На основі математичного та логічного моделювання у складі технологічної системи функціонування акумуляторної батареї розроблена технологія підтримки зміни ємності батареї, що базується на прогнозуванні зміни напруги при вимірюванні температури електроліту в об'єму акумуляторів. Використання інтегрованої системи оцінки зміни напруги, здобутої на основі узгодження електрохімічного та дифузійного процесів розряду та заряду, надає можливість приймати своєчасні рішення на підзаряд щодо недопущення перезаряду та недопустимого розряду

Ключові слова: свинцево-кислотний акумулятор, математичне та логічне моделювання, прийняття рішень

На основе математического и логического моделирования в составе технологической системы функционирования аккумуляторной батареи разработана технология поддержки изменения емкости батареи, которая базируется на прогнозировании изменения напряжения при измерении температуры электролита в объеме аккумуляторов. Использование интегрированной системы оценки изменения напряжения, полученной на основе согласования электрохимического и диффузионного процессов разряда и заряда, позволяет принимать своевременные решения на подзаряд по недопущению перезаряда и недопустимого разряда

Ключевые слова: свинцово-кислотный аккумулятор, математическое и логическое моделирование, принятие решений

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DEVELOPMENT OF ENERGY-SAVING TECHNOLOGY TO SUPPORT FUNCTIONING OF THE LEAD-ACID BATTERIES

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1. Introduction

The use of alternative energy sources under conditions of natural fuel saving and reduction of harmful emissions into the atmosphere requires coordination of production of energy and consumption based on accumulation [1, 2]. For example, in paper [2], it was proposed to manage the accumulation of electric energy on the basis of control over energy flows in relation to their redistribution using a specially designed measuring device, which uses semiconductor transducers. Known operating modes of accumulator batteries are: buffer, cyclic, mixed. Buffer mode, in which the accumulator battery is constantly charged, that is, it operates under the mode of constant recharge, levels off the uneven electricity consumption. The cyclic mode of operation that supports the discharge-charge cycle allows connecting the load after the battery charge is over. There are various means of charge of lead-acid batteries: a charge by stabilized current, a charge by stabilized voltage, two-stage charge by stabilized current and voltage, accelerated charge, charge by asymmetric current, etc. When charging a battery under the action of constant charging current, sulfuric acid is additionally formed due to the transition of lead sulfate to lead dioxide and spongy lead, which is accompanied by an increase in the density of electrolyte in the pores of the plates and above the plates. Under condition of feeding constant charge current after reaching a certain voltage of charge, the value of which is difficult to determine, there is a decomposition of water into oxygen and hydrogen, which characterizes the boiling of the electrolyte. Long-term gas emissions not only cause unnecessary energy expenditure, but can also damage the battery plates. During discharge, the active mass of both electrodes is converted into lead sulfate. This reaction consumes sulfuric acid and forms water. Due to this, the density of the electrolyte in the pores of the plates and above the plates decreases as the discharge decreases. Measurement of the temperature of the electrolyte in the volume of used batteries allows adjusting the charge and discharge voltage using voltage measurements. In order to prevent recharge and unacceptable battery discharge, support for the electrochemical and diffusion processes that accompany the charge and discharge of the battery should be in coordinated cooperation. Forecasting a change in the voltage of charge and discharge with the use of estimation of change in the temperature of electrolyte in the pores of plates and over plates while measuring temperature of the electrolyte in the volume of batteries makes it possible to change the operating modes of the battery on time. This substantiates the relevance of the present work.

2. Literature review and problem statement

The means of optimization of the process of accumulator battery charge are based on the improvement of intelligent charge control systems with the use of special charge controllers. In paper [3], it was concluded, on the basis of the developed model of the electric accumulator battery, that it is necessary to create a specialized control system for each type of battery in connection with the effect of the battery design on the charge parameters. Thus, in article [4], a special system to control accumulator batteries based on the real-time monitoring of voltage and current was presented. The control system prevents the recharge of each battery element, but it is based on voltage measurements. Paper [5], for example, which provides an intelligent battery charge support system based on the determination of the limit charge current by a segmentation method, is devoted to enhancing control system of charge of accumulator battery, but the boundary of the change of charge current in the battery charge process was not determined. In paper [6], an intelligent system of battery charge was presented, based on information using voltage sensors, battery current, electrolyte temperature, but based on measurements of charge parameters and using electrolyte temperature measurement only for the purpose of temperature compensation of voltage change. In order to optimize the maintenance of the accumulator battery sub-charge under conditions of a partial discharge, article [7] presented experimental methods to determine the capacity of the accumulator battery remaining after discharge, but the methods are based on measurements in real time. In paper [8], it was concluded that the traditional control systems for a change in the charge parameters based on voltage measurements and associated with the change of external factors, such as the change of solar radiation while using photovoltaic systems are not effective. In connection with the influence of diffusion processes on the charge of a battery, it was proposed to use a fuzzy logic controller, but without coordination with the electrochemical charge process [9]. Well-known intelligent charging controllers are PWM controllers and MPPT controllers. PWM controllers operate by the method of pulse-width modulation of charge current. MPPT controllers allow tracking the point of maximum power of the power source for matching the change of voltage with the change of current. The use of these controllers is based on parameter measurements, which makes it difficult to align the electrochemical and diffusion processes that accompany the charge and discharge of the accumulator battery. While measuring the temperature of electrolyte in the volume of batteries, it is necessary to determine the limit change in the temperature of electrolyte at a charge for the supply of direct current and to set the limit voltage change with respect to subsequent charge and discharge when changing consumption of electric energy. By measuring the temperature of electrolyte in the volume of batteries, it is necessary to align the electrochemical and diffusion processes that accompany the charge and discharge of the battery. This can be done based on the prediction of voltage change using a change in the temperature of electrolyte in the pores of the plates and above the plates. This approach will make it possible to take preliminary steps to support a changing in the capacity of accumulator battery.

3. The aim and objectives of the study

The objective of present work is to develop an energy-saving operation technology of the lead-acid batteries in the structure of a technological system.

To achieve the objective, the following tasks were set:

– to substantiate the necessity of an analytical estimation of the charge and discharge voltage changes by measuring the temperature of electrolyte in the volume of accumulators for making preliminary decisions about a change in the capacity of accumulator battery;

– to develop a structural circuit and to perform comprehensive mathematical and logical modeling in order to obtain a reference and functional estimation of the charge and discharge voltage changes;

– to develop a structural circuit and perform logical modeling in terms of support of operating modes of accumulator battery;

– to propose an integrated system for the estimation of a change in the voltage of accumulator battery relative to the energy-saving technology for supporting a change in capacity.

4. Energy-saving technology of the operation mode of lead-acid batteries

Based on methodological and mathematical substantiation of the architecture of technological systems [10, 11], an architecture of the technological system for operating an accumulator battery was proposed. It is based on an integrated dynamic subsystem with a charge controller and an accumulator battery (Fig. 1). Technological system also includes the following parts: units of charge, recharge, discharge, and the unit of estimation of functional efficiency, which are in the coordinated interaction with the dynamic subsystem (Fig. 1).

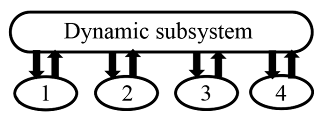

Fig. 1. Architecture of the technological system: 1 — charge unit; 2 — recharge unit; 3 — discharge unit; 4 — unit for the evaluation of functional efficiency

The operation of the accumulator battery can be considered as a reproduction of external and internal influences and changes in the initial conditions, for example, changes in production and consumption of electric energy. The nature of the reaction is determined by inertia of the devices and the rate of transition processes, that is, the dynamic properties. Dynamic properties of the accumulator battery are determined from the dynamic characteristics, that is, by the assessment of change voltage and discharge voltage depending on time. Thus, the accumulator battery is a dynamic system. Therefore, support for the operation of the accumulator battery should be a part of such technological system that is based on the dynamic system. By representing design of the technological system as an organization of a complex system, we expand it, by building on its basis – the dynamic subsystem – units that predict components of the technological process: charge, recharge, discharge, evaluation of functional efficiency. Proceeding from the system-structural substantiation of the architecture of technological systems [10, 11], we establish relationships of the dynamic subsystem with other units of the technological system on the basis of mathematical modeling of their logical relations that change over time. Such an approach makes it possible to set new properties of the dynamic subsystem and units of the technological system. Proceeding from the system-structural substantiation of the architecture of technological systems [10, 11], the category of relation is considered as the organizing interactions inside the elements of dynamic subsystem and units of the technological system. This makes it possible to perform control over workability and conduct identification of the state of the dynamic subsystem and to confirm new operating conditions from the units of the technological system on the basis of the developed method of the cause-effect relations graph (Fig. 2).

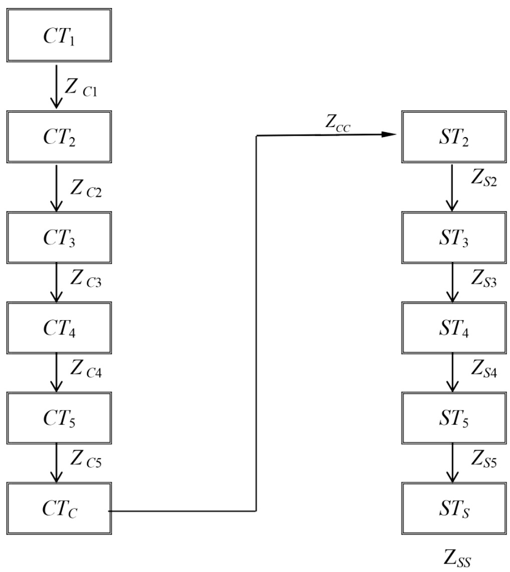

Fig. 2. Cause-effect relations graph: *CT* – control of the event; *Z* – logical relations; *ST* – identification of the event. Indices: 1 – impacts; 2 – parameters that are diagnosed; 3 – coefficients of mathematical description; 4 – output parameters; 5 – dynamic parameters; *c* – workability control; *s* – state

A mathematical substantiation of the architecture of a technological system for the operation of accumulator battery is described using formula (1):

$$TSFB=\left\{\begin{matrix}\left[D(P(\tau)\langle x_0(\tau),x_1(\tau),x_2(\tau),f(\tau),K(\tau),y(\tau),d(\tau)\rangle,Z(\tau),P(\tau)),\right]\\ R(\tau),(P_i(\tau)\langle x_1(\tau),f_i(\tau),K_i(\tau),y_i(\tau)\rangle),\end{matrix}\right\}, \quad (1)$$

where *TSFB* is the technological system of accumulator battery operation; *D* is the dynamic subsystem (charge controller and an accumulator battery); *P* are the properties of elements of the technological system; τ is time, sec; *x* are the impacts; *f* are the parameters that are diagnosed; *K* are the coefficients of mathematical description; *y* are the output parameters; *d* are the dynamic parameters; *Z, R* are the logical relations in *D, TSFB*, respectively. Indices: *i* – number of elements of the technological system; 0, 1, 2 – initial stationary mode, external, internal character of impacts.

A mathematical substantiation is proposed of supporting the operation of accumulator battery based on the prediction of a change in the charge and discharge voltage while measuring the temperature of electrolyte in the volume of battery. The mathematical description (2) is based on the mathematical substantiation of the architecture of technological systems, methodology of the mathematical description of the dynamics of energy systems, method of the cause-effect relations graph [10, 11].

$$SB=\left\{\left[\left[\begin{matrix}(D(P(\tau),MM(z,\tau),AI(\tau),C(\tau),LC(\tau)\\ \langle x_0(\tau),x_1(\tau),x_2(\tau),f(\tau),K(\tau),y(\tau),d(\tau),FI(\tau)\rangle,\\ LMD(\tau),MD(\tau),NC(\tau),S(\tau),LS(\tau)\langle f(\tau),K(\tau),y(\tau),d(\tau),FI(\tau)\rangle\\ P(\tau))),R(\tau),(P_i(\tau)\langle x_1(\tau),f_i(\tau),K_i(\tau),y_i(\tau)\rangle),\end{matrix}\right]\right]\right\}, \quad (2)$$

where *SB* is the support of the operation of battery; *D* is the dynamic subsystem – charge controller and accumulator battery; *P* are the properties of *SB* elements; *MM* is the mathematical modeling of voltage dynamics of charge and discharge of battery; *AI* is the reference information; *C* is the workability control; *MD* is decision-making; *S* is the identification of state; *LC, LMD, LS* are the logical relations in *C, MD, S*, respectively; *FI* is the functional resulting information; *NC* are the new operating conditions; *R* are the logical relations between the dynamic subsystem and the units of charge, recharge, discharge, evaluation of functional efficiency, which are parts of the system supporting the operation of accumulator battery; *x* are the impacts; *f* are the parameters that are diagnosed; *K* are the coefficients of mathematical description; *y* are the output parameters; *d* are the dynamic parameters; *z* is the coordinate of length, m; τ is time, sec. Indices: *i* – number of *SB* elements; 0, 1, 2 – initial mode, external, internal character of impacts.

The mathematical description (2) makes it possible to maintain the operation of accumulator battery by using the following actions: accumulator battery workability control (*C*(τ)) based on the mathematical (*MM*(τ)) and logical (*LC*(τ)) modeling to obtain the reference (*AI*(τ)) and functional (*FI*(τ)) estimate of change in the total charge and discharge voltage; decision making (*MD*(τ)) to support a change in the capacity of accumulator battery based on logical modeling (*LMD*(τ)) with the use of a functional evaluation of change in the total charge and discharge voltage (*FI* (τ)); identification (*S*(τ)) of the new conditions of the accumulator battery operation (*NC*(τ)) on the basis of logical modeling (*LS*(τ)) and their confirmation (*R*(τ)) from the units of technological system.

The basis for the alignment of electrochemical and diffusion processes of charge and discharge of the accumulator battery is the prediction of change in the charge and discharge voltage while measuring the temperature of electrolyte at the input and output from the accumulator battery. For this purpose, a mathematical model is constructed of the dynamics of change in the voltage of accumulator battery at charge and discharge.

A transfer function of the channel: "charge voltage – temperature of electrolyte in the volume of accumulator battery", which makes it possible to predict a change in the voltage of charge based on the assessment of change in the temperature of electrolyte in the pores of plates and over the plates, both over time and along the length of the battery plates, is represented in the following way:

$$W_{u-t_1}=\frac{K_t K_u \varepsilon\left(1-L^*_{ch}\right)}{(T_{ch}+1)\beta-1}\left(1-e^{-\gamma\xi}\right), \quad (3)$$

where

$$K_t=\frac{m\left(\theta_0-t_{e2}\right)}{G_{ch0}};$$

K_u=(0.84+(ρ+0.0007(t_{e1}–t_{e25})+$I_{ch}R_{ch}n$;

$$\varepsilon=\frac{\alpha_{disch0}h_{disch0}}{\alpha_{ch0}h_{ch0}};$$

$$L^*_{ch}=\frac{1}{L_{ch}+1};$$

$$L_{ch}=\frac{G_{ch}C_{ch}}{\alpha_{ch0}h_{ch0}};$$

$$\gamma=\frac{(T_{ch}S+1)\beta-1}{\beta};$$

$$\xi=\frac{z}{L_{ch}};\;\; T_{ch}=\frac{g_{ch}C_{ch}}{\alpha_{ch0}h_{ch0}};$$

$$\beta=T_{м}S+\varepsilon^{*}+1;\;\; T_{m}=\frac{g_{m}C_{m}}{\alpha_{ch0}h_{ch0}};\;\; \varepsilon^{*}=\varepsilon(1-L_{ch}^{*}),$$

where α is the coefficient of heat emission, kW/(m^2·K); C is the specific heat capacity, kJ/(kg·K); G is the consumption of substance, kg/s; g is the specific mass of substance, kg/m; h is the specific surface, m^2/m; t, θ is the electrolyte temperature in the volume of battery, plate wall, respectively, K; t_{e1}, t_{e2} is the temperature of electrolyte at the input to the battery and at the battery output, respectively, K; t_{e25} is the temperature of electrolyte in the volume of battery at 25 °C; U is the total voltage, W; R is the resistance of the battery, Ohm; z is the coordinate of length of the plates of accumulator battery, m; T, T_m are the constants of time, characterizing thermal accumulation ability of the electrolyte, metal, s; m is the indicator of heat emission coefficient dependence on consumption; ι is time, s; ρ is the density of electrolyte, g/m^3; n is the number of accumulators in the battery; I is current, A; S is the Laplace transform parameter; $S=\omega j$; ω is frequency, 1/s. Indices: 0 – initial stationary mode; 1 – input to the accumulator battery; ch, disch. are the charge, discharge of the accumulator battery, respectively; m is the metal wall.

Transfer function for the channel "charge voltage – electrolyte temperature in the volume of accumulator battery" (3) is obtained based on solving the system of nonlinear differential equations using a Laplace transformer. The system of differential equations includes the state equation as an estimate of the physical model of the accumulator, the equation of charge energy and discharge energy, the equation of heat balance for the wall of the plates of the accumulator. The equation of charge energy was developed with the representation of changes in the temperature of the electrolyte in the pores of the plates and above the plates not only over time, but also along the spatial coordinates of accumulator plates. The charge energy equation includes K_u coefficient, which estimates a change in the charge voltage of accumulator when the electrolyte temperature at the input to the accumulator battery changes.

The transfer function for the channel "discharge voltage – electrolyte temperature in the volume of accumulator battery", which makes it possible to predict a change in the discharge voltage based on the estimation of change in the temperature of electrolyte in the pores of the plates and above the plates not only over time but also along the spatial coordinates of accumulator plates, is represented in the following way:

$$W_{u-t_1}=\frac{K_t K_u\varepsilon\left(1-L_{disch}^{\;*}\right)}{(T_{disch}S+1)\beta-1}\left(1-e^{-\gamma\xi}\right), \tag{4}$$

where

$$K_t=\frac{m\left(\theta_0-t_{e2}\right)}{G_{disch0}};$$

K_u=(0.84+(ρ–0.0007(t_{e1}–t_{25})–$I_{disch}R_{disch}$)n;

$$\varepsilon=\frac{\alpha_{ch0}h_{ch0}}{\alpha_{disch0}h_{disch0}};$$

$$L_{disch}^{*}=\frac{1}{L_{disch}+1};\;\; L_{disch}=\frac{G_{disch}C_{disch}}{\alpha_{disch0}h_{disch0}};\;\; \gamma=\frac{(T_{disch}\,S+1)\beta-1}{\beta};$$

$$\xi=\frac{z}{L_{disch}};\;\; T_{disch}=\frac{g_{disch}C_{disch}}{\alpha_{disch0}h_{disch0}};$$

$$\beta=T_{m}S+\varepsilon^{*}+1;\;\; T_{m}=\frac{g_{m}C_{m}}{\alpha_{disch0}h_{disch0}};\;\; \varepsilon^{*}=\varepsilon(1-L_{disch}^{*}).$$

Transfer function for the channel "discharge voltage – electrolyte temperature in the volume of accumulator battery" was obtained based on solving the system of nonlinear differential equations using a Laplace transformer. The system of differential equations includes the state equation as an estimate of the physical model of the accumulator, the charge energy and discharge energy equation, the equation of heat balance for the wall of accumulator plates. The equation of discharge energy was developed with the representation of change in the temperature of electrolyte in the pores of the plates and above the plates not only over time but also along the spatial coordinates of accumulator plates. The equation of discharge energy includes a K_u coefficient, which evaluates a change in the discharge voltage of accumulator when the temperature of electrolyte at the input to the accumulator battery changes.

A valid part of the transfer function (3) was separated to estimate a change in the charge voltage when the electrolyte temperature changes in the volume of accumulators:

$$O(\omega)=\frac{(L_1A_1)+(M_{1\cdot}B_1)K_{в}K_u\varepsilon(1-L^{*})}{(A_1^{\,2}+B_1^{\,2})}. \tag{5}$$

Coefficient K_t includes temperature of the dividing wall θ:

$$\theta=(\alpha_{ch}(\sigma_1+\sigma_2)/2)+A(t_1+t_2)/2)/(\alpha_{ch}+A), \tag{6}$$

where σ_1, σ_2 are the temperatures of electrolyte at the input and output to the accumulator, K, respectively;

$$A=1/(\delta_m/\lambda_m+1/\alpha_{disch}), \tag{7}$$

where δ is the thickness of wall of the plate of accumulator, m; α is the coefficient of heat emission, kW/(m^2·K); λ is the heat conductivity of metal of the accumulator plate, kW/(m·K); t_1, t_2 is the temperature of electrolyte in the pores of the plates and above the plates at the input and output to accumulator, K, respectively. Indices: *ch* – accumulator battery charge; disch – discharge of the accumulator battery; *m* – metal wall.

To use the valid part $O(\omega)$, the following coefficients were obtained:

$$A_1=\varepsilon^{*}-T_{ch}T_m\omega^2;\;\; A_2=\varepsilon^{*}+1;$$

$$B_1=T_{ch}\varepsilon\omega+T_{ch}\omega+T_m\omega; \tag{8}$$

$$B_2=T_m\omega;\;\; C_1=\frac{A_1A_2+B_1B_2}{A_2^{\,2}+B_2^{\,2}};\;\; D_1=\frac{A_2B_1-A_1B_2}{A_2^{\,2}+B_2^{\,2}}; \tag{9}$$

$$L_1=1-e^{-\zeta C_1}\cos(-\xi D_1);\;\; M_1=-e^{-\zeta C_1}\sin(-\xi D_1). \tag{10}$$

A valid part of the transfer function (4) was separated to estimate a change in the discharge voltage when the electrolyte temperature changes in the volume of accumulators:

$$O(\omega)=\frac{(L_1A_1)+(M_1B_1)K_tK_u\varepsilon(1-L_p^*)}{(A_1^2+B_1^2)}. \quad (11)$$

Coefficient K_t includes temperature of the dividing wall θ:

$$\theta=(\alpha_{disch}(\sigma_1+\sigma_2)/2)+ \\ +A(t_1+t_2)/2)/(\alpha_{disch}+A), \quad (12)$$

where σ_1, σ_2 is the temperature of electrolyte at the input and output to the accumulator, K, respectively;

$$A=1/(\delta_m/\lambda_m+1/\alpha_{ch}), \quad (13)$$

where δ is the thickness of wall of the plate of accumulator, m; α is the coefficient of heat emission, kW/(m²·K); λ is the heat conductivity of metal of the accumulator plate, kW/(m·K); t_1, t_2 is the temperature of electrolyte in the pores of the plates and above the plates at the input and output to the accumulator, K, respectively. Indices: ch – accumulator battery charge; disch – discharge of the accumulator battery; m – metal wall.

The implementation of transfer functions (3), (4) obtained by using the operator method for solving the system of nonlinear differential equations, hold a Laplace transform parameter – $S(S=\omega j)$, where ω is the frequency, 1/sec. The valid parts (5), (11), obtained from the mathematical processing of the transfer functions, were selected for the transition from the frequency region to the time region in order to obtain dynamic characteristics of the charge and discharge voltage. These parts are included in the integral (14), which makes it possible to obtain estimates of a change in the charge and discharge voltage over time using the inverse Fourier transform.

Using the integral of transition from the frequency region to the time region, a change in the voltage of charge and discharge was determined in the following way:

$$U(\tau)=t(z,\tau)K_u(\tau)=\frac{1}{2\pi}\int_0^\infty O(\omega)\sin(\tau\omega/\omega)d\omega, \quad (14)$$

where t is the temperature of electrolyte in the pores of the plates and above the plates, K.

By using formulae (1, 2) for comprehensive mathematical and logical modeling in order to obtain the reference and functional estimation of change in the total charge and discharge voltage, a structural circuit (Fig. 3) was developed, according to which, at the established limit change in the temperature of electrolyte at charge and discharge, parameters of heat transfer, time constants and coefficients of the dynamics of changes in charge and discharge have been determined (Table 1–3), the reference integrated system of charge and discharge (Table 4, Fig. 4) and functional resulting information (1)–(3) on decision making to support a change in the capacity of accumulator battery using the graph method of cause-effect relations [10, 11] were obtained.

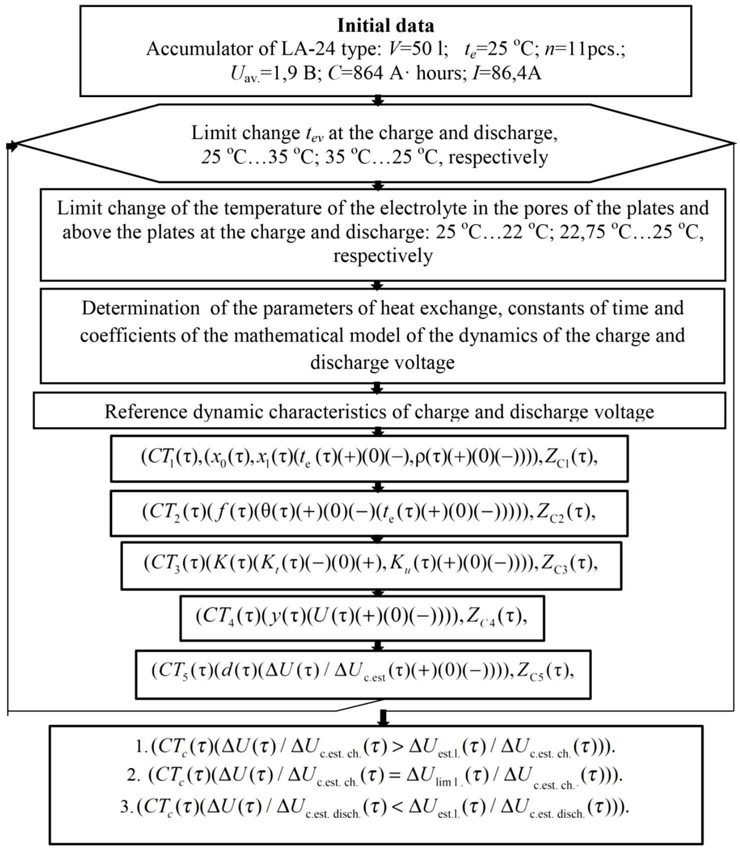

Fig. 3. Schematic of comprehensive mathematical and logical modeling of a 12 V accumulator battery

In Fig. 3: V – volume of electrolyte – 25 % solution of sulfuric acid in one accumulator, l; n – number of accumulator plates, pcs .; U – voltage, V; C – capacity, A· hours; I – current at 10-hours discharge, A; $t_{ev,}$ t_e – temperature of the electrolyte in the volume of accumulators, at the input of the accumulator battery, respectively, K; CT – event control; Z – logical relations; d – dynamic parameters; x – impacts; f – parameters which are diagnosed; y – output parameters; K – coefficients of mathematical description; Indices: c – work-status control; mid. – the average parameter value; c.est.ch., c.est.disch. – constant estimated value of the parameters of charge and discharge, respectively; est.l. – estimated value of the parameter of the level of functioning; 0, 1, 2 – initial stationary mode, external, internal parameters; 3 – coefficients of the equations of dynamics; 4 – essential parameters that are diagnosed; 5 – dynamic parameters

Table 1

Parameters of heat exchange at charge and discharge

Level of functioning	Parameter		
	α_{ch}, W/(m²·K)	α_{disch}, W/(m²·K)	k, W/(m²·K)
Charge, discharge	14.179	14.185	3.25

Note: α_{ch} – coefficient of heat emission from the electrolyte to the wall of the battery plate at a charge, W/(m²·K); α_{disch} – coefficient of heat emission from the wall of the battery plate to the electrolyte at discharge, W/(m²·K); k – coefficient of heat transfer, W/(m²·K)

Table 2

Values of time constants and coefficients of mathematical model of the dynamics of change in the voltage when charging the accumulator battery

Level of functioning	T_{ch}, s	T_m, s	ε	ε*	ζ	L_{ch}, m	L_{ch}^*
Charge	1467.56	13352.5	1	0.973	0.647	35.51	0.027

Table 3

Values of time constants and coefficients of mathematical model of the dynamics of dischange in the voltage when discharging the accumulator battery

Level of functioning	T_{disch}, c	T_m, c	ε	ε*	ζ	L_{disch}, m	L_{disch}^*
Discharge	1466.94	13346.86	1	0.973	0.647	35.51	0.027

The voltage of charge in the preset time period is determined in the following way:

$$U_{chi+1}(\tau)=U_{chi}+((\Delta U_{chi}(\tau)/\Delta U_{c.est.ch}(\tau)- \\ -\Delta U_{chi+1}(\tau)/\Delta U_{c.est.ch}(\tau))/(t_{ech.output}-t_{echinputi})U_{chi}(\tau))), \quad (15)$$

where index i is the number of charge levels.

For example, over a period of 3000 sec (0.83 hours) from the onset of charging the accumulator battery at an electrolyte temperature at the input to the accumulator battery, which is 25.62 °C, the absolute value of voltage during this period is determined in the following way:

$$12.1396\ \text{V}=12.1072\ \text{V}+(1-0.9732)/(35\ ^\circ\text{C}-25\ ^\circ\text{C})12.1072\ \text{V}.$$

The voltage of discharge in the preset time period is determined in the following way:

$$U_{dischi+1}(\tau)=U_{dischi}-((\Delta U_{dischi}(\tau)/\Delta U_{c.est.disch}(\tau)- \\ -\Delta U_{dischi+1}(\tau)/\Delta U_{c.est.disch}(\tau))/(t_{edischinput}-t_{edischioutput})U_{dischi}(\tau))), \quad (16)$$

where index i is the number of charge levels.

Table 4

Reference integrated charge and discharge system of a 12 V accumulator battery

Time, τ, 10^3 sec	I_{ch}=86,4 A $t_{e\ ch\ output}$=35 °C Change $t_{e\ ch\ input}$, °C	$\Delta U_{ch}(\tau)/\Delta U_{c.est.ch.}(\tau)$	$U_{ch}(\tau)$, V	$I_{disch.}$=86,4 A $t_{edischoutput}$=25 °C Change $t_{e\ disch.\ input}$, °C	$\Delta U_{disch}(\tau)/\Delta U_{c.est.disch.}(\tau)$	$U_{disch.}(\tau)$, V
0	25	1	12.1072	35	–1	12.0486
3	25.62	0.9732	12.1396	34.375	–0.9198	11.9520
6	26.25	0.9545	12.1638	33.75	–0.8396	11.8498
9	26.875	0.9358	12.1897	33.125	–0.7593	11.7411
12	27.5	0.9170	12.2179	32.5	–0.6790	11.6251
15	28.125	0.8983	12.2485	31.875	–0.5987	11.5006
18	28.75	0.8795	12.2818	31.25	–0.5183	11.3661
21	29.37	0.8608	12.3226	30.625	–0.4379	11.2217
24	30	0.8420	12.3689	30	–0.3574	11.0611
27	30.62	0.8232	12.4154	29.375	–0.2770	10.8832
30	31.25	0.8044	12.4699	28.750	–0.1964	10.6827
33	31.87	0.7857	12.5321	28.125	–0.1158	10.4531
36	32.5	0.7669	12.6075	27.5	–0.0352	10.1835
39	33.12	0.7481	12.7023	27.2	0	10.0566
42	33.75	0.7292	12.8303	–	–	–
45	34.37	0.7104	13.0233	–	–	–
48	35	0.6916	13.4150	–	–	–

Note: $t_{e\ ch\ input}$, $t_{e\ ch\ output}$, $t_{e\ disch.\ input}$, $t_{e\ disch\ output}$ – electrolyte temperature at the input to the accumulator battery and at the battery output at the charge and discharge, °C, respectively; I_{ch}, I_{disch} – charge, discharge current, A, respectively; U_{ch}, U_{disch} – the voltage of charge and discharge, V, respectively. Index: c.est.ch, c.est.disch – constant estimation value of the parameter for charge and discharge, respectively

For example, over a period of 3000 sec (0.83 hours) from the onset of discharging the accumulator battery at an electrolyte temperature at the input to the accumulator battery, which is 34.375 °C, the absolute value of voltage during this period is determined in the following way:

11.9520 V=12.0486 V–
–(–0.9198)–(–1))/(35 °C–25 °C)12.0486 V.

Based on the proposed mathematical substantiation of support of the functioning of energy systems at the decision-making level (1), (2), a structural circuit (Fig. 5) was compiled for making decisions about supporting a change in the capacity of accumulator battery using a functional integrated system of change in the discharge voltage of accumulator battery (Table 4, 5) and $\Delta U_{ch}(\tau)/\Delta U_{c.est.ch}(\tau)$ (Table 4).

An integrated system was designed to support a change in the capacity of accumulator battery (Table 7, Fig. 6) to predict a voltage change at continuous measurement of the temperature of electrolyte at the input to the accumulator battery and at the output of the accumulator battery

Table 5

Functional integrated system of change in the charge voltage of a 12 V accumulator battery within a change in the capacity to 50 %

Time, τ, 10^3 sec	0	3	6	9	12	15	18
$t_{e\ disch\ input}$, °C	35	34.375	33.75	33.125	32.5	31.875	31.25
$\Delta U_{disch}(\tau)/\Delta U_{c.est.disch}(\tau)$	–1	–0.9198	–0.8396	–0.7593	–0.6790	–0.5987	–0.5183
$U_{disch}(\tau)$, V	13.415	13.3074	13.1936	13.0725	12.9433	12.8047	12.6550

Note: $t_{e\ disch.input}$ – electrolyte temperature at the input to the accumulator battery, °C, respectively; U_{disch} – discharge voltage, V. Index: c.est.disch – constant estimated value of the parameter at discharge

Table 6

Functional integrated system of change in the charge voltage of a 12 V accumulator battery within a change in the capacity at 50 %

Time, τ, 10^3 sec	21	24	27	30	33	36	39
$t_{e\ disch\ input}$, °C	30.625	30	29.375	28.750	28.125	27.5	27.2
$\Delta U_{disch}(\tau)/\Delta U_{c.est.disch}(\tau)$	–0.4379	–0.3574	–0.2770	–0.1964	–0.1158	–0.0352	0
$U_{disch}(\tau)$, V	12.4925	12.3137	12.1157	11.8925	11.6399	11.3397	11.1984

Note: $t_{e\ disch.input}$ – electrolyte temperature at the input to the accumulator battery, °C, respectively; U_{disch} – discharge voltage, V. Index: c.est.disch – constant estimated value of the parameter at discharge

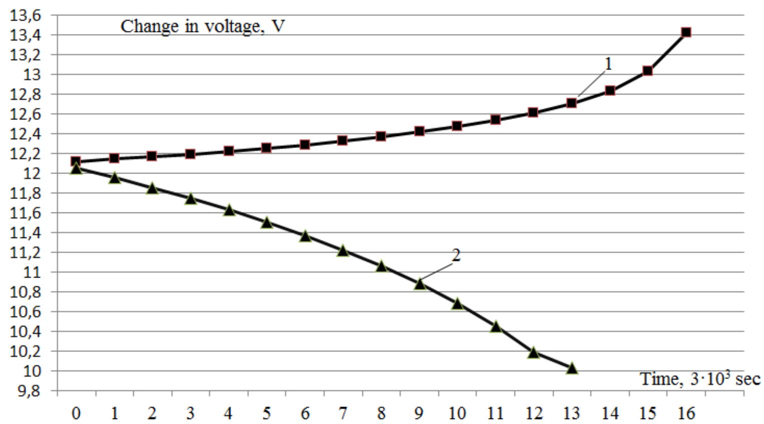

Fig. 4. Reference integrated system of change in the voltage of a 12 V accumulator battery, where 1 — accumulator battery charge, 2 — accumulator battery discharge

Making a decision about charging the accumulator battery over a time of $15\cdot10^3$ sec (4.17 hours) is confirmed by a change in the charge voltage, which has the following absolute value calculated using formula (15):

13.0406V=12.9433V+
+(0.7669–0.7481)/(35 °C–
–32.5 °C)12.9433V.

Thus, the prediction of change in the discharge voltage of accumulator battery makes it possible to take preliminary decisions about charging the accumulator to support a change in capacity.

For example, over a period of $15\cdot10^3$ sec (4.17 hours) after recharge and the onset of the discharge of accumulator battery, it was found that the temperature of electrolyte in the volume of accumulator battery decreased from 35 °C to 32.5 °C (Table 7), which may lead to a decrease in the battery capacity larger than by 25 %. In order to support a change in the battery capacity, it was decided to charge the battery by using data (Table 7) related to the supply of charge current and restoring the battery capacity within 25 % when connected to charge for further recharging. The absolute value of discharge voltage using formula (16) over a period of $15\cdot10^3$ is determined in the following way:

12.9433V=13.0725V–(–0.6790–
–(–0.7593)/(33.125 °C–25 °C)13.0725V.

Table 7

Integrated system to support functioning of a 12V accumulator battery

Time, τ, 10^3 sec	Change in the battery capacity	$\Delta U(\tau)/\Delta U_{c.est}(\tau)$	$U(\tau)$, V
0	$I(\tau)=I_{rech}(\tau)$. Recharge. $t_{e.input}$=35 °C; $t_{e.output}$=35 °C	0.6916	13.4150
3	$I(\tau)=I_{disch}(\tau)$. Discharge. $t_{e.input}$=35 °C; $t_{e.output}$=27.5 °C	–1	13.4150
6	$I(\tau)=I_{disch}(\tau)$. Discharge: $t_{e.input}$=34.375°C; $t_{e.output}$=27.5 °C	–0.9198	13.3074
9	$I(\tau)=I_{disch}(\tau)$. Discharge. $t_{e.input}$=33.75 °C; $t_{e.output}$=27.5 °C	–0.8396	13.1936
12	$I(\tau)=I_{disch}(\tau)$. Discharge: $t_{e.input}$=33.125°C; $t_{e.output}$=27.5 °C	–0.7593	13.0725
15	Decision making about charge. $I(\tau)=I_{ch}(\tau)$. $t_{e.input}$=32.5 °C; $t_{e.output}$=27.5 °C	–0.6790	12.9433
18	$I(\tau)=I_{ch}(\tau)$. Charge. $t_{e.input}$=32.5 °C; $t_{e.output}$=35 °C	0.7669	12.9433
21	$I(\tau)=I_{ch}(\tau)$. Charge $t_{e.input}$=33.125 °C; $t_{e.output}$=35 °C	0.7481	13.0406
24	$I(\tau)=I_{ch}(\tau)$. Charge $t_{e.input}$=33.75 °C; $t_{e.output}$=35 °C	0.7292	13.1720
27	$I(\tau)=I_{ch}(\tau)$. Charge $t_{e.input}$=34.37 °C; $t_{e.output}$=35 °C	0.7104	13.3701
30	Decision making about recharge. $I(\tau)=I_{rech}(\tau)$. Recharge $t_{e.input}$=35 °C; $t_{e.output}$=35 °C	0.6916	13.4150
33	$I(\tau)=I_{rech}(\tau)$. Recharge. $t_{e.input}$=35 °C; $t_{e.output}$=35 °C	0.6916	13.4150

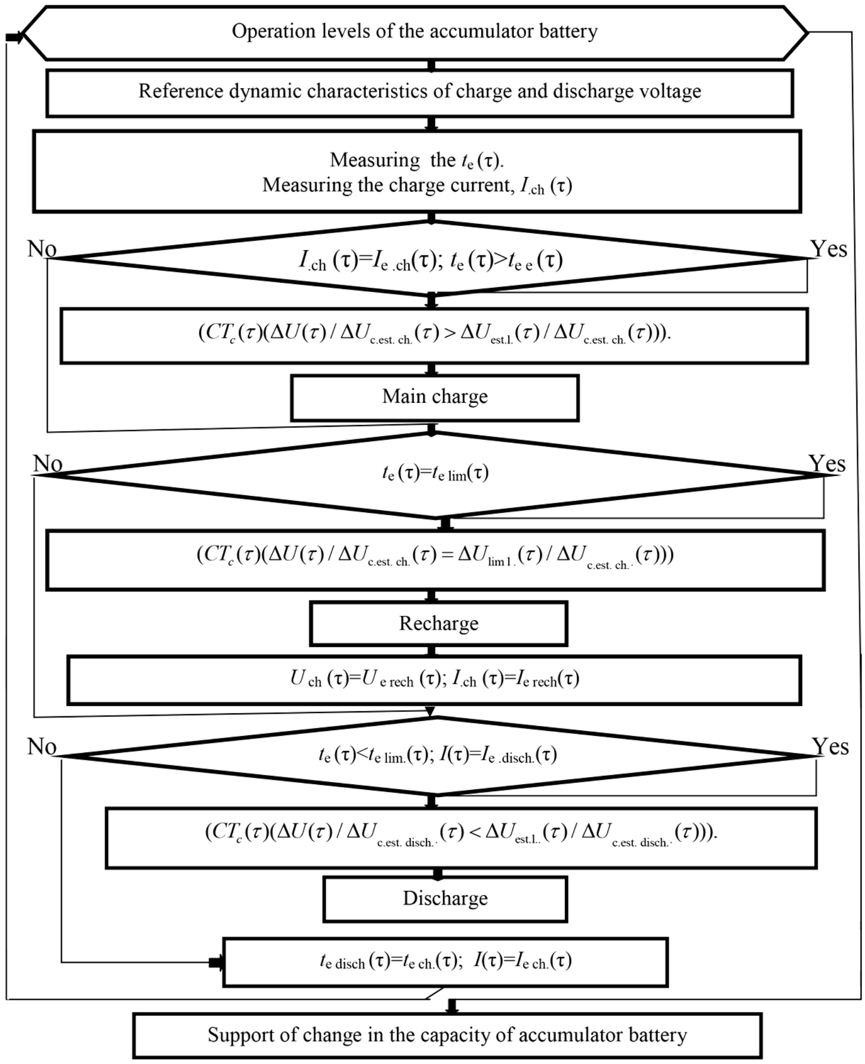

Fig. 5. Schematic of support of change in the capacity of accumulator battery, where, $I_{e\,ch}$, $I_{e\,disch}$, $I_{e\,rech}$ – the reference current of charge, discharge, recharge, respectively, A; U – voltage, V; $t_{e\,e}$, t_e – reference and functional temperature of the electrolyte in the volume of accumulators, K. Indices: lim – limit change in temperature of electrolyte; ch – charge, disch – discharge; e rech – reference value of the recharge parameter; τ – time, sec

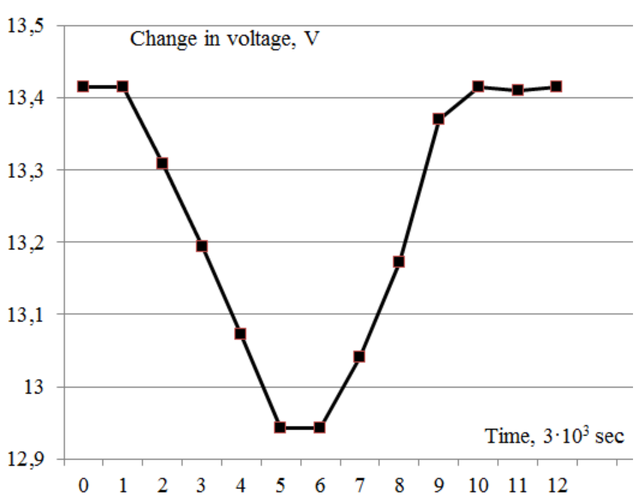

Fig. 6. Support of change in the capacity of a 12V accumulator battery

5. Discussion of results of studying energy-saving operation technology of lead-acid battery batteries

As a result of the research conducted, the limit change of the electrolyte temperature at the charge for direct current supply was determined and the limit voltage change for the subsequent recharge and discharge when the electric energy consumption is changed was established. It is proposed to measure the temperature of electrolyte in the volume of accumulators to predict a voltage change using the estimation of change in the temperature of electrolyte in the pores of the plates and above the plates. The electrochemical and diffusion processes were aligned, which accompany charging and discharging the battery, to make preemptive decisions to support a change in the capacity of accumulator battery and to prevent gas formation.

An analytical estimation of the change in voltage and discharge voltage without connecting the load and when connecting the load was obtained. The functional system of change in the voltage of accumulator battery was developed, which makes it possible to maintain capacity of the battery based on the prediction of change in the discharge voltage when measuring the temperature of electrolyte in the volume of accumulators using switching to charge. This makes it possible to provide maintaining the capacity and to prevent the recharge and unacceptable battery discharge. Determining the exact time of charge before the start of gas formation makes it possible to reduce the charge time to save electricity and to prevent the formation of gas. Presented study results are continuation of work in the direction of coordination of production and consumption of energy [1, 10, 11]. The study results presented could be used when developing intelligent systems for the operation of charge controllers. We plan to test study results under conditions of applying accumulator batteries of different capacity and power as a part of the developed system to support operation.

6. Conclusions

1. Support of the operation of accumulator battery requires alignment of the electrochemical and diffusion processes that accompany charging and discharging the accumulator battery. It is necessary to predict a change in the voltage of accumulator battery to take preemptive decisions to change the capacity.

2. A structural circuit of comprehensive mathematical and logical modeling is proposed, which makes it possible to obtain an integrated reference estimation of a change in the charge and discharge voltage. The circuit also includes a logical unit to control the workability of accumulator battery, which operates by the principle of cause-effect relations. The logical unit has components that evaluate: a change in the temperature of electrolyte at the input to the accumulator battery, which is measured; a change in the temperature of wall of the battery plate; a change in the coefficients of mathematical model of dynamics, K_t, K_u; a change in voltage; a change in the dynamic parameters; resulting control unit over workability.

3. A structural circuit to support a change in the capacity of accumulator battery is proposed. A special feature of this circuit is a comparison of the temperature of electrolyte at the input to the accumulator battery, which is measured, with the reference value. Determining summary information makes it possible to take preliminary decisions about changing the operating modes of accumulator battery to support a change in capacity.

4. An integrated system for the estimation of voltage change in the accumulator battery is proposed, which allows maintaining capacity of the accumulator battery based on the prediction of a voltage change when measuring the temperature of electrolyte at the input to the accumulator battery.

5. Alignment between the electrochemical and diffusion processes that accompany battery charging and discharging makes it possible to determine a boundary change in voltage to prevent the formation of gas. Under conditions of operating a wind power plant with a capacity of, for example, 10 kW, reduction in the charge time and the absence of gas formation decreases the cost of energy production and the payback period of the wind power plant by up to 25 %.

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