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PROPOSAL OF UNMANNED GROUND VEHICLE POWERED BY FUEL CELL

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Abstract: The presented article deals with the design of an unmanned ground vehicle (UGV) with electric drive, using a fuel cell as a source of electricity. The introduction describes the principle of the fuel cell, followed by the design of the UGV propulsion system. The UGV design, taking into account specific technical parameters, is processed into a model in the simulation environment MATLAB / Simulink / Simscape. Simulation results are presented in graphical form of selected physical quantities over time.

Keywords: Unmanned ground vehicle; UGV; Fuel cell; MATLAB.

1 INTRODUCTION

Unmanned vehicles are widely used in the civilian and military spheres. They are used as carriers of various types of payloads. The determining parameter of their use is primarily the method of their drive. From the point of view of military use, the electric drive appears to be very promising, which has several advantages (high efficiency, high torque, quiet operation).

The problem with the electric motor, however, is the energy source - current batteries, especially based on lithium, still have a low energy density. This results in a short operating time during which such an accumulator is able to supply energy to the electric motor. The solution could be another energy carrier - e.g. hydrogen. Fuel cells are devices in which hydrogen is chemically reacted with atmospheric oxygen to produce water, heat and electricity. This paper deals with the use of a fuel cell as a source of electrical energy for an unmanned electric vehicle. The aim was to design the concept of such a vehicle.

2 FUEL CELL

A fuel cell is an electrochemical device that is capable of directly converting the chemical energy contained in a fuel into electrical energy. The result of the chemical reaction is direct current, water and waste heat.

They consist of two electrodes, between which there is a layer of electrolyte. There are two electrodes, a negative electrode - an anode and a cathode. The electrodes are coated on the surface with a layer of catalyst in the form of a precious metal, e.g. platinum or nickel. [1]

2.1 Polymer-electrolyte membrane fuel cells / proton exchange membrane (PEMs/PEFCs)

PEM fuel cells provide a high degree of energy density and their advantage is low weight and volume compared to other cells. They are the most used type of articles. They have a high energy density with respect to the area, up to 0.7 W.cm^{-2}. The membrane passes only positively charged hydrogen ions from the anode to the cathode, i.e. only in one direction. It does not let through reaction gases or electrons. The electrodes are porous and contain a platinum catalyst. Thus, only hydrogen and atmospheric oxygen are needed for them to function. [2]

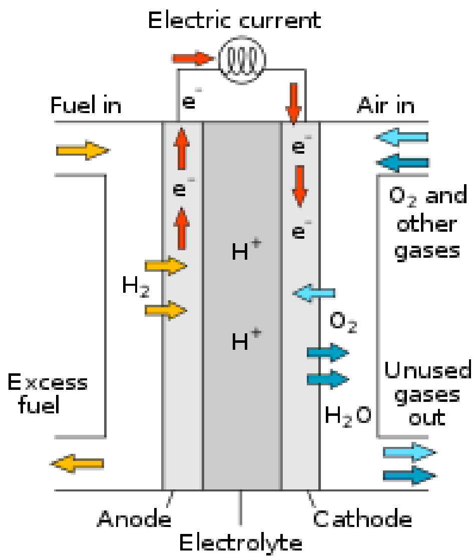

Fig. 1 Principle scheme of the fuel cell
Source: [3].

Hydrogen reacts at the anode, releasing electrons and becoming a positively charged ion. These H$^+$ ions travel through the electrolyte to the cathode, while the released electrons pass through an external circuit (this directed movement of the electrons creates an electric current). The electrolyte allows the passage of positively charged ions. [4]

Reaction at the anode:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

At the cathode, hydrogen ions react with electrons and oxygen. The product of the reaction is water.

Reaction at the cathode:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

These cells operate at relatively low temperatures, around 60 ˚C - 80 ˚C. Their efficiency is about 65 % at these temperatures. Working pressure is 100 - 200 kPa. The low operating temperature has the advantage of a rapid start to electricity generation. They are able to work even below freezing. The disadvantage is the need to use precious metals such as. platinum as a catalyst. [5]

3 DESIGN OF UGV

An important part of the vehicle is a logic element (energy management system), represented by a control system responsible for managing energy flows from individual sources (battery, fuel cell, supercapacitor).

3.1 Description of the EMS function

To start the vehicle, battery power is required to turn on the control, information and communication systems. It is also used to cover the input energy requirements during the start-up of the fuel cell or during the heating of the metal hydride tank in order to release hydrogen. Hydrogen begins to enter the fuel cell under pressure.

The energy of the battery is also used for the initial movement of the vehicle. After stabilizing the energy state in the initial phase of the vehicle's movement, the EMS switches the power supply to the fuel cell. From this moment on, the entire operation of the vehicle is ensured by energy from the fuel cell. In the case of excess energy produced by the cell, this energy is stored in the accumulator or in the supercapacitor. The order of charging will depend on the current state of charge of the battery and supercapacitor.

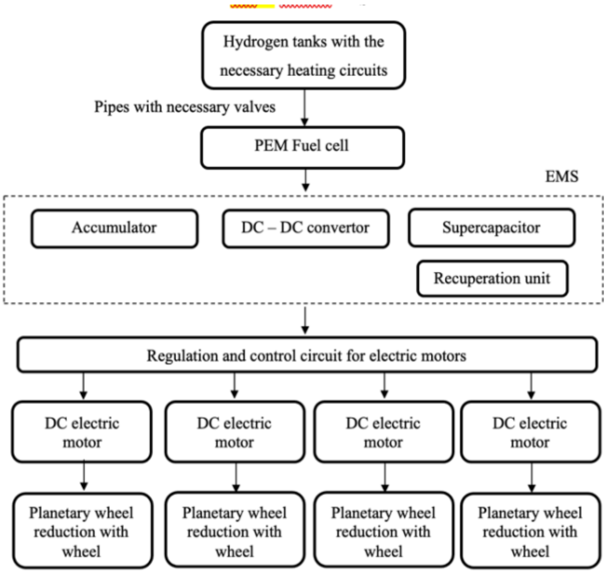

Fig. 2 Scheme of EMS
Source: authors.

If the vehicle overcomes a large incline or requires a short-term but enormous increase in energy, for example to overcome an obstacle, the energy stored in the supercapacitor will be used. On the contrary, recuperation is used during braking and the energy thus obtained is stored in the supercapacitor.

3.2 Vehicle propulsion

Due to the projected vehicle weight up to 35 kg, we choose components that are able to provide the vehicle for a given weight sufficient dynamic parameters. The vehicle uses a fixed wheel chassis without steerable axles. Each wheel is driven by its own DC motor. Turning is ensured by changing the speed of individual wheels.

3.3 DC electric motor and planetary gearbox

The vehicle has four Maxon DCX26L DC motors, which are powered by 12 V. The maximum long-term current is 4.5 A. The maximum electrical power of one DC motor is 40 W. According to the technical description, the maximum motor torque is 46.9 Nm.

The wheels are driven via a two-speed planetary gearbox, where the crown wheels are firmly connected to the vehicle structure. The drive from the DC motor is fed to the central wheel and then via the satellite carrier to the central wheel of the second gearbox. The wheel itself is directly connected to the satellite carrier. This ensures high torque on the wheels. The first planetary gearbox has a ratio of 7:1, the second 3:1. The overall gear ratio is 21:1. This slows down the engine speed and at the same time increases the torque on the wheel.

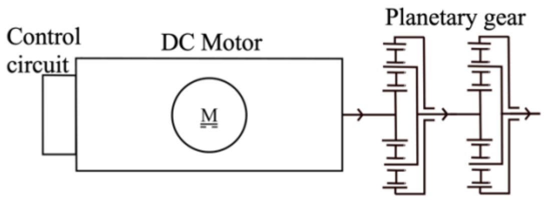

Fig. 3 Scheme of DC motor and planetary gear
Source: authors.

It follows from the theory of planetary gearboxes that the greatest torque is obtained from the planetary series just by the connection that we used, ie the central wheel as the driving element and the satellite carrier as the driven element.

To calculate the gear ratio, we must know the basic kinematic equation of the planetary gearbox, the parameter of the planet series α and the element that is driving and driven. The parameter α is calculated as the ratio of the radius of the crown r´ and the central r of the wheel, respectively as the ratio of the number of teeth of these wheels:

$$\alpha = \frac{r'}{r} = \frac{z'}{z} \tag{3}$$

The basic kinematic equation has the form:

$$n + n'.\alpha - n_o \cdot (1 + \alpha) = 0 \tag{4}$$

The variable *n* represents the speed of the central wheel, n_O the speed of the satellite carrier and n' the speed of the crown wheel. The calculation is based on the basic kinematic equation, where the constraints are determined based on the design. Our connections with the connection of the central wheel driven, the crown wheel firmly connected to the structure and the torque taken from the satellite carrier will have the shape:

$$n = n_{driving} \quad n_0 = n_{driven} \quad n' = 0$$

To calculate the gear ratio, we must adjust the basic kinematic equation to the form:

$$i = \frac{n_{driving}}{n_{driven}} \tag{5}$$

We substitute the formed bonds into the basic kinematic equation, which gives:

$$n_{ci} + 0 - n_{ný}\,(1 + \alpha) = 0 \tag{6}$$

After adjustment, we get the resulting value of the gear ratio:

$$i = \frac{n_{driving}}{n_{driven}} = 1 + \alpha \tag{7}$$

When using two planets in a row, their gear ratios are multiplied. The calculations show that to achieve a gear ratio of 7:1, the planetary line parameter must be $\alpha = 6$ and for a 3:1 gear ratio, the planetary line parameter must be $\alpha = 2$.

3.4 Hydrogen tank

We assume the storage of hydrogen in the form of a metal hydride. The tank is capable of holding up to 910 liters of hydrogen. Its diameter is 114 mm and height 287 mm. Weight up to 6.7 kg including hydrogen. The pressure of stored hydrogen is 1200 kPa. [6]

3.5 Fuel cell

The fuel cell used is of the PEMFC type, uses a solid electrolyte and is a low-temperature cell. The average temperature at which it operates is 35 °C. The cell used in our vehicle forms a complete set with control circuits, coolers and the necessary voltage stabilizers from HES. The start of the cell is within 30 seconds. The maximum power is 1300 W. The given power is sufficient to cover the maximum required current and voltage for the four DC motors and at the same time has a sufficient power reserve for losses caused by voltage and current converters and stabilizers. The power reserve is also used to power all on-board systems and sensors. Hydrogen consumption at maximum output is 16.5 liters per minute. With a volume of 910 liters of hydrogen in the tank, this cell is able to operate for approximately 55 minutes at maximum power. [7]

Fig. 4 Fuel cell from HES
Source: [8].

3.6 Accumulator

The battery type is a Li-ion from Samsung with the type designation 35E. One cell has a voltage of 3.6 V and a capacity of 3,500 mAh. Long-term current, which is a battery can be used 8 A, maximum peak up to 13 A. To cover our required power, we need 24 cells, where six cells will be connected in series. The cells connected in this way are then connected in parallel, thus creating 4 parallel branches with a voltage of 21.6 V and a capacity of 14 Ah. The power provided by batteries is 691 W. With a battery, we must also take into account cooling. The battery is able to supply the required amount of current while generating heat. It is advisable to use a fan before more efficient cooling. [9]

3.7 Supercapacitor

We use six Maxwell BCAP0650 supercapacitors with a voltage of 2.6 V and a capacity of 720 F for our vehicle. The supercapacitors are connected in series, thus providing a voltage of 16.2 V and a capacity of 120 F. The stored energy is a total of 3.96 Wh. To supply the four motors we have selected, we need almost 20 A of current at 12 V. If we take into account the 80% loss caused by the DC-DC converter through which the motor drive circuit is supplied, we get to the required current value of up to 25 A. If we need to provide energy for at least 30 seconds, we need approximately 2.3 Wh of stored energy. [10]

3.8 Model of vehicle

Table 1 shows the basic parameters of the individual elements that are in the vehicle. The overall dimensions of the vehicle provide enough space for all the necessary components.

Tab. 1 Dimensions and weights of the vehicle

	Type	Length [mm]	Width/ diameter [mm]	Height [mm]	Weight [g]
Vehicle skeleton	Plastic, composite	720	300 + 170 wheels	208	8 000
Fuel cell	PEM	194	127	193	1 800
DC motor	DC	-	26.2	60	170
Planetary gear	Metal	-	22	31.7	78
Accumulator	Li-ion	-	18,55	65.25	50
Metal hydride tank	Metal	-	114	287	6 700
Supercapacitor	Maxwell	-	60.4	51	160

Source: authors.

In the construction of the vehicle, we assume the maximum use of polymer composites, which will ensure low weight and sufficient strength. Holders for all necessary elements are part of the vehicle frame. The vehicle has a low side silhouette, only 208 mm. The designed vehicle together with the basic dimensions is shown from the profile in the following figure.

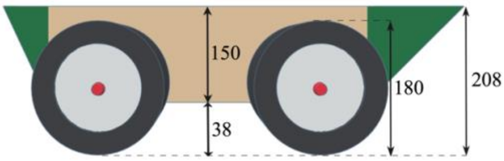

Fig. 5 Side view of UGV
Source: authors.

The wheels of the vehicle have a diameter of 18 cm and a thickness of 8.5 cm. This will ensure high vehicle throughput and sufficient traction. The large diameter of the wheels will provide enough torque to overcome obstacles.

The figure no. 6 shows the internal arrangement of the elements in the vehicle. The figure does not consider electrical circuits and pressure hoses and valves. However, they are taken into account in the design, so the model has enough space to store them.

The assumed weights of the individual elements in the vehicle and thus also the weight of the vehicle skeleton itself are in Table 2. The weight of the vehicle skeleton with all circuits and holders is approximately determined on the basis of the size of the vehicle.

Table 2 shows that the total weight of the vehicle will be 31.6 kg. When calculating the required power of DC motors and the required power of the fuel cell, batteries and supercapacitors, we used a vehicle weight of 35 kg. This has increased the weight usable for the additional components.

The power of the DC motor is 40 W. The power of the whole vehicle is 160 W. The fuel cell provides electrical power up to 1,000 W in the long run, at peak times up to 1,300 W. When calculating the required cell power, we calculated the efficiency of the DC engine itself, losses in the planetary and also in the control circuit. Losses will also be in voltage stabilizers and DC-DC converters. Therefore, we chose a cell with such a power reserve. We also confirmed the need for such a powerful cell in simulations, where weaker cells were not able to provide sufficient values of currents and voltages for the movement of the vehicle.

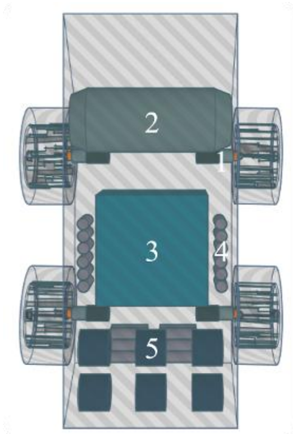

Fig. 6 Internal arrangement of the elements in the vehicle (1 – DC motor; 2 – Hydrogen tank; 3 – Fuel cell; 4 – Accumulator; 5 – Supercapacitors)
Source: authors.

Tab. 2 Total weight of the vehicle components

	Number of pieces in the design	Total weight [g]
Vehicle skeleton	1	19 000
Fuel cell	1	1 800
DC motor	4	680
Planetary gear	4	312
Accumulator	24	1 200
Metal hydride tank	1	6 700
Supercapacitor	6	960

Source: authors.

3.8 Increasing the internal volume of the vehicle

In the case of a requirement for a longer range of the vehicle, or if it is necessary to place more complex systems and sensors in the vehicle, which are more difficult to install, we can modify the design of the vehicle by adding a superstructure. Should we need to increase the service life, it is possible to add another hydrogen tank. This will increase the weight by 6.7 kg. This tank would be located above the rear axle, which would contribute to a better weight distribution. The superstructure itself weighs up to 1 kg. The vehicle profile will increase by only 50 mm, which means that the side profile of the vehicle will be 258 mm and the total weight will increase to 40 kg.

4 VEHICLE SIMULATION IN MATLAB

We performed the simulation in the Matlab program, in its Simulink toolbox, using Simscape blocks.

The overall simulation scheme contains several subsystems, in which there are individual controls and components. The subsystem facilitates orientation in individual branches.

As power source in simulation, we use fuel cell (model shown in Fig. 8) and accumulator (model shown in Fig. 9)

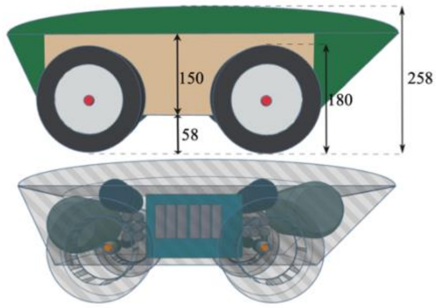

Fig. 7 Increasing the internal volume
Source: authors.

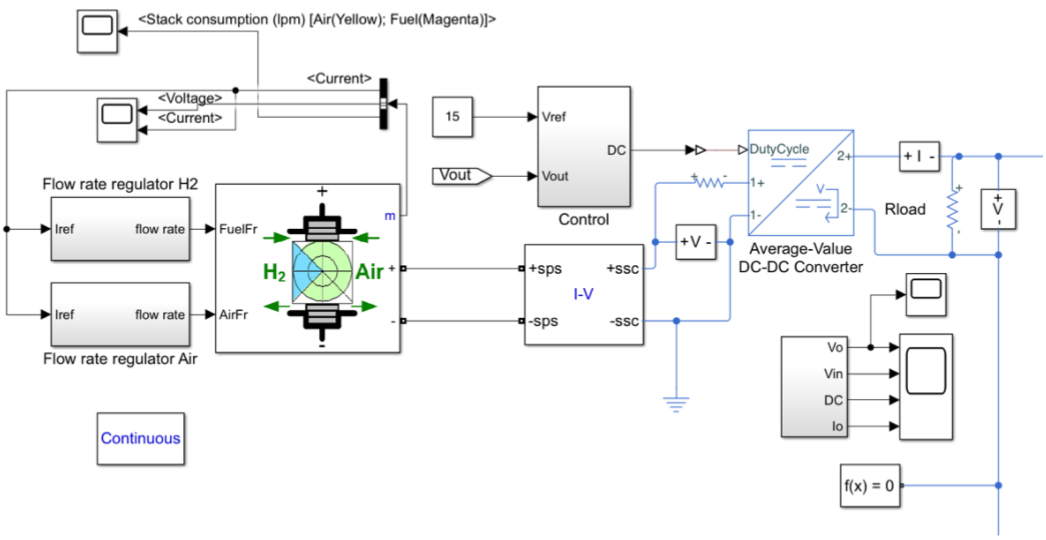

Fig. 8 Fuel cell vehicle powered model
Source: authors.

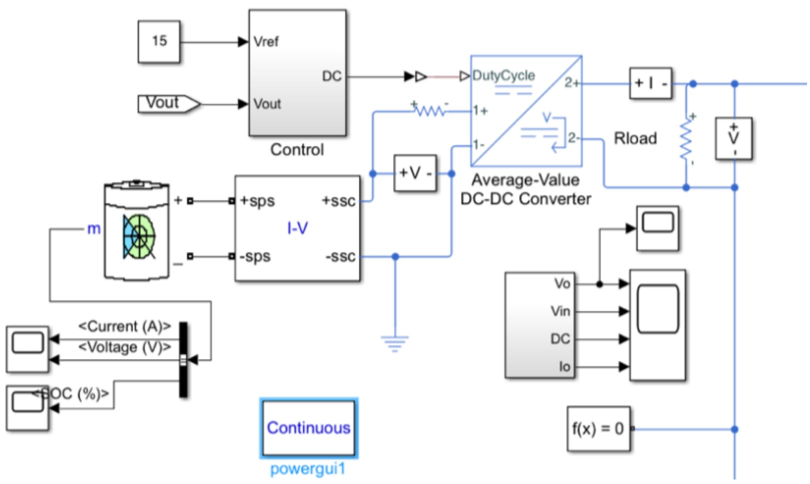

Fig. 9 Accumulator vehicle powered model
Source: authors.

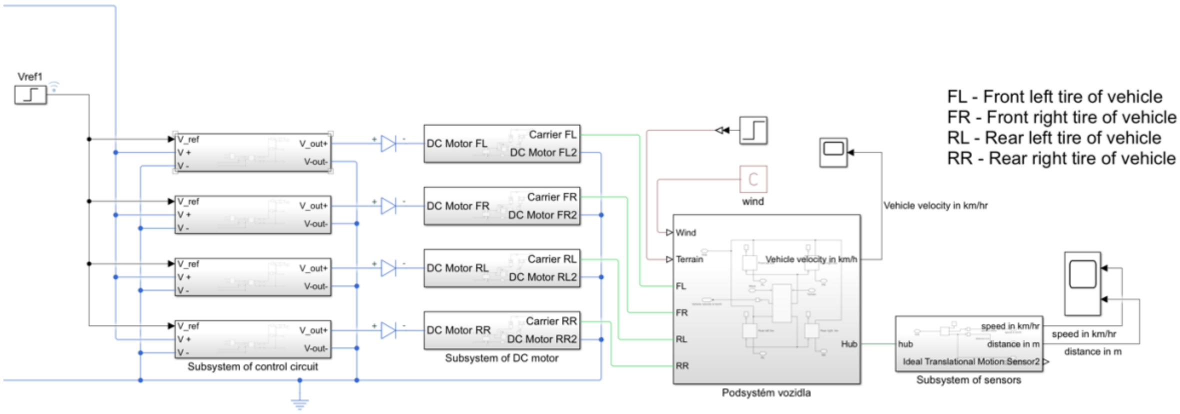

Fig. 10 Model of a 4-wheeled vehicle platform with electric motors and their regulators
Source: authors.

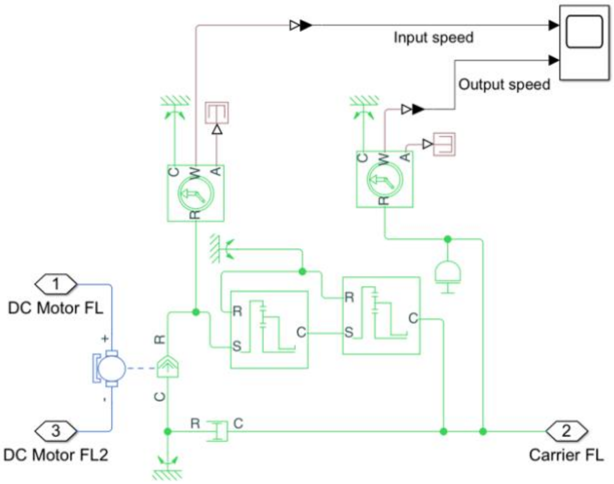

Fig. 11 Detailed view of the model of the DC motor - planetary gearbox subsystem
Source: authors.

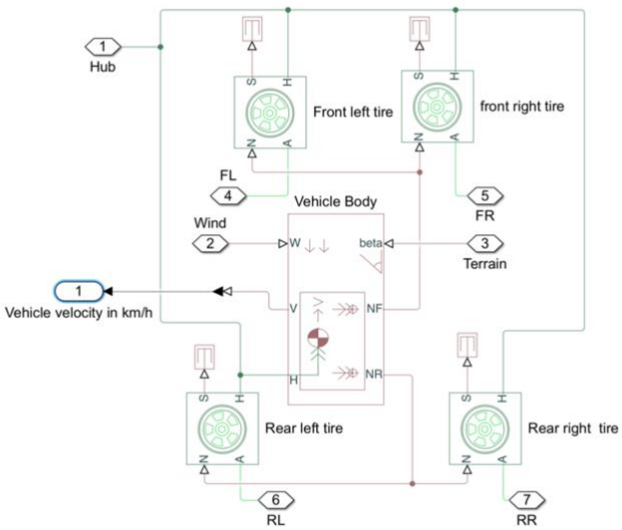

Fig. 12 Detailed view of the model of the vehicle's 4-wheel platform subsystem
Source: authors.

The parameters for each component were set by technical data sheets. The efficiencies of the converters are 80 %. We brought the simulation as close as possible to the real conditions and we set all resistances and inertia values as accurately as possible and as close as possible to the real values. We used a proportional integration (PI) controller to control individual DC motors according to referenced voltage, in our model simulated by source of signal, in Fig. 10 marked as "Vref1"

5 SIMULATION RESULTS

First, we will show a simulation of a vehicle powered by a fuel cell at 12 V, reducing the voltage to 6 V after 90 seconds. The simulation time is 180 seconds, which is enough time to stabilize the speed at a given voltage. Voltage changes are only made on the DC motor control circuit. Since the control system is connected, the fuel cell also responds to the change. From the fuel cell we get a voltage of 15 V. This is due to the reserve for powering the control circuit of the DC motor, which is realized through a DC DC converter with an efficiency of 80 %.

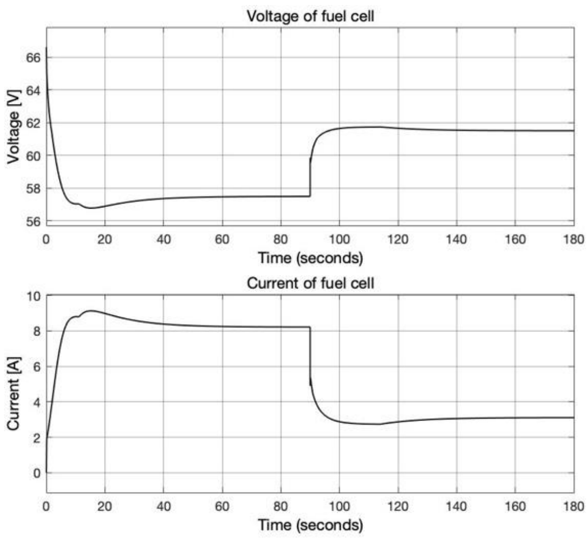

Fig. 13 Graph of FC voltage and current when changing power supply of motors from 12 V to 6 V
Source: authors.

When the vehicle is started and 12 V is consumed, the motors consume almost 9 A. The voltage drops from an initial voltage of 66 V to 57 V. At a steady speed, the current consumption is stabilized at 8 A and the voltage at 57.5 V. When the required voltage changes from 12 V to 6 V, the current consumption drops to less than 3 A. The voltage rises to 62 V.

At the start it is necessary to overcome a large torque and thus the current rises and as we have loaded the power source, its voltage decreased.

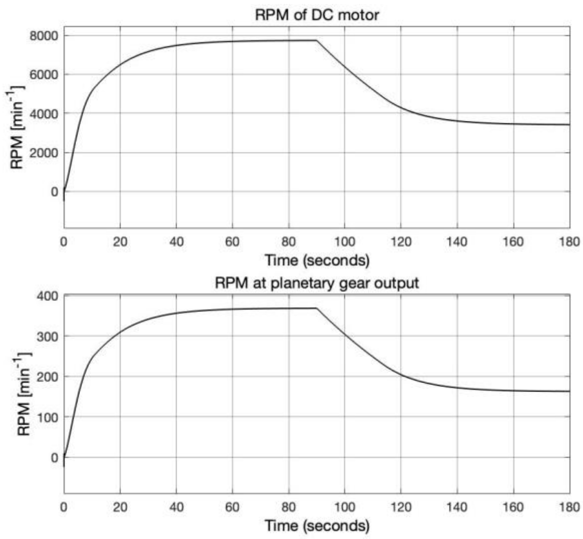

Fig. 14 Graph of gearbox speed when changing the supply voltage of motors from 12 V to 6 V
Source: authors.

The motor speed is at a voltage of 12 V and at a steady current of 4 A approximately 7800 min ^{1}, the output speed is reduced 21 times, approx. 371 min$^{-1.}$

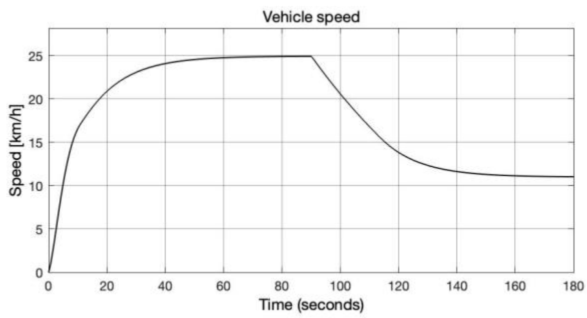

Fig. 15 Graph of vehicle speed when changing the power supply of motors from 12 V to 6 V
Source: authors.

The vehicle speed stabilized at 25 km / h at 12 V on the DC motor, which is the maximum vehicle speed. When changing to 6 V, the speed dropped to approximately 10.5 km / h. This change represents the functionality of the control circuit. By changing the speed of the individual wheels, we are able to turn.

Next, we will simulate the situation of changing the supply voltage from 6 V to 12 V. The input conditions are the same as in the simulation. The voltage at the output of the fuel cell is given by a DC-DC converter to 15 V, the voltage at the DC motor is initially 6 V and after 90 seconds it changes to 12 V.

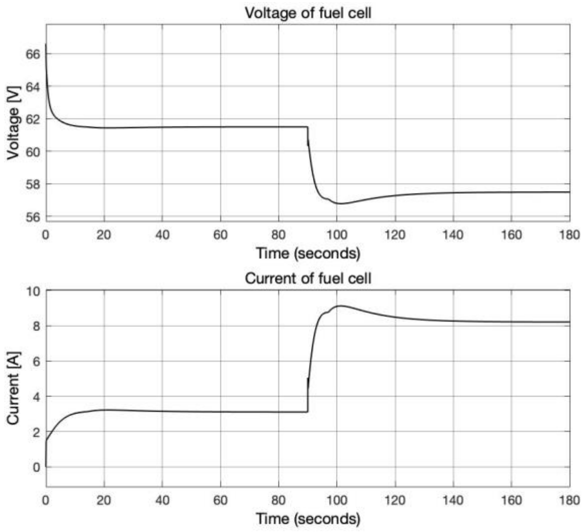

Fig. 16 Graph of FC voltage and current when changing power supply of motors from 6 V to 12 V
Source: authors.

When the vehicle is started and DC motors 6V and 3.2 A are consumed, the FC voltage drops from an initial voltage of 66 V to 61.8 V. When the required voltage changes from 6 V to 12 V, the voltage drops below 57 V and the voltage is maintained when the speed stabilizes. at 57.5 V. In 90 seconds, the current consumption rises to 9 A and drops to 8.1 A after stabilizing the speed.

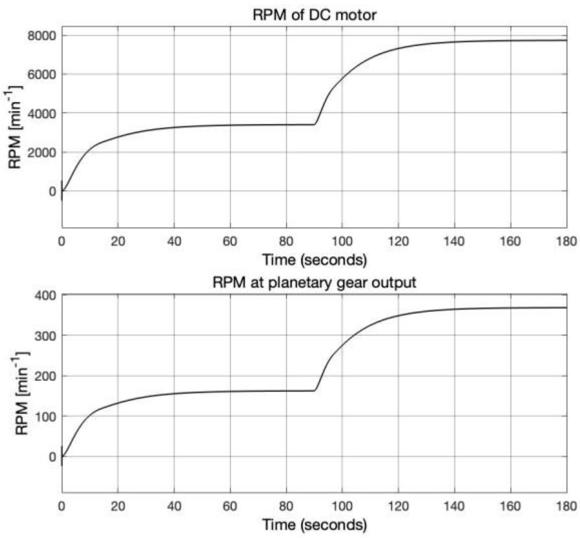

Fig. 17 Graph of gearbox speed when changing the supply voltage of motors from 6 V to 12 V
Source: authors.

The speed at the output and output of the gearbox changed as expected. At the beginning of the graphs, however, we can notice large changes in the speed of both the DC motor and the gearbox. This change is very short, in the order of tenths of a second. This fluctuation would probably not occur in real conditions.

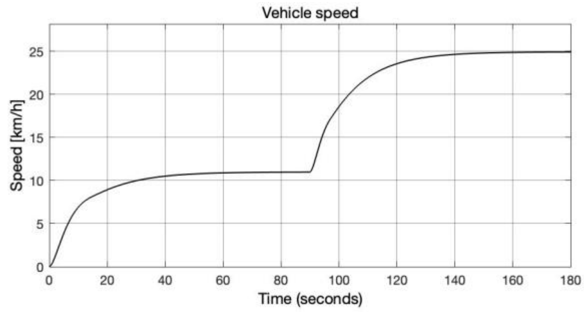

Fig. 18 Graph of vehicle speed when changing the power supply of motors from 6 V to 12 V
Source: authors.

The initial speed at 6 V stabilized at approximately 10.5 km / h, increasing to 12 V reached a maximum vehicle speed of 25 km / h.

6 CONCLUSION

It was verified by simulation that a vehicle weighing about 32 kg is able to reach a maximum speed of 25 km/h using a fuel cell - due to the capacity of the tank, for 55 minutes. As the vehicle does not move at this speed continuously, the operating time is extended even further. If a second hydrogen tank (with the same volume as the first tank) is also installed in the vehicle, the operating time will be doubled.

If operating time is a priority for the use of UGV, then a fuel cell-based energy source is a better solution than a lithium battery.

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