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Development and Operation Modes of Hydrogen Fuel Cell Generation System for Remote Consumers' Power Supply

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Abstract: At the present stage of electric power industry development, special attention is being paid to the development and research of new efficient energy sources. The use of hydrogen fuel cells is promising for remote autonomous power supply systems. The authors of the paper have developed the structure and determined the optimal composition of a hybrid generation system based on hydrogen fuel cells and battery storage and have conducted studies of its operating modes and for remote consumers' power supply efficiency. A simulation of the electromagnetic processes was carried out to check the operability of the proposed hybrid generation system structure. The simulation results confirmed the operability of the structure under consideration, the calculation of its parameters reliability and the high quality of the output voltage. The electricity cost of a hybrid generation system was estimated according to the LCOE (levelized cost of energy) indicator, its value being 1.17 USD/kWh. The factors influencing the electricity cost of a hydrogen generation system have been determined and ways for reducing its cost identified.

Keywords: hydrogen power source; hydrogen fuel cell; optimization; modeling and simulation

1. Introduction

The global trends in the modern electric power industry are decarbonization and decentralization aimed at improving the environmental friendliness, reliability and quality of power supply to consumers [1]. Hydrogen is an important energy carrier of the future because it can be produced from a variety of renewable and nonrenewable resources including in remote places without electricity infrastructure [2]. Fuel cells (FC) are the most promising type of power plant for power production from hydrogen. The key advantages of fuel cells are higher energy efficiency due to reliability (no moving parts), absence of energy conversion intermediate stages (electrical efficiency up to 60%), harmful emissions and noise [3].

Hydrogen fuel cells are already widely used in the transport industry, space industry, etc. [4,5]. However, expanding the range of applications for hydrogen fuel cell power plants is essential to accelerate technology development and reduce production costs.

The paper is devoted to the development of a hydrogen fuel cell generation system (HFCGS) for power supply to remote low-power consumers (up to 3 kW). A generation system of such capacity may be needed to supply:

- consumers along the oil and gas pipelines (for example: electrochemical protection, linear telemechanics, radio relay communication equipment, cleaning device launchers);
- stationary railway objects (communication devices, automatic crossing signaling);
- autonomous meteorological and telecommunication stations.

Diesel power plants are now widely used for such systems; however, diesel power plants have a number of disadvantages, such as low efficiency and reliability, the need for frequent maintenance, environmental pollution, noise and vibration.

Hydrogen fuel cells eliminate these problems, and they are promising power sources for remote low-power consumers. Meanwhile, fuel cells have disadvantages such as slow dynamic response, long start-up time and soft discharge characteristic [6]. These problems can be solved by combining fuel cells with a storage system and electricity converters in a hybrid generation system.

Many studies are devoted to the development of mathematical and simulation model or prototypes of hybrid systems based on fuel cells, storage systems and other types of energy sources (usually renewable).

Experimental studies of hybrid systems based on fuel cells and solar photovoltaic panels (PV) with a power of 500 W and 200 W are presented in [7] and [8], respectively. The electricity generated by PV is used to power a hydrogen generator. The joint operation of PV and fuel cells is not considered. The concept and prototype of a hybrid system that integrates PV, battery storage and hydrogen fuel cells for power supply of remote telecommunications is described in [9]. This system powers a 12-V load with a power of just under 10 W during the day. The PV panel is the main source while FCs are only required for relatively short timescales to charge the battery or when inclement weather and PV power is not enough. This study shows that FCs can be a useful alternative to PV or wind in case of the small loads of remote consumers.

One of the areas of research is devoted to improving the structure and development of control systems for fuel cells hybrid systems. The control system of a PV-Fuel cell hybrid system is presented in [10]. In [11], the control system of a PV-Wind-Fuel cell hybrid system was developed. The parameter coordination of renewable energy sources and fuel cells is carried out using a DC bus. Additional DC/DC and AC/DC converters are used to connect the sources to the DC bus. Fuel cells are considered as a backup power source to compensate for fluctuations in the power of PV and wind turbines.

In [12], a single-inductor dual-input single-output boost converter was used to coordinate the sources parameters of stand-alone hybrid PV-Fuel cell system. Compared to using a DC bus, this reduces the number of components and the size of the hybrid system, but it requires a high computational performance of the controller. A hybrid system based on a proton exchange membrane (PEM) fuel cell and storage batteries is presented in [13]. Two DC/DC converters are used to match PEM and battery parameters.

This paper represents a continuation of the research in [14] and presents a hydrogen fuel cell generation system (HFCGS) based on hydrogen fuel cells and battery storage. The HFCGS is designed to power remote consumers with a changing daily load schedule.

The study goal is to develop the structure and select the optimal composition of an HFCGS that provides a minimum number of converters and the size of the system and to study its operation modes and the efficiency of its use as a power supply for remote consumers.

2. Analysis and Selection of the Hydrogen Fuel Cell Generation System Main Units

2.1. Fuel Cells

The key element in the structure of the HFCGS is the block of fuel cells, which largely determines the efficiency and reliability of consumer's power supply. When developing the structure and determining the composition of the HFCGS, the most important task is to select the most suitable fuel cells type.

Fuel cells are classified according to the type of electrolyte, operating temperature and fuel. Considering these parameters, five main types of fuel cells that use hydrogen as a fuel can be singled out:

- fuel cells with a polymer or proton exchange membrane—PEMFC;
- fuel cells with alkaline electrolyte—AFC;
- fuel cells with phosphate electrolyte—PAFC;
- fuel cells with molten carbonate—MCFC;
- fuel cells with solid oxide electrolyte—SOFC.

The main structural features of the fuel cell types are shown in Table 1 [15–19].

Table 1. Structure features of hydrogen fuel cells.

Fuel Cell Type	Electrolyte	Electrode Material	Anodic Reaction	Cathodic Reaction	Critical CO Content in Fuel
PEMFC	Perfluoro-sulfonic acid (Nafion)	Anode: Pt, PtRu Cathode: Pt	$H_2 \rightarrow 2H^+ + 2e^-$	$0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O$	CO > 10–100 ppm
AFC	Potassium hydroxide, soaked in a matrix KOH	Anode: Ni Cathode: Ag	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$	$0.5O_2 + H_2O + 2e^- \rightarrow 2OH^-$	CO > 10 ppm
PAFC	Phosphoric acid soaked in a matrix	Anode: Pt, PtRu Cathode: Pt	$H_2 \rightarrow 2H^+ + 2e^-$	$0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O$	CO > 0.5%
MCFC	Carbonate solution	Anode: Ni-5Cr Cathode: NiO(Li)	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$0.5O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	does not poison the catalyst
SOFC	Yttria-stabilized zirconia, or more recently, lanthanide-doped ceria	Anode: Ni-YSZ Cathode: Lanthanum strontium manganite (LSM)	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$0.5O_2 + 2e^- \rightarrow O^{2-}$	does not poison the catalyst

PEMFCs operate within 60–120 °C temperature range and are classified as low-temperature fuel cells. PEMFC are characterized by high efficiency of electricity generation (efficiency up to 60%), with a service life of 3000 to 5000 h [20]. The important advantages of PEMFCs are their high power density, a short start and stop time, a high load change rate within a wide range, ease of operation and the ability to work in a wide range of ambient temperatures [21]. The main disadvantage of PEMFCs is the high requirements for the hydrogen quality (catalysts are susceptible to CO poisoning due to low temperatures) [22]. Therefore, additional purification of hydrogen may be required when using PEMFCs.

AFC as well as PEMFC refer to low-temperature fuel cells (operating temperature is 50–100 °C) [23]. AFC technologies are the most studied, therefore their power generation efficiency reaches 60% and the service life is estimated at 10,000 to 15,000 h. The main advantages of AFCs are similar to PEMFCs. The disadvantage of AFCs is their high sensitivity to CO₂, which reacts with the electrolyte and reduces the efficiency of the fuel cell. CO₂ can be contained in the air, so the use of AFCs is limited to closed spaces (space environment, submarines).

PAFCs operate at temperatures from 150 to 220 °C and are classified as medium-temperature fuel cells. The main advantages of PAFCs are the relative simplicity of their structure, their low electrolyte volatility and their high stability. As a result, PAFC service life is estimated at about 65,000 h. PAFC can use impure H₂ as fuel and can tolerate up to 1.5% CO at operating temp. However, the efficiency of PAFC is about 40% and is inferior to other types of fuel cells [23].

MCFCs are high-temperature fuel cells that operate at temperatures from 600 to 800 °C. MCFCs have a fairly high efficiency (the efficiency of electricity generation is 50–60%). MCFCs are less demanding on the purity of hydrogen due to the high operating temperature (catalysts are not susceptible to CO and CO₂ poisoning). The main disadvantages of MCFCs are a short service life (7000–8000 h) due to the destruction of components and corrosion, a slow start-up time and the impossibility of restarting after a stop.

SOFCs are fuel cells with the highest operating temperature from 650 to 1000 °C. SOFCs are characterized by high efficiency of electric power generation (efficiency is about 60%). The service life of SOFCs is estimated at over 20,000 h due to low material

degradation. High temperatures also allow fuel to be used without special pretreatment and generate combined electric and thermal power. However, SOFCs are characterized by the significant amount of time to reach the optimal operating mode and the impossibility of changing the power generation due to high operating temperatures. This significantly complicates the use of SOFCs in power supply systems.

The results of a comparative analysis of hydrogen fuel cells are shown in Figure 1.

Figure 1. Comparative analysis of hydrogen fuel cells.

The type of fuel cell most suitable for use in an HFCGS is largely determined by the consumer power.

Thus, power supply sources for medium-power consumers (from 10 to 100 kW) must provide high energy efficiency and the minimum cost of electricity generated. The priority criteria for selecting a particular type of fuel cell as part of hybrid generation systems are:

- high electricity generation efficiency;
- low requirements for fuel quality (to reduce the cost of special preparation and large fuel volumes processing);
- the possibility of additional use of the heat released by the fuel cell (to increase the overall source efficiency).

Meanwhile, the daily load schedule of medium-power consumers usually changes during the day, but the consumption does not go down beyond a certain level. This makes it possible to continuously stabilize the operating mode of the fuel cell (by using an energy storage system).

Thereafter, it is promising to use high-temperature fuel cells in a hybrid energy complex to supply medium-power consumers (from 10 to 100 kW), which allow the use of fuel without special pretreatment and provide combined production of electrical and thermal energy. SOFCs are considered the most efficient in terms of energy performance and service life among high-temperature fuel cells.

Low-power consumers (from 1 to 10 kW), in most cases, are characterized by a changing daily load schedule ranging from a decrease in consumption to zero and sharp peaks. Energy sources for such consumers, first of all, must ensure high stability of power supply and duration of autonomous operation. Therefore, the decisive criteria for selecting a fuel cell are a short start and stop time and the ability to quickly change generation over a wide range (for generation schedule to electrical load schedule maximum approximation).

These requirements are met by low-temperature fuel cells—PEMFCs and AFCs. They operate on high quality hydrogen fuel. At the same time, the use of AFCs (due to its

high sensitivity to CO₂) is limited to closed spaces (submarines, spacecraft). PEMFCs can operate in a wide temperature range without significant restrictions to environmental conditions (vehicles, low-power stationary consumers, etc.).

The developed HFCGS is designed to power a 3-kW load. Therefore, the most applicable FCs are PEMFCs, which are characterized by a high load change rate, ease of operation and the ability to work in a wide range of ambient temperatures.

2.2. Battery Storage

To increase the duration of the HFCGS autonomous operation without refueling, it seems relevant to use a combination of fuel cells with battery storage (BS). BS will ensure the operation of the fuel cells in the most efficient modes at a changing load schedule.

Lithium batteries are the most common. They are characterized by a high energy density and a minimum self-discharge rate, which significantly increases the storage period and extends the service life without deteriorating functional performance. BS must be equipped with a protective controller (BMS board) to prevent the complete loss of the battery cells potential. Lithium batteries are widely used in technology and consumer electronics, electric transport, and also serve as an uninterruptible power supply source.

The main element of any BS is a battery cell. The characteristics of the BS (capacity, reliability and functionality) depend on the parameters of the battery cell. Several types of these can be singled out, depending on the cathodes and electrolytes (Table 2). Lithium polymer batteries were excluded from this comparison as they are fire hazardous when overcharged and overheated.

Table 2. Lithium battery cell parameters.

Type	Li-Ion	LiFePO ₄		LTO	
Type (form factor)	cylindrical	cylindrical	prismatic	cylindrical	prismatic
Capacity C, Ah	0.7–7	1.1–50	10–280	1.3–40	2.9–23
Gravimetric energy density, Wh/kg	120–270	80–140	110–165	70–96	46–90
Cell voltage, V	3.6	3.2	3.2	2.4	2.3–2.4
Standard charge current, C·A	0.5	0.5	0.5	0.5	1.0
Maximum charge current, C·A	1.0	1.0	1.0	5.0	4.0
Long-term discharge current, C·A	2.0	1.0–3.0	1.0–3.0	1.0–5.0	1.0–3.0
Maximum discharge current, C·A	3.0	3.0–5.0	3.0–5.0	5.0–10.0	4.0–10.0
Service life, cycles (not less)	1000	2000	3500	10,000	15,000
Charge-discharge depth, %SOC	20–80	20–80	20–80	0–100	0–100
Operating temperature (discharge), °C	−20–+60	−20–+60	−20–+55	−30–+60	−30–+60
Specific cost, USD/Ah	1.0–2.5	0.7–3.0	0.5–0.9	0.75–3.0	1.0–2.1

Figure 2 shows the dependence of gravimetric energy density on the capacity value for various types of battery cells.

Table 2 shows that LTO battery cells are the optimal type of BS for use in stand-alone power supply systems to remote consumers. They have the highest service life (up to 20,000 cycles), allow for complete battery discharge and can operate in subzero temperatures. However, their high unit cost and low energy intensity (Figure 2) hinder their widespread distribution.

The optimal type of cells for creating an energy storage system is LiFePO₄ with an HFCGS power up to 100 kW. LiFePO₄ cells are available in a wide range of capacities (from 1.1 to 280 Ah), have a high efficiency (up to 95%) and a service life of more than 2000 cycles (up to 8000 cycles at standard charge–discharge currents). Their main advantages are complete safety (they have thermal and chemical stability) and a long service life. Therefore,

to create the HFCGS storage system, the cylindrical cells LiFePO₄ 3.2 V PLB IFR26650-35A, 3500 mAh were selected [24].

Figure 2. The diagram of the gravimetric energy density dependence on the capacity value for various types of battery cells.

In the power range from 100 to 1000 kW, LTO is preferable due to the high values of the charge–discharge current (10C) and the high charge rate. However, in order to increase the current, it will be necessary to increase the total capacity of the batteries using parallel LTO cell connections.

3. Materials and Methods

Operability and efficiency of the HFCGS depend on the optimal choice of its structural and circuit solutions.

The functional diagram of the developed HFCGS power circuits is shown in Figure 3. The proposed structure provides uninterrupted power supply of the combined resistive and inductive load Z_L from the HFCGS or from the AC mains (if available). Switching the power supply from the HFCGS to the centralized electrical network is carried out by high-speed solid-state relays KV1–KV4 controlled by a microcontroller.

Figure 3. Functional diagram of the HFCGS power circuits.

The HFCGS functional diagram contains fuel cells (FC) and battery storage (BS) based on LiFePO₄ batteries. The battery functions as an electric buffer, providing together with the fuel cells the required output power level for a given time. The power circuit also contains a converter (C) and an output autonomous voltage inverter (AVI) with PWM.

The converter matches the relatively low FC voltage level with the increased AVI voltage and also realizes the galvanic isolation of the fuel cells from the remaining power circuit. It is made based on AVI with a latitude regulation of the output voltage and a transformer output.

The output AVI is made according to a single-phase bridge circuit and operates in unipolar sinusoidal PWM mode, making it possible to reduce the required power consumption of its output filter (in Figure 3, this filter and the EMC filter are included in the AVI structure). The HFCGS converters are based on MOSFETs and IGBTs.

In the developed device, the batteries are connected in series to obtain the voltage that provides the required level of AVI power supply voltage and HFCGS preset output voltage (220 V), respectively.

“Converter—fuel cell” power circuit section has a feedback system on the output FC power, so on the interval of standby power supply load FC operates in the mode of a constant rated power source.

HFCGS power circuit also contains filter capacitors C1 and C2, which block the AC components generated by the converters.

The main parameters of the HFCGS key units are shown in Table 3. The parameters of each device elements were calculated to develop a HFCGS simulation model.

Table 3. HFCGS key units and parameters.

Unit	Symbol (Figure 3)	Type	Nominal Parameters
Fuel cell	FC	PEMFC	1 kW, 46 V
Battery storage	BC	LiFePO ₄ , cylindrical	3.5 Ah, 12 × 36 V
Converter	C	single-phase bridge, MOSFET/IGBT	see Section 3.5
Autonomous voltage inverter	AVI	single-phase bridge, MOSFET/IGBT	single-phase, 220 V
Filters	C1, C2	capacitors	see Section 3.3
Relays	KV1-KV4	solid-state	-
Load	Z _L	-	3 kW, 220 V
Electrical mains	U	if applicable	220 V

3.1. Calculation of Fuel Cells Internal Resistance

The discharge characteristic of the selected 48 V FC with a power of 1 kW is shown in Figure 4.

Figure 4. Fuel cell discharge characteristic.

FC internal resistance r_{FC} according to its discharge characteristic is:

$$r_{FC} = \frac{\Delta U}{\Delta I} = \frac{70 - 57}{18.2 - 3.5} = \frac{13}{14.7} = 0.88 \Omega \quad (1)$$

3.2. Battery Storage Parameters Calculation

To create a HFCGS battery storage system, a series assembly of 12 LiFePO₄ batteries 36 V 3.5 Ah (configuration 12S1P) with BMS boards is used. Table 4 shows the parameters of the battery storage system.

Table 4. HFCGS battery storage system parameters.

Parameter	Value
Capacity C, Ah/kWh	3.5/1.6
Nominal voltage, V	460.8
Maximum voltage U_{BSmax} , V	518.4
Minimum voltage U_{BSmin} , V	360
Continuous charge current, A	3.5
Maximum discharge current, A	28
Internal resistance AC 1 kHz r_{BSmax} , Ω	2.6
Operating temperature t , °C	−20/+50
Volumetric Energy Density, Wh/L	306
Gravimetric Energy Density, Wh/kg	125

Figure 5 shows the discharge characteristics of the selected batteries.

Figure 5. Discharge characteristics of 3.2 V PLB IFR26650-35A batteries: (a) for various values of ranging from 0.5C to 10.0C; (b) when discharged with a constant current of 0.5C at various ambient temperatures.

3.3. Filter Capacitance Values Calculation

To determine the capacitances, we used the equations describing time dependence on the averaged current consumed by a single-phase bridge AVI with sinusoidal PWM:

$$\tilde{i}_1 = \frac{1}{2} \mu I_m [\cos \varphi_L - \cos(2\omega t - \varphi_L)], \quad (2)$$

where I_m is amplitude of the averaged output current of a single-phase bridge AVI, μ is output voltage modulation depth, φ_L is load current phase angle and ω is mains voltage angular frequency.

The maximum value of the amplitude of the variable component of the averaged input current with a circular angular of 2ω ($f = 100$ Hz) is:

$$I_{m\max} = \frac{1}{2} \mu_{\max} I_m \quad (3)$$

The variable component of the averaged input current, i.e., the current generated by the AVI into the power circuit is closed through the battery, FC and filter capacitors C_1 and C_2 , which causes the pulsations of AVI supply voltage and, as a consequence, distortion of HFCGS output voltage.

Maximum AVI voltage ripple amplitude is determined by the equation:

$$U_{m\max} = \frac{1}{2} \mu_{\max} I_m \cdot \frac{r''_{FC} \| r_{BS}}{\sqrt{1 + 4(r''_{FC} \| r_{BS} \cdot C''_1 \| C_2 \cdot \omega)^2}}, \quad (4)$$

where r''_{FC} is the FCs' internal resistance reduced to AVI source voltage; r_{BS} is battery storage internal resistance; C''_1 is C_1 capacitance value reduced to AVI source voltage; C_2 is C_2 capacitance; $r''_{FC} \| r_{BS}$ and $C''_1 \| C_2$ are total resistance and capacitance of parallel-connected elements, respectively.

For real values of the FC and battery parameters, the following relations are valid:

$$r''_{FC} \gg r_{BS}; C''_1 \ll C_2, \quad (5)$$

And the $U_{m\max}$ calculated equation takes on the form:

$$U_{m\max} \approx \frac{1}{2} \mu_{\max} I_m \cdot \frac{r_{BS\max}}{\sqrt{1 + 4(r_{BS\max} C_2 \omega)^2}}. \quad (6)$$

The ripple factor of AVI supply voltage at 100 Hz frequency is determined by the equation:

$$k_U = \frac{U_{m\max}}{U_{BS\min}} \quad (7)$$

By substituting (7) into (6), we obtain an equation for calculating the required value of capacitor C_2 providing a given value of the ripple factor:

$$C_2 = \frac{1}{2r_{BS\max}\omega} \sqrt{\frac{1}{4} \left(\frac{\mu_{\max} I_m r_{BS\max}}{k_U U_{BS\min}} \right)^2 - 1}. \quad (8)$$

With AVI voltage ripple factor $k_U = 0.045$:

$$C_2 = \frac{1}{2 \cdot 2.6 \cdot 314} \sqrt{\frac{1}{4} \left(\frac{0.95 \cdot 24 \cdot 2.6}{0.045 \cdot 360} \right)^2 - 1} = 940 \mu\text{F}. \quad (9)$$

The capacitance value of $C_2 = 1000 \mu\text{F}$ is accepted.

According to (5) an insignificant part of the variable current component generated by AVI into the power circuit is closed through the FC and C_1 filter capacitor, and its value has no significant impact on HFCGS output voltage. The required value of C_1 capacitance can be selected from the following approximate ratio:

$$C_1 \approx \frac{r_{FC}}{r_{BS\max}} \cdot C_2. \quad (10)$$

Value of C_1 capacitance:

$$C_1 \approx \frac{r_{FC}}{r_{BS\max}} \cdot C_2 = \frac{0.88}{2.6} \cdot 1000 = 318 \mu\text{F}. \quad (11)$$

The values of the half-bridge AVI capacitances are taken slightly lower than the calculated ones and equal to $C = 2 \cdot C_1 = 470 \mu\text{F}$.

3.4. AVI Output Voltage Modulation Depth Calculation

AVI output voltage with PWM modulation depth is determined by the equation:

$$\mu = \frac{U_{m.out}}{U_{BS}}, \quad (12)$$

where $U_{m.out}$ is the amplitude of the HFCGS output voltage.

For a given value of the output voltage, the maximum required modulation depth $\mu_{\max}$ calculated value is:

$$\mu_{\max} = \frac{U_{m.out}}{U_{BSmin} - r_{BSmax} \cdot \frac{P_{out}}{U_{BSmin}}}, \quad (13)$$

where P_{out} is the power supplied by the HFCGS to the load.

At the effective output voltage value $U_{out} = 220 \text{ V}$ and output power $P_{out} = 3 \text{ kW}$, the maximum required calculated $\mu_{\max}$ value according to (13) is:

$$\mu_{\max} = \frac{\sqrt{2} \cdot 220}{360 - 2.6 \cdot \frac{3 \cdot 10^3}{360}} = 0.92. \quad (14)$$

Taking into account voltage drop across the open transistors and dead time of switching AVI transistors, the value of $\mu_{\max} = 0.95$ is taken.

3.5. Converter Output Voltage Boost Coefficient Calculation

This converter is made on the basis of the AVI with a high frequency transformer and matches relatively low fuel cell output voltage to battery voltage. Output voltage boost coefficient k_b is calculated in accordance with the equation:

$$k_b = D_{\max} k_{21} = \frac{U_{BSmax}}{U_{FCmin}}, \quad (15)$$

where $D_{\max}$ is the maximum relative duration of switching on converter transistors and k_{21} is the transformation ratio of converter matching transformer.

Coefficient k_b :

$$k_b = D_{\max} k_{21} = \frac{U_{BSmax}}{U_{FCmin}} = \frac{518.4}{57} = 9.1. \quad (16)$$

Setting the $D_{\max}$ value, the required k_{21} transformation ratio for the AVI bridge circuit is:

$$k_{21} = \frac{k_b}{D_{\max}}. \quad (17)$$

When using a half-bridge AVI in the converter, the transformation ratio value is calculated by the equation:

$$k_{21} = \frac{2k_b}{D_{\max}}; \quad (18)$$

$$k_{21} = \frac{2k_b}{D_{\max}} = \frac{2 \cdot 9.1}{0.8} = 22.8. \quad (19)$$

4. Simulation Modeling of Hydrogen Fuel Cell Generation System Operation Modes

An electromagnetic processes simulation modeling was carried out in MATLAB Simulink in order to test the operability of the proposed structure of the HFCGS.

The initial data for the modeling and the parameters of the HFCGS power circuit elements are given in Table 5.

Table 5. Parameters of the HFCS power circuit elements.

Parameter	Value
Load rated power P , kW	3
Power factor $\cos \varphi_L$	0.8
The effective value of the HFCS output voltage (single phase) U_{out} , V	220
Output voltage frequency f_{out} , Hz	50
FC rated power P_{FC} , kW	1
Battery voltage U_{BSmin}/U_{BSmax} , V	360/500
Converters clock frequency f_{CL} , kHz	20
Output L-C filter L , $\mu\text{H}/C$, μF	500/2
Capacities C_1 , $\mu\text{F}/C_2$ and C_3 , mF	235/1.0 and 2.0

The autonomous inverter and converter simulation model structures are shown in Figures 6 and 7, respectively.

Figure 6. Autonomous inverter simulation model.

Figure 7. Converter simulation model.

5. Results and Discussion

The simulation results are presented by the timing diagrams of the autonomous inverter (Figure 8) and the voltage converter (Figures 9–11).

Figure 8. Output AVI operation diagrams: (a) AVI output voltage; (b) Battery current; (c) HFCGS output voltage; (d) AVI output current.

Figure 9. Converter operation diagrams: (a,b) Converter output current and voltage; (c) FC output current; (d) Battery voltage.

Figure 10. Converter operation diagrams: (a,b) Converter output current and voltage; (c) FC output current; (d) Battery voltage.

Figure 11. Converter operation diagrams: (a) Converter output power; (b) Battery voltage.

Figure 10 shows the same converter operation curves as in Figure 9, but for a 0.5 ms time interval.

In addition to analyzing the instantaneous values of the current and voltages of the HFCGS's major components, an analysis of the harmonic components of the autonomous inverter output voltage has been carried out (Figures 12 and 13).

Figure 12. Spectral analysis of the HFCGS output voltage curve at $C_2 = 1000 \mu\text{F}$.

Figure 13. Spectral analysis of the HFCGS output voltage curve at $C_2 = 2000 \mu\text{F}$.

Figures 12 and 13 show that HFCGS output voltage contains a triple frequency component of 150 Hz in addition to the first frequency harmonic 50 Hz due to the AVI supply voltage amplitude modulation. The third harmonic amplitude at the selected values of C1 and C2 capacitances does not exceed 1–2% of the first harmonic.

The simulation results confirmed the considered HFCGS structure's operability, the reliability of its parameter calculations and the high quality of its output voltage.

6. Cost Estimation of Electric Power Generated by Hydrogen Fuel Cell Generation System

The levelized cost of energy (LCOE) was calculated to analyze the HFCGS's competitiveness as follows:

$$\text{LCOE} = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t + Carb + Util}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}, \quad (20)$$

where I_t is the annual investment (capital) costs, USD; M_t is the annual operating costs and maintenance costs, USD; F_t is the annual fuel costs, USD; E_t is the annual quantity of generated electric energy, kWh; $Carb$ is the annual cost of greenhouse gas emission (carbon footprint); $Util$ is the decommissioning charge after the HFCGS end-of-life; r is the discount rate; and $t = 1, \dots, n$ is the service life.

The following factors affect the cost per unit of electrical energy generated by a HFCGS:

- Hydrogen cost. The price of hydrogen may vary depending on the country of origin and the prices of fossil fuels in it, on the method of producing hydrogen (steam reforming of hydrocarbons, gasification of solid fuels, thermochemical decomposition of water using the energy of a high-temperature gas-cooled reactor (HTGR), electrolysis of water), its transportation (by pipeline or in cylinders) and its state (compressed or liquefied). The methods to produce hydrogen differ in the amount of costs for electricity, H₂O, natural gas, etc. In addition, each method of producing H₂ is characterized by a different amount of CO₂ emissions;
- The power of the hydrogen plant, its duty factor and its fuel consumption;
- Cost of greenhouse gas emissions and hydrogen plant utilization after the end of its life.

Table 6 provides a comparative analysis of various methods for producing hydrogen from the standpoint of specific energy consumption and carbon dioxide emissions.

Table 6. Comparative analysis of various methods for producing compressed hydrogen [25,26].

H ₂ Production Technology	Energy Consumption per 1 kg H ₂					CO ₂ Emission per 1 kg H ₂ , kg
	Natural Gas, m ³	Coal, kg	H ₂ O, kg	Electrical Energy, kWh	Thermal Energy, kWh	
Steam methane reformation	5–5.5	-	4–4.5	0.7–0.9	-	9.5
Coal gasification	-	7–7.5	9	0.7–0.8	-	21
Thermochemical water splitting based on HTGR	-	-	9–20	2–2.5	60–65	1.7
Electrolysis (from an electrical network)	-	-	9	55–60	-	41.1
Electrolysis (from a wind turbine)	-	-	9	55–60	-	-
Electrolysis (from a solar energy station)	-	-	9	55–60	-	-

To obtain liquefied hydrogen, it is necessary to spend three to seven times more electricity than to obtain compressed gaseous hydrogen. This also increases CO₂ emissions.

Table 7 provides an estimate of the energy resources cost, the specific investments for hydrogen production and the cost of transporting hydrogen fuel.

Table 7. Cost value estimation of hydrogen production [25–28].

Parameters	Value
Energy prices	
Natural gas, thousand m ³	111
Coal, USD/ton	112
Electric energy from a centralized source, USD/kWh	0.05
Specific capital investment in auxiliary energy sources	
HTGR, USD/kW (thermal power)	500
Solar power plants (SPP), USD/kW	1000
Wind power plants (WPP), USD/kW	500
Specific investment in elements of hydrogen production technology	
Electrolyser, USD/kW	740
Methane reformer, USD/kg H ₂	25–30
Hydrogen compressor, USD/kW	2000
H ₂ liquefaction unit, USD/kg H ₂ /day	1100
The cost of transporting hydrogen per 100 km	
Compressed pipeline, USD/kg	0.09
Liquefied by auto transportation in cryogenic tanks, USD/kg	0.04

The change in the cost of compressed hydrogen production for various technologies depending on the volume of hydrogen production is shown in Figures 14 and 15 [25,29,30].

Figure 14. Cost of hydrogen production for steam methane reformation (SMR) technologies, coal gasification and thermochemical water decomposition using HTGR.

Figure 15. Cost of producing compressed hydrogen for water electrolysis technologies based on electric energy from the network and renewable energy sources.

Thus, regardless of the volume of hydrogen production, the cheapest method is the method of steam methane reformation (SMR). The cost of hydrogen starts from 3 USD/kg H_2 at low capacities of SMR units, but with a capacity of more than 500 tons per day, it decreases to 1.7 USD/kg H_2 . Hydrogen production process by coal gasification at low productivity is strongly inferior to SMR, although at high productivity the coal option is practically equal to the SMR method. The method of thermochemical decomposition of water based on HTGR is applicable only at capacities of more than 35–50 tons H_2 per day. In this case, the cost of hydrogen turns out to be at least 3 USD/kg H_2 . The hydrogen production based on electrolysis is significantly inferior in cost indicators to the methods discussed above.

The cost of electrolytic hydrogen turns out to be much higher: from 7–8 USD/kg H_2 when operating on electric energy from the power system to 9–13 USD/kg H_2 when receiving electricity from wind power plants and up to 35–50 USD/kg H_2 when using photovoltaic converters as electricity source.

The specific costs of hydrogen transportation is shown in Figure 16. The liquefaction of hydrogen allows for reducing transportation costs by two to five times as compared to the option of compressed hydrogen. Likewise, hydrogen production and the cost of transport will depend on the pace of technology development and cost reduction [31].

Figure 16. Specific cost of hydrogen transportation in different forms by various transport.

Table 8 shows hydrogen cost estimation results obtained by Russian scientists compared to data from foreign publications. The total hydrogen cost values calculated by foreign researchers appears more optimistic for most technologies, as shown by Table 8 [25,27,31].

Table 8. Comparison of the hydrogen cost estimation results by Russian specialists with global data.

Hydrogen Production Technology		Hydrogen Cost, USD/kg H ₂	
		Estimates of Russian Experts	Estimation of Global Experts
compressed	SMR (natural gas)	1.2–2.7	1.8–3.5
	Coal gasification	1.9–2.3	1.6
	Thermochemical water splitting with HTGR	3.3–7.5	1.0–1.6
	Electrolysis (from an electrical network)	4.3–9.3	4.7
	Electrolysis (from a wind turbine)	4.4–25.9	3.9–7.1
	Electrolysis (from a solar energy station)	7.1–50	6.4–25.8
liquefied	SMR (natural gas)	2.9–4.4	3.8
	Coal gasification	3.8–4.1	4.5–5.1
	Thermochemical water splitting with HTGR	5.7–10.2	1.4–2.1
	Electrolysis (from an electrical network)	5.7–11.6	7.8
	Electrolysis (from a wind turbine)	6.0–31.3	4.5–9.5
	Electrolysis (from a solar energy station)	9.1–60.0	7.5

The initial data for calculating electric energy cost from the HFCGS are given in Table 9.

Table 9. Initial data for electric energy cost calculation.

Parameter	Value
Fuel cell power, kW	1
Hydrogen consumption, liters per minute	12
Hydrogen source service life, years	10
The total cost of hydrogen source experimental sample (with hydrogen generator), thousand USD	50
Distilled water cost, USD/m ³	18
Inflation rate, %	5.1

The investment costs consist of the HFCGS components cost (fuel cell, batteries, converters, hydrogen generator) and the cost of installation and commissioning. A hydrogen generator based on electrolysis with a 12 L per minute capacity serves as a source of hydrogen in the HFCGS experimental sample. An average of 1000 L of H₂ is produced from 1 L of distilled water according to its technical parameters.

The operating and maintenance costs of HFCGS include the cost of source services.

The costs of paying for greenhouse gas emissions and the costs of HFCGS decommissioning after the end of service life are taken as equal to 0.

LCOE = 1.17 USD/kWh is calculated substituting the values from Table 9 into Equation (20).

Figure 17 shows the LCOE for diesel, gasoline and hydrogen power plants of the equal capacity.

Figure 17. LCOE for diesel, gasoline and hydrogen power plants of the equal capacity.

7. Conclusions

The paper presents results of the structure development and choice of the optimal composition of a hydrogen generation system based on fuel cells and an accumulation system, as well as the research results of its operation modes.

The structural and functional diagrams of the hydrogen fuel cell generation system have been developed. One of the main elements of the HFCGS is fuel cells, the PEMFC type being the most suitable ones. They are characterized by a high rate of load change, ease of operation and the ability to work in a wide range of ambient temperatures. A sequential assembly of 12 LiFePO₄ 36 V 3.5 Ah batteries is defined as a buffer storage system for HFCGS, providing the required level of output power together with the fuel cell. The HFCGS power circuit also includes a converter and an output autonomous voltage inverter with PWM. The proposed scheme eliminates the need to install an additional converter for matching batteries and HFCGS voltages, which significantly simplifies the HFCGS, stabilizes its operation and improves the weight-size parameters.

The parameters calculation of the device elements has been performed—filter capacitors, converter, autonomous voltage inverter, fuel cells and batteries. The HFCGS simulation model was built to test the operability of the considered structure using the obtained parameters. The operation diagrams of the output autonomous voltage inverter, converter, as well as the spectral analysis of HFCGS output voltage curve have been constructed. It was found that the HFCGS output voltage contains the third harmonic and its value does not exceed 1–2% of the amplitude of the fundamental harmonic. The simulation results confirmed the operability of the considered HFCGS structure, the reliability of its parameter calculations and a high quality of output voltage.

The cost estimation of the electric power generation by the hybrid energy complex has been carried out. It exceeds the electric energy cost from power plants running on gasoline and diesel. It has been established that the electric energy cost is influenced by both the cost of energy source itself and the hydrogen cost. This allows us to identify two important directions in reducing the electric energy cost—improving the elements that make up a hydrogen source (fuel cells, converters, batteries, etc.) and development methods of more efficient ways of hydrogen production.

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