# Biogas Heat Pump Power Supply Based on Smart Grid Functioning Solar Electric System Network

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**Abstract:** A comprehensive integrated solar power plant system has been developed to support the operation of a biogas plant based on a heat pump, for which fermented wort is a low-potential energy source. The change in the power factor of the solar power system connected to the grid and the temperature of the coolant entering the heat exchanger built into the methane tank are predicted. Promising solutions include changing the power of the heat pump compressor to maintain biogas production, unloading fermented wort and loading fresh material while maintaining the power factor of the grid solar system and changing the level of electricity transmission to the grid. The voltage at the input of the hybrid inverter, the voltage at the output of the frequency converter to assess their ratio and the voltage frequency are constantly measured. When changing the voltage at the input of the hybrid inverter from 240 V to 600 V, promising solutions were adopted to reduce the power of the heat pump from 3.14 kW to 1.58 kW in the production of biogas 352.5 $m^3$/day to maintain the temperature of the heating coolant entering the heat exchanger built into the methane tank at 55° C - 45 °C in order to obtain biogas, unload fermented wort and load fresh raw materials. There is an increase in the power of electricity transmission to the grid from 0.27 to 1 and an increase in the power factor by 40% from 0.58 to 0.98. The use of the developed Smart Grid technology allows preventing peak loads of the power system, reducing electricity consumption from the grid by up to 30%.

**Keywords:** Solar energy, Smart Grid, Power factor, Biogas plant**,** Heat pamp power supply.

## 1. INTRODUCTION

Distributed generation of electricity using renewable sources requires improvement of production and consumption coordination management technologies. Thus, the author [1] proposes to maintain voltage in the distribution system when using a solar grid power system based on integrated storage management. A comprehensive integrated system for supporting the operation of a grid solar power system has been developed based on forecasting changes in the storage capacity and the power factor of the grid solar power system. Promising solutions for changing the capacity of the thermoelectric storage device redistribute the accumulated electricity. Changing the level of electricity transmission to the grid allows maintaining voltage in the distribution system by maintaining the power factor of the grid solar power system. Peak load on the power system is prevented, which reduces energy consumption from the grid by up to 14%. In [2], a method for optimizing wind energy consumption based on a thermal storage device is proposed in the context of stepped carbon trading. The optimization method is applied to thermal power plants and takes into account the limitations of the thermoelectric coupling of the cogeneration plant, the electric power balance and the thermal power balance. Taking the least total cost of thermal power plants as the objective function, the Cplex solver in Matlab is used to solve the objective function. The wind energy consumption of the system, the $CO_2$ emissions of thermal power plants and the system economy areanalyzed under different scenarios. The results of the computational example show that the model proposed in this paper not only improves the wind energy consumption rate of the system and reduces the $CO_2$ emissions of thermal power plant, but also improves the economy. For example, the presented research paper [3] studies the properties of peroxide material as an absorber layer for solar panels. The open-circuit voltage, short-circuit current and energy conversion efficiency were significantly improved by using a hybrid structure. The efficiency of the hybridization process in producing the active absorber layer was established. A review article such as [4] allows evaluating the possibilities of switching to solar energy, which requires the use of modern energy storage devices to coordinate production and consumption, such as lithium-ion batteries. A qualitative review and analysis of the presented studies in the field of application of design principles and development trends of silicon anode binders for lithium-ion batteries is carried out. Prospects for further research in the field of economic and environmental studies in this area are outlined. In this paper [5], an equality constraint optimization method is used based on cost-effective load sharing between locally available renewable energy sources. The HOMER-based software platform is used for cost analysis. Based on locally available renewable energy sources, micro hydroelectric power plants and solar photovoltaic installations are considered for the analysis. The resulting model for a specific region can be modified for other regions. In the paper [6], an improvement of the universal power quality compensator in the distribution system (MFUPQC) using a photovoltaic module is presented. Intelligent control of the DC link with hybrid fuzzy logic of

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MFUPQC is presented. The effectiveness of the proposed hybrid fuzzy logic control MFUPQC for improving power quality (PQ) and DG integration is verified using the MATLAB/Simulink software tool, and the simulation results are accompanied by a comparative analysis. The coordination of electricity production and consumption presented in [7, 8] requires uncertainty models, such as using the Monte Carlo method [7] or the genetic algorithm [8], which is based on deep learning for long-term memory. Therefore, for example, a blockchain-based data aggregation scheme is proposed for privacy preservation in smart grids [9]. Uncertainty can be prevented by using, for example, large-scale seasonal thermal storage (ATES) [10] for intelligent control of distributed energy generation. The novelty of the work should be presented. Distributed generation of electricity using renewable sources requires improvement of production and consumption coordination management technologies. Traditionally, control the voltage in an electric network is carried out by means of, for example, transformers, capacitor batteries, voltage regulators, static synchronous compensators, etc. The installation and maintenance costs of these devices can be quite high and some have a relatively slow response time of about a few seconds The heat pump system, as an element of the complex solar biogas heat pump electric system, acquires the additional status of a voltage regulator in the distribution system. The change in the power factor of the solar power system connected to the grid and the temperature of the coolant entering the heat exchanger built into the methane tank are predicted. Promising solutions include changing the power of the heat pump compressor to maintain biogas production, unloading fermented wort and loading fresh material while maintaining the power factor of the grid solar system and changing the level of electricity transmission to the grid. The voltage at the input of the hybrid inverter, the voltage at the output of the frequency converter to assess their ratio and the voltage frequency are constantly measuredThe set voltage ratio is part of the $K_{pf}$ coefficient of the transfer function (3) in relation to complex mathematical modeling as part of the solar biogas heat pump electric system. The result of complex modeling is obtaining a reference estimate of the change in power factor and the temperature of the coolant entering the heat exchanger built into the methane tank. During the operation of the electric system, there is a change in the established ratio of the voltage at the input to the hybrid inverter and the voltage at the output of the frequency converter, which are measured. Therefore, with the use of mathematical justification of the architecture, support for the functioning of the electrical system, and the transfer function, the performance control was performed. The result of the logical modeling is the acquisition of the resulting information regarding the adoption of anticipatory decisions to change the power of the heat pump system and the transmission of electrical energy to the network using a logical model. The power factor and and the temperature of the coolant entering the heat exchanger built into the methane tank are maintained. For this purpose, based on logical modeling, an integrated Smart Grid system harmonization of production and consumption of solar biogas heat pump electric systemwas obtained. This means that the obtained scientific result in the form of an integrated Smart Grid system based on the support of the power factor of solar biogas heat pump electric system and the temperature of the coolant entering the heat exchanger built into the methane tank is relevant, which allows solving the problems of using Smart Grid technologies in order to achieve stability and reliability of energy systems in order to provide consumers with high-quality electricity in terms of energy saving, progressive from theoretical points of view From a practical point of view, the developed integrated system allows determining the conditions for improving the technology of distributed energy generation in order to prevent the peak load of the energy system. Thus, an applied aspect of the use of the obtained scientific result is the possibility of applying the obtained results in the development of intelligent Smart Grid systems as part of the use of renewable energy sources. This constitutes the prerequisites for the transfer of the obtained technological solutions. An urgent task in the context of further development of distributed energy is the use of solar energy for biogas production [11], to maintain the balance of production and consumption of the network solar power system based on heat pump power supply of the biogas plant, the low-potential energy source for which is fermented wort [12, 13]. Thus, the energy-saving technology for maintaining the operation of the biogas plant [12] allows predicting the change in the fermentation temperature and setting the temperature of the coolant at the inlet to the heat exchanger built into the methane tank, using heat pump power supply. The temperature of the heat carrier is measured at the outlet of the heat exchanger during the period of biogas production, loading of fresh material and unloading of fermented raw materials.The use of a comprehensive system for assessing changes in fermentation temperature, obtained on the basis of mathematical and logical modeling, ensures continuous release of biogas, timely unloading of fermented wort and loading of fresh raw materials while maintaining the balance of fresh and fermented raw material flows. Forecasting the change in fermentation temperature requires making advance decisions on changing the temperature of the heating coolant at the inlet to the heat exchanger installed in the methane tank. Thus, the energy-saving technology of maintaining the operation of the heat pump power supply [13] allows making advance decisions on changing the number of revolutions of the compressor of the heat pump electric motor. The change in the temperature of the heated water occurs in the ratio of the refrigerant pressure at the outlet of the heat pump condenser and the evaporation pressure at the outlet of the evaporator.The aim of the work is to develop Smart Grid technology to support the integrated operation of a biogas plant and a solar grid power system that provides power to a heat pump which uses fermented wort as a low-potential source of energy. The change in the power factor of the network solar electric system and the temperature of the heating coolant entering the heat exchanger built into the methane tank are predicted. Prospective decision-making is aimed at changing the power of the heat pump compressor to maintain biogas production, unloading fermented raw materials, loading fresh material and when changing the level of electricity transmission to the network.

To achieve the goal, the following tasks were set:

– to offer support for the integrated operation of a biogas plant and a solar grid power system that provides power to a heat pump which uses fermented wort as a low-potential source of energy. The change in the power factor of the grid-connected solar electric system and temperature of the heating coolant entering the heat exchanger built into the methane tank and are predicted. Prospective decision-making is aimed at changing the power of the heat pump compressor to maintain biogas production, unloading fermented raw materials, loading fresh material and when changing the level of electricity transmission to the grid. The voltage at the input of the hybrid inverter, the voltage at the output of the frequency converter and the voltage frequency are measured. The change in the ratio of the voltage at the input of the hybrid inverter and the voltage at the output of frequency converter is estimated;

– develop a structural diagram and perform complex mathematical modeling to obtain a reference estimate of the change in the power factor of the grid-connected solar electric system and the temperature of the heating coolant entering the heat exchanger built into the methane tank;

– propose making advanced decisions on changing the power of the heat pump electric motor and the level of electricity transmission to the grid. To do this, develop a structural diagram and conduct logical modeling to obtain a functional assessment of the change in the power factor of the grid solar electric system and the temperature of the heating coolant entering the heat exchanger built into the methane tank;

– to develop the block diagram and to perform logical modeling regarding obtaining the integrated Smart Grid system of maintenance of the a network solar electric system and a biogas plant at the decision making level;

– to develop an integrated system for coordinating the production and consumption of electrical energy based on forecasting changes in the the power factor of the grid solar electric system and the temperature of the heating coolant entering the heat exchanger built into the methane tank for transmitting electrical energy to the grid**.**

## 2. PROPOSED METHOD

### 2.1. Methodological and Mathematical Substantiation

Based on the methodological, mathematical, logical substantiation of the technological systems [12–14] the architecture, mathematical substantiation of the architecture (1) are proposed (Figure **1**).

The mathematical substantiation of the architecture of the solar biogas heat pump electric system Smart Grid (1), (Figure **1**), based on the methodology of the mathematical description of dynamics of power systems, the method of the graph of cause-effect relations [12–14] is proposed.

Were *SBGHPESSG*(τ) is the Smart Grid solar biogas heat pump electric system; τ is the time, s; *ID*(τ) is the integrated dynamic subsystem (power grid, photovoltaic module, hybrid inverter, two-way Smart Meter for changing the power level of electric energy transmission to the network, the biogas plant, the heat exchanger built into the methane tank, the heat pump, the frequency converter); *P*(τ) is the properties of the elements of the solar biogas heat pump electric system; *x*(τ) is the influences (a change in parameters: change in solar radiation, the temperature of heating water at the outlet from the heat exchanger fitted in the methane tank, the temperature of refrigerant at the outlet from the condenser, evaporation pressure, condensation pressure, voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency; *f*(τ) is the measured parameters (the temperature of heating water at the outlet from the heat exchanger fitted in the methane tank, the temperature of refrigerant at the outlet from

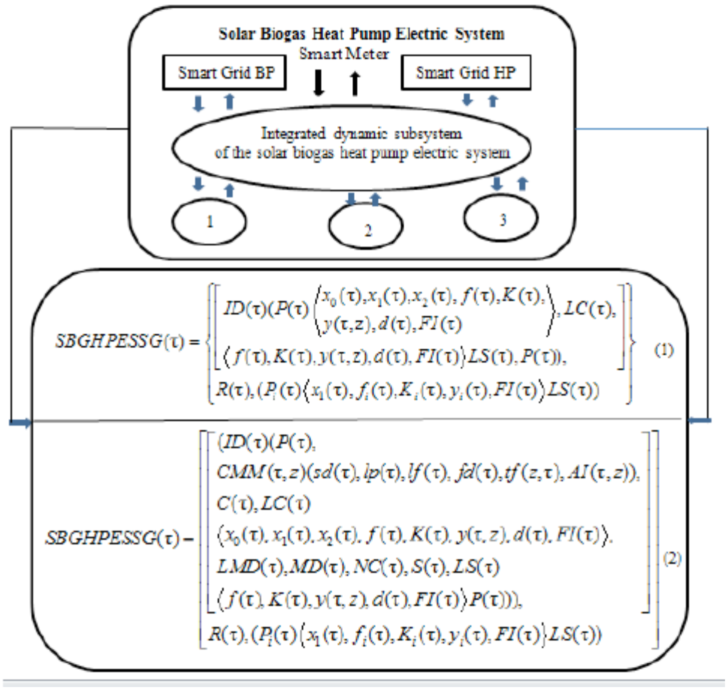


**Figure 1:** Smart Grid solar biogas heat pump electric system: the architecture: BP – biogas plant with heat exchanger built into the methane tank; HP – heat pump system; 1– charge unit; 2–discharge unit; 3 – unit of evaluation of functional efficiency. Mathematical substantiation of the architecture (1). Mathematical substantiation of maintenance of the operation (2).

the condenser, evaporation pressure, condensation pressure, voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency); $K(\tau)$ is the coefficients of the mathematic description of the dynamics of the temperature of heating water at the outlet from the condenser**,** the power factor of the network solar electric system; $y(\tau, z)$ is the output parameters (the temperature of heating water at the outlet from the condenser, the power factor of the network solar electric system); $z$ is the coordinate of the length heat pump condenser, m; $d(\tau)$ is the dynamic parameters of a change in the temperature of heating water at the outlet from the heat pump condenser; $FI(\tau)$ is the functional final information; $LC(\tau)$ is the logical relations regarding the control of the solar biogas heat pump system operability; $LS(\tau)$ is the logical relations regarding the identification of the state of the solar biogas heat pump system; $R(\tau)$ is the logical relations in $SBGHPESSG(\tau)$ to confirm the correctness of decisions made from the units of the system. Indices: $i$ is the number of elements in the solar biogas heat pump system; 0, 1, 2 are the initial stationary mode, external and internal character of influences.

The mathematical substantiation of maintenance of the operation of the solar biogas heat pump electric system Smart Grid (2), (Figure **1**), based on the methodology of the mathematical description of dynamics of power systems, the method of the graph of cause-effect relations [12–14] is proposed. The basis of the proposed rationale is the mathematical description of the architecture of the solar biogas heat pump electric system Smart Grid (1), (Figure **1**).

Were $SBGHPESSG$ $(\tau)$ is the Smart Grid maintenance of the operation of the solar biogas heat pump electric system; $\tau$ is the time, s; $ID(\tau)$ is the integrated dynamic subsystem (power grid, photovoltaic module, hybrid inverter, two-way Smart Meter for changing the power level of electric energy transmission to the network, the biogas plant, the heat exchanger built into the methane tank, the heat pump, the frequency converter););  $P(\tau)$ is the properties of the elements of the integrated dynamic subsystem, units of the solar biogas heat pump electric system; $CMM(\tau, z)$ is the complex mathematical modeling of dynamics of the temperature of the heating water at the outlet of the condenser of the heat pump, a change in power factor; $sd(\tau)$ is the input data (productivity of the photovoltaic module, productivity of the biogas plant, the heat pump type and its power, the integrated system of maintenance of fermentation temperature, the frequency converter type; $lp(\tau)$ is the boundary change in parameters (the temperature of heating water at the outlet from the heat exchanger fitted in the methane tank, the temperature of the refrigerant at the inlet to the condenser and at the outlet of the condenser, the temperature of the wort at the outlet of the evaporator, voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency, $lf(\tau)$ is the levels of operation of solar electric system, biogas plant, heat pump system; $fd(\tau)$ is the obtained parameters (parameters of heat exchange in the heat exchanger fitted in the methane tank, heat pump system, time constants and coefficients of the mathematical model of dynamics of a change in, the temperature of the heating water at the outlet of the condenser of the heat pump, power factor; *tf*(τ,*z*) is the transfer function of predicted parameters – the temperature of the heating water at the outlet of the condenser of the heat pump, power factor; *AI*(τ,*z*) is the standard information regarding the evaluation of the maximum admissible change in the heating water at the outlet of the condenser of the heat pump, power factor; *C*(τ) is the control of operability of the solar biogas heat pump electric system**;** *LC*(τ) is the logical relations of temperature of the heating water at the outlet of the condenser of the heat pump, power factor, the control of the solar biogas heat pump electric system operability; *x*(τ) is the influences (a change in parameters: change in solar radiation, the temperature of heating water at the outlet from the heat exchanger fitted in the methane tank, the temperature of refrigerant at the outlet from the condenser, evaporation pressure, condensation pressure, voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency; *f*(τ) is the measured parameters (the temperature of heating water at the outlet from the heat exchanger fitted in the methane tank, the temperature of refrigerant at the outlet from the condenser, evaporation pressure, condensation pressure, voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency); *K*(τ) is the coefficients of the mathematic description of the dynamics of a change in the temperature of heating water at the outlet from the condenser, power factor; *y*(τ, *z*) is the output parameters (the temperature of heating water at the outlet from the condenser, power factor); *z* is the coordinate of the length heat pump condenser, *m*; *d*(τ) is the dynamic parameters of a change in the the temperature of heating water at the outlet from the heat pump condenser, the power factor of the solar biogas heat pump electric system; *FI*(τ) is the functional final information regarding decision making; *LMD*(τ) is the logical relations of decision making; *MD*(τ) is decision making; *NC*(τ) is the new conditions of the solar biogas heat pump electric system operation; *S*(τ) is the identification of the state of the solar biogas heat pump electric system; *LS*(τ) is the logical relations of identification of the state of the solar biogas heat pump electric system; *R*(τ) is the logical relations between the dynamic subsystem and units of charge, discharge, functional estimation of efficiency that belong to the system. Indices: *i* is the number of elements of *SBGHPESSG* (τ); 0, 1, 2 are the initial, external, and internal character of influences.

Mathematical substantiation of the architecture of the Smart Grid solar biogas heat pump electric system (1) and mathematical substantiation of maintenance of the operation of the Smart Grid solar biogas heat pump electric system (2) (Figure **1**) make it possible to maintain the operation of the system using the following actions:

- operability control (*C*(τ)) of the dynamic subsystem based on complex mathematical (*CMM*(τ, *z*)) and logical (*LC*(τ)) modeling regarding obtaining standard (*AI*(τ,*z*)) estimate of a change in the temperature of heating water at outlet from the condenser, power factor of the solar biogas heat pump electric system;
- operability control (*C*(τ)) of the dynamic system based on complex mathematical (*CMM*(τ, *z*)) and logical (*LC*(τ)) modeling regarding the obtaining functional (*FI* (τ)) estimate of a change in temperature of heating water at the outlet from the condenser, power factor of the solar biogas heat pump electric system;
- decision making (*MD*(τ)) with the use of the functional resulting information (*FI* (τ)), obtained based on logical modeling (*LMD*(τ));
- decision making to maintain the temperature of heating water at the outlet from the condenser, power factor, with the use of the functional resulting information (*FI* (τ));
- identification (*S*(τ)) of the new conditions of functioning of the solar biogas heat pump electric system (*NC*(τ)) based on logical modeling (*LS*(τ)) as a part of the dynamic subsystem and confirmation of new operating conditions based on logical modeling (*R*(τ)) from the units of the solar biogas heat pump electric system.

## 3. COMPLEX MATHEMATICAL MODELING OF THE SMART GRID SOLAR BIOGAS HEAT PUMP ELECTRIC SYSTEM

According to formulas (1), (2) (Figure **1**) it is proposed to forecast changes in the power factor of the solar biogas heat pump electric system and the temperature of heating water at the outlet of the condencer for the heat exchanger fitted in the methane tank. The temperature of heating water at the outlet from the heat exchanger fitted in the methane tank, the temperature of refrigerant at the outlet from the condenser, evaporation pressure, condensation pressure, voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency are measured. The transfer function for the “power factor of the solar biogas heat pump electric system – power of the compressor electric motor" relation is complex. The transfer function along the channel power factor of the solar biogas heat pump electric system – power of the compressor electric motor " is presented as follows:

$$W_{pf-N\mathrm{epc}} = \frac{K_{\mathrm{pf}} K_{\mathrm{r}}}{(T_{\mathrm{hw}} S + 1)\beta - 1}\left(1 - e^{-\gamma\xi}\right), \tag{3}$$

were

$$K_{\mathrm{pf}} = \frac{I(U_1 - U_2)}{N_{\mathrm{epc}}};\quad K_{\mathrm{r}} = \frac{m(\theta_0 - \sigma_0)}{G_{r0}};\quad T_{\mathrm{hw}} = \frac{g_{\mathrm{hw}} C_{\mathrm{hw}}}{\alpha_{\mathrm{hw0}} h_{\mathrm{hw0}}};$$

$$\beta = T_{\mathrm{m}} S + \varepsilon^* + 1;\quad T_{\mathrm{m}} = \frac{g_{\mathrm{m}} C_{\mathrm{m}}}{\alpha_{\mathrm{hw0}} h_{\mathrm{hw0}}};\quad \varepsilon^* = \varepsilon(1 - L_{\mathrm{r}}^*);$$

$$\varepsilon = \frac{\alpha_{\mathrm{r0}} h_{\mathrm{r0}}}{\alpha_{\mathrm{hw0}} h_{\mathrm{hw0}}};\quad L_{\mathrm{r}}^* = \frac{1}{L_{\mathrm{r}} + 1};\quad L_{\mathrm{r}} = \frac{G_{\mathrm{r}} C_{\mathrm{r}}}{\alpha_{\mathrm{r0}} h_{\mathrm{r0}}};$$

$$\gamma = \frac{(T_{\mathrm{hw}} S + 1)\beta - 1}{\beta};\quad \xi = \frac{z}{L_{\mathrm{hw}}};\quad L_{\mathrm{hw}} = \frac{G_{\mathrm{hw}} C_{\mathrm{hw}}}{\alpha_{\mathrm{hw0}} h_{\mathrm{hw0}}}.$$

were *PF* is the power factor of the solar biogas heat pump electric system; *I* – current, A; $U_1$ and $U_2$ – voltage at the grid inverter input and at the frequency converter output, respectively, volts; *N*epc – the power of the compressor electric motor, kW; *C* is the specific thermal capacity, kJ/(kg·K); α is the heat transfer factor, kW/(m$^2$·K); *G* is the consumption of substance, kg/s; *g* is the specific weight of a substance, kg/m; *h* is the specific surface, m$^2$/m; *t*, σ, θ – temperature of heating water, temperature of refrigerant and of the separating wall, respectively, K; *z* is spatial coordinate of the condenser coincides with the direction of the flow of motion of the medium, m; $T_{\mathrm{hw}}$, $T_{\mathrm{m}}$ are the time constants that characterize the thermal accumulating capacity of heating water, metal, s; *m* is the indicator of the dependence of heat transfer factor on consumption; τ is the time, s; *S* is the Laplace parameter; *S* = ω*j*; ω is the frequency, 1/s.; Indices: 0 – initial stationary mode; 1 – inlet to the condenser; hw – heating water; r – refrigerant; *m* – metal wall

A real part of the transfer function (3) was separated:

$$O(\omega) = \frac{(L_1 A_1) + (M_1 B_1)\varepsilon(1 - L_{\mathrm{r}}^*)}{(\mathrm{A}_1^2 + B_1^2)}. \tag{4}$$

The $K_{\mathrm{r}}$ factor includes the temperature of the separating wall θ:

$$\theta = (\alpha_{\mathrm{hw}}(\sigma_1 + \sigma_2)/2) + A(t_1 + t_2)/2)/(\alpha_{\mathrm{hw}} + A) \tag{5}$$

where $\sigma_1$, $\sigma_2$ are the temperatures of refrigerant at the inlet and the outlet of the condenser, respectively, K; $t_1$, $t_2$ are the temperatures of heating water at the inlet and the outlet of the condenser, respectively, K; α is the heat transfer factor, kW/(m$^2$·K); Indices: hw is internal flow: heating water.

$$A = 1/(\delta_{\mathrm{m}}/\lambda_{\mathrm{m}} + 1/\alpha_{\mathrm{r}}) \tag{6}$$

where δ is the thickness of a wall of the condenser, m; λ is the thermal conductivity of the metal wall of the condenser, kW/(m·K). α is the heat transfer factor, kW/(m$^2$·K); Indices: r – external flow: refrigerant; *m* – metal wall of a condenser.

To use the real part *O* (ω), the following factors were obtained:

$$A_1 = \varepsilon^* - T_{hw} T_m \omega^2 \tag{7}$$

$$A_2 = \varepsilon^* + 1 \tag{8}$$

$$B_1 = T_{\mathrm{hw}}\varepsilon\omega + T_{\mathrm{hw}}\omega + T_{\mathrm{m}}\omega \tag{9}$$

$$B_2 = T_m \omega \tag{10}$$

$$C_1 = \frac{A_1 A_2 + B_1 B_2}{A_2^2 + B_2^2} \tag{11}$$

$$D_1 = \frac{A_2 B_1 - A_1 B_2}{A_2^2 + B_2^2} \tag{12}$$

$$L_1 = 1 - e^{-\xi C_1}\cos(-\xi D_1) \tag{13}$$

$$M_1 = -e^{-\xi C_1}\sin(-\xi D_1) \tag{14}$$

The transfer function (3) which was obtained based on the use of the operator method of solving the system of nonlinear differential equations, includes the Laplace transform parameter – S (S = ωj), where ω is the frequency, 1/s. To switch from the frequency area to the time area, a real part (4), obtained as a result of the mathematical treatment of transfer functions, was separated. It is this part that is included in the integrals (15, 16) which makes it possible to obtain dynamic characteristics of a change the power factor of the solar biogas heat pump electric system, the temperature of heating water at the outlet of the condencer for the heat exchanger fitted in the methane tank using the inverse Fourier transform:

$$t_{\mathrm{hw}}(\tau, z) = \frac{1}{2\pi}\int_0^\infty K_{\mathrm{pf}} K_{\mathrm{r}} O(\omega)\sin(\tau\omega/\omega)\,d\omega \tag{15}$$

$$PF(\tau) = \frac{1}{2\pi}\int_0^\infty K_{pf} K_r O(\omega) \sin(\tau\omega/\omega) d\omega, \tag{16}$$

where $t_{hw}$ is the the temperature of heating water at the outlet of the condencer for the heat exchanger fitted in the methane tank, K; *PF* is the power factor of the Smart Grid solar biogas heat pump electric system.

Analyzing the mathematical model, we set the internal parameters included in the coefficients of the dynamics equations. The linearization performed to solve the system of nonlinear differential equations is correct. In real conditions of the energy system operation, during the transition from stationary states and the receipt of external and internal effects, the coefficients of the dynamics equations are reconstructed in time due to a change in the internal parameters that are measured.

Smart Grid solar biogas heat pump electric system includes the following components:photoelectric panels JA SOLAR 545 JAM72S30-545/MR 545 Wp, type, photoelectric module – 10 kW; hybrid inverter Deye SUN -10K-SG04LP3-EU. The biogas plant with a capacity of 325 m$^3$/day of biogas production includes the following components: the heat exchanger fitted in the methane tank with wort consumption 0.145 kg/s, heating water consumption – 0.4 kg/s. The heat pump system type, Vailliant VWW 41/3 (Germany) with a heating capacity of 19.8 kW, consumed electric power 3.5 kWm, *COP* – coefficient of performance of the heat pump system 5.7. Boundary change of refrigerant temperature at the inlet of condencer: 60…50°C, boundary change of the heating water at the outlet of the condenser 55…45°C and temperature of the wort at the outlet of the evaporator: 21…4°C. The following levels of operation of the heat pump system have been established for the change in the temperature of the refrigerant at the inlet to the condenser and at the outlet from the condenser: – first level: 60–55.5°C; second level: 57.1–52.6°C; third level: 54.9–50.4°C; fourth level: 52.5–48°C; fifth level: 50°C –45.5°C. They correspond to changes in the temperature of heating water: 44.15–55°C; 43.06–52.1°C; 42.3–49.9°C; 41.35–47.5°C. 40.3–45°C and refrigerant evaporation temperature 18.5°C, 15.42°C, 10.77°C, 7.21°C, 1.5°C.

According to formulas (1–3) and the proposed block diagram (Figure **2**), the results of complex mathematical modeling of the solar biogas heat pump electric system are presented (Tables **1**-**3**).

Time constants and the coefficients that are components of mathematical model of dynamics (3)

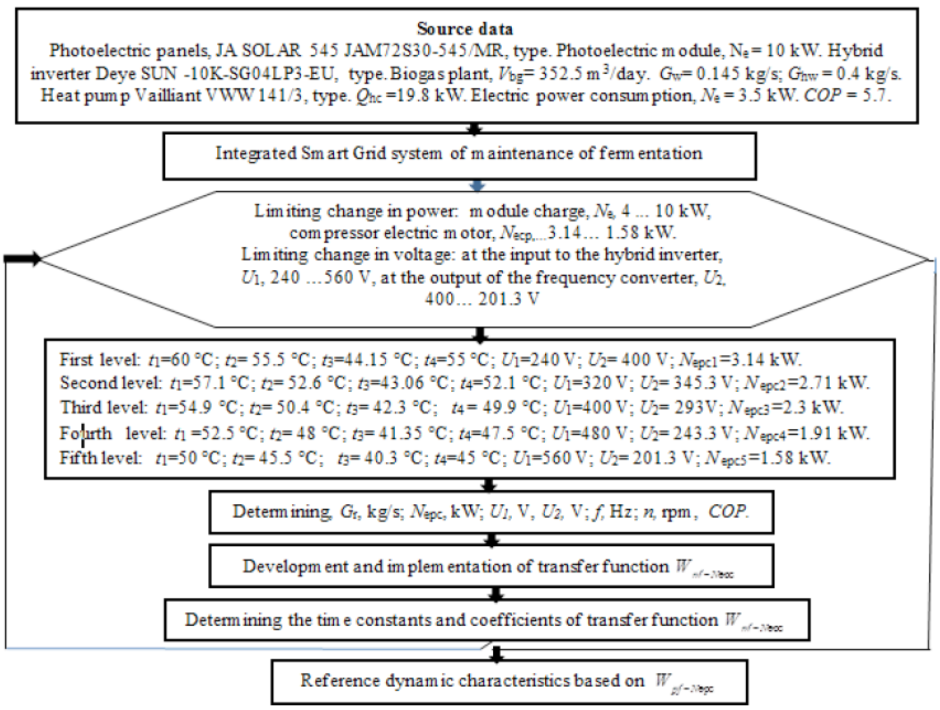


**Figure 2:** Block diagram of comprehensive mathematical modeling of the of the solar biogas heat pump electric system: $V_{bg}$ – capacity of biogas plant, m$^3$/day. $G_w$, $G_{hw}$ – consumption of wort, heating water, respectively, kg/s; $Q_{hc}$ – heat pump thermal efficiency, kW; ; $t_1$, $t_2$ – the temperature of the refrigerant at the inlet to the condenser and at the outlet of the condenser, respectively, °C; $t_3$, $t_4$ – the temperature of the heating water at the inlet to the condenser and at the outlet of the condenser, respectively, °C; $G_r$ – refrigerant consumption, kg/s; $N_e$, $N_{epc}$ – the power of photoelectric module and heat pump, respectively, kW; $U_1$, $U_2$ – voltage at the input to the hybrid inverter and at the output of the frequency converter, respectively, V; f – voltage frequency, Hz; n – the number of revolutions of the compressor electric motor, rpm; COP – coefficient of performance of the heat pump system.

**Table 1: Operating Parameters of the Smart Grid Solar Biogas Heat Pump Electric System**

| Levels of Operation | $U_1$, V | $U_2$, V | $G_r$, kg/s | $N_{epc}$, kW | *f*, Hz | $n$,. rpm | *COP* |
|---|---|---|---|---|---|---|---|
| First level | 240 | 400 | 0.1196 | 3.14 | 50 | 1500 | 5.79 |
| Second level | 320 | 345.2 | 0. 1026 | 2.71 | 43.5 | 1294.5 | 5.59 |
| Third level | 400 | 293 | 0.0806 | 2.30 | 36.60 | 1098 | 5.53 |
| Fourth level | 480 | 243.3 | 0. 0641 | 1.91 | 30.41 | 912.3 | 5.38 |
| Fifth level | 560 | 201.3 | 0. 0480 | 1.58 | 25.17 | 755.1 | 5.00 |

Note: $U_1$, $U_2$ – voltage at the input to the hybrid inverter and at the output of the frequency converter, V; Gr – refrigerant consumption, kg/s; Nepc – power of the compressor electric motor, kW; f – voltage frequency, Hz; n – the number of revolutions of the compressor electric motor, rpm; COP – coefficient of performance of the heat pump system.

**Table 2: Heat Transfer Parameters of the Smart Grid Solar Biogas Heat Pump Electric System**

| Levels of Operation | Parameter | | |
|---|---|---|---|
| | $\alpha_r$, kW/(m$^2$·K) | $\alpha_{hw}$, kW/(m$^2$·K) | *k*, kW/(m$^2$·K) |
| First level | 1.569 | 1.475 | 0.743 |
| Second level | 1.681 | 1.589 | 0.796 |
| Third level | 1.808 | 1.653 | 0.841 |
| Fourth level | 2.054 | 1.727 | 0.911 |
| Fifth level | 2.530 | 1.828 | 1.033 |

Note: $\alpha_r$ – coefficient of convective heat transfer from the refrigerant to the condenser wall, kW/(m2·K); $\alpha_{hw}$ – coefficient of convective heat transfer from the condenser wall to heating water, kW/(m$^2$·K); k – heat transfer coefficient, kW/(m$^2$·K).

**Table 3: Time Constants and Coefficients of the Mathematical Models of the Dynamics of Smart Grid Solar Biogas Heat Pump Electric System**

| Levels of Operation | $T_{hw}$, s | $T_m$, s | $L_{hw.}$, m | ε | $L_{r.}$, m | $L_r^*$ | $\varepsilon^*$ | ζ |
|---|---|---|---|---|---|---|---|---|
| First level | 3.20 | 4.10 | 75.39 | 1.2635 | 7.40 | 0.1190 | 0.1131 | 0.4097 |
| Second level | 2.97 | 3.81 | 69.98 | 1.2760 | 5.34 | 0.1577 | 1.0748 | 0.4320 |
| Third level | 2.86 | 3.66 | 67.28 | 1.2993 | 3.85 | 0.2061 | 1.0315 | 0.4415 |
| Fourth level | 2.74 | 3.50 | 64.40 | 1.4128 | 2.0 | 0.3333 | 0.9419 | 0.4438 |
| Fifth level | 2.58 | 3.31 | 60.82 | 1.6432 | 1.14 | 0.4673 | 0.8753 | 0.4340 |

presented in Table **3** were obtained based on the parameters presented in Tables **1**, **2**.

Based on the proposed mathematical substantiation Smart Grid maintenance of functioning of the solar biogas heat pump electric system (1) to (3) the block diagram for the control of serviceability of the solar biogas heat pump electric system (Figure **3**) is developed.

Control of operability of the solar biogas heat pump electric system (Figure **3**) enables obtaining the resulting information for on advance decision-making about the harmonization of production and consumption of solar biogas heat pump electric system. Based on the proposed mathematical substantiation Smart Grid (1) to (3) the block diagram of maintenance of operation of the solar biogas heat pump electric system (Figure **4**) is developed.

Maintaining the transmission of electrical energy to the grid allows the production and consumption of electrical energy to be coordinated (Figure **4**).

## 4. RESULTS AND DISCUSSION

### 4.1 Smart Grid Solar Biogas Heat Pump Electric System at the Decision-Making Level

A comprehensive integrated system (Table **4**) has been developed to maintain the operation of a heat pump power supply for a biogas plant, for which fermented wort is a low-potential energy source, and a grid-connected solar power system. The change in the temperature of the heating coolant entering the heat exchanger built into the methane tank and the power factor of the grid-connected solar power system are predicted. Promising solutions are aimed at changing the power of the heat pump compressor to maintain biogas production, loading fresh material and

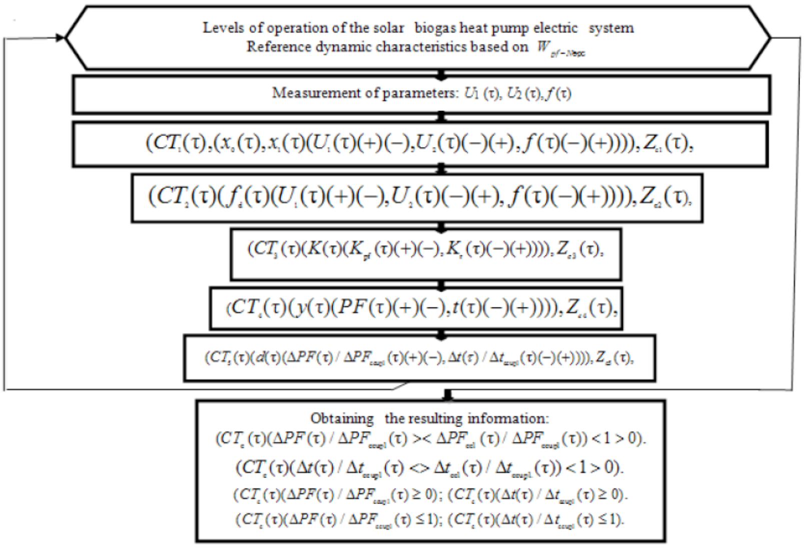


**Figure 3:** Block diagram of the solar biogas heat pump electric system functioning control: $U_1$, $U_2$, – voltage at the input to the hybrid inverter and at the output of the frequency converter, respectively, V; f – voltage frequency, Hz; *KF* – power factor of the solar biogas heat pump electric system; *t* is heating water temperature at the outlet from the condenser, °C; *CT* – event control; *Z* – logical relations; *d* – dynamic parameters; *x* – effects; $f_d$ – parameters measured; *y* – parameters predicted; *K* – coefficients of mathematical description; ι – time. Indices: *c* – control of operability; ccup– constant calculated value of the parameter of upper level of operation; ccl – constant calculated value of the parameter of level of operation; 0, 1, 2 – initial stationary mode, external, internal influences; 3 – coefficients of dynamics equations; 4 – significant predicted parameters; 5 – dynamic parameters.

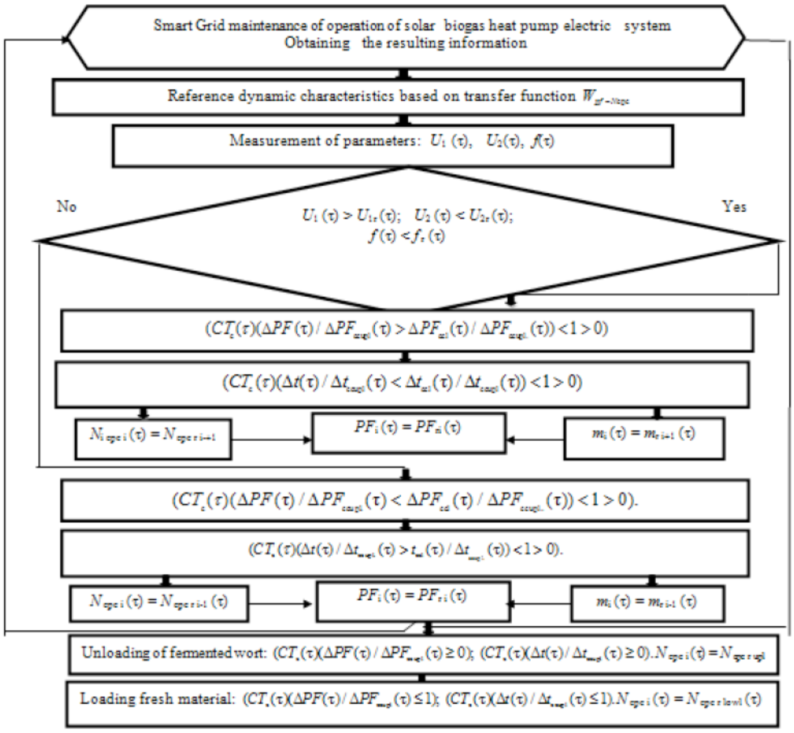


**Figure 4:** Block diagram of maintenance of operation of the solar biogas heat pump electric system: $U_1$, $U_2$,– voltage at the input to the hybrid inverter and at the output of the frequency converter, respectively, V; f – voltage frequency, Hz; *KF* – power factor of the biogas heat pump electric system; *t* is heating water temperature at the outlet from the condenser, °C; $N_{epc}$ – the power of the compressor electric motor, kW; *m* – the power level of the network solar electric system; ι – time, s. Indices: *i* – number of operation levels; r – the reference value of the parameter; ccup– constant calculated value of the parameter of upper level of operation; ccl – constant calculated value of the parameter of level of operation; r upl, r lowl –the reference upper level, the reference low level of operation, respectively.

unloading fermented raw materials when changing the level of electrical energy transfer to the grid. The voltage at the input of the hybrid inverter, the voltage at the output of the frequency converter and the voltage frequency are continuously measured. The change in the ratio of the voltage at the input of the hybrid inverter and the voltage at the output of the frequency converter is estimated.

**Table 4: Integrated Smart Grid Harmonization of Production and Consumption of Solar Biogas Heat Pump Electric System**

| Time, τ, $10^2$ s | Change of Parameters | $\Delta PF(\tau)/\Delta PF(\tau)_1$ | $PF(\tau)$ | $\Delta t_{hw\,out}(\tau)/\Delta t_{hwout}(\tau)_1$. | $t_{hwout}(\tau)$, °C |
|---|---|---|---|---|---|
| 13 | Loading fresh material<br>$U_1$ = 240 V; $N_e$ = 4 kW; $U_2$ = 400 V; $f$=50 Hz; $N_{epc}$=3.14 kW; $t_{r\,in}$ =60°C;<br>$t_{r\,out}$ = 55.5°C; $t_{hw\,in}$=44.15°C; m = 0.4 | 1 | 0.58 | 1 | 55 |
| 26 | Charge – discharge<br>$U_1$ =280V; $N_e$ = 4.7 kW; $U_2$= 369V; $f$=49.95Hz; $N_{epc}$ =2.9 kW; $t_{r\,in}$ = 60°C;<br>$t_{r\,out}$ = 56°C; $t_{hw\,in.}$ =43.06°C; m =0.47 | 0.6842 | 0.7063 | 0.6842 | 51.84 |
| 39 | Decision making<br>$U_1$ = 320 V; $N_e$ = 5.3 kW; $U_2$= 345.2 V; $f$=43.15 Hz; $N_{epc}$ =2.71 kW; $t_{r\,in}$ = 57.1°C;<br>$t_{r\,out}$ = 52.6°C; $t_{hw\,in}$ =43.06°C; m =0.53 | 0.6762 | 0.7095 | 0.6762 | 51.76 |
| 52 | Charge – discharge<br>$U_1$ =360V; $N_e$ = 6 kW; $U_2$= 319.7V; $f$=40Hz; $N_{epc}$ =2.51 kW; $t_{r\,in}$ =57.1°C;<br>$t_{r\,out}$ = 54.5°C; $t_{hw\,in}$ =42.3°C; m =0,60 | 0.4480 | 0.8008 | 0.4480 | 49.48 |
| 65 | Decision making<br>$U_1$ =400 V; $N_e$ = 6.7 kW; $U_2$ = 293V; $f$=36.6 Hz; $N_{epc}$ =2.3 kW; $t_{r\,in}$ =54.9°C;<br>$t_{r\,out}$ = 50.4°C; $t_{hw\,in.}$ =42.3°C; m =0.67 | 0.3986 | 0.8206 | 0.3986 | 49 |
| 78 | Charge – discharge<br>$U_1$ = 440V; $N_e$ = 7.3 kW; $U_2$ = 280.2V; $f$=33.5Hz; $N_{epc}$ =2.2 kW; $t_{r\,in}$ =54.9°C;<br>$t_{r\,out}$ = 52.6°C; $t_{hw\,in}$ =41.5°C m =0.73 | 0.2514 | 0.8795 | 0.2514 | 47.53 |
| 91 | Decision making<br>$U_1$ = 480 V; $N_e$ = 8 kW; $U_2$ = 243.3V; $f$=30.41Hz; $N_{epc}$ =1.91 kW; $t_{r\,in}$ =52.5°C;<br>$t_{r\,out}$ = 48°C; $t_{hw\,in}$ =41.5°C; m =0.80 | 0.2238 | 0.8905 | 0.2238 | 47.25 |
| 104 | Charge – discharge<br>$U_1$ = 520V; $N_e$ = 8.7 kW; $U_2$= 220.4V; $f$=25.5Hz; $N_{epc}$ =1.73 kW; $t_{r\,in}$ =52.5°C;<br>$t_{r\,out}$ = 50.6°C; $t_{hw\,in}$ =40°C; m =0.87 | 0.1553 | 0.9179 | 0.1553 | 46.57 |
| 117 | Decision making<br>$U_1$ = 560 V; $N_e$ = 9.3 kW; $U_2$ =201.3 V; $f$=25.17 Hz; $N_{epc}$ =1.58 kW; $t_{r\,in}$ =50°C;<br>$t_{r\,out}$ = 45.5°C; $t_{hw\,in}$ =40.3°C; m =0.93 | 0.1292 | 0.9283 | 0.1292 | 46.31 |
| 130 | Unloading of fermented wort<br>$U_1$ = 600 V; $N_e$ = 10 kW; $U_2$ = 201.3 V; $f$=25.17 Hz; $N_{epc}$ =1.58 kW; $t_{r\,in}$=50°C;<br>$t_{r\,out}$ = 49.8°C; $t_{hw\,in}$ =37.04°C. m =1 | 0 | 0.98 | 0 | 45 |

Note: $U_1$, $U_2$ – voltage at the network inverter input and the frequency converter output, volts; f – voltage frequency, Hz; $N_e$, $N_{epc}$ are the power of photoelectric module, power of the compressor electric motor, respectively, kW; $t_{r\,in}$, $t_{r\,out}$ are refrigerant temperatures at the inlet to the condenser, at the outlet from the condenser, respectively, °C; $t_{hw\,in}$, $t_{hw\,out}$ are heating water temperature at the inlet to the condenser, at the outlet from the condenser, respectively, °C; *m* – level of transmission of electricity to the network; τ – time, s. Indexes: hw – heating water; 1 – constant, calculated value of the parameter of the upper level of functioning.

The integrated Smart Grid system of maintenance of operation of the solar biogas heat pump electric system network (Table **4**) provides an opportunity to coordinate electric power production and consumption.

The power factor of the of the solar biogas heat pump electric system network is determined as follows:

$$PF_{i+1}(\tau) = PF_i + \left( \begin{array}{l} \Delta PF_{i+1}(\tau)/\Delta PF_1(\tau) - \\ -\Delta PF_i(\tau)/\Delta PF_1(\tau) \end{array} \right)(PF_2 - PF_1), \quad (17)$$

where *PF* – power factor of the solar biogas heat pump electric system network; $PF_1$, $PF_2$ – initial and final values of the power factor; τ – time, s. Indices: 1– constant calculated value of the parameter of the upper level of operation; *i* – the number of levels of operation of the network solar electric system.

The temperature of heating water from outlet of the condencer in the established period is determined as follows (Table **4**):

$$t_{i+1}(\tau) = t_i - \left( \begin{array}{l} \Delta t_i(\tau)/\Delta t_1(\tau) - \\ -\Delta t_{i+1}(\tau)/\Delta t_1(\tau) \end{array} \right)(t_1 - t_2), \quad (18)$$

where *t* is the temperature of heating water, °C; $t_1$, $t_2$ are the initial, final values of temperature of heating water; τ is the time, s. Index: 1 is the constant calculation value of the parameter of the upper level of operation; *i* is the number of levels of functioning of the biogas plant-heat pump system.

For example, over a period of 39 $10^2$ s (1.08 h), from the loading of fresh material into the biogas plant (Table **4**), the power factor was predicted to increase to a level 0.7095 with an increase in the voltage at the input of the hybrid inverter at 320 V. The value of the power factor was determined using formula (17) as follows (Table **4**, Figure **6**):

$$0.7095 =0.7063+(0.6842–0.6762)(0.98–0.58).$$

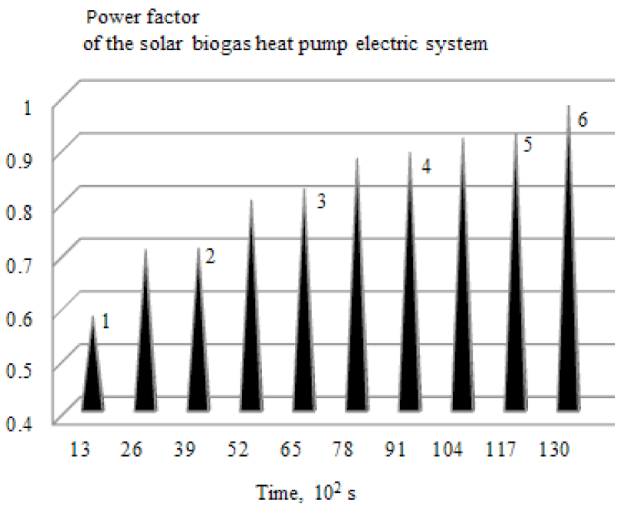


**Figure 6:** Maintenance of change in the power factor, where 2, 3, 4. 5 – decision-making to change the power of the heat pump, 1, 6 – support for loading fresh wort and unloading of fermented material, respectively.

In this period of time, it is necessary to make a preliminary decision to reduce the power of the heat pump to the level of 2.7 kW and increase the level of power of transmission of electrical energy to the network from 0.47 to 0.53. The temperature of heating water from outlet of the condencer in that period was determined using formula (18) as follows (Table **4**, Figure **7**):

$$51.76°C=51.84°C- (0.6842–0.6762)(55°C –45°C).$$

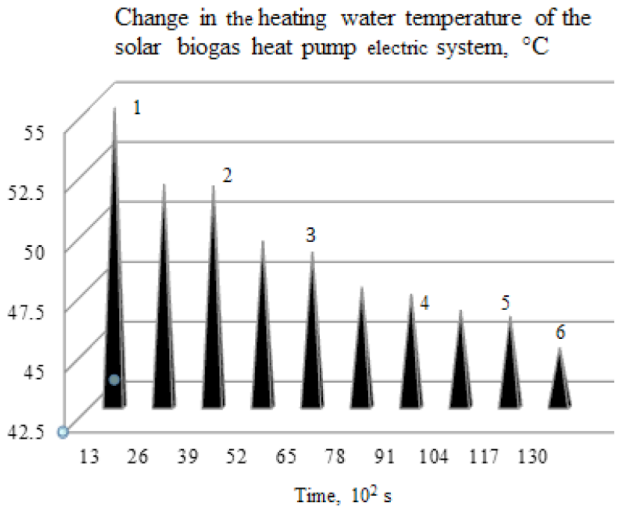


**Figure 7:** Maintenance of change in the heating water temperature, where 2, 3, 4. 5 – decision-making to change the power of the heat pump, 1, 6 – support for loading fresh wort and unloading of fermented material, respectively.

Performing such actions will enable maintenance of fermentation temperature in biogas plant to coordinate the production and consumption of electric power [12] (Figure **8**.)

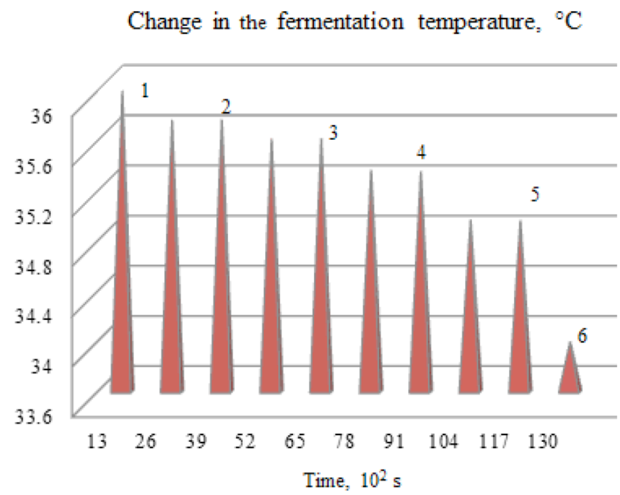


**Figure 8:** Suppot of the fermentation temperature based on frequency control of the heat pump compressor electric motor, where 2, 3, 4. 5 – decision-making to change the power of the heat pump, 1, 6 – support for loading fresh wort and unloading of fermented material, respectively.

It is the proposed technology of operation of a biogas plant [12], using a heat pump in the production of biogas, for example, 352.5 $m^3$/day, which allows, with an increase in the marketability of the biogas plant by 13.94%, to obtain a biogas savings of 25.4 thousand $m^3$/year. This provides additional resources for the creation of a complex system for the production of electric energy using biogas and solar.

The author's work[12] presents an energy-saving technology for biogas production, the author's work [13] presents an energy-saving technology for the operation of heat pumps, the author's work [14] presents Smart Grid Technologies for solar systems, *i.e*. each of the components of the presented scientific research is new, which makes the complex system of solar biogas heat pump unique. The research can be continued by adding electrical systems included in the proposed integrated system and hrough the use of new renewable energy sources.

## 5. CONCLUSIONS

1. It was proposed support for the integrated operation of a biogas plant and a solar grid power system that provides power to a heat pump which uses fermented wort as a low-potential source of energy. The change in the ratio of the voltage at the input of the

hybrid inverter and the voltage at the output of frequency converter is estimated. For example, when the changing the voltage at the input of the hybrid inverter from 240 V to 600 V, promising solutions were adopted to reduce the power of the heat pump from 3.14 kW to 1.58 kW to maintain the temperature of the heating coolant entering the heat exchanger built into the methane tank at 55°C – 45°C in order to obtain biogas, unload fermented wort and load fresh raw materials. There is an increase in the power of electricity transmission to the network from 0.27 to 1 and an increase in the power factor of the network solar power system by 40 % from 0.58 to 0.98.

2.A structural diagram has been developed and complex mathematical modeling has been applied to obtain a reference estimate of the change in the power factor of the grid-tied solar system and the temperature of the heating coolant entering the heat exchanger built into the methane tank. Estimation of the measured voltage ratio at the input to the hybrid inverter and at the output of the frequency converter is a unifying element of the mathematical modeling of the dynamics. The heat exchange parameters in the heat pump system, time constants and coefficients of the mathematical models of the dynamics for the established operating levels have been determined. Reference dynamic estimates of the change in the power factor (0.58, 0.7095, 0.8206, 0.8905, 0.9283, 0.98) and the temperature of the heating coolant entering the heat exchanger built into the methane tank entering the heat exchanger built into the methane tank (55° C°, 51.76° C, 49° C, 47.25° C, 46.31° C, 45° C) in accordance with the established operating levels have been obtained.

3. It is proposed to make advanced decisions on changing the heat pump capacity to maintain the operation of a biogas plant. A structural diagram has been developed and logical modeling has been performed for the integrated control of a biogas plant and a grid-tied solar system based on the principle of cause-and-effect relationships. The logical block has components that evaluate the change in voltage in the range of 240-600 V at the input of the hybrid inverter and 400-201.3 V at the output of the frequency converter. According to the structural diagram, changes in the coefficients of mathematical models of the dynamics of Kr, Kpf, dynamic parameters of changes in the power factor from 0.58 to 0.98 and the heating water temperature from 55 ° C to 45 ° C were estimated. In the resulting performance monitoring block, a resulting functional assessment of the change in the power factor and temperature was obtained. In real operating conditions of solar biogas heat pump electric system, when transitioning from stationary states and under the influence of external and internal influences, the coefficients of the dynamic equations Kr, Kpf are rebuilt over time due to a change in the measured ratio of the voltage at the input to the hybrid inverter and the voltage at the output of the frequency converter

4. Based on the developed structural diagram of logical modeling, a comprehensive Smart Grid system for maintaining the integrated operation of a biogas plant and a grid-connected solar electric system has been developed. Maintaining the power factor from 0.58 to 0.98 was carried out based on comparing the voltages at the input of the hybrid inverter and the voltage at the output of the frequency converter with the reference values. According to the established operating levels, the reference values of the voltage at the input of the hybrid inverter were 240 V, 320 V, 400 V and 480 V, 560 V, 600 V . The reference value of the voltage at the output of the frequency converter was 400 V, 345.2 V, 293 V, 243.3 V, 201.3 V.

5. Coordination of electric power production and consumption was provided based on predicting the changes in the power factor and the heating water temperature. Advanced solutions for changing the power level of the heat pump to support the operation of the biogas plant made it possible to change the level of electricity transmission to the grid. Using the developed Smart Grid technology allows you to prevent the peak load of the energy system, reducing the consumption of electrical energy from the network to 30%.

## CONFLICTS OF INTEREST

The authors declared no potential conflicts of interest.

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