Comparative analysis of the hybrid power system topology for a high efficiency prototype vehicle

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Abstract. The paper presents a comparative analysis of three solutions of the power supply topology of a high-efficiency hybrid vehicle. The analysis was carried out for the Hydros prototype vehicle developed at the Lublin University of Technology for the Shell Eco Marathon competition. This vehicle is driven by an electric motor powered by two energy sources: hydrogen fuel cells and supercapacitors, allowing temporary energy buffering. Three variants of the mutual connection of the two energy sources to a single receiver were analysed, taking into account the voltage converter systems between the individual components of the system. The aim of these analyses was to determine the most energy-efficient solution.

1. Introduction

Currently, about 82.2 % of vehicles are driven by internal combustion engines fuelled by fossil fuels as an energy source [1]. The widespread use of internal combustion engines in all branches of transport is responsible for about 12 % of the emissions of greenhouse gases and air pollutants such as carbon dioxide and oxide, sulphur and nitrogen compounds and particulate matter, produced in fuel combustion [2,3].

This results in increased public awareness leading to ever stricter emission standards and a focus on finding new, environmentally friendly solutions. These works are focused, among others, on: optimisation of the design of currently used drives [4, 5], use of alternative fuels, including those from renewable sources [6, 7], and use of alternative drive sources such as electric motors [8, 9].

The first cars using electric motors for propulsion were built in the middle of the 19th century; however, this technology did not get much interest at that time because of the lack of a suitable source of electric power for mobile vehicles and an insufficient level of electrical engineering at that time [10]. Vehicles based on combustion of liquid fuels have gained a winning position and, despite their low efficiency, made possible to achieve much longer ranges and greater comfort of use than electric drives.

With the development of technology, there has been a renewed interest in the use of electric drives in cars. Modern materials have made it possible to construct energy-efficient electric motors and batteries of a sufficiently high energy density. However, batteries are still the biggest problem for electrically powered vehicles. Currently used batteries can accumulate about 300 Wh/kg [11], while petrol about 12 000 Wh/kg. This causes problems in obtaining satisfactory ranges of electric vehicles due to the necessity of using battery packs of very high mass.
Solutions are therefore being sought to alleviate this problem. Two approaches are being used: hybridisation of power trains and alternative methods of electricity generation.

The former one is hybrid cars which use an internal combustion engine and an electric motor. This solution combines advantages of both powertrains and significantly reduces emissions during use. In these systems, the combustion engine operates within its highest efficiency range, often under steady-state conditions, which results in low fuel consumption. Dynamic states are assisted by the electric motor which is also very often capable of regenerative braking. Such cooperation enables a very low level of energy consumption with an acceptable increase in vehicle mass [12,13].

The latter technology currently under strong development is renewable fuels. The most developed technology is fuel cells which use hydrogen to power electric cars. A fuel cell converts the chemical energy of a fuel into electricity. The reaction in the cell corresponds to reverse electrolysis. It involves separating an electron from a hydrogen atom and then combining hydrogen with oxygen (from the atmosphere) to form water. The reaction occurs at a low temperature (65-80 °C in PEM-type cells), without noise, and the cell itself contains no moving parts [14-17]. In simple terms, a hydrogen cell consists of three parts: an anode, a cathode and an electrolyte separating them. Hydrogen delivered to the anode is broken down into a positive ion and a free electron. The positive hydrogen ion is passed through the electrolyte to the cathode, while free electrons collect at the anode. Because of the potential difference between the anode and cathode, it is possible to use electron flow (electric current) in an external circuit. At the cathode, electrons combine with hydrogen ions and oxygen; the only by-products of the reaction are water and heat [18-20]. Hydrogen has an energy density of 38000 Wh/kg - much higher than petrol [15]. Due to its very low density, it requires, however, adequate storage - either high pressures or liquefaction at low temperatures. Current technologies allow ranges of about twice that of battery packs [21].

However, using a hydrogen cell only to power a vehicle can be problematic due to its non-linear current-voltage characteristics. The voltage produced at electrodes of the cell decreases as the current drawn from the cell increases. This relationship is not linear and is a major problem in systems operating under variable loads [15-18, 22-27].

Due to a wide variety of current consumption conditions for an electric motor in a vehicle, it is necessary to use an energy buffer which is capable of dissipating a lot of energy in a short period of time in the case of increased load (uphill, acceleration) and of being quickly recharged during lower energy demand. Supercapacitors are frequently used because of their high power density. Due to large differences in the electrical characteristics of the hydrogen cell, supercapacitors and the energy consumer - the electric motor, it becomes important to choose the right system architecture and control methods for its individual components to ensure optimal energy efficiency.

The aim of the paper is to analyse possible topographies of a propulsion system based on fuel cells and supercapacitors to minimise energy consumption by the vehicle. The article focuses on the construction of the propulsion system of the prototype vehicle of "Hydros" prepared by students from the Students Research Club “Aircraft Propulsion” from the Lublin University of Technology for the Shell Eco Marathon competition.

2. Description of the test object
The research object is Hydros - a prototype hydrogen-powered vehicle, built by students who are members of the Students Research Club “Aircraft Propulsion” at the Department of Thermodynamics, Fluid Mechanics and Aircraft Propulsion at the Faculty of Mechanical Engineering of the Lublin University of Technology. This vehicle is designed to minimise fuel consumption and energy losses. The main purpose of its construction is to take part in the international Shell Eco-marathon [30]. This is a competition where teams from all over the world can compete to create a vehicle with the lowest possible energy consumption. Hydros was built to compete in the prototype vehicle category, in the hydrogen class. A summary of the main features of the vehicle is presented in Table 1.
Table 1. Technical specifications of the Hydros vehicle.

| Specification            | Value          |
|--------------------------|---------------|
| Length                   | 2920 mm       |
| Height                   | 625 mm        |
| Width                    | 680 mm        |
| Axle base                | 1600 mm       |
| Front wheel base         | 620 mm        |
| Mass                     | 37 kg         |
| Coefficient of drag $C_x$| 0.106         |
| Hydrogen cell power      | 300 W         |
| Engine type              | BLDC          |

The monocoque shown in figure 1 was designed to achieve the best possible aerodynamics with its as much as possible minimised weight. For this reason, carbon fibre reinforced with aluminium spacers in the areas of highest load was selected as its main construction material. These are mostly two layers of carbon fibre mats bonded by resin. This material guarantees very high strength without a significantly increased weight of the vehicle, a key aspect of Shell-eco Marathon competitions. The process of manufacturing the monocoque was carried out in an autoclave by the team members using equipment from the Lublin University of Technology.

![Figure 1. External view of the Hydros prototype vehicle [own photo].](image)

Hydros is a three-wheel vehicle with a 2+1 construction (2 front swivel wheels + 1 rear wheel connected directly to the drive system). The heart of the drive system is a brushless BLDC electric motor - Maxon EC 90 flat of a power of 260 W [29]. The motor operation is controlled by a dedicated Maxon ESCON 50/5 controller that is supplied directly from the vehicle electrical system. The motor itself is powered by two sources: a fuel cell and a supercapacitor battery that is connected to the rear drive wheel by a chain. The arrangement of the components making up the drivetrain is shown in figure 2.
The main power source for the vehicle is a hydrogen cell capable of converting the chemical energy of hydrogen into electricity. The selected cell is Horizon H300 type PEM (Proton Exchange Membrane) with a rated power of 300 W [28] that can operate at low temperatures and in any geometrical orientation. The basic elements of this type of cells are: an anode, a cathode and an electrolyte forming a membrane. In addition to the cell itself, the power supply system (schematic diagram is presented in figure 3) also comprises: a 0.4 l gas cylinder, a solenoid valve acting as a safety device, a flow meter registering gas consumption, and a hydrogen pressure regulator.

**Figure 2.** Vehicle drive system [own photo] (1) - supercapacitors, (2) - motor, (3) – fuel cell.

**Figure 3.** Schematic diagram of the power supply system.
3. Power system topologies
The vehicle's propulsion system consists of two independent power sources and one power consumer. A hydrogen fuel cell is used as its main propulsion source. The second source is a package of supercapacitors and is also an energy buffer in transient states. The only consumer is an electric motor controller. Due to the fact that all these elements have their own operating characteristics, differing as to the requirements and points of optimum operation, it is necessary to combine them in an appropriate topology to achieve minimum fuel consumption. Therefore, three topologies were analysed, as described below:

3.1. Topology 1: Self-regulating parallel circuit

![Figure 4. Schematic of the self-regulating power system.](image)

The self-regulating power system is characterised by its simple design. It consists of a fuel cell and supercapacitors connected directly to the DC motor without any system regulating the energy flow. The supercapacitors in the system serve as an energy buffer and the size of their pack is dependent on the operating voltage of the system. The biggest advantage of this system is its simple construction and its self-regulation. No additional devices are required to regulate the voltage on individual elements, as this regulation is performed independently based on the characteristics of the fuel cell (figure 5).

The disadvantage of this topology is its low efficiency because the fuel cell operates in different states. In this case, the operating point of the cell changes automatically depending on the current consumption of the engine power system and the state of charge of the capacitor package. An increase in load causes the voltage on the cell to drop, which lowers the voltage supplying the motor and reducing its efficiency. A decrease in the demand for energy causes an increase in the voltage on the cell increasing the voltage difference between it and the supercapacitors (which leads to their charging). The system must therefore be voltage matched in such a way that in the case of very low current consumption, the voltage on the cell does not exceed the values allowed for powering the other systems, especially the supercapacitors. It should be noted that most of these circuit elements operate with the highest efficiency at the rated voltage and any deviation from this value causes a decrease in their operating efficiency. Therefore, self-regulation in this case will lead to the system operating practically all the time under suboptimal conditions.
Figure 5. Voltage vs. the current affecting the PEM fuel cell (in steady-state of operation) created during the testing (measurements) compared with the characteristic developed by the manufacturer [31].

3.2. Topology 2: Cell and supercapacitors connected via DC/DC converters

The parallel power system has a separate voltage rail matched to the nominal voltage of the DC motor. The system consists of a fuel cell hydrogen fuelling system (composed of a cylinder filled with hydrogen, a hydrogen pressure regulator, a safety valve), two inverters to which the fuel cell and the supercapacitor package are connected. The converters enable all elements to operate at their optimum operating points by adjusting the output voltage to the needs of the electric motor without imposing an input voltage from the energy sources. By adjusting the output voltage from the fuel cell system, we can simultaneously adjust the amount of power generated by the system and thus keep energy production constant for maximum efficiency. A second bidirectional inverter allows the supercapacitor battery to be charged by the energy drawn from the voltage rail at idle. In the case of a high load of the DC motor, it serves as an energy buffer. Moreover, the use of such an inverter makes it possible to select the optimum capacitor pack.

Figure 6. Schematic of the parallel power supply system with the separate voltage bus.
Due to the specific design of capacitors, they have a high capacity, but at low voltage (2-3V). Creating a package of supercapacitors requires connecting them in series to increase the voltage, which results from formula (1):

\[ U_{c\text{max}} = U_{c1} + U_{c2} + U_{cx} \]  

(1)

where:

- \( U_{c\text{max}} \) – maximum voltage of the supercapacitor package,
- \( U_{c1} \) – voltage of supercapacitor 1,
- \( U_{c2} \) – voltage of supercapacitor 2,
- \( U_{cx} \) – voltage of supercapacitor x,

but its capacity decreases, as follows from the formula (2),

\[ \frac{1}{C_z} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_x} \]  

(2)

where:

- \( C_z \) – resultant capacity,
- \( C_1 \) – capacity of supercapacitor 1,
- \( C_2 \) – capacity of supercapacitor 2,
- \( C_x \) – capacity of supercapacitor x.

When identical supercapacitors are connected in series, the maximum operating voltage of the entire system equals the sum of the voltages of all the capacitors. The resultant capacitance is equal to the capacitance of a single capacitor divided by the number of capacitors. If two supercapacitors of 1000F capacity are connected in series, their resultant capacitance will be 500F. This is a disadvantageous phenomenon because less energy can be obtained from them at the load of the DC motor. The use of an inverter makes it possible to lower the required voltage of the set, and thus use more capacity to store energy with fewer supercapacitors in the package. This will not only increase the efficiency of the system, but also reduce its weight. Thanks to the use of an inverter which allows the voltage to be increased (or decreased) to the nominal operating voltage of the DC motor, the system can operate with higher efficiency than in the previously discussed variant. The disadvantage of this system is the complicated topology of the system which requires additional elements and their special control to achieve the desired effects. In this case, the system is not self-regulating and requires an additional supervisory system, especially to maintain an adequate energy flow (supercapacitor charging). The cost of the system also increases.

### 3.3. Topology 3: Serial Layout

The serial power system consists of a fuel cell to which a supercapacitor package is connected using a converter. Power to the engine is supplied directly from the supercapacitor system. The advantage of such a system is the possibility to obtain the highest efficiency of fuel cell operation by maintaining a constant voltage at the optimum point of its operation. This is possible thanks to an inverter which will maintain a constant operating voltage on the cell despite a voltage drop on the pack. It will also allow the amount of energy drawn from the fuel cell to be regulated, which compensates for spikes in power consumption. This will also increase the efficiency of the cell. Dynamic changes in electrical load are done by supercapacitors which serve as an energy buffer. It should be noted, however, that if the supercapacitor battery is discharged and the voltage on it drops, the DC motor will start to lose power. So, it is important to choose a cell that will provide a reserve of energy to prevent the voltage from
dropping below the nominal value of the motor. Another solution to this problem is to correctly manage the energy stored in the pack so as not to discharge it below the nominal value of the DC motor. This requires a large supercapacitor package and thus an increase in the weight of the system. This is a disadvantage of this system adversely affecting the efficiency of the system. The problem is also obtaining an appropriate supply voltage for the motor. The greater the number of supercapacitors connected in series in the package, the smaller the capacity of the battery, so the energy buffer depends on the voltage of the DC motor.

4. Analysis

Analysing the above presented topologies, it must be stated that a direct answer as to which of them is the best one is not possible without assessing their suitability in a specific vehicle design and choosing an appropriate power management strategy. The advantages and disadvantages of these topologies are shown in Table 2.

The self-regulating system (topology 1) is the simplest one to construct, does not generate additional losses due to indirect regulators and is made out of cheap components, but the regulation here is limited by the current-voltage characteristics of the fuel cell, which means that the higher the current consumption, the higher the voltage drop on the cell causing potential differences between the supercapacitor pack and the fuel cell. This causes the system to operate in sub-optimal conditions, not reaching its maximum efficiency. This is quite a compromise solution. Higher efficiency of energy conversion is obtained in topologies 2 and 3. Both topologies enable higher hydrogen-to-electricity conversion efficiency by allowing the fuel cell to operate at much better operating points. The losses recorded on additional elements (converters and starter systems) reduce this gain, but, in general, the balance of changes should be positive. Such a solution, however, is burdened with a significant increase in the degree of complexity of the system and the necessity to introduce supervisory systems to regulate the flow of energy inside the system. All this entails quite a significant increase in costs (especially in the case of topology 2) due to the use of a larger number of additional elements which are not affordable due to their complexity and capabilities, although this is compensated by the high quality and efficiency of the entire system.

Another issue is how to correctly select supercapacitors so that their capacity and nominal voltage would be appropriate. In the case of topologies 1 and 3, it is necessary to select a package of supercapacitors for the required voltage of the motor supply, which involves a loss in their capacity. This will require a large (and therefore heavy) package, which generates a further decrease in the efficiency of the system (entire vehicle). Such a system will need more energy if its total mass is larger and its dynamics will deteriorate. In the case of topology 2, it is possible to use a much smaller package, which will reduce both cost and weight of the system.

![Figure 7. Schematic of the series power supply system with an inverter.](image-url)
|                | Topology 1 | Topology 2 | Topology 3 |
|----------------|------------|------------|------------|
| Regulation     | Self-regulating | Requires adjustment of 2 inverters | Requires adjustment of 1 inverter |
| Number of components | Smallest | Highest | Medium |
| Cost           | Low        | Highest   | Medium |
| System efficiency | Low     | Highest   | Medium |
| System weight  | Medium     | Medium    | Medium |

5. Conclusion
Summarising the analyses carried out, it can be stated that:

1) The use of a self-regulating system (topology 1) is the simplest solution, but has the lowest efficiency of the topologies analysed;
2) The parallel system uses two converters on the supply line (topology 2) to regulate the engine supply voltage by drawing energy from a fuel cell connected in parallel to a package of supercapacitors with additional control systems (converters) that enable the highest system efficiency. However, it is a more complicated solution because requires a special design of the control system and a well-chosen control strategy adapted to requirements of vehicle trajectories.
3) The series system with a single converter between the fuel cell and the supercapacitor battery (topology 3) is simpler to construct than the parallel system and also optimises the fuel cell's operation. This reduces the losses generated by the intermediate components but increases the efficiency of the cell. However, the lack of a circuit to stabilise the output from the supercapacitor battery pack introduces a capacity limitation on the engine supply voltage.

The choice of the topology appropriate for the vehicle under analysis must, therefore, be based not only on the above-mentioned analyses, but also on analyses of vehicle mass, space to install systems, and the expected strategy of electric energy flow control. It should be pointed out, however, that the choice should be made between topology 2 and 3. Topology 3 should be chosen for a heavier vehicle with a large space for accessories, whereas in other cases despite higher construction costs of the system, topology 2, only if correctly tuned and installed in a vehicle that will have an opportunity to make use of its advantages, seems to be a better solution to achieve the best results.

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