency of the current in the rotor f_1. Therefore, when a frequency converter changes the rotor speed, the frequency of the current in the rotor is inversely proportional by reducing the rate of rotation of the frequency of the current in the rotor increases. The supply of the rotor winding with a voltage of increased frequency leads to an increase in losses in steel and the rotor winding. Losses will increase in modes other than the calculated ones, which means an increase in losses at rotational frequencies lower than the calculated ones, which reduces ECE at low revs. This was reflected in the limited range of changes in power in the article [5, 6]. The works provide data on the shift in generator ECE with power changes. For a machine with a rated power of 150 kW, the deviation of the ECE value of 2-5% is maintained at a lower power value of 50 kW. The article [4, 5] discusses the use of machines in the range of variation of the rotational speed of 950-1050 rpm.

In autonomous power plants, synchronous generators with claw-shaped poles, inductor generators and, less commonly, asynchronous generators, are widely used. The main criterion in favour of the listed generators is the mechanical reliability of the structure (the ability to operate at high speeds), low weight and dimensions[11], and a soft external characteristic improves the consistency of the generator characteristics with batteries, by limiting the load current.

According to the results of the research [6], it was shown that traditional generators without additional devices could not ensure the maintenance of the voltage value. By reducing the speed below 53-55% ensure the preservation of voltage due to saturation of the magnetic circuit of the generator. The more extensive the frequency change range, the lower the generator ECE. The use of inverters with maintaining a constant voltage value with a change in the input voltage can extend the working field. However, the question of maintaining the ECE of the generator does not provide such a solution.

Thus, the development of a universal generator rotating from a power shaft with different and variable rotational speeds and at the same time maintaining the required voltage and satisfactory ECE without using specialised devices is relevant.

A group of scientists of the Almaty University of Power Engineering and Telecommunications has developed an electromechanical converter with a wide range of rotational frequency and power, capable of maintaining a constant voltage value with a cubic dependence of energy on the rotational frequency. The electromechanical converter operates at a reduction of the nominal (calculated) speed of more than five times, and power, respectively, more than 125 times and at the same time maintains a satisfactory value of ECE in the range from 0.75 to 0.94 [12]. The idea of development is to manufacture the anchor winding of the generator from several parallel branches connected to their rectifier and forming valve blocks. The valve blocks are combined into a switched rectifier with the possibility of changing in series, in parallel and series in parallel. In fact, in one case several generators are connected for different operating modes. The switched rectifier is a discrete regulator and the smooth maintenance of the voltage produced by the excitation current. A switched rectifier dynamically changes the stages under load. Implementing a dynamic switching without a switched rectifier will be difficult. Therefore, when working as part of a wind power plant, a large number of parallel branches with a minimum number of switching contactors is justified by the scheme.

When working as part of DPP the range of rotational speed variation is 1: 2, the rotational speeds of the power take-off shaft may differ by three times for different agricultural equipment. Figure 3 shows a schematic solution for a universal generator for free use, but by switching the armature winding circuit in it is made without load.

Therefore, it is proposed to adapt the idea of an electromechanical converter with a switched rectifier [12] to agricultural installations and technology. Universal valve generator should operate at different speeds of 1: 3 and power (in the range of 1: 4 or more).

The valve generator presented on figure 3, which has an anchor winding consisting of "n" parallel branches (in the particular case n = 2) and "n" switching devices, and one single-phase rectifier. The beginning of the first parallel branch is connected and forms a star connection. The ends and the beginning of the other parallel branches through the switching devices are connected and with the rectifier through switching devices. The ends of one of the parallel branches are connected to the rectifier.

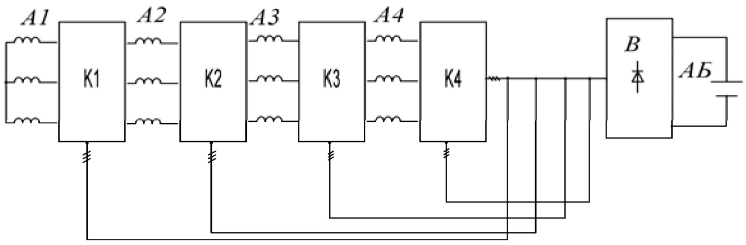


Figure 3 – Valve generator

A change in the connection scheme of parallel branches is made on the AC side, which imposes additional requirements on switching equipment. The development of semiconductor switches of alternating current makes it possible to abandon the switching of valve blocks with each other on direct current.

At a high frequency of rotation, the switching devices connect all the parallel branches according to the "star" scheme and parallel to each other, each of which is connected to a rectifier. When operating at a lower frequency of rotation, the switching devices connect lateral branches in series with each other. The number of switches depends on the number of parallel branches.

A circuit solution is proposed for a universal valve generator rotating from a power take-off shaft with the various and variable rotational speed with the maintenance of the required voltage value and satisfactory ECE.

From the previously developed circuit solutions of an electromechanical converter with a switched rectifier, this circuit solution is distinguished by the possibility of using a standard rectifier and the option of turning on the AC side.

Theory. According to the theory of electric cars, the output voltage of the generator can be determined by the expression [13]:

$$U_{Г} = 4{,}44 \cdot f \cdot W_{ф1} \cdot Ф = 4{,}44 \frac{p \cdot n}{60} W_{ф1} \cdot \alpha \cdot \tau \cdot l \cdot B_{\delta} = 4{,}44 \frac{p \cdot \tau \cdot l \cdot \alpha}{60} W_{ф1} \cdot n \cdot B_{\delta} = K_{Г} \cdot W_{ф1} \cdot n \cdot B_{\delta}, \quad (1)$$

where $W_{\Phi 1}$ – the number of effective the number of effective turns in one parallel phase branch; B_δ – air-gap induction; $K_Г$ – constructive constant of generator; *p* - number of pole pairs; *α* – pole overlap coeffi-cient; *τ* – pole division; *l* – length of the core; *f* - current of frequency; *n* – calculated frequency of rotation.

From the phrase it is seen that reducing the rotational speed twice will require a corresponding increase in induction (excitation current), which in turn will lead to a rise in losses in the excitation winding and saturation of the magnet wire. According to the recommendation for the design of electric machines, the induction in the air gap is taken in the range of 0.6-0.7 T, while the selection in the prongs usually reaches a value of 1.3-1.6 T, and the saturation of electrical steel in the field of 1.8-1, 9 T [14]. Consequently, there is no possibility of increasing the induction in the air gap in proportion to the change in rotational speed. Designing a machine with a low induction value will lead to oversized weight and size indicators and an increase in the influence of the armature response on the load characteristics. This follows from the expression defining the Arnold coefficient [13]:

$$\frac{D^2 l_1 n}{P^{/}} = \frac{6{,}1 \cdot 10^7}{(\alpha_i k_\Phi k_o A B_\delta)} = C_A \ , \qquad (2)$$

where C_A – Arnold machine constant; *P* – rated power; k_Φ – curvy field form factor; k_o – winding coefficient; *A* – linear load.

As follows from expression (1) with low induction, there is need to increase the number of turns in the winding, and this, in turn, will affect the magnitude of the reaction of the armature, as follows from the expression [13]:

$$F_P = 0{,}9 \cdot m \frac{W_1 \cdot k_0}{p} \cdot I_\Phi , \qquad (3)$$

where *m* – number of phases; I_Φ – phase current.

For the proposed circuit design of the valve generator, the expression for determining the voltage varies as follows.

The voltage of the universal generator with two parallel branches, according to its concept, allows two stages of switching the connection circuit of the winding branches and are determined by the expressions:

- the first stage, at the highest rotation frequency, all the branches are parallel [12-14]:

$$U_Г = U_1 + U_2 = K_Г \cdot W_{\Phi 1} \cdot n \cdot B_\delta \qquad (4)$$

- the second stage of the branch is connected in consistently;

$$U_Г = U_1 + U_2 = 2W_{\Phi 1}(K_Г \cdot n \cdot B_\delta) \ . \qquad (5)$$

Expression (1) can be rewritten as follows:

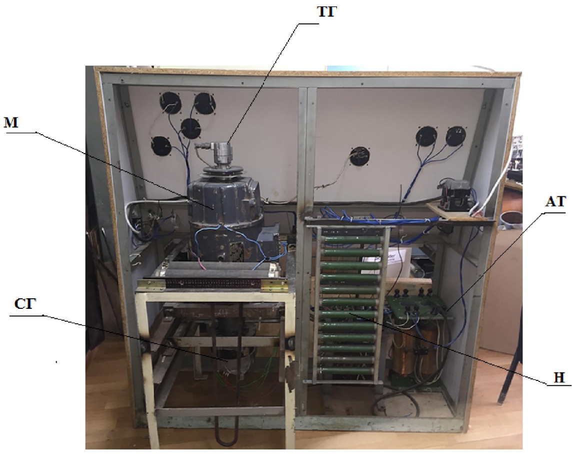
$$U_Г = U_1 + U_2 = a \cdot W_{\Phi 1} \cdot K_Г \cdot n \cdot B_\delta \ . \qquad (6)$$

Switching the connection pattern of parallel branches is equivalent to changing the number of turns in parallel branches of the armature winding. According to expression (1), as the windings increase in the winding, the induction required to maintain the voltage decreases.

Results of experiment. The efficiency of the concept was tested on an experimental setup, which is shown in figure 4.

The test bench is assembled at a laboratory based at the Almaty University of Power Engineering and Telecommunications. As the generator was used automotive type generator G-286V (SG). The main technical characteristics of the generator type G-286V, rated voltage 14 V, rated current 50 A, the rota-tional speed with voltage regulator during self-excitation and voltage 13V without load 650 rpm, with load current 20A at 750 rpm.

The maximum load current is 75A and at 5000 rpm. The generator is rotated by a driving motor (M) of a direct current P32M, with a power of 2.2 kW, with a nominal speed of 1500 rpm. The anchor winding of the generator is rewound and made with two parallel branches for a voltage of 24 V. The field winding has not changed.



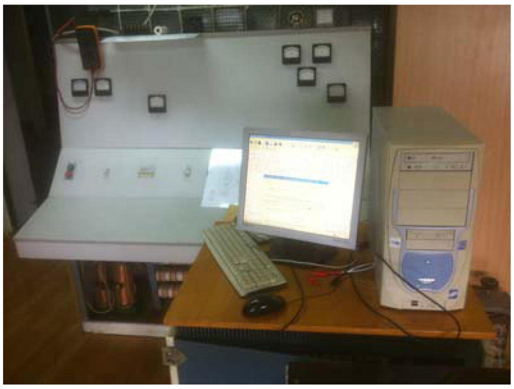


Figure 4 – Exterior view of the test bench

A schematic diagram of the test bench is shown in figure 5. The power shaft was modelled by a DC motor of independent excitation P-32M (M), with a power of 2.2 kW and a rotational speed of 1500 rpm. Regulation of the frequency of rotation of the generator was made by regulating the voltage of the engine through an autotransformer.

According to the concept, the synchronous generator SG is connected to the shaft by a drive motor M in which the angular velocity is measured with the TG tach generator TG. The windings of the SG are divided into two parallel branches A1 and A2, which are connected to the rectifier through the switching keys K1 and K2.

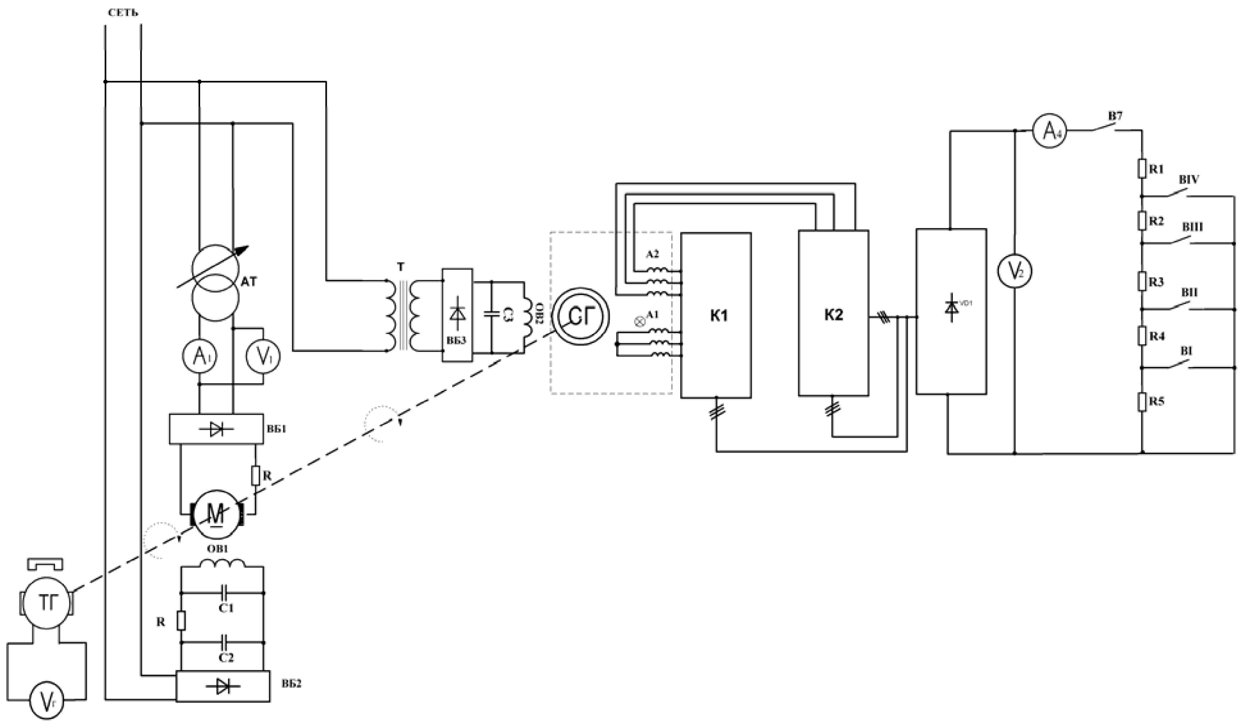


Figure 5 – Schematic diagram of the test bench

Voltage in parallel branches was measured on the DC side at the terminals of the rectifiers and the AC side at the terminals of the parallel branches.

Based on the experimental data in figure 6 shows a unique characteristic of idling.

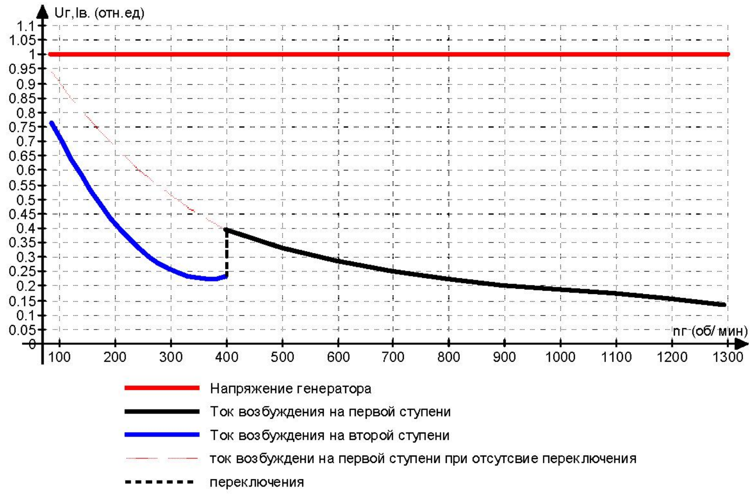


Figure 6 – The special characteristic of idling of the generator

It is built at a constant voltage (line 1) and when the rotational speed changes from 1250 to 100 rpm. To match the scale of the voltage and excitation current of the generator, they are built in relative values. The voltage throughout the entire range of changes in rotational speed is equal to the nominal value, and in relative units, it is taken as a unit. The excitation current at a rotational speed of 100 rpm is 3 A, and this maximum value is considered as a unit.

Switching parallel branches makes it possible to increase or decrease the voltage value following the needs. Figure 7 shows the experimental characteristics of idling.

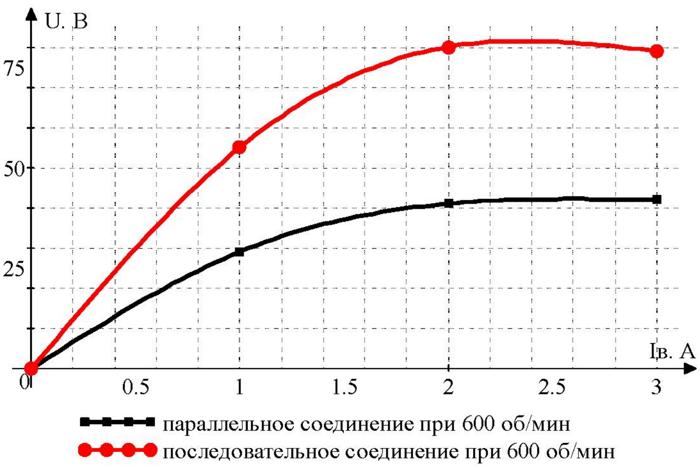


Figure 7 – Special idle characteristic

Discussion of the results. The experiment used an automotive generator G286V, which was rewound at a design speed of 1200 rpm. The number of parallel branches taken a = 2, power 300 watts. According to the concept of a valve generator, with "a = 2" the number of stages is 2. In figure 6 voltage line (line 1) excitation current in two steps (curves 2, 3) are given. The dotted line shows the change in the excitation current in the absence of switching. According to the experimental results it can be seen that the generator voltage is kept constant throughout the entire range of rotational speed.

Recalculation of the generator was carried out on the calculated rotational speed of 1200 rpm. and with a lower calculated induction in the air gap of 0.2 Tesla. The range of variation of the excitation current is from 0.4 to 3 A. On the graph, the maximum value of the excitation current is 3A. The curve of the excitation current in the first stage in the absence of switching in relative units varies in the range from

0.15 to 0.9. The wide range is due to the low value of the calculated induction. Turning to the next stage reduces, according to the concept, the amount of the excitation current by two times (dotted curve line connecting curve 2 and 3). Characteristic of idling VG is determined by the dependence of the excitation current $I_в$ on the rotation frequency $n_г$, with a constant output voltage $U_Г$=const and $I_н$=0. It can be seen from the figure that when idling at lower speeds to avoid steel saturation by switching the connection circuit of parallel branches, the excitation current can be reduced with constant maintenance of the output voltage.

In figure 7 when switching the circuit for connecting the parallel branches, it can be seen that, with two parallel branches, switching from a parallel connection to a serial one increases the voltage twice. At the same time, the rotational speed remains constant. The range of voltage variation while maintaining the rotational speed is directly proportional to the number of parallel branches. The generator power depends on the frequency of the calculated rotational speed and is determined by the expression (2).

Findings and conclusion. The article speaks on the efficiency of the proposed concept of a valve generator for an autonomous power plant intended for remote agricultural consumers, designed to generate voltages of various sizes at constant speeds or to maintain a constant value of energy at different rates [15].

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ЖИІЛІГІ ӨЗГЕРІСТІ БІЛІГІ БАР ЖЕТЕГІНДЕГІ ВЕНТИЛДІ ЭЛЕКТРОГЕНЕРАТОРДЫ ЖАСАУ

Аннотация. Мақалада жиілігі өзгерісті білігі бар жетегіндегі вентилді электрогенератордағы шығыс кернеуі деңгейін қажетті мәнде тұрақтандыру сұрақтары қарастырылды. Ротор білігінің айналу жиілігінен якор орамдарының әмбебап қосылу мүмкіндігі бар синхронды генератор сұлбасы ұсынылды. Редукторсыз жалғанған электргенератордың тәжірбиелік үлгісі сынақтан өткізіліп эксперименттік мәліметтер келтірілген.

Түйін сөздер: электрлік генератор, айналу жиілігі, якорлық орам, вентильді коммутатор, түзеткіш, инвертор.

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РАЗРАБОТКА ВЕНТИЛЬНОГО ЭЛЕКТРОГЕНЕРАТОРА С ПРИВОДОМ ОТ ВАЛА ПЕРЕМЕННОЙ ЧАСТОТЫ ВРАЩЕНИЯ

Аннотация. В статье рассматриваются вопросы поддержания требуемого значения выходного напряжения на электрогенераторе с приводом от вала с переменной частотой вращения. Предложены схемы создания такого синхронного генератора с возможностью комбинирования соединений обмоток якоря в зависимости от частоты вращения вала ротора. Проведено тестирование опытного образца безредукторного электрогенератора и представлены экспериментальные данные.

Ключевые слова: электрический генератор, частота вращения, якорная обмотка, вентильный коммутатор, выпрямитель, инвертор.

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