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Overview of Fuel Cell-Hybrid Power Sources Vehicle Technology: A Review

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Research Article

Abstract

Today, the world suffers from excessive and unfair consumption of non-renewable energy sources, such as high rate of global pollution and global warming. Accordingly, fields of life in general and industry in particular, led by the automobile industry, tended to use clean and renewable energy in industry and consumption to reduce the negative impacts on the global environment. The automotive industry tended to produce electric cars that do not depend at all on traditional energy sources from fossil fuel derivatives. Accordingly, it was necessary to find alternative energy sources that achieve both goals: avoiding the negative impact on the environment, and producing sufficient energy to achieve the requirements of performance and efficiency from the use of electric cars to be a permanent alternative to traditional cars that run on fossil fuels. This scientific paper provides an overview of one of the versions of modern technology in the field of electric vehicles energy performance to provide the vehicle with energy continuously and the mechanism of control and management in this system. This paper studies the hybrid power sources technology in electric and hybrid cars that depend on a main power source, Fuel Cells (FC), and a secondary power sources, Battery and Ultracapacitor, in the vehicle. This paper presents a brief overview of this system, its components, their characteristics, the advantages of hybridization in this type of energy source with the working mechanism of the system, an overview of the control systems in this technology and a set of challenges facing this type technology and its future perspectives.

Keywords: Fuel cell, Battery, Supercapacitor, Energy Management, Hybrid power sources, Challenges, future perspectives.

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1. Introduction

The transition from fossil fuels, as non-renewable energy, to sustainable energy sources in the automotive industry has been driven by concerns over environmental degradation, dwindling global fossil fuel reserves, and the unsustainability of traditional internal combustion engines (ICE). Consequently, the industry has increasingly shifted its focus towards the production of electric vehicles (EVs), which rely solely on clean and renewable energy sources. This move has been propelled by heightened restrictions on producing ICE vehicles, primarily due to their reliance on fossil fuels [1].

Electric Vehicles (EVs) offer a dual advantage of being environmentally friendly while maintaining high-performance efficiency compared to their traditional counterparts. However, the transition from conventional to fully electric vehicles (FEV) has been hindered by technological challenges. While replacing traditional engines with electric ones is feasible, ensuring the provision of electrical energy required for optimal performance poses a significant challenge. Unlike conventional vehicles that rely on refueling from a readily available fuel tank, EVs require pre-stored energy as Battery-based electric vehicles (BEVs), often necessitating several hours of charging before use. Where the concept of "full charge mileage" has emerged as a key benchmark for comparing EVs [1].

Amidst technological advancements in the automotive industry, hybrid electric vehicles (HEV) have become a pivotal transitional phase between conventional and FEVs. HEVs integrate multiple energy sources, typically combining a conventional engine with an electric motor as power-driving sources. This technological evolution has reduced reliance on traditional engines while increasing the integration of electric motor technology to manage vehicle operations [2].

The Fuel-Cell (FC) technology has emerged as a promising alternative energy source for both EVs and HEVs due to its zero emissions, reliance on clean energy sources like hydrogen gas, high energy density, and continuous energy production. Meanwhile, advancements in electrochemical batteries have led to rapid developments in battery manufacturing, resulting in various battery types with distinct specifications. On the other hand, Ultracapacitors, or supercapacitors, offer high power density, rapid charging capabilities, and extended life cycles, further enhancing electric energy storage options in EVs [3].

The integration of fuel cells, batteries, and ultracapacitors in EVs as hybrid energy sources (FCHEV) represents a significant research trend in the automotive industry, with the potential to shape the future of electric vehicles. Researchers are actively exploring the feasibility, features, and management techniques of this integrated energy system, highlighting its importance in advancing EV technology [4].

Tie et al. [1] conducted an extensive review encompassing numerous scientific papers to offer a comprehensive overview of energy technology in automotive applications. Their study delved into various aspects, including the types of storage and production methods for electric energy sources utilized in electric vehicles (EVs), examining the unique characteristics of each. Furthermore, they explored the mechanisms involved in integrating these diverse energy sources into a unified system and the complexities of electrical energy management systems. Additionally, the researchers investigated the different control levels inherent in these systems, shedding light on the intricacies of managing and optimizing electric energy utilization within automotive contexts.

Sulaiman et al. [2] undertook a comprehensive review encompassing a multitude of scientific papers focusing on Energy Management Systems (EMS) for Fuel Cell Hybrid Electric Vehicles (FCHEVs), particularly regarding the integration of energy from batteries and supercapacitors. The review delineated several classifications of FCHEV-EMS, elucidating various types of control models and algorithms employed to achieve optimal control strategies for EMS. Moreover, the study summarized the performance outcomes of different FCHEV system combinations in tables along with their respective references. Through this research, Sulaiman and colleagues provided an exhaustive examination of FCHEVs, covering aspects such as energy source models, combinations, and management systems, among others, as developed by diverse researchers in the field.

Hannan et al. [3] conducted an extensive study encompassing numerous scientific papers to offer a comprehensive summary of technologies and power systems utilized in various hybrid vehicles. Their research delved into multiple sources of energy, including fuel cells, batteries, supercapacitors, and solar cells. Additionally, they investigated dynamic models associated with these energy sources and examined methods for managing and converting energy within hybrid vehicle systems. Furthermore, the study elucidated a range of challenges encountered by these technologies at different levels, encompassing energy sources, energy management, electronic systems, and electric motors within hybrid vehicles, providing valuable insights into the complexities of hybrid vehicle technology.

Kasimalla et al. [4] undertook a comprehensive study involving an extensive review of scientific papers aimed at providing insights into various power conversion configurations and Energy Management Systems (EMSs) tailored for Fuel Cell Hybrid Electric Vehicles (FCHEVs). Their research specifically focused on FCHEVs integrated with Batteries and Ultracapacitors to enhance high-energy storage performance. The study evaluated the performance of different energy management combination schemes involving Fuel Cells, Batteries, and Ultracapacitors, comparing them with alternative configurations and presenting experimental findings. Additionally, Kasimalla and colleagues investigated Braking Control schemes designed to reduce hydrogen consumption in FCHEVs when combined with other energy storage systems. Furthermore, the research summarized the diverse aspects of energy utilization, configuration, and EMSs of FCHEVs as developed by various researchers, providing a comprehensive overview of the advancements and challenges in this domain.

M. Waseem et al [5] studied many scientific papers to provide a discussion of Fuel-Cell Electric vehicles (FCEV) their main characteristics, challenges approaches, advantages and disadvantages, and the future view of this type of technology. Where, a brief overview of EV technology, and FC's electrochemistry energy generation technologies were provided. on the other hand, the researchers provided a comparative discussion between FCEV and FCHEV in order of chemical energy storing capacity, power transformation topologies, communication protocols, and technological developments.

This research aims to investigate hybrid power systems wherein the Fuel Cell (FC) serves as the primary power source, supplemented by two secondary energy sources: The Battery and The Ultracapacitor (UC). Drawing upon a collection of scientific papers that summarize various approaches and cutting-edge research in this field, the study provides a comprehensive overview of such hybrid systems. In the first section, the research elucidates the rationale behind the adoption of these hybrid systems in modern EVs. Subsequently, the second section delves into the concept of hybridization between these energy sources in EVs, highlighting the individual advantages and disadvantages of each source. The third section classifies hybridization approaches between the FC and the secondary energy sources. Following this, the fourth section outlines methodologies for energy management systems (EMS) and control in such hybrid systems. Additionally, the fifth section evaluates system performance during both power supply and energy regeneration processes. The sixth section addresses current and future challenges facing hybrid energy sources of this nature, while the seventh section discusses the future outlook of the system. Finally, the research concludes by presenting the overall findings and conclusions derived from the study in the eighth and final sections.

2. Power sources classification

Electric cars with hybrid power sources contain two or more energy sources. This paper investigates hybridization between three energy sources: Fuel cells, Battery, and Supercapacitor.

2.1. Fuel-Cell (FC)

Fuel cell is a productive power source. The fuel cell produces electrical energy by converting chemical energy, which is stored in the Hydrogen fuel into electrical energy by Oxidation-Reduction reactions of Hydrogen with Oxygen. These chemical processes produce water and heat as outputs of the reaction in the cell [1, 3, 5]. Theoretically, a single cell can generate a (1.23 Volt) at a temperature of (25 °C) and (1 atm) of pressure [3].

There are several types of FC, such as Direct Methanol Fuel Cell (DMFC), Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Alkaline-electrolyte Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC) [6]. These types differ among themselves in terms of the internal chemical composition of the cell, the amount of power produced, and the operating temperature at which the cell operates. Therefore, the applications in which each cell is used differ according to the specifications and working conditions. The DMFC, PEMFC, PAFC, and AFC are classified as low-operating temperature fuel cells, which are used in the transportation sector [1, 5]. Also, the PEMFC is preferable for vehicular applications due to its high power density, low operating temperature, and quick startup actions [7]. The main FC advantages in the transportation sector are the high-efficiency operating, silence, low emissions, and the simplicity of the working principle [1] where a multi-fuel-cell stack configuration can be used to enhance the average lifetime of the power supply system of a Fuel-cell Vehicle (FCV) [8].

2.2. Battery

The battery is an electrical energy storage device, not a production device, as is the case in a fuel cell [1]. The electrical energy is chemically stored inside the battery (electrochemical mechanism) and produces or releases electric current (chemical to electrical energy conversion) when the battery is connected to an electrical load. A battery consists of a group of cells connected in series to increase the total amount of voltage produced by the cells according to the application in which the battery will be used [9].

The characteristics of batteries differ according to the type of battery, based on the chemical composition of the cell components in the battery. Table (1) shows the difference between the characteristics of the main electric car batteries according to their type [10]. Each type of battery has its pros and cons, and in general, lithium-based batteries are the best batteries for multiple uses in cars, because they have high energy and power characteristics compared to other batteries [1].

2.3. Ultracapacitor

The Ultracapacitor (UC) or Supercapacitor (SC) is an energy storage system in electric cars, as it is characterized by the ability to feed the system with a high capacity of power. The UC is no different from the ordinary capacitor in principle, where the electrical capacitance of the UC is affected by the same factors that affect the capacitance of the normal capacitor, in addition to the effect of operating temperature and type of materials constituting the UC, but the capacitance of the UC is too much larger than the capacitance of the normal capacitor.

Depending on the type of UC's plate material, there are three types of UC: Electric Double Layer Capacitor (EDLC), Pseudo Capacitor, and Hybrid Capacitor (a mixture of EDLC and Pseudo-capacitor). As a result of this difference between the types of UCs, some of the electrical characteristics differ between them in terms of the amount of specific energy, specific power, and the number of life cycles, but not to the extent that makes the comparison between them clear in a distinct way [1, 7].

Table 1. Technical characteristics of main battery types used for EV

Battery Technology (type)	Pb-acid	Ni-Cd	NiMH	Li-ion	Li-ion polymer	Na-NiCl
Specific Energy (Wh/kg)	40	60	70	125	200	125
Energy /Volume coefficient (Wh/L)	70	100	250	270	300	300
Power /Weight coefficient (W/kg)	180	150	1000	1800	3500	1500
Self-discharge coefficient (% per 24 h)	1	5	2	1	1	0
Number of recharging cycles	500	1350	1350	1000	1000	1000

2.4. Power sources comparison

The fuel cell is characterized by continuity in the production of electrical energy as hydrogen fuel is constantly available in the system. Accordingly, it is characterized by a high amount of specific energy, but the production of this energy is at a low voltage for the cell compared to energy storage sources. Table (2) shows a comparison of the electrical characteristics of a supercapacitor, battery, and fuel cell; where the FC has low values of power density compared to other power sources [11]. The fuel cell is characterized by a slow dynamic response compared to other power sources based on the fast-changing of the loads in the system. Figure 1 shows the difference in the power source's dynamic responses compared to the rapid change of load in the system [12].

The battery is similar to the fuel cell in terms of low values of specific power and high values of specific energy, but the battery is distinguished from the fuel cell by a faster dynamic response to load requirements and a higher value of voltage per cell. The supercapacitor differs from both the battery and the fuel cell in its higher specific power and lower specific energy [4]. Therefore, the supercapacitor cannot be the only source of energy in the system, but rather a secondary system auxiliary to a primary system characterized by a high amount of specific energy, such as a battery or a fuel cell where it has a lower voltage value than the single-cell battery [3]. On the other hand, the SC has a rapid dynamic response to load requirements [12]. Also, the difference between a battery and a supercapacitor as an energy storage source is the faster charging rate that the supercapacitor has than the battery, as well as the longevity of use (life cycle) [4].

Table 2. Technical characteristics of FC, batteries, and SC

Parameters	Fuel cell	Battery	Supercapacitor
Power Rating (MW)	Up to 100	Up to 50	Up to 1
Discharge Duration (hours)	24	10	0.3
Power Density (KW/kg)	< 0.5	< 1	> 10
Energy Density (Wh/kg)	> 1000	> 100	< 10
Operating Life (years)	15	10	20
Operating Life (cycle)	20,000	2,500	1,000,000
Low temperature (°C)	0	-20	-40
High temperature (°C)	+80	+60	+80 to +100
Response time	Seconds	Seconds	Milliseconds
Principle	Chemical	Electrochemical	Electrostatic

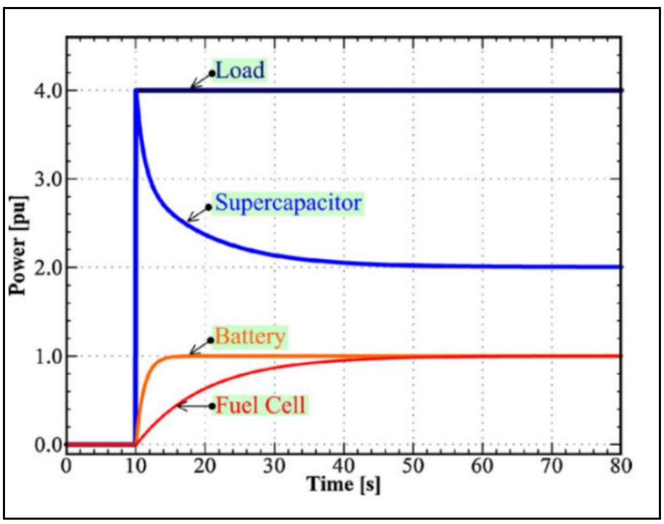

Fig. 1. Hybrid power sources respond during a high positive load [12]

3. Classification of Hybridization of Power Sources

As previously explained, Fuel cells are characterized by high output energy density, low power density, and slow dynamic response. Accordingly, there cannot be an electric car that relies entirely and solely on the fuel cell as the only energy source. In general, the fuel cell system was integrated into Hybrid Electric Vehicles (HEV) to feed the electric motor in addition to the presence of the conventional engine (ICE) in the vehicle. To compensate for the deficit in the fuel cell performance and to increase the role played by the electric motor compared to the conventional motor in hybrid cars, it was necessary to integrate the fuel cell system with battery and supercapacitor (Energy Storage Sources; ESS) so that the efficiency and performance of the system would increase in various working conditions. Where, the electric load conditions of the electric motor vary according to driving requirements such as starting, acceleration, braking, cruising a certain performance mode, and others. Hybridization levels between the fuel cell as the main energy source and other ESSs are illustrated as follows [2, 13,14]:

3.1. FC – Battery HEV

The battery has the characteristics of higher energy density, relatively low power density, and higher responsiveness to load requirements than a fuel cell; This is due to the availability of electrical energy in the form of storage, not productivity, as is the case in the fuel cell. Thus, the battery can provide the motor with a high starting current and sufficient power to cause the fuel cell to start initially with low output power and increase as the amount of energy in the battery (State of Charge: SOC) decreases.

Figure 2 shows a general block diagram of the FC-Battery HEV structure, where the battery is a secondary power source with the fuel cell to feed the electric motor. The battery is connected to the fuel cell in parallel to form an intermediate electrical link between the power sources and the electrical motor known as the DC Bus. This principle of Energy Management Systems (EMSs) allows the load sharing between two energy sources, and accordingly, provides the necessary energy to the DC bus. Then, the Inverter converts the DC voltage into AC voltage to feed the AC electrical motor [2].

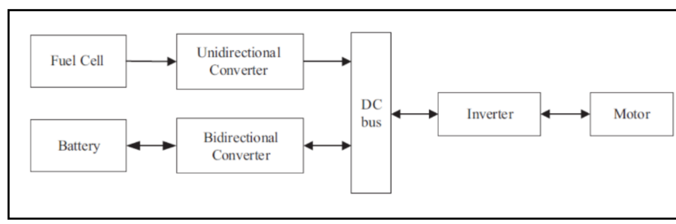

Fig. 2. Connection structure of FC - Battery HEV.

The battery is connected to a bidirectional converter and the fuel cell is connected to a unidirectional converter; This is due to the ability of the battery to be recharged, unlike the fuel cell, which is a productive source of energy, not a storage one (it cannot be charged). The charging sources for the battery are either through the fuel cell itself so that the cell charges the battery if the State of Charge (SOC) decreases or through the reverse energy generated from the braking process (Regenerative Braking), where the electric motor works as a generator by converting the wheel's kinetic energy into electrical energy, which stored in the battery. The energy flow in the system is in reverse, that is, the inverter converts the current from Alternating Current (AC) to Direct Current (DC) from the generator (electric motor) to the DC bus and then to the energy storage source (the battery).

The process of integrating a storage energy source with the fuel cell system provides an opportunity to take advantage of the kinetic energy wasted in the system that depends on the fuel cell as the only source of energy. Accordingly, the hybrid system between the fuel cell and the battery reduces the rate of wasted energy in the system, which increases the efficiency of the system and reduces the load stress on the fuel cell due to the decrease in the required energy to recharge the battery. The decreasing of stress on the fuel cells reduces the consumption of hydrogen fuel, thus minimizing the unit size of the fuel cell in the system.

Based on the above, the importance of the battery is clear in providing the system with instantaneous electrical energy that is not available in the fuel cell. The battery feeds the system with energy in the case of low power frequency (light load case), and the energy sharing of the fuel cell increases with the increase in the power frequency in the system, and this provides smoothness and regulation in the DC bus voltage and reduces the load stress on the battery, which causes a relative increase in battery life. Where the ratio of energy sharing between the battery and the fuel cell depends on the SOC of the battery, and therefore the stress on the fuel cell increases in the case of a decrease in the SOC of the battery.

3.2. FC-SC HEV

As an energy storage source, a supercapacitor has the advantage of the highest power density, highest cycle life, and fastest response time to load requirements than both a fuel cell and a battery, but the lowest energy density. Therefore, the combination of the supercapacitor and the fuel cell increases the system's responsiveness to load requirements such as fast starting and high acceleration demands. The supercapacitor is also characterized by the speed of charging and discharging due to the high power density, which causes an increase in the charging-discharging frequency of the SC in the system, and this contributes to increasing the efficiency and performance of HEV by providing a continuous high power density for high and fast load demands.

Figure 3 shows a general block diagram of the FC-SC HEV structure, which is similar to the FC-B HEV system. The supercapacitor shares with the fuel cell the energy feeding to the system, where the fuel cell feeds the DC bus with a constant DC voltage, and the power shared by the fuel cell in the system is the average power required according to the load, while the supercapacitor supplies the system with high power for peak power demands. Thus, this provides a smooth and regulate of the performance of the DC bus [3].

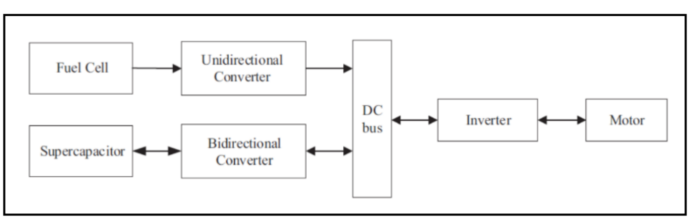

Fig. 3. Connection structure of FC-SC HEV.

Since the supercapacitor is a rechargeable storage energy device that has the advantage of fast charging with a high power density; It is considered the best device for absorbing the "regenerative braking" energy, as the energy regeneration process is at a high and instantaneously values of power, which can be absorbed by the supercapacitor. This contributes to minimizing the power loss in the system, as well as reducing the fuel consumption in the fuel cells due to the reduction of stress on FCs. However, this system lacks high energy density as the supercapacitor is a storage energy source with very low energy density.

3.3. FC-B-SC HEV

As was previously explained, the integration of the fuel cell system with an energy storing source is beneficial to the system in terms of improving performance and raising efficiency, but each of the previous systems has advantages and disadvantages depending on the type of device used as an energy storing source (Battery or SC). Accordingly, the combination of the fuel cell as the main energy system in the vehicle with two ESS as a secondary system, i.e. the battery and the SC together, as shown in Figure 4, will duplicate the effectiveness of the system and reduce the negatives of the separately systems.

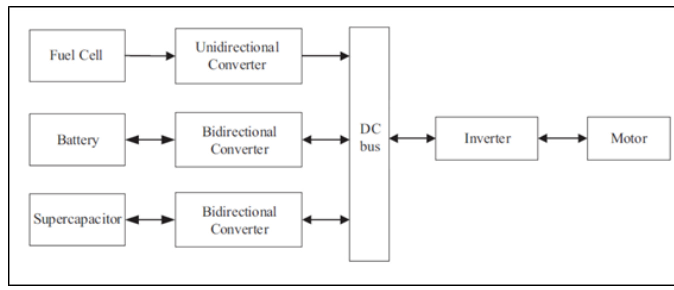

Fig. 4. Connectoin structure of FC-B-SC HEV.

This system is characterized by high energy and power density due to the battery and SC, respectively. Thus, the load stress will be reduced on the fuel cell in a relatively greater way, which will cause a reduction in the size of the fuel cells in addition to a decrease in fuel consumption. Sharing the three sources of providing energy to the system, will reduce the stress on each unit separately, which will increase its life cycles, this will also stabilize the DC bus voltage and the power flow will be smoother and regulated. So that the fuel cell shares with the battery the tasks of supplying the system with a balanced amount of energy, while the SC will provide the system with a high amount of power at critical power demands. This participatory system of supplying energy to the electric system will raise the efficiency of the electrical system in the car in many aspects, including increasing the distance traveled by the electrical system and increasing the electric motor torque and speed.

The presence of the supercapacitor will increase the efficiency of the system's response to the load requirements, and this will increase the efficiency of the electrical system in cases of starting of movement, acceleration, high load, and fast maneuver driving modes. Also, the presence of two sources of energy storage (the battery and the SC) will greatly reduce the power loss, especially in the regenerative braking case, the generated energy will be stored quickly in the SC, and the surplus energy, if the SC is full, will go to charge the battery; this increases the response of the system to re-store the generated energy and reduces the dependence on the fuel cell charging system, thus reducing the consumption of hydrogen fuel directly.

As explained, and according to the SC high power density with fast response characteristics in charging and discharging modes during regenerative braking or high power demands; the power will be less requested for FC and Battery pack. This powering mode will be effective in reducing the Hydrogen fuel consumption in FC and decreasing the battery output power levels, in terms of increasing the battery-SOC serving time [15].

The presence of three power sources in the electrical system working in an integrated manner with each other, according to the load power demands and the State of Charge (SOC), will necessitate finding a good Energy Management System (EMS) for the system power flow between power sources and the motor with other electrical components of the system according to the different working conditions of the system as power feeding, charging and regenerative braking, etc. So, the importance of having a good energy management system emerges, whether from the hardware aspect represented by the electrical components of the system and the way they are connected and the characteristics of each of them or from the software aspect that controls the organization of the work of the components of the system with each other according to the different data of the system.

4. Energy Management System (EMS)

The multiplicity of power sources in the electrical system of hybrid or electric vehicles necessitates the presence of an energy management system to control the energy flow within the electrical system in the vehicle. The presence of a good energy management system improves the overall vehicle performance and achieves the highest level of efficiency and response to driving requirements (load requirements). As the distribution of the electrical load on the different power sources, according to the condition of each of these power sources and the level of the load, prevents wasting energy and achieving the highest possible performance in the system through the momentary exploitation of power sources according to the power specifications of each of them. The proper distribution of power between the power sources during the regenerative braking phase reduces the chances of wasting energy, which mainly increases the system efficiency and reduces fuel consumption in the fuel cells. Proper energy management and good power distribution reduce the energy load stress, which increases the lifetime of the energy sources and provides a higher energy density in these sources due to the non-invasive use of these sources in the system. Thus, the energy management system in the electric or hybrid vehicle, especially when more than one source of energy is available, is considered one of the most essential elements for raising the efficiency and performance of the electrical vehicle [1, 4, 16].

The energy management system consists of two levels: Low Level of control, which is concerned with the internal electrical components in the system, and High Level of control, which is concerned with the low-level components controlled by a specific algorithm or software [1].

4.1. Low-level control

The development of power electronics technology has raised the level of control in electric vehicles. Whereas, power electronics have a function of converting, transferring, cascading, and controlling the energy to and from energy sources within the system. Power electronics technology depends on the technology of electrical converters and the mechanism of linking these converters with hybrid energy sources within the electrical system [1, 16].

4.1.1. Power-electronic converters topology

Four types of converter are known, which are: AC-AC converter, DC-DC converter, DC-AC inverter, and rectifier. Many DC-DC converters were developed to achieve the requirements of specific applications, which are classified into many groups. Currently, many types of Unidirectional (2-quadrant) and Bi-directional (4-quadrant) non-isolated DC–DC converter topologies are being used in EV applications such as Cascade Buck-Boost, Half-Bridge, Cuk, SEPIC/Luo, and Split-pi converters [1, 13].

Converters generally consist of a group of active/passive components such as capacitors, inductors, semiconductors, and control switches. The methods of connecting these components differ to form one electrical circuit, and the difference in the topology of these electrical circuits is what generates the difference between the types of converters. Converters vary in performance efficiency according to several factors, including the number of active/passive components in the converter, connection simplicity, input-to-output voltage range, thermal and electrical stresses, continuity of the electric current (whether the input or output current), as well as the simplicity of controlling the converters (dynamic simplicity). Among the defects that can be characterized by a particular converter: are the magnetic effect of the internal electrical components, the switching noise, and the distortion of the waveform of the produced electric current [1, 17].

Normally, converters require low ripple or narrow tolerances. However, a higher performance topology is required to achieve high performance in automotive applications, such as Interleaved converters, Power Swap converters, Hybrid Switched-Capacitor Bi-directional converters, Z-source converters, Half-Bridge converters, and Bi-directional triable DC–DC converter. These improved topologies aim to increase the transient response to load changes, reduce the overall weight and size of conventional converters, improve the output voltage range, increase the power conversion performance, and reduce the Electro-magnetic Interface (EMI) of the converters [1, 13, 18].

4.1.2. Hybridization topology of the energy storage sources

The topology of energy management is to design power transfer - -drivetrain architecture and control the energy and power flow in these drivetrains. A hybrid Energy Storage System (HESS) is a system that combines two or more Energy Storage Systems (ESS) in the electrical system in the vehicle, so that these systems are linked together in a common DC bus system and it is the mediator between the electric motor and the energy sources, i.e. it is considered the energy-providing medium for the motor. Thus, bi-directional converters are considered an essential part of the system to unify the voltages of the sources concerning each other and manage the two-way energy transformations for each energy storage source during the charging and discharging operations. While, some determinants determine the selection of the appropriate type of converter, such as source peak power value, output power requirement, and power rating of the converters. Therefore, the size and type of the converters vary according to the requirements of the electrical system in the car [1, 19].

According to the researchers, there are some low-component control systems configurations for HESS and converter arrangement topology, such as Passive Parallel Connection, one and two bi-directional DC–DC converter in series, two input bi-directional DC–DC converter in parallel, multiple input ZVS bi-directional DC–DC converter. These types of interconnection systems differ among themselves in the following characteristics: voltage and power limitations, power sharing performance, DC bus stability, life cycle, total weight and cost reduction of converters, and energy conversion efficiency, in addition to flexibility, stability, and efficiency in low-level components control [1, 17-20].

4.1.3. Hybridization topology of the power sources

A hybrid powertrain system consists of a Battery, Supercapacitor, and Fuel Cell (FC) as power sources. Where the battery and SC are the HESS and the FC is the main power source in the vehicle. The available FC power sources generate a low-level DC voltage, where a double DC-DC converter is used to raise it to the useful constant voltage. The three power sources connect in the same DC bus; due to that, the load and power participation are distributed, which feeds the motor or that produced from the regenerative braking process. [4].

4.2. High-level control.

The high level of control is a controlling of the Low-level control components. Where, it improves the vehicle performance by improving the power consumption efficiency, which depends on live and future data of power flow operations. The Event-based or Time-based conditions coordinate the control operations between the High-levels components. Where the hybrid drivetrain is considered a discrete dynamic system; a time-varying system with multi-domain and nonlinear variables. Therefore, to improve the low-level controlling components performance in a hybrid drivetrain; a more intelligent controlling algorithm is needed. Accordingly, there are three known classes of control: Rule-based (RB) control, Optimization-approaches control, and Learning-based control. The control strategies chart is shown in Figure 5 [1, 12, 14, 21-24].

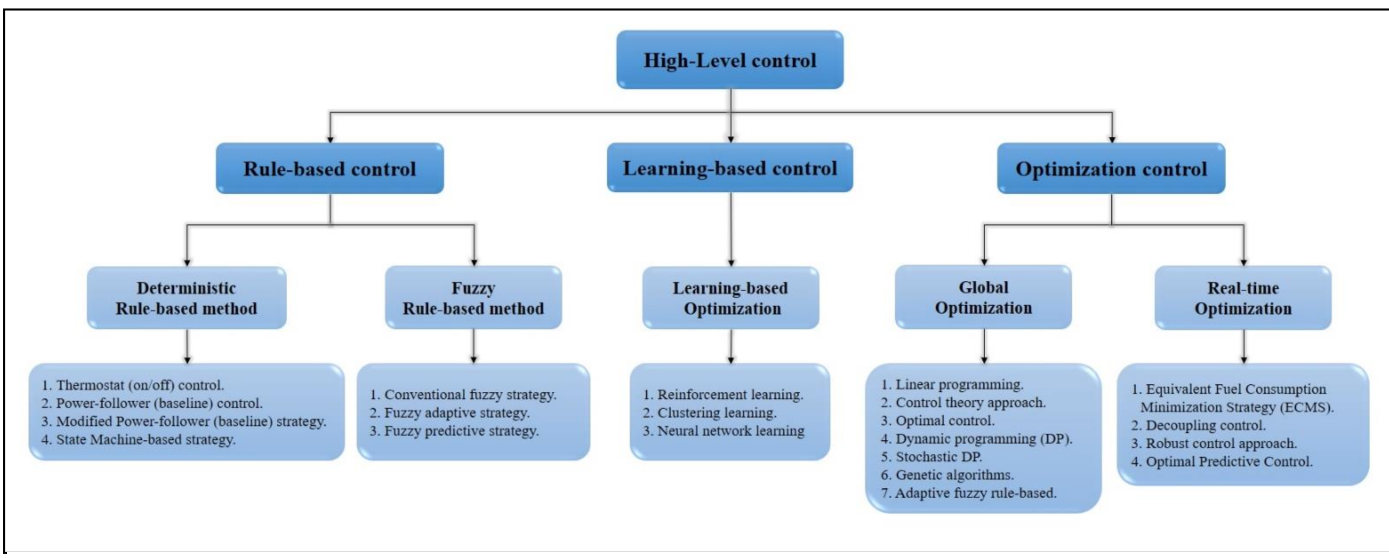

Fig.5. The available electric vehicle control strategies

4.2.1. Rule-based control

Rule-based (RB) control represents a control paradigm rooted in human expertise, incorporating engineering knowledge, heuristics, intuition, mathematical models, pre-defined driving cycles, and load-leveling strategies in vehicle operations. RB control manifests in two main forms: Deterministic rule-based methods and Fuzzy rule-based methods. Deterministic rule-based approaches rely on look-up tables, which contain non-real-time data to formulate deterministic rules governing system behavior. Conversely, Fuzzy rule-based methodologies leverage real-time parameters and suboptimal power allocation strategies, drawing from nonlinear data and linguistic knowledge to compute optimal system outputs. [1, 14, 21-26].

Deterministic rule-based control encompasses several distinct strategies: Thermostat (on/off) control, Power-follower (baseline) control, Modified Power-follower (baseline) strategy, and State Machine-based strategy. The thermostat control strategy is characterized by its robustness, simplicity, and ease of implementation. It operates by triggering frequent on-and-off states (charging and discharging) of energy sources, contingent upon their state of charge (SOC). In contrast, the power-follower control strategy aligns power delivery with vehicle demands and sources SOC. The modified power-follower strategy introduces considerations of energy utilization and emissions by incorporating cost functions. Finally, the state machine-based approach responds to shifts in driver demand, thereby adapting the control strategy based on dynamic changes in operational requirements.

Fuzzy rule-based control encompasses three main strategies: conventional fuzzy strategy, fuzzy adaptive strategy, and fuzzy predictive strategy. The conventional fuzzy strategy integrates a driver's intention predictor, power balance controller, and load-leveling mechanisms to regulate system behavior. In contrast, the fuzzy adaptive strategy adjusts control parameters, such as the weight of the power equation, to account for varying driving environments, including roadway type, driving situations, and energy flow within the drivetrain. However, the fuzzy predictive strategy relies on driving history to anticipate future states, albeit its limitation lies in the inability to execute real-time control tasks effectively.

4.2.2. Optimization-approaches control

The optimization approach to control relies on either analytical or numerical operations, categorized into global optimization and real-time optimization methods (RTO). Global optimization leverages both past and future power demands to minimize a cost function, enhancing fuel efficiency and reducing emissions over a fixed driving cycle. Strategies under global optimization include linear programming, control theory approaches, optimal control, dynamic programming (DP), stochastic DP, genetic algorithms, and adaptive fuzzy rule-based (RB) strategies. On the other hand, real-time optimization operates based on current system variables, focusing on instantaneous cost functions. Real-time optimization strategies encompass techniques such as Equivalent Fuel Consumption Minimization Strategy (ECMS), decoupling control, robust control approaches, and optimal predictive control. These methods enable dynamic adjustments in control actions to optimize performance in real-time scenarios. [1, 14, 22-24, 27-30].

In the realm of global optimization, various methodologies are employed to enhance the efficiency and performance of hybrid drivetrain systems. Linear programming employs piecewise-linear approximations to transform the inherently nonlinear convex optimization problems related to hybrid drivetrain dynamics and fuel efficiency into linear programming formulations. This enables efficient optimization leveraging convex optimization techniques. The control theory approach aims to optimize system performance by making decisions regarding torque and gear selection, seeking a globally optimal solution. This method relies on analytical techniques to find solutions that satisfy performance criteria while considering system constraints. Similarly, optimal control techniques share characteristics with the control theory approach, emphasizing analytical methods to determine the most effective control actions. These techniques are particularly adept at addressing complex control problems with rigorous mathematical frameworks. Dynamic programming (DP) is a powerful optimization tool that constructs cost functions based on prior knowledge of future driving conditions. While DP can handle intricate decision rules, its computational demands make it less suitable for real-time control applications. Nonetheless, DP serves as a benchmark for evaluating and improving other control strategies. Stochastic dynamic programming (SDP) offers a real-time implementation alternative, employing cost functions and optimal algorithms to adaptively adjust control actions. This method is well-suited for dynamic environments and uncertainties, making it suitable for real-time control applications. Genetic algorithms (GA) provide a versatile approach to solving complex nonlinear optimization problems by simulating the evolutionary processes of natural selection. GA exploits the concept of swarming and intelligent movement to efficiently explore solution spaces and find optimal solutions. Adaptive fuzzy rule-based methods combine fuzzy logic with optimization techniques to achieve adaptive and robust control strategies. By integrating linguistic knowledge and optimization algorithms, these methods can effectively handle uncertainties and variations in system dynamics, enhancing overall performance.

In real-time optimization for hybrid drivetrain systems, various methodologies are employed to ensure efficient operation under dynamic conditions. Equivalent Fuel Consumption Minimization Strategy (ECMS) replaces the global cost function with a local one, dynamically minimizing fuel consumption by optimizing power distribution among energy sources at each sampling instant. Decoupling control integrates algorithms like ECMS to maintain drivability, meet power demands, and regulate battery state of charge (SOC) within acceptable limits, ensuring smooth drivetrain operation. The robust control approach focuses on minimizing fuel consumption by solving the power split problem in Plug-in Hybrid Electric Vehicles (PHEVs) using torque and power input profiles, thus enhancing fuel efficiency across varying operational scenarios. Optimal Predictive Control utilizes predictive information about driving patterns and conditions to optimize fuel economy in real time. This strategy anticipates future driving conditions by employing a look-ahead window, enabling dynamic adjustment of control actions to achieve optimal fuel efficiency based on projected driving scenarios. Meanwhile, Sliding Mode Control (SMC) is a multi-function control methodology that is considered a robust controller, focused on robustness to uncertainties and disturbances, and as an optimal predictive controller by emphasizing optimal control performance based on a model of the system dynamics. These real-time optimization techniques collectively contribute to the effective management of hybrid drivetrain systems, ensuring optimal performance and fuel efficiency in dynamic operating environments.

4.2.3. Learning-based control

This approach discusses the utilization of data mining techniques to enhance controller performance in Fuel Cell Electric Vehicles (FCEVs). Learning-based energy management systems eliminate the need for absolute model knowledge, although building an accurate database can be challenging and time-consuming. Various learning methods, including reinforcement learning, clustering learning, and neural network learning, are employed in FCEV studies to supervise energy flow within the system. Reinforcement learning involves a learning agent and an environment interacting continually, where the agent monitors the environment's state and selects actions accordingly, autonomously determining optimal actions without prior forecasts or predetermined instructions. In clustering learning, a model is constructed by extracting patterns from input data, involving steps such as comment generation, analytical reduction of repetition, and editing for similarity. Neural network learning, based on neuron models, offers a robust solution for handling nonlinear FC systems, albeit demanding a substantial amount of training data for effective network training [14, 23-24, 31-33].

5. Hybrid power sources performance characteristic

5.1. Motoring mode

Figure 6 shows the results of an acceleration test of an electrical motor. It shows the speed of the motor during the test time compared to the voltages of the DC bus, fuel cell, battery, and supercapacitor, as well as the amount of load, electric current, and power of the three power sources. The figure shows the motoring mode characteristics of an FC-hybrid power system, where it becomes clear that the main supplier of power during the acceleration process is the supercapacitor, and its voltage decreases as a result of the discharging rate of the stored energy inside it (it has become empty of energy). In the case of a steady state, the main source of power is the battery and the fuel cell. Where it is noted that the fuel cell effectiveness increases with the decrease in the state of charge in the battery (voltage decrease). The figure also shows the response speed of the power sources to the load changing, through the electric current waveforms for each of them. It is noted that the supercapacitor is the fastest power source in response to the load, then the battery and the fuel cell are the slowest. The supercapacitor is also considered the best performance source suitable for load changes in terms of response speed [12].

5.2. Regeneration mode

Figure 7 shows the results of the braking test of the same electric motor, where the motor stopped rotating in a short time and generated an energy called regenerative braking energy through the work of the electric motor as a reverse power generator. This power is converted to the appropriate voltage and fed to the DC bus. Thus, the storage energy sources are affected by this energy, so that the charging process begins. The supercapacitor is the best response to regenerated energy because of its charging speed characteristic, and therefore it recovers a large amount of energy during the regenerative braking process. The fuel cell continues to feed power to the DC bus to charge both the supercapacitor and the battery. The amount of energy fed to the battery is proportional to the state of charge of the supercapacitor so that it becomes the only source under the charging process in the case of the SC being fully charged, where the fuel cell continues the charging process until the battery is fully charged [12].

It is noted from Figures 6 and 7 that the DC bus voltage is constant during the motoring and regenerative braking phases; This explains the effect of energy management systems in the system through the set of converters used (low-level control) and the control unit software (high-level control) of the power flow in the system, and determining the rate of participation of energy sources in the acceleration process. Likewise, determining the power flow from regenerative braking and the fuel cell to charge storage energy sources, each according to its own SOC.

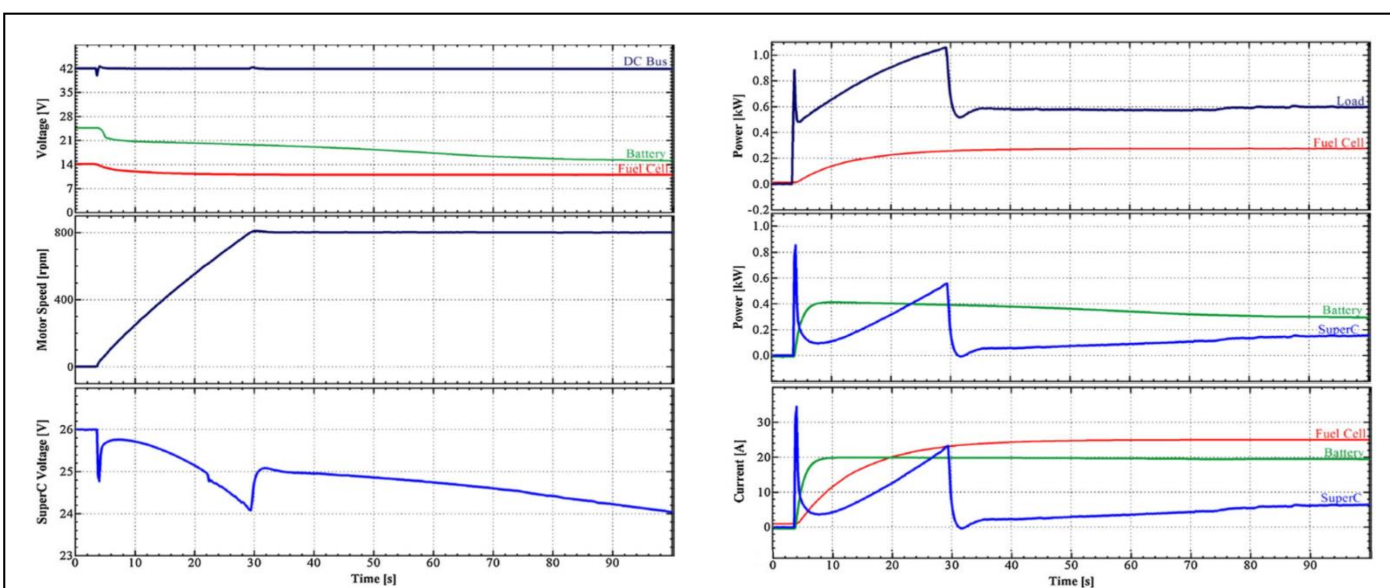

Fig. 6. Hybrid power sources response variation during motoring mode [12].

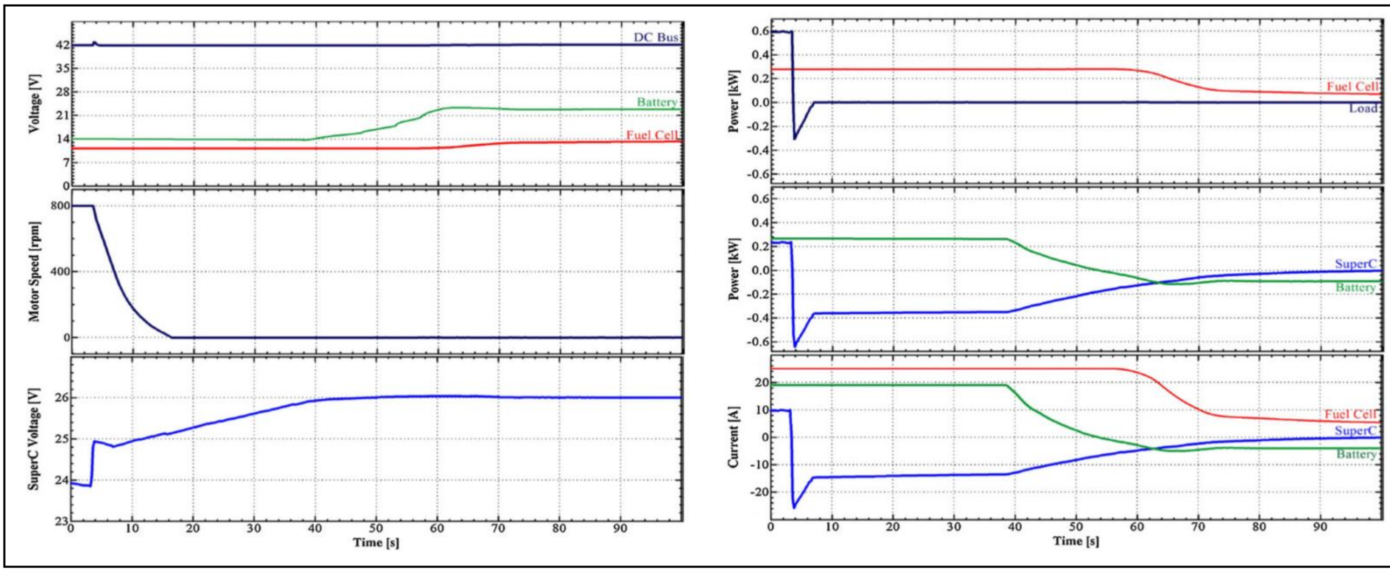

Fig. 7. Hybrid power sources response variation during regeneration mode [12].

6. The challenges of hybrid power sources in vehicles

The risk of running out of fossil fuels and the decline in global oil reserves, as well as the high levels of pollution in the environment and the increase in the effect of global warming as a result of the excessive use of fossil fuels at the expense of the environment; was the motive to direct attention towards the use of the renewable and clean energy, that contains the principle of zero emissions, to be a source of energy for modern and future vehicles. This includes the dependence of Internal Combustion Engines (ICE) in modern vehicles on hydrogen as a clean source of energy, as well as the shift to the manufacture of hybrid and electric vehicles as an alternative to traditional vehicles; to reduce dependence on the ICE partially or totally and thus reduce fuel consumption and greenhouse emissions. However, this technological thinking faces a set of obstacles, such as renewable energy sources having drawback power and energy density compared to fossil fuels, the high cost of electric and hybrid cars, as well as the weak infrastructure supporting electric cars in many countries around the world [3].

One of the most important modern trends within the framework of energy technology in modern cars is the fuel cell system since this system is characterized by zero emissions of greenhouse gases, as well as its dependence on hydrogen (a clean energy source), which is characterized by high energy content by weight. However, the biggest obstacles facing hydrogen energy is the hydrogen infrastructure, including; the processes of hydrogen production, storage, transportation, and the hydrogen environmental impacts with the cost of the processing infrastructure. For example: Hydrogen production requires chemical processes that need modern technology, long processing time, and high cost. Also, the storage of hydrogen, requires that it be stored liquefied or pressurized to be dealt with safely, whether in transportation or use. Thus, the technology of using the fuel cell is considered high-cost concerning hydrogen and the technology of internal design of the fuel cell, while the overall performance efficiency of the fuel cell is described as relatively low in terms of power density [2, 23].

To raise the overall efficiency of the fuel cell; it is integrated with energy storage systems, batteries, and supercapacitors. The battery is considered the best source of energy storage with a high energy density. Battery technology develops with the advancement of material technology, as the basic characteristics of the battery depend on the materials from which it is made, so this technology has some limitations such as the abundance of materials used in the manufacture of batteries and thus the high production cost, size and weight of the battery that negatively affects the specifications of the car, also the relatively low battery life, as well as the long charging time for the battery. While the supercapacitor is characterized by fast charging and high power density, the low energy density in SCs harms it. As the frequency of charging-discharging for supercapacitors increases, the load on the control system increases providing alternative energy for the system throughout the discharge period, as well as a high rate of providing energy for charging the SCs [2, 3].

Connecting the fuel cell with other energy-power sources requires a management system to manage the combination of these energy sources. Where two levels of control levels must be provided: The first level deals with the multiplicity of voltages and current produced for hybrid energy sources, which necessitates a group of different converters, inverters, power switching, and integration of many electronics devices to unify the power of the system within certain limits and is common to all energy sources in what is known as the DC bus. Where, this situation can negatively result in conversion errors, distortion in voltage and current values, switching losses during turn-on-and-off modes, switching frequency of multi-operating modes, the durability of the switching devices, noise and EMI consideration, and damage to some electrical and electronic parts. The second level is the software and algorithm for controlling the first-level devices and the power flow in the motoring and regenerative braking modes according to the different cases of energy sources on the one hand,

and the agreement of the general system state with the requirements of load, acceleration, stopping, road requirements, and providing energy to the secondary systems of the vehicle on the other hand; This may cause mismanagement, poor performance, waste of energy, and damage to system components. Good and efficient design to address this complexity and difficulty in managing and overlapping tasks is the biggest challenge and obstacle to the energy management system in a hybrid power source vehicle [2, 3, 23].

7. FCHEV Future perspective

Despite the current and future challenges facing electric vehicle (EV) technology, generally, and fuel-cell-based electric vehicles (FCEVs), particularly, many futuristic research perspectives indicate that electric vehicles (EV) are the future technology of the automotive industry. This is due to the negative environmental impact of traditional vehicles and the imposition of strict environmental regulations on the modern and future production of vehicles, which aim to preserve the environment and reduce emissions[23,34-37].

The significant industrial and research-oriented shift towards EVs, whether battery-based electric vehicles (BEVs) or FCEVs, will drive the development of the FCHEV technology as the future technology of EVs. Research and development efforts will focus on increasing hydrogen production efficiency from various sources and improving the infrastructure aimed at providing hydrogen fuel to users through highly efficient and widely dispersed refueling stations. Consequently, production and operational costs will decrease with increasing demand. Moreover, there is a developmental trend towards improving the efficiency of fuel cells to increase power productivity and serving-life of time, enabling the use of fuel cell technology across various powertrain designs and vehicle versions, including small cars, commercial vehicles, and trucks. This reinforces the idea of a future shift towards FCV technology[23, 34-35].

The significant and continuous advancement in electric motor technology, power electronics, and modern energy management control (EMC) systems also contributes to the idea of transitioning towards EV technology in the future. Modern EMC systems rely on Artificial Intelligence (AI), machine learning, and Up-to-date information linkage systems between vehicles and manufacturers through wireless networks to enhance power management efficiency in vehicles under various evolving driving conditions over time [36-37].

Consequently, FCHEVs are expected to be one of the prominent features of future EV technology worldwide.

8. Conclusion

The FC system stands out as a highly promising energy solution within the electric vehicle sector, characterized by its zero emissions and impressive energy density. Nevertheless, the FC system requires integration with complementary ESS, particularly batteries and UC, to function effectively within an FEV. This symbiotic relationship has significantly enhanced the efficiency and performance of the FC system, thereby enabling the production of FEVs based on hybrid power source technology. The amalgamation of the fuel cell system as the primary power source with battery and supercapacitor systems as secondary auxiliary power sources has yielded notable improvements in the electrical system's performance and efficiency. This enhancement is evident in various aspects, including increased energy density within the system, greater power delivery to electrical motors, and reduced energy wastage through features like regenerative braking systems.

However, the exceptional performance of this hybrid power system goes beyond merely capitalizing on the strengths of individual energy sources. The effectiveness of the system relies heavily on a robust EMS, serving as a crucial pillar for ensuring seamless cooperation among these sources. Such a management system is essential for orchestrating energy flows within the system, elevating overall efficiency, minimizing fuel consumption, and reducing energy losses. The meticulous design of control levels, encompassing both lower and higher levels, plays a pivotal role in achieving these objectives and overcoming the challenges associated with this technology. Ultimately, effective EM holds the key to unlocking the full potential of hybrid power systems, which are poised to shape the future of modern EVs worldwide.

In conclusion, this research has provided a concise yet comprehensive overview of the Fuel Cell Hybrid Electric Vehicle (FCHEV) system as a promising technology in the future of Electric Vehicles (EVs). The study underscored the significance of the FCHEV system and delved into the individual aspects of its component energy sources, elucidating the mechanism of integrating them to form an integrated hybrid energy system. Furthermore, the research offered a summary of the most crucial energy management systems (EMSs) within the FCHEV system across various levels. This encompassed the lower EM level, which pertains to the electronic power units within the system, as well as the higher level, concerned with orchestrating the lower level and its components through diverse and modern control systems.

Moreover, the research highlighted key challenges that may influence the future trajectory of this system, providing insights into the obstacles that need to be addressed for its continued advancement. Lastly, the study offered a future outlook on the expected evolution and potential advancements of the FCHEV system, shedding light on its anticipated role in shaping the landscape of EVs in the coming years. Through its comprehensive examination and forward-looking perspective, this research contributes valuable insights into the development and potential impact of FCHEV technology in the realm of EVs.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Taqi Aldeen Abo Alkibash: Conceptualization; Writing-original draft, Data curation.
Şule Kuşdoğan: Supervision, Writing, Review, Editing.

References

[1] Tie SF, Tan CW. A review of energy sources and energy management system in electric vehicles. Renew Sustain Energy Rev. 2013;20:82–102.

[2] Sulaiman N, Hannan MA, Mohamed A, Majlan EH, WanDaud WR. A review on energy management system for fuel cell hybrid electric vehicle: Issues and challenges. Renew Sustain Energy Rev. 2015;52:802–14.

[3] Hannan MA, Azidin FA, Mohamed A. Hybrid electric vehicles and their challenges: A review. Renew Sustain Energy Rev. 2014;29:135–50.

[4] Kasimalla VK, Srinivasulu G, Velisala V. Review on energy allocation of fuel cell/battery/ultracapacitor for hybrid electric vehicles. Int J Energy Res. 2018; DOI: 10.1002/er.4166.

[5] Yavuz BN, Kahraman H. Performance Analysis of Geometric Properties of Fuel Cell Components. International Journal of Automotive Science And Technology. 2023;7(1):11-7.

[6] Bromaghim G, K.G., Serfass J, Serfass P, Wagner E. Hydrogen and fuel cells; The U.S. market report. 2010.

[7] Kocakulak T, Arslan TA. Investigation of the Use of Fuel Cell Hybrid Systems for Different Purposes. Engineering Perspective. 2023;3:1-8.

[8] Jahromi MM, Heidary H. Durability and economics investigations on triple stack configuration and its power management strategy for fuel cell vehicles. Int J Hydrogen Energy. 2021;46(7):5740–55.

[9] Ehsani M, Gao Y, Gay SE, Emadi A. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles. CRC Press; 2004. ISBN: 0-8493-3154-4.

[10] Manzetti S, Mariasiu F. Electric vehicle battery technologies: From present state to future systems. Renew Sustain Energy Rev. 2015;51:1004–12.

[11] Krishan O, Suhag S. Grid-independent PV system hybridization with fuel cell-battery/supercapacitor: Optimum sizing and comparative techno-economic analysis. Sustain Energy Technol Assess. 2020;37:100625.

[12] Thounthong P, Raël S, Davat B. Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications. J Power Sources. 2009;193:376–85.

[13] Kilic A. Charging Techniques, Infrastructure, and Their Influences. Engineering Perspective. 2023;3(4):68-74.

[14] Zhao X, Wang L, Zhou Y, Pan B, Wang R, Wang L, Yan X. Energy management strategies for fuel cell hybrid electric vehicles: Classification, comparison, and outlook. Energy Convers Manage. 2022;270:116179.

[15] Changizian S, Ahmadi P, Raeesi M, Javani N. Performance optimization of hybrid hydrogen fuel cell-electric vehicles in real driving cycles. Int J Hydrogen Energy. 2020;45(60):35180–97.

[16] Das HS, Salem M, AAM Zainuri, Dobi AM, Li S, Ullah MH. A comprehensive review on power conditioning units and control techniques in fuel cell hybrid systems. Energy Rep. 2022;8:14236–58.

[17] Garcia O, Zumel P, De Castro A, Cobos A. Automotive DC-DC bidirectional converter made with many interleaved buck stages. IEEE Trans Power Electron. 2006;21(3):578–86.

[18] Zhou X, Sheng B, Liu W, Chen Y, Wang L, Liu YF, Sen PC. A high-efficiency high-power-density on-board low-voltage DC-DC converter for electric vehicles application. IEEE Trans Power Electron. 2021;36(11):12781–94.

[19] Lai JS, Nelson DJ. Energy management power converters in hybrid electric and fuel cell vehicles. Proc IEEE. 2007;95(4):766–77.

[20] Liu D, Li H. A ZVS bi-directional DC–DC converter for multiple energy storage elements. IEEE Trans Power Electron. 2006;21(5):1513–7.

[21] Marzougui H, Kadri A, Martin JP, Amari M, Pierfederici S, Bacha F. Implementation of energy management strategy of hybrid power source for electrical vehicle. Energy Convers Manage. 2019;195:830–43.

[22] Panday A, Bansal HO. A review of optimal energy management strategies for hybrid electric vehicle. Int J Veh Technol. 2014.

[23] İnci M, Büyük M, Demir MH, İlbey G. A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing, and future aspects. Renew Sustain Energy Rev. 2021;137:110648.

[24] Oladosu TL, Pasupuleti J, Kiong TS, Koh SPJ, Yusaf T. Energy management strategies, control systems, and artificial intelligence-based algorithms development for hydrogen fuel cell-powered vehicles: A review. Int J Hydrogen Energy. 2024;61:1380–404.

[25] Lü X, Wu Y, Lian J, Zhang Y. Energy management and optimization of PEMFC/battery mobile robot based on hybrid rule strategy and AMPSO. Renew Energy. 2021;171:881–901.

[26] Kaleybar HJ, Brenna M, Li H, Zaninelli D. Fuel cell hybrid locomotive with modified fuzzy logic based energy management system. Sustainability. 2022;14(14):8336.

[27] Fu Z, Zhu L, Tao F, Si P, Sun L. Optimization based energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle considering fuel economy and fuel cell lifespan. Int J Hydrogen Energy. 2020;45(15):8875–86.

[28] Mehbodniya A, Kumar P, Changqing X, Webber JL, Mamodiya U, Halifa A, Srinivasulu C. Hybrid optimization approach for energy control in electric vehicle controller for regulation of three-phase induction motors. Math Probl Eng. 2022.

[29] Xu D, Liu Q, Yan W, Yang W. Adaptive terminal sliding mode control for hybrid energy storage systems of fuel cell, battery and supercapacitor. IEEE Access. 2019;7:29295–303.

[30] Rahman AU, Ahmad I, Malik AS. Variable structure-based control of fuel cell-supercapacitor-battery based hybrid electric vehicle. J Energy Storage. 2020;29:101365.

[31] Mohammed AS, Atnaw SM, Salau AO, Eneh JN. Review of optimal sizing and power management strategies for fuel cell/battery/supercapacitor hybrid electric vehicles. Energy Rep. 2023;9:2213–28.

[32]Savrun MM, İnci M. Adaptive neuro-fuzzy inference system combined with genetic algorithm to improve power extraction capability in fuel cell applications. J Clean Prod. 2021;299:126944.

[33]Benmouna A, Becherif M, Boulon L, Dépature C, Ramadan HS. Efficient experimental energy management operating for FC/battery/SC vehicles via hybrid Artificial Neural Networks-Passivity Based Control. Renew Energy. 2021;178:1291–302.

[34]Tanç B, Arat HT, Baltacıoğlu E, Aydın K. Overview of the next quarter century vision of hydrogen fuel cell electric vehicles. Int J Hydrogen Energy. 2019;44(20):10120–8.

[35]Boyacıoğlu NM, Kocakulak T, Batar M, Uyumaz A, Solmaz H. Modeling and Control of a PEM Fuel Cell Hybrid Energy System Used in a Vehicle with Fuzzy Logic Method. International Journal of Automotive Science and Technology. 2023 ;7(4):295-308.

[36]Haidar F, Arora D, Soloy A, Bartoli T. Study of Proton-Exchange Membrane Fuel Cell Degradation and its Counter Strategies: Flooding/drying, Cold Start and Carbon Monoxide Poisoning. International Journal of Automotive Science and Technology. 2024;8(1):96-109.

[37]Khalatbarisoltani A, Zhou H, Tang X, Kandidayeni M, Boulon L, Hu X. Energy management strategies for fuel cell vehicles: A comprehensive review of the latest progress in modeling, strategies, and future prospects. IEEE Trans Intell Transp Syst. 2023.