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REVIEW

ENERGY STORAGE WILEY

Energy management control strategies for energy storage systems of hybrid electric vehicle: A review

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Abstract

Continuous efforts to preserve the environment and to reduce gaseous emissions due to the massive growth of urban economic development and heightened concerns over crude oil depletion have accelerated researchers to find long-term solutions, particularly in the transportation sector with the focus on powertrain electrification. This article delivers a comprehensive overview of electric vehicle architectures, energy storage systems, and motor traction power. Subsequently, it emphasizes different charge equalization methodologies of the energy storage system. This work's contribution can be identified in two points: first, providing an overview of different energy management methods to researchers and scholars. Second, to highlight the state-of-the-art leanings in major components and to highlight promising approaches to hybrid electric vehicle future development.

KEYWORDS

charge equalization, energy management strategy, energy storage system, hybrid electric vehicles, supercapacitor

1 | INTRODUCTION

The environmental and economic issues are providing an impulse to develop clean and efficient vehicles. CO_2 emissions from internal combustion engine (ICE) vehicles contribute to global warming issues.[1,2] The forecast of worldwide population increment from 6 billion in 2000 to 10 billion in 2050, and subsequently, increase the demand for new vehicles approximately by 350% as shown in Figure 1.[3] It is suggested to explore population

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Abbreviations: APC, angular position control; BEV, battery electric vehicle; BLDC, brushless DC motor; CCC, current chopping control; DSPM, doubly salient permanent magnet; EV, electric vehicle; FCEV, fuel cell vehicle; FCPM, flux-controllable permanent magnet; FMPs, flux-modulation poles; FRPM, flux-reversal permanent magnet; FSPM, flux switching permanent magnet; HEV, hybrid electric vehicle; PHEV, plug-in hybrid electric vehicle; PMSM, permanent magnet synchronous motor; SoC, state of charge; SRM, switched reluctance motor; TFPM, transverse-flux permanent magnet; VPM, vernier permanent magnet; VRPM, variable reluctance permanent magnet machine.

and vehicle development worldwide over the next 50 years. By concern, ICE controls entire transportation, and the gas and crude oils will be rapidly exhausted, resulting in greenhouse gas emissions. Therefore, energy conservation and environmental precautions develop widespread apprehension.

Nowadays, one of the solutions for these issues is to implement vehicle electrification technologies.[4,5] Broadly interpreted as a promising alternative to conventional ICE vehicles were electric vehicles (EVs). This can be seen as, worldview progress to efficient and greener transportation if the electrical energy is sourced from a renewable source.[6] There are three types of EV classifications: battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs).[7] The timeline in Figure 2 displays the gradual historical growth of EVs.[8]

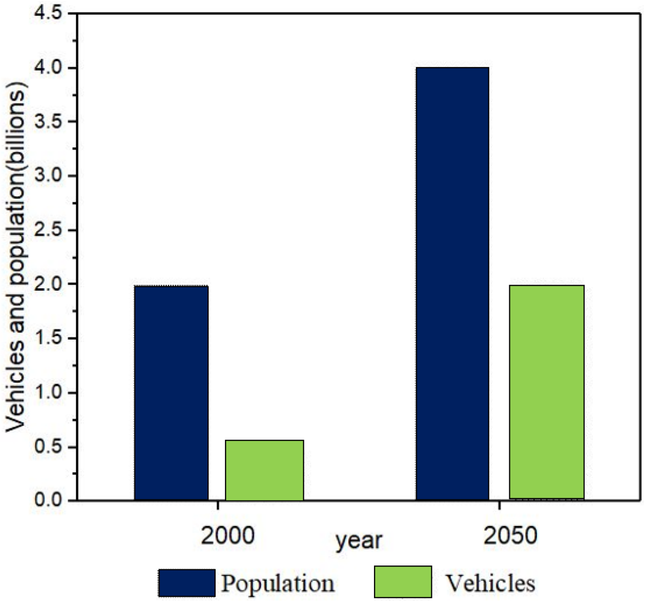

FIGURE 1 Increment of vehicles w.r.t. population vs year.

Due to the enveloping technology and the major characteristics such as emission, driving range and cost of the three types of EVs as shown in Table 1,[9] EVs are currently in different stages of development.

Despite offering zero tailpipe emission, BEV has technical limitations such as high battery costs, lower energy density compared to fossil fuels; short driving range per single charge, more time to recharge, and vehicle space is less. These technical barriers can hamper BEV demand and be very challenging in the near future to be solved.[10] FCEV, on the other hand, gaining more importance for future developing vehicles.[11] Nevertheless, the technology and refilling of hydrogen systems are quiet in the early stage of development.[12,13] Consequently, with an initial cost and management breakthrough in the battery, HEV is considered to be an interim solution before BEV is fully marketed.[14,15] Hence this article delivers a comprehensive overview of major components and also providing an overview of different HEV energy management strategies in order to highlight promising approaches to HEV future development. The rest of this article is organized into the sections

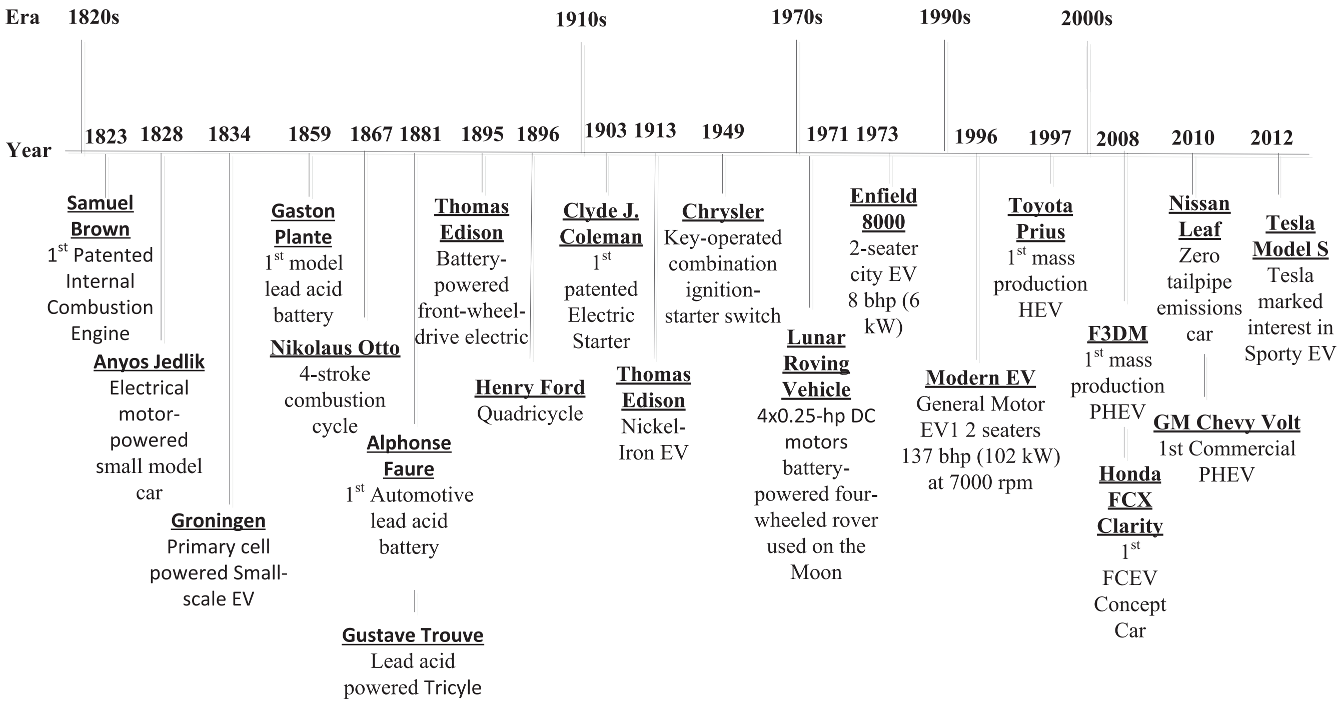

FIGURE 2 Historical timeline diagram of different electrical vehicles.

TABLE 1 The major characteristic of three types of EV.

Types of EV	PEV	HEV	FCEV
Energy source	• Battery	• Battery/ultracapacitor • Internal combustion engines	• Fuel cells
Propulsion technique	• Electric motor drives	• Electric motor drives • Internal combustion engines	• Electric motor drives
Characteristics and feature	• Zero emission • Short driving range • Higher initial costs	• Low emission • Longer range • Complex	• Zero emission • Highest initial costs • Medium driving range
Major techniques	• Electric motor control • Battery management • Charging device	• Electric motor control • Battery management • Managing multiple energy sources and optimal system efficiency • Components sizing	• Fuel processor • Fueling system • Fuel cost

below: Introduction, Configuration of HEV, Electrical motors in EV and HEV, Energy storage systems, Charge equalization of the supercapacitor, and Energy management of an energy storage system. All sections will clearly explain the strengths and weaknesses of each topic.

2 | CONFIGURATIONS OF HEVs

According to the International Electrical Technical Commission's Technical Committee 69[4] (Electric Road Vehicles), an HEV is a vehicle comprises of two sources in which one source can supply electrical power to propel the vehicle. HEV consists of various types such as battery and ICE, battery and capacitor, and battery and flywheel. HEVs currently possess an effective utilization of multiple power sources to propel the vehicle. It requires one or more motors along with the ICE or fuel cell as the main supply source. As a bidirectional energy storage system, a battery or supercapacitor provides power to the drivetrain and also recovers parts of the braking energy that are otherwise dissipated in conventional ICE vehicles. HEVs are therefore newly classified into four types[4,12] and the architectures are depicted in Figure 3.

i. Series HEV.
ii. Parallel HEV.
iii. Series-parallel HEV.
iv. Plug-in complex HEV.

2.1 | Series HEV configuration

The series HEV is known as one of the simplest kinds of HEV. The series HEV system architecture involves an electrical motor, a transmission, an ICE, a battery pack, a control unit, a power electronic (PE) converter, fuel storage, and a generator. The ICE generator is exploited to recharge the batteries or/and supply the motor with electrical power via a PE converter but does not directly propel the vehicle.[16] Merely the wheels of the vehicle are driven through the electric motor by amplifying the transmission.

Strengths:

1. Series HEVs have a distinct benefit for the location of an ICE generator set, in which ICE and the driving wheels are coupled mechanically. Furthermore, the ICE always operates in a very narrow maximum efficiency region, regardless of the speed of the vehicle. These features enable ICE to be reduced and operate in a steady-state to minimize harmful gas emissions.
2. The need for a complex multi-gear transmission is eliminated in a series HEV, which also eliminates the requirement for a clutch. As a result, the architecture of the drivetrain system can be simplified, leading to cost savings. Additionally, this simplified design allows for greater flexibility in incorporating independent motors for each wheel. This enables independent control of the speed and torque of each wheel, thereby enhancing the overall performance of the vehicle dynamics attributes.[17]

Challenges:

1. The propulsion of vehicles based on this architecture relies primarily on a single electric motor, which necessitates a larger and more complex battery pack and electric motor to generate sufficient power for optimal vehicle performance. Due to the increased size and components, such as an additional generator, series HEVs often incur higher costs compared to parallel HEVs.

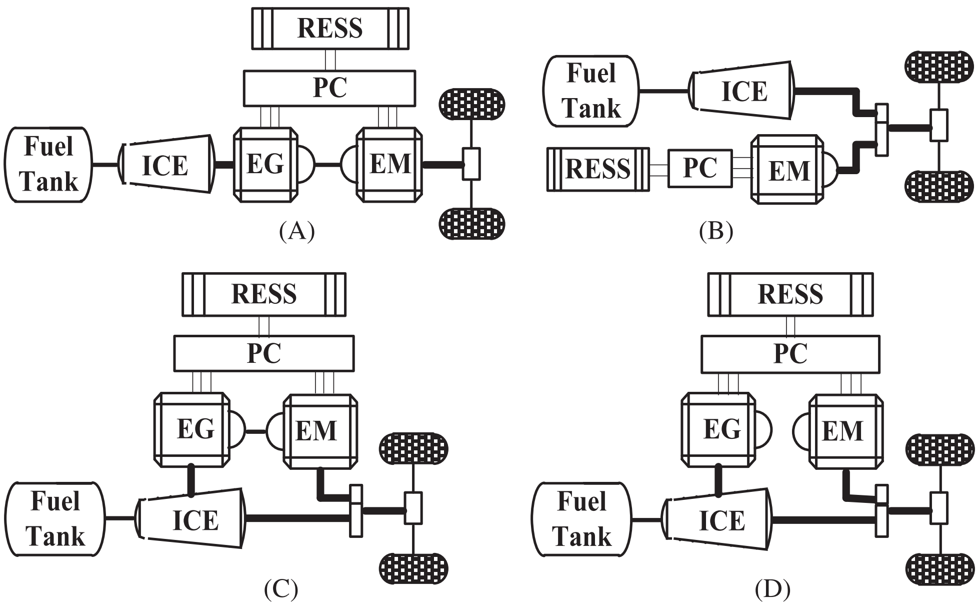

FIGURE 3 Different configurations of hybrid electric vehicle (A) configuration of series hybrid; (B) configuration of parallel hybrid; (C) configuration of series-parallel hybrid; (D) configuration of complex hybrid.

RESS – Rechargeable Energy Storage System; **EM** – Electric Motor

EG – Electric Generator; **ICE** – Internal Combustion Engine

PC – Power Converter

2. The series HEV has to perform twice the energy conversion procedure due to the simplicity of its drivetrain. Hence the series HEV has less efficiency.[8]

2.2 | Parallel HEV configuration

In the parallel HEV, the propulsion of the vehicle is based on both an electric motor and the ICE which is in contrast to the series HEV. The electric motor and ICE are usually combined via two clutches and transmission to the wheels drive shaft. Using this powertrain architecture, either the ICE only or the electric motor alone or both propulsion systems can offer the propulsion power. This powertrain architecture is inherent in an ICE vehicle concept that is electrically assisted. When the ICE power exceeds the power demand of a vehicle makes the electric motor works as a generator to charge the battery during braking and decelerating, which shows the reduction of tailpipe emission and fuel consumption.[18]

Strengths:

1. It reduces energy losses during the process of converting mechanical power to electrical power compared to the series HEV and vice versa. The process increases the overall system efficiency, particularly during vehicle cruising and highway long-distance driving.
2. In parallel HEV, controlling the ICE and the electric motor leads to propelling the vehicle, which shows a reduction of stress on the sources and also the flexibility to improve the efficiency. The propulsion power switching capability can enhance the vehicle's drivability attribute, that is, acceleration.
3. The electric motor and the battery pack sizes can be optimized owing to balancing the required power between the source and load. Besides, the parallel HEV only requires one electric motor/generator which minimizes the power train system cost.

Challenges:

1. The parallel HEV powertrain system architecture is rather complicated; this makes the control strategies and the energy management added complex compared to series HEV.
2. In this architecture, the ICE does not operate within a narrow or consistent speed range due to the mechanical coupling between the ICE and the wheels through the drivetrain system. This leads to challenges in regulating the engine's efficiency, especially at low rotational speeds. Additionally, the battery pack cannot be charged when the vehicle is stationary due to the mechanical coupling between the ICE and the electric motor.

2.3 | Series-parallel HEV configuration

This kind of HEV configuration, also known as the power-split HEV, merges the HEV series and parallel HEV characteristics. Related to the parallel HEV, it involves an added generator and mechanical connection to the series HEV. The ICE has a direct mechanical link to two electric motors. The primary electric motor helps the ICE in supplying the vehicle with mechanical propulsion power and also performs as a generator during regenerative braking to recharge the battery. The dedicated generator unit is always connected to the ICE and during vehicle operation also works as a starter engine.

Strengths:

1. The series-parallel HEV (SPHEV) shares the same benefits with the HEV series and the parallel HEV architectures. SPHEV is the most flexible and gives the parallel HEV architecture a greater degree of freedom to control the operating conditions.
2. It presents an efficient approach to minimize the proportion of energy flow in series HEVs, which involves two energy conversion processes. This strategy effectively reduces the overall energy losses associated with the system. The ICE speed and torque are separated from the output shaft in the power split arrangement, enabling the ICE to work in its optimum operating regions, optimizing the Brake Specific Fuel Consumption (BSFC).
3. Since the electric motor functions as the propulsion motor or generator, it is possible to achieve greater flexibility and performance of the system.

Challenges:

1. Compared to the series and parallel HEV with series-parallel HEV, SPHEV's architecture is added complex and costly
2. It needs more advanced energy management strategies to enhance the energy efficiency of the system.

2.4 | Plug-in complex HEV

A plug-in complex HEV is a HEV whose battery can be recharged by plugging into an external power source. This type of HEV, as reflected by its name, includes a more complex architecture that cannot be categorized directly into the three groups above. But it is the same as series-parallel hybrids, with the greatest difference between electrical flows. The fundamental difference between complex hybrid and series-parallel hybrid is in the series-parallel hybrid, unidirectional power flow from the generator whereas in the complex hybrid, bidirectional power flow from the electric motor.[19]

Strengths:

1. Most of the vehicles are presently adopting this architecture because of bidirectional and unidirectional power flows.

Challenges:

1. The main disadvantage of plug-in complex HEV is the high powertrain system architecture complexity.

Table 2 presents based on the architecture some of the existing HEV on the road are provided.[4]

3 | ELECTRIC MOTOR DRIVES FOR TRACTION

One of the major technologies for EVs is an electric motor. EV electric motor's general requirements are higher than those for industrial applications. The requirements and classifications for electric motors are summarized below.[20,21]

- A High density of torque and high density of power;
- Wide range of speeds concealing low-speed and elevated speed travel;

TABLE 2 Review of some of the current existing configurational HEV.

Manufacture company	Product	Configuration	Year
Toyota	Prius	Series-parallel	1997
Honda	Insight	Parallel	1999
Nissan	Tino	Series-parallel	2000
Honda	Civic	Parallel	2001
Toyota	Lexus LS 600h	Series-parallel	2007
Toyota	Toyota Auris	Series-parallel	2010
Lexus	Lexus CT 200h	Series-parallel	2011

- More efficiency across wide ranges of torque and speed;
- Wide operating capacity for constant power;
- High performance and grade ability torque;
- High capacity for intermittent overtaking;
- High reliability for the vehicle environment and robustness;
- Low noise in acoustics; and
- Reasonable price.

There are some additional requirements for the vehicle when the electric motor desires to function with the ICE for different HEV architectures:

- Wide speed range enhances efficiency;
- Wide-speed voltage for Effective regulation;
- It can be integrated with the ICE.

3.1 | Direct current motors

For EVs, direct current (DC) motors are widely accepted. Depending on-field excitation methods DC motors are categorized into self-excited DC and the separately excited DC types. Similar wound-field DC and Permanent Magnet (PM) DC types[22] comes under the source of field excitation. DC motors comprise separately excited DC, shunt DC, series DC and PM DC types as presented in Figure 4. Independently the field and armature voltages are controlled for the separately excited DC motor. Owing to the linear speed-torque characteristics, when torque increases relatively the speed decreases and vice versa. Even though the structure is different for the shunt DC motor the feature is similar to a separately excited DC motor. In the DC series motor, the field and armature currents are the same. The speed-torque characteristics are the same as the DC shunt motor for the PM DC motor owing to the field being unable to control. In addition, it has a larger power density and increased efficiency owing to the absence of field losses.[23]

Strengths:

1. DC motors have major advantages owing to maturity and simplicity.

Challenges:

1. As a result of the use of commutators and brushes, all DC motors deteriorate from the common difficulty of periodic maintenance.
2. Owing to Commutators the speed of the motor is limited and the occurrence of torque ripples where friction and radio frequency interference are responsible as brushes.
3. Wear and tear components always require periodic maintenance of brushes and commutators. These disadvantages lead to less reliability and unfit to operate without maintenance.

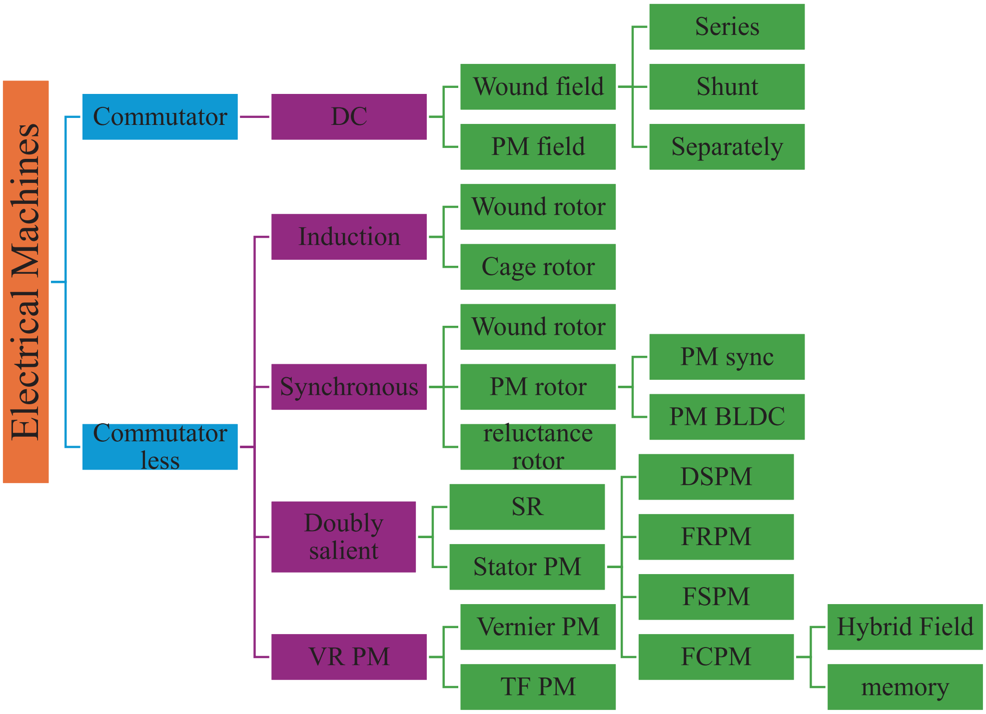

FIGURE 4 Classification of different electric machines for EVs and HEVs.

3.2 | Induction motors

Currently, the induction motors (IMs) are among various commutatorless motors the most mature technology. Based on the rotor the IMs are categorized into the wound-rotor and the cage-rotor. Due to the necessity of maintenance, high cost and deficit of robustness, the wound-rotor IM is paying a lesser amount of attention compared to the cage-rotor counterpart. Hence the cage rotor IM is commonly stated as the IM. In general, the IMs are operated in two modes namely field-oriented control (FOC) and the control of the variable-voltage variable-frequency (VVVF).[24]

If the frequencies are less than the base frequency the VVVF control method uses constant volts/hertz or v/f control and the variable frequency control with constantly rated voltages are used above the base frequency. The voltage boosting is applied for very low frequencies (typically less than about a quarter of the base frequency) in order to match the applied voltage and the induced EMF, which is caused by the drop-in stator resistance. The air-gap flux drifting and sluggish responses are the limitations of IM, which affects the high-performance EV operation based on VVVF control.[25] The FOC allows for similar control of the IM to the separately excited DC motor. The FOC-based IM attaining more attention for modern EV applications with the initiation of powerful low-cost microcontrollers.

Strengths:

1. In addition to the collective benefits of commutatorless motors like brushless and maintenance-free operation, the IM has the significant benefits of low cost and robustness.

Challenges:

1. When the electric motor enters the weakening system of the field (the back emf decreases), a large number of currents developed within the extended constant power range.

3.3 | Switched reluctance motors

The potential of switched reluctance motors (SRMs) for EV applications is considerable.[26,27] SRMs basically have two modes of operation.[28] If the velocity is lower than the baseline velocity the current may be limited by chopping, known as the current chopping control (CCC). The peak current is limited during high-speed operation by the phase winding back electromotive force (EMF). The corresponding characteristic, known as angular position control (APC), is effectively controlled by phase switching instants comparative to the rotor position. The characteristic of constant-power can be attained in the APC mode. Nevertheless, their applications to EVs have been limited over the years.

Strengths:

1. SRM has a simple construction, low production costs, and exceptional speed-torque characteristics.

Challenges:

1. SRM's major drawback is the high torque and acoustic noise.

3.4 | Permanent magnet brushless motors

For EV applications, PM brushless motors are becoming more attractive.[29] The PM brushless motors can be classified into two main categories based on excitation.[30] They are (i) brushless PM DC (BLDC) and (ii) brushless PM AC (BLAC). Generally, the PM BLAC engine is known as the PM Synchronous (PM Syn) engine.[29] Compared to the sinusoidal current interaction and the sinusoidal field, the motor torque output is higher in the rectangular current interaction and the trapezoidal field. Accordingly, the power density of the PM BLDC motor is higher than the PM Syn motor.[31]

The PM BLDC motor also has a considerable torque pulsation while a constant instantaneous and smooth torque profile[32] is produced by the PM Syn motor. The rotor arrangement of PMs will determine the type of PM brushless motors such as assembly-mounted PM rotor, surface-inset PM rotor, interior-radial PM rotor, and interior-circumferential PM rotor. In surface-mounted PM rotors by utilizing epoxy adhesives, the PMs are on the rotor surface, for the reason that the permeability of PMs is near the air gap. The resultant reaction field of the armature and the inductance of the stator winding is less. Besides, subsequently, the winding inductances of the d-axis and q-axis stator are almost similar; its torque of reluctance is almost zero. The PMs are inserted in the rotor surface for the surface-inset PM rotor. Thus, the inductance of the q-axis develops more than the inductance of the d-axis, resulting in an additional torque of reluctance. Owing to the PMs on the surface of the rotor it can able to endure high-speed operation centrifugal force, thus offering good mechanical integrity.

The PMs are radially magnetized and hidden within the rotor of an interior-radial PM rotor. The PMs are mechanically protected, similar to the surface-inset PM rotor, thus allowing high-speed operation. An additional torque of reluctance is also generated due to its d-q saliency. Nevertheless, linear PMs are easier to insert and machinable and are adopted by the interior-radial PM rotor. The PMs are circumferentially magnetized and inserted within the rotor of an interior circumferential PM rotor. Nevertheless, a non-magnetic shaft is usually needed owing to its considerable flux leakage at the internal extremities of PMs. Its constant-power operation can be suggested by the use of advanced control of the conductive angle or the use of polygonal-winding interconnections.[33,34]

Strengths:

1. Subsequently, high-energy PMs excite the magnetic field, and the resultant power overall weight and volume are considerably declined, resulting in high power density.
2. Efficiency is naturally high owing to the lack of rotor copper losses. The heat mainly occurs in the stator and can be effectively dissipated into the environment.
3. The rotor has a low constant of electromechanical time that can increase the acceleration of the rotor.

Challenges:

1. The PM brushless motors suffer the relatively high cost of PM material and uncontrollable PM flux disadvantages.

3.5 | Advanced PM motors for EVs applications

Different classifications are developed based on the various electric motor topologies. Traditionally, based on DC and AC, they were classified as commutator and commutatorless as shown in Figure 4. In EVs applications advanced PM motors like PM commutatorless or brushless motors are creating an interest in the manufacturers, exclusively the type of stator-PM motor and the type of variable reluctance (VR) PM motor.[35]

3.6 | Stator-PM motors

As the name reflects the PMs are in the stator, while salient poles are in both the stator and the rotor.[36] These types of motors are appropriate for vehicle operation owing to the absence of PMs in the rotor and are also simple in structure. It can be divided into subtypes of double-salient PM (DSPM), flux-reversal PM (FRPM) flux-switching PM (FSPM) depending on the location of PMs.

3.7 | Variable reluctance PM motors

These types of PM motors are used in low-speed high-torque drive applications. The operating principle is based on the contact among a set of PMs and its teeth, where the changes in armature flux. In general, the numbers of pole pairs excited by the winding of the stator armature and the PMs of the rotor are different. The toothed-pole structure based on modulation function is used to acquire steady torque when heteropolar fields can interact with each other.[37] Vernier PM (VPM) motor and the transverse-flux PM (TFPM) motor subtypes are classifications of VR PM motors,[38,39] depending on the relationship between the motion plane and the flux plane.

3.8 | Assessment of advanced PM motors for applications in EVs and HEVs

Owing to their classifications, the above-mentioned advanced PM motors are currently in the development phase for application to EVs, their performance was not completely revealed. Nevertheless, a qualitative evaluation is given among them in Table 3 to give a suggestive appraisal of their suitability for applications for EVs and HEVs. Due to its inherent compact design, the TFPM motor has the best power density and torque density. In torque density, the VPM motor also outperforms the others as it essentially recommends a low-speed operation. Due to its ability to control flux for efficiency optimization, the FCPM motor is relatively the best in terms of its efficiencies, while the VPM motor and the TFPM motor suffer large copper loss owing to low power factor. The FCPM motor offers the definite advantage of exceptional flux controllability, including the hybrid field and the memory PM types. As concerns the protection of PMs from accidental demagnetization, the FRPM motor is

TABLE 3 Grading of different advanced commutatorless double salient stator permanent magnet machines.

Specifications	DSPM	FRPM	FSPM	FCPM	VPM	TFPM
Power density	2	1	1	1	1	3
Torque density	2	1	1	1	3	3
Efficiency	1	1	1	3	2	2

Note: Where 1, good; 2, medium; 3, excellent.

comparatively vulnerable owing to marginal irreversible demagnetization of the weak stator teeth surface. Conversely, the FSPM motor arranges the PMs in order to minimize the effect on their working point of an armature reaction field, thus providing good PM immunity. Due to its simple magnetic structures, the DSPM motor has relatively having the best mechanical robustness, whereas with a complicated three-dimensional flux path structure the TFPM motor deteriorates. The structural complexity and control of the motor are primary concerns of design. Among the three types of motors such as DSPM, FCPM, and TFPM, the DSPM motor has the advantage of being easy to manufacture but it is difficult to manufacture the FCPM motor and the TFPM motor.

Finally, the DSPM motor is relatively well established in terms of its maturity compared to FCPM and VPM motors. The above-mentioned advanced motors ensure benefits as well as limitations. The significance of their benefits and limitations also differs from the application types for EVs. Perhaps, owing to its maturity and reliability, the DSPM motor is easily applicable to the current EV scenario. Due to its all-around performance, the FSPM motor is appealing for short-term applications to EVs. On the other hand, the FCPM motor is gaining more attention for EVs, which requires a broad operating range of constant power. These types of motors are suitable for HEVs, which involves various speed ranges and high starting torque from the Integrated Stator Generator. In contrast, the VPM motor is preferable to in-wheel direct drive EVs owing to its low-speed profile with high torque density.

3.9 | Integrated PM motors for EVs applications

Electrical motor development is not at all restricted to the design and operation of a specific motor. Essentially, for a more compact design and improved system efficiency, the modern research way is now prolonged to system integration. The subsequent sub-section will discuss two promising integrated PM machine technologies, specifically (i) Integrated magnetic geared PM brushless motors for EV applications and (ii) Integrated electric variable transmission (EVT) motors for HEV applications.

3.9.1 | Integrated magnetic-geared PM brushless motors

PM brushless motors are attaining more interest in EV applications as they offer inherently high-power density with more efficiency. Furthermore, the application of brushless PM motors in the in-wheel motor act as an electronic differential role.[12] Perhaps, the brushless in-wheel PM motor can be a low-speed gearless outer-rotor or a high-speed planetary-geared inner-rotor when the speed of the wheel is approximately 600 rpm. Whereas the outer rotor offers the benefit of gearless operation, it leads to heavyweight and bulky size owing to low-speed operation.

Apart from the benefits of a planetary-geared inner rotor like the small size and lightweight, the inner rotor has unavoidable mechanical losses, acoustic noise, and regular lubrication. Due to the high efficiency, low acoustic noise and maintenance-free magnetic gears attain more attention recently.[40,41] To further improve their performance, it can adopt interior-magnet planning or the Halbach magnet array.[42] In order to achieve the desired low-speed direct drive and the high-speed motor design, integrate the magnetic gear into the PM BLDC motor.[43] Hence BLDC motor's outer rotor and the magnetic gear of the inner rotor share the common PM rotor. Even though the integrated magnetic-geared PM BLDC motor is based on the outer-rotor but the operating principle is similar to the planetary-geared high-speed inner-rotor motor.

3.9.2 | Integrated electric variable transmission PM brushless motors

These integrated EVT PM brushless motors are suitable for HEV applications for power split of the ICE output. Majorly it consists of two power flow paths for its operation in which one is coupled to the ICE output mechanically with the motor output; whereas the other path is coupled electrically to the generator output and motor input via two power converters.[36] Therefore, a continuously variable ratio can be achieved between the speed of the ICE and the speed of the wheel. Nevertheless, as mentioned above, the PM brushless motor gets the fundamental disadvantage of planetary gearing.

The magnetic gearing has distinct advantages such as the transmission of non-contact torque and speed dissimilarity utilizing the PM Fields modulation effect. Thus, a silent operation, high transmission efficiency, and maintenance-free operation can be achieved. Compared to conventional transmission, the corresponding mechanical torque transmission has a simple design.

4 | ENERGY STORAGE DEVICES

The onboard energy storage system (ESS) is highly subject to the fuel economy and all-electric range (AER) of

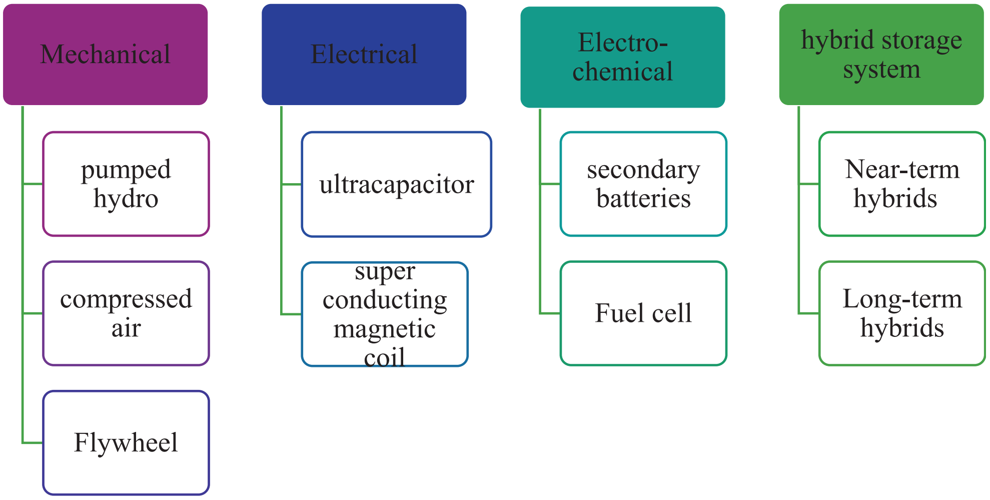

FIGURE 5 Classification of different energy storage systems.

EVs. The energy storage devices are continuously charging and discharging based on the power demands of a vehicle and also act as catalysts to provide an energy boost.[44]

Classification of ESS:

As shown in Figure 5,[45] ESS is categorized as a mechanical, electrical, electrochemical and hybrid storage system.

4.1 | Mechanical storage systems

The generation of world electricity is mainly depending on mechanical storage systems (MSSs). Three types of MSSs exist, namely, flywheel energy storage (FES), pumped hydro storage (PHS) and compressed air energy storage (CAES). PHS, which is utilized in pumped hydroelectric power plants, is the most popular MSS. In order to generate electricity, high head reserved water is utilized and pumped into an electricity turbine with a generator is needed. Globally the PHS contributes about 3% of electricity generation capacity and 99% of electric storage capacity. In the CAES, the mixture of compressed air and natural gas is used for electricity production, where the mixture is expanded and transformed into a reformed gas to feed into a gas turbine connected to a generator.[46] However, PHS and CAES are generally used for the generation of utility power systems and are out of this article's scope.

4.1.1 | FES system

In EV and power system applications, FES is appropriate Owing to the advanced technologies in material engineering and power electronics. FES efficiency and rated power range from 90%-95% to 0-50 MW, correspondingly.[47-49] The flywheel consists of a generator and motor that is, a power transmission device mounted with a common shaft, a rotating cylindrical body in a chamber and the coupling bearings.[47,48] The energy is stored by the flywheel's constant rotation, which converts kinetic energy to electrical energy through a mechanical gear system.

4.2 | Electrical storage system

An ultracapacitor (UC) is similar in structure and function to a normal capacitor,[50] generally known as a supercapacitor. The UC has a high electrical capacity, the specific power is about 1000-2000 W/kg with an energy efficiency of 95%.[51,52] Nearly 40 years of the longest lifespan for UC among all electrical storage systems. The benefits of UC are applicable for EVs applications such as high electrical power storage capacity, free from maintenance, displays insensitivity to temperature and a long operating time. During vehicle braking and coasting down, the UCs are utilized as the electrical energy storage system for fast charging/discharging; and in vehicle rapid acceleration act as the electrical energy source.

The UCs break down into three groups: an electric double-layer capacitor (EDLC), a pseudo capacitor and a hybrid capacitor. The EDLC has a higher density of electrical power among all the capacitors but has a high self-discharge and cost, the low specific density of electrical energy of 5-7 Wh/kg.[53,54] Due to these reasons, in EVs and HEVs applications, the UCs are combined with other ESS such as the batteries and the FCs to achieve high electrical power output, high electrical density, and an overall life extension.[55] Organic UCs are typically utilized to power the EVs owing to their high energy and terminal voltage density.[50]

4.2.1 | Superconducting magnetic ESSs

A superconductive magnetic ESS (SMESS) in the form of a magnetic field stores electrical energy. More amount of electrical energy can be stored in the SMESS systems, a long-life cycle of 100 000 and a fast millisecond response, a full capacity for energy discharge. The initial cost, however, is high for a typical SMESS, which is \$205-340/kW, even though the cost is below the EDLC.[56,57] The electrical energy-measuring units in SMESS are in kW to MW. Approximately 2-4 K temperature of liquid helium for niobium-titanium alloys can be used in SMESS to store electrical energy.[58,59] To maintain low temperature and power conversion of energy, SMES requires a cooling system and converters.[60,61] A cheaper coolant medium like liquid nitrogen was used in high-temperature superconducting materials. Therefore, for low and high operating temperatures, a hybrid SMESS system could be available; and higher storage capacity.[59] The SMESS was used with the battery system in EVs and HEVs. The energy stored by SMESS depends exactly on the coil and the current square self-inductance that flows through it.[57]

4.3 | Electrochemical storage systems

Chemical storage systems (CSSs) generate electricity through chemical reactions of multiple compounds that lead of form other compounds in the system.[62] FC is one type of electrochemical storage device in which electrical energy production is based on the fuel chemical reaction.[63] The main dissimilarity between FC and the battery system is supply sources. The fuel and the oxidant are provided from outside for electricity generation in FC whereas this setup is arranged internally in the battery (excluding metal-air batteries).[56] There are multiple FC types owing to the combination of electrolyte type, operating temperature, and fuel oxidant applications. Such types are a solid polymer fuel cell-proton exchange membrane FC (SPFC-PEMFC), a molten carbonate FC (MCFC), a direct methanol FC (DMFC), a solid oxide FC (SOFC) and an alkaline FC (AFC).[61] PEMFC, AFC, RFC, and PAFC are directly utilized as the anode hydrogen fuel.[62] Further down electrochemical storage systems (EcSSs), especially secondary rechargeable batteries and flow batteries (FBs), all conventional rechargeable batteries are used.

In EcSSs, the chemical energy to electrical energy and electrical energy to chemical energy are obtained by a reversible process in which the system attains high efficiency and low physical changes.[64] But due to the chemical reaction cell life decreases and generates low energy.[56] The batteries of this type have low harmful emissions and maintenance and also dual role working in storing and producing electrical energy by simply reversing the phases.[60] Primary batteries refer to a voltaic battery or cell that is used once and then discarded (in primary batteries, recharging is not possible). Although the primary batteries are very stable and have long been on the market, they are beyond the scope of the vehicle application.

4.3.1 | Secondary (rechargeable) batteries

The secondary (rechargeable) batteries (SBs) commercially used in all electrical and electronic appliances for convenient storing of electrical energy. The SB generally contains two electrodes, one anode and one cathode; one electrolyte; one separator; and one case.[65,66] The SB has good features like negligible memory effect, high specific energy and power density, low resistance, flat discharge profile and withstand temperature capability. The majority of batteries, however, comprise toxic materials. Therefore, consideration must be given to the ecological impact during battery disposal.[67] In major EV applications, due to the enhancement of battery technologies and reasonable costs, SBs offer high specific power and high energy density. Among many types of batteries[62,66] lead-acid (LA) and lithium batteries are playing a major role which is discussed as follows.

4.3.2 | Lead-acid batteries

Commercially LA batteries have gained more importance as energy storage devices since 1860.[56] The LA batteries are utilized for ICE vehicles as a quick starter, auxiliary source, renewable application, and storage purposes due to their roughness, safe operation, temperature withstands capability and low price.[68] The Life span of an LA battery is around 6-15 years with a maximum of 2000 life cycles and 70%-90% efficiency.[54] Owing to its fast-charging capacity, high specific power, low maintenance and initial cost, a Valve-regulated LA (VRLA) gaining more attention for powering EVs.[65] Continuing research is investigating minimizing the weight and size of advanced VRLA battery materials and the high capability of electrical energy.[68,69]

4.3.3 | Lithium batteries

On account of its high electrical density and specific electrical energy and power, lithium is a promising battery chemistry for EVs energy storage applications; and is lightweight.[70] Besides, lithium batteries have no memory effect unlike mercury or lead compositions, which have no harmful effects. Nevertheless, this type of battery is costly compared to other battery types. It usually costs \$150/kWh and requires maintenance during operation and cell balancing for regular battery operation at the same voltage and charging level.[63] For high temperatures (41-113°F) and adjustable to the surrounding temperature applications lithium batteries are before being used other than sodium-beta batteries.[71] Among all other lithium batteries, lithium-sulfur batteries are lightweight and have more capacity for electrical energy (500 Wh/kg).

4.4 | Hybrid energy storage systems

ESSs are used in EVs and other storage applications require the maximum influence of ESSs. Practically all ESSs are unable to provide all required characteristics like the density of electrical energy, the density of electrical power, rate of discharge, life cycle and cost. Therefore, ESS is required to optimize the energy storage and transfer balance features by combining two or more ESSs with additional features to ensure optimum ESS performance. A hybrid ESS (HSS) has been developed, combining the electrical output of two or more ESSs with additional features electronically.[72] To deliver the optimum power for traction motors, the power electronic configurations had to take into account the grouping of a high electrical power density and electrical energy density, or a fast and slow ESS response, or a high-cost and low-cost ESS. HSSs can be categorized into different combinations based on applications shown in Table 4.[73,74]

TABLE 4 Hybrid storage system combinations based on near-term and long-term aspects.

Near-term hybrid combination	Long-term hybrid combination
Battery and battery hybrids	Fuel cell and ultracapacitor hybris
Battery and ultracapacitor hybrids	Fuel cell and ultra-high-speed flywheel
Fuel cell and battery hybrids	CAES and ultracapacitor hybrids
Fuel cell and battery and UC hybrids	
Battery and SMES hybrids	
Battery and flywheel hybrids	
CAES and battery hybrids	

4.5 | Issues and challenges of ESSs in EV applications

For the EVs propulsion energy storage system, the existing development of ESSs is acceptable. It also reduces oil demand and subsequently reduces CO_2 emissions. With the technological changes and improvements, ESSs are continually maturing. The ESSs, nevertheless, still face several issues such as support for raw materials and proper disposal, energy management, power electronic converters, system component sizing, security measures, and cost. These are the main challenges requiring advanced research activities. The EVs propulsion system usually uses superconducting magnetic coils, FCs, hybrid ESSs and UCs.[65,71]

Since the long-term solution is to reduce dependence on fossil fuel vehicles, researchers are actively developing advanced propulsion systems that utilize other energy sources such as FCVs and FC combinations. However, the low voltage response of the FC may not work in the transient state due to that, a combination of FC with battery or supercapacitor is more powerful and efficient than the FC alone. Due to the limitations of the battery such as more weight, short driving range and high charging time makes the FC with a combination of UC is gaining attention for EVs applications.[75] In Table 5, some FCV features with the combination of SC[76] were assessed.

Vehicle applications require the ultracapacitors to be charged quickly and discharged, especially in the transient electrical demand.[77] Due to overvoltage,[78,79] the unbalanced cells resulted in under-use of the UC capacity and the danger of damaging individual cells. Therefore, the appropriate benefit of the energy management strategy,[80] the next sections will review the charge equalization or cell balance methods of supercapacitors.

TABLE 5 Achievable features in a long-term solution of a hybrid storage system based on architecture existing with a supercapacitor.

Architecture	Features
Supercapacitors connected to fuel cells directly	• Highest fuel economy • Less costly • Moderate reduction in stress on fuel cells
Supercapacitors coupled with fuel cells via a converter	• Suitable power-splitting strategy • Load leveling • High fuel economy and lowest stress on fuel cells

5 | CHARGE BALANCING OF SUPERCAPACITOR

The UCs are used in EVs as auxiliary power devices. The energy flows inside the UC during powertrain operation in/out of the device. Nevertheless, there are two distinctive ways to use ESS SC. It can be used as energy storage units with charging status (SoC) as the level of the indicator and as pulse power devices within a generally limited scope of SoC.[81] Due to the charge imbalance of cells,[82] the voltages of energy storage cells are affected. The performance of EVs and optimal energy managers can be achieved by optimizing capacitor and ESS cell balancing techniques. In addition, the cell balancing in the SC stack[83,84] can also maintain a strategic distance from supercapacitor overloading and overloading. Several types of balancing of cell voltage were reviewed and will be discussed in this article.[85,86]

The supercapacitor has two primary approaches to balance, which are passive and active techniques. The resistors are used in the strategies of passive cell balance, parallel to the supercapacitor to overcome the overload through the passive components. This technique has low efficiency due to the power consumption of resistors.[87] The strategies for active cell balancing depend on the inductors, the condensers and the controllers or converters that are switched. The cells transmit electrical energy from high to low voltage.[88,89] The active balancing strategies are therefore more efficient than the passive balancing technique.[90] Figure 6 shows the differences between the existing charge-balancing methods.

5.1 | Comparison between the existing balancing methods

Table 5 presents the evaluation of some of the conventional methodologies in terms of a number of essential components. A balancing topology based on a buck-boost converter can be designed with an acceptable number of components.[91,92] Nevertheless, the transfer of electrical energy from these methodologies is inadequate between the cell-to-cell balancing. Also, when the count of the cells is increased in the stack, which affects the balancing speed.

Furthermore, the balancing system based on a buck-boost converter needs a greater number of switches and an intelligent control system leads to an increase in the complexity and system cost. In MWT-based balancing topologies,[93] the leakage inductance of the multi-winding transformer is the main limitation not only because of the changing in secondary windings but also because stringent parameter matching requirements for the turn's ratio leads to the occurrence of charge imbalance. In the voltage multiplier, a circuit with diodes and capacitors is used to balance the cells.[94] The circuit, however, depends on the capacitor impedance.

The increment of capacitor value affects the balancing time. If the equivalent resistance and voltage of the diode are not uniform, a residual voltage imbalance will occur. The balanced cell voltages indicate a significant decrease compared to the average cell voltage. There are limited numbers of topology studies on battery balancing systems. Hence this article is expected to draw the targets set out in Table 6 and analyze the control strategies for the optimal balancing solution based on the conventional characterization technique.

6 | OVERVIEW OF HEVs CONTROL STRATEGIES

The design of sub-system and system control strategies is very challenging caused by the complex architecture of HEVs/PHEVs. The primary control goals of most HEV control strategies are optimizing fuel consumption and tailpipe emission without compromising the vehicle performance attributes and the auxiliary source as a supercapacitor SoC.[80] Energy management strategies (EMS) have a significant impact on HEVs' fuel efficiency. It is mainly utilized for splitting power between two sources. Smartly, power splitting leads to better fuel economy and regulates the power flow. The Energy Management Strategies (EMS) are divided into two different control strategies rule-based (RB) and optimization methods as shown in Figure 7.

6.1 | Rule-based methods

This method is a basic control scheme that depends on the operating mode. With real-time supervisory control, they can be easily applied to supervise the energy flow in the HEV powertrain system. The rules are determined based on human intelligence, heuristics, and mathematical models; and generally, without prior vehicle duty cycle knowledge. Also known, as static controllers are rule-based controllers. Mostly, the operating point of system components (ICE, electric motor, generator, etc) is determined most efficiently by using the rule tables or flowcharts to meet the driver and other system component requirements (electrical loads and battery). The decisions are based solely on instant inputs. This strategy is further sub-categorized into the foundation of the deterministic rule and the Fuzzy rule.

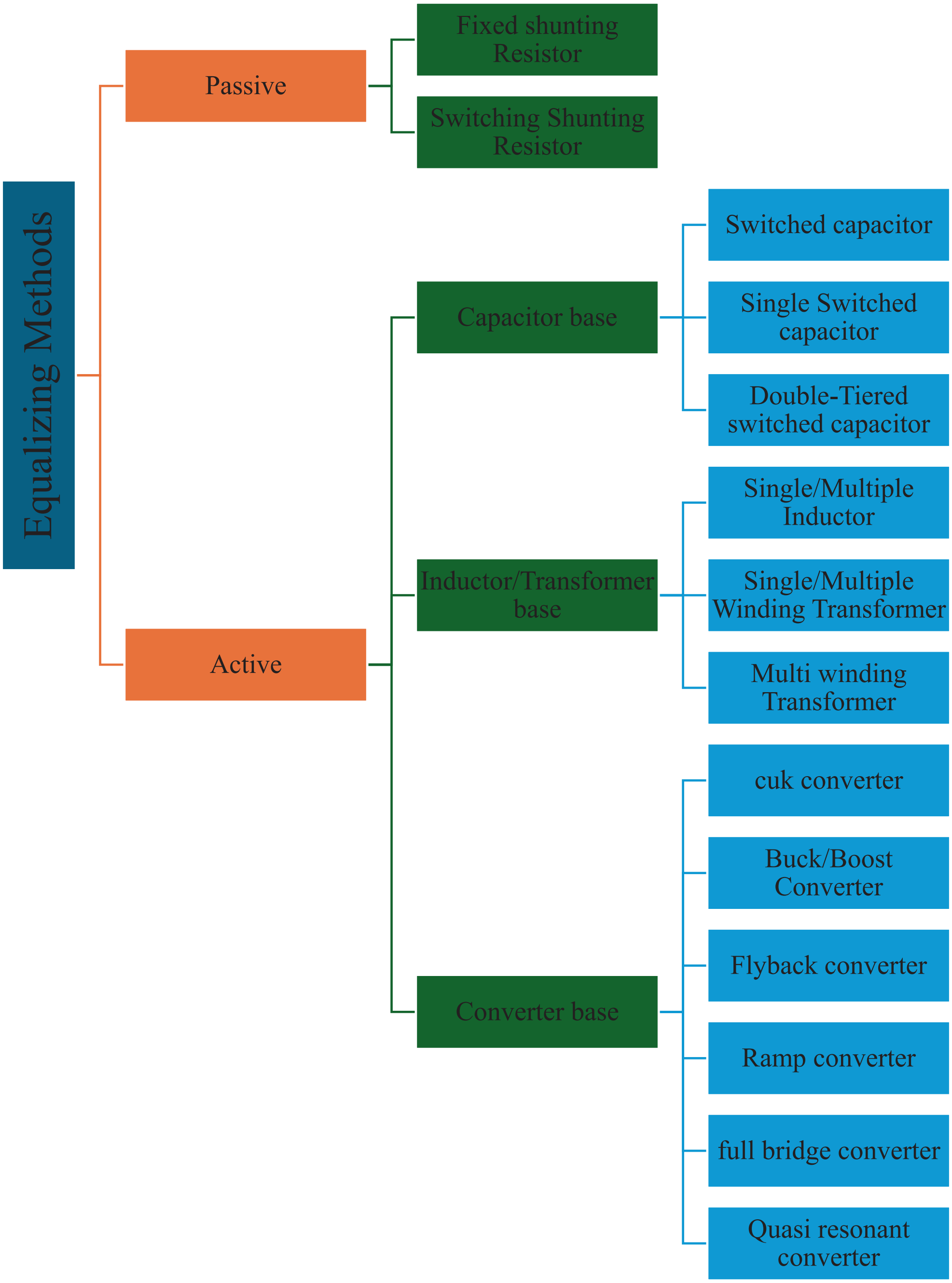

FIGURE 6 Classification of charge equalization methods for supercapacitor.

TABLE 6 Existing topologies of balancing type of converters by their number of components.

Type of converter	Topology	No. of the components				Transformer
		Switch	D	C	L	
Switched capacitor converter	Basic SCC[95]	2n	–	n − 1	–	–
	Double-Tiered SCC[50]	2n	–	2n − 3	–	–
	Single SCC[90]	n + 5	–	1	–	–
	Quasi-resonant SCC[96]	2n	–	n − 1	n − 1	–
Buck-boost converter	Basis topology[91]	2 (n − 1)	–	–	n – 1	–
	Cuk converter[84]	2 (n − 1)	–	n − 1	2 (n − 1)	–
Multi-winding transformer	Flyback converter[93]	1	n	–	–	1 (n) PW
	Forward converter[92]	n	1	–	–	1 (n) PW

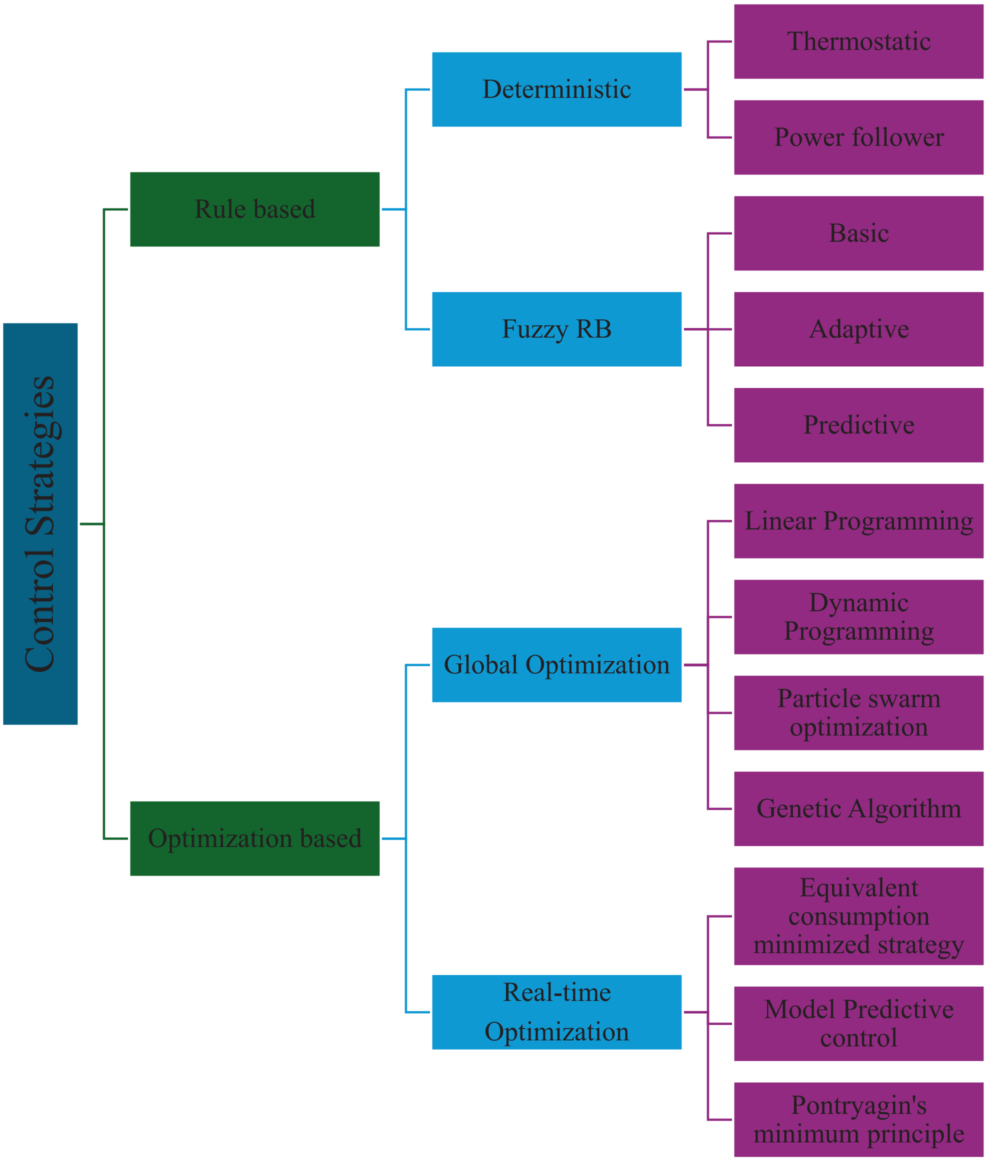

FIGURE 7 Classification of energy management strategies for hybrid electric vehicle based on rule-based and optimization-based techniques.

6.1.1 | Deterministic rule-based methods

In terms of fixed rules, the deterministic RB methods are formulated. For example, the ICE shut-off, the power split and the battery charging algorithms, where the operating limits are already prescribed in the regulated commands. The methods of deterministic RB are explained as follows:

Thermostat control strategy

Thermostat control strategy (TCS) is also known as the *On-Off* control strategy.[97] Under this strategy, at its highest efficiency point, the ICE operates with a fixed power and turns *On* and *Off* created on the battery SoC. Let $S_g(t)$ be the set ICE-generator *On-Off* state. The $S_g(t) = 1$ equation means the engine is *On*, and $S_g(t) = 0$ means the engine is *Off*. The logic of the TCS control is set out in Equation (1). Where SoC_U means an upper limit state of charge and where SoC_L means a lower limit state of charge.

$$S_g(t) = \begin{cases} 0 \begin{cases} \text{if } SoC\left(t^-\right) \ge SoC_U \text{ or} \\ SoC\left(t^-\right) > SoC_L \text{ and } S_g\left(t^-\right) = 0 \end{cases} \\ 1 \begin{cases} \text{if } SOC\left(t^-\right) \ge SoC_L \text{ or} \\ SoC\left(t^-\right) > SoC_U \text{ and } S_g\left(t^-\right) = 1 \end{cases} \end{cases} . \tag{1}$$

The corresponding distribution of TCS power is described as equated (2).

$$P_g(t) = \begin{cases} 0\, S_g(t) = 0 \\ P_e\left(T_{s,\eta}, \omega_{s,\eta}\right) \eta_g\left(T_{s,\eta}, \omega_{s,\eta}\right), S_g(t) = 1 \end{cases}. \tag{2}$$

The above Equation (2) rewritten as follows,

$$P_g(t) = \begin{cases} 0\, SoC\,(t) < SoC_L \\ P_r(t) - P_g(t)\, SOC_L \leq SoC\,(t) < SoC_U \\ P_r(k)\, SoC\,(t) > SoC_U \end{cases}, \tag{3}$$

where the pair $\left(T_{s,\eta}\,(torque), \omega_{s,\eta}(speed)\right)$ are the fixed ICE-generator set operational conditions that offer the best fuel economy. Where $\mathrm{SoC_U}$ means an upper limit state of charge and $\mathrm{SoC_L}$ means a lower limit state of charge. $P_g\ (t)$ is a generator power with respect to time, $P_r(t)$ is a rated power of the generator, and η_g is the generator efficiency.

Power follower control strategy

The basic idea of the Power Follower Control Strategy (PFCS)[58] is as follows. Pretend, ICE-generator is the major power source and monitoring will adjust the output power of the ICE-generator to meet the power demand. The ICE generator is active under almost all driving conditions, excluding when low vehicle power demand is essential and the SoC of the battery is higher than the $\mathrm{SoC_U}$ equation determines the corresponding power output (4).

$$P_g(t) = \begin{cases} 0 \text{ if } S_g(t) = 0 \\ P_{g,min} \begin{cases} \text{if } S_g(t) = 1 \text{ and} \\ SoC\,(t) > SoC_U \\ \left(P_r \geq P_{g,min}\right) \end{cases} \\ P_{gm}(t) \begin{cases} \text{if } S_g(t) = 1 \text{ and} \\ SoC_L \leq SoC\,(t) \leq SoC_U \end{cases} \\ P_{g,max} \begin{cases} if\ S_g(t) = 1 \text{ and} \\ SoC\,(t) < SoC_U \end{cases} \end{cases}, \tag{4}$$

where $P_{gm}(t)$ from the above Equation (4) is expressed in Equation (5).

$$P_{gm}(t) = P_r + P_{ch}\left[\frac{SoC_U + SoC_L}{2} - SoC\,(t)\right], \tag{5}$$

P_{ch} is the chosen charge power magnitude. $P_{g,min}$ and $P_{g,max}$ is the minimal and the maximum electric power outputs respectively of ICE-generator.

6.1.2 | Fuzzy rule-based methods

Most of the HEVs use this method of energy management, which increases the benefits output proportionality to various operating conditions. The robustness to modeling errors and inaccurate measurements are tuned by fuzzy rules. In the following section, the fuzzy-based approaches will be explained step by step.

Basic fuzzy

As the HEVs consist of system non-linearity and multi-variables, the fuzzy logic controller (FLC)[98] is more considerable for the EMS control. Using a list of *If* and *Then* rules, the controller connects its outputs to inputs. Indicates the condition for which a rule holds *If* part of the rule. The *Then* part of a rule refers to the output variables' values in order to acquire the output of the controller. The variables are allocated a degree of affiliation corresponding to the definition of affiliation functions. *If* part of all rules is assessed and all *Then* part rules are averaged and weighted by these degrees of affiliation.

Adaptive fuzzy

By adapting the control parameters to the current operating conditions, the functioning of basic fuzzy methods can be improved. In reference 99, a 'Driver Command Interpreter' is to convert the driver commands and the vehicle speeds into vehicle power demands. A 'Driving Mode Detector' is used to decide the driving modes as specified in the fuzzy controller. An adaptive fuzzy logic-based energy management strategy (AFEMS) controller has three inputs; Driver Command Interpreter power demands, Driving Mode Detector vehicle driving modes, and UC SOC reflecting HESS states. Note that the battery is considered as long-term electrical energy storage in this article[99] and thus its SOC only affects the system efficiency slightly. Therefore, only the UC SOC is used to indicate the states of HESS. For the AFEMS controller, the response of energy storage is combined with the power demand, which decides how the energy storage components in the HESS act and how their SOC changes respectively.

Predictive fuzzy

The current driving conditions achieve their optimal results by adding predicted responses to the fuzzy controller. A route can be represented as a traffic sequence in reference 100. It is believed that useful information will be provided to predict traffic conditions by analyzing the driving data.

6.2 | Optimization-based control strategy

A controller's objective in optimization-based control strategies is used to reduce cost function. Depending on the applications, the cost function or objective function for the HEVs involves torque demand, fuel consumption, and emission. Optimizing over a fixed DC may attain the optimum global solutions. These types of control methods cannot deliver real-time energy management, nonetheless, based on an instant cost function where it is appropriate to obtain a real-time control strategy. The instant cost function relies only on the current time system variables. It should incorporate a corresponding fuel consumption to ensure the electrical path's self-sustainability. The control strategies based on optimization are classified as, global optimization and real-time optimization (RTO). In the next section, the details of these two techniques will be discussed.

6.2.1 | Global optimization

The global optimization technique for EMS in the HEVs needs knowledge of the entire driving pattern including the SoC battery, the driving conditions of the vehicle, the response of the driver and the route of the vehicle. They are not easily implementable for real-time applications due to computational complexity. There are typically four types of global optimization techniques used to solve energy management issues for vehicles, namely linear programming, dynamic programming (DP), genetic algorithm (GA), and particle swarm optimization (PSO).

Linear programming

Owing to the size of the Mixed Integer Linear Programming (MILP) formulation, the optimization problems are often difficult to solve accurately over a long scheduling period.[101] Furthermore, the charging and discharge schedules of HEVs must be updated instantly when updating the power demands and HEV's departure times. MILP formulation's feasible solution can be achieved by turning up an optimal solution to its linear programming relaxation problem instead of applying the time-consuming exact algorithms. The linear programming-based heuristic algorithm consists of two steps: (i) solving the MILP formulation linear programming relaxation problem and (ii) rounding up an optimal (fractional) linear programming relaxation problem to achieve a feasible (integer) MILP formulation solution.

Dynamic programming

The DP can easily handle the constraints and the non-linearity of a problem by obtaining a globally optimal solution.[102] It is used to solve the problem of two-point boundary optimization and to analyze HEVs 'power management strategies. The DP can be related to various kinds of problems with optimization. It proposes the opportunity to reflect the state and control variable's constraints. The algorithm is based on Richard Bellman's principle of optimality. The algorithm[103] solves the concern problem sequentially by calculating the optimal control in each state set at each stage of the problem, going back in time.

The cost of employing an action and the resulting optimal cost of the following time step, calculated before the particular action, are reflected while evaluating the optimal decisions. Therefore, the accumulated cost in states x_k can be defined by an instantaneous cost $g_k(x_k, u_k)$ that occurs due to an applied action u_k and the remaining cost J_{k+1} reflecting all results in the following time steps $k+1, k+2, ..., N$. In the recursive formulation given in Equation (6), this relationship is formulated. The optimal control which minimizes this recursive relationship is given in Equation (7).

$$J_k(x_k, u_k) = \min_{u_k \in U_k} \{g_k(x_k, u_k) + J_{k+1}(x_k+1)\}, \tag{6}$$

$$u_k^* = \arg\min_{u_k \in U_k} \{g_k(x_k, u_k) + J_{k+1}(x_k+1)\}. \tag{7}$$

Thus, to take the constraints on the state and control variables into account, the penalty terms $\phi_k(x_k)$ and $\phi_N(x_N)$ for the final state, constraints are incorporated in the algorithm cost function. The modified cost functional as indicated in Equation (8).

$$J_\pi(x_k) = g_N(x_N) + \phi_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k, w_k) + \phi_k(x_k). \tag{8}$$

Particle swarm optimization

The PSO is a gradual development of computing techniques based on the population, inspired by the bird flocking social behavior and optimizes a function by using a population of particles that fly within the hyperspace solution. The particles are prepared randomly and at each iteration, the search for the optimal solution is performed by updating their velocity and position. The renewing policy for each particle consists of one's and the entire population's best experience. Using the PSO,[104] optimum energy storage weighting parameters are calculated.

The program flow steps are outlined below:

Step 1: PSO parameters such as swarm size, coefficients of acceleration, the weight of inertia; maximum velocity and iteration are identified. Each particle's positions are initialized randomly within a predefined range.

Step 2: For each particle, the objective function of fitness is calculated.

Step 3: The best particle position (*pbest*) and the best global position (*gbest*) are attained from the fitness evaluation.

Step 4: The particle velocities will be calculated using the evaluated fitness data and the positions will be updated. The formulas for speed and position are given in Equations (9) and (10).

$$v(t+1) = wv(t) + c_1 r_1(t)(pbest(t) - p(t)) + c_2 r_2(t)(gbest(t) - p(t)), \tag{9}$$

$$p(t+1) = p(t) + v(t+1), \tag{10}$$

where c_1 and c_2 are the acceleration coefficients, the weight factor is w, random variables are r_1 and r_2 and position of the particle is p.

Step 5: If the fitness has exceeded a specified value or maximum iteration, the algorithm will exit the loop.

Step 6: The PSO algorithm is finished and the optimum constraints are attained.

Genetic algorithm

GA is an appropriate tool for optimizing multi-objective optimization issues. The GA is capable of efficiently exploring the solution space and determining the global optimum. In HEV, the GA helped determine the optimum value of decision parameters to increase fuel efficiency and reduce emissions from the tailpipe. The GA is also used to optimize powertrain parameters or to decide the optimum size of the vehicle components. Another application of GA is to optimize the constraints of the vehicle for the threshold value to turn the ICE *On/Off* to achieve the best fuel efficiency.[105] The GA has different features such as (i) it does not require any information about initial conditions, (ii) the target is the global optima, (iii) it works with multiple design parameters, (iv) it is easy to use, and (v) it does not need any additional information about the objective function.

6.2.2 | Real-time optimization

Instant power handling policies are applied by RTO methods to reduce cost function based on future energy equivalent consumption assumptions. In general, in terms of computational approaches and memory properties, mathematical formulation plays a major role in real-time applications.

Equivalent consumption minimized strategy

The equivalent consumption minimized strategy (ECMS)[106] is part of the optimized strategies instantaneously. The instant operating costs are minimized by the DC's optimal power. P^*_{dc} converter specified in Equation (11).

$$P^*_{dc} = argminH', \tag{11}$$

where H' = all-instant cost shown in Equation (12).

$$H' = M_{H_2} b_e P_{fc} + M_{ele} P_{bat} \left(\mathfrak{y}_{dis}\, \mathfrak{y}_{chg}\right)^{-sgn\,(P_{bat})}. \tag{12}$$

Considering $P_{fc} = (P_m/\mathfrak{y}_m + P_{aux} - P_{bat})$ the optimal min H' problem is corresponding to the equation below (13).

$$\begin{cases} \min(P_{bat}\, K) \\ K = -M_{H_2} b_e/\mathfrak{y}_{fc} + M_{ele}\left(\mathfrak{y}_{dis}\, \mathfrak{y}_{chg}\right)^{-sgn\,(P_{bat})}. \end{cases} \tag{13}$$

The coefficient K is a constant less than zero based on the power train system parameters. Hence, the battery's optimum electrical discharge power is equal to the battery's maximum electrical output allowed. The ECMS strategy corresponds to a Charge Depleting Charge Sustaining (CDCS) strategy, taking into account the constraint on the SoC of the battery. The powertrain system operates in a battery electrical mode in the CD stage and the powertrain system operates in a charging mode in the CS stage.

Model predictive control

The model predictive control (MPC) algorithm[107] comprises three steps (i) handle the system's dynamic model to forecast future outputs over the optimization horizon; (ii) assessment of the cost function for the system's future output set; (iii) apply the control policy's first element with the minimum cost. The MPC originated from the chemistry industry as the optimal control method and is characterized by slow dynamics, which gives adequate time to calculate its problem optimization. The following Equation (14) provides the general plant model for HEV applications.

$$\left\{ \begin{aligned} x(k+1) &= A(k)x(k) + B(k)u(k) + n(k) \\ y(k) &= C(k)x(k) + D(k)u(k) + v(k) \end{aligned} \right\}, \tag{14}$$

where $x(k)$ is the state; $u(k)$ is the control inputs; $y(k)$ is the outputs; $n(k)$ is the state noise; $v(k)$ is the measurement noise.

TABLE 7 Comparison of different auxiliary tools integration used for EMS.

Auxiliary tools	Types	Conducted by	Integrated to	Achievement/output
Rules optimization	• Qualitative • Quantitative	• Static optimization	• Rule-based	• Robustness of RB
Multi-rate computing	• Fixed rate • Adaptive rate	• Case-based • Parallel computing	• Optimization-based	• Computational Time Reduction
Pattern recognition	• Driving patterns • Route/ road type	• Machine learning • Fuzzy logic/NN	• Rule-based • Optimization-based	• Case-based Optimized Solutions
Prediction/estimation	• Driving conditions • SoC estimation	• Statistics/HMM • Observers/filter	• Optimization-based	• Prior knowledge of future drive conditions
Intelligent traffic systems (ITS)	• V2V • V2I	• Communication • Technologies	• Rule-based • Optimization-based	• Current traffic conditions • Next refueling options

To display the reference tracking error and the control effort, an objective function is proposed.

Pontryagin's minimum principle

In the exceptional case of the Euler-Lagrangian equation, under some reasonable postulates, the Pontryagin's minimum principle is appropriate to solve real-time state-constrained issues. Using the equations from reference 108, the Hamiltonian H can be expressed for all $t \in (0, t_f)$ as:

$$H(x(t),u(t),\leftthreetimes(t),t) = \leftthreetimes^T(x(t),u(t)) + \mathcal{L}(x(t),u(t)), \quad (15)$$

where $\leftthreetimes^{\mathrm{T}} = -\frac{\partial H}{\partial x}$ ($\leftthreetimes$ is the Lagrangian multipliers vector).

To achieve optimality, an optimal $u*$ control exists that produces trajectories $x*$ and $\leftthreetimes*$ of an optimal state and costate's respectively and fulfills in the period of the predetermined time.

$$H(x*(t),u*(t),\leftthreetimes*(t),t)*H(x*(t),u(t),\leftthreetimes*(t),t). \quad (16)$$

Assuming that the partial form that T_f is a priority, that is, $-\frac{\partial H}{\partial t} = 0$, the optimal solution can be achieved by simplifying the problem in real-time.[109,110] This method leads to optimality by the initial costate determination of a core factor owing to its exact influence on the trajectory of the state and the convergence of the solution. Feedback control methods perform the dynamic correction of this value. The fixed formulation and small flexibility in disparity driving conditions are the major limitations of traditional RB methods. In contrast, due to their increased computational load, optimization-based approaches are less appropriate in real-time. To address these disadvantages, the subsidiary adaptation tools are combined into both approaches. Optimal-based real-time methods are classified into five main classifications as shown in Table 7.[111]

Consequently, to increase the robustness of the methods against the disparity of driving conditions, the optimization rules are related to RB methods (fuzzy and deterministic). Hence balanced performance can be achieved for different vehicle driving conditions by searching or defining optimal control parameters that is, quantitatively or qualitatively. The problem of optimization can be allowed to multi-rate computing, which is reduced into two subgroups to allocate an appropriate rate of processing. This rate can be set to obtain the instantaneous (short-term) or strategic (long-term) optimal solutions for slow and fast-predefined cases. Pattern recognition is utilized for optimum control based on the identification of the situation. The recognized patterns are possibly road type (urban, highway) and driver style (eg, calm, aggressive, etc). By using more sophisticated machine learning methods (eg, neural networks [NN], fuzzy logic rules [FL]), the pattern recognition algorithms are formulated.

Furthermore, to unravel a restricted optimization problem, the estimation of future vehicle driving conditions is used. Frequently, the Markov model is applied on the basis of statistical data analysis to predict the change in the next vehicle's driving conditions. An observatory/Kalman filter is also utilized to estimate the SoC behavior of the battery to improve the power split strategy accordingly. Based on vehicular communication techniques like Vehicle-to-Grid (V2G), Vehicle-to-Vehicle (V2V), Vehicle-to-Interface (V2I), and more, an intelligent traffic system is an add-on tool for the Energy management

TABLE 8 Advantages and challenging features of soft computing techniques of EMS.

Techniques	Advantages	Challenges
Expert systems also called knowledge-based systems (KBS)	• Cost reduction in achieving a complex task	• The lack of expertise
Artificial neural networks (ANNs)	• Most of the problems are now able to be solved • Representing I/O relationships for nonlinear systems	• Is only a special mathematical technique
Fuzzy logic (FL)	• Applied successfully in a large number of uncertain applications	• Input/output controls of the process are complicated
Genetic algorithms (GAs)	• Optimization	• Successful for some applications
Hybrid system (ANNs & FLS), (FLS & ANNs), (GAs & FLS) and (GAs & ANNs)	• Combination technique is capable of solving all problems of the engineering discipline	• No

problem. These smart-systems provide more information on the nearby refueling possibilities, jammed routes, traffic lights, and the shortest route to the destination for enhancing the development of Energy management and depletion/sustaining policies for battery charging. Different soft computing techniques have appeared as suitable tools to solve complex engineering problems that traditional methods could not handle. The soft computing techniques provide effective modeling, analysis, and decision-making as shown in Table 8.[112,113]

The work in this article aims to provide scholars and researchers with the needed knowledge on energy management strategies as well as various components of HEVs, shedding light on advanced methods and solutions, and helping to recognize the most promising future development opinions.

7 | CONCLUSIONS AND FUTURE SCOPE

In summary, the energy management strategies of HEV have been discussed in detail. The EMS is one of the most important attributes for the efficiency and the performances of HEV. This article reviews the EMS and evaluates the existing methodologies by means of discussing its advantages, limitations, and performance measures. Nevertheless, there is still a big gap in the EMS of HEV for delivering efficient energy to the sub-system and system levels. The article can also potentially help researchers to understand the state-of-the-art in optimal energy management and to motivate advanced research. In addition, the charge balancing of the capacitor can also be explored for the HEV, to monitor the charging and discharging characteristics of the supercapacitor. The charge balancing helps to prevent the supercapacitor from overcharging.

In order to influence the EMS in future transportation, hybrid algorithms are more effective and efficient than utilizing a single algorithm. Furthermore, the swift advancement of communication, information, and positioning technology necessitates that energy management strategies be both predictive and adaptive. So, advancements in technologies among software developers offer researchers the chance to harness the utmost potential in designing new control algorithms. This can be achieved by combining these advancements with existing techniques, aiming to eradicate uncertainties concerning the strength and reliability of the EMS.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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