Theoretical Design of A Power Generator Powered by Hydrogen and A Fuel Cell

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Abstract— *The article deals with the theoretical design of a power generator using hydrogen combustion as an alternative source of electrical energy. The core of the article includes the design of a power generator utilizing the H-1000 XP fuel cell and MNTZV-60 hydrogen storage tanks. The design incorporates a hydrogen connection diagram, an electrical circuit diagram, a cooling loop, and the construction of a standalone power generator. The article also includes a theoretical analysis and verification of the system's functionality. The result is a power generator design capable of producing electricity in an environmentally friendly manner, with an emphasis on sustainability and the efficient use of alternative fuels.*

Keywords*— *hydrogen, power generator, metalhydride.

I. INTRODUCTION

Hydrogen is receiving increasing attention both in Europe and worldwide. The most important aspect is the fact that the energy conversion of green hydrogen in fuel cells produces no emissions into the atmosphere. It thus represents a potential solution for partially decarbonizing industrial processes and economic sectors.

In both mobile and stationary infrastructure, it is necessary to focus on alternative propulsion fuels and systems generated from renewable energy sources. Naturally, these systems will also contribute to the reduction of greenhouse gas emissions [1], [2].

Currently, two technological platforms appear to be long-term fuel sources: electromobility and hydrogen-based transport systems. One of the main challenges is increasing the safety of hydrogen fuel storage. At present, hydrogen is stored at extremely high pressures of 35–95 MPa, which poses significant safety risks. Solid-state hydrogen storage materials, primarily metal hydrides, have proven to be promising candidates for storage applications due to their high volumetric density, low operating pressures—ranging from 1 bar to 3 MPa, which is significantly lower than in high-pressure systems—and, last but not least, higher safety [3].

One of the devices in which hydrogen technologies can be implemented is the power generator. The aim of this article is to design a fuel cell-powered generator that uses hydrogen as the primary fuel.

II. DESIGN OF THE HYDROGEN CIRCUIT FOR THE POWER GENERATOR

The design of the hydrogen circuit for the power generator is based on the EC 79 standard, according to which a hydrogen circuit diagram was created, including all the necessary components. Fig. 1 shows designed hydrogen circuit of small power generator:

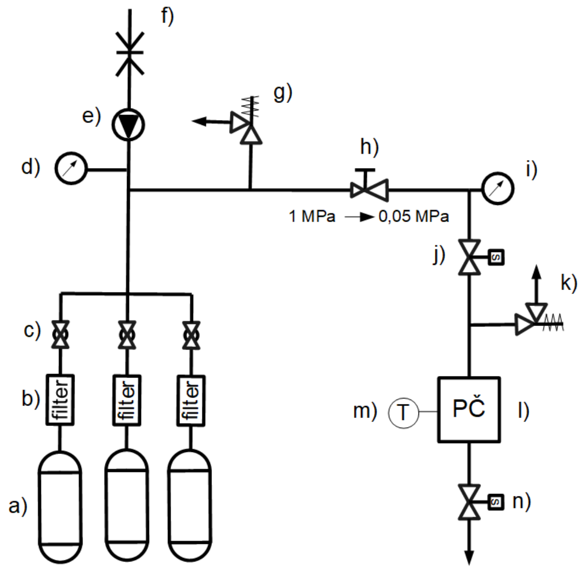

FIGURE 1: Hydrogen Circuit Diagram of the Power Generator

The components used in the network are as follows: a) metal hydride tanks MNTZV-60, b) filter, c) ball valves, d) analog pressure sensor, e) flow sensor, f) refueling nozzle, g) TPRD safety pressure valve, h) pressure regulator, i) analog pressure sensor, j) solenoid valve, k) TPRD safety valve, l) fuel cell, m) temperature sensor, n) solenoid valve.

The hydrogen distribution system consists of two branches: one for transporting hydrogen from the storage tanks to the fuel cell, and the other for refilling the hydrogen storage tanks. The individual components are connected by copper pipes with a diameter of 6 mm.

The branch for refilling hydrogen into the storage tanks consists of a refuelling nozzle that connects to the hydrogen distribution system. A flow sensor is located after the refuelling nozzle to determine the amount of hydrogen flowing into the storage tanks. Following the flowmeter, an analogue pressure sensor is installed for safety reasons and in accordance with standards, allowing the pressure in the system to be monitored.

The branch for transporting hydrogen from the storage tanks to the fuel cell starts with three MNTZV-60 tanks, which contain a metal hydride alloy branded Hydralloy© C5 from the German company GFe.

Each tank is equipped with a filter and a ball valve. The filter captures particles released from the Hydralloy© C5 metal hydride alloy, which exists in the tanks as a fine metallic powder with varying grain sizes. The grain size of the metal hydride alloy ranges from 0.1 to 2 mm, but after several cycles, it reduces to sizes between 100 and 5 microns. Significant particle size reduction occurs already during the initial activation of the alloy, so it is essential to place a filter at the beginning of the system. This prevents the passage of metal particles that could clog or damage valves, or even contaminate the fuel cell.

Behind the ball valve is a TPRD safety pressure valve, which serves a protective function in the distribution system. The TPRD safety valve is designed to activate at a predetermined pressure. If this value is exceeded, the valve opens to release hydrogen into the surroundings, and then closes again. This safety valve is intended to protect the storage section of the distribution system.

A pressure reducing valve is placed after the safety valve. It is essential in the system due to the higher pressure in the storage tanks. The pressure in the tanks is around 3 MPa, and this needs to be reduced to 0.05 MPa, as hydrogen can only be supplied to the fuel cell at such a pressure.

An analogue pressure sensor is located after the pressure-reducing valve. This analogue pressure sensor allows verification that the pressure-reducing valve is functioning correctly—specifically, it is used to monitor the pressure at which hydrogen is entering the fuel cell.

Next in the distribution system is a safety valve and a solenoid valve. Compared to the previously mentioned safety valve, this one has a preset lower pressure value, which corresponds to the pressure at which hydrogen may enter the fuel cell. If this pressure value is exceeded, the solenoid valve closes, thereby protecting the fuel cell.

The final component in this branch is a PEM fuel cell, specifically the Horizon 1000 XP model, which converts the chemical energy of the fuel into electrical energy. The basic parameters of the selected fuel cell are shown in Table 1. The fuel cell includes two temperature sensors: one for the fuel cell itself and one for ambient temperature.

Unreacted hydrogen and the by-product of the chemical reaction—water—are directed from the fuel cell into piping with a solenoid valve, and are then discharged into the surroundings:

TABLE 1
BASIC PARAMETERS OF THE SELECTED FUEL CELL HORIZON 1000 XP

dimensions (mm) (length x width x height)	264 x 203 x 104
Weight (kg)	4,9
Efficiency (%)	59
Hydrogen consumption (l·min^{-1})	12,5
Output voltage (V)	25-48

III. DESIGN OF THE ELECTRICAL CIRCUIT OF THE HYDROGEN POWER GENERATOR

Since the fuel cell generates electrical energy that needs to be delivered to an electrical appliance, it is necessary to design the electrical circuit of the power generator. The schematic of the power generator's electrical circuit is shown in Figure 2.

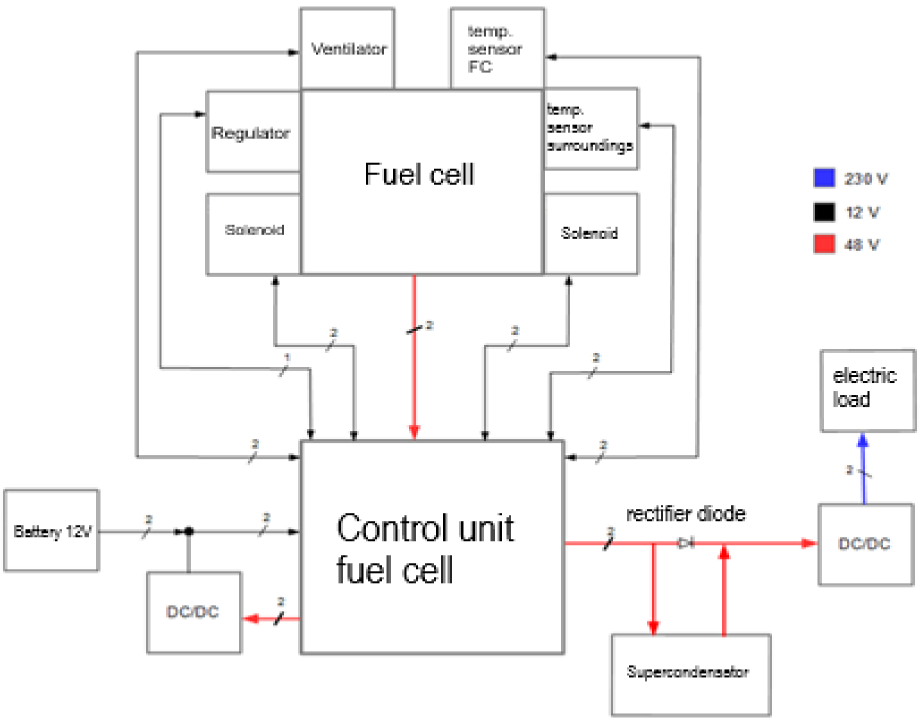

FIGURE 2: Schematic of the Electrical Circuit of the Power Generator

The electrical circuit begins with a starter battery with a voltage of 12 V. The starter battery's purpose is to power on the fuel cell control unit. Using the control unit, the PEM fuel cell H-1000 XP—as designed in Section 5.1—is subsequently activated. The value of the generated voltage and current depends on the output of the fuel cell. The fuel cell produces direct current (DC) voltage in the range of 25–48 V, but the electrical appliances powered by the generator require alternating current (AC) voltage of 230 V. Therefore, a power inverter must be included in the circuit to convert the DC voltage into AC voltage.

The circuit considers the use of the RSI 1KP-F31 inverter, designed by Absopulse Electronics, a company based in Canada. This inverter is used in railway transport vehicles. The parameters of this device meet the requirements for the proposed power generator.

A supercapacitor and a rectifier diode are placed between the control unit and the inverter. The rectifier diode is the simplest type of rectifier, characterized by low resistance in the forward direction and high resistance in the reverse direction. When current flows in the forward direction, there is a voltage drop in the range of 0.6 to 1.2 V. If the electrical appliance consumes all the energy generated by the fuel cell, the diode allows it to pass without restriction. However, if the appliance does not use all the generated energy, the diode redirects the excess to the supercapacitor, where it is stored. At the same time, the diode prevents reverse current flow back into the fuel cell, thus protecting the circuit from damage. In this system, the supercapacitor serves not only as an energy storage device for excess power but can also supply power during a short circuit, which could enable uninterrupted operation of the system without external power.

IV. COOLING SYSTEM DESIGN

The cooling system in a hydrogen power generator is a crucial component for the proper operation of metal hydride storage tanks, because during the absorption of hydrogen into the metal alloy structure, an exothermic reaction occurs, generating heat. This heat reduces the absorption capacity of the metal hydride alloy. Conversely, during desorption, the alloy becomes subcooled, which slows down the hydrogen release process from the metal structure. Therefore, thermal management of the proposed generator must be carefully addressed.

Before designing the cooling system, it is necessary to determine the cooling power that the cooler should be able to provide. The cooling power of the cooler will be determined from the following equation (1).

$$P_{CH} = \frac{Q_{MH}}{\tau_t} \quad \text{(W)} \qquad (1)$$

Where Q_{MH} is the heat generated during the storage of hydrogen in the metal hydride, and τ is the time within which the hydrogen should be stored in the tanks. A filling time shorter than 90 minutes is considered. The heat generated during the storage of hydrogen in the metal hydride alloy $Q_{MH0} = 1.01\ MJ{\cdot}m^{-3}$. Since the hydrogen distribution system contains three tanks, it is necessary to determine the volume of stored hydrogen and the heat generated during storage in these three tanks. The volume of stored hydrogen is calculated using equation (2).

$$V_{H_2} = \frac{m_{H_2}}{\rho_{H_2}} \quad (\text{m}^3) \qquad (2)$$

Kde: m_{H2} is the mass of hydrogen stored in the three tanks, amounting to 0.3 kg and ρ_{H2} is the density of hydrogen vapor, which equals 0.0898 $kg{\cdot}m^{-3}$ at a temperature of 20 °C and pressure of 101,325 Pa. Substituting these values into equation (2) results in a volume of 3.34 m^3. The heat generated during the storage of hydrogen in the metal hydride tanks is calculated using the following equation (3).

$$Q_{MH} = V_{H_2} \cdot Q_{MH0} \quad \text{(J)} \qquad (3)$$

By substituting into equation (3), the generated heat in the MNTZV-60 metal hydride tanks is found to be 3.36 MJ, and thus the required cooling power can be determined from equation (1). Substituting into equation (1), the cooling power amounts to 561 W.

For cooling, a heat exchanger Alphacool NexXxoS UT60 with an Alphacool ES 120mm fan will be used, which can provide a cooling capacity of 800 W. These are commonly used for cooling processors and electronic components.

Design of the Structural Layout of the Power Generator

This chapter focuses on the design of the structure itself. When designing the structure, it is necessary to consider the dimensions and weight of all the proposed components. Since some devices have fans, it is important to ensure unobstructed air circulation between the power generator and the surrounding environment.

The structure will consist of a frame welded from aluminum profiles and a galvanized sheet metal panel attached to the frame. The individual components will be gradually mounted onto the galvanized sheet metal. The entire frame will be clad with galvanized sheet metal. Galvanized sheet metal was chosen due to its properties, which include high corrosion resistance and abrasion resistance.

The frame of the power generator is 1000 mm wide, 1000 mm long, and 300 mm high. The frame consists of two different aluminum profiles. The wider profiles are placed at the bottom of the frame because the galvanized sheet metal will be mounted on them, and thus they will bear the greatest load. The profiles have a rectangular cross-section, with a height of 20 mm; the wider profiles are 40 mm wide, and the narrower ones are 20 mm wide. The wall thickness of the profiles is 1 mm.

Since power generators are typically used in remote locations where electrical infrastructure is not available, there is a need to transport the power generator to these sites. Thanks to its compact dimensions, transportation by vehicles should not be a problem. However, situations may arise where it is not possible to transport the power generator to the intended location by vehicle, for example, due to difficult terrain. For this reason, the frame of the structure will be equipped with a simple chassis to facilitate transport under these conditions. The chassis consists of two shafts mounted on radial ball bearings and two pairs of wheels.

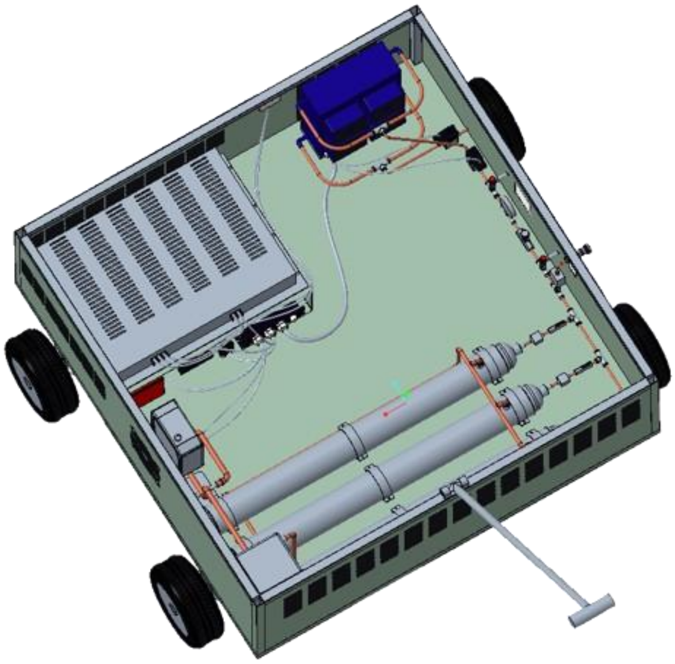

FIGURE 3: Model of the Designed Hydrogen Power Generator

The frame was subsequently strength-verified, with maximum stresses reaching 65.82 MPa, and the highest stress occurring at the point where the tanks are attached to the sheet metal. Plastic deformation will not occur anywhere since the yield strength of the material from which the sheet metal is made is not exceeded.

V. ENERGY BALANCE OF THE HYDROGEN POWER GENERATOR

In this section of the article, the amount of electrical energy produced, and the overall efficiency of the power generator will be determined. The amount of stored chemical energy is calculated using equation (5).

$$E_{chem} = m_{H_2} \cdot Q_{H_2} \tag{5}$$

Where the amount of stored hydrogen in the power generator is 0.3 kg and the combustion heat of hydrogen is 141.9 MJ.

$$E_{chem} = 0{,}3 \cdot 141{,}9 = 42{,}57\ MJ \tag{6}$$

There is 42.57 MJ of chemical energy stored in the tanks. This chemical energy is converted into electrical energy by the fuel cell. The efficiency of the fuel cell is 59%. The amount of electrical energy is defined by equation (7).

$$E_{el} = E_{chem} \cdot \eta_{\ PČ} \tag{7}$$

$$E_{el} = 42{,}57 \cdot 0{,}59 = 25{,}116\ MJ \tag{8}$$

The fuel cell produces 25.116 MJ of electrical energy. Subsequently, the converter transforms direct current into alternating current. The usable energy is given by equation (41), considering the converter’s efficiency of 80%.

$$E_v = E_{el} \cdot \eta_{\ M} \tag{9}$$

$$E_v = 25{,}116 \cdot 0{,}8 = 20{,}1\ MJ \tag{10}$$

The power generator outputs 20.1 MJ of electrical energy, which is equivalent to 5583.33 Wh. The overall efficiency of the power generator is determined according to equation (11).

$$\eta_C = \eta_{PČ} \cdot \eta_M \tag{11}$$

$$\eta_C = 0{,}59 \cdot 0{,}8 = 47{,}2\ \% \tag{12}$$

The overall efficiency of the power generator is therefore 47.2%. The maximum power supplied by the power generator is determined using equation (13).

$$P_{max} = \frac{E_v}{\tau_s} \frac{5583{,}33 \cdot 3600}{25\ 100} = 800\ W \tag{13}$$

VI. CONCLUSION

The article discusses the design of a power generator that uses a fuel cell to generate electricity from hydrogen. The selected fuel cell, the Horizon H-1000 XP, was chosen based on its satisfactory technical parameters, particularly its efficiency of up to 59%.

Hydrogen storage is implemented using three MNTZV-60 tanks filled with Hydralloy C5 metal hydride alloy. The system's energy balance confirms that the generator is capable of producing up to 20.1 MJ of electrical energy, with an overall system efficiency of 47.2%. The maximum available output power is 800 W.

The work also includes a structural strength analysis of the frame and the chassis shaft. Simulation results confirmed that the maximum stresses and deformations in various parts of the structure do not exceed the strength limits of the materials used, ensuring sufficient mechanical durability.

The next task involves the actual implementation of the hydrogen power generator in a real-world application.

ACKNOWLEDGEMENTS

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