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INVESTIGATION OF DC-AC CONVERTER WITH MICROCONTROLLER CONTROL OF INVERTER FREQUENCY

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Abstract. *The paper discusses the key aspects of the development of a frequency-controlled direct current to alternating current (DC-AC) converter based on a microcontroller. Electric energy converters play an important role in ensuring energy stability, especially in the conditions of frequent and unpredictable power outages, which are characteristic of Ukraine. Emphasis is placed on improving the parameters of the inverter to increase its efficiency, stability of operation, and the possibility of using alternative energy sources, such as batteries and solar panels. The work investigates the structure and principle of operation of the inverter, which includes such main components as a direct current source, a MOSFET bridge, a low-frequency filter, and an output transformer. A voltage frequency control circuit using an ATmega328P microcontroller is proposed, which allows for maintaining a stable output voltage under conditions of changing input voltage parameters. The research methodology involved conducting an experimental analysis based on a symmetric non-composite Box-Benkin plan, which made it possible to optimize the design of the device. In particular, the influence of the parameters of the secondary winding of the transformer, the power of the transistors, and the input voltage on the output power of the device was studied. The obtained results demonstrated the efficiency of the device with a rational choice of element base. In the course of the research, a mathematical model of the process of optimizing the converter parameters was developed. It was concluded that increasing the power of field-effect transistors and changing the geometrical parameters of the transformer contribute to increasing the performance of the device. Prospects for further research include modernization of the microcontroller software, integration of protective sensors, and adaptation of the device to work with different types of loads.*

Keywords: inverter, frequency control, microcontroller, optimization, renewable energy

BADANIA PRZETWORNIKA DC-AC Z MIKROKONTROLEREM STERUJĄCYM CZĘSTOTLIWOŚCIĄ INWERTERA

Streszczenie. *W artykule omówiono kluczowe aspekty rozwoju przetwornicy prądu stałego na prąd przemienny (DC-AC) sterowanej częstotliwościowo na bazie mikrokontrolera. Przetwornice energii elektrycznej odgrywają ważną rolę w zapewnieniu stabilności energetycznej, zwłaszcza w warunkach częstych i nieprzewidywalnych przerw w dostawie prądu, które są charakterystyczne dla Ukrainy. Nacisk położono na poprawę parametrów przetwornicy w celu zwiększenia jej sprawności, stabilności pracy i możliwości wykorzystania alternatywnych źródeł energii, takich jak baterie i panele słoneczne. W pracy zbadano strukturę i zasadę działania przetwornicy, która obejmuje takie główne elementy, jak źródło prądu stałego, mostek MOSFET, filtr niskiej częstotliwości i transformator wyjściowy. Zaproponowano obwód sterowania częstotliwością napięcia z wykorzystaniem mikrokontrolera ATmega328P, który umożliwia utrzymanie stabilnego napięcia wyjściowego w warunkach zmieniających się parametrów napięcia wejściowego. Metodyka badań obejmowała przeprowadzenie analizy eksperymentalnej opartej na symetrycznym niekompozytowym planie Boxa-Benkina, co pozwoliło na optymalizację konstrukcji urządzenia. W szczególności zbadano wpływ parametrów uzwojenia wtórnego transformatora, mocy tranzystorów i napięcia wejściowego na moc wyjściową urządzenia. Uzyskane wyniki wykazały wydajność urządzenia przy racjonalnym wyborze bazy elementów. W toku badań opracowano model matematyczny procesu optymalizacji parametrów przekształtnika. Stwierdzono, że zwiększenie mocy tranzystorów polowych i zmiana parametrów geometrycznych transformatora przyczyniają się do zwiększenia wydajności urządzenia. Perspektywy dalszych badań obejmują modernizację oprogramowania mikrokontrolera, integrację czujników ochronnych i dostosowanie urządzenia do pracy z różnymi typami obciążeń.*

Słowa kluczowe: inwerter, regulacja częstotliwości, mikrokontroler, optymalizacja, energia odnawialna

Introduction

An electrical energy converter is a device that connects two or more electrical systems with different parameters and allows for changing these parameters according to a given law, ensuring the exchange of electrical energy between these systems [13]. Semiconductor voltage converters connect alternating and direct current systems, namely inverters of direct voltage to alternating current [2]. Energy stability is the most important aspect of modern society's functioning. However, in many countries, especially in Ukraine, the energy infrastructure is often severely tested by external and internal factors, which leads to long-term blackouts. Power outages cause significant inconvenience to the public and can have serious consequences for industry, commerce, healthcare facilities, and general economic stability. In this regard, the issue of providing backup power and developing effective solutions for emergencies is more relevant than ever. One of the important means of overcoming the consequences of a power outage is the use of an inverter – a device that converts direct current (DC) into alternating current (AC). Inverters are key components in backup power systems, such as batteries or PV generators, that can keep critical equipment running in the absence of mains power. In the case of frequent and unpredictable power outages, the creation of simple and reliable inverter circuits becomes an integral part of the energy security strategy. As a rule, existing inverters on the market offer a wide range of functions and complex circuits, but the price and complexity of maintenance of such devices are an obstacle to large-scale use in the private sector. In addition, installing and configuring complex systems often requires specialized knowledge, which can be a challenge for untrained users. Common problems with inverters include poor efficiency, excessive standby power consumption, and difficulty in repair and maintenance. A lack of reliable control schemes and control mechanisms can lead to unnecessary inverter failures or even inverter failures in case of sudden voltage or load surges [12].

Another promising technology is the use of microcontrollers for flexible control of inverters. Microcontrollers make it possible to increase the energy efficiency of the device, optimizing its operation in standby mode and under light loads, and also provide more accurate control of the output parameters of the alternating current. The purpose of the study is to study the DC-AC converter with microcontroller frequency control of the inverter. This will allow us to automate and improve the characteristics of the device, as well as to conduct analysis and research of the input and output parameters of the electric current.

The research will be carried out in the following stages:

1. Analysis of input and output parameters of the DC-AC converter.
2. Identification and systematization of factors influencing the output data of the device.
3. Optimization of the element base of the DC-AC converter to improve its technical characteristics.

1. Literature review

Energy converters based on electromechanical devices were the first to appear [11]. The electric motor converted electrical energy into mechanical energy, which, with the help of a generator, was converted into electrical energy with the required parameters [7]. Modern energy conversion devices do not contain moving elements, so they are called static converters, in particular, DC-AC inverters convert a constant voltage of 12 V into an alternating voltage of 220 V. The inverter is much cheaper than a mini power station, it is miniature and light [14]. Together with one or several batteries, it can work as an autonomous source of uninterrupted power for the house, boiler room, fire, and security systems. If there is a mains voltage of 220 V, it simply passes it "through" itself and, if necessary, charges the batteries. If the voltage in the network disappears, the inverter instantly starts generating an alternating voltage of 220 V from the batteries [5]. The time of autonomous operation depends on the power of the load and the capacity of the batteries. So, for example, four batteries of 190 A/h are enough for approximately 16 hours of autonomous operation at a constant load of 0.5 kW [6]. When the mains voltage appears, the device will automatically switch to the initial standby state and charge the batteries.

The most popular technical solutions for DC-AC inverters are bridge inverter circuits and their modifications [15]. At the input of the power two-stage filter, the cascade forms multi-pulse sequences. The power transformer, which is part of the constant voltage converter, is powered by the bridge cascade of MOSFET transistors [10]. With this version of the inverter construction, despite the additional energy conversion in the pulse voltage converter (440 V), with a rational design of the constant voltage converter (in this case, the operating frequency is 80 kHz), high energy and mass-dimensional characteristics are achieved (Fig. 1) [4].

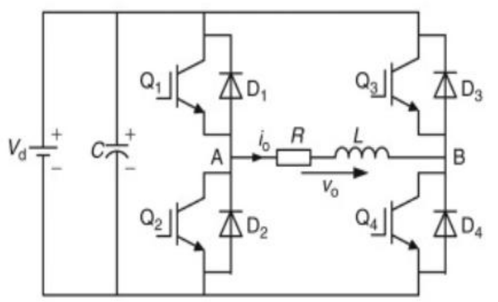

Fig. 1. Typical DC–AC inverter [4]

Two-stroke circuits made on field-effect transistors have become the most widely used in industrial design. The bridge stage and the power filter are covered by negative feedback, which ensures high energy characteristics of the inverter. To ensure the required form of the sinusoidal output voltage, a double-circuit LC filter of alternating current is used, which performs the functions of a choke made on a ring core with MO – permalloy (Fig. 2) [4, 8].

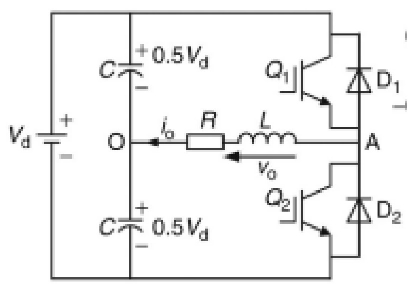

Fig. 2. Single-phase half-bridge inverter [4]

The main components of the inverter circuit:

- direct current (DC) power source;
- DC converter (necessary for the output to have the appropriate voltage level);
- MOSFET inverter bridge;
- pulse generator (PWM controller);
- low-pass filter;
- output transformer.

Advantages of the inventory scheme:

The possibility of using alternative energy sources (this inverter circuit allows the use of batteries, solar panels, and other sources of direct current to power devices that require alternating current power), is especially important for renewable energy systems.

1. Backup power supply in the event of a power outage (allows you to power the equipment during a power outage).
2. Compactness and mobility (can be portable for use in remote or emergencies).
3. Flexible application (can be used with different types of loads, they allow you to adjust the alternating voltage and frequency according to the requirements of a specific device).
4. High efficiency (PWM technology is used to ensure high efficiency of energy conversion while minimizing heat loss or noise).
5. Overvoltage and short circuit protection.

2. Researches methodology

The research methodology is as follows:

- the influence of the geometric parameters of the secondary winding of the transformer on the output power of the voltage converter was investigated;
- laboratory tests of the developed device for voltage conversion were carried out using the mathematical method of planning the experiment on four factors on three levels, namely the symmetrical non-composite plan for the implementation of the second-order Box-Benkin experiment [1];
- the influence of input voltage, output frequency, power of transistors, geometric parameters of the secondary winding of the transformer on the output power of the DC-AC inverter was investigated. The structural diagram of the device is shown in Figure 3.

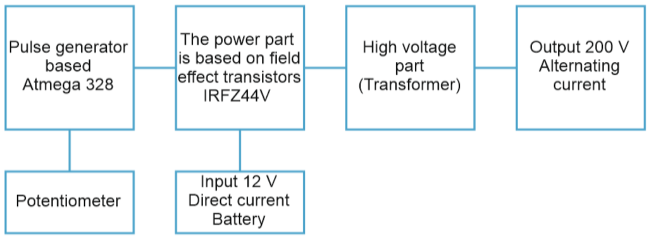

Fig. 3. Structural scheme of the experimental sample

The DC power source, most commonly a 12 V battery, is connected to the transformer via a three-position switch. The commutator is a set of electronic switches that provides 3 states: a power source of positive polarity is connected to the primary winding of the transformer, a power source of negative polarity is connected to the primary winding of the transformer, and the state when the primary winding is short-circuited. By sequentially switching these states, an alternating voltage with a frequency of 50 Hz and an amplitude of 12 V is formed on the primary winding. At the same time, a voltage with the same frequency and form is formed on the secondary winding of the transformer, but the effective voltage is 220 V. Idealized graphs of the voltage on the transformer are shown in Figure 4 [3, 9]. The output voltage is removed from the secondary winding, so it has similar parameters.

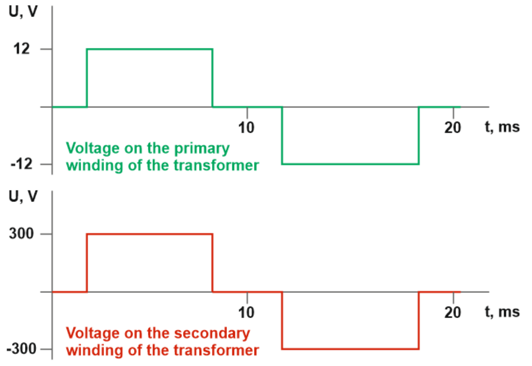

Fig. 4. Voltage graphs of the "modified sine wave" type on the transformer [3]

This form of voltage is called "modified sine wave" and is widely used in inverters for the 50 Hz network. In general, the parameters that determine the shape of the modified sinusoid are the amplitude of the output voltage and the fill factor, which shows the ratio of the pulse duration to the signal period. These parameters are set when designing inverters. Because the inverter must replace the 220 V / 50 Hz network, the amplitude value of the modified sine wave voltage is usually ≈ 310 V. At the same time, to ensure an effective voltage of 220 V, the same as in the network, the filling factor is 0.5. However, in this type of inverter, the amplitude of the output voltage is directly proportional to the source voltage. If a battery is used as an energy source, and this is the most common case, then its voltage during discharge decreases, and the amplitude of the modified sine wave at the output of the converter also decreases, accordingly, the effective value of the voltage at the output of the converter decreases. To improve the power quality at the output of the converter in these conditions, control circuits are often used that change the duty cycle of the output voltage to keep the effective voltage constant..

Figure 3 shows the block diagram of the device, the algorithm of which consists of alternately turning on and off the 17th and 18th pins of the ATmega 328P microcontroller. The corresponding signals are sent to the gates of the field-effect transistors, which in turn control the voltage and current on the transformer, which raises the voltage from 12 V to 220 V. For example, an inverter designed for a 12 V source voltage works from a discharged battery with a voltage of 10 V. At the same time, the amplitude of the output voltage decreases proportionally to 259 V. The control scheme changes the filling factor of the output voltage to 0.72, while the effective voltage remains equal to 220 V. However, the shape of the voltage and its amplitude changes, and this may not be acceptable for some loads.

The study of the DC-AC converter was carried out by the experimental method since this method will most accurately demonstrate the operation of the inverter under different conditions and elements of this device. In the research process, data will be obtained that characterize the operating conditions of the inverter in the optimal mode, which is visually confirmed by graphic material. at different modes of operation of the inverter. The most optimal and effective operating mode of the device was formed only based on checking the adequacy of the model. The proposed changes to the voltage converter will speed up the operation and increase the power of this device, thanks to the replacement of the parameters of the transformer, transistor, and microcontroller, which in turn allows the inverter to connect more electrical devices and stabilizes the output voltage, namely the modified sine wave.

The results of the study showed the efficiency of the inverter with rational parameters while determining the most optimal and efficient element base for it. An analysis of the operation of the device for different input voltages was also carried out. The structural diagram of the device is shown in Figure 5.

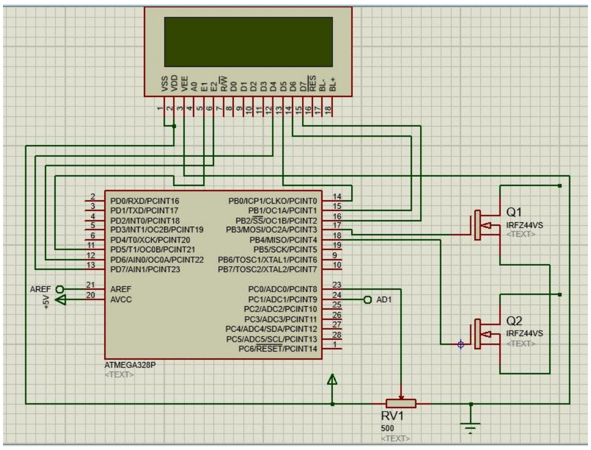

Fig. 5. Inverter model in the Proteus program

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3. Results

A photo of the developed installation is presented in Figure 6.

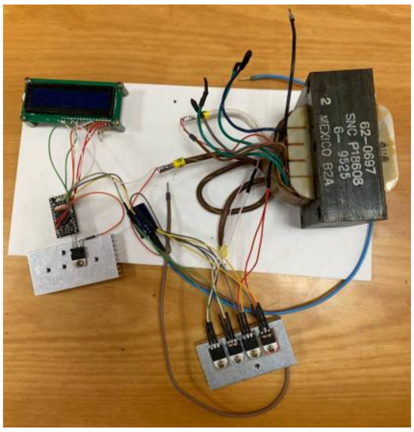

Fig. 6. Appearance of the developed DC-AC converter

The complexity of the technological process of the voltage converter with its structure does not allow us to fully determine the rational design parameters and optimal operating modes of the device analytically. Therefore, to establish the effect on the power and stability of the device, laboratory and production tests of the developed device were carried out with different component elements using the mathematical method of planning the experiment.

The analysis of the results of the theoretical study of the process of optimizing the parameters of the inverter showed that the determined power of the field-effect transistors and the thickness of the conductor of the secondary winding of the transformer and the input voltage have a significant impact on the output voltage and power of the device. The results of experimental studies show that the power is also affected by the output frequency of the converter. Therefore, to study the operation of the device, it was decided to conduct a four-factor experiment.

To conduct a full factorial experiment, it is necessary to conduct N experiments, which are determined by the formula:

$$N = m^k \tag{1}$$

where m is the number of research levels; k is the number of factors in the research series.

Conducting a full factorial experiment on four factors at three levels requires 81 experiments. Taking into account the laboriousness and cost of conducting experiments, it was important to reduce their number to the optimal and necessary value. This problem can be solved by using a symmetric non-composite implementation plan of the second-order Box-Benkin experiment. To conduct a four-factor experiment, according to the above-mentioned plan, it is necessary to conduct 27 experiments.

The planning of the experimental study included the following stages: factor coding; drawing up a table of factors and levels of variation; compilation of the planning matrix; implementation of the experiment plan according to the planning matrix; compilation of the regression equation to determine the coefficients; assessment of the significance of regression coefficients; checking the adequacy of the obtained mathematical model.

When compiling the table of factors and levels of variation (Table 1), the results of previous studies were taken into account. The Box-Benkin plan is designed to use three levels for each factor: upper (+1), zero (0), and lower (-1).

Table 1. Factors and levels of variation

Levels of variation	Factors			
	Input voltage U_{in}, V	Output frequency ν, Hz	Power field transistors P, W	Cross-sectional area of the secondary winding of the transformer S, mm^2
	x_1	x_2	x_3	x_4
Upper (+1)	15	150	300	0.7
Zero (0)	12	100	200	0.5
Lower (-1)	9	50	100	0.3
Variation interval, ε	3	50	100	0.2

The research was conducted using the planning matrix. In the decoded form, the experiment planning matrix and the order of experiments are presented in the table. The relationship between coded and natural values of the factors was established by dependencies:

$$x_1 = \frac{U_{in} - U_{in0}}{\varepsilon_1};\ x_2 = \frac{\nu - \nu_0}{\varepsilon_2};\ x_3 = \frac{P - P_0}{\varepsilon_3};\ x_4 = \frac{S - S_0}{\varepsilon_4} \tag{2}$$

where x_1, x_2, x_3, x_4 coded values of factors, respectively, input voltage, output frequency, power of field-effect transistors, and thickness of the conductor of the secondary winding of the transformer; U_{in}, ν, P, S – natural values of factors, respectively, input voltage, output frequency, power of field-effect transistors and thickness of the conductor of the secondary winding of the transformer; U_{in0}, ν_0, P_0, S_0 – natural values of factors at the zero level; ε_1, ε_2, ε_3, ε_4 – intervals of factor variation.

The non-linear nature of the expectation of the response functions of the inverter research degree in the area of the factor space is presented in the form of a regression equation:

$$\begin{aligned} y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{12}x_1x_2 + \\ + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + \\ + b_{34}x_3x_4 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 \end{aligned} \tag{3}$$

The regression coefficients after the implementation of the experimental plan are determined by the following formulas:

$$b_0 = 0.33333\sum_{j=1}^{n} y_j - 0.16667\sum_{i=1}^{k}\sum_{j=1}^{n} x_{ij}^2 y_j \tag{4}$$

$$b_i = 0.08333\sum_{j=1}^{n} x_{ij} y_j \tag{5}$$

$$b_{ii} = 0.125\sum_{j=1}^{n} x_{ij}^2 y_j + 0.0625\sum_{i=1}^{k}\sum_{j=1}^{n} x_{ij}^2 y_j - 0.16667\sum_{j=1}^{n} y_j \tag{6}$$

$$b_{ir} = 0.25\sum_{j=1}^{n} x_{ij} x_{rj} y_j \tag{7}$$

where j is the experiment number in the planning matrix; n – the number of experiments in the planning matrix; y_j is the value of the response function in the j-th experiment; k – number of factors; x_{ij}, x_{rj} – encoded values of the i-th or r-th factor in the j-th experiment; i, r – factor numbers.

The variances of the regression coefficients and their covariances are determined by the formulas:

$$S_{b_0}^2 = 0.33333\,S_y^2 \tag{8}$$

$$S_{b_i}^2 = 0.08333\,S_y^2 \tag{9}$$

$$S_{b_{ii}}^2 = 0.1875\,S_y^2 \tag{10}$$

$$S_{b_{ir}}^2 = 0.25 S_y^2 \tag{11}$$

$$\mathrm{cov}_{b_0 b_{ii}} = -0.16667\,S_y^2 \tag{12}$$

$$\mathrm{cov}_{b_i b_{rr}} = 0.0625\,S_y^2 \tag{13}$$

The significance of the regression coefficients was checked by comparing the absolute value of these coefficients with their confidence intervals. Confidence intervals were calculated according to the formulas:

$$\Delta b_0 = t_{0.05;\,f_1}\,S_{b_0} \tag{14}$$

$$\Delta b_i = t_{0.05;\,f_1}\,S_{b_i} \tag{15}$$

$$\Delta b_{ir} = t_{0.05;\,f_1}\,S_{b_{ir}} \tag{16}$$

$$\Delta b_{ii} = t_{0.05;\,f_1}\,S_{b_{ii}} \tag{17}$$

where $t_{0.05;\,f_1}$ is the tabular value of the Student's criterion at the 5% level of significance and $f_1 = n_0 - 1$ is the number of degrees of freedom of the dispersion of reproducibility (n_0 – the number of experiments in the center of the plan).

The regression coefficient was considered statistically significant when its absolute value was greater than or equal to the confidence interval. Insignificant coefficients were removed from the model.

The adequacy of the equation was checked with the help of F_F – Fisher's test. Adequacy of the obtained model will take place if the calculated value of the $F_{f_2;\,f_1}^{calc}$ criterion is less than the table value for the accepted level of significance:

$$F_{f_2;\,f_1}^{calc} \le F_{0.05;\,f_2;\,f_1}^{table} \tag{18}$$

where $F_{0.05;\,f_2;\,f_1}^{table}$ is the tabular value of Fisher's test at the 5% level of significance and the degrees of freedom of variance of inadequacy f_2 and variance of reproducibility f_1. $f_2 = n - k'$ – the number of degrees of freedom of the inadequacy variance, taking into account the number k' of the remaining regression coefficients (including b_0).

The estimated value of the Fisher test is:

$$F_{f_2;\,f_1}^{calc} = \frac{S_{\text{inadequate}}^2}{S_y^2} \tag{19}$$

where $S_{\text{inadequate}}^2$ is the dispersion of inadequacy, which is determined with f_2 – the number of degrees of freedom; S_y^2 – the dispersion of the reproducibility of the experiment, which is determined with f_1 – the number of degrees of freedom.

According to the experiment planning matrix, the number of experiments at the zero level is three. This made it possible to use the following formula to determine the dispersion of the reproducibility of the experiment:

$$S_y^2 = \frac{\sum_{u=1}^{n_0}\left(y_{0_u} - \bar{y}_0\right)}{f_1} \tag{20}$$

where u is the experiment number in the center of the plan; y_{0_u} – the value of the response function in the u-th experiment in the center of the plan; $\bar{y}_0$ – the average arithmetic value of the response function obtained from the results of n_0 experiments in the center of the plan.

The variance of inadequacy was determined using the following formula:

$$S^2_{\text{inadequate}} = \frac{SS_{\text{inadequate}}}{f_2} \tag{21}$$

When calculating the variance $S^2_{\text{inadequate}}$, we took into account the fact that only one of all experiments in the plan was repeated during the experiments (the experiment in the center of the plan). Therefore, the sum of the squares of $SS_{\text{inadequate}}$ is equal to:

$$SS_{\text{inadequate}} = n_0\left(\hat{y}_0 - \bar{y}_0\right)^2 + \sum_{j=1}^{n-n_0}\left(\hat{y}_j - y_j\right)^2 \tag{22}$$

where $\hat{y}_0$ is the value of the response function in the experiment from the center of the plan, calculated according to the regression equation; $\hat{y}_j$ – the value of the response function in the j-th experiment, calculated according to the regression equation; y_j – the value of the response function in the j-th experiment, determined experimentally.

The planning of the experiment and the procedure of the experiments were carried out according to Table 2.

Table 2. Factors and results of the experiment

Experiment number	Conducting procedure	Factors: Microcontroller frequency, Hz	Transformer operating frequency, Hz	Power field transistors, W	Transformer secondary winding, mm²	Results: Output power, P_1, W	Output power, P_2, W	Output power, P_3, W	Output power, P_{aver}, W	Efficiency, %
1	7	16	150	200	0.5	90	91.5	88.5	90	80
2	1	1	150	200	0.5	82.8	81.4	80	81.4	74
3	10	16	50	200	0.5	93	91	92	92	90
4	16	1	50	200	0.5	88.11	89.3	86.92	88.11	89
5	22	8	100	300	0.7	92.8	90.8	91.8	91.8	85
6	3	8	100	100	0.7	90.72	89.3	92.14	90.72	84
7	11	8	100	300	0.3	69.45	74.21	71.33	71.663	67
8	15	8	100	100	0.3	77	82.9	71.1	77	70
9	20	16	100	200	0.7	85.8	90	94.2	90	75
10	26	1	100	200	0.7	79.92	81.05	78.79	79.92	74
11	5	16	100	200	0.3	83.4	86	84.7	84.7	77
12	23	1	100	200	0.3	84.15	82.6	81.7	82.817	85
13	4	8	150	300	0.5	80.14	82.22	81.18	81.18	82
14	24	8	50	300	0.5	91.04	93.31	88.77	91.04	88
15	12	8	150	100	0.5	82.17	78.51	85.83	82.17	83
16	6	8	50	100	0.5	81.4	82.7	80.1	81.4	74
17	25	16	100	300	0.5	86	90	88	88	80
18	1	1	100	300	0.5	95	92.6	90.2	92.6	86
19	27	16	100	100	0.5	92.7	94.5	93.6	93.6	78
20	13	1	100	100	0.5	71.02	73.52	72.27	72.27	73
21	2	8	150	200	0.7	86.17	89.03	87.6	87.6	73
22	17	8	50	200	0.7	90.7	92.4	94.1	92.4	84
23	21	8	150	200	0.3	73.04	72.27	71.5	72.27	73
24	14	8	50	200	0.3	77.67	74.79	76.23	76.23	77
25	19	8	100	200	0.5	83.38	82.1	84.24	83.24	78
26	8	8	100	200	0.5	74.43	75.24	76.05	75.24	76
27	18	8	100	200	0.5	84.7	85.05	84.35	84.7	77

As a result, the regression equation was obtained:

$$y = 0.024x_1^2 - 0.027x_1 - 0.089\cdot 10^{-2}x_3^2 - 0.009x_3 - \\ -0.001x_2 - 0.253x_4 + 0.153$$

Figures (7) - (12) were constructed according to this equation.

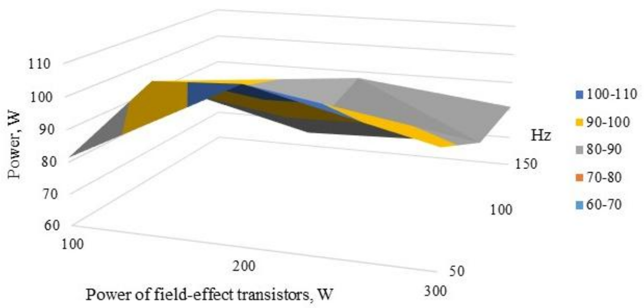

Fig. 7. Dependence of inverter power on frequency and power of field-effect transistors

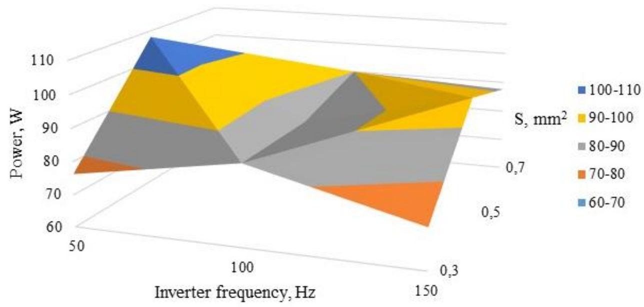

Fig. 8. Dependence of the inverter power on the frequency and cross-section of the transformer winding

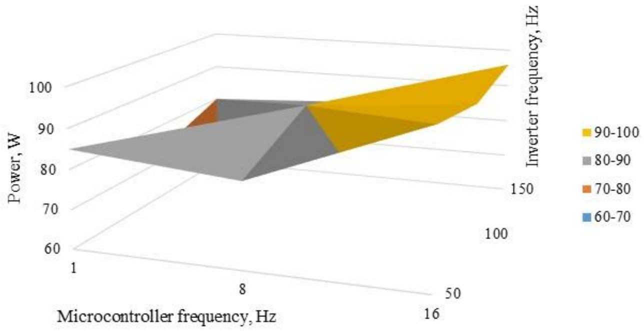

Fig. 9. Dependence of power on the frequency of the microcontroller and the frequency of the inverter

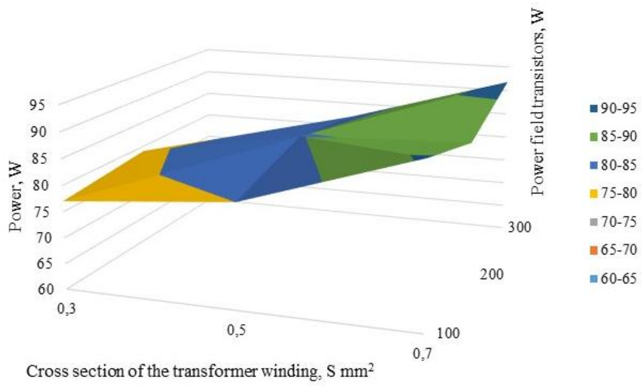

Fig. 10. Dependence of power on the cross-section of the transformer and the power of field-effect transistors

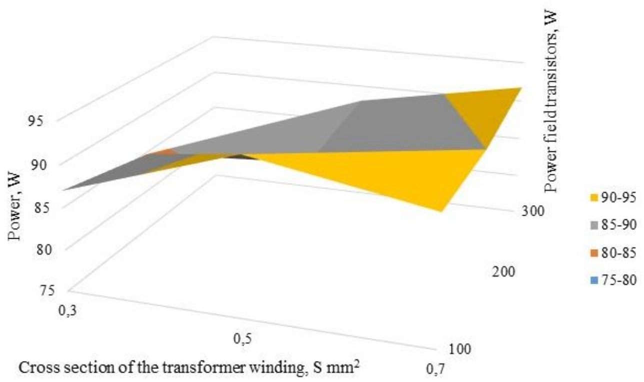

Fig. 11. Dependence of power on the cross-section of the transformer winding and the power of field-effect transistors

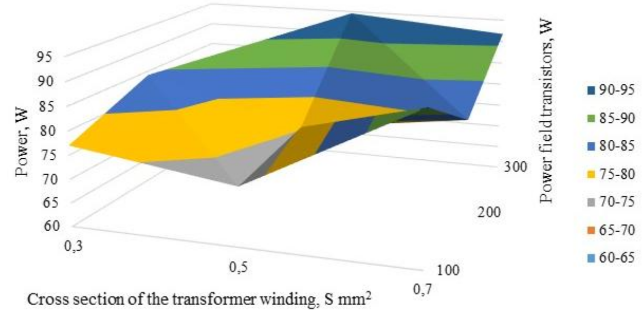

Fig. 12. Dependence of power on the cross-section of the transformer winding and the power of field-effect transistors

This study will allow automation and improve some elements of the device and analyze input and output data while varying such factors as: input voltage, output frequency, power of field-effect transistors, and secondary winding of the transformer.

4. Conclusions

The research results confirmed the hypothesis about the feasibility of using the optimal characteristics of the inverter. The highest power is observed for the thickness of the secondary winding of the transformer d = 0.5 mm^2, the frequency of the transformer v = 50 Hz, the frequency of the microcontroller v = 16 Hz, and the power of the field-effect transistors P = 200 W. The maximum power can reach P = 94 W.

A fragment of the software code that is responsible for the operation of the developed algorithm for the experimental installation:

```
digitalWrite(N,HIGH);
delayMicroseconds(k);
digitalWrite(N,LOW);
delayMicroseconds(k);
digitalWrite(M,HIGH);
delayMicroseconds(k);
digitalWrite(M,LOW);
//----
#define N 11
#define M 12
int h=5000;
int k=5000;
//----
```

This code element provides the generation of rectangular voltage pulses with a delay of 5000 to 1250 nanoseconds. The generation of pulses is carried out on terminals MK 11 and 12. The delay between pulses is mandatory because it is necessary to give a time interval for the completion of the transient processes of the transistors. It is possible to change the duty cycle of the pulses, which will help draw more power from the output transformer, but this will have negative consequences in the long run, such as overheating of the transistors and a change in the shape of the output signal.

To change the frequency, a potentiometer with a nominal value of 20kΩ was used, which is connected to the input of MK ADC 0.

The implementation of the ADC with a value from 0-1023 is carried out by the following fragment of the program code:

$$k = map(\text{analogRead}(0), 0, 1023, 5000, 1250)$$

The *map* function plays a leading role because it converts the data (mapping) of the range 0…1023 to the range of values 5000…1250.

A 16×2 two-line LCD monitor based on the HD44780 controller was used to display data.

```
lcd.setCursor(0,0);
lcd.print("Hz=");
lcd.setCursor(3,0);
lcd.print(Hz);
int v = (analogRead(1)/1023.0) * 20;
delayMicroseconds(k);
lcd.setCursor(0,1);
lcd.print("v=");
lcd.setCursor(2,1);
lcd.print(v);
```

The standard LiquidCrystal library was used to work with this monitor. The display is connected to legs MK 4, 5, 6, 7, 8, 9, 10. It interactively displays the current frequency in hertz and the state of battery charge in percent. ADC analog input 1 was used to obtain data on the state of charge. A resistive voltage divider was used to operate the ADC with increased battery voltage. The following code fragment shows the conversion of the received data into volts and percentages of the battery charge level:

$$int\ v = (\text{analogRead}(1) / 1023.0)\cdot 20$$

The control microcontroller operates at a frequency of 16 MHz with an external quartz resonator, which allows to obtain an acceptable level of accuracy of pulse generation.

The result of the research was:

1. A mathematical model of the optimization process of the voltage converter when changing its elemental basis was obtained in the form of a regression equation, the response function of which is the power of the inverter.
2. Analysis of output data at different input voltages, comparative characteristics of voltage converter capabilities with changed elements.

The obtained results of the conducted studies may indicate certain features of the change in the properties of the inverter. Thus, as the power of the field-effect transistors increases, the power of the converter increases. In addition, in the presence of a larger conductor of the secondary winding, which must be taken into account when choosing a transformer, the power also increases. In the event of an increase in the frequency of the device, it may harm the efficiency of the transistors and the microcontroller. Therefore, when designing the optimal components of the device, it is necessary to use a multivibrator in its design.

In the future, t'he device could be improved by changing the frequency by changing the microcontroller software code. In addition, various sensors can be connected to protect the electronic components of the system.

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