Performance Analysis Of Hybrid Fuel Cell Electric Vehicle With Energy Storage Elements Using Optimization technique

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Abstract— This paper discusses the design and implementation of a hybrid power source that combines a fuel cell with a battery or supercapacitor. The fuel cell serves as the primary power source for the driving system, with the battery or supercapacitor serving as an auxiliary power source. When compared to electric vehicles purely driven by a fuel cell, this has the advantage of storing regenerative energy in a battery or super- capacitor during slowdown and transferring it back to the drive system during acceleration. The research compares various energy storage systems such as fuel cells, batteries, and supercapacitors, and then examines several architectures of fuel cell-based electric vehicles. After that, a standard topology is used.

Keywords—*hybrid power source; fuel cell; battery; supercapacitor; conventional topology; floating voltage topology.*

I. INTRODUCTION

With the expansion of human environmental awareness on sustainable development, the same advancement occurs in the automobile business as time passes. The creation of efficient, clean, and safe transportation has been stressed in recent decades in transportation research and development [1]. Manufacturers are constantly developing more energy-efficient, environmentally friendly automobiles, eventually replacing internal combustion engine (ICE) vehicles with electric vehicles (EVs). In the United States, Europe, Asia, and other nations, electric vehicles are gradually replacing conventional vehicles, resulting in a large market share demand in transportation.

Hybrid electric cars (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) are the three primary categories of EVs characterised by the degree of electrification [2]. (BEVs). Because HEVs and PHEVs utilise both gasoline and electricity, their exhaust contains a lot of greenhouse gases (GHGs) and other harmful pollutants, whereas BEVs can reduce GHG emissions to some extent but not completely [3]. As a result of the great energy efficiency and exceptionally low emissions of the fuel cell (FC), renewable energy power transportation allows fuel cell electric vehicles (FCEVs) to become a superior alternative, gaining considerable interest for the future fossil fuel free traffic sector.

FCEVs are an excellent method to achieve both a low-carbon society and economic prosperity. The most basic structure is that only the FC is used to move the vehicle, and that because to the FC's low power density, a large volume and weight are required to provide the power need throughout the course of a driving cycle. Furthermore, the FC has been subjected to a hostile environment, which includes all transient load changes and no-load idle states, resulting in substantial deterioration and a reduction in the FC's lifetime [4]. The main issue is that the energy flow in this topology is unidirectional, which means that no component in the system can absorb the regenerative energy generated during the deceleration and braking process, resulting in the failure of the system.

To address these difficulties, an energy storage system (ESS) is required to handle peak power while also preserving regenerative energy. As a result, numerous energy storage technologies for EVs have been developed, including lithium-ion batteries [5], supercapacitors [6], flywheels [7], and super-conducting magnetic energy storage [8]. The lithium-ion battery has the best energy density (about 70 200Wh/kg) and the lowest capital cost per unit energy, but its power density (around 150 500W/kg) is lower than the others. The supercapacitor, on the other hand, is thought to offer the highest power density (1000–10000W/kg) and the lowest capital cost per unit power [9]. Because of these factors, lithium-ion batteries and supercapacitors are more extensively utilised in electric vehicles (EVs), which can fully use the advantages of high-capacity batteries.

This research compares EVs with an FC fused with a battery or a supercapacitor, in which the FC serves as the primary energy source and the battery or supercapacitor serves as a backup power source. The remaining parts are organised as follows. In part II, a full comparison of FC, battery, and supercapacitor is offered, along with advantages and limits. Part III compares the structures of fuel-cell-based electric vehicles, as well as two hybrid power source topologies and the energy management system. Part IV presents simulation results and analyses based on these two topologies, followed by conclusions in the last section.

II. ENERGYSTORAGE TECHNOLOGIES

One of the most important components of electric vehicles is the energy storage device, and Fig. 1 compares current energy storage methods in terms of specific energy and specific power [10]. Because the FC has the highest energy density but the lowest power density, it must be hybridised with a battery or a supercapacitor to properly utilise the device's energy density and power density. In comparison to the supercapacitor, the battery has a higher energy density but a lower power density. However, due to the limitation of the charging current, the charging period of the battery is fairly long, taking many hours; in contrast, the supercapacitor may be fully charged in a matter of seconds, since the supercapacitor can tolerate huge charging current in a very short time.

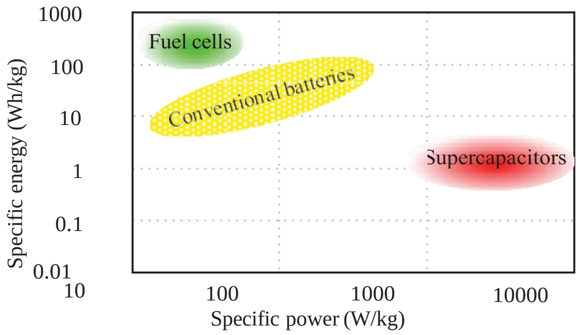


Fig. 1 Energy storage technologies

Figure 2 depicts some significant lithium-ion battery and supercapacitor properties, with values normalised to the maximum [11]. When the energy per dollar and the power per dollar are employed, it means that the higher the number, the more cost-effective and appealing it is.

Supercapacitors also have the disadvantages of a rapid self-discharging rate and a high power cost. The longer a supercapacitor is left after it has been fully charged, the more energy it loses. In terms of supercapacitor cost, it is likely to drop dramatically in the future, which would not be a problem for supercapacitors used in commercially produced EVs.

As a result, FC, lithium-ion battery, and supercapacitor all have benefits and drawbacks, and combining them is a wonderful approach to get the most out of each.

III. HYBRIDIZATION OF FUEL CELL

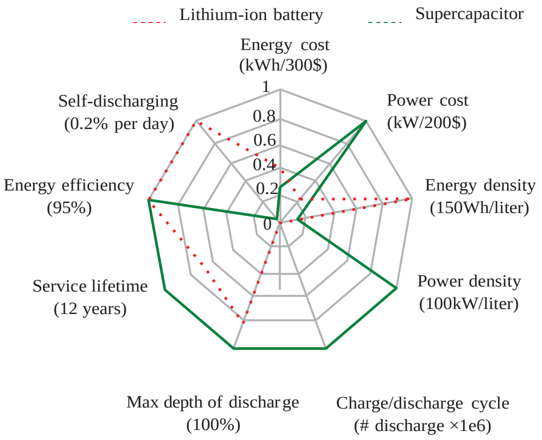


Fig. 2 Comparison between lithium-ion battery and supercapacitor

The lithium-ion battery has a higher energy density than the supercapacitor due to distinct chemical processes, which is one of the main reasons why it has been recommended to be hybridised with the FC in the field of EVs. The supercapacitor, on the other hand, has evident advantages in terms of power density and charge/discharge cycle. Because of its low internal resistance, supercapacitors can produce large amounts of transient power in a short period of time, making them ideal for power shaving because they are not bound by the charge/discharge cycle. In addition, the supercapacitor has a larger maximum depth of discharge and a longer service life, resulting in superior system performance.

DREIVETRAIN

A. Topology Comparisons

Many researchers have researched fuel-cell-based EVs that combine a battery or supercapacitor, and in which FC is utilised as the primary power source. They may be categorised into six topologies, as illustrated in Fig. 3. The FC and battery or supercapacitor can be linked directly to the DC bus of the DC/AC inverter, which is known as passive topology, or through one, two, or three DC/DC converters connected to the drive inverter, which is known as active topology.

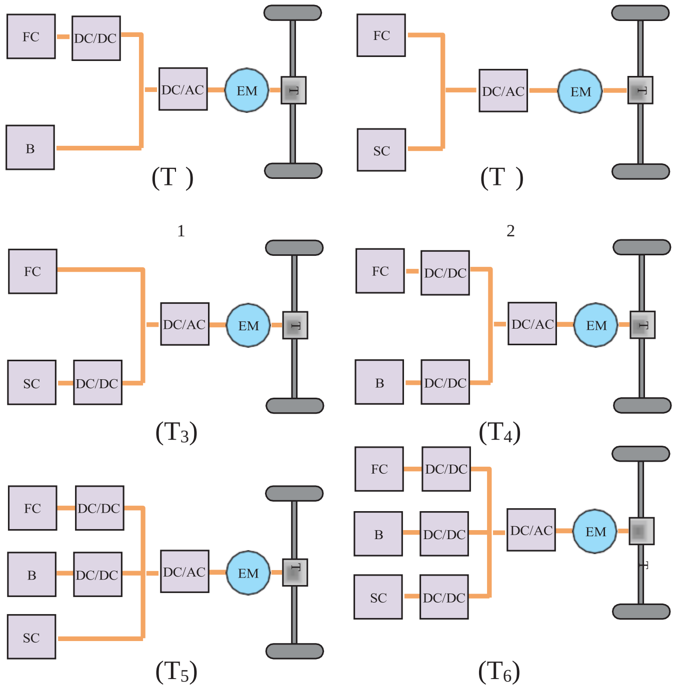


Fig. 3 Topologies of fuel-cell-based EVs

FC is connected to the DC/AC inverter via a DC/DC converter in the first topology (T1), and a battery is connected in parallel. In [12], a topology like this is examined, and the fuzzy controller is used to regulate energy. [13] provides an analytical energy management solution. The DC bus is changeable in the second topology (T2) due to the absence of a DC/DC converter, resulting in a floating DC voltage. This is the simplest topology, although references are scarce [14-15]. The FC and battery are used for direct hybridization in this floating voltage topology [15]. The electric load is used in [16] to observe the power split between these two devices, where the bus voltage and current are automatically managed.

It also suggests a way for managing the power split, which involves adjusting the internal impedance of the FC by controlling its operating curve, with a limited range of adjustment. [14] examines a power supply consisting of an FC and a supercapacitor and provides a control approach based on power decoupling. However, without taking into account the drive inverter and the electric machine, investigations on hybridization between FC and supercapacitor are incomplete.

The third topology (T3) depicts a supercapacitor connected to a DC/AC inverter through a DC/DC converter, with the FC connected directly to the inverter. The experimental validation of a cascaded control loop with a decoupling method in the frequency domain is explained [14]. Researchers like the following topology (T4) because it allows them to better manage the power flow between the FC and the battery. On the basis of this topology, several energy management solutions are proposed. [17] proposes a nonlinear flatness-based control, while [18] proposes a rule-based power management technique.

In [19], employed a fuzzy logic control to decide the power distributions between these devices in topologies T5 and T6, both of which contain FC, battery, and supercapacitor, with the only variation being the supercapacitor connection. In [20], a wavelet-fuzzy logic-based energy management technique is given for topology T6. In comparison to T3, T4, and T5, this design allows the battery and supercapacitor to handle power flow more efficiently. However, because three DC/DC converters are involved, the structure and control strategies are overly complicated.

T1, T3, T4, T5, and T6, which are termed active topologies, may generate power distributions by altering current and voltage with DC/DC converters. These technologies, which are widely employed in EVs with a variety of energy management tactics, have been researched, simulated, tested, and assessed. In dealing with power distribution, several energy management solutions have been proposed [21]. The power supply required by the load is addressed by the control algorithms mentioned above [22, 23]. As a result, the FC serves as the traction drive's main power source, charging the battery or supercapacitor as needed, while the battery or supercapacitor supplies transient power and recovers regenerative energy.

B. The Topology of the Hybrid Power Sources

Figures 4 and 5 provide a comparison of two topologies. A traditional design, with a primary electrical setup and a DC/DC converter, is shown in Fig. 4, which is extensively utilised by many car manufacturers. The DC/DC converter regulates the output voltage and current of the FC to keep the voltage at the motor drive's input approximately constant. The battery is intended to supply instantaneous power in order to improve system performance and to recover braking energy in order to improve energy performance and efficiency. The battery is thus considered the peak power system, which is immediately connected in parallel with the FC system and coupled to the inverter's DC bus.

A DC/DC converter, on the other hand, adds a major expense to the vehicle system, and the two-stage FC power conditioning system has problems due to its cascaded power conversion stages, such as being large, expensive, and inefficient.

To address these difficulties, Fig. 5 depicts a floating voltage topology without a DC/DC converter, which is projected to save money and enhance efficiency due to the structure's compactness. Due to the minimal internal resistance of the supercapacitor, this architecture has the advantage of delivering substantial transient power without generating a considerable amount of heat or voltage drop, and the charging current can be much higher than the battery. As a result, the supercapacitor can deliver a huge amount of power in a short amount of time, meeting the peak power requirement.

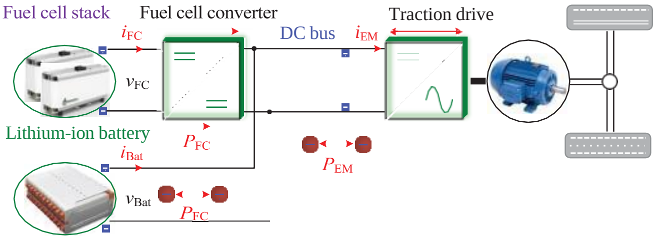


Fig. 4 Conventional topology

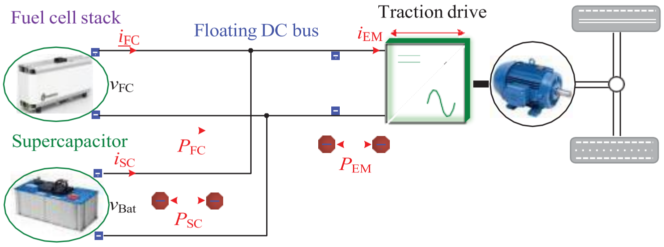


Fig. 5 Floating voltage topology

C. Energy Management of the Hybrid Power Sources

FC is an electrochemical energy device in which hydrogen and oxygen are reacted to generate electricity, which is then used to supply power to the load, with water as a by-product. Thus, the hydrogen and oxygen flow rates are modified according to the FC's needed output current, while the FC's output current is decided by the energy management's power distribution.

a. Conventional Topology

To determine the power split in the topology of FC and battery, an energy management system is necessary. Figure 6 depicts the traditional topology's energy management technique.

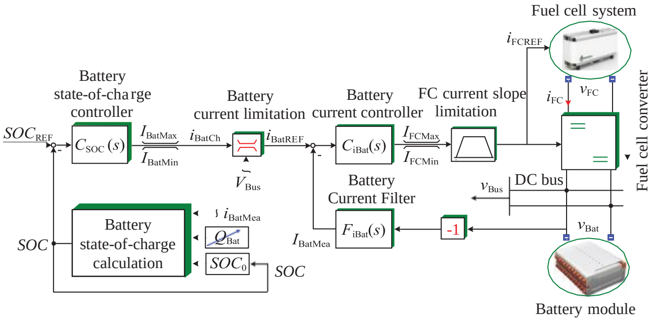


Fig. 6 Energy management strategy

In Fig. 6, the outer loop is the battery state-of-charge (SOC) controller, which is used to determine the charging current reference signal IBATREF, and the centre loop is the battery current controller, which is linked to the FC current reference signal IFCREF. When SOC is lower than SOCREF, the battery for the FC must be charged with a constant current, and when SOC is higher than SOCREF, the battery must be drained. The battery's power output is therefore constrained by the charging and discharging currents.

b. Floating Voltage Topology

The power distribution in a floating voltage topology is determined by the impedance of the FC and supercapacitor, as shown in Fig. 7.

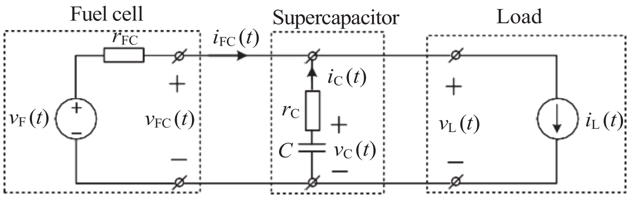


Fig. 7 The equivalent circuit of floating voltage topology

The FC is represented by a voltage source and its internal resistance, whereas the supercapacitor is represented by its nominal capacitance C and internal resistance rC. The current flowing from the FC has a spectra that is given by

$$I_{FC}\left(j\omega\right) = I_L(j\omega)\cdot H_C(j\omega) \quad (1)$$

Where, $I_{FC}(j\omega)$ and $I_L(j\omega)$ are the Fourier transforms of the FC current and the load current, respectively, and

$$H_C(j\omega) = \frac{1+j\omega C r_C}{1+j\omega C\left(r_{FC}+r_C\right)} = \left|H_C(j\omega)\right| e^{j\theta_C(j\omega)} = \sqrt{\frac{1+\left(\omega C r_C\right)^2}{1+\left(\omega C\left(r_{FC}+r_C\right)\right)^2}}\, e^{j\theta_C(j\omega)} \quad (2)$$

$H_C(j\omega)$ is a low-pass filter with a unity DC gain and $\left|H_C(\infty)\right| = \frac{r_C}{r_C+r_{FC}} \to 0$, when $r_C \ll r_{FC}$. Hence, the FC supplies the average power of the load, while the supercapacitor provides virtually all the high-frequency peak power.

IV. SIMULATION

A hybrid powertrain system is created in Matlab/Simulink 2017ra to assess the effectiveness of proposed topologies, and tests on acceleration and drive cycle are implemented to compare the operating performance of two systems. The dynamic constants of the EVs utilised in the simulation are shown in Table I.

In a conventional topology, the fuel cell power is 100kW, while in a floating voltage topology, it is 48kW, with a battery capacity of 4kWh and a supercapacitor capacity of 0.37kWh. The electric machine's peak power is 100kW, and the operating curve in Fig. 8 defines the maximum torque and output power of the electric machine.

TABLE I. PARAMETERS USED IN THE SIMULATION

Constant [Unit]	**Values**
Air density, ρ_a [kg/m³]	1.18
Drag coefficient, C_d [-]	0.26
Cross-section area, A_f [m²]	2.711
Wind speed, v_{wind} [m/s]	0
Vehicle mass, m [kg]	1625
Slope [%]	0
Wheel Radius [m]	0.25
Rolling resistance coefficient C_r [-]	0.0098
Gear ratio [-]	7.2

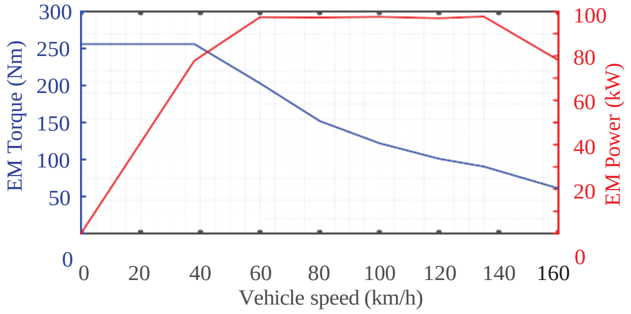


Fig. 8 Operation curve

A. *Acceleration Test*

Figure 9 depicts the simulation results during vehicle acceleration when using a constant accelerator.

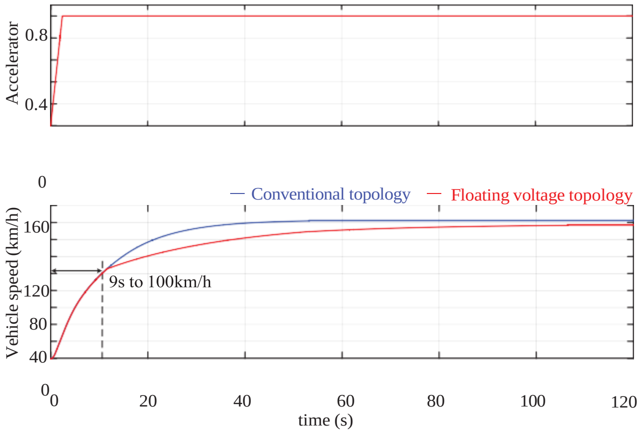


Fig. 9 Acceleration simulation

The vehicle can reach 100 km/h in 9 seconds in both systems, and there is no difference in this time. The traditional topology's maximum speed is 165km/h because the FC's power is 100kW, whereas the floating voltage topology's maximum speed is 156km/h since the maximum power is 48kW, half that of the conventional system. It shows that the floating voltage architecture can accelerate to 100 km/h with the same performance as the conventional topology, but the ability to reach the maximum speed is slightly lower due to the FC rated power limitation. This architecture, on the other hand, can be employed in applications where maximal speed is not a requirement.

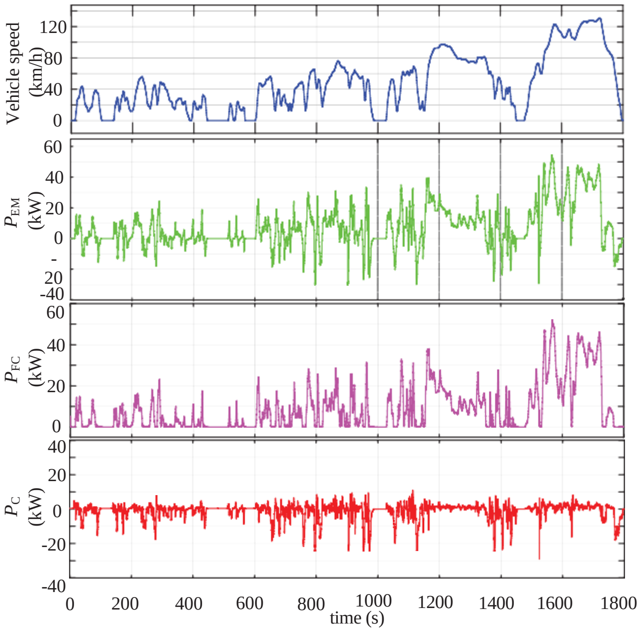
B. *Drive Cycle Test*

To assess the functionality and performance of powertrain systems under real-world driving conditions, several drive cycles have been developed in different countries. In United States, FTP-75, SC03, UDDS, US06 and LA92 are used for testing of fuel consumption and polluting emissions.

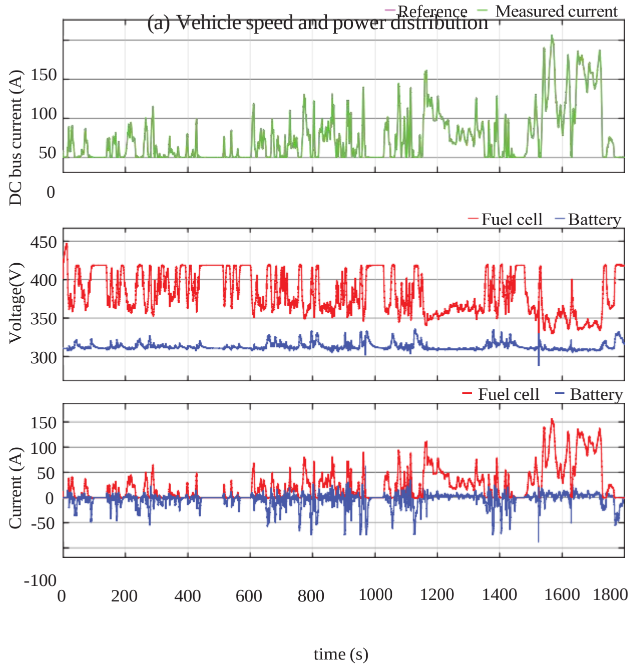
The NEDC cycle is a hybrid of the ECE and EUDC cycles, and it is used in Europe to measure fuel economy and other vehicle emissions. Japan, like Europe, uses the JC08 cycle for regulatory testing [24]. From 2017 to 2019, the worldwide harmonised light vehicles test cycle (WLTC) has replaced the European NEDC for type approval testing of light-duty vehicles [25]. WLTC is used in this paper to compare the performance of two topologies.

1) *Conventional topology*

Fig. 10 shows that the dynamic response of the conventional topology when WLTC drive cycle is applied.

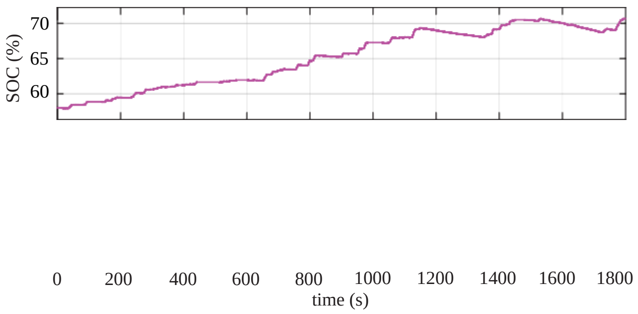


(a) Vehicle speed and power distribution



(b) Voltage & current

During the test, the battery can absorb regenerative power when the vehicle decelerates, but due to current limitations during charging and discharging, it can only supply limited power when the load varies; on the other hand, the FC supplies the main power when the vehicle is operating, but the power variation is still very large, with quite wide magnitude variations. The battery's SOC climbs dramatically at the end of the test, which is due to the fact that the SOC is lower than the reference SOC.

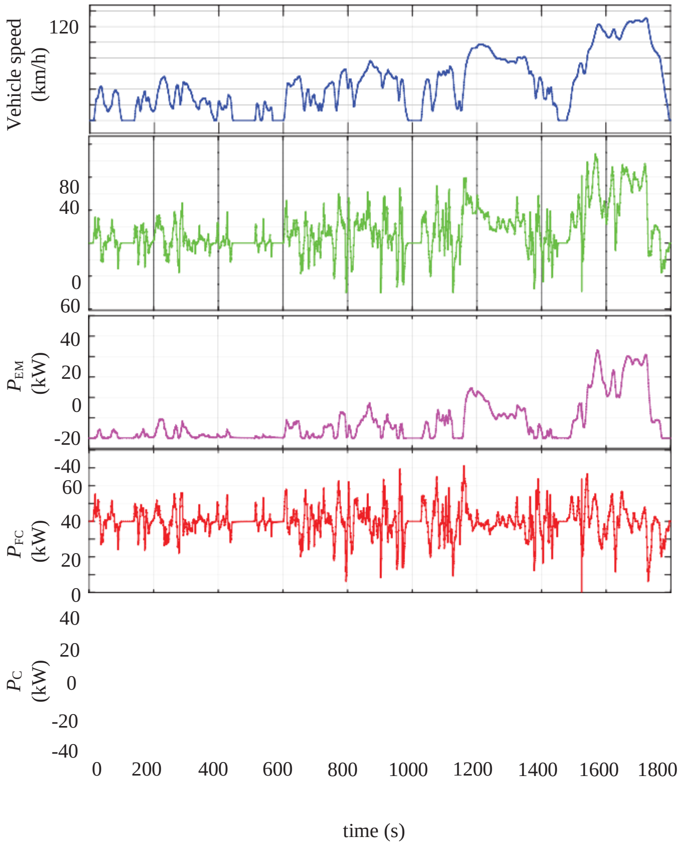


(c) SOC of battery

Fig. 10 Dynamic response of the conventional topology

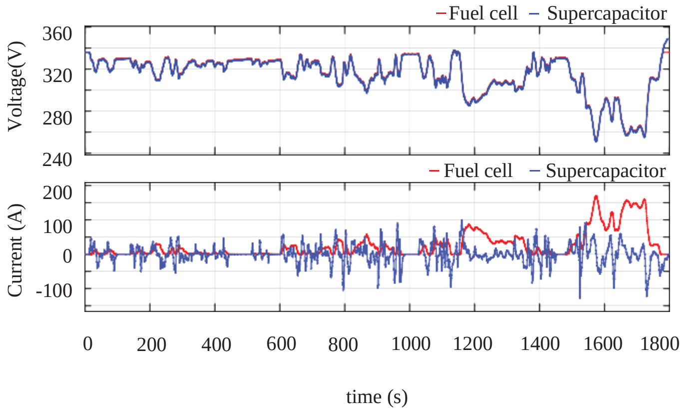
2) *Floating voltage topology*

When the WLTC drive cycle is applied to the floating voltage topology, the simulation is displayed in Fig. 11. The power supplied by the FC is clearly flatter than in the conventional topology, allowing the FC to avoid the significant transient power rate during operation. In this method, the FC's degeneration can be slowed and its lifespan extended. The supercapacitor, on the other hand, can give more power to the load due to its lower impedance, allowing the FC's rated power to be reduced. Additionally, the supercapacitor can absorb more regenerative power than the battery during deceleration, saving energy. The FC and supercapacitor, on the other hand, have a similar percentage of the market.

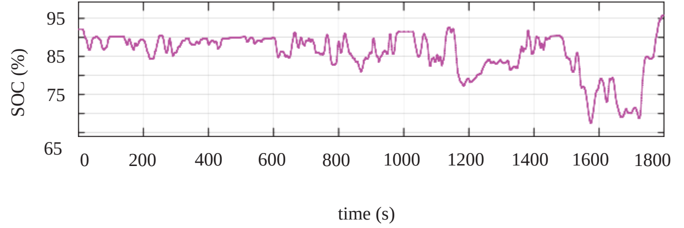


(a) Vehicle speed and power distribution

We can observe that with the floating voltage architecture, the FC's rated power is reduced, which has no effect on the vehicle's acceleration time from 0 to 100 km/h. In contrast, the FC's greater performance in the WLTC test is owing to the supercapacitor's excellent dynamic performance, which can slow down the degradation of the FC and improve its longevity.



(b) Voltage & current of the fuel cell and supercapacitor



(c) SOC of supercapacitor

Fig. 11 Dynamic response of the floating topology

V. CONCLUSION

Three energy storage technologies are compared in this research, with FC having the highest energy density and zero GHG emissions, making FC more appealing in EV applications. While the low power density of FC necessitates its hybridization with a battery or a supercapacitor, which provides benefits such as reduced rated power of FC, reduced system energy consumption, and reduced stress on energy storage devices. Thus, topologies of fuel-cell-based electric vehicles are investigated; a conventional topology based on FC and battery is simulated, as is a floating voltage topology based on FC and supercapacitor. Due to the more efficient assistance of the supercapacitor, the simulation results demonstrate that the hybridization of FC and supercapacitor has the superior performance.

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