Chapter 9
Evolution and Recent Advancements in Electric Vehicle (EV) Technology

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Abstract This paper presents the main components of electric vehicles (EV) and the evolution of technologies used in them. The electric vehicles are gaining importance globally as it is seen as a factor of reducing air pollution and smog. This paper focuses on advantages of EVs compared to internal combustion engine (ICE)-based vehicles, different types of EVs and their greenhouse gas emissions, different types of EV motors and their developments, evolution of batteries and their advanced technologies, different types of battery management system (BMS), different types of powertrains and challenges encountered by different types of EVs. EVs are diversified and sophisticated, with different elegance options, but all with the reliability and power of conventional, gasoline-powered vehicles. The main aim of this paper is to give a general image of the present EV innovation and the ways for further improvement to aid future researches in this area.

Keywords Electric vehicle · Traction motors · Battery management system · Powertrain technologies

9.1 Introduction

Afore the Industrial Revolution, our vitality needs were unassuming. For heat, we relied on the sun and burned wood, straw and dried dung when the sun failed us. For transportation, the potency of the wind in sea and in land, horses took us to every corner of the world [1]. After 1800 A.D, many inventions were made in the transport and subsystems of it, and hence, the usage of electric carriages came into

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V. Kamaraj et al. (eds.), *Emerging Solutions for e-Mobility and Smart Grids*,
Springer Proceedings in Energy, https://doi.org/10.1007/978-981-16-0719-6_9

existence. In 1900 A.D, the ICE-based vehicles became popular and brought a new era in transport. Due to the low price of petrol and diesel, the usage of two wheelers become larger nowadays which paved the way for air pollution and lot of health problems. So, the automobile industries shifted their attention towards EVs after the invention of lithium ion batteries. Hence, many researchers are focusing on different types of EVs which are classified based on their energy sources. Also, the research papers in electric vehicles are aimed at idealizing and developing the batteries with high density of energy and longer life, fuel cells and its types, battery management system, traction motors, innovative power management and control systems with regenerative braking. This paper presents the literature survey of dark period and come back of EV, comparison between EV and other modes of transport based on energy sources, motor drive technologies and comparison of efficiency and losses of different EV motors, history of batteries, topologies of battery management system, future batteries, powertrain technologies and its advancement and challenges faced by EVs.

9.1.1 Dark Period of Electric Vehicles

As the motor vehicles gained popularity around 1900 A.D, the electric cars were greater in number when compared to diesel/petrol cars. The development of electric starter for petrol cars eliminated the conventional drawback of utilizing a hand crank to get the car moving. After the huge production of Model T by Henry Ford, the era of electric car had come to an end as the price of petrol car is half of the price of an electric car. So, the manufacturing of electric cars was stopped by the year 1935 [2].

9.1.2 Come Back of Electric Vehicles

There was resurgence in electric cars due to the shortage of oil in Gulf countries in 1970s and 80s. With the accessibility and cost of oil being demonstrated to be progressively unstable, people could optically recognize the possible advantages of battery-powered cars. The chance of getting aids and strict regulations made the auto manufacturers of USA, Japan and Europe to develop EVs. Most of the companies in Japan and Europe have developed their EVs around 1960s. The experimental EVs like Electrovair in 1966, Electrovan in 1968, Electrovette in 1979 were launched by General Motors. Following the general motors, many companies started producing different kinds of EVs in late 90s.

9.1.3 Importance of Electric Vehicles

Currently, the global population is 6 billion, and if it increases with the current trend, it may become 10 billion by 2050. This will pave the way for increase in the usage of vehicles 700 million (as per reports in 2000) to 2.5 billion by 2050, and if all these vehicles are IC engine-based vehicles, then most likely all the cities will be covered with permanent smog with extreme air pollution. [3]. This will bring severe health issues. Hence, it is essential to shift the attention towards pollution-free transport. One of the promising solutions is sustainable transport. It means the use of low or zero emission vehicles for public transport. Hence, the captivation of fossil fuels will be less as it is the major source of pollution. So, to better apprehend the benefits and shortcomings of EV, the comparison among different types of EV and ICE-based vehicles can be done on following parameters [4–6].

The parameters considered for comparison are energy sources; pollution, energy diversification, efficiencies, performance capital and operating cost are listed in Table 9.1.

The graph shown in Fig. 9.1 illustrates about the emissions of different types of vehicles. On analysing the figure, it is evident that ICEV-based vehicles have greater percentage of emissions compared to BEV. The other types of vehicles such as HEV, PHEV and REV are in the middle of these two ICEV and BEV.

In India, Bharat Stage regulation permits automobile manufacturers to do research for minimizing the emission of greenhouse gases [7]. The energy diversifications of electric vehicles are given in Fig. 9.2.

The IC engine vehicles normally use liquid fuels and gaseous fuels which are obtained from either oil or natural gas. The pure electric vehicle such as BEV and FCEV uses electricity and hydrogen as energy carters, respectively. Thus, EVs have more benefits compared to IC engine-based vehicles. Among the various types of electric vehicles, PHEV is the most energy diversified as it can run on both liquid fuels and electricity [8].

9.2 Motor Drive Technologies of Electric Vehicles

9.2.1 Evolution of EV Motors

The interesting facts about EV motors are that in 1831, Joseph Henry used electromagnetism for oscillatory motion of beam motor, and this was considered as one of the most primitive motors of the present DC motor. This invention has shown the way for the introduction of the first actual electric motor in 1834 by Thomas Davenport. Following this, Frank J. Spague developed a non-sparking constant-speed motor fixed with brushes. This motor maintained constant speed under varying loads [9].

Table 9.1 List of parameters

Energy sources: The different types of energy sources are liquid fuels, gaseous fuels, battery, ultra-capacitors and ultra-flywheels	
Liquid fuels	Petrol and diesel are called liquid fuels. The specific energy of both petrol and diesel is similar. But the diesel has higher energy content per unit volume as it is denser than petrol. The diesel is more economical compared to petrol due to higher energy density
Gaseous fuels	Compressed natural gas (CNG) and hydrogen are called gaseous fuels. The CNG has lower energy density and higher specific energy compared to liquid fuels. Meanwhile, hydrogen requires storage at a very high compressed state, and therefore, it requires additional accessories around its fuel tank. On the other hand, it has higher energy density compared to petrol, diesel and CNG. Subsequently, there is an exertion to make hydrogen-based fuel cell electric vehicles as a commercial feasibility
Battery	Batteries convert chemical energy directly into electrical energy. Among various types of batteries, let us consider the lithium ion battery. Lithium ion battery has 25 times lower energy density and 75 times lower specific energy compared to petrol. Thus, the mass and volume of lithium ion battery will be 75 times and 25 times more compared to petrol for the same energy content. This is the major drawback of batteries compared to liquid fuels.
Ultra-Capacitors	Ultra-capacitors store the energy in electrostatic form, and it provides very high specific power. But it can store only constrained energy
Ultra-flywheel	Ultra-flywheel stores the energy in mechanical form at high speeds, but it has drawbacks of reliability, and the safety concern has to be considered around it when it is utilized inside the electric vehicle
Pollution: There are different types of pollutants discharged from the vehicles which are the main reasons for air pollution and smog. Some of them are particulate matter (PMx), greenhouse gases, NOx gases, volatile organic compounds (VOC), total hydrocarbons and SOx gases.	

(continued)

Table 9.1 (continued)

Particulate matter	These are the particles released as a part of combustion cycle which are drastically in the range of micrometres. Hence, they cannot be sifted by human throat and nose, and thus, it influences heart, lungs and brain. The particulate matters are released more by diesel engine than petrol engine. PM particles less than 10 µm are known as PM10 are very dangerous and if breathed in, it can cause extreme harm to health
Greenhouse gases (carbon dioxide, methane and nitrous oxide)	Carbon dioxide, Methane and Nitrous Oxide are clubbed and alluded as PM2.5. These gases are known as greenhouse gases. Because of these gases, the infrared radiations are captured in the atmosphere and cause greenhouse effects such as environmental change and a worldwide temperature alteration
NOx gases, VOC and total hydrocarbons	These are responsible for creating ground level ozone layer. If the ozone layer is present at the ground level then humans will be affected by major respiratory diseases such as asthma and lung inflammation. The diesel engine is the key factor of NOx gases. However, these NOx gases can be filtered using urea filters

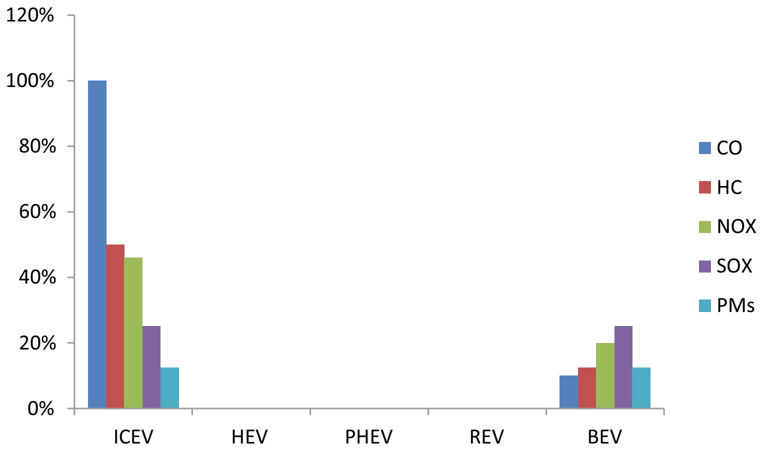

Fig. 9.1 Emissions of different types of vehicles

One of the remarkable inventions in scientific world is the induction motor. Speed regulation, high efficiency and the significant distance dispersion of power conceivable make the induction motor more popular in industries. The induction motor was first invented by the Nikola Tesla in 1887.

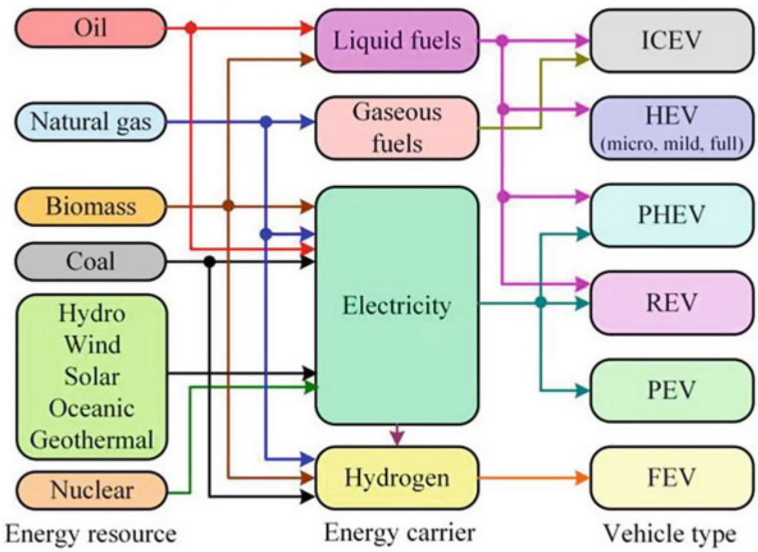

Fig. 9.2 Energy diversification of electric vehicles

In EVs, motor plays a vital role in the drive train. The evolution of EV motors is depicted in Fig. 9.3. The factors given below should be considered for selecting the suitable motor for EVs.

9.2.2 Main Requirements of an EV Motor

- Maximum torque and high speed.
- High power and energy density.
- High speed constant power region.
- Low speed constant torque region.
- High reliability and robustness.
- Good voltage regulation in wide speed and
- High efficiency.
- Controllability, steady state and dynamic response.

9.2.3 Classification of EV Motors

EV motors are generally classified into brushed DC motors and brushless motors. Brushes and commutator will be present in brushed DC motors and are absent in brushless motors. Generally, all DC motors are commutator-based motors. As the

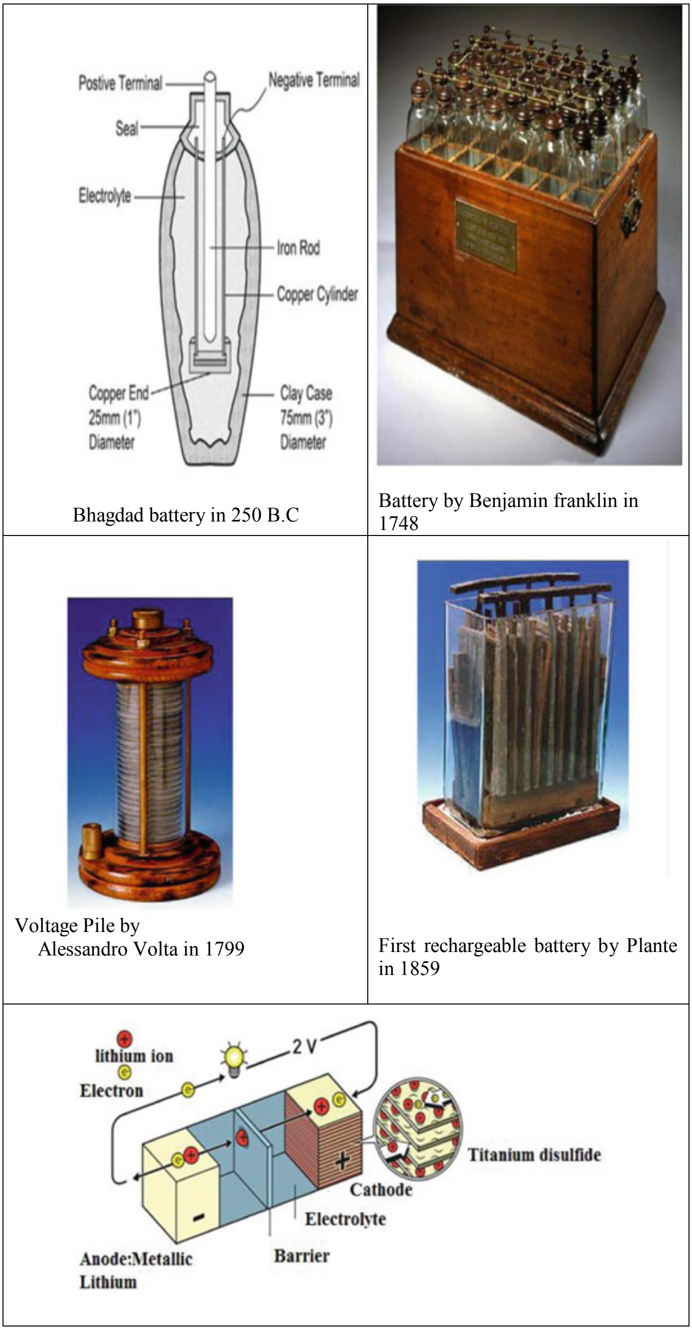

Fig. 9.3 Evolution of EV batteries

construction of DC motors provides symmetrical control of flux and torque, they offer very simple control. Furthermore, the DC motors provide high torque only at low rpm, and the efficiency is only 75–80%. Also, the DC motors require regular maintenance, and life span is short due to the deterioration of brushes. Thus, DC motors are not taken into consideration in EVs [10–13].

AC motors are normally brushless motors. Among them, induction motors and permanent magnet motors are commonly used in EVs. Brushless DC motors (BLDC) and permanent magnet synchronous motors (PMSM) are categorized under permanent magnet motors. BLDC motors are mostly preferred in two wheelers. Thus, the induction motors and PMSM are gaining importance in EVs as they provide high torque at all speed, require less maintenance, and the efficiency is between 85–90%. The comparisons of brushless motors based on different parameters are shown in Table 9.2.

Among these motors, induction motor is mostly desired in industries as it offers maintenance free operation and long life. In early Tesla model cars, the rotor copper bars were used in cage rotor to achieve 85 to 91%. But now; the automobile industries like Tesla, Nissan, Kia motors, BMW have shifted their attention towards permanent magnet motors as these motors are providing high speed-torque characteristics, high

Table 9.2 Comparisons of brushless motors based on different parameters

Items	Brushless motors			
	Induction motor	Permanent magnet (PM) motors		
		Surface mounted PM motor	Interior buried PM motor	PM synchronous reluctance motor
Permanent magnet	No permanent magnet	Magnets are fixed on the exterior of the rotor	Magnets are fixed on the interior of the rotor	Fewer magnets are fixed when compared to IPM
Torque generation	Rotor flux induced by stator flux	Magnetic torque	Magnetic torque and reluctance torque	High reluctance torque than magnetic torque
Efficiency	High	High	High	High
Cost	Low	High	High	High
Speed	Good for high speed	Mechanically weak, particularly at high speed	Good for high speed	Good for high speed
Design	High robust	Less robust	More robust than the SPM	High robust
Field weakening	Field weakening range is high	Not good in field weakening	Field weakening range is medium	Efforts in field weakening necessary

efficiency and power factor. Also, many researches are under progress on the optimization of design parameters and direct torque control of EV motors, and also, the comparisons of efficiencies on different types of EV motors are done in many literatures. Such a comparative analysis has been done on torque (50 Nm) at lower and higher speed in the motors like interior permanent magnet synchronous motor [IPMSM] with 48/8 and 12/8 topologies, induction motor 48 slot/36 rotor bars and switched reluctance motor with 12 stator slot/8 pole [14]. These motors are designed with the same specification of achieving 300 Nm peak torque at 1500 rpm and high torque of 60 Nm at 6000 rpm. Table 9.3 shows the comparison of losses and efficiency of IPMSM, SRM and IM with the torque of 50 Nm at high and low speed [15].

From the above Table 9.3, it is observed that IPMSM with 12 slot/8 pole has the efficiency of 95% at higher speed with lower losses compared to IPMSM with

Table 9.3 Comparison of losses and efficiency of IPMSM, SRM and IM

Type of motor	Torque (Nm)	Speed (rpm)	Permanent magnet loss (W)	Copper loss (W)	Stator copper loss (W)	Rotor copper loss (W)	Core loss (W)	Efficiency (%)
Interior permanent magnet synchronous motor (IPMSM with 48 slot/8 pole)	50	1000	0.01	186	–	–	53	95.5
	50	5000	1.33	767	–	–	552	95
Interior permanent magnet synchronous motor (IPMSM with 12 slot/8 pole)	50	1000	4	88	–	–	66	97
	50	5000	651	418	–	–	299	95
Induction motor (IM with 48 slot/36 rotor bars)	50	1000	–	–	274	215	36	91
	50	5000	–	–	489	458	111	96
Switched reluctance Motor (SRM with 12 stator slot/8 pole)	50	1000	–	283	–	–	379	88.5
	50	5000	–	296	–	–	1346	94

48 slot/8 pole, induction motor and SRM. Hence, IPMSM is providing promising solutions to the EV manufacturers, and hence, it is the most preferred EV motor.

9.3 Batteries and Battery Management System (BMS)

9.3.1 History of Batteries

It is an interesting fact to know about the history of batteries. The history of batteries begins from 250 B.C. approximately. The oldest electric battery was found near Baghdad by a German archaeologist in 1938. This battery comprised of a clay case, an iron rod and a copper cylinder, and some scientists believed that these batteries were used for electroplating gold onto the surface of silver. A set of linked capacitor was described as the battery by the American scientist Benjamin franklin in 1748, and he was the first person to coin the name "battery". The first electric battery "voltage pile" was invented by the Italian scientist Alessandro Volta [16, 17]. Volta set up a fairly untidy pile of zinc and silver plates arranged alternatively and isolated by brackish water splashed cloth. The term volts, unit of voltage is entitled after Alessandro Volta in 1881 in his memory and respect. In 1859, the most generally utilized rechargeable battery was introduced by the French physicist Plante [7]. The evolution of batteries is shown in Fig. 9.3.

The nickel–cadmium (Ni–Cd), nickel metal hydride (NiMH), zinc battery chemistries were developed from 1850 to 1980. The invention of lithium ion battery by John Good Enough in 1980 becomes the eye-opener for the automobile industries to concentrate on electric vehicles. These lithium ion batteries are playing crucial role in all electric vehicles manufactured today as they have high power and energy density, high efficiency, long life span with low self-discharge rate. Lithium ion batteries occupy the superior position over different batteries due to its several advantages [18]. The comparison of lithium ion battery and other batteries is presented in Table 9.4.

The word lithium ion focuses on a group of batteries that have resemblances but have great variation in their chemistries. Such different chemistries of lithium ion are lithium cobalt oxide (LCO), lithium nickel cobalt aluminium oxide (NCA), lithium manganese oxide (LMO), lithium nickel manganese oxide (NMC), and these batteries are comparable as they convey a high volume and are utilized in handy applications. In spite of lower voltage and capacity, lithium iron phosphate and lithium–titanate oxide (LTO) are entirely robust [19]. Table 9.5 describes the features of the most important lithium ion batteries.

NCA is the flawless winner as it has high specific energy than other batteries. In terms of thermal stability and specific power, LMO and LFP are superior. LTO has lower capacity, but it overrides the other batteries in terms of life span and performance in cold temperature performance.

Table 9.4 Comparison of different types of batteries

Battery type	Lead acid	Nickel–cadmium	Nickel metal hydride	Zinc–bromine	Iron–chromium	Lithium ion
Power density Wh/kg	180	150	250–1000	–	70–100	1800
Life cycle	200–300	1500	300–500	>2000	–	500–1000
Energy efficiency (%)	70	60–90	75	80	66	80
Overcharge tolerance	High	Moderate	Low	High	Moderate	Very low
Thermal stability	Less stable	Less stable	Less stable	Less stable	Stable	Highly stable

9.3.2 Future Batteries

In order to create infrastructure based on multi-dimensional energy and to avoid complete dependence on lithium ion batteries, many breakthrough battery technologies are under research to make advancements in powertrain [20]. Table 9.6 shows the different chemistries of lithium ion which may become newer technologies in the near future.

9.3.3 Battery Management System (BMS)

As lithium ion cells are utilized as packs in electric vehicles, which are highly unstable, an observing framework is vital for an individual cell to prevent overcharging and discharging below the threshold value [21]. Thus, BMS gains importance in EVs.

BMS is used in EVs for the following activities:

1. To ensure safe operation and durability of batteries.
2. To disclose state-of-charge and state-of-health.
3. To alert the user during thermal run away of batteries.
4. To alarm the users, when the discharge rate is below the threshold level.

BMS can be classified into centralized BMS, master–slave BMS, modular BMS and distributed BMS [18]. Table 9.7 shows the comparison between the different types of BMS.

Table 9.5 Comparison of different types of lithium ion batteries

Chemistry	Lithium Cobalt oxide	Lithium Manganese oxide (V) ()	Lithium Nickel Manganese Cobalt oxide	Lithium Iron Phosphate	Lithium Nickel-Cobalt Aluminium oxide	Lithium Titanate oxide
Nominal voltage (V)	3.6	3.7	3.6	3.3	3.6	2.4
Voltage at fully charged condition (V)	4.2	4.2	4.2 (or higher)	3.7	4.2	2.9
Voltage at fully discharged condition (V)	3	3	3	2.5	3	1.8
Specific energy (Wh/kg)	150–200	100–150	150–220	90–120	200–260	70–80
Thermal runaway (°C)	150	250	210	270	150	Highly stable at higher temperatures
Applications	Used in mobile phones, laptops and cameras	Used in power tools and medical devices	Used in E-bikes and in medical devices	Used in mobile phones and in watches	Used in industrial and medical applications	Used in UPS and EVs
Comments	High energy, limited power	High power. In order to improve the performance, LMO is mixed with NMC	High capacity and high power	Constant discharge voltage, high power low capacity, very safe	Highest capacity with moderate power	These batteries have fast charging ability, operating in wide range of temperature and longer life. But the cost is very high

Table 9.6 Different chemistries of lithium ion batteries

Chemistry	Lithium-air	Lithium-metal	Solid-state Lithium	Lithium-sulphur Li-S
Type of cathode and anode materials	Cathode-air; Anode-Lithium	Cathode-graphite; Anode-Lithium	Cathode-lithium based oxides Anode-Lithium	Cathode-sulfur; Anode-Lithium
Voltage per cell (V)	1.7–3.2	3.6	3.6	2.1
Comments	Borrowed from "breathing" zinc-air and fuel cell concept	Fast charging capacity and high power	Will be commercialized by 2020	Due to lower cost and higher capacity, these batteries may replace lithium ion batteries in future

Table 9.7 Comparison between the different types of BMS

Centralized BMS	Master-slave BMS	Modular BMS	Distributed BMS
Cells are connected through huge number of wires, and a single controller controls the entire system	Cells are connected through wires and are controlled by slave boards	BMS boards are divided into limited banks and are connected together in a daisy chain. These boards are connected to each cell	Each cell is mounted by a BMS board
	The slave boards are distributed at different sites, and these are controlled by a single master controller	A central controller is connected to BMS boards through a cable	Communication between battery and its controller is done through a cable
The centralized BMS architecture is well suited to battery packs with a small number of cells	1. This architecture divides the tasks of software among the slave boards 2. No additional software requirement, reliabilty are the advantages	Difficult to achieve isolated master–slave communications in electric vehicles	The advantages of this design include its simplicity and high reliability

9.4 Powertrain Technologies

Powertrain embraces of set of components that generate the required power to rotate the wheels and to move the vehicle. In an EV, the powertrain comprises fewer components than internal combustion engine-based vehicles. It includes battery pack, DC-AC converter, electric motor, motor control mechanism and on-board charger

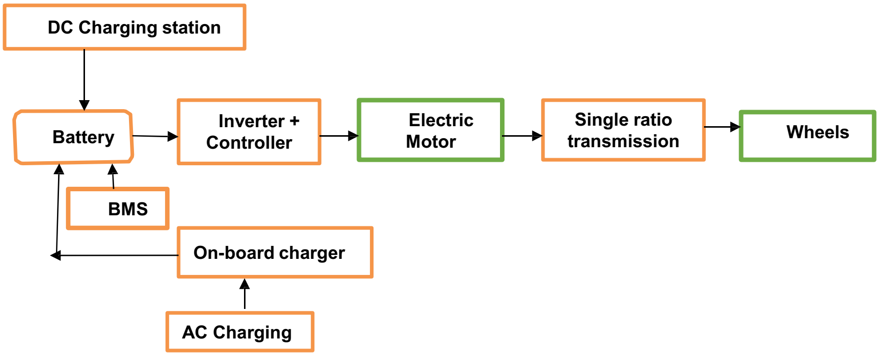

Fig. 9.4 Core parts of powertrain

[14, 22–24]. Along with the core parts, there are also several software and hardware components in the powertrain. Electronic control units (ECUs) are generally software programs combined with the powertrain components to aid data transfer and processing. There are some other several small ECUs like battery management system, DC-DC converter, thermal management system and body control module in an EV that executes particular functions. The communication between different ECUs is normally carried over by CAN protocol. The core parts of powertrain are shown in Fig. 9.4.

A juncture of emanations guidelines, advancements in core technologies and competitions in creating market is making automakers forcefully put resources into new "EV powertrain technologies" and "E-Mobility" solutions. The different architectures of powertrain like front wheel drive, rear wheel drive, all wheel drive and four wheel drive are vying for noticeable quality in different sections of the market [25]. The different types of powertrain technologies are depicted in Table 9.8.

9.4.1 Advanced Powertrain Technologies

It will be always an interest fact to have an inside look of Tesla cars. As Tesla is the pioneer in EVs, the technologies used by them will be always differing from other cars. Recently, two powertrain technologies namely Raven powertrain and Plaid powertrain have been introduced in Tesla cars. The main details about these technologies have been explained below.

9.4.1.1 Raven Powertrain Technology

The Raven powertrain shown in Fig. 9.5 is currently available in the Model S and Model X, but only in performance and long-range guises. This Raven powertrain technology couples the battery available in a Model S or X with the permanent magnet synchronous reluctance motor at the rear side. Compared to induction motor, permanent magnet synchronous reluctance motor is more efficient and powerful than the induction motor. Around 824 lb-ft of torque and 690 horse power is likely to be the total system output [26, 27].

Table 9.8 Different types of powertrain technologies

Item	Picture	Nature of drive
Front wheel drive		• The most common driven cars on the road today • The mass of the engine and transmission is balanced directly on top of the front wheels, providing better traction than rear wheel Drive (RWD) when climbing hills or on slippery roads • Highly stable and efficient [25]
Rear wheel drive (RWD)		• This framework utilizes a long driveshaft that transmits power from the engine to the differential at the back hub • Better weight distribution • More number of components • Better in dry surface [25]

(continued)

Table 9.8 (continued)

Item	Picture	Nature of drive
All wheel drive		• AWD provides better clutch and control under all road conditions • Gives sportier dealing with and footing to a more extensive scope of vehicles • Reduces fuel economy • Increases the complexity and weight of vehicles [25]
Four wheel drive		• Can be used only off-roading and not in everyday life • With 4WD, the vehicle's capacity is part between each of the four wheels, giving the driver the greatest footing and control on the lopsided landscape. This will be helpful when climbing on steep slopes, rolling over rocks and stones or attempting to get the vehicle out of a snowbank [25]

9.4.2 Plaid Powertrain Technology

Tesla Company has announced that Plaid mode will be faster than Ludicrous mode which is already available in Tesla models. Three electric motors will be used in Plaid mode will use rather than the two available in other Tesla models [28, 29].

9.5 Challenges Faced by EV

Even though the development in the design, construction and performance of EV is increasing day by day, the challenges faced by EV in the aspect of cost, range, oversizing and energy density cannot be denied [12]. Table 9.9 explains about the challenges faced by different types of EVs.

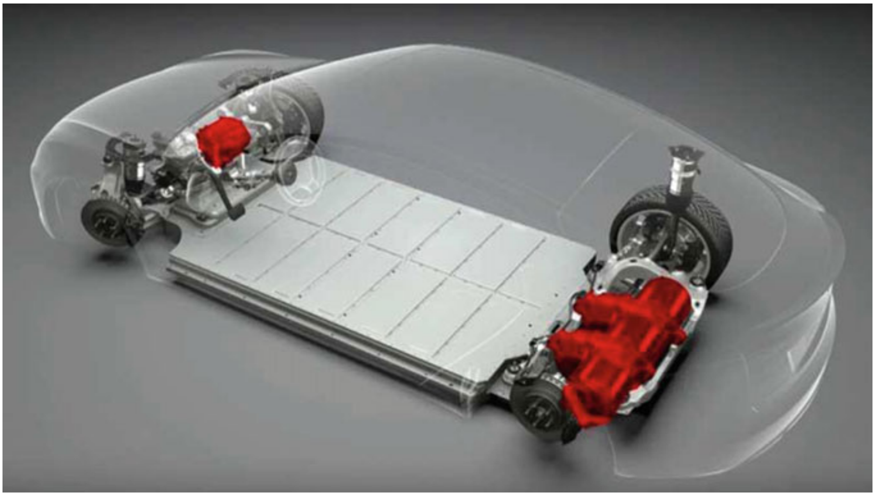

Fig. 9.5 Raven powertrain technology

Table 9.9 Challenges faced by different types of EVs

S. No.	Type of EV	Challenges of the vehicle
1.	Battery electric vehicle (BEV)	(a) Lower energy storage capacity due to low specific energy and low energy density of battery (b) Limited driving range (c) Increase in number of batteries leads to oversizing and high cost (d) Lack of charging infrastructure (e) Charging time can be reduced by increasing the voltage, but it creates stress
2.	Hybrid electric vehicle (HEV)	(a) No zero emissions (b) Dependence on liquid fuels and natural gas (c) Fuel economy can be achieved by variable transmission system, but it requires complex coordinated system, and it creates heavy losses and lot of noise
3.	Grid-able HEV	(a) Capacity of the battery should be high (b) High cost (c) Constraints are similar to HEV
4.	Fuel cell electric vehicle (FCEV)	(a) High cost of fuel cell (b) Lack of infrastructure for hydrogen storage and refuelling (c) Requirement of high safety concerns
5.	Ultra-capacitor electric vehicle	(a) High cost (b) Low specific energy (c) Requirement of battery as hybrid energy source
6.	Ultra-flywheel electric vehicle	(a) High cost (b) Low specific energy (c) Requirement of battery as hybrid energy source (d) Less reliable (e) High safety concern is required as flywheels store mechanical energy at higher speed

9.6 Conclusion

The objective of this paper is to concentrate on the key parts of EV. As EVs become progressively pervasive, pioneering solutions will be essential to create them and their powertrain segments, battery technologies, battery management system, thermal management system and charging system proficiently. The challenges faced by different types of EV presented in this paper will be helpful to concentrate in various domains of EV to improve their efficiency. Also, different types of optimization techniques and power electronic configurations have to be focused in future to simplify the controlling methods.

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