It is shown that use of correcting circuits allows achieving phase shift uniformity at adjustment of power attenuation. It is assigned that in modified T-shaped attenuator the phase shift change does not exceed 10° in attenuation range 2,5...8,2 dB in frequency band 0,05...4,0 GHz; it is almost in 2,6 times lower than in attenuator without correction. In comparison with diode attenuators, the T-shaped bridge circuit does not give considerable advantages from the point of view of phase shift minimum.

In attenuator in the mode with adjusted slope of current-voltage characteristic a minor change of phase shift – to 5° in the same range of frequencies and attenuations may be achieved. The obtained results are close to the experimentally observed values.

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SIMULATOR OF FUEL CELLS CHARACTERISTICS ON THE BASIS OF THE SEMICONDUCTOR CONVERTER

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The results of development and research of the simulator of fuel cells characteristics based on the operated pulse converter with direct current and digital alarm processor have been considered. The electrochemical model of fuel cell considering its static and dynamic characteristics is incorporated in the algorithm of the processor work. The specified simulator has on loading terminals the same characteristics of output capacity as a real system. It allows abandoning the use of both the elements and expensive accompanying systems at stages of research, design and realization of independent systems of power supply on the basis of fuel cells.

Introduction

In order to provide competitiveness with independent feed systems on the basis of well known sources of electric energy, the systems on the basis of fuel cells (FC) should operate with comparable efficiency [1]. Such systems behavior in transients is one of the key issues at the stage of their design [2]. Simulator of FC characteristics is the device having at loading terminals the same characteristics of output power as the real system. In order to develop the simulator of FC characteristics the mathematical model of electrochemical generator directed to the analysis of the system by techniques of automatic control theory and electrical engineering should be designed.

Currently, the investigations in this field, introduced in domestic and foreign sources, may be conditionally divided into two directions: the first one (given in the majority of works) is the investigation in the field of electrochemistry the aim of which is the development of the FC components (electrolytes, gas-diffusion electrodes etc.) and selection of optimal work areas on current-voltage, parametric and other curves. Such models are based on laws of electrochemistry of porous structures, thermodynamics and mechanics of gaseous and liquid media [3, 4]. They are not suitable for analysis of transients in FC system by the techniques of automatic control theory and electrical engineering.

Another direction is the investigation in the field of electronics and microprocessor engineering allowing modeling FC characteristics [5]. However, insufficient coverage of these questions in scientific literature resulted in necessity of developing mathematical model of closed-loop control of FC, designing physical model computer control simulator of FC characteristics for experimental investigations of its characteristics; as well as developing the control system allowing providing the specified characteristics of the transients.

The authors proposed a new device on the basis of computer controlled pulse converter of direct current on the basis of FC electrochemical model (software) included in it. The simulator on the basis of the mentioned converter has on its loading terminals the same dependence of output continuous stress on load current as the real FC [6, 7].

The principle of modeling FC characteristics by the simulator consists in controlling voltage on the load according to the electrochemical model BFC included in DTS. The required value of voltage is formed by the change of pulse ratio controlling pulse converter of direct current. Necessary operating conditions are computed by bundled software on the basis of data of current and voltage sensors. The converter acts as the controlled source of continuous voltage source providing the load with the same power as the real FC.

The model describing static characteristics of fuel cell with proton-exchange membrane

The fuel cell model used in the work is based on several basic equations given in the form of mathematical blocks in Simulink package, and it is of the following form:

$$U_{\text{ТЭ}}=E_{\text{Нернст}}-\Delta E_{\text{ом}}-\Delta_{\text{акт}}-\Delta E_{\text{кон}},$$

where
$$E_{\text{Нернст}}=1{,}23-8{,}5\cdot10^{-4}(T-298{,}15)+$$
$$+4{,}31\cdot10^{-5}\cdot T(\ln P_{\text{H}_2}+1/2\cdot\ln P_{\text{O}_2}),$$
$$\Delta E_{\text{ом}}=i_{\text{ТЭ}}\cdot R_M,$$
$$\Delta E_{\text{акт}}=-[\xi_1+\xi_2\cdot T+\xi_3\cdot T\ln P_{\text{O}_2}\xi_4\cdot T\cdot\ln(i_{\text{ТЭ}})$$
$$\Delta E_{\text{кон}}=-B\cdot\ln(1-J/J_{\max}),$$

where $E_{\text{Нернст}}$ is the open-circuit voltage of FC; $\Delta E_{\text{ом}}$ is the ohmic drop on FC internal voltage; $\Delta E_{\text{акт}}$ is the voltage drop owing to anode and cathode activation; $\Delta E_{\text{кон}}$ is the voltage drop owing to decrease of reactive gas concentration; $i_{\text{ТЭ}}$ is the FC load current, A; R_M is the membrane equivalent resistance, Ohm; J is the current density of FC load, A/cm²; n is the number of FCs used in a battery; T is the membrane temperature at work, K; A is the membrane active area, cm²; l is the membrane thickness; P_{O_2} and P_{H_2} are the partial pressures of oxygen and hydrogen, atm; R_C is the equivalent contact resistance of the membrane, Ohm; B, ξ, ψ are the parametric coefficients.

The expression for the equivalent resistance of the membrane:

$$R_M=\frac{\rho_M l}{A},$$

where ρ_M is the membrane specific resistance calculated by the formula:

$$\rho_M=\frac{181{,}6\cdot\left[1+0{,}03\cdot\left[\dfrac{i_{FC}}{A}\right]+0{,}062\cdot\left[\dfrac{T}{303}\right]^2\left[\dfrac{i_{FC}}{A}\right]^{2,5}\right]}{\left[\psi-0{,}634-3\left[\dfrac{i_{FC}}{A}\right]\right]\cdot\exp\left[4{,}18\cdot\left[\dfrac{T-303}{T}\right]\right]}.$$

A load characteristic (LC) of fuel cell in Fig. 1, *a*, represents a theoretical dependence of fuel cell output stress on load current. In this case LC of a FC battery was studied for comparison with the results of the experiment on training sample of Avista Labs SR-12. The given LC describes only static behavior of FC battery as each X-direction point of the curve is obtained at achieving stable value.

The experimental LC of FC battery is introduced in Fig. 1, *b*; its parameters were taken as a principle at designing mathematical model for static mode of operation. Low-frequency pulses on the obtained diagram are described by low demands made to the quality of the output voltage used in the experiment of the training sample. Calculating the correlation coefficients of theoretical and practical LC the coefficients k_U=0,91 and k_P=0,89 for the curves of the output voltage and output power of FC battery, respectively, are obtained. This gives a reason to confirm that the stated electrochemical model of FC reproduces correctly the behavior of the system in static modes of operation considering the accepted assumptions.
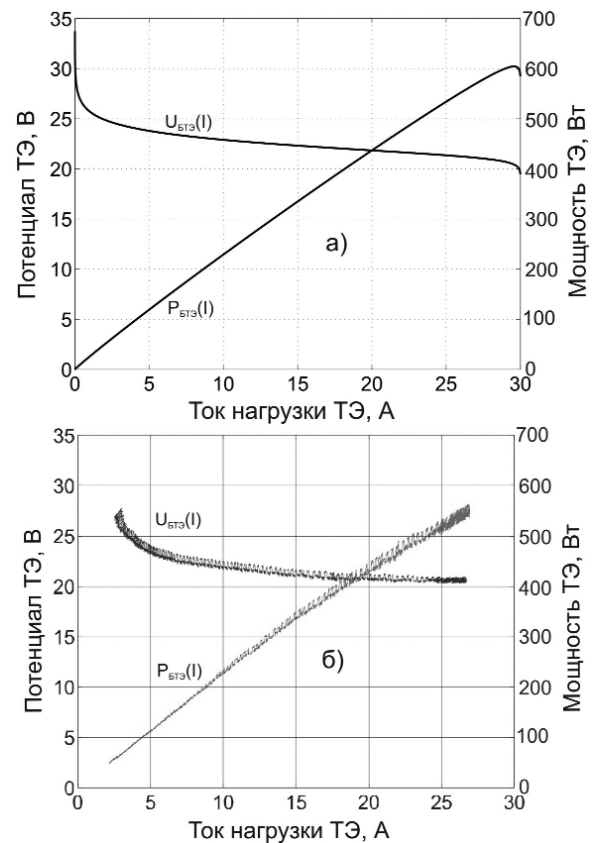

Fig. 1. *Theoretical (a) and experimental (b) load characteristics of FC*

Dynamic behavior of FC with proton-exchange membrane is based on a phenomenon of accumulation of charge double layer in the place of electrode and membrane contact. If load current of FC changes then the charge needs some time for redistribution [7]. One of the simplest methods for modeling this situation consists in use of the equivalent circuit (astatic link of the first order) where the charge double layer would be represent in the form of condenser and resistors would correspond to internal resistances of FC. The circuit is modeled in Simulink package and the results are introduced in Fig. 2, *a*.

The assumptions accepted at design of this model are the following: FC temperature and reactive gas pressure are constant during the whole transient. Load cur-

rent in the experiment changes in step from 0 to 25 A and back. Sharp voltage fall is conditioned by close values of time constants in transfer function of the equivalent circuit. This fall can not be balanced by automatic control system. This result shows that supplementary power source is required for balancing voltage fall of FC at abrupt jumps of load. Long duration of the transient is conditioned by the value of equivalent circuit capacity making farad units. This capacity is proportional to the area of a complex porous structure of the membrane which exceeds in some orders its geometric area.
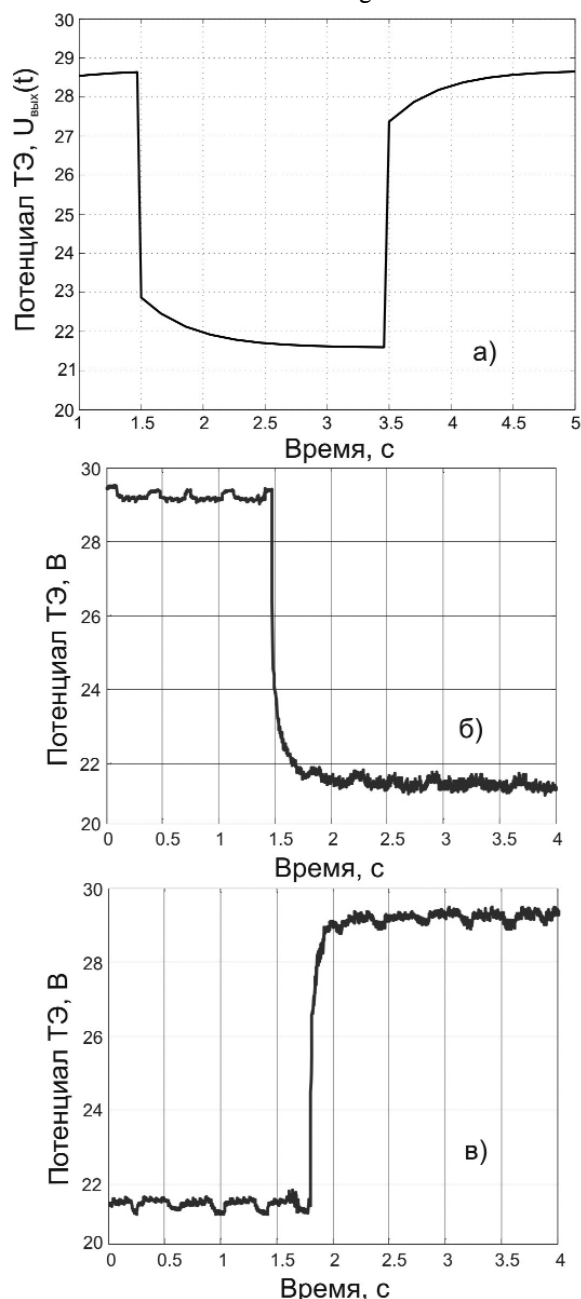

Fig. 2. *System response to load jump: a) modeled; b, c) experimental*

The response family of open loop to load current jump at different initial and final current values obtained experimentally is given in Fig. 2, *b, c*. Calculating

the correlation coefficient for the modeled and experimental results the coefficients $k_{\text{наброс}}=0{,}88$ and $k_{\text{сброс}}=0{,}85$ for the curves corresponding to load-on and load-off of FC battery, respectively were obtained. It gives the reason to confirm that the represented model for transient condition of FC transfers correctly its behavior in dynamic operation modes considering the accepted assumptions.

The simplest method of implementation of simulator strength part is the use of voltage-dropping regulator, in the authors' opinion. Its advantages are a simple mathematical model, linear dependence of output voltage on control PDM-pulse ratio, possibility of applying this schematic solution for load feed with power to several kW.

Block diagram of the proposed configuration of simulator with regulator is introduced in Fig. 3, *a*. Block FCPEM (fuel cell with proton-exchange membrane) represents the electrochemical model of FC in this Figure.
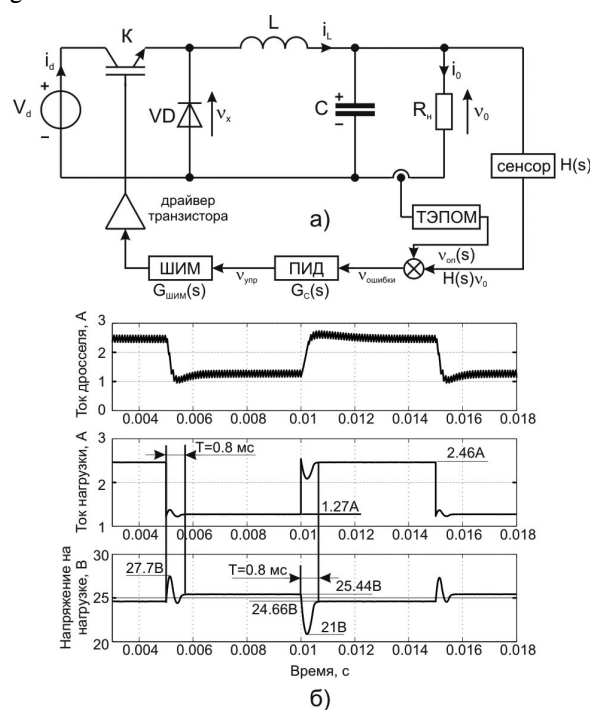

Fig. 3. *Block diagram of the proposed simulator configuration of FC characteristics (a) and time diagrams of closed system behavior (b)*

The proposed simulator configuration was introduced in the form of blocks of Simulink package and modeled for obtaining transient characteristics of the system at load current jump. The diagrams show the transient time less than 1 ms. After finishing the transients in the system the perturbation is completely suppressed and levels of load current and voltage correspond to the specified ones (рис. 3, *b*).

For further investigation of simulator of FC characteristics the time constants of the air-delivery system to FC should be defined. They may be determined analytically or obtained experimentally. One of the experi-

ments described in scientific literature is examined as an example [8]. In order to determine the KKP of air-delivery system in the experiment the compressor rotational velocity and pressure at compressor output as a function of engine velocity signal was measured. Processing the results of the experiment the program computes the correlation coefficient of a transfer function with the experimental data.

On the basis of the used experimental data the whole system was introduced in the form of links of the automatic control system. Synthesis of this model with models obtained before considering static and dynamic FC characteristics allowed making complete mathematical model of the closed-loop control of electrochemical generator presented similarly in the form of links of automatic control system (Fig. 4, *a*). The block combining the direct current motor (DCM) and converter is given in Fig. 4, *b*.

System input action is a signal of voltage assignment and the output action is the measured voltage of fuel cell terminals. In order to determine the transfer characteristics of synthesized system it is introduced in the form of blocks of Simulink package.
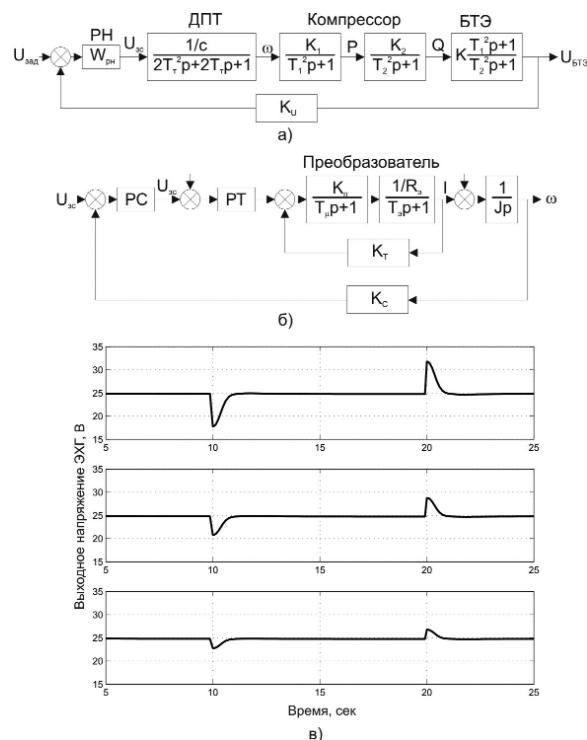

Fig. 4. Block diagram of closed control system of electrochemical generator (a, b) and system response to load current jump (c)

The results of computer simulation are given in Fig. 4, *c*. The closed system response to load current jump is modeled in the experiment as an example. The output voltage of the system is specified on the level of 25 V.

The first of three system responses corresponds to the most unfavorable case when the load current jumps from zero to peak value. In this case the transient dura-

tion amounts to 1,5 s and peak stress achieves 32 V exceeding stabilizing voltage by 28 %. The second and the third system responses correspond to the jumps of load current from 5 to 20 A (excess of stabilizing level by 16 %) and from 10 to 15 A (excess of stabilizing level by 8 %) respectively. The transient time in all three cases is nearly the same. The output voltage stabilizes on the set level at the end of transient time.

The above-mentioned research is the base for physical implementation of FC simulator control on the basis of real time equipment dSPACE. After calculation of parameters of simulator and compensator strength part the computer simulation of the closed control system behavior is carried out, the model of strength part is exchanged by real equipment. The regulator is given in the form of Simulink blocks.

The control algorithm is loaded in interface card controller. The data from current and voltage sensors enter the computer at virtual oscillograph through the analog-digital converter. The device is controlled through the graphical user interface. It contains two oscillographs for measuring load current and voltage, two oscillographs for control signal and error voltage as well as adjustments of proper regulator constituents and option dialog box.

The control card of electronic power keys, cards of amplifier prestages and filtering of measured signals of the experimental device are shown in Fig. 5. The output LC filter is shown here as well.
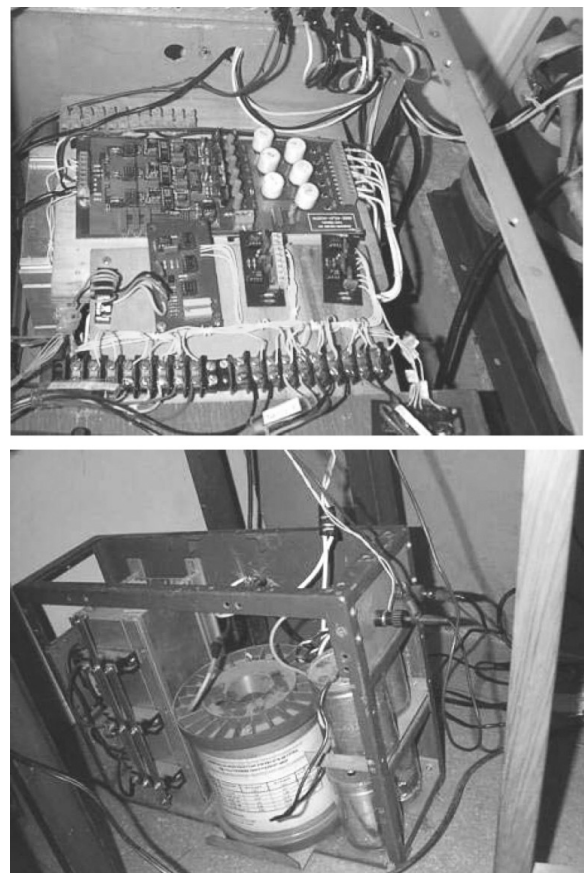

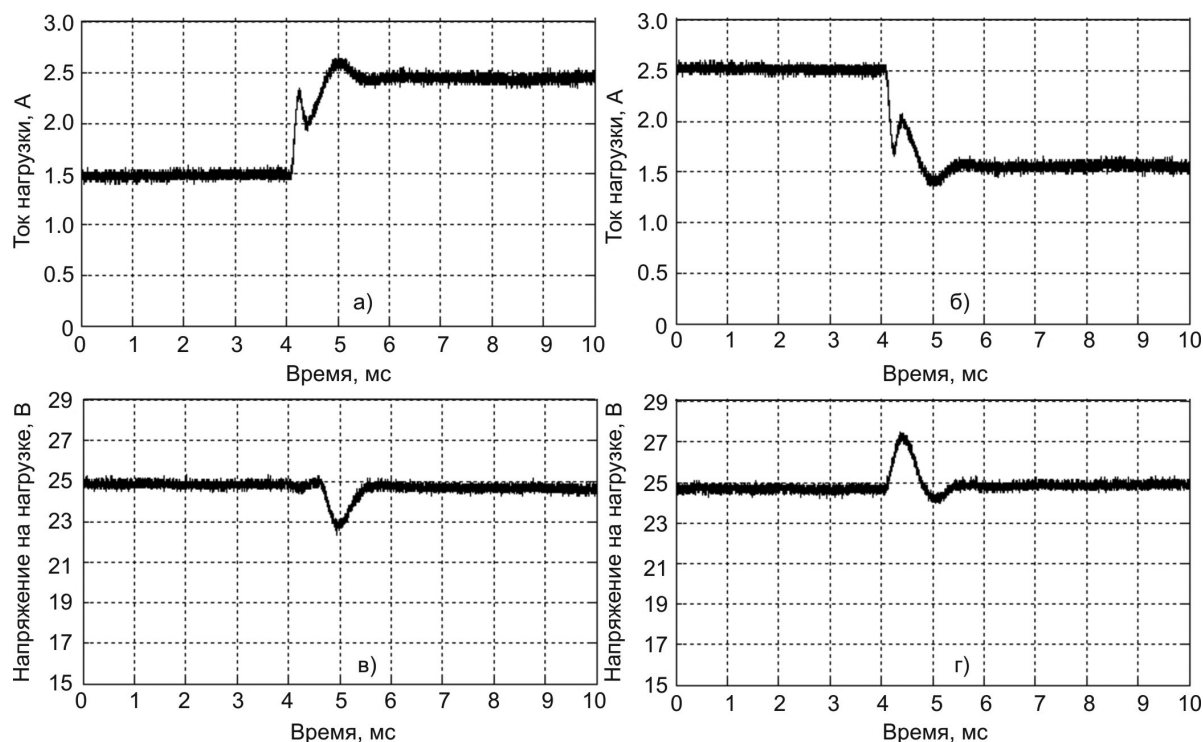*Fig. 5.* Experimental device: card of control/measure and LF filter

Fig. 6. *Time diagrams of simulator of FC characteristics at load jump*

In the series of experiments (Fig. 6) the load jumps. The diagrams correspond to minor change of load current (from 1,5 to 2,5 A and back) near the working point selected at regulator calculation.

Comparing the obtained characteristics with the results of computer simulation one can note that the current overshoot is absent here as well and voltage overshoot does not exceed 10 %. Thus, the results of the experiment coordinate with the data obtained at computer simulation. The transient time at the experiment amounted to less than 2 ms that exceeds slightly the predicted value; usually by the reason of analog-digital and reverse conversions introducing delay into a control circuit.

Conclusion

1. The mathematical models considering static and dynamic properties of fuel cells applicable to wide range of these devices and intended for use in closed-loop control by simulator of fuel cell characteristics were developed.

2. The close-loop control of electrochemical generator was designed. The computer analysis of transients on the device output terminal was carried out.

3. A new semiconductor converter installation – simulator of fuel cell characteristics was developed and implemented in the form of a model.

4. A circuit solution of fuel cell power converter with power battery, the flow of which is controlled according to the data of output current and voltage sensors was proposed.

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