Investigation of the electro-technical complex with alternative energy sources

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Abstract. The article considers hybrid electric power complexes. The prospects of their development are shown. The expediency of using alternative energy sources for sustainable electricity and heat supply to consumers is proven. A mathematical model of an autonomous electrical complex with a fuel cell and a photovoltaic station as power supply sources is presented. The necessity of taking into account mutual influence of individual subsystems of the electrical complex, as well as their influence on the complex as a whole is reasoned.

Keywords: electrical engineering complex, photovoltaic plant, fuel cell, alternative energy sources.

1. Introduction
Currently, there is a growing trend in discussing and implementing alternative energy sources into the established global energy complex, both because of the geopolitical reasons and of the environmental impact. Firstly, traditional energy sources are exhaustible. According to preliminary forecasts, their reserves will last only until the end of the century. Secondly, traditional energy resources are characterized by the toxicity of emissions of their processed products into the atmosphere, which has a negative impact on the environmental situation not only in the fuel processing region, but worldwide. In addition, the search, extraction, processing and distribution of non-renewable energy resources require significant labor and financial costs [1, 2].

One of the solutions to these problems is the use of solar insolation as a source of energy. It is an inexhaustible, as well as easily accessible and efficient source of energy in most regions of Russia, including West Siberia. Photovoltaic power plants and panels (PVPP) convert solar energy into electrical energy with the efficiency of about 47 % [3]. The non-uniformity of the power generation of the PVPP during the day can be solved by combining several alternative energy sources into a single hybrid electrical complex (HEC). It is possible to use fuel cells (FC) together with the PVPP in hybrid electrical complexes [4 - 6].

Fuel cell is an electrochemical generator that converts chemical energy of hydrogen (hydrogen compound) interaction and oxygen (air) into electrical and thermal energy. The electrical efficiency of the fuel cell ranges from 40 % to 70 %, depending on the type of the electrolyte used. When using the generated heat, the efficiency of the hybrid electrical complex is significantly higher [7].

As primary sources energy Such HEC uses resources that are unlimited in volume and in the process of its recycling does not have a significant negative impact on the environment. If there is an excess of energy from the PVPP, it can be used to produce hydrogen using electrolysis, its accumulation and subsequent use as fuel for fuel cells. The system will be autonomous, which is an important factor for consumers who are not connected to a centralized power supply system or consumers of a special category [8 - 11].
Such systems are applied abroad and are gradually being implemented. It should be noted that the processes occurring in the subsystems of the HEC have a different physical nature. They are not fully studied in general and require additional research to develop effective and economically viable HEC.

2. Problem Statement
To develop an effective electrical complex with a photovoltaic panel and a fuel cell as energy sources, it is necessary to develop mathematical models of its elements and to study the electromagnetic and electrochemical processes occurring in the subsystems (elements) of the complex.

Simulation of various physical processes in the elements of the complex will allow us to reasonably develop criteria influencing the optimal mode of operation of the HEC and its maximum efficiency.

3. Theory
In general, a HEC model consists of photovoltaic panels, a fuel cell, converters, inverters, an electrolyzer, and a hydrogen storage device. The block diagram of the HEC is shown in Figure 1.

With an excess of the generated electrical power, the PVPP turns on the electrolyzer, and produces hydrogen, which is collected in the hydrogen storage tank. If there is a shortage of power generated by the PVPP, the fuel cell is turned on and the hydrogen from the storage device enters it.

![Figure 1. Block diagram of the HEC](image)

Direct current load can be performed as: battery charging stations, DC electric drives, hot water installations, control and alarm systems, and smart home systems.

For alternating current, consumers can include: general household appliances, charging stations for electronic devices and gadgets, pumping and motor loads, heating and air conditioning systems, etc.

3.1. Model of the PVPP
There are equivalent circuits of solar cells with different level of detail of processes. In this article, we use the electrical circuit of the PVPP replacement shown in Fig. 2.
Figure 2. An equivalent circuit of the photovoltaic panel

Current of the PVPP can be found as follows:

\[ I = I_L - I_d - I_p \]  

where \( I_L \) is the solar panel photocurrent generated from the conversion of solar radiation; \( I_d \) is the diode current proportional to the saturation of the photovoltaic panel; \( I_p \) is the current for losses account in the parallel branch [12, 13].

Diode current can be found in the following way:

\[ I_d = I_0 \left( \exp \left( \frac{V + R_s I}{a} \right) - 1 \right), \]  

where \( I_0 \) is the diode fault current; \( V \) is the voltage on the diode; \( R_s \) is the series resistance of the circuit; \( a \) is the thermal voltage.

Thermal voltage \( a \) can be presented as:

\[ a = \frac{N_S A \cdot k \cdot T_c}{q}, \]  

where \( N_S \) is the number of modules connected in series; \( k \) is the Boltzmann constant; \( T_c \) is the temperature of the solar panel; \( q \) is the electron charge; \( A \) is the ideality factor of the diode.

Loss current in parallel circuit can be found as follows:

\[ I_p = \frac{V + R_s I}{R_p}. \]  

where \( R_p \) is the resistance in the parallel circuit.

In general, the current of the PVPP can be found in the following way:

\[ I = I_L - I_0 \left( \exp \left( \frac{V + R_s I}{a} \right) - 1 \right) - \frac{V + R_s I}{R_p}, \]  

Power of the PVPP can be found as follows:

\[ P = V \cdot I \]
The output characteristics of the PVPP are affected by several parameters: the level of solar radiation directly influencing the volume of the generated power; the shading effect of the solar module as because of the limits placed on the panel shade the unit gets the required amount of radiation; the effect of dust, similar in principle to the shading effect, but the cause is contamination of the surface of the solar panel; mounting angle of the panel in which without taking into account the characteristics of the terrain, the unit will operate inefficiently. The temperature of the solar panel, which is inversely related to the performance of the solar panel, also influences the output characteristics.

3.2. Model of the fuel cell

The operation of the fuel cell is based on the chemical conversion of fuel and oxidizer into electrical energy. The by-products of this electrochemical reaction are heat and water vapor.

The power output of the fuel cell stack is as follows:

\[ P_{FC} = N_{FC} \cdot V_{FC} \cdot I_{FC}, \]  

where \( N_{FC} \) is the number of fuel cells in the stack, \( V_{FC} \) and \( I_{FC} \) are the voltage and current of the fuel cell [14].

The voltage of the fuel cell can be found in the following way:

\[ V_{FC} = E_{OC} - V_{act} - V_{ohm} - V_{con}, \]  

where \( V_{act}, V_{ohm} \) and \( V_{con} \) is the activation voltage, ohmic and concentration voltage drop.

The open circuit voltage of the fuel cell can be found in the following way:

\[ E_{OC} = E_0 + \frac{RT}{2F} \ln \left( \frac{P_{H_2}^2 P_{O_2}}{P_{H_2O}^2} \right), \]  

where \( T \) is the operating temperature of the fuel cell, \( P_{H_2}, P_{O_2}, \) and \( P_{H_2O} \) are the partial pressures of hydrogen, oxygen, and water, and \( F \) is the Faraday constant.

Activation voltage can be found as follows:

\[ V_{act} = A \sinh^{-1} \left( \frac{I_{load}}{2I_{0,a}} \right) + A \sinh^{-1} \left( \frac{I_{load}}{2I_{0,c}} \right), \]  

where \( I_{load} \) is the load current density, \( A \) is the slope of the Tafel curve, \( I_{0,a} \) is the exchange current density at the anode, and \( I_{0,c} \) is the exchange current density at the cathode.

Voltage drop can be found as follows:

\[ V_{ohm} = I_{load} \cdot R_{ohm}, \]  

where \( R_{ohm} \) is the ion resistance.

The drop in the concentration voltage can be found as follows:

\[ V_{con} = B \ln \left( 1 - \frac{I_{load}}{I_L} \right), \]  

where \( I_L \) is the limiting current density, \( B \) is a constant.
The I_{FC} fuel cell current can be defined as a function of the hydrogen flow rate:

$$I_{FC} = \frac{2F}{N_{FC}} \left( \frac{W_{H2}}{M_{H2}} \right), \quad (13)$$

where $W_{H2}$ is the molar flow rate of hydrogen supplied to the fuel cell, $M_{H2}$ is the molar mass of hydrogen.

A number of factors influence the operation and performance of the fuel cell the quality of the supplied fuel and oxidizer. The higher the hydrogen content in the fuel, the more efficient the fuel cell is. It is also important to maintain the pressure of the supplied fuel and oxidizer at a given level, as well as to maintain the stack temperature within acceptable values.

### 3.3. Inverter Model

The inverter is designed to convert the direct current generated by the photovoltaic modules and the fuel cell into alternating current. The inverter is selected based on the maximum load.

Inverter power $P_{\text{inv}}$ can be found as follows:

$$P_{\text{inv}}(t) = \frac{P_L(t)}{\eta_{\text{inv}}}, \quad (14)$$

where $P_L(t)$ and $\eta_{\text{inv}}$ are the load power and the inverter efficiency, respectively [15].

### 3.4. Electrolyzer Model

Water electrolysis is performed in an electrolyzer using electricity to separate water into oxygen and hydrogen. At the anode, water is divided into oxygen and protons. At the cathode, the generated electrical energy merges with protons to form hydrogen.

Power transmitted from the cell to the hydrogen tanks,

$$P_{elz-\tau} = P_{\text{surp-eltz}}(t) \cdot \eta_{eltz}, \quad (15)$$

where $\eta_{eltz}$ is the efficiency of the electrolyzer, which should be at the level of 85%.

$$P_{\text{surp-eltz}}(t) = P_{ppv}(t) - P_{\text{inv}}(t) \quad (16)$$

where $P_{ppv}(t)$ is the power generated by the photovoltaic plant.

The stored energy of hydrogen in the reservoir at the time step $t$ is estimated as

$$E_{H2}(t) = E_{H2}(t - 1) + P_{elz-\tau} \cdot \Delta t. \quad (17)$$

### 3.5. Simulation

The article examines the subsystem of a hybrid electrical complex that is a photovoltaic panel. In accordance with the previously discussed propositions of the mathematical modeling of HEC, a simulation model of a photovoltaic plant was developed (Fig. 3) in the Simulink/Matlab environment. During the experiment, the maximum values of power, current and voltage were determined depending on the degree of irradiance of the PVPP. The nature of the influence of changes in the irradiance of the photovoltaic module on the output parameters of the photovoltaic station was determined. The initial data is taken for a real solar panel FSM -150. The model of a photovoltaic plant consists of 36 solar modules connected in series, as well as two shunt diodes.
Figure 3. The simulation model of PVPP

During the experiment, the irradiance of the PVPP was discretely changed in the range from 1000 W/m² to 200 W/m² with a control step of 200 W/m². For each step of irradiance, the maximum power value is determined and the corresponding current and voltage values are obtained.

Figure 4. Current-voltage characteristic when changing the irradiance of the PVPP

Figure 5. Volt-watt characteristic when changing the PVPP irradiance
4. Experimental results
During the simulation, numerical values of currents and voltages were obtained at different levels of irradiance of photovoltaic panels. The maximum values of the generated power are determined. The peak values of the output characteristics depending on the intensity of solar radiation are found.

5. Results and discussion
The simulation results of the photovoltaic panels with the changes in irradiation levels are graphs of the current and power of photovoltaic panel dependence on the voltage. The maximum power curve is determined depending on the irradiance level. According to the set of characteristics, it is possible to draw a conclusion about the nature of the influence of the studied parameter on the output values of the photovoltaic panel.

6. Conclusion
The electro-technical complex with alternative energy sources is considered. Mathematical models of every element of the HEC system are described in a general form. Every HEC subsystem influences the operation of the system as a whole and is characterized by the mutual influence on individual subsystems. The curve of the maximum power is constructed depending on the level of irradiance of the PVPP, which allows us to determine the modes of effective operation of the HEC subsystem and the HEC as a whole according to this criterion.

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