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DEVELOPMENT OF ENERGY-SAVING TECHNOLOGY TO MAINTAIN THE FUNCTIONING OF A WIND-SOLAR ELECTRICAL SYSTEM

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Розроблено інтегровану систему підтримки функціонування вітро-сонячної електричної системи на основі прогнозування зміни ємності акумуляторної батареї при вимірюванні напруги на вході в гібридний контролер заряду, напруги на виході із інвертора та частоти напруги. Прийняття випереджуючих рішень на підтримку ємності акумуляторної батареї щодо зміни потужності теплоелектроакумулятора базується на встановленні співвідношення напруги на вході в гібридний контролер заряду та напруги на виході із інвертора, що вимірюються. Забезпечено зміну числа обертів електродвигуна циркуляційного насоса щодо зміни витрати та температури води, що нагрівається, зменшивши термін заряду до 30 %. Виконано комплексне математичне та логічне моделювання вітро-сонячної електричної системи, що базується на математичному обґрунтуванні архітектури технологічної системи та математичному обґрунтуванні підтримки функціонування вітро-сонячної електричної системи. Основою запропонованої технологічної системи є динамічна підсистема, що включає наступні складові: вітроенергетичну установку, фотоелектричний модуль, гібридний контролер заряду та інвертор, масив акумуляторних батарей, теплоелектроакумулятор. Визначено постійні часу та коефіцієнти математичних моделей динаміки щодо зміни ємності акумуляторної батареї, числа обертів електродвигуна циркуляційного насоса, витрати місцевої води. Здобуто функціональну оцінку зміни ємності акумуляторної батареї, числа обертів електродвигуна циркуляційного насоса, витрати місцевої води щодо зміни температури місцевої води в діапазоні 30–70 °С. Визначення підсумкової функціональної інформації щодо прогнозування зміни ємності акумуляторної батареї надає можливість приймати наступні випереджуючі рішення: на зміну числа обертів електродвигуна циркуляційного насоса, зміну витрати місцевої води. Підтримка ємності акумуляторної батареї відбувається на основі узгодження виробництва та споживання енергії

***Ключові слова:** вітро-сонячна електрична система, акумуляторна батарея, теплоелектроакумулятор, гібридний контролер заряду, інвертор*

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1. Introduction

Given the need to save natural fuel and reduce harmful emissions into the atmosphere, supporting the operation of wind-solar electrical systems requires improvements in terms of accumulating electrical energy. Thus, for example, based on the mathematical and logical modeling related to the technological system of functioning of a rechargeable battery, the technology has been devised to support a change in the battery capacity, based on predicting a voltage change when measuring the temperature of the electrolyte in the volume of rechargeable batteries. Application of the integrated evaluation system of voltage change, obtained on the basis of adjusting the electrochemical and diffusion processes of discharge and charge, makes it possible to take timely decisions about additional charging to prevent recharge and inadmissible discharge [1].

Owing to the combination of two different energy sources into a single wind-solar electric system, predetermined by the need to expand the duration of electric energy consumption, specialized hybrid controllers have been designed to control the charging of rechargeable batteries. PWM controllers' operation is based on the pulse-width modulation of the charge current. MPPT controllers that operate on the principle of finding the maximal power of energy generation adjust a change in voltage to the change in current. Known methods for charging MPPT controllers are based on scanning aimed at establishing a point of maximum power. Thus, according to the Perturb and Observe method, the controller performs a full scan of the volt-ampere characteristic, thereby finding the point of maximum power over a specified time duration. Until the next full scanning, the controller calculates a change in power and sets the operating point to new voltage if the power is larger at it. Improvement of the method for determining the optimal maximum power is performed at the level of assessing a change in the cycle of complete scanning, depth, and frequency of iterations, etc. According to the Scan and Hold method, following the primary scanning, the defined maximum power point does not change until the next full scanning. The method of Percentage of open circuit voltage makes it possible to use operating voltage based on the estimation of idling voltage. The choice of a working point without scanning is also supported by the method to evaluate maximum power of energy generation in compliance with the maximum capacity of a rechargeable battery. Under conditions of unstable solar radiation and changing wind speed, obtaining the total maximum power of two energy sources does not coincide in time, both during the day and over the year. Under difficult conditions for electrical energy generation at changing consumption, it is a relevant task, related to the further development of the technologies of wind-solar electrical systems, to support the capacity of a rechargeable battery in terms of adjusting the generation and consumption of energy under conditions of energy efficiency. To this end, it is necessary to predict the change in the capacity of a rechargeable battery when measuring voltage at the input to a hybrid charge controller, as well as voltage at the output from an inverter, in order to estimate their ratio when measuring the frequency of the voltage. Making preliminary decisions about a change in the power of a thermoelectric battery makes it possible, while maintaining capacity of the rechargeable battery, to change rotational speed of the electric motor of the circulating pump in order to change local water consumption and the heating level.

2. Literature review and problem statement

Known methods for the optimization of wind-solar electrical systems are based on improving the intelligent management systems based on hybrid charge controllers, emphasizing the relevance of combining two different sources of energy. One direction to optimize wind-solar electrical systems is to improve the function of MPPT controllers in terms of finding maximum power. For example, paper [2] proposed an MPPT algorithm for hybrid controllers based on integration between management of fractional order and a method of incremental conductivity to improve the accuracy of monitoring. Study [3] established the possibility to obtain maximum power in a different period, both during the day and over the year; article [4] underlined the maximum efficiency of hybrid controllers MPPT in terms of defining maximum power at efficiency of up to 99.60 %. Paper [5] has established, based on the proposed technological scheme, the increase in the efficiency of a wind-solar electric system in comparison with separate application of a wind-solar electric system employing the MPPT function of hybrid controllers. Authors of [6], in order to improve the MPPT function of hybrid controllers, suggested a specialized algorithm that was developed based on the simulation of subsystems of wind and solar power, rechargeable battery, and inverter, based on MATLAB Simulink. Paper [7] proposed using a constant voltage method to maximally transmit power based on the MPPT function of hybrid controllers. The conclusion was drawn about the necessity to define key features in the application of the method. However, by emphasizing the relevance of the combination of two different energy sources and the MPPT capability of hybrid controllers for finding maximum power, authors of [3–5, 7] do not consider the need to maintain the capacity of a rechargeable battery in terms of adjusting the generation and consumption of energy in the structure of a wind-solar electric system. The constructed algorithms [2, 6], aimed at improving the MPPT function of hybrid controllers, which confirmed the ability to obtain maximum power from each source of energy, do not take into consideration electricity consumption in terms of its adjustment to its generation. Improvement of intelligent control systems has been addressed in work [8], which presented a hybrid controller with fuzzy logic to manage the generation and transmission of energy. The authors described command signals, as well as determined the ratio of renewable energy system integration. However, the proposed technology does not include aligning the generation and consumption of electrical energy, which is why the excess energy was directed into the system of electrolysis to obtain hydrogen. More to the point, the reported technology requires a network connection to ensure peak consumption. Paper [9] suggested using a neural model to forecast changes in the parameters for a wind-solar electric system as a nonlinear dynamic system. The optimization of predictive control is based on the representation of the subsystems that generate wind energy, solar energy, as well as rechargeable battery and load. Based on computer simulation, the authors established performance efficiency of the intelligent control over a distributed model, but failed to assess a change in the capacity of a rechargeable battery in terms of adjusting the generation and consumption of energy. Study [10] reported the optimization of a wind-solar electric system based on control over inverter operation. The authors introduced an additional module of dispatching control to track the maximum power of energy sources. They used special methods for the simultaneous collection of energy under different climatic conditions. For a photovoltaic system, the algorithm Perturb & Observe; for a wind turbine, Hill Climb Search. Maintaining the consumption of energy generated based on establishing constant voltage and frequency of voltage does not estimate a change in the capacity of a rechargeable battery. Paper [11] proposed an economic model for the optimization of a wind-solar electric system based on minimizing operating costs. The authors applied the methods of meta heuristic optimization to compare a genetic algorithm and the Particle Swarm Optimization algorithm. The optimization takes into consideration the costs of production of solar and wind energy, recovery of thermal energy from a fuel cell, energy supply, electricity exchange in a network, as well as maintenance. The authors established the economic feasibility of the structure of a hybrid combined wind-solar electric system, connected to the grid and with a heat element, but at the static level. They established the benefits of using a genetic algorithm for obtaining the optimization results, but without predicting the change of parameters for the system's components.

Based on analysis of the scientific literature [2–11], it was found that the hybrid charge controller as part of a wind-solar electric system maintains the charge of a rechargeable battery by using a thermoelectric battery as a non-regulated ballast. Resetting the excess energy to the ballast when using the MPPT functions of controller leads to the uncompensated-for losses of electrical energy, which does not make it possible to ensure an appropriate level of the charge capacity of a rechargeable battery. Moreover, the use of a thermoelectric battery as a ballast eliminates the need to maintain the operation of a wind energy installation by using the accumulation of heat to regulate the power of a wind turbine. Failure to consider this property of a thermoelectric battery could lead to the acceleration of a wind turbine at considerable wind speed and to its malfunctioning. It is the thermoelectric battery that appears to be the main center of adjusting a change in the total power of a wind-solar electric system to power consumption through redistribution of the accumulated heat and electric energy in terms of consumption. Therefore, it is proposed to measure the total voltage at the input to a hybrid charge controller and voltage at the output from inverter to estimate the ratio of electrical energy generation to its consumption when measuring the frequency of the voltage. It is known that a thermoelectric battery is executed in line with a thermostat principle, that is, when determining the required temperature for heating local water, the thermoelectric battery is disconnected from power. Not using a change in the consumption of local water over the period of thermoelectric battery charging increases the charging time and leads to considerable costs related to electricity consumption. Thus, it has been an unresolved problem in maintaining the operation of a wind-solar electric system to forecast a change in the capacity of a rechargeable battery. In order to save energy, it is necessary to measure voltage at the input to a hybrid charge controller and voltage at the output from the inverter to estimate their ratio when measuring the frequency of the voltage. Making preliminary decisions about changing the power of a thermoelectric battery makes it possible, while maintaining the capacity of the rechargeable battery, to change rotational speed of the electric motor of the circulating pump. Changing a flow rate of the local water supplied to a thermoelectric battery ensures the set level of change in the temperature of heated local water. That substantiated the need to undertake a research in this field.

3. The aim and objectives of the study

The aim of this study is to devise an energy-saving technology to maintain the operation of a wind-solar electric system as part of the technological system.

To achieve the set aim, the following tasks must be solved:

– to substantiate the need to forecast a change in the capacity of a rechargeable battery in order to take preliminary decisions about changing the power of a thermoelectric battery based on changing rotational speed of the electric motor of the circulating pump, as well as the consumption of local heated water;

– to propose using an estimate of change in the ratio of total voltage of a wind turbine, photoelectric module at the input to a hybrid charge controller, voltage at the output from the inverter, which are measured, when measuring the frequency of the voltage;

– to build structural diagrams and perform integrated mathematical and logical modelling for obtaining the reference and functional assessment of change in the capacity of a rechargeable battery, rotational speed of the electric motor of the circulating pump, local water consumption;

– to design a structural diagram and perform logical modeling for obtaining an integrated support system for maintaining the operation of a wind-solar electrical system at the level of decision-making.

4. Materials and methods used in the study into maintaining the operation of a wind-solar electric system

4. 1. Mathematical substantiation of the technological system's architecture

Based on the methodological and mathematical substantiation of the architecture of technological systems [1, 12–14], the architecture and mathematical substantiation of the technological system's architecture for the operation of a wind-solar electric system have been proposed. Its basis is the integrated dynamic subsystem, which includes the following components: a wind-energy installation, a photoelectrical module, a hybrid charge controller, an inverter, an array of rechargeable batteries, a thermoelectric battery (Fig. 1). There are other units that are part of the technological system, specifically units of charge, discharge, as well as a unit to estimate functional effectiveness, all aligned with the dynamic subsystem (Fig. 1).

In Fig. 1: *TSFWS* – technological system for operating a wind-solar electric system; *D* – dynamic subsystem (a wind-energy installation, a photoelectric module, a hybrid charge controller and an inverter, an array of rechargeable batteries, a thermoelectric battery); *P* – properties of the elements in a technological system; τ – time, s; x – influences (change in solar radiation, change in wind speed, change in electricity consumption, etc.); f – measured parameters (voltage at the input to a hybrid charge controller, voltage at the output from the inverter, voltage frequency); f_i – diagnosed parameter (power of a thermoelectric battery); K – coefficients for the mathematical description of the dynamics of change in the capacity of a rechargeable battery, the rotational speed of the electric motor of the circulating pump, changes in the local water consumption; K_i – coefficients for the mathematical description of functional efficiency of a technological system; y – starting parameters (change in capacity of a rechargeable battery, rotational speed of the electric motor of the circulating pump, local water consumption); y_i – estimation of the functional efficiency of a wind-solar electric system); d – dynamic parameters for change in the capacity of a rechargeable battery; the rotational speed of the electric motor of the circulating pump, local water consumption; Z – logical relationships in D to obtain summarized information for decision-making to maintain the capacity of a rechargeable battery; R – logical relationships in *TSFWS* to confirm the correctness of decisions made from the units as part of a technological system. Indexes: i – the number of elements in a technological system; 0, 1, 2 – initial stationary mode, external, internal character of influences.

Mathematical substantiation has been proposed for maintaining the operation of a wind-solar electric system based on predicting a change in the capacity of a rechargeable battery when measuring the following parameters: voltage at the input to a hybrid charge controller, voltage at the output from the inverter, and voltage frequency.

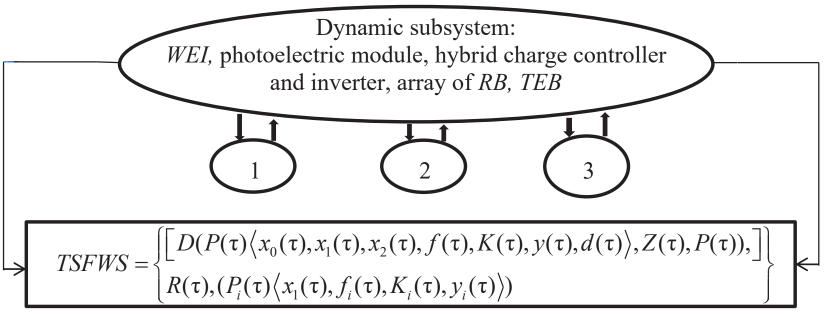

Fig. 1. Architecture and mathematical substantiation of the architecture of a technological system: 1 – charge unit; 2 – discharge unit; 3 – unit to estimate functional efficiency, where *WEI* – wind-energy installation; *RB* – rechargeable battery; *TEB* – thermoelectric battery

Mathematical notation (1) is based on the mathematical substantiation of the architecture of technological systems, the methodology of mathematical description of the dynamics of energy systems, the method of causation graph [1, 12–14].

$$SFWS(\tau)=\left\{\left[\left[\begin{array}{l}(IDS(\tau)(PIDS(\tau)\\ \langle sd(\tau),lp(\tau),lf(\tau),fd(\tau)\rangle,\\ MMIDS(\tau,z),CIDS(\tau),LCIDS(\tau)\\ \left\langle\begin{array}{l}x_0(\tau),x_1(\tau),x_2(\tau),f(\tau),\\ K(\tau),y(\tau,z),d(\tau),FIIDS(\tau)\end{array}\right\rangle,\\ LMDIDS(\tau),MDIDS(\tau),\\ NCF(\tau),SIDS(\tau),LSIDS(\tau)\\ \langle f(\tau),K(\tau),y(\tau,z),d(\tau),FIIDS(\tau)\rangle\\ PIDS(\tau))),R(\tau),(PB_i(\tau)\\ \langle x_1(\tau),f_i(\tau),K_i(\tau),y_i(\tau)\rangle)CNCF(\tau)),\\ \end{array}\right]\right]\right\}, \quad (1)$$

where $SFWS(\tau)$ – maintaining the operation of a wind-solar electric system; $IDS(\tau)$ – integrated dynamic subsystem (a wind energy installation, a photoelectric module, a hybrid charge controller and an inverter, an array of rechargeable batteries, a thermoelectric battery); $PIDS(\tau)$, $PB(\tau)$ – properties of the elements in an integrated dynamic subsystem, units in a technological system, respectively; $sd(\tau)$ – starting data (the power of a wind-energy installation; the power of a photoelectric module; the type of a hybrid charge controller and an inverter, the capacity of a rechargeable battery; the power and volume of a thermoelectric battery); $lp(\tau)$ – limit to change in parameters (voltage at the input to a hybrid charge controller, thermoelectric battery's power); $lf(\tau)$ – levels of functioning according to a change in voltage at the input to a hybrid charge controller and at the output from the inverter; fd – derived parameters (parameters for heat transfer in a thermoelectric battery, the rotational speed of the electric motor of the circulating pump, the flow rate of heated water, the charge duration of a thermoelectric battery for the established levels of functioning; $MMIDS(\tau, z)$ – mathematical modeling of the dynamics of change in the capacity of a rechargeable battery, rotational speed of the electric motor of the circulating pump, local water consumption; $MIIDS(\tau)$ – maximally permissible change in the total power of a wind-solar electric system, the power of a thermoelectric battery, the rotational speed of the electric motor of the circulating pump, local water consumption, the temperature of local water; $CIDS(\tau)$, $MDIDS(\tau)$, $SIDS(\tau)$ – control of workability, decision making, identification of the status in the dynamic subsystem, respectively; $LCIDS(\tau)$, $LMDIDS(\tau)$, $LSIDS(\tau)$ – logical relationships in $CIDS(\tau)$, $MDIDS(\tau)$, $SIDS(\tau)$, respectively; $FIIDS(\tau)$ – functional summarized information for decision making in the dynamic subsystem; $NCF(\tau)$, $CNCF(\tau)$ – new conditions of operation, confirmation of the new conditions for functioning from the units in a technological system; $R(\tau)$ – logical relationships between a dynamic subsystem and the discharge units, charge units, functional assessment of performance, included in the technological system for operating a wind-solar electric system; $x(\tau)$ – influences; $f(\tau)$ – diagnosed parameters; $K(\tau)$ – coefficients for mathematical notation; $y(\tau, z)$ – starting parameters; $d(\tau)$ – dynamic parameters; z – length coordinate, m; τ – time, s.

Indexes: i – number of elements $SFWS(\tau)$; 0, 1, 2 – initial mode, external, internal character of influences.

Mathematical notation (1) and mathematical substantiation of the architecture of a technological system (Fig. 1) make it possible to maintain the functioning of a wind-solar electric system by employing the following actions:

– control over workability ($CIDS(\tau)$) of the dynamic subsystem based on the mathematical ($MMIDS(\tau, z)$) and logical ($LCIDS(\tau)$) modelling to obtain a reference ($MIIDS(\tau)$) estimate of change in the capacity of a rechargeable battery, rotational speed of the electric motor of the circulating pump, local water consumption;

– control over workability ($CIDS(\tau)$) of the dynamic subsystem based on the mathematical ($MMIDS(\tau, z)$) and logical ($LCIDS(\tau)$) modelling to obtain a functional ($FIIDS(\tau)$) estimate of change in the capacity of a rechargeable battery, rotational speed of the electric motor of the circulating pump, local water consumption;

– decision making ($MDIDS(\tau)$) using the functional information ($FIIDS(\tau)$), acquired on the basis of logic simulation ($LMDIDS(\tau)$);

– making decisions on changing the frequency of voltage using the functional estimate of change in the capacity of a rechargeable battery, rotational speed of the electric motor of the circulating pump, local water consumption, ($FIIDS(\tau)$);

– identification ($SIDS(\tau)$) of the new conditions for operating a wind-solar electric system ($NCF(\tau)$) based on logic simulation ($LSIDS$ (τ)) as part of the dynamic subsystem and confirmation of the new conditions for functioning based on logic simulation ($R(\tau)$) from units in a technological system.

4. 3. Mathematical modeling of the dynamics of change in the capacity of a rechargeable battery

According to formula (1) and mathematical substantiation of the architecture of a technological system (Fig. 1), it has been proposed to predict a change in the capacity of a rechargeable battery when measuring voltage at the input to a hybrid charge controller, when measuring voltage at the output from the inverter and the voltage frequency. A transfer function along the channel: «capacity of rechargeable battery – power of thermoelectric battery» was derived from solving a system of nonlinear differential equations. A change in the capacity of a rechargeable battery when using the estimate of change in the local water temperature both in time and along the coordinate of length of the heater in a thermoelectric battery, takes the following form:

$$W_{ec-Nm_1}=\frac{K_{ec}K_w\left(1-L_w^{*}\right)}{(T_wS+1)\beta-1}\left(1-e^{-\gamma\xi}\right), \quad (2)$$

where

$$K_{ec}=\frac{IU_1}{(U_1-U_2)};$$

$$K_w=\frac{m\left(\theta_0-t_0\right)}{G_{w0}};$$

$$L_w^{*}=\frac{1}{L_w+1};\quad L_w=\frac{G_wC_w}{\alpha_{w0}h_{w0}};\quad \varepsilon^{*}=(1-L_w^{*});$$

$$\gamma=\frac{(T_wS+1)\beta-1}{\beta};\quad \xi=\frac{z}{L_w};\quad T_w=\frac{g_wC_w}{\alpha_{w0}h_{w0}};$$

$$\beta = T_m S + \varepsilon^* + 1;\ \ T_m = \frac{g_m C_m}{\alpha_{w0} h_{w0}},$$

where *EC* is the capacity of a rechargeable battery, A·hours; *N* is the power of a thermoelectric battery, kW; *I* is current, A; U_1, U_2 are the voltage at the input to a hybrid charge controller and at the output from the inverter, respectively, V; *C* is the specific heat capacity, KJ/(kg·K); α is the coefficient of heat transfer, kW/(m^2·K); *G* is the substance flow rate, kg/s; *g* is the specific mass of a substance, kg/m; *h* is the specific surface, m^2/m; *t*, θ are the temperatures of local water, separating wall, respectively, K; *z* is the coordinate of the heater's length, m; T_w, T_m are the time constants, characterizing the thermal accumulating capacity of local water, metal, s; *m* is the indicator of dependence of heat transfer coefficient on flow rate; τ is time, s; *S* is the parameter of Laplace transformation; *S*=ω*j*; ω is frequency, 1/s. Indexes: 0 – original stationary mode; 1 – input to an electric system; *w* – local water; *m* – metallic wall.

A transfer function along the channel: «capacity of rechargeable battery – power of thermoelectric battery» was derived from solving a system of nonlinear differential equations using a Laplace transform. The system of differential equations includes an equation of state as an estimate of the physical model of an electrical system. The system of differential equations also includes equations of energy in the transmitting and receiving environments – the heater of a thermoelectric battery and local water, respectively, as well as the equation of thermal balance for the wall of a thermoelectric heater.

The equation of energy for the receiving environment was built to represent a change in the local water's temperature both over time and lengthwise a spatial coordinate, which coincides with the direction of the environment flow and includes coefficient K_w. The equation of energy for the transmitting environment includes coefficient K_{ec}, which assesses a change in the capacity of a rechargeable battery to estimate the ratio of energy generation and consumption.

4. 4. Mathematical modeling of the dynamics of change in the rotational speed of the electric motor of the circulating pump

According to formula (1) and mathematical substantiation of the architecture of a technological system (Fig. 1), it has been proposed to estimate a change in the rotational speed of the electric motor of the circulating pump in a thermoelectric battery when measuring the voltage frequency. A transfer function along the channel: «rotational speed of the electric motor of the circulating pump – voltage frequency» takes the following form:

$$W_{n-f_1} = \frac{K_f \chi_t S}{\gamma}\left(1 - e^{-\gamma_1 \xi}\right), \tag{3}$$

$$K_f = \frac{120 f (1-s)}{p_n};\ \ \chi_t = -f_s \frac{\partial \rho}{\partial t};\ \ \gamma = \frac{(T_w S + 1)\beta - 1}{L_w \beta};$$

$$T_w = \frac{g_w C_w}{\alpha_{w0} h_{w0}};\ \ L_w = \frac{G_w C_w}{\alpha_{w0} h_{w0}};$$

$$\beta = T_m S + \varepsilon^* + 1;\ \ T_m = \frac{g_m C_m}{\alpha_{w0} h_{w0}};$$

$$\varepsilon^* = (1 - L_w^*);\ \ L_w^* = \frac{1}{L_w + 1};$$

$$\gamma_1 = \frac{(T_w S + 1)\beta - 1}{\beta};\ \ \xi = \frac{z}{L_w},$$

where *n* is the rotational speed of the electric motor of the circulating pump, rpm; *f* is the voltage frequency, Hz; p_n is the number of pairs of poles in the electric motor of the circulating pump; α is the coefficient of heat transfer, kW/(m^2·K); *t* is the temperature of local water, K; ρ is the density of local water, kg/m^3; *fs* is the bypass for local water, m^2; *C* is the specific heat capacity, KJ/(kg·K); *G* is the consumption of a substance, kg/s; ρ is the density of local water, kg/m^3; *g* is the specific mass of a substance, kg/m; *h* is the specific surface, m^2/m; *z* is the coordinate of length of the heater, m; T_w, T_m are the time constants, characterizing the thermal accumulating capacity of local water, metal, s; *S* is the parameter of Laplace transformation; *S*=ω*j*; ω is frequency, 1/s.

Indexes: 0 – original stationary mode; 1 – input to an electric system; *w* – local water; *m* – metallic wall.

4. 4. Mathematical modeling of the dynamics of change in local water consumption

According to formula (1) and mathematical substantiation of the architecture of a technological system (Fig. 1), it has been proposed to estimate a change in the local water consumption when changing the rotational speed of the electric motor of the circulating pump. To this end, a system of differential equations, which includes a local energy equation and an equation of thermal balance for the wall of a heater, is supplemented with the local water equation of continuity. The result of solving a system of differential equations using a Laplace transform is the transfer function along the channel: «flow rate of local water – rotational speed of the electric motor of the circulating pump», which estimates a change in water flow rate when changing power of a thermoelectric battery:

$$W_{Gw-n_1} = \frac{\chi_t S}{\gamma}\left(1 - e^{-\gamma_1 \xi}\right), \tag{4}$$

where

$$\chi_t = -f_s \frac{\partial \rho}{\partial t};$$

$$\gamma = \frac{(T_w S + 1)\beta - 1}{L_w \beta};$$

$$T_w = \frac{g_w C_w}{\alpha_{w0} h_{w0}};\ \ L_w = \frac{G_w C_w}{\alpha_{w0} h_{w0}};$$

$$\beta = T_m S + \varepsilon^* + 1;\ \ T_m = \frac{g_m C_m}{\alpha_{w0} h_{w0}};$$

$$\varepsilon^* = (1 - L_w^*);\ \ L_w^* = \frac{1}{L_w + 1};$$

$$\gamma_1 = \frac{(T_w S + 1)\beta - 1}{\beta};$$

$$L_w^* = \frac{1}{L_w + 1};\ \ \xi = \frac{z}{L_w},$$

where *n* is the rotational speed of the electric motor of the circulating pump, rpm; a is the coefficient of heat transfer, kW/(m^2·K); *t* is the temperature of local water, K; f_s is the bypass for local water, m^2; C is the specific heat capacity, KJ/(kg·K); G is the flow rate of a substance, kg/s; ρ is the density of a substance, kg/m^3; g is the specific mass of a substance, kg/m; h is specific surface, m^2/m; z is the spatial coordinate of the heater's length, m; T_w, T_m are the time constants, characterizing the thermal accumulating capacity of local water, metal, s; S is the parameter for a Laplace transformation; $S=\omega j$; ω is frequency, 1/s. Indexes: 0 – original stationary mode; 1 – input ton an electric system; w – local water; m – metallic wall.

A valid part of the transfer function (2) was determined concerning a change in the capacity of a rechargeable battery:

$$O_1(\omega)=\frac{(L_1A_1)+(M_1B_1)K_wK_{ec}(1-L_w^*)}{(A_1^2+B_1^2)}. \qquad (5)$$

The structure of coefficient K_w includes the temperature of separating wall θ:

$$\theta=(\alpha_w(t_1+t_2)/2)+A(t_1+t_2)/2)/(\alpha_w+A), \qquad (6)$$

where t_1, t_2 is the temperature of local water at the inlet and outlet from a thermoelectric battery, K, respectively; α is the coefficient of heat transfer, kW/(m^2·K). Indexes w – local water.

$$A=1/(\delta_m/\lambda_m+1/\alpha_w), \qquad (7)$$

where δ is the thickness of a heater's wall, m; λ is the thermal conductivity of a metal of a heater's wall, kW/(m·K); Indexes: w – local water; m – metallic wall of a heater.

To use the valid part $O_1(\omega)$, the following coefficients were derived:

$$A_1=\varepsilon^*-T_wT_m\omega^2;\;\; A_2=\varepsilon^*+1; \qquad (8)$$

$$B_1=T_w\varepsilon^*\omega+T_w\omega+T_m\omega; \qquad (9)$$

$$B_2=T_m\omega;\;\; C_1=\frac{A_1A_2+B_1B_2}{A_2^2+B_2^2};\;\; D_1=\frac{A_2B_1-A_1B_2}{A_2^2+B_2^2}; \qquad (10)$$

$$L_1=1-e^{-\zeta C_1}\cos(-\xi D_1);\;\; M_1=-e^{-\zeta C_1}\sin(-\xi D_1). \qquad (11)$$

The valid part of transfer function (3) has been selected concerning a change in the rotational speed of the electric motor of the circulating pump:

$$O_2(\omega)=K_f\chi_tL_w(C_1L_1)-(D_1M_1). \qquad (12)$$

To use the valid part $O_2(\omega)$, the following coefficients were derived:

$$A_1=-T_m\omega^2;\;\; A_2=\varepsilon^*-T_wT_m\omega^2;\;\; B_1=(\varepsilon^*+1)\omega; \qquad (13)$$

$$B_2=T_w\varepsilon^*\omega+T_w\omega+T_m\omega+\varepsilon^*, \qquad (14)$$

$$C_1=\frac{A_1A_2+B_1B_2}{A_2^2+B_2^2};\;\; D_1=\frac{A_2B_1-A_1B_2}{A_2^2+B_2^2}; \qquad (15)$$

$$L_1=1-e^{-\zeta C_1}\cos(-\xi D_1);\;\; M_1=-e^{-\zeta C_1}\sin(-\xi D_1). \qquad (16)$$

The valid part of transfer function (4) was selected concerning the estimate of change in the consumption of local water:

$$O_3(\omega)=\chi_tL_w(C_1L_1)-(D_1M_1). \qquad (17)$$

To use the valid part $O_3(\omega)$, the following coefficients were derived:

$$A_1=-T_m\omega^2;\;\; A_2=\varepsilon^*-T_wT_m\omega^2;\;\; B_1=(\varepsilon^*+1)\omega; \qquad (18)$$

$$B_2=T_w\varepsilon^*\omega+T_w\omega+T_m\omega+\varepsilon^*, \qquad (19)$$

$$C_1=\frac{A_1A_2+B_1B_2}{A_2^2+B_2^2};\;\; D_1=\frac{A_2B_1-A_1B_2}{A_2^2+B_2^2}; \qquad (20)$$

$$L_1=1-e^{-\zeta C_1}\cos(-\xi D_1);\;\; M_1=-e^{-\zeta C_1}\sin(-\xi D_1). \qquad (21)$$

Transfer functions (2) to (4), derived from using the operator method for solving a system of non-linear differential equations maintain the parameter for a Laplace transform – S ($S=\omega j$), where ω is frequency, 1/s.

To make a transition from the frequency domain to the time domain, the valid parts of (5), (12), (17) were selected, derived from mathematical treatment of transfer functions. These parts are part of integrals (22) to (24), providing a possibility to derive the dynamic characteristics of change in the capacity of a rechargeable battery, rotational speed of the electric motor of the circulating pump, local water consumption, respectively, using the inverse Fourier transform.

$$CE(\tau)=\frac{1}{2\pi}\int_0^\infty O_1(\omega)\sin(\tau\omega/\omega)d\omega. \qquad (22)$$

$$n(\tau)=G_w(\tau,z)K_f(\tau)=\frac{1}{2\pi}\int_0^\infty O_2(\omega)\sin(\tau\omega/\omega)d\omega. \qquad (23)$$

$$G_w(\tau,z)=\frac{1}{2\pi}\int_0^\infty O_3(\omega)\sin(\tau\omega/\omega)d\omega, \qquad (24)$$

where CE is the capacity of a rechargeable battery, A·hours; n is the number of rotations of the circulating pump's electric motor; rpm. G_w is the flow rate of local water, kg/s.

5. Results of research into the technology for maintaining the operation of a wind-solar electric system

5. 1. Reference estimate of change in the capacity of a rechargeable battery, the number of rotations of the circulating pump's electric motor, consumption of heated local water

According to formulae (1) to (4), integrated mathematical modelling of a wind-solar electric system has been performed using the designed structural diagram (Fig. 2).

According to the proposed structural diagram (Fig. 2), Tables 1, 2 give the results from integrated mathematical modelling of a wind-solar electric system.

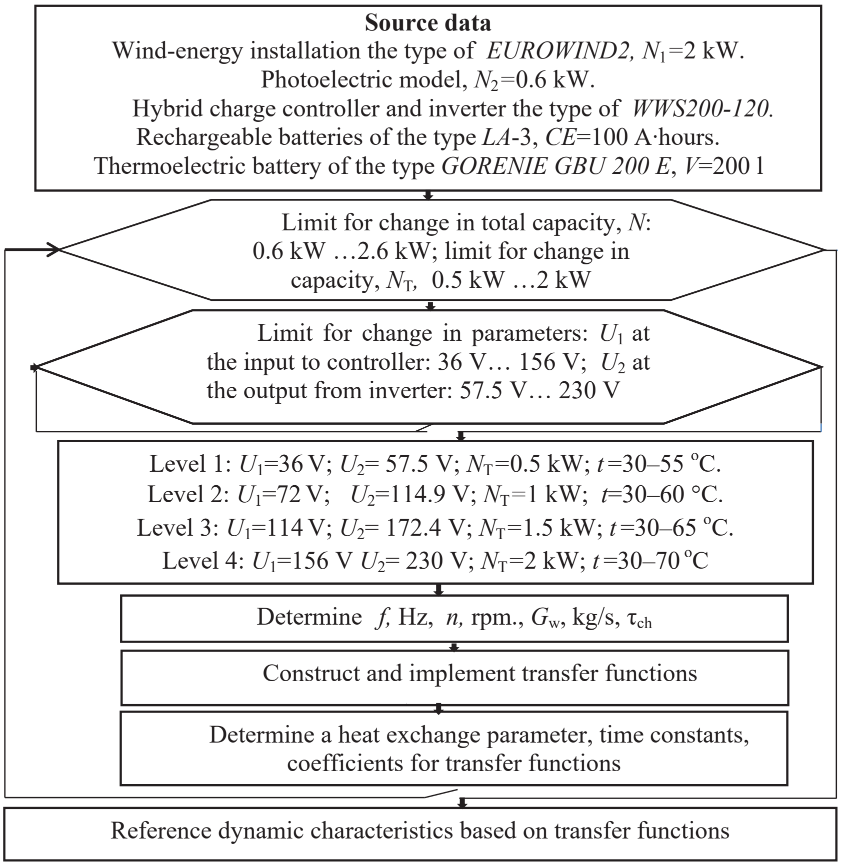

Fig. 2. Structural diagram of integrated mathematical modelling of a wind-solar electric system: N, N_1, N_2, N_T — total power of a wind-solar electric system, power of a wind energy installation, photoelectric module, thermoelectric battery, respectively, kW; CE — capacity of a rechargeable battery, A·hours; V — volume of a thermoelectric battery, l; U_1, U_2 — voltage at the input to a hybrid charge controller and at the output from the inverter, respectively, V; t — temperature of local water, °C; f — voltage frequency, Hz; n — the number of rotations of the circulating pump's electric motor, rpm; G_w — flow rate of local water, kg/s

Table 1

Mode parameters for a wind-solar electric system

Functioning levels	N, kW	N_T, kW	t, °C	G_w, kg/s	τ_{ch}, hours	U_1, V	U_2, V	f, Hz	n, rpm
Level 1	0.6	0.5	55	0.0024	3.87	36	57.5	12.5	712.5
Level 2	1.2	1	60	0.0043	0.21	72	114.9	25	1425
Level 3	1.9	1.5	65	0.0060	0.17	114	172.4	37.5	2137.5
Level 4	2.6	2	70	0.0073	0.098	156	230	50	2850

Note: N, N_T – total power of a wind-solar electric system, thermoelectric battery, respectively, kW; t – temperature of local water at the output from a thermoelectric battery, °C; τ_{ch} – charge duration of a thermoelectric battery; G_w – flow rate of local water, kg/s; U_1 – voltage at the input to a hybrid charge controller, V; U_2 – voltage at the output from the inverter, V; f – voltage frequency, Hz; n – number of rotations of the circulating pump's electric motor, rpm.

Table 2

Values for a heat exchange parameter, for time constants and coefficients for the mathematical models of dynamics

Functioning levels	α_w, W/(m^2·K)	T_w, s	T_m, s	L_w, m	L_w^*	ε^*	ζ
Level 1	507.2	97.85	6.65	0.1316	0.8837	01116	3.32
Level 2	564.7	87.54	5.97	0.2117	0.8253	0.1677	2.08
Level 3	595	82.53	5.67	0.2804	0.7810	0.2102	1.57
Level 4	636.8	78.82	5.29	0.3187	0.7583	0.2320	1.38

Note: α_w – coefficient of convective heat transfer from an electric heater to local water, W/(m^2·K)

5. 2. Functional assessment of change in the capacity of a rechargeable battery, the number of rotations of the circulating pump's electric motor, consumption of heated local water

Based on the proposed mathematical substantiation to maintain the operation of a wind-solar electric system (1)–(5), a structural diagram has been built (Fig. 3) regarding control over feasibility of a wind-solar electric system.

5. 3. An integrated system to maintain the functioning of a wind-solar electric system at the level of decision-making

Based on the proposed mathematical substantiation (1)–(5), a structural diagram has been built (Fig. 4) to maintain the operation of a wind-solar electric system based on maintaining capacity of a rechargeable battery.

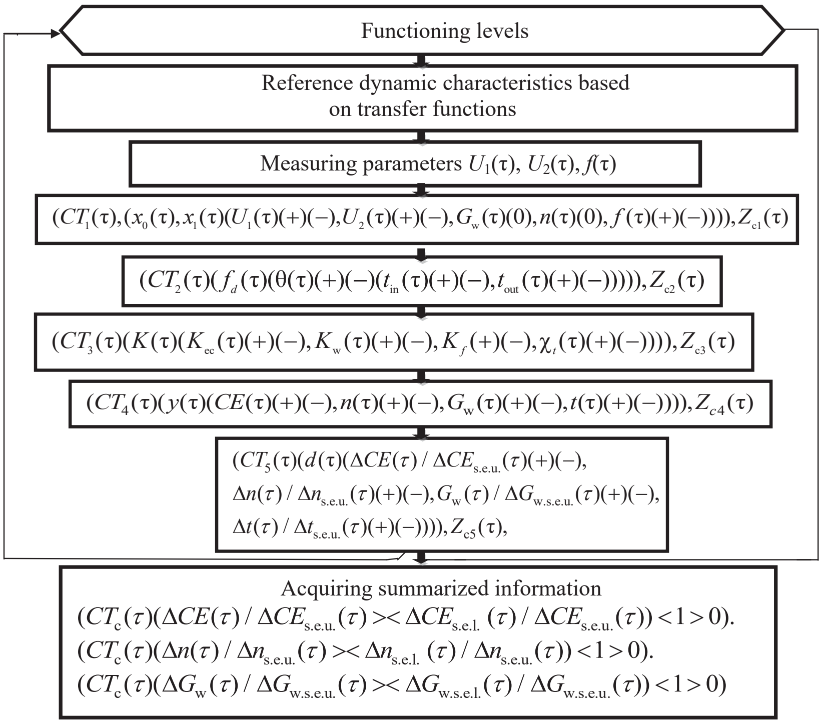

Fig. 3. Structural diagram of control over feasibility of a wind-solar electric system: U_1, U_2 voltage at the input to a hybrid charge controller and at the output from the inverter, respectively, V; f — voltage frequency, Hz; n — number of rotations of the circulating pump's electric motor, rpm; G_w — flow rate of local water, kg/s; t_{input}, t_{output}, θ — local water temperature at the input and the output from a thermoelectric battery, separating wall, respectively, K; CE — capacity of a rechargeable battery, A·hours; CT — event control; Z — logical relationships; d — dynamic parameters; x — influences; f_d — diagnosed parameters; y — starting parameters; K — coefficients for mathematical notation; τ — time. Indexes: c — control over workability; s.e.u. — steady, estimated value for the parameter of the upper level of functioning; s.e.l — steady, estimated value for the parameter of the level of functioning; 0, 1, 2 — initial stationary mode, external, internal parameters; 3 — coefficients for equations of dynamics; 4 — essential parameters that are diagnosed; 5 — dynamic parameters

An integrated comprehensive system to support the operation of a wind-solar electric system has been devised (Table 3), which is based on predicting a change in the capacity of a rechargeable battery at continuous measurement of voltage at the input to a hybrid charge controller, voltage at the output from the inverter, and voltage frequency.

Making preliminary decisions about changing the power of a thermoelectric battery makes it possible, while maintaining the capacity of a rechargeable battery, to enable a change in the temperature of local water based on changing the number of rotations of the circulating pump's electric motor in order to change water consumption. Capacity of a rechargeable battery over the established period of time is determined from:

$$CE_i(\tau)=CE_i(\Delta CE_i(\tau)/\Delta CE_{s.e.u.}(\tau), \tag{25}$$

where CE – capacity of a rechargeable battery, A·hours; τ – time, s. Index: *s.e.u.* – steady, estimated value for the parameter of the upper level of functioning; i – number of functioning levels of a wind-solar electric system.

The rotational speed of the electric motor of the circulating pump over the established period is determined from:

$$n_{i+1}(\tau)=n_i+((\Delta n_{i+1}(\tau)/\Delta n_{s.e.u.}(\tau)-$$
$$-\Delta n_i(\tau)/\Delta n_{s.e.u.}(\tau))(n_2-n_1)), \tag{26}$$

where n is the number of rotations of the circulating pump's electric motor, rpm; n_1, n_2 – initial and final number of rotations of the circulating pump's electric motor, rpm, respectively; i – number of levels of functioning of a wind-solar electric system; τ – time, s. Index: s.e.u. – steady, estimated value for the parameter of the upper level of functioning.

Local water flow rate over the established period is determined from:

$$G_{w_i+1}(\tau)=G_{wi}+((\Delta G_{wi+1}(\tau)/\Delta G_{w\,s.e.u.}(\tau)-$$
$$-\Delta G_{wi}(\tau)/\Delta G_{w\,s.e.u.}(\tau))(G_{w_2}-G_{w1})), \tag{27}$$

where G_w – local water flow rate, kg/s; G_{w1}, G_{w2} – initial and final values for local water consumption, kg/s, respectively (Table 3); i – number of functioning levels of a wind-solar electric system; τ – time, s. Index: s.e.u.– steady, estimated value for the parameter of the upper level of functioning; i – number of functioning levels of a wind-solar electric system.

For example, over the period of $15\cdot10^3$ s (4.17 hours) the absolute values for capacity of a rechargeable battery, the number of rotations of the circulating pump's electric motor, local water consumption, applying formulae (25) to (27), are equal to:

$$48.65\text{ A·hours}=(0.4865)100\text{ A·hours}$$

$$1069.7\text{ rpm}=992.3\text{ rpm}+(0.1998-0.1636)\times$$
$$\times(2850\text{ rpm}-712.5\text{ rpm}).$$

$$0.0045\text{ kg/s}=0.0040\text{ kg/s}+(0.6505-0.5420)\times$$
$$\times(0.0073\text{ kg/s}-0.0024\text{ kg/s}).$$

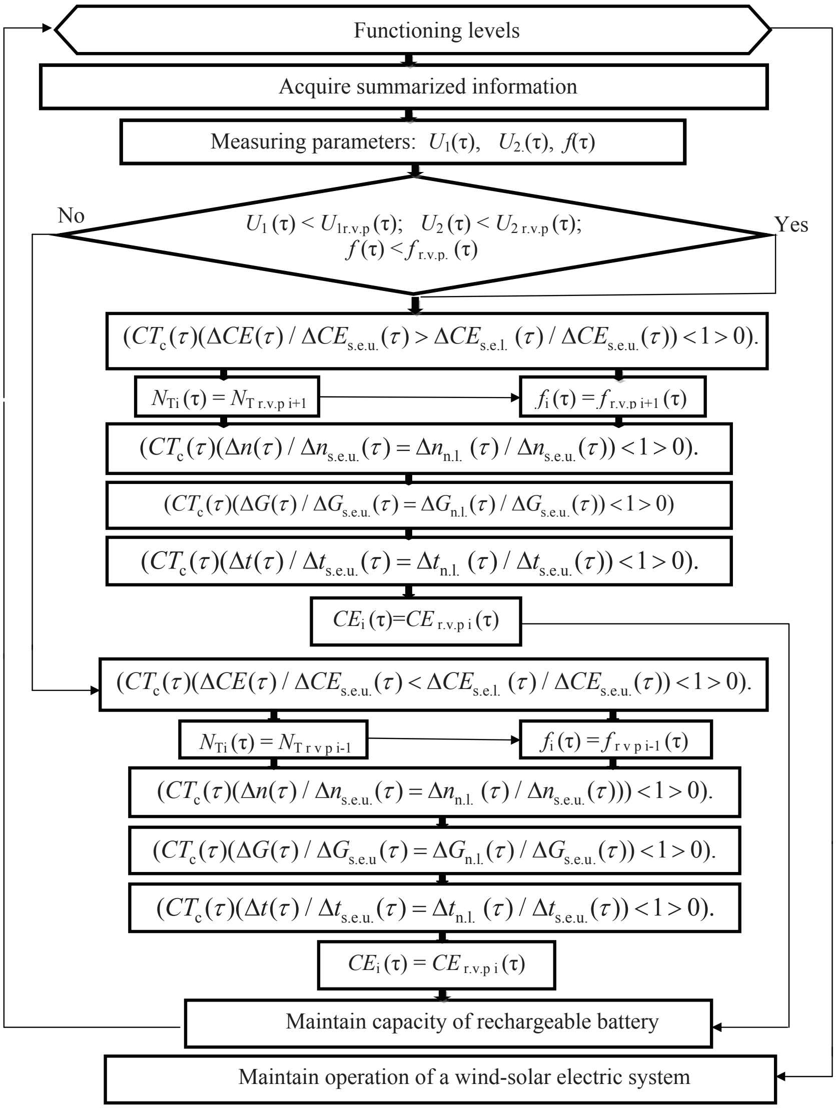

Fig. 4. Structural diagram for maintaining the operation of a wind-solar electric system: U_1, U_2 voltage at the input to a hybrid charge controller and at the output from the inverter, respectively, V; f — voltage frequency, Hz; CE — capacity of a rechargeable battery, A·hours; N_T — thermoelectric battery power, kW; n — number of rotations of the circulating pump's electric motor, rpm; G — flow rate of local water, kg/s; t — temperature of local water, K; τ — time. Indexes: i — number of functioning levels; e — reference value for parameter; s.e.u. — steady, estimated value for the parameter of the upper level of functioning; s.e.l. — steady, estimated value for the parameter of the level of functioning; n.l. — new level of functioning

Table 3

Integrated system to maintain the capacity of a rechargeable battery

Time, τ, 10^3 s	Change in parameters	$\Delta CE(\tau)/\Delta CE_{s.e.u.}(\tau)$	$\Delta n(\tau)/\Delta n_{s.e.u.}(\tau)$	$\Delta G_w(\tau)/\Delta G_{w s.e.u.}(\tau)$	$CE(\tau)$, A·hours	$n(\tau)$, rpm	$G_w(\tau)$, kg/s
1	2	3	4	5	6	7	8
0	Charge U_1=12 V; U_2=57.5 V; f=2.5 Hz; t_1=30 °C; t_2=55 °C	0.0473	0.0327	0.3252	4.73	712.5	0.0024
3	Charge U_1=18 V; U_2=57.5 V; f=2.5 Hz; t_1=30 °C; t_2=55 °C	0.0817	0.0654	0.3614	8.17	782.4	0.0027
6	Charge U_1=24 V; U_2=57.5 V; f=7.5 Hz; t_1=30 °C; t_2=55 °C	0.1285	0.0982	0.4068	12.85	852.5	0.0030
9	Charge U_1=30 V; U_2=57.5 V; f=10 Hz; t_1=30 °C; t_2=55 °C	0.1946	0.1309	0.4646	19.46	922.4	0.0034
12	Charge U_1=36 V; U_2=57.5 V; f=12.5 Hz; t_1=30 °C; t_2=55 °C	0.2987	0.1636	0.5420	29.87	992.3	0.0040
15	Deciding on discharge U_1=42 V; U_2=57.5 V; f=12.5 Hz; t_1=30 °C; t_2=55 °C	0.4865	0.1998	0.6505	48.65	1069.7	0.0045

Continuation of Table 3

1	2	3	4	5	6	7	8
18	Discharge $f=20$ Hz; $U_1=42$ V; $U_2=92$ V; $t_1=30$ °C; $t_2=60$ °C	0.3198	0.3196	0.7	31.98	1325.8	0.0047
21	Charge $U_1=54$ V; $U_2=114.9$ V; $f=25$ Hz; $t_1=30$ °C; $t_2=60$ °C	0.3321	0.3996	0.7447	33.21	1496.8	0.0049
24	Charge $U_1=72$ V; $U_2=114.9$ V; $f=25$ Hz; $t_1=30$ °C; $t_2=60$ °C	0.6285	0.4351	0.8183	62.85	1496.8	0.0053
27	Deciding on discharge $U_1=78$ V; $U_2=114.9$ V; $f=25$ Hz; $t_1=30$ °C; $t_2=60$ °C	0.7914	0.4351	0.8410	79.14	1496.8	0.0054
30	Discharge $f=30$ Hz; $U_1=78$ V; $U_2=137.9$ V; $t_1=30$ °C; $t_2=65$ °C	0.5785	0.5222	0.8651	57.85	1758.4	0.0055
33	Charge $U_1=114$ V; $U_2=172{,}4$ V; $f=37.5$ Hz; $t_1=30$ °C; $t_2=65$ °C	0.8676	0.6526	0.8894	86.76	2037.1	0.0056
36	Deciding on discharge $U_1=120$ V; $U_2=172.4$ V; $f=37.5$ Hz; $t_1=30$ °C; $t_2=65$ °C	1	0.7548	0.9096	100	2255.5	0.0057
39	Discharge $f=40$ Hz; $U_1=120$ V; $U_2=183.9$ V; $t_1=30$ °C; $t_2=70$ °C	0.8856	0.8053	0.93	88.56	2363.4	0.0058
42	Charge $U_1=150$ V; $U_2=230$ V; $f=50$ Hz; $t_1=30$ °C; $t_2=70$ °C	0.8894	1	0.9530	88.94	2780.6	0.0059
45	Charge $U_1=156$ V; $U_2=230$ V; $f=50$ Hz; $t_1=30$ °C; $t_2=70$ °C	1	1	1	100	2850	0.0073

Note: U_1, U_2 – voltage at the input to a hybrid charge controller and at the output from the inverter, respectively, V; f – voltage frequency, Hz; t_1, t_2 – temperature of local water at the input to a thermoelectric battery and at the output from a thermoelectric battery, respectively, °C; CE – capacity of a rechargeable battery, A·hours; n – number of rotations of the circulating pump's electric motor, rpm; G_w – flow rate of local water, kg/s; τ – time, s. Index: s.e.u. – steady, estimated value for the parameter of the upper level of functioning

The graphical dependence of change in the capacity of a rechargeable battery on change in the power of a thermoelectric battery is shown in Fig. 5.

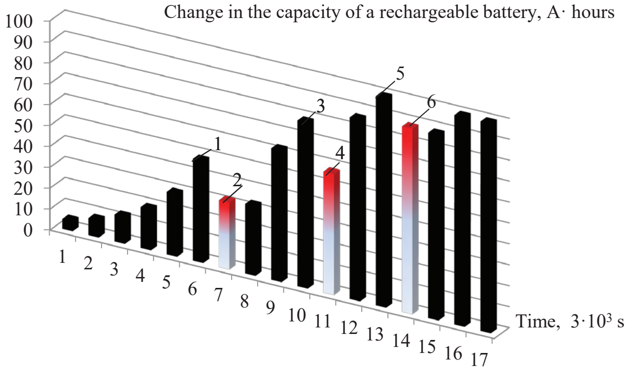

Fig. 5. Maintaining the functioning of a wind-solar electric system, where 1, 3, 5 – deciding on a change in the power of a thermoelectric battery; 2, 4, 6 – discharge to maintain a change in the capacity of a rechargeable battery

Thus, for example, over time of $15\cdot10^3$ s (4.17 hours) when changing voltage at the input to a hybrid charge controller to the level of 42 V, while predicting an increase in the capacity of a rechargeable battery to 20 %, it is necessary to take a preliminary decision about increasing the capacity of a thermoelectric battery based on a change in voltage frequency from 12.5 Hz to 20 Hz. Increasing the number of rotations of the circulating pump's electric motor to the level of 1,328 rpm makes it possible to increase the consumption of local water to the level of 0.0047 kg/s and to increase the temperature of local water up to 60 °C. Implementing these measures will make it possible to maintain a 20 % change in the capacity of a rechargeable battery, thereby maintaining the operation of a wind-solar electric system.

6. Discussion of results of studying the energy-saving technology to maintain the operation of a wind-solar electric system

An integrated system to maintain functioning of a wind-solar electric system has been built, based on adjusting the generation and consumption of energy in terms of energy efficiency. Typically, a hybrid charge controller included in a wind-solar electric system maintains the charge of a rechargeable battery by using a thermoelectric battery as a non-regulated ballast. Resetting excess energy to the ballast when using the MPPT function of the controller leads to the uncompensated-for losses of electrical energy, which does not make it possible to ensure an appropriate level of capacity for the charge of a rechargeable battery. Moreover, the use of a thermoelectric battery as a ballast eliminates the need to maintain the operation of a wind energy installation by using the accumulation of heat in order to regulate the power of a wind turbine. Failure to account for this property of a thermoelectric battery could lead to the acceleration of the wind turbine at considerable wind speed and to its malfunctioning. It is known that a thermoelectric battery is controlled in line with the thermostat principle, that is, when establishing the required temperature of heated local water, the thermoelectric battery is disconnected from power. Not using a change in the local water flow rate during the period of thermoelectric battery charge, when changing capacity, prolongs the duration of charge and leads to considerable expenditures on electricity. A technique to overcome these difficulties has been proposed. It is the thermoelectric battery that must become the main center of adjusting a change in the total power of a wind-solar electric system to power consumption by redistributing the accumulated heat and electric energy in terms of consumption. It has been proposed to predict a change in the capacity of a rechargeable battery when measuring the total voltage at the input to a hybrid charge controller and voltage at the output from the inverter to estimate the ratio of electrical energy generation and consumption when measuring the voltage frequency. This ratio is part of the coefficient K_{ce} for a transfer function aimed at predicting a change in the capacity of a rechargeable battery, which could act as a unifying element in the integrated mathematical and logical modeling as part of a technological system to maintain the operation of a wind-solar electric system.

Making preliminary decisions on changing the power of a thermoelectric battery makes it possible, while maintaining the capacity of the rechargeable battery, to ensure a change in the temperature of heated local water, based on changing the number of rotations of the circulating pump's electric motor in terms of water flow rate, thereby reducing the charge duration by up to 30 %. The results reported in the current study is continuation of work that addresses the adjustment in energy generation and consumption [1, 12–14]. The obtained results could be used in the development of intelligent systems for operating the hybrid charge controllers in terms of maintaining the functioning of wind-solar electrical systems. The representation of the thermoelectric battery as the main center in redistribution of the accumulated energy provides an opportunity to use the generated electrical energy completely, in terms of adjusting it to consumption.

When connected to the electric grid, reducing the duration of charging a thermoelectric battery by up to 30 % makes it possible to receive cash savings on electricity consumption and increase cash income by applying a «green tariff». However, efficient electrical power consumption can be limited by the established ratio of generation and consumption of electric energy. In this case, one must employ SMART GREAD technologies under conditions of adjusting the generation of electric power to efficient consumption.

Further advancement of the current research implies the planned verification of the results under conditions of using wind-solar electrical systems of varying power. It is planned to expand the operation of a wind-solar electric system when it is connected to the grid in order to use the thermoelectric battery in thermal-pump energy supplies [14] as part of the proposed technological system.

7. Conclusions

1. It was proposed to predict a change in the capacity of a rechargeable battery based on estimating a change in the ratio of total voltage at the input to a hybrid charge controller, voltage at the output from the inverter, which are measured, when measuring the voltage frequency.

2. Taking preliminary decisions about changing the power of a thermoelectric battery ensures maintaining the capacity of the rechargeable battery based on changing the number of rotations of the circulating pump's electric motor. Changing the flow rate of heated local water makes it possible to reduce the charge duration by up to 30 %.

3. A structural diagram has been built, and integrated mathematical modelling of a wind-solar electric system has been performed, which is based on mathematical modeling of the dynamics of estimating a change in the capacity of a rechargeable battery, the number of rotations of the circulating pump's electric motor, the flow rate of local water. The unifying element of mathematical modeling is the estimate of the ratio of voltage at the input to a hybrid charge controller and voltage at the output from the inverter, which are measured. The maximum change in the capacity of a thermoelectric battery has been determined: 0.5...2 kW. The mode parameters for a wind-solar electric system have been defined, as well as the heat exchange parameter for a thermoelectric battery, the charge duration of a thermoelectric battery at a change in water flow rate, time constants and the coefficients for mathematical models of the dynamics for the established levels of functioning. The reference dynamic estimates of change in the capacity of a rechargeable battery have been derived, as well as the number of rotations of the circulating pump's electric motor, the flow rate of local water. A structural diagram has been built, as well as logical modeling of control efficiency of a wind-solar electric system has been carried out, which is based on the principle of causation. The logical unit has components that estimate: a change in voltage at the input to a hybrid charge controller, voltage at the output from the inverter, the voltage frequency, which are measured; a change in the temperature of the heater's wall; a change in coefficients for mathematical models of the dynamics, K_{ce}, K_f, $\varkappa_t$; a change in the number of rotations of the circulating pump's electric motor, the flow rate of local water, the temperature of local water; a change in dynamic parameters; the resulting unit to control workability in order to obtain a functional estimate of change in the capacity of a rechargeable battery, the number of rotations of the circulating pump's electric motor, the local water flow rate.

4. An integrated system to maintain the functioning of a wind-solar electric system has been proposed, based on the designed structural diagram for logical simulation. Maintaining the capacity of a rechargeable battery is based on comparing voltage at the input to a hybrid charge controller, voltage at the output from the inverter, the voltage frequency, which are measured, to reference values. Applying a functional estimate of change in the capacity of a rechargeable battery that is predicted makes it possible to take preliminary decisions about changing the power of a thermoelectric battery based on changing the number of rotations of the circulating pump's electric motor in order to change the flow rate of heated local water.

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