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A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects

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ABSTRACT

The implementations of fuel cells (FCs) in the vehicle industry have gained great attention for the last few decades owing to simple utilization, silent operation, high efficiency and modular structure. Technological advancements show that the use of FCs in electric vehicles (EVs) will increase rapidly and cause a revolution, and will be an alternative to traditional vehicles in the future. Commercial vehicles, projects and research show that work is underway to ensure that FCEVs have sufficient performance advances for their daily transportation needs. However, the lack of a detailed study that will shed light on researchers working in this field is obvious. It aims to provide a comprehensive scientific publication on the current status and future expectations to engineers and researchers interested in this field. In the current study, numerous studies have been examined in detail and added as supplementary to the bibliography. In this context, FCEVs are classified under headings of configurations, systems components, control/management, technical challenges, marketing and future aspects. First of all, FC types and electric motors are discussed in terms of their application areas, characteristic properties and operating conditions. Power converters, which are voltage regulation and motor drive topologies used in FCEVs, are detailed according to the structural frequency of use, structure, and complexity. In the next sections, control issues for converters and technical challenges are branched for FCEVs. In final section, the current status and future aspects are reported using a large number of marketing and target data.

1. Introduction

In today's life, fossil fuels meet the needs of the transportation sector in a significant amount and bring various negative effects such as air pollution, noise and global warming [1,2]. Furthermore, the rapid decline of underground petroleum resources that occur with overuse in fossil fuels is seen as another major problem for the transportation sector [3–5]. As a result of these effects, researchers and industrialists have tended to efficient energy units such as battery and fuel cells (FCs). Among these energy unit types, interest in FCs, which is a clean energy source, has been recently increasing with industrial developments [6]. High efficient operation and flexible power ratings of FCs make them available for various transportation applications such as passenger cars, light commercial vehicles, buses and trucks [7–10]. These transportation applications, which consist of an FC instead of a battery, or combination with auxiliary energy generation units such as battery and/or ultracapacitor (UC), are also called fuel cell electric vehicles (FCEVs) [11–13]. Most FCEVs are known as low-pollutant vehicles that give off heat energy and water in addition to electrical power for kinetic energy [7,14]. In addition, FCEVs not only aid in supporting a clean ambient but also diminish the financial damage of fuels compared to traditional vehicles [15].

In the literature, a lot of studies in the vehicle market that makes FCEV popular and effective are available. There is also a considerable amount of review studies and reports on electric vehicle technology in the literature. While the vast majority of these studies concerns either classical electric vehicles [16–19], only a small portion is concerned with powertrain structures [20,21] and energy management methods [22–24] in FCEV systems. For instance, in Ref. [20], the study focuses on

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Nomenclature

AC	Alternating current
AFC	Alkaline fuel cell
BDC	Bidirectional DC-DC converter
BLDC	Brush-less DC
CAN	Controller area network
CGA	Compressed Gas Association
CSA	Canadian Standards Association
DC	Direct current
DMFC	Direct methanol fuel cell
EM	Electric motor
EMS	Energy management system
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FL	Fuzzy Logic
GA	Genetic algorithm
GWO	Grey wolf optimization
IM	Induction motor
ISO	International Organization for Standardization
MCFC	Molten carbonate fuel cell
MLI	Multi-level inverter
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
PM	Permanent magnet
PSO	Particle swarm optimization
PV	Photo-voltaic
SAE	Society of Automotive Engineers
SMES	Superconducting magnetic energy storage
SOC	State of charge
SOFC	Solid oxide fuel cell
UC	Ultra-capacitor
UDC	Unidirectional DC-DC converter

only power conditioning units and topologies of FCEVs. The architectures for energy management in FCEVs are briefed in Ref. [21]. In addition to these studies, the authors in Refs. [22,23] classify the energy managements according to rule-based and optimization-based methods. In another study, the researchers in Ref. [24] deal with issues and difficulties of energy management used in FCEVs. However, there is not sufficient study to describe the progress and developments in the FCEV technology in detail. Moreover, the power electronic-based classification, marketing and future aspects are not considered in the existing studies related to FCEVs. For this reason, it is a great need to classify FCEV structures in all aspects, to provide guidance and to show expectations in this field. The current study aims to better understand the FCEV topologies, power-electronic based converter topologies, control issues, marketing and future aspects in detail by reviewing current literature and identifying fundamental research needs.

In the construction design of FCEVs, FCs are connected to electric motors through controlled electronic interfacing components [25–27]. The main components of a typical FCEV are given as an FC, a voltage regulation converter, motor drive, electric motor and auxiliary energy generation units (optional) [28–32]. In the literature, it is obvious that there are a lot of configuration topologies related to interfacing components and energy management strategies [33,34]. For this purpose, FCEVs should be categorized according to their powertrain structures, voltage regulation topologies, motor drive converters (inverters) and energy management methods [35–37]. In this way, it is necessary to provide a guidebook for researchers and commercial manufacturers. Therefore, a detailed classification of system structure and expectations in this field is needed for the potential development of FCEVs.

In this paper, the existing systems in the field of FCEV are investigated in order to show the shortcomings in the fundamental system and to help find potential study topics for future studies. In the current study, unlike the previous review studies, FCEV's current energy production sources, topological classifications, powertrain converters and motor drive types are comprehensively explained along with their merits and demerits. In this context, in this work, FCs used in FCEVs are widely presented according to their common usage rates and advantages/disadvantages. Also, power electronic converters used in these vehicles are detailed under two headings as voltage regulation topologies and motor drive converter topologies. Voltage regulation topologies are further classified as unidirectional and bidirectional. Unidirectional voltage converters used in FCs are examined and classified in detail. Bidirectional converters are investigated for auxiliary energy storage units used in FCEVs. In the next section, inverters used in motor drives and their specific information are shared. In addition, the control methods applied in motor drive converters, energy management methods, and the effective operation of the system play an important role in smooth operation. For this reason, scalar and vector-based controllers used in motor drivers are detailed. Furthermore, technical difficulties are emphasized in this study, such as FC life, durability, safety standards, optimization issues, integration and fault diagnosis in these vehicles. Subsequently, the current status of FCEVs, marketing information obtained from automobile manufacturers, and future developments are also presented in this study.

The organization of the current study is laid out as follows: In section "Topological Classification", topological power supplies, FC types, electric machines and power electronic interfacing components are expressed in detail. Then, section "Control and management" presents the energy management methods for voltage regulation converters and drive/speed control methods for inverter topologies. In the next part, technical challenges and problems are clarified. Subsequently, the existing commercial vehicles and actual trends related to FCEVs are elucidated in the sections of "Marketing" and "Future Aspects", respectively. Finally, the study is thoroughly summarized in the "Conclusions and Suggestions" section.

2. Topological classification

In terms of power transmission for FCEVs, the system includes an FC stack, hydrogen tank, a UDC for FC-side, a BDC for an auxiliary unit (optional), a motor drive converter and an electric motor [38–40]. Fig. 1 shows the powertrain scheme of an FCEV. In the operation of an FCEV, the FC stack supplies energy to the dc-bus and keeps the required DC bus voltage [41]. Then, the UDC directly connected to the FC is a system element to keep the dc-bus voltage constant and transfer the energy generated for the propulsion of the vehicle to the motor drive converter [42,43]. DC-AC converter (inverter) supervises motor speed and torque for safe operation. Finally, the electric motors supervised by the drive controller convert electrical energy into kinetic energy [44].

In the following subsections, the classification according to energy supply, FC types, electrical machines and power electronic-based interfacing converters used in FCEVs are presented.

2.1. FC hybridization and power supplies

Fig. 2 shows the classification of FCEVs according to used energy units. In FCEVs, the main energy generation unit is an FC in addition to sub-energy power supply components [45]. In hybrid applications of FCs, different energy generation/storage units are employed to support the FC stacks. Batteries, UCs, superconducting magnetic energy storage (SMES), photovoltaic panels and flywheels are supplementary energy

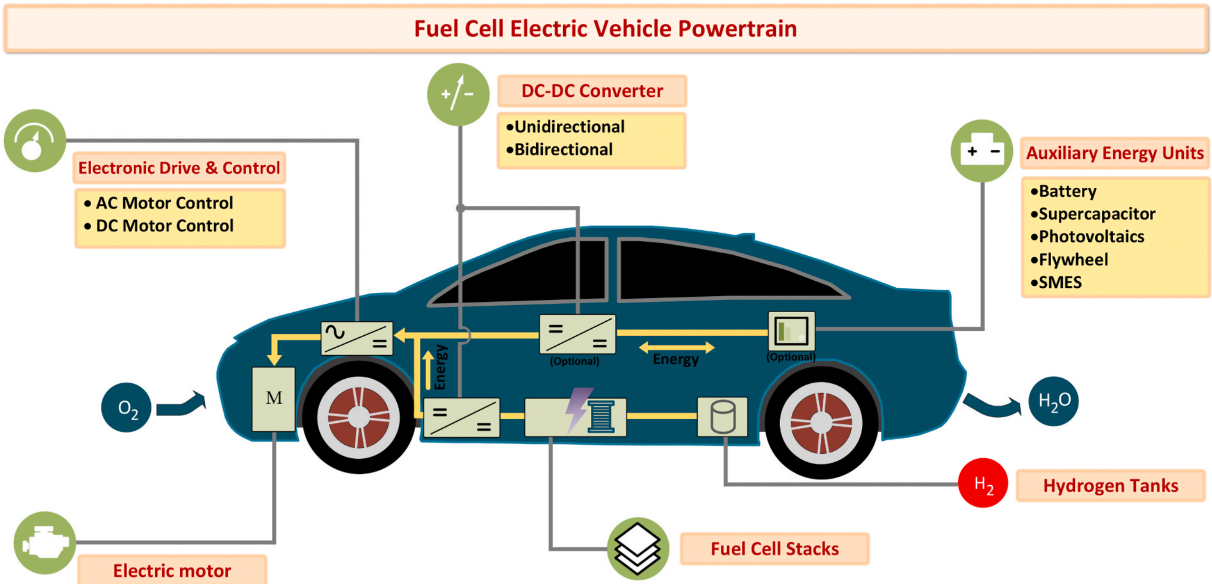

Fig. 1. A general scheme of an FCEV power transmission structure including auxiliary power supplies.

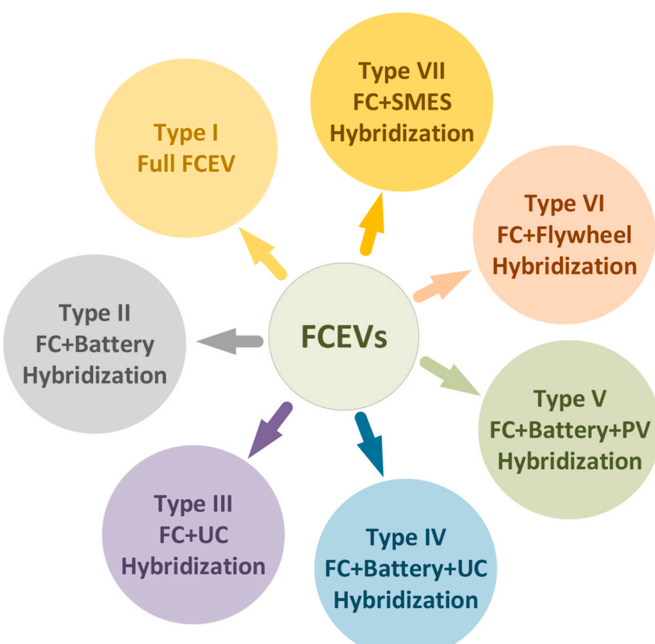

Fig. 2. Topological classification of FCEVs according to power supplies.

units to provide hybridization in FC based electric vehicles.

In FCEVs, the power supplies are divided into two categories: generation and storage. Energy generation/storage elements and their characteristic properties are presented in Table 1. It shows that FCs have very higher energy density and efficiency in comparison with other power supplies. Also, the modular structure of FCs makes it suitable for electric vehicle applications [46]. Also, the lifetime of an FC is approximately between 20 and 25 years. The battery is also a popular power supply as a portable/rechargeable energy storage system for FCEV hybridization. But, its lifetime is very short and useful for a limited time [47]. In FCEV applications, UC is a storage element used to increase the dynamic response of the system. But, the fundamental deficiency of UC is rapid discharging [48]. PV is an energy generation unit, but it is bulky for transportation applications. A flywheel is an energy storage element with high energy density. But, it is heavy weighty together with a long charge time. SMES generates high power at the output but its energy density is fairly low. Furthermore, SMES has short-duration energy storage though high-cost [49].

Table 1
Power supplies used in FCEVs.

Type	Unit	Energy density (Wh/kg)	Lifetime (Year)	Advantages/Disadvantages (+)/(−)
Generation	FC	Very high	20–25 years	• High-efficient energy generation (+) • Modular and compact (+) • Smooth power output (+) • Expensive (−)
	PV	Medium	15–20 years	• Clean and silent (+) • Intermittency of power output (−) • Bulky for a vehicle (−)
Storage	Battery	High	4–6 years	• Portable and rechargeable (+) • Useful for a limited time (−) • Recharging time (−)
	UC	Very low	10–20 years	• Rapid response (+) • Short-term energy storage (−)
	Flywheel	High	5–10 years	• High-speed charging capability (+) • High power rating (+) • Long charge time (−) • Heavyweight (−)
	SMES	Low	25–30 years	• High power output (+) • Short duration energy storage (−) • High-cost (−)

FC based vehicles are categorized into two main topologies: full FC and hybridization with FC. According to this, several hybridization topologies are available in the literature. The FC-based vehicles are classified as follows (i) Full FC (ii) FC + Battery Hybridization, (iii) FC + UC Hybridization, (iv) FC + Battery + UC Hybridization, (v) FC + Battery +

PV, (vi) FC + Flywheel Hybridization and (vii) FC + SMES Hybridization.

2.1.1. Full FCEV

This vehicle is a type that uses a stack of FCs as an energy source in Refs. [50,51]. Fig. 3 shows the general scheme of a full FCEV. It is clear from the scheme that this topology uses only FC stack without other energy generation units. It has a simple structure consisting of a fuel tank, an FC stack, a DC-DC power converter, an inverter, and an electric motor [46]. In addition to structural simplicity, the main properties of these vehicles are a high driving range, fast charging time, high efficiency, cold start capability, silent operation since there are no moving parts, continuity in energy supply, and low emissions [52].

The suitable application areas for full FCEVs include low-speed vehicles such as forklifts, buses, airline vehicles, trams, marine vehicles.

2.1.2. FC + Battery hybridization

In FCEV's hybridization, the most common topology is known as the combination of FC + battery units (Type II) [53–56]. FC is connected to the DC bus using a unidirectional DC-DC converter (UDC), and the battery is tied to a bi-directional DC-DC converter [57], as shown in Fig. 4. In the operational process of FC + battery hybridization, an initial start-up with the battery is provided to prevent the FC from operating in the low-efficiency zone. Therefore, it provides a high current to start the electric motor [47]. After the first start-up of the vehicle, the FC is activated to maintain the operation of the electric motor. At this time, the battery is charged according to the charge status requirement.

2.1.3. FC + UC hybridization

In Type III, FC + UC topology uses an ultracapacitor instead of a battery [48,58], as illustrated in Fig. 5. The UC supports FC only to meet the transient power demand in sudden situations [48]. However, since UC's energy density is low, it is not permanently used to provide energy.

2.1.4. FC + Battery + UC hybridization

The fourth topology, FC + Battery + UC Hybridization (Type IV), has the primary energy source (FC) and two supplementary units (battery and ultracapacitor) in comparison with the previous hybridization topologies [59–61]. In this architecture, the FC is connected to the DC bus with a one-way DC-DC converter. The energy storage units, battery and UC, are connected to the DC bus using bidirectional DC-DC converters (BDCs), as shown in Fig. 6. This topology has the advantages of FC + battery and FC + UC systems, where it provides continuous energy and enhances the dynamic response of FC during transient events [61].

2.1.5. FC + Battery + PV hybridization

In recent years, PV panels have been integrated with FC based electric vehicles for hybridization. In Type V, PV panels generate dc voltages connected to the DC bus with a uni-directional converter for FC + Battery + PV Hybridization [62,63]. In FC + Battery + PV architecture, the FC is used as the main source and the PV panel is considered as the additional energy generator. Both FC and PV are connected to the DC bus via uni-directional converters. The battery is

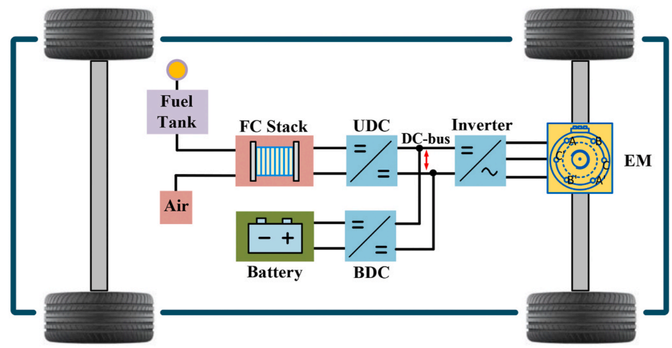

Fig. 4. The powertrain of FC + Battery hybridization (Type II).

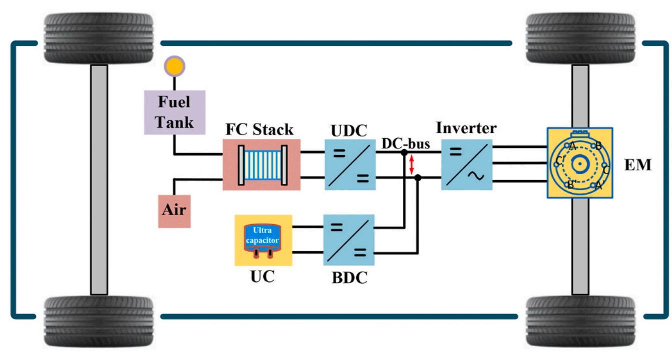

Fig. 5. The powertrain of FC + UC hybridization (Type III).

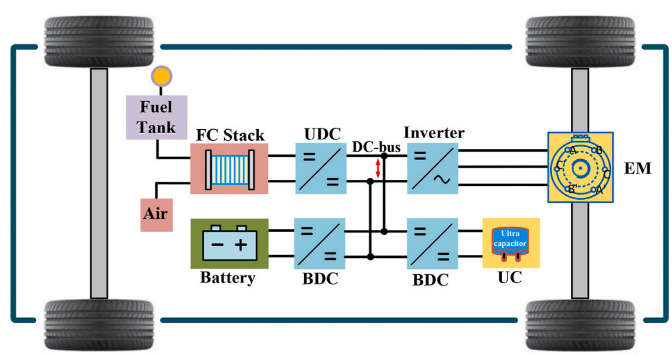

Fig. 6. The powertrain of FC + Battery + UC hybridization (Type IV).

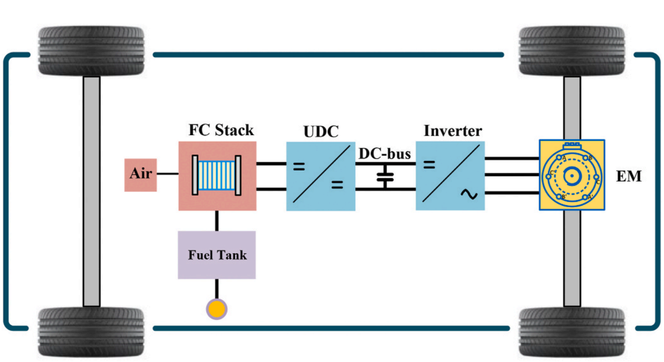

Fig. 3. The powertrain of full FCEV structure (Type I).

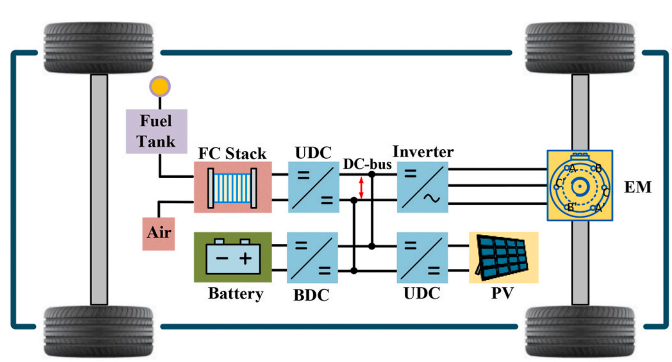

Fig. 7. The powertrain of FC + Battery + PV hybridization (Type V).

connected to the DC bus through a bi-directional converter, as demonstrated in Fig. 7. The power generated by PV panels varies according to the intensity of solar radiation, the temperature, and the direction. According to this, the generated PV power feeds directly the electric motor or charges the battery. On the other hand, the sudden fluctuations in PV panel output can be assumed by the UC because of its high power density, providing low power fluctuations.

2.1.6. FC + Flywheel hybridization

In addition to the previous topologies, an additional topology is used with FC + flywheel hybridization (Type VI) in Refs. [64,65], as shown in Fig. 8. In this topology, similar to Type II, the FC is applied as the main energy source and the flywheel is connected for energy storage as an alternative device to batteries. Flywheels are connected to store the energy mechanically with high rotational speed and transform this mechanical energy into electricity through a generator to support power once EM requires high energy. Furthermore, flywheels have high speed charging capability, high efficiency and high power rating in comparison with batteries [66]. Furthermore, flywheels are environmentally friendly and have a wide temperature operation range, high energy storage capability and long lifetime [66].

2.1.7. FC + SMES hybridization

Fig. 9 shows the powertrain of FC + SMES hybridization (Type VII). This topology does not still investigated for hybrid FCEV applications. However, in the next years, it is expected to use an SMES unit together with an FC stack. SMES performs energy storage through a magnetic field that is created by a direct current flowing on a superconducting coil. SMES has shorter charging and discharging time compared to other storage technologies. Besides, it has quite high charge/discharge cycles and an almost 95% power conversion ratio [49]. However, SMES currently has high cost that constraint its application with FCEVs [67].

2.1.8. FC types and operation

FCs are known as electrochemical energy conversion devices that convert chemical energy directly into electrical energy and heat [68]. The electrochemical transformation is a chemical reaction of oxidant and reductant to produce electricity and water in stack output [69].

2.1.9. Operating principle

The constructional pattern of a hydrogen FC is introduced in Fig. 10. An FC system can be examined in three parts as a component structure. These are an anode, a cathode, and an electrolyte, respectively. The production outputs of an FC stack are water and electrical energy [70].

In an FC structure, the input products for an electrochemical treatment are hydrogen and oxygen. In the process, hydrogen fuel is supplied by anode of the FC, while oxygen is supplied by the cathode terminal [70,71]. During the reaction, hydrogen decomposes into positive protons and negative ions on the anode side. The resulting positive particles reach the cathode tip through the electrolyte, which allows only the positively charged particles to pass [72]. The electrons, the negative ions at the end of the anode, tend to reunite with the positively charged particles and pass to the cathode side with an external circuit [73,74]. Therefore, this electron flow in the external circuit generates electricity. The electrons passing to the cathode side combine with positive charged particles and oxygen to produce pure water and heat [75]. The equation for this reaction is given in Eq. (1), and the chemical reaction equations on the anode and cathode side are given in Eq. (2) and Eq. (3) [76].

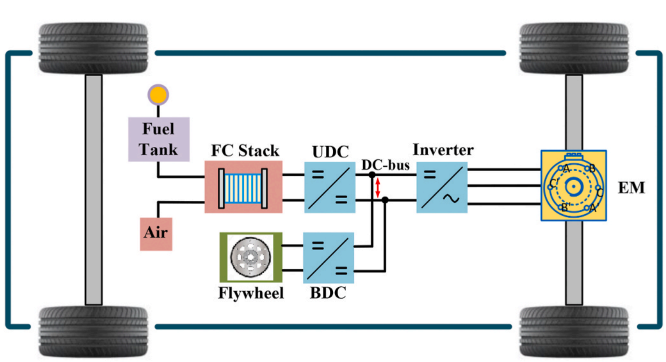

Fig. 8. The powertrain of FC + flywheel hybridization (Type VI).

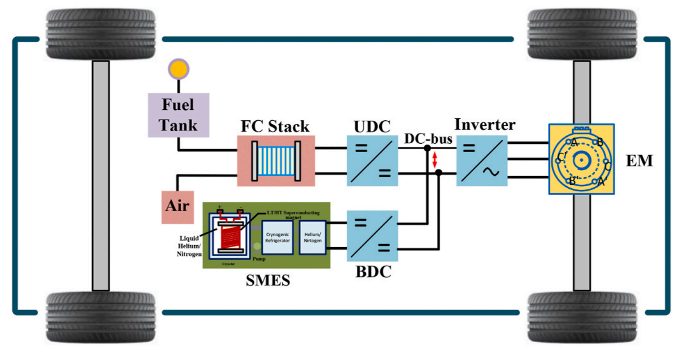

Fig. 9. The powertrain of FC + SMES hybridization (Type VII).

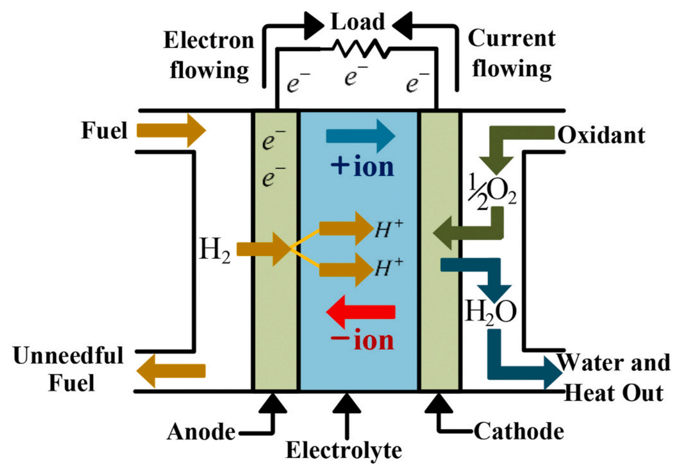

Fig. 10. The basic operation of an FC.

The anode is negatively charged and cathode is positively charged.

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1}$$

$$H_2 \rightarrow 2H^+ + 2e^- \tag{2}$$

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{3}$$

The generated voltage by the reaction of hydrogen and oxygen is theoretically 1.23 V, and the defined value is less in practical applications. Basically, for practical applications, an FC unit generates a voltage of about 0.6–0.7 V at rated current. Due to various factors such as loss of activation, ohmic loss and mass transport loss in the chemical reaction, the produced voltage reduces and the current increases [77].

2.1.10. Operation characteristics

The operation characteristics of a typical FC is significant for estimating the dimensions of the power circuit to be used in different applications. In this respect, it is essential to know the voltage-current (V–I) curves as the electrical characteristic of an FC. The performance characteristics of an FC stack are shown in Fig. 11.

Under various operating conditions, some essential criteria such as accuracy, speed rate, graphical interface and flexibility are used to

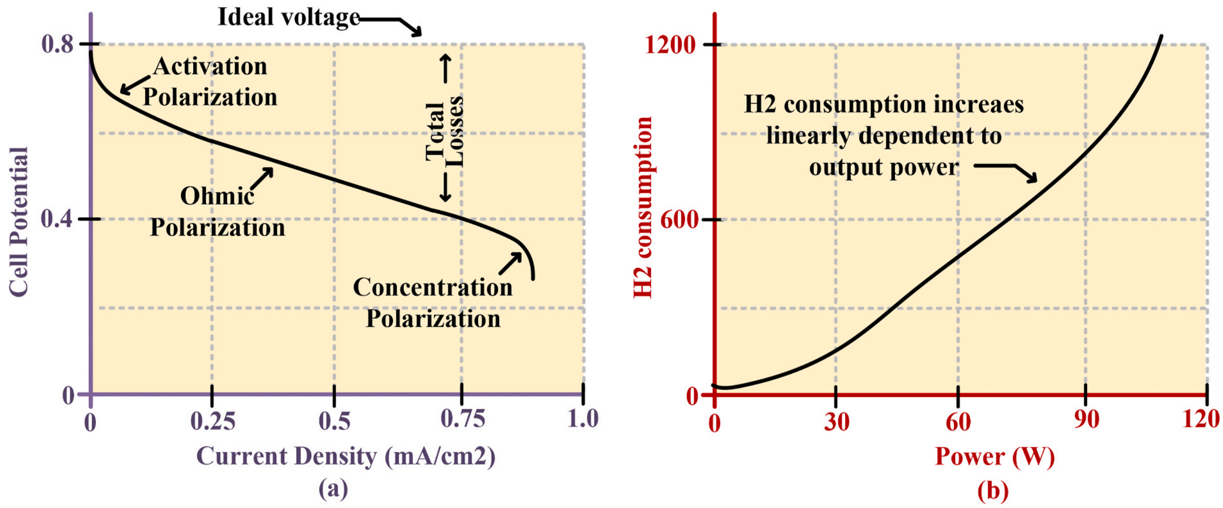

Fig. 11. Electrical performance characteristics of a typical FC (a) V–I curve and (b) H_2 consumption/power curve.

establish an FC model and design its parameters. In the literature, there are various FC models, especially PEMFC model, focusing on dynamic, static or thermal features: FC stack, chemical, electric, fluidic etc. The modeling objectives are performed according to parameter identification, energy management, control, fault tolerance and diagnosis [78].

Three common static FC models are reported in the literature. These are Amphlett, Larminie and Dicks and Chamberlin-Kim models [79]. The most common static model presented in the literature is Amphlett model that is based on Nernst and Tafel equations. In this model, the physical parameters such as pressure, temperature and concentration are taken into account. The other static model is Larmine and Dicks model. This model determines FC voltage-current characteristic by using empirical equations. In this model, the FC voltage versus current amplitude curve is obtained. Three zones are obtained in this curve. These zones are electrochemical activation, linear part and diffusion kinetics of gases [78]. The third static FC model is presented as Chamberlin-Kim model. This model defines the FC voltage in terms of current density [79]. Besides, five parameters are stated in this model, which are varied by fuel-oxidant rate, local temperature, humidity and Membrane-Electrode Assemblies.

In the literature, three widespread models are presented for the dynamic modeling of FC. These models are reported as impedance model, Becherif-Hissel and Dicks-Larminie models [78]. The impedance model proposed in Ref. [80] includes layer capacitance, diffusion impedance and resistances of ions transfer, membrane and contact. In Dicks-Larminie model, the Nernst voltage and the polarization of ohmic, concentration and activation are modelled. This model consists of a voltage source, two resistances and a capacitor. The voltage source demonstrates the Nernst voltage. The resistances model the flow of electrons-hydrogen and losses of activation-concentration. The capacitance models the charge layers. In Becherif-Hissel model, the pneumatic characteristic is considered to obtain the equivalent model for electrical components [81]. In pneumatic characteristics, conservation of mass, energy and charge is taken into consideration.

The dynamic temperature values in an FC unit are significantly high in the time of loading variations. According to the thermal model of an FC, a significant part of the generated energy is converted to heat energy (nearly 50% for a nominal situation) and this situation creates an unfavorable influence which causes a degradation complication and thermal stresses [82]. In an FC stack, the thermal power value must be removed from cells through cooling devices to prevent the overheating and it is defined by using thermodynamic energy balance in a single cell [83].

2.1.11. FC types

FCs are generally divided into different groups according to their chemical properties and operating temperatures, as shown in Table 2. In FCEVs, the used FCs are proton exchange membrane FC (PEMFC) [47,48,58,59,84–89], solid-oxide FC (SOFC) [90–92], direct methanol FC (DMFC) [93,94], alkaline FC (AFC) [95], molten carbonate FC (MCFC) [96] and phosphoric acid FC (PAFC) [97], respectively. These FCs are used for commercial and/or research & development applications. The specifications of FCs are detailed according to typical stack size, theoretical cell voltage, operating temperature, electrical efficiency, advantages and disadvantages [98]. In this context, FCs are used in distributed generation, portable power, backup power, military, space and vehicle applications. In vehicle applications, low temperature and pressurized PEMFCs are the most common FCs thanks to their high power density, lower operating temperature (60–80 °C) and lower corrosion than other FCs [48,99].

2.2. Electric machines

Electric motors and motor drives play an important role in FC-powered vehicles. First of all, electric motors are generally classified into two types: AC and DC. Then, the electric motors exist in different types called asynchronous AC, reluctance AC, synchronous AC, brushed DC and brush-less DC. The main classification of electric motors used in FCEVs is accomplished and given in Fig. 12. Among these motor types, the most common types of an electric motor are induction, permanent magnet and brush-less motors used in FC vehicle applications. A comparison of various EMs applied in EVs is given in Table 3 according to their efficiency, cost, lifetime, size, reliability and controlability. It is noted that the early commercial EVs were used BDC motor. On the other side, IMs and PMs are preferred in the recent commercial EVs owing to their propulsion system [100]. Further details of EMs are presented in the following section.

2.2.1. AC electric motors

In FC vehicles, asynchronous electric motors, also known as induction motors, are preferred thanks to its suitability, reliability, easiness, robustness and wideband speed range, implemented in Refs. [44,101–108]. There are two types of induction motors used in FCEVs: squirrel cage [101] and wound rotor (slip ring) [65]. In the second AC motor type, asynchronous motors can be investigated in three types: sinusoidal [109], brush-less [110], and reluctance [111]. In permanent magnet (PM) motor, it has outstanding characteristics such as high efficiency, low weight, lower volume, high torque, and high power density [112,113]. But, these motors have a narrow constant power range due to

Table 2
Comparison of FCs used in FCEVs.

Disadvantages	Expensive catalyst cost Sensitive to hydrogen impurity	Expensive catalyst cost Long start time	Sensitive to CO2 levels in oxygen and hydrogen	High operation temperature, corrosion and breakdown Long start time	High operation temperature Long start Power density	Intermediates adhesion to the catalyst surface
Advantages	Low operating temperature Fast starting Less corrosion & electrolyte management problem	Higher efficiency with CHP Increased tolerance in fuel impurity	Higher performance Faster cathode reaction and start Lower material cost Low operating temperature	Suitable for CHP Higher efficiency Fuel flexibility Hybrid/gas turbine cycle	Suitable for CHP Higher efficiency Fuel flexibility	Low cost due to lack of fuel reformer
Efficiency (%)	40–60	40	60	60	50	40
Operating temperature (C)	<100	150–200	90–100	500–1000	600–700	60–200
Cell Voltage (V)	1.1	1.1	1	0.8–1	0.7–1	0.2–0.4
Stack power (kW)	<1-250	50–100	1–100	<1-3000	300–3000	0.001–100
Type	**PEMFC** [48]	**PAFC** [97]	**AFC** [95]	**SOFC** [90]	**MCFC** [96]	**DMFC** [93]

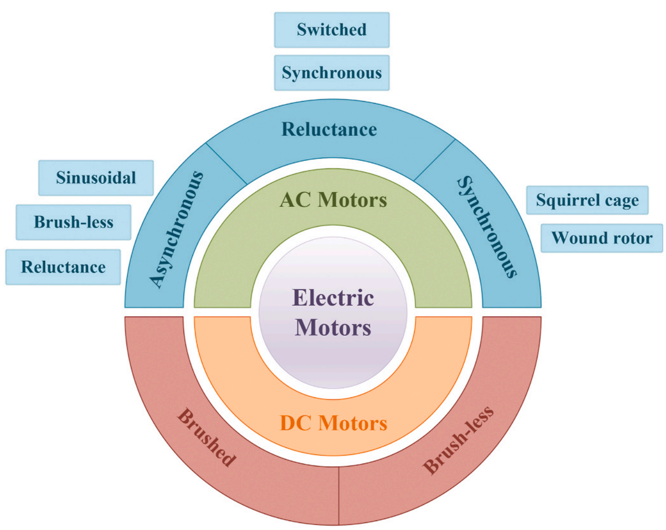

Fig. 12. The classification of electric motors used in FCEVs.

Table 3
A comparison of EMs in terms of some criteria.

Specification	BDC	BLDC	PMSM	Syn-RM	Sw-RM	IM
Lifetime	*	***	***	****	****	****
Cost	**	*	*	****	***	****
Volume	*	****	****	***	***	***
Efficiency	*	****	****	***	***	***
Controllability	****	***	***	***	**	***
Reliability	*	***	***	****	****	****

(* bad, **average, ***good, ****excellent).

the field attenuation limited by the PM. Due to PM's low rotor losses compared to IM, a high-efficiency operation can be achieved [109]. Also, there are two types of permanent magnet motors in FCEVs: surface [114] and interior [115]. Wound-rotor motors are known as electric motors whose armature and field windings are separately tied to a common point at outside. Brush-less synchronous motors employ the induction in the stator to rotate the rotor by using a rotating magnetic field in Refs. [116,117]. Although PMSMs currently have wide usage, the price fluctuation and limited resource in PMSM materials will lead to increase the usage of Syn-RM and Sw-RMs [100]. In reluctance ac motors, the quantity of stator and rotor poles are equal to each other [111], and rotor losses are less than compared to a traditional induction motor [118]. Switched reluctance motors can reach a wide range of constant power levels [119,120]. [119,120]. The rotor structure of these motors are simple and robust. In addition, they inherently perform a fault-tolerant ability [121]. For traction applications, the main disadvantage of the switched reluctance motor is considerable torque fluctuations, vibration and high noise [120]. Furthermore, this motor has lower torque density in comparison with PMSM [100].

2.2.2. DC electric motors

In FCEVs, DC motors are classified as brushed and brush-less. The first DC motor type used in FCEVs is brushed dc motor, a simple structure implemented in Refs. [122–125]. In this kind of motor, permanent magnets are replaced by windings in the stator, depending on the application [122]. Nevertheless, this motor type has no further application in recent commerical EVs. The brush-less dc (BLDC) motor used in FCEVs is a DC motor type like an AC motor [126,127]. Furthermore, this motor is similar to the PMSM as its operating principle because there is no brush component attached to the armature itself. The condition that separates the BLDC motor from the PMSM that has an ac supply [128]. BLDC motors recently have more interest in application with EVs. Similar to PMSM, BLDC has low volume and high efficiency with great motor control ability. Moreover, many sensorless methods have been proposed for commutation to reduce the cost further. But, the cost of this motor type is still higher than induction motors [129].

2.3. Power electronics interfaced converters

In this section, the power electronic converters used in FCEVs are given and described in detail. In FCEVs, two main converters are used: DC-DC and DC-AC. The suitable converters should be chosen according to topology and application target. Therefore, it will be better to conduct the electric machines and additional supplementary components used in FCEVs before explaining the converters' details.

PV, battery and UC may be used with FCEVs, as mention in the previous section. In FVEC systems, there is the main DC bus where all components are connected to this DC bus via a converter. To decide the type of the converter, the power flow of these components should be understood. Meanwhile, FC and PV have only energy generation capability, while the battery and UC have energy storage and generation capabilities. Thus, UDCs are preferred in FC and PV systems, and BDC topologies are used for battery and UC. Besides, the inverters are used as motor drive systems in electric motors. The details of all converters used in FCEVs are particularly given in the following section.

2.3.1. Voltage regulation topologies

In this section, dc voltage regulation topologies in FCEVs are conducted. DC-DC power converters are used to regulate the dc voltage and to satisfy optimum power transfer. In general, these converters are classified as isolated and non-isolated in some previous studies. In hybrid FCEVs, unidirectional and bidirectional DC-DC converters are used according to the power flow direction. In FCEVs, unidirectional DC-DC converters are chosen for utilization with FC, and PV included topologies. On the other side, BDCs are required for energy storage based hybridization topologies.

In FCEVs, several UDC topologies are used with FC and PV. Fig. 13 demonstrates UDC topologies used in FCEVs. Among these topologies, boost converter is the most commonly applied one because of its advantages such as simplicity and low-cost [59–63,130,131]. However, the boost converter has a high output voltage ripple. A high capacity capacitor is needed to reduce the voltage ripple, which results in a quite large volume [132]. To reduce the output voltage ripples in the boost converter, two-phase interleaved boost converter topology is proposed in Refs. [86,133,134]. In this configuration, two boost converters with the same rating values are connected in parallel with having a common DC bus. Thus, the input current is shared between the legs, reducing the current stress on switching components and ensuring high FC power transfer. In addition, the voltage ripple in two-phase interleaved boost converter is lower than the conventional boost converter by ¼ factor [135]. Besides, the reduced current ripple leads to increase the lifetime of FC and output capacitor. A four-leg interleaved boost converter is proposed in Ref. [50] to further decrease the output voltage ripple. Moreover, a four-leg floating interleaved boost converter is offered in Ref. [50] to increase the output voltage ratio with the same duty cycle and to decrease the voltage stress on the switching components. In addition to the aforementioned interleaved boost converters, a multi-phase interleaved converter is performed in Ref. [136]. A high voltage gain boost converter is applied in Ref. [137] to raise the output voltage gain by cascading two boost converters. In this topology, twice components are used in comparison to the conventional boost converter. A distinct boost converter topology which is called a modified wide voltage range gain boost is proposed by Zhang, Y et al. [138] to enhance voltage gain range. The main advantage of this topology is that wide voltage gain is obtained by using a single switching component. A capacitor clamped H-type boost converter is proposed in Ref. [58]. This configuration has high voltage gain opportunities while avoiding narrow PWM signal pulsing. Another UDC topology is isolated full-bridge topology [51,139]. In this topology, the FC is isolated from the DC bus via a transformer. Thus, the FC can be prevented from a fault at the DC bus side. Besides, a high voltage gain can be obtained through changing the transformer turn ratio.

BDC structures are also required in FCEV hybridization applications once an auxiliary storage component is used. Battery and/or UC is used with FC to ensure high initial start-up current and prevent the FC from a low efficient operation zone. The most commonly used topology in the literature, shown in Fig. 14(a), it is a bidirectional buck-boost converter used in Refs. [47,54,61,140–142]. This topology has a simple structure

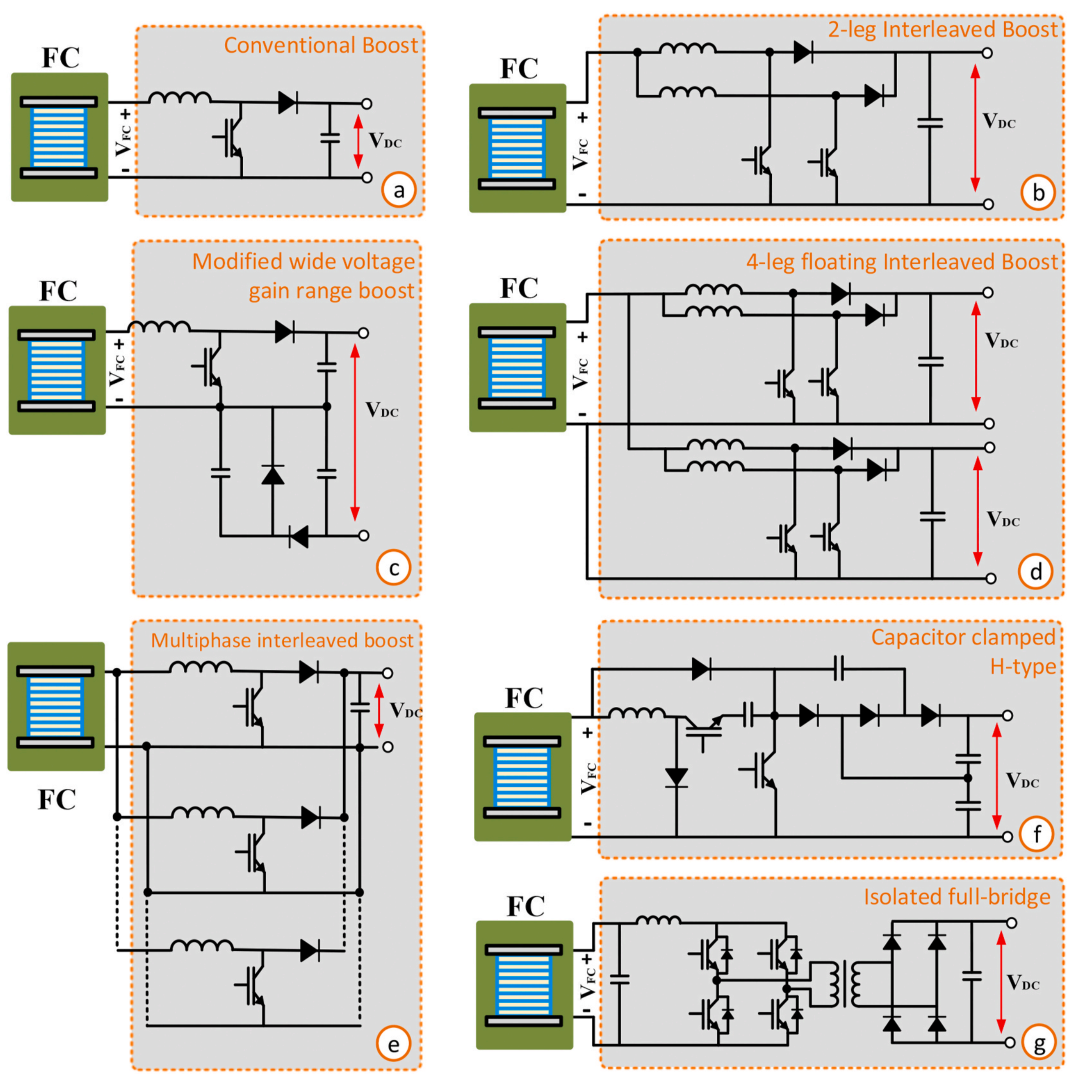

Fig. 13. Unidirectional DC-DC converters in FCEVs (a) conventional boost, (b) interleaved boost, (c) modified wide voltage gain range boost, (d) 4-leg floating interleaved boost, (e) multiphase interleaved boost, (f) capacitor clamped H-type, (g) isolated full-bridge.

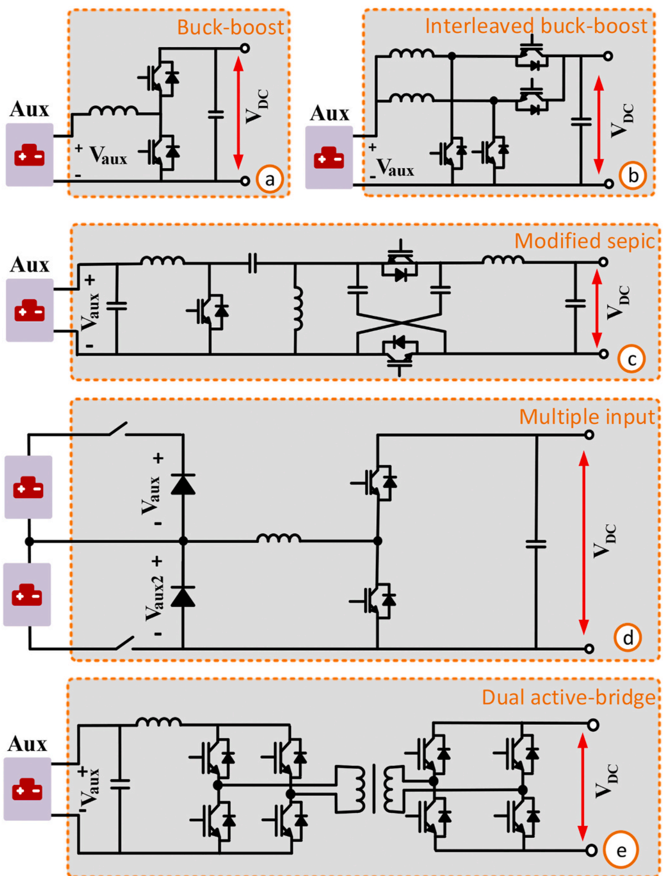

Fig. 14. Bidirectional converter topologies used in auxiliary energy generation elements (battery, ultracapacitor, et) of FCEVs (a) conventional buck-boost, (b) interleaved buck-boost, (c) modified sepic, (d) multiple-input and (e) dual active bridge.

and operation principle, and two switching elements (an inductor and a capacitor) are used. Furthermore, its structure is the same as a half-bridge inverter. Similar to unidirectional interleaved boost converter, the bidirectional buck-boost converter is transformed into the interleaved configuration by paralleling the switching components & inductors, expressed in Ref. [86], as shown in Fig. 14(b). Another bidirectional converter, shown in Fig. 14(c), is a modified SEPIC converter proposed by authors in Ref. [143]. SEPIC converter is also known as the current-voltage-current converter used where energy storage is required. This topology has a wide conversion ratio of input voltage and low voltage stress on switching components. Modular multiple-input converter, shown in Fig. 14(d), is applied in FCEVs to obtain higher power in Refs. [144,145]. In this topology, two or more input energy sources can be used to transfer energy to DC bus. A bidirectional isolated dual full-bridge converter is applied in Refs. [139,146]. This topology is suitable for providing isolation between FC and DC bus side and low stresses over the switches.

Table 4 summarizes the DC-DC converter topologies applied in FCEVs regarding energy flow direction, isolation, number of switches, and application complexity. To sum up, a unidirectional converter is sufficient for FCEV applications if no hybridization or FC + PV hybridization is performed. On the other hand, a bidirectional converter is necessary when a storage element is added. The selection decision among these converters can be performed according to complexity, cost, and operation safety.

2.3.2. Motor drive topologies

Electric motors need to operate effectively and to be properly

Table 4
The specifications of DC-DC converters in FCEVs according to the significant classification values.

Topology	Direction	Isolated	Switch #	Used in	Complexity
Conventional boost [62, 63]	Unidirectional	No	1	FC, PV, SMES	Simple
Interleaved boost [135]	Unidirectional	No	2	FC	Simple
Capacitor clamped H-type boost [58]	Unidirectional	No	2	FC	Medium
Four-leg floating interleaved boost [50]	Unidirectional	No	4	FC	High
Multiphase interleaved boost [136]	Unidirectional	No	n	FC	Medium
Modified wide voltage gain range boost [138]	Unidirectional	No	1	FC	High
Isolated boost full bridge [139]	Unidirectional	Yes	4	FC	High
High voltage gain boost	Unidirectional	No	2	FC	High
Conventional buck-boost [140]	Bidirectional	No	2	Battery	Simple
Interleaved buck-boost [86]	Bidirectional	No	n	Battery, UC	Simple
Modified sepic [143]	Bidirectional	No	3	Battery	High
Modular multiple input [144]	Bidirectional	No	n	Battery, UC	Medium
Dual active bridge [146].	Bidirectional	Yes	8	Battery	High

controlled. The converter topologies in this section include power converters, namely motor drivers, that transfer energy to control the EM [147]. Commonly used power converters in FC applications are classified into two main categories; low voltage three-phase inverters and multi-level inverters. These classified topologies are shown in Figs. 15 and 16, respectively. The most widespread topology in FCEVs is three-phase three-wire VSI [148–153]. as shown in Fig. 15(a). This topology includes a DC-link bus and a three-phase bridge inverter and has a simple control algorithm. As shown in Fig. 15 (b), another topology used in FCEV is three-phase three-wire CSI [154,155]. This topology has performance superiority of current control, and it is faster than VSI configuration. As presented in Fig. 15(c), another attractive topology in FCEVs is a z-source inverter (ZSI) used in Refs. [54,156,157]. Unlike a traditional inverter, ZSI has two inductors and capacitors in front of the dc-link of the inverter which can operate in buck and boost mode, leading to a wide range operation of FC output voltage. This topology can perform motor control, battery state of charge (SOC) control, and FC power control at the same time. A diode rectified quasi z-source inverter (qZSI) as shown in Fig. 15 (d) is studied by Yun Zhang et al. [158]. Additional diodes are added to conventional ZSI topology. In this way, a common ground point is provided at input and output sides, which reduce EMI problems and ensure maintenance safety [158]. To reduce the number of switching components and inverter cost, a four-switch inverter is proposed in Ref. [159]. The circuit diagram of the four switch inverter is demonstrated in Fig. 15(e).

Multilevel inverters are also investigated for FCEV applications because of having many benefits such as less switching losses, EMI in

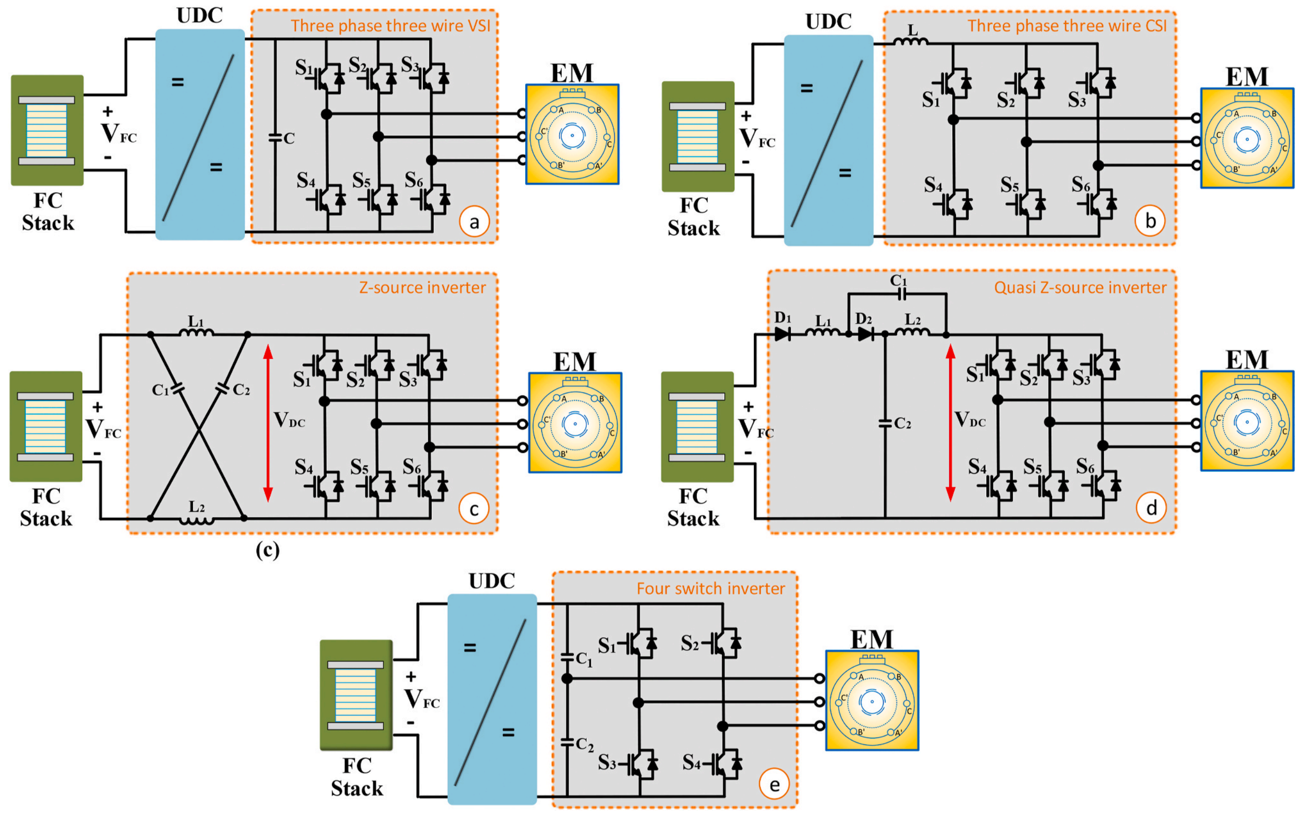

Fig. 15. Low voltage three-phase inverters implemented in FCEVs (a) three-phase three-wire VSI, (b) three-phase three-wire CSI, (c) Z-source inverter, (d) quasi-Z-source inverter and (e) four-switch inverter.

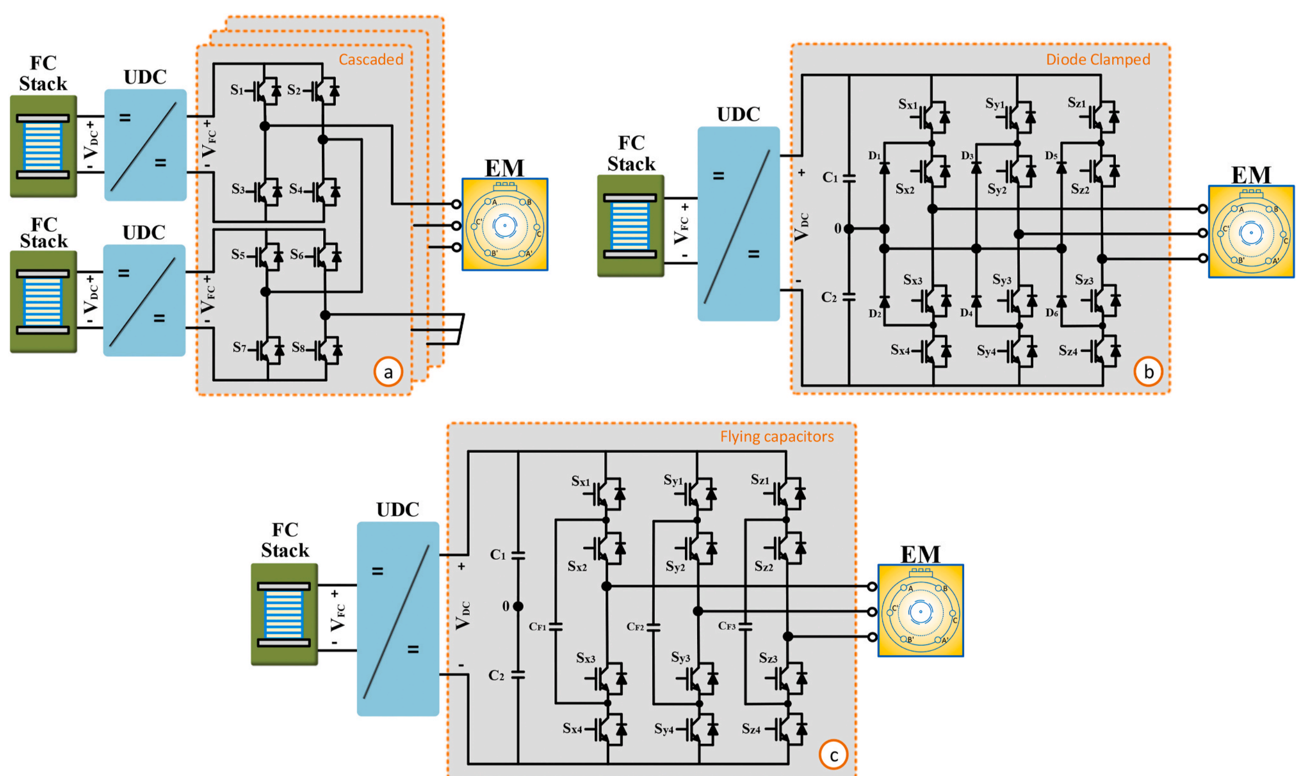

Fig. 16. Multilevel inverter topologies in FCEVs (a) cascaded, (b) diode clamped and (c) flying capacitors.

outputs and harmonic ripples [160,161]. Fig. 16 shows three multilevel inverter configurations used in FCEVs. The first topology is cascaded H-bridge MLI shown in Fig. 16 (a). This topology is formed by two series-connected single-phase H-bridge inverters [162,163]. Cascaded h-bridge inverter has the advantages of switching redundancies and fault-tolerant operation [162]. The second MLI topology is diode clamped (neutral point clamped) inverter, composed of two-phase VSIs mounting one VSI over the other one [164,165], as illustrated in Fig. 16 (b). The output voltage and power levels can be expanded by increasing the number of switches and clamping diodes. The other MLI configuration is flying capacitors [166]. The flying capacitor MLI is demonstrated in Fig. 16(c). It has a similar configuration with diode clamped MLI, only flying capacitor is replaced with diodes. In this topology, the neutral point can be performed by connecting the output to the middle point of the dc-link capacitors. The flying capacitor MLI topology has the property of being flexible more than diode clamped topology [167]. To sum up, the power rating, efficiency and application areas of the inverter topologies in FC based systems are given in Table 5.

3. Control and management

The control issue of power electronic interface converters plays an important role in the efficient and safe operation of FC based vehicles. In these systems, many studies have been conducted on the control of power flow and energy management. In this part, the control mechanisms are expressed and clarified for energy management and power flow through the DC-DC converter and inverter, respectively [168]. The control and management strategies are focused on (1) minimization of fuel consumption and loss, (2) simplifying the structure, (3) increasing the maximum efficiency and (4) ensuring the robustness and satisfactory driving performance [169,170].

3.1. Energy management methods

Energy management methods in FC electric vehicles deal with the control of DC-DC converters and integration of FC, battery, UC, and PV. Fig. 17 introduces the classification of energy management methods used in the control of the DC-DC converter part. In addition, the advantages and disadvantages of the methods are summarized in Table 6.

3.1.1. Rule-based methods

The rule-based strategy is the most commonly known method to achieve real-time management in FCEV applications [171–173]. The rule-based methods are basic control structures that rely on operation mode. These methods are static controllers, where the operation point of the device (i.e. motor) is decided through rule tables to achieve the requirements of other devices (i.e. battery) and driver. The rules are stated according to mathematical, human intelligence or heuristics models

Table 5
The properties of motor drive converters used in FCEVs.

Topology	Complexity	Voltage Stress	Switch #	DC-link	Cost
Three-wire VSI [153]	Simple	High	6	1	Low
Three-wire CSI [155]	Simple	High	6	1	Low
Z-source [157]	Medium	High	6	2	Medium
Quasi Z-source [158]	Medium	High	6	1	Medium
4-switch [159]	Simple	High	4	2	Low
Cascaded [162]	High	Low	n/2 + 1	n	High
Diode Clamped [166]	High	Low	n/2 + 1	n	High
Flying Capacitor [167]	High	Low	n/2 + 1	n	High

n: voltage level

[174]. In FCEVs, two main types of rule-based methods, Fuzzy rule-based and deterministic rule-based strategies, are used to supervise energy management from FCs to electric motors [175].

Fuzzy rule-based strategies: Fuzzy logic control is unique to use numerical data and linguistic information simultaneously. Fuzzy control method has high robustness, and it is easy to implement [174]. Among rule-based strategies, fuzzy rule-based approach is a commonly applied technique used in dc-link voltage control [47,59]. As introduced in Fig. 18, the fuzzy rule-based strategy operates according to the decision rules and includes three steps: fuzzification, decision making and defuzzification [176]. The performance of an FL strategy is determined by the membership function and fuzzy rules at the fuzzy reasoning stage. There are three types of fuzzy rule-based strategy: optimized [177,178], adaptive [179] and predictive [180]. The first fuzzy-based method, called optimized fuzzy, is performed to adjust the control mechanism for fuel consumption, emission reduction, repair the state of charge, and performance enhancement of driving. By using these methods, membership function and decision rules are optimized through particle swarm optimization [181], genetic algorithm [182], bee algorithm [183], and proportion factor algorithm [184] in FCEVs. The second method based on FL is defined as an adaptive fuzzy rule-based strategy. In this strategy, adaptive methods are integrated into FL rule-based strategy to enhance self-adjustment [185]. In the literature, FL is also integrated into neural networks [173], machine learning [186], and decentralized control [187]. Furthermore, predictive based fuzzy logic control is available in addition to optimized and adaptive based methods. This strategy is operated basis on the rules of prediction of the next state and real-time adaptation [188].

Deterministic rule-based control strategies: The rules to be determined by the emission or fuel economy plan of the traction engine are decided for deterministic rule-based control strategies. The implementation of these rules is often achieved through the previously calculated searching tables. State machine control [189–191], thermostat [189,192], power follower [141], and gliding-average [193] are methods based on deterministic rule-based control. The state machinery (multi-mode) method operates according to the states of the defined flowchart and its states [190]. The thermostat method is also known as on/off method and provides a fixed-torque and limited speed between defined values [192]. The power follower is also called baseline control which regulates the power supply to pursue the required power of FCEV [141]. In addition to the methods mentioned above, gliding-average is used as a deterministic rule-based control strategy in FCEV [193].

3.1.2. Optimization-based methods

The optimization-based mechanism is used to minimize vehicle emissions and fuel consumption (cost functions) by calculating the optimum torque reference or transmissions ratio. There are two solutions, known as global optimization and real-time optimization [18].

Offline optimization methods: These strategies aim to minimize the energy loss during an information-priority cycle and can be investigated in four groups: direct, indirect, gradient, and derivative-free. The most common offline direct optimization method is dynamic programming [194,195] used in FCEV systems. Dynamic programming is a control technique that aims to find optimal control methods using a multi-step decision-making process. The algorithm in dynamic programming is an optimization problem with multiple stages selected from a certain number of decision variables at each time step of a decision based on the optimization criterion. Dynamic programming and its advantages are applicable to linear and nonlinear systems [196]. In FCEVs, Pontryagin's minimum principle is an indirect optimization method to acquire the forced global issue. The gradient optimization methods used in FC based vehicles are linear programming [197] and convex programming [198,199]. Among these methods, linear programming is calculated by approximating the nonlinear model of EV's fuel consumption to achieve a globally optimal solution [200]. Linear programming has been successfully carried out in EMS problems in vehicle

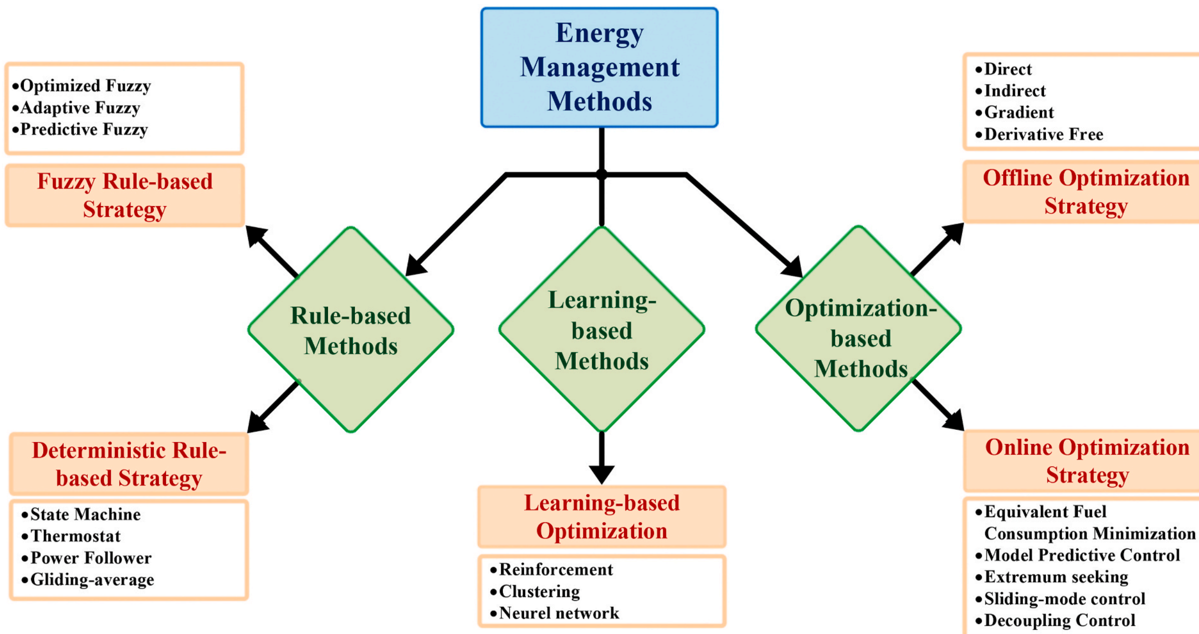

Fig. 17. The classification of energy management systems used in FCEVs.

Table 6
Benefit/drawback of energy management methods.

Method		Benefit	Drawback
Rule-based	Fuzzy	Usage of real-time parameter leads to robust system Useful for physical process reasoning Low hydrogen consumption	Long run time Limited input parameter Require expert knowledge to determine the fuzzy rules
	Deterministic	Simple and easy control Low initial cost Improving hydrogen fuel economy Minimization energy transmission loss	Not accurate enough Require a rule table with human reasoning under optimal conditions Low energy optimization and gas emission
Optimization-based	Online	Localize global optimization problem Minimization of fuel consumption Suitable for real-time analysis	High computational time Need to an instantaneous cost function
	Offline	Cost reduction of basic techniques Low computation cost Optimization of irregular issues	Approximation may not suitable for complex drive train system Not suitable for real-time analysis The need of prior information from driving cycles
Learning-based	Learning	Absolute model knowledge not required	Accurate data mining is difficult and time-consuming

applications. With convex programming, FCEV system models are simplified to suit convexity demands [198,199].

In the energy management part of FCEVs, derivative-free methods are solution techniques based on meta-heuristic algorithms. Simulated annealing [201], stochastic control [202–205], genetic algorithm [206], particle swarm [207], grey-wolf optimization [86] and divided rectangular [177] are used derivative-free methods in FCEV systems. Among these methods, simulated annealing uses a stochastic technique to search for solutions and takes candidates for solutions [201]. It also takes into account improvements to the objective function. But, this method cannot demonstrate that an acceptable optimal result has been obtained [201]. Stochastic control is a strategy developed to model optimization problems with uncertain situations and to find a solution. In this approach, the infinite vision stochastic dynamic optimization problem is solved and formulated [202–205]. A genetic algorithm (GA) is an intuitive search algorithm created to find solutions to problems in optimization. In Ref. [196], GA begins with a series of chromosomes called populations to create an optimal solution for a technical problem. The solutions created by each population are taken and selected according to their degree of suitability to create new and more advanced versions. Particle swarm optimization (PSO) is based on an intelligent computational strategy [208]. PSO is a population-based optimization technique developed basis on the behavior of flocks of birds and fish [209]. Grey Wolf Optimization (GWO) is a strategy based on solving problems limited by noticeable convergence success [86]. GWO is proposed inspired by the hunting and social behavior of grey wolves [210]. In Ref. [86], GWO is proposed for EMS to reduce FC harmful current transitions and increase FC's component life with fast optimization and convergence. In divided rectangular method, it is performed to supervise the most dominant controlling parameter through a variety of driving period [177].

Online optimization methods: These methods are applicable for real-time analysis unlike offline methods. A cost function is introduced in this method, which of depending on the current state parameters of the system. By using these optimization methods in FCEVs, the systems are controlled through the equivalent consumption minimization strategy [53,211], model predictive control [205], extremum seeking [212], sliding mode control strategies [213,214], and decoupling strategy [215,216].

The operational scheme of the equivalent consumption minimization strategy is presented in Fig. 19. The equivalent fuel consumption strategy aims to turn the global optimization problem into a local optimization problem and to ensure that the equivalent fuel consumption is minimized continuously [53,211,217]. The main purpose of this control strategy is to keep the sum of FCEV hydrogen consumption and equivalent hydrogen consumption to a minimum.

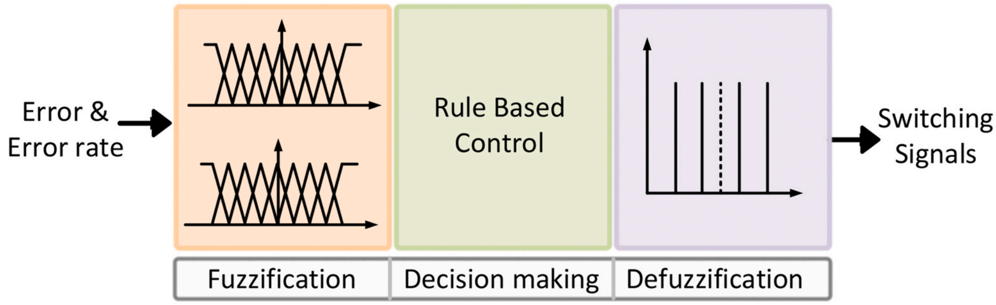

Fig. 18. The common rule-based method: fuzzy control.

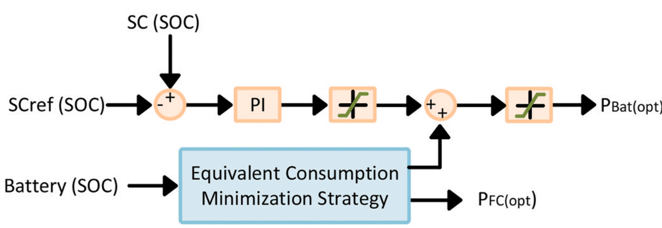

Fig. 19. The common optimization-based method called equivalent consumption minimization strategy.

In Refs [218,219], model predictive control is used as a control strategy based on the future output estimate used in FCEVs. This strategy uses a model to predict future output values based on the system's previous and current values [220]. There are different mode predictive control methods used in FCEVs: deterministic [194,221], stochastic [222] and telematics [223]. Fig. 20 presents the operating diagram of model predictive control in an FCEV system. According to model predictive control operation, it works with a prediction structure based on three basic stages: (1) to calculate the optimum input values to diminish the target related to enforcements, (2) to implement the initial item of the derived optimum inputs to the environmental system and (3) to move the all prediction view and to repeat from the previous stage.

In online optimization methods, extremum seeking method obtains maximum/minimum values for a nonlinear power construction in Ref. [212]. Also, the authors use sliding-mode control in the FCEV application due to its simplicity and robustness in Refs. [213,214]. Sliding mode control is performed to supervise engine/generator torque within optimum values. In decoupling control, the researchers employ this method to manage the regulation of common dc-bus voltage in FC-battery hybridization [215,216].

3.1.3. *Learning-based methods*

These methods exploit data mining arrangements to generate optimum controller performance in FCEVs. In learning-based energy management systems, absolute model knowledge is not required to perform the system check. But, creating an accurate database, which has a direct impact on control performance and size, is difficult and time-consuming. In FCEV studies, different learning-based methods such as reinforcement learning, clustering learning, and neural network learning are performed to supervise energy flow in the system.

In reinforcement learning-based vehicles, the supervision includes two sections named as learning agent and an ambient. The learning agent affects each other permanently with the ambient. The learning agent monitors the state of the ambient and selects an activity that enters the ambient. Fig. 21 introduces the operational process of a reinforcement learning-based method. The aforementioned method can autonomously determine the optimum action based on data entries, without any forecasting and pre-described comments.

In the clustering learning algorithm, a model is created through the extraction of arrangements in the entry information in Ref. [224]. The extraction procedure is followed as (1) generate comments, (2) implement an analytical step to diminish the repetition and (3) edit information for resemblance [224]. Another learning method modelled basis of neurons is neural network and it is a robust approach for handling complex problems on nonlinear FC systems, used in Ref. [225]. Similar to an actual multi-link neuron, nodes are objects with multiple inputs and outputs in a neural network. But, the main drawback of the neural network is that it requires a large number of training data to train the networks [226].

3.2. *Drive & speed control*

This section presents the state of the art of recent progress in drive/speed control methods used in electric motors. The motor speed control performs the transfer of electric power into mechanical power. Speed control is not a simple subject from FCs to electric motors, and it is dependent on smoothing drive control methods through power electronic interfacing elements [6]. An inverter connected between the DC bus and the electrical machine is an interfacing element to realize motor control in full FCEVs and hybrid FCEVs. The inverter ensures variable voltage and frequency for motor control. Several inverter structures applied for motor control are given in the previous section. In FCEVs, BLDC motor, synchronous motor and induction motor are usually preferred as mentioned in the Marketing Section. The control of these

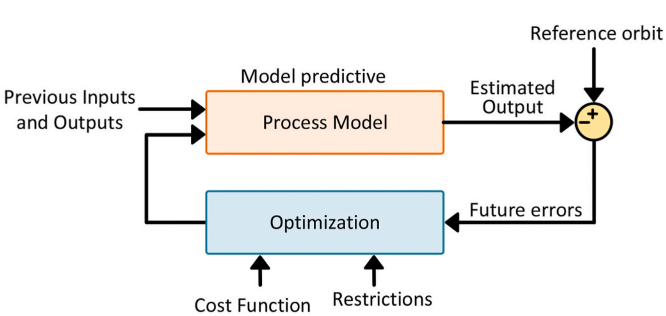

Fig. 20. Model predictive control.

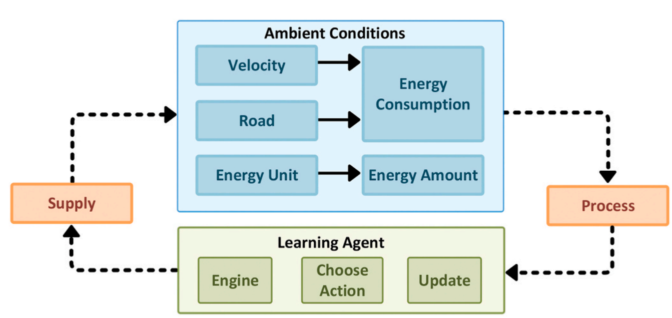

Fig. 21. The operational process of the reinforcement learning algorithm.

motors can be fulfilled through similar inverter topologies [227]. Speed control is realized by using inverters connected to electrical machines. However, their control algorithms may differ from each other. An electric motor's control algorithm can be either conventional PID control or high performance adaptive, fuzzy or ANN controls. Special attention is required to decide the appropriate motor control method for FCEVs.

The interfacing inverter element's main function is to control the rotation direction, speed, acceleration, and torque of EM. To achieve this control, there are different control methods implemented in AC/DC motors for FCEVs. In the literature, the motor control is mainly achieved by using scalar control [228] or vector control [229] for AC motors and PWM control for DC motors. The drive details of the most commonly used AC and DC motors are given below.

3.2.1. AC motor control

Induction motors are the most widely preferred AC motor for FCEVs. Scalar control or vector control methods are used for IM in FCEVs. In scalar (V/f) control, the speed of AC motor is controlled through a supply frequency basis on a simple operation [230]. But, this control method has demerits in terms of operational efficiency such as torque oscillations. There are two control methods for motor drives in vector control: field-oriented control and direct torque control [102,231]. It is also shown that field-oriented control can be investigated in two groups called direct [103] and indirect [232]. Fig. 22 shows the operating schemes of V/f control, DFOC, IFOC used in FCEVs.

The direct torque control method maintains the DC bus voltage at certain values if the rotor speed changes in engines with FC vehicles [233]. In direct field orientation control, flux amplitude and angle values are directly obtained by using voltage or current pattern [234,235]. In indirect field orientation control, flux and torque commands are used to control motor speed together with inverter voltage/current [236]. Among the vector control methods, the indirect field-oriented control method is more widely used in FCEVs owing to the closed-loop structure and flexible speed range from zero to high-speed values [237].

There are also further enhanced IM control algorithms investigated for various applications but have not yet been applied for FCEVs, as presented in Fig. 23. The authors estimate that these algorithms will be applied and examined in future studies for FCEVs as well. For instance, in recent literature, an adaptive speed estimation is performed for water pumping IM drive control in Ref. [238]. The motor drive control is performed through a direct active and reactive power control in Ref. [239]. Thus, the system efficiency is enhanced, and average motor speed is ensured with the proposed method. Moreover, a sensor-less adaptive direct flux amplitude estimation is fulfilled with a modified model observer for IM drive control in Ref. [240]. In this way, limited drift error is provided, and a more stable system is ensured even at low speed. Furthermore, a dual-inverter fed open-end winding IM drive [241] can also be examined for FCEVs in future studies.

3.2.2. DC motor control

DC motor drives are mainly divided into two main classes; brushed DC motor drives and permanent magnet BLDC motor drives. Fig. 24 shows the DC motor control methods implemented in FCEVs. DC motor drives are simpler and cheaper compared with AC motor drives. In Ref. [242], separately excited DC motor is applied in FCEV. The motor control in this study is examined with PI, Fuzzy Logic and Fuzzy Logic based self-tuning PI controllers. On the other side, BLDC motors are

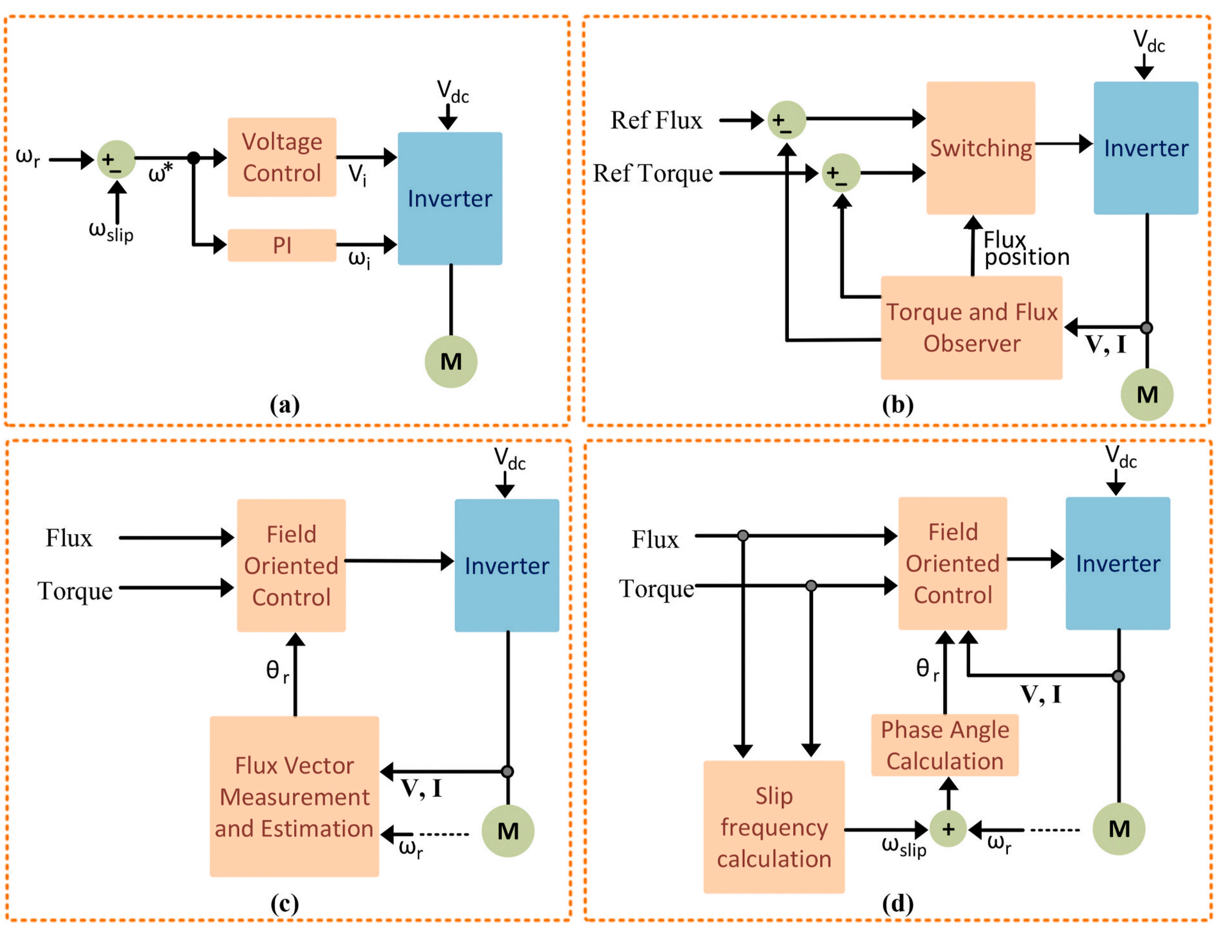

Fig. 22. Power flow/speed control methods implemented in FCEVs (a) V/f control, (b) Direct torque control, (c) Direct field-oriented control and (d) Indirect field-oriented control.

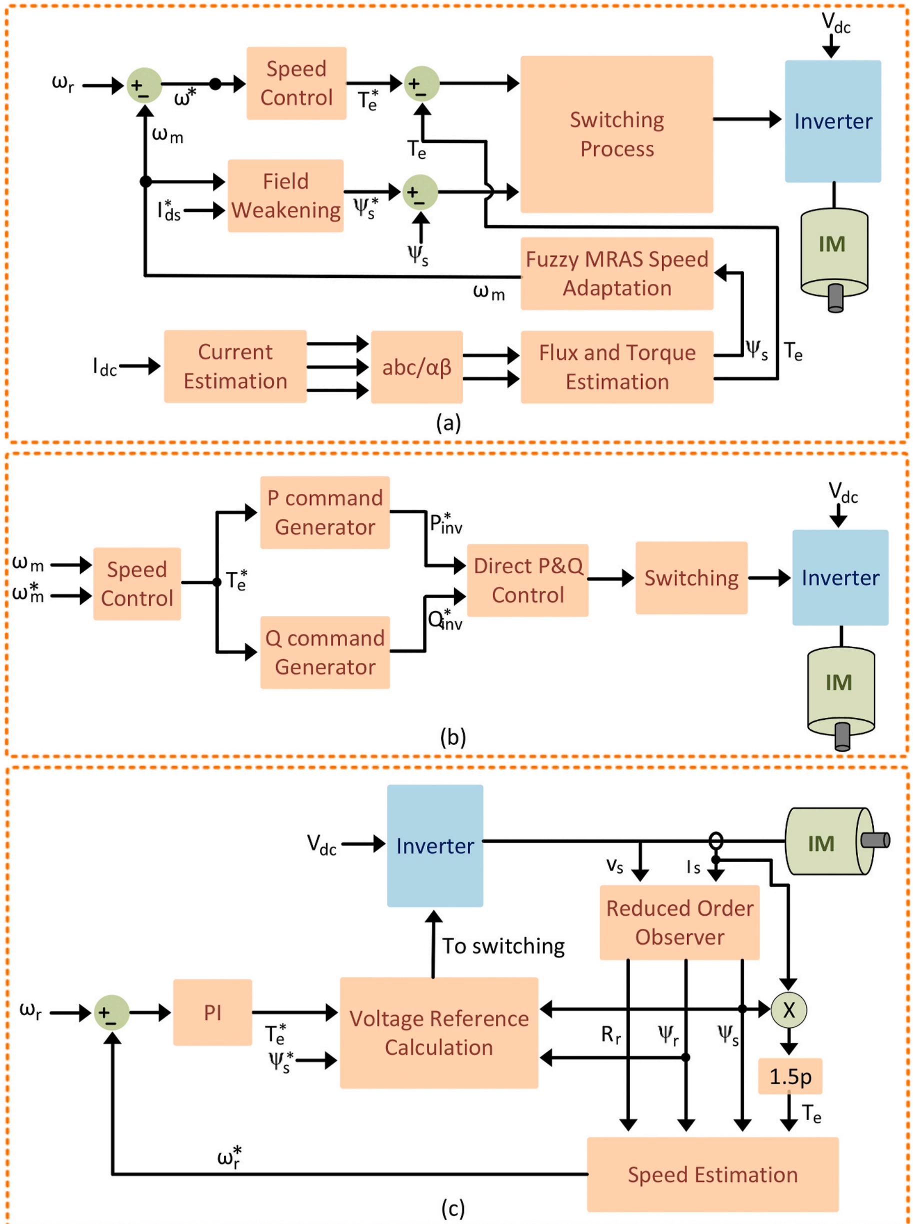

Fig. 23. Advanced ac motor control methods (adaptive speed estimation based control (b) direct active and reactive power control and (c) adaptive direct flux magnitude estimation in sensorless predictive voltage control.

usually chosen in FCEVs because of high efficiency and power density. Moreover, the motor drives can produce higher efficiency than other motor drives owing to the presence of magnetic poles in BLDC motor [243]. Similarly, the inverter topology applied with IM can be used for the drive control of the three-phase BLDC motor. In Ref. [129], a fractional-order PI (FOPI) controller is applied to control BLDC motor speed. This controller has better tracking performance compared to the conventional PI method. The parameters of the FOPI controller are obtained by using Moth Swarm Algorithm. Moreover, a five-phase VSI [244] or seven-phase VSI [103] are also used for multiphase BLDC motors. On the other side, the drive control algorithm of the BLDC motor should be fault-tolerant via detecting, identifying, and recovering the fault [243].

Similar to AC motor drives, there are also enhanced drive control for BLDC motors in recent literature. Some of these studies aim to develop a control algorithm by reducing some components such as sensor number. In Ref. [245], the sensor-less drive control is achieved by the back electromotive force of the virtual third harmonic for high-speed BLDC motor. The rotor position is obtained by this method and commutation error is compensated in this way. The commutation error and torque ripple are diminished by a current waveform based method in Ref. [246]. Moreover, explicit torque control of BLDC is performed by a modified switching scheme in Ref. [247]. The switching ripple components are decreased by 33% using this method. Differently, there are some studies deal with fault detection of BLDC. For instance, fault detection of high resistance connection for BLDC motor is realized in Ref. [248]. Besides, demagnetization faults are analyzed for BLDC motor by developing a hybrid method that combines electrical equivalent circuit and numerical formulation [249].

4. Technical challenges

In the FCEVs, operation of the vehicle components, including mechanical and electronic elements, should be fulfilled the technical

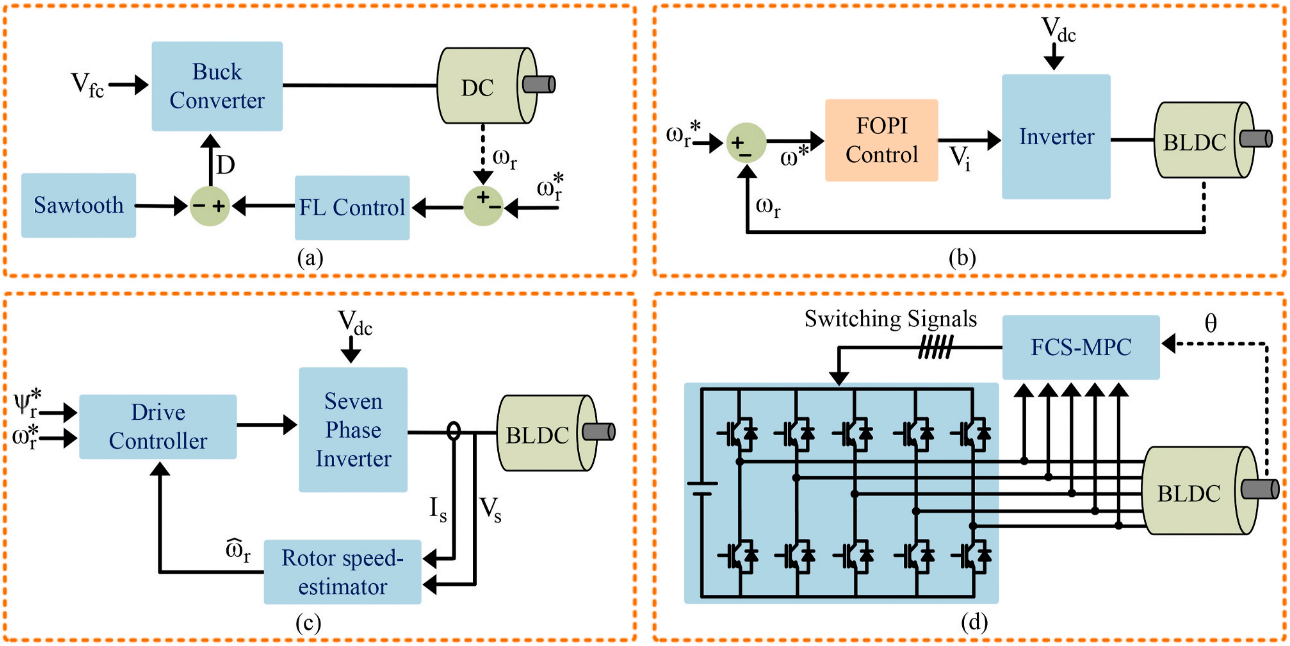

Fig. 24. DC motor control methods (a) FOPI control, (b) fuzzy logic-based self-tuning control, (c) sensorless control with rotor speed estimation, and (d) fault-tolerant control set model predictive control.

proficiency of integration with FC stacks [250,251]. This is to ensure efficient operation and safe trip by FCEVs [252]. In this study, the technical challenges and system problems in FCEVs are also classified and presented in Fig. 25. Technical challenges in the FCEV system will be detailed in the following sub-parts.

4.1. FC lifetime

In today's vehicle market, FCs need to be as durable and robust as conventional engines. In FCs, environmental factors such as start, shutdown, freezing, the suitability of oxygen pressure, relative humidity and temperature are the most important factors to affect the lifetime of FCs [253–255]. Besides, for vehicle applications, the FC is subjected to

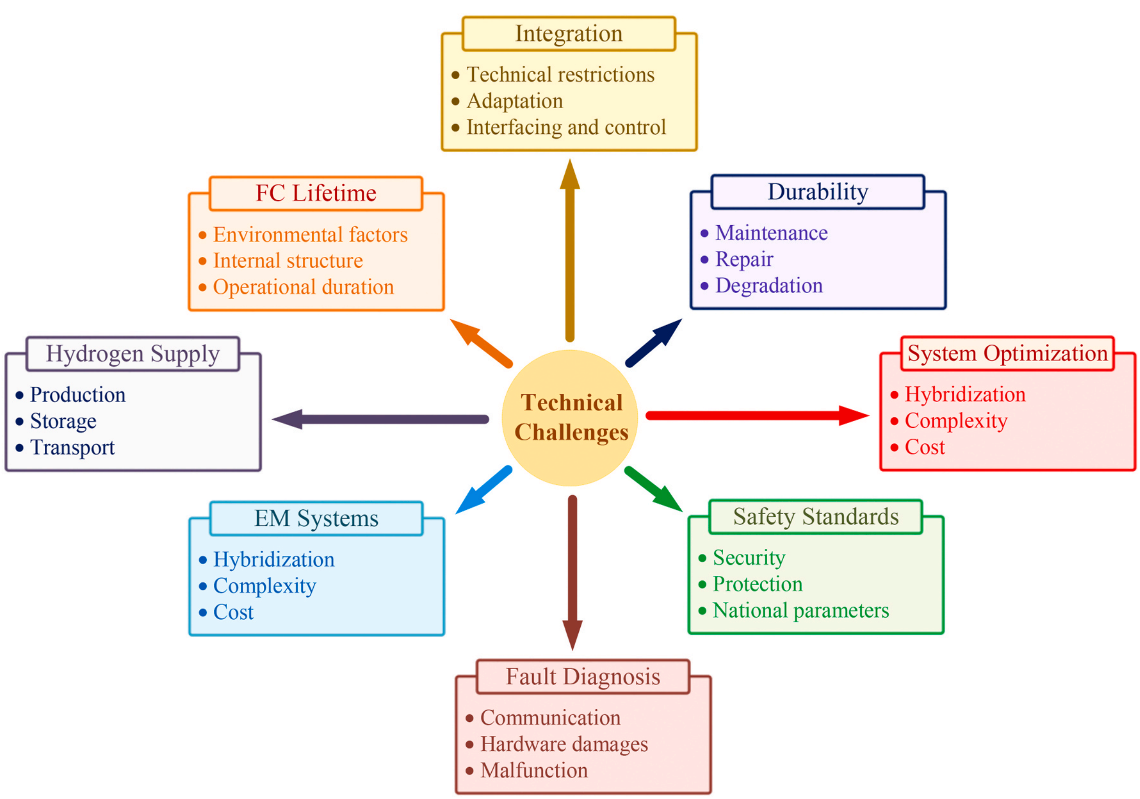

Fig. 25. The classification of technical challenges and system problems in FCEVs.

complex operating situations such as variable start-stop and exposure to too many different loads [256]. Therefore, an FC's lifetime in Type I FCEVs is shorter than the lifetime of the FCs used in other fixed applications [257,258]. Also, Membrane degradation is one of the weakest points for PEMFC durability, and therefore the lifetime of PEMFC is also highly dependent on the lifetime of the ion exchange membrane [57]. The distortion that occurs during the life of the membrane causes a pinhole-shaped formation rapidly. Accordingly, it can eventually cause a stack problem [259].

The states of FC stacks change from time to time with temperature, high or low voltage, variable relative humidity and gas values that can change suddenly. In this cycle, physical and chemical changes may occur, which can sometimes lead to disastrous results [260,261]. Therefore, deterioration in the current performance of the FC is inevitable. Under normal conditions, the FC's breakdown rate is expected to be less than 20% loss in efficiency by the end of its lifetime [262]. The lifetime of FC is one of the most crucial barriers in front of the FCEV industry. To provide more feasible FCEVs, it is necessary to apply novel strategies for the recovery of valuable technological FC materials [263].

4.2. Hydrogen supply

FCEVs are divided into two main categories in terms of fuel supply; direct hydrogen and indirect methanol FCEVs. In the case of direct hydrogen FCEVs, FC's output power is directly controlled by DC/DC converter. However, the supplementary of direct hydrogen fuel and refueling of FCEV are critical challenges for the reliability of FCEVs, which includes production, storage, and transport of hydrogen fuel [264]. These challenges decelerate the industrial growth of FCEV in comparison to conventional battery EVs. The storage of sufficient hydrogen on-board a vehicle is a challenge because of its low energy density [265]. The insufficient hydrogen storage onboard results in adequate drive range. To obtain an adequate drive range, the storage container must be either too heavy or too large. There are a few storage methods in the literature such as pressurized tanks, hydrogen uptake in metal-based compounds, and cryogenic liquid hydrogen [266]. On the other side, indirect FCEVs use methanol to produce hydrogen via an on-board catalytic reformer and this hydrogen is pumped to FC stack. However, Catalyst material is made from platinum for anode and cathode sides, which results in high cost for research progress [267]. Further progress can be performed once the usage of platinum is minimized. Besides, large scale production of hydrogen and methanol is another major difficulty. The technology of FCEV is nowadays in the early research stage. It is estimated that FCEV may become feasibly at least the following twenty years [264]. The number of hydrogen refueling stations in operation is also quite low, requiring more stations to be installed.

4.3. Durability

FCEVs need further maintenance and repair compared to conventional battery EVs for durability conditions. In addition, the facilities for maintenance and repair are not enough. There is a necessity for FCEVs maintenance and repair facilities because this technology is quite new and does not have the benefits of battery EVs [264,268]. Besides, in FCEVs, unbalanced flow distribution between FCs may cause an improper operational arrangement of cells and stacks. This situation introduces high uncertainty and degradation of efficiency. Also, frequent maintenance and repair downtime can be impacted [268].

Degradation in an FC system is defined as a reduction of FC performance or its actual failure. It can also simply be determined as a loss of voltage versus time [269]. The degradation of FC components has inverse effects on system durability. The voltage reduction for constant load at maximum 75 ^0C is low in the range of $1-2\,\mu V/\,h$. This voltage drop range may increase by orders of amplitude once some circumstances occurs, i.e higher temperature values, start-stop cycles, load change [270]. The degradation of electrodes, membrane, bipolar plates, and seals is reported in Ref. [270]. The electrolyte membrane in FC is made from an inactive polymer with including acidic group. It works as a conductor between anode and cathode, a gas barrier and electronic current insulator [269]. These membrane functions must remain unobstructed during the lifetime of FC. The conductivity of the proton should be as 0.1 S cm^{-1} and the gas permeability should be minimum as $<10^{-11} mol.O_2/cm.s.kPa$ and $<10^{-12} mol.H_2/cm.s.kPa$ [271]. Furthermore, the electrode of PEMFC involves catalyst which requires electrons, protons, gas and water for fast reaction, which may result in loss of electromechanical surface area [270]. Moreover, the bipolar plate serves the electronic current conduction between two adjacent cells. The conduct resistance of these two plates is crucial in the long term characteristics of FC. The long term resistance of bipolar plates is suggested to be lower than $50 m\Omega cm^2$ [272]. Furthermore, seals in FC work as preventing gas leakage and outside coolants. Besides, they serves as electric insulator and height control of stack [273]. In general, the degradation of seals is not well understood. More attention is required to solve this phenomenon. Otherwise, the durability of FC is affected inversely.

4.4. Safety standards

Transport monitoring agencies set security standards around the world. The most well-known popular vehicle standard in the world is SAE located in United States. SAE J2578 is on requirements for collision and vehicle integration for FCVs. This standard defines the proposed requirements for integrating hydrogen storage and handling systems, the FC system, and an FCEV electrical system [274]. In the United States, CGA Publication PS31 standard has been defined standards for cleaning the components of PEMFCs, outlet pipes, fuel system components found in hydrogen fuel vehicles in Canadian Standards Association (CSA) America HGV3.1 standard [275,276]. In another standard, the requirements for ISO 23273:2013 safety and protection against hydrogen hazards in FC vehicles filled with compressed hydrogen have been defined for FC vehicles [277]. European Commission (EC) has been described as the standards of the European Union. Upon type-approval of hydrogen-powered vehicles, EC No.79/2009 standard was established. In China, GB/T 23645-2009 defined the FC power system's test method for personal cars. The FC test system's technical characteristics and standards are found in motor vehicles with GB/T 25319-2010 [278,279]. The National Standards of the Republic of China (CNS) 15499 1-2-3-4 series express the internal rechargeable energy storage system (RESS), vehicle operating safety and vehicle protection against malfunctions [280]. It has defined electrical safety standards for protection against crash and vehicle collision [20,281].

4.5. System optimization

System optimization is crucial for FC based vehicles [282]. Despite this, optimization algorithms have several issues or difficulties similar to EMS. Studies that stand out from these problems are limited to simulations and some studies do not even include the name of the simulation application or tool. Optimization problems limited to simulations were handled as an ant colony algorithm and dynamic programming in addition to the combination of PI and PI with linear programming [251].

A significant part of the studies related to optimization is the proper component sizing, fuel economy, cost reduction, appropriate parameter selection, weight, power management, and optimum FC lifetime [130,150,283–286]. The researchers present a design space method based on Pinch to size the elements of FCEV using a driving cycle in Ref. [287]. A sizing method based on the fulfillment of power requirements, including sustained speed tests and stochastic driving cycles is expressed in Ref. [217]. The operational condition identification of energy storage unit and car driving performance is detailed in Ref. [288]. Also, a stochastic power management technique for heavy duty vehicle applications is presented for the efficient operation of auxiliary units [289]. This generally appears as the optimization priority given to hardware sizing and not taking into account the life and deterioration of ESS components.

The lifetime of an FC is affected by load changes and start-stop cycles as mentioned above. The load changes and start-stop cycles may be decreased by the design of an optimized hybrid FCEV system. Extreme load changes can be prevented by including storage devices with FC. Besides, the start-stop cycles can be diminished by employing storage components, where the FC operation will continue charging the storage device at the lowest speed while the car stops [282].

4.6. Energy management system

An EMS aims to manage the control of the energy source during supplying the electric motor. Controlling the flow of power is as important as meeting the high expectations of the vehicle market in the hybrid system, which is the result of the hybridization of an FCEV with multiple energy sources [290]. The EMS ensures efficient power apportionment of energy among FC, energy storage system and an electric motor to prevent FC power irregularity, the service life of FC and energy storage devices. One of FCEV's most critical challenges is in the optimal configuration of the complexity and the design of the appropriate controller, due to the proper integration of other systems in the vehicle [102]. The primary aim of EMS is to minimize hydrogen consumption and thus optimize ESS coordination [24]. On the other hand, optimum energy recycling is expected during regenerative braking. It is expected that researchers should consider the SOC limiting of the energy storage system, FC support throughout high loads and optimal energy recovery during regenerative braking [24].

Although most EMS studies are on simulation, some studies have been carried out experimentally [251]. This situation revealed that the conditions such as the FC's oxygen pressure should be examined as well as the life of the battery and UC. Since ESS components' lifetime depends on SOC and depth of discharge, they should be analyzed in the best way before application [24]. The cost and performance balance must be at the optimum level when choosing the battery and UC for hybridization. The realization of an EMS suitable for FCEV is essential as it can directly affect the vehicle's maintenance and operating cost [150,291].

4.7. Integration

The integration of FCEVs is achieved similar to traditional ICE vehicles. With the current FC vehicle technology, integration with a highly powerful drivetrain is possible for a passenger vehicle. Also, there are no technical restrictions for vehicle integration of a possible FC system. Thanks to the FC system's scalability during the production phase, its adaptation to the vehicle dimensions can be achieved. In this way, it is possible to adapt an FC system developed for any vehicle to a different model. In general, the most optimal location should be determined for mounting hydrogen storage tanks to the vehicle at the rear. The most important disadvantages are that tanks cannot store too much hydrogen due to the excess space used by their increased volumes [292].

The power values of the DC-DC converters and DC-AC inverters used in the power transfer stage are determined according to the electrical loads' power peak values. They are combined according to the ideal current and voltage degrees at a certain switching frequency. In the converters and inverters used, IGBT and diodes are used at high powers according to the degree of load and switching, while power MOSFETs and diodes are used for low power loads [293]. The transfer of electric energy to the rotation is performed by an electric motor, which can be an AC or DC motor. In the motor integration, the low pole number requirement of induction motors used in vehicle drive requires large copper winding ends. This requires a stator outer iron coating, which partially causes weight gain. In switched reluctance motors, the electromagnetic compatibility problem caused by transient situations (high frequency and high peak currents) should be considered. Also, the stator and electronic structure in SRM are different from existing built-in technology. Moreover, this motor type has high noise and low efficiency. In PMSM motors, mostly preferred in EV applications, the current cost of energy magnets is high. On the other hand, fixed flux provides a low range of speed range at fixed speed values of the vehicle [294].

4.8. Fault diagnosis

A fault occurs once a device in EV operates out of standard characteristic conditions. This fault in the vehicle may result in detoration of dynamic stability or costly breakdown of EV [295,296]. Thus, it is curical to detect the fault and monitor it for the vehicle's functional safety and stability. It is stated that the fault can be in the form of electrical, electronic, mechanical, and software [297]. Furthermore, electric and electronic components have the highest failure ratio (almost 42%) among these fault forms [298,299].

In FCEV, the fault may occur in FC systems, storage systems, power converters, measurement devices, and electric motor. These faults can be overloading of FC, over-charge of storage device, short-circuit or open circuit of motor stator windings, open or short switch in power converter components, overheating in devices, etc. Some of these faults may degrade the vehicle's performance, lead to vibration and noise, or damage the vehicle dynamic system [300].

In an FCEV vehicle, controller area network (CAN) based systems are generally used for control and communication [301]. It is very important in terms of FCEV's safety and reliability due to the need for diagnostics of the electronic control system in the vehicle [302]. Fault diagnosis is divided into two types: online and offline. When a possible fault is detected in any part of the online diagnosis system, the code specified for the warning status is sent to the vehicle management system via CAN data. The fault data obtained here is transferred to the display screen. Here, an alarm is given as an audible warning along with the alarm fault code on the screen. Offline diagnostics means reading past faults when the vehicle is in the parked state. When a possible malfunction occurs, the vehicle management system offline diagnostics becomes active to perform the operation that corresponds to the malfunction warning condition. The system controls the storing and recalling of the error information in the opening and closing situations [303]. FC's failure diagnosis, storage devices, sensors, converters and motor drive systems in FCEVs must be detected as soon as possible for the functional safety of driver and vehicle.

5. Marketing

Along with the rapid developments in the vehicle industry, the interest in FCEV technology has been increasing significantly in recent years to reduce the cost and increase efficiency. The development of high-power FC systems for the transportation sector and the manufacture of commercial/passenger FCEVs confirm these systems' potential in the vehicle market. Also, the need to conserve natural resources and protect the environment has led many vehicle manufacturers to develop new, more efficient and cleaner powertrains. The rapid advances in the vehicle industry, as well as interest in FCEV technology, have increased significantly in recent years to reduce cost and increase efficiency significantly. The hydrogen FCEV industry is divided into sections by vehicle type, FC technology type and region. FCEV technology, which is reserved for passenger cars and commercial vehicles depending on the vehicle type, is divided into PEMFCs, PAFCs and others depending on the type. Furthermore, according to the region, the hydrogen FCEV market is analyzed in North America, Europe, Asia-Pacific and LAMEA.

Due to the technological developments in hydrogen production, storage and conversion to energy, the sales prices of vehicles have shown a significant decrease from million-dollar levels. With the increase in the number of researchers interested in FCEVs, vehicle manufacturers started their production in hydrogen fuel passenger vehicles in 2002 [304]. They have been producing with many models until today. It is known that these manufacturers also deal with light commercial vehicles [305], buses [306] and trucks [307] in addition to passenger cars [308,309]. FCEVs commercially available until today, their manufacturers and their specific features are detailed in Table 7. As shown in evolution, most passenger car manufacturers have been developing FCEVs in recent years. Manufacturers such as General Motors, Toyota, and Honda generate their own FC stacks and other companies such as Ford, Mazda, DaimlerChrysler, Mazda, Hyundai, Fiat, and Volkswagen buy from FC manufacturers. In the specification of available FCEVs, it is clear that battery hybridization (Type II) is currently more widely preferred. Moreover, recently, plug-in FCEVs have been generated by manufacturers by Honda, Hyundai and Mercedes. PEMFC is the most common FC stack and its rating increases day by day for FCEVs. It is shown that Toyota, Honda and Mercedes have PEMFCs higher than 100 kW while Honda FCX-V4 produced in 2002 uses a PEMFC in the rating of 78 kW.

On the other hand, the most effective factors to increase the preference of the hydrogen FCEV are the increase in environmental concerns, government initiatives for the development of the hydrogen FC infrastructure, the production of fuel-efficient, high performance and low emission vehicles. Vehicle emissions have a negative impact on the environment and human life; therefore, some government bodies implement strict emission standards for vehicles [324]. FCEVs are likely to be in high demand in the market as they are low-emission vehicles and comply with state standards. Increasing awareness among car manufacturers on the environmental impact of vehicle emissions by developing alternative powertrains is also expected to drive the market growth. In addition, government incentives to be implemented in the development and installation of hydrogen refueling stations as well as the production of R&D studies and vehicles are expected to increase the

Table 7
The specifications of commercial FCEVs produced by automobile manufacturers.

Appearance	Title	Year (Interval)	Type (#)	Plug (Y/N)	Range (km)	Motor (Type)	Top speed	FC (Type)	FC Power	Ref [#]
	Honda FCX-V4	2002–2008	Type III	No	260–310	Induction motor	150 km/h	PEMFC	78 kW	[310]
	Ford Focus FCV	2008–2011	Type II	No	320	Induction motor	129 km/h	PEMFC	85 kW	[311]
	Nissan X-Trail FCV	2003–2013	Type II	No	350	Synchronous motor	Not given	PEFC	90 kW	[312]
	Mercedes-Benz A F-Cell	2005–2007	Type I	No	160–180	–	132 km/h	PEMFC	–	[313]
	Chevrolet Equinox FC	2007–2009	Type II	No	310	Permanent magnet motor	141 km/h	PEMFC	93 kW	[314]
	Honda FCX Clarity	2008–2015	Type II	No	390	Brush-less dc motor	130 km/h	–	100 kW	[315]
	Mercedes-Benz B F-Cell	2010–2014	Type II	No	310	–	132 km/h	PEMFC	–	[316]
	Hyundai Tucson FCEV	2014-Now	Type II	No	594	Induction motor	160 km/h	PEMFC	100 kW	[317]
	Toyota Mirai FCEV	2015-Now	Type II	No	480	Induction motor	160 km/h	PEMFC	114 kW	[318]
	Nissan e-Bio Fuel Cell	2016-Now	Type II	Yes	600	–	–	SOFC	5 kW	[319]
	Honda Clarity	2019-Now	–	Yes	590	PM Synchronous Motor	178 km/h	PEMFC	103 kW	[320]
	Mercedes-Benz GLC F-CELL	2020-Now	Type II	Yes	478	Induction electric motor	160 km/h	PEMFC	100 kW	[321]
	Hyundai Nexo	2020-Now	Type IV	Yes	570	Interior PM Synchronous Motor	179 km/h	PEMFC	95 kW	[322]
	Gumpert Aiways Nathalie	2021-	Type II	Yes	820	Brush-less dc motor	305 km/h	DMFC	130 kW	[323]

growth in the FCEV market. Among the factors that are thought to negatively affect the share of FCEVs in the market, these vehicles are expensive, and hydrogen per kilogram is presently high. These two factors are expected to limit the FCEV market demand. For this purpose, many manufacturers and researchers aim to reduce these costs with the R&D studies.

6. Future aspects

Despite numerous successes in recent years, FC technologies for automotive applications face significant technical challenges. In order to overcome these difficulties, both automotive manufacturers and researchers need intensive work in areas such as pure hydrogen production, built-in hydrogen storage, FC durability and reliability, consumer's easy access to hydrogen and safety. In addition to all these difficulties, the high costs are currently reducing the preferability of FCEVs. However, considering the advantages of hydrogen FCEVs mentioned in the previous section, it is predicted that the demand for such vehicles will increase by overcoming these difficulties [325]. In addition, increasing the security of the use of hydrogen and increasing the number of filling stations where the consumer can reach hydrogen are the factors that will increase the demand for such vehicles [326]. It is thought that the production of passenger car manufacturers will increase to meet the demand in the global transportation industry with the development of FCEV technologies. This situation will increase the investments of these companies in this technology and accelerate the developments. With the acceleration of technological development, investments and incentives, it is expected that its share in the market will increase in the following years.

With the development of technologies used both in hydrogen production techniques and in components such as FC and battery, the production costs of hydrogen FCEVs are expected to decrease and their production will increase to meet the demand that will arise accordingly. The market size of hydrogen FC-based vehicles is worth $ 651.9 million in 2018 and is projected to reach $ 42,038.9 million in 2026, which corresponds to an annual compound growth rate of 66.9% from 2019 to 2026 [327,328]. The key factors affecting the global market's growth include an increase in environmental concerns, an increase in government initiatives to improve the hydrogen FC infrastructure, the first high investment and technological progress in infrastructure, and future commercial potential. Each of these factors is expected to have a definitive impact on the vehicle market in predicting the number of vehicles. Fig. 26 shows the variations in the number of FCEVs from 2013 to 2030 based on three regions: North America, Europe, and Asia-Pacific. The number of FCEVs, which was only 20 in 2013, was increased to 11900 in 2018. It is also expected to reach approximately 31000 at the end of 2020, with an increase of roughly 160% compared with 2018 [329,330]. The projected numbers for future vehicles in these areas show that FC-based electric vehicles' production has increased year by year. It is stated that the total number forecasted in the number of FCEVs is 582400 for 2030, and it is assumed that there will be a 1784% increase in the number of vehicles within the next decade [331].

The increase in the number of electric vehicles also means an increase in hydrogen demand for the next decade [332–334]. Nowadays, there are many methods such as steam treatment [335], purification of waste gases [336], electrolysis [337] are applied to obtain hydrogen. These studies are continuing intensively in the storage of produced hydrogen [338,339]. The FCs, which produce electricity using the hydrogen in the tank and the oxygen received from the air directly, is an efficient method used especially in passenger cars to obtain energy from hydrogen [340]. For this reason, one of the most important conditions in the marketing strategy of vehicles, which has an important role in the increase in the number of FCEVs, is to provide easy access to hydrogen for storing and using in these vehicles [341,342]. Fig. 27 introduces the variation in the number of target hydrogen refueling stations in the leading countries for the FCEV until 2030. It is obvious that if the drivers can easily reach the fuel stations for hydrogen, the preferred rates of FCEVs will increase. Therefore, it is inevitable that the number of hydrogen fuel stations will also increase for the next ten years, based on the forecast that the number of vehicles will increase worldwide [267].

7. Conclusions and suggestions

The trend towards alternative energy sources has increased due to the depletion of fossil fuel resources and the instability in oil prices, the need to increase the efficiency of existing technologies in transportation, and the increasing trend towards environmentally friendly technologies to minimize the effects of global warming. The impact of fuels used in

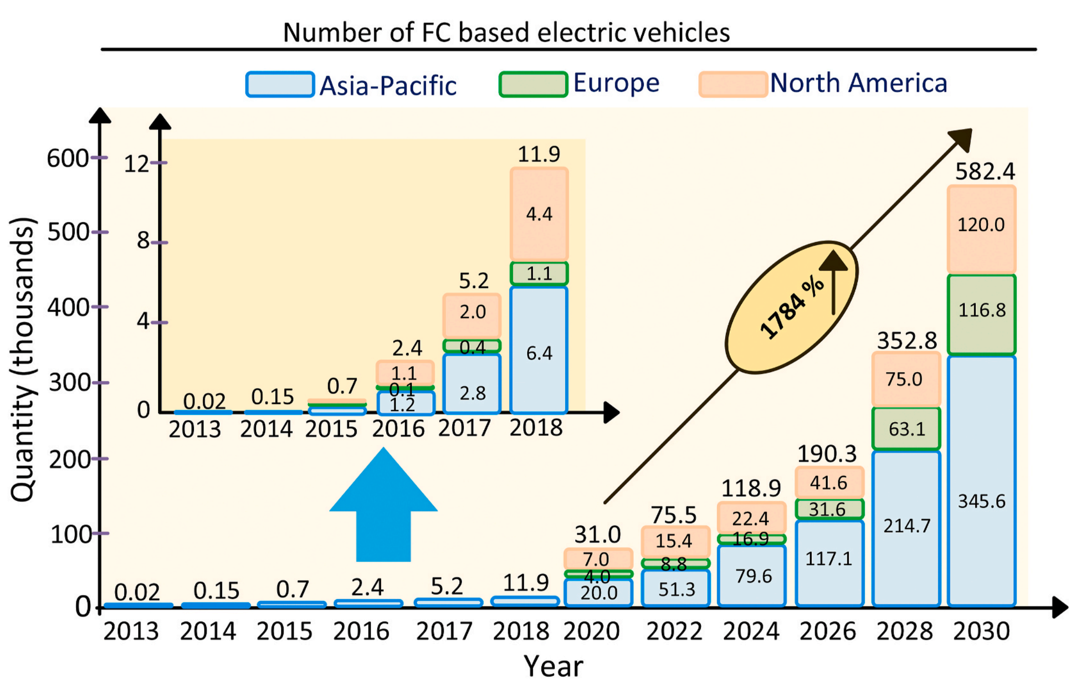

Fig. 26. The number of FCEVS according to regions.

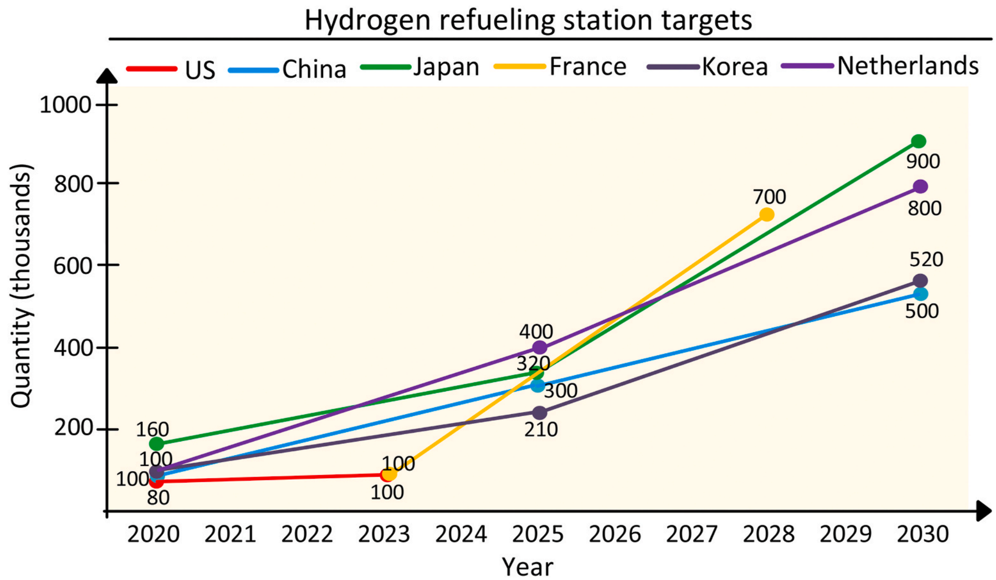

Fig. 27. The quantity of hydrogen refueling station targets for pretentious countries.

vehicles and related carbon emission values on global warming is one of the most important factors determining the automotive industry's future. Accordingly, it is inevitable that in the near future, the share of electric vehicles in use will increase depending on the conditions of each country. They have advantages such as low fuel and maintenance costs, low noise levels and high efficiency in addition to being environmentally friendly since electric vehicles have an electric motor instead of an internal combustion engine. However, since the battery is the only energy source in these vehicles and the battery technology is insufficient today, they are more preferred in urban applications with limited distances.

In the current study, the power transmission configurations, equipment, control strategies applied on various equipment to achieve the desired efficiency, the future situations/predictions and technical challenges in the FCEV technology are discussed in detail. In addition, FCEVs are divided into Full FCEV (where the FC is used only as an energy supplier) and Hybrid FCEV (where the FC is used with different connection types with another energy supplier/storage). In these structure, energy generation/storage topologies, including FC, battery, UC, PV panel, flywheel and SMES are given with their advantages and disadvantages for these types. FCs, electric motors, and converters that allow adjustment in voltage and current depending on the appropriate topology and application target are detailed regarding FCEVs' study in the literature. Besides, energy management, power transfer and speed control methods are elaborated. FCEVs' applications to minimize fuel consumption, increase efficiency, simplify the structure and achieve robust driving performance are emphasized. Moreover, the studies on the optimization of technical challenges in FCEVs such as FC life, energy management system, safety standards, size, fuel consumption, power management and cost, the integration of the FC system into the vehicles and online/offline fault diagnosis were examined.

The market shares of FCEVs, which will be formed depending on factors such as energy policies and environmental effects in the current and following decade's perspective, have been evaluated regionally and nationally. It is seen that the number of FCEVs will increase rapidly both regionally and nationally in line with the decreasing costs and investments with the development of technology in the field. Depending on this situation, the need for hydrogen utilization will increase, and the studies on the applied processes to obtain hydrogen from the other energy sources are expected to increase. In addition, considering that the storage of the produced hydrogen is a serious problem, it is seen that the studies for storing/using it safely in passenger cars are essential for sustainability. FCEVs are expected to continue their movement in the most efficient way possible after converting hydrogen into energy. Control and design studies for transformers gain great importance with optimization studies for structure simplification, speed control, and performance improvement to ensure this situation.

With the developing technology and the current studies on FCEV, it is obvious that several parts of the technical difficulties will be overcome within the next ten years. The prices of these vehicles, which were around 1 million dollars 10 years ago, will see significant decreases. In line with the increasing demand due to falling prices and their advantages, automotive companies will increase their investments in this field and increase the supply and accelerate technology development. Also, providing easy access to hydrogen by users depending on the increasing number of vehicles to meet the demand is one of the main factors affecting its growth. For this reason, it is predicted that the number of stations that provide hydrogen refueling in leading countries will increase in the near future. It is thought that strategic partnerships and collaborations between leading companies and governments in this field will contribute significantly to increasing production income and expanding global reach. Thus, the development of all technologies related to FCEV will accelerate with interest and importance.

The utilization of FCs in the electric vehicle field is becoming widespread, and the progress is expected to accelerate in the following years. Along with the decreasing financial cost of FC stacks, this type of vehicle is expected to become more common in modern life. Obviously, as the capacity of FCs increases, they will have more range and replace classic cars. However, it is of utmost importance to increase energy efficiency to higher levels and minimize these systems' problems. In this regards, the research and practical studies in FCEVs are going to take attention in the following captions:

- To reduce the cost which limits FCEVs' production,
- To increase hydrogen refueling stations,
- To obtain higher efficiency by replacing conventional inverters with advanced multilevel inverters,
- To reduce the high-frequency electrical energy signals by using switching ripple filters such as LCL and LLCL,
- To apply high gain high-efficient dc-dc converters instead of conventional converters,
- To integrate FCEVs with vehicle-to-grid technology,
- To increase the dynamic response of FCs under dynamic speed changes,
- To increase the power ratings of FCs used in these vehicles,

- To eliminate the power quality problems in the grid connection of FCEVs,
- To extract maximum power from FC stacks using online optimization methods.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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