

A Technology Review of Energy Storage Systems, Battery Charging Methods and Market Analysis of EV Based on Electric Drives

Sachin B. Shahapure¹, Vandana A. Kulkarni (Deodhar)², Sanjay M. Shinde³

¹Research Scholar (ADF), EE Dept., GEC Aurangabad, Maharashtra, India, sachinshahapure186@gmail.com

^{2,3}AP, Department of Electrical Engineering, GEC Aurangabad, Maharashtra, India, kul111@rediffmail.com²,
sanjayshindekansurkar@gmail.com³

*Corresponding Author: Sachin B. Shahapure; Email: sachinshahapure186@gmail.com

ABSTRACT- The transportation sector is by far the largest oil consumer making it a prime contributor to air pollution. EVs (Electric vehicles) will be beneficial to the environment and will help to alleviate the energy crisis due to their low dependence on oil and negligible emissions. Technology innovation in EVs is of significant interest to researchers, companies, and policy-makers in many countries. EVs integrate various kinds of distinct technologies where some of the important factors in considerations related to EVs are: a wide range of electrical drive configurations; advanced electronics that enable automotive innovations; meeting the challenges of automotive electronics; electrifying transportation in the future. This paper reviews the recent progress in EV technology, which consists of various motor drives applied in EV propulsion, classification of EVs such as BEV, PHEV, HEV, FCEV, and types of energy storage system with chargers, and software simulating devices. This paper also highlights the EV market with various challenges. The main findings of this research are: (1) Battery technology is the EV's bottleneck. Lithium-ion batteries for vehicles have high capacity and large serial-parallel numbers, which, coupled with problems such as safety, durability, uniformity, and cost, impose limitations on the wide application. (2) Incentives and encouragement for EV owners should be tailored to their specific needs in order to improve their socioeconomic standing. (3) Hyundai, MG Motors, Tesla, and Tata Motors appear to be the key players in India's critical subdomains of the EV market. (4) EV simulation software is necessary for vehicle design and development before the mass production of EVs. (5) PMSM has the potential to provide a high torque-to-current ratio, a high power-to-weight ratio, high efficiency, and robustness. Currently, the BLDC (Trapezoidal SPMSM) motors are the most preferred motors for electric vehicle applications due to their traction characteristics.

Keywords: Distributed Generation (DG), Electric Vehicle (EV), Hybrid Electric Vehicle (HEV), Fuel Cell Electric Vehicle (FCEV), PHEV, Battery Electric Vehicle (BEV), Hardware in Loop (HIL), Multilevel Inverter (MLI), Maximum power point tracker (MPPT), Permanent magnet synchronous motor (PMSM), Brushless DC motor (BLDC).

ARTICLE INFORMATION

Author(s): Sachin B. Shahapure, Vandana A. Kulkarni (Deodhar) and Sanjay M. Shinde;

Received: Nov 16, 2021 **Accepted:** Mar 09, 2022 **Published:** Mar 30, 2022 ;
E- ISSN: 2347470X;

Paper Id: 0122SI-IJEER-2022-04;

Citation: doi.org/10.37391/IJEER.100104

Webpage-link:

www.ijeer.forexjournal.co.in/archive/volume-10/ijeer-100104.html



Publisher's Note: FOREX Publication stays neutral with regard to jurisdictional claims in Published maps and institutional affiliations.

1. INTRODUCTION

As the green movement increases in popularity, more and more electric vehicles (EVs) of all types, such as electric scooters, cars, buses, and cargo trucks will be on the roads in the future. Electric energy can be easily transmitted over long distances. The conversion of electrical energy to other energy forms is simple. Large-scale storage with the help of different storage devices is possible. The urban population and the registration of motor vehicles in India have increased in recent years. India has the potential to provide significant energy

savings, improve energy security, reduce emissions, and alter the future demand for transportation fuels. The transportation sector consists of several industries such as airlines, railways, marine, roadways, etc., which are the world's largest oil consumers and thus the prime contributors to air pollution. In recent years, for example, this sector has contributed nearly 20% to 25% of global Greenhouse Gas (GHG) emissions. Figure 1 shows the generalized diagram of the electric vehicle powertrain. The Indian government has accomplished resolving New Delhi's air pollution concerns through a motivated policy of shifting 100% of the light-duty consumer transportation vehicles to EVs by the year 2030. The popularity of EVs will significantly benefit the environment and reduce energy crises. Hence, electric vehicles can be called the future vehicles of the world. The impact of EVs on the power grid results in compromising the grid reliability, overheating of transformers, and power quality issues that include voltage-related problems such as voltage sag, swell, unbalance, and current-related problems such as harmonics and low power factor [1].

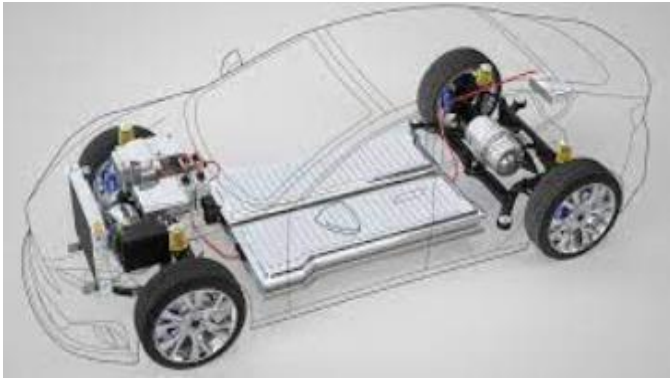


Figure 1: Electric vehicle powertrain from Infineon Technologies

The performance of electric vehicles can be enhanced from the improvement in EV battery, power converter, EV motor, and energy recovery with the help of a regenerative braking system. It is needed to move towards the electric vehicle which can replace conventional IC engine vehicles for reducing the pollution and dependency on crude oil also for increasing the efficiency and performance of the vehicle. EV designers will have the challenge to provide EVs which are widely accepted on the basis designing of their operating performance, travel range, initial cost of the vehicle, maintenance required, running cost, safety ratings battery degradation, and performance. Electric vehicles are most suitable in the current scenario because the EV motors (PMSM, BLDC, and SyRM) are having an efficiency of nearly 90%, the efficiency of the battery is nearly 70% and the efficiency of the power converter is nearly 90% hence overall efficiency of an electric vehicle is nearly 75% which is very high in comparison with IC engine vehicles whose efficiency is very low as 5% to 10%. [2-3]. In recent years the applications of synchronous motor drives such as PMSM, BLDC, and synchronous reluctance motor are expanded in different areas because of the advantages over the induction motor and dc motor. Initially, synchronous motor drives were mostly employed in industrial control systems, commercial equipment, and domestic appliances because to their higher efficiency, very high power density, ease of control, broad speed range, and excellent dependability. Recently, these drives have been used to water pumping, subsea, electrical vehicles, servo drives, aerospace, marine propulsion, locomotives, and high-speed blowers and fans, among other applications. [4-5]

2. TECHNOLOGICAL DEVELOPMENT IN ELECTRIC VEHICLES

The term "Electric Vehicle" (EV) commonly means a vehicle consisting of an electric motor drive system that is working on rechargeable batteries or fuel cell energy. Researchers, companies, and policy-makers of different countries importantly attract the technological revolution in electric vehicles and different aspects such as development can consider the EV industry such as an energy storage system that based on the development of battery's energy storage system, battery management system, and recent development in fuel

cell technology. It also includes recent development in EV motor drives technology, which consist of power converters, Electric motors, processors, and controllers. Technological development of EVs also consists of the technical enhancement in battery charging methods such as conductive charging, inductive charging, and battery swapping methods [6-8].

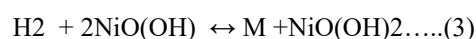
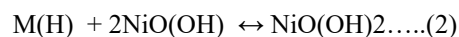
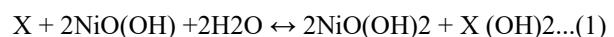
2.1. Development in the energy storage system

2.1.1 Recent development in battery energy storage system

The technological revolution in traction battery energy storage systems has had a great impact on the electric vehicle industry because the battery pack is the most important part of the EV powertrain. *Figure 2* shows the batteries and their various factors which should be considered for electric vehicle applications, such as batteries and energy transformations, the human and environmental cost of batteries, batteries in cars and grids, battery demand and production, battery research and development, battery recycling and second life. In the market, different types of batteries, having technologies developed and having higher capacities, are available. These batteries have superiorities such as very high specific energy and power, and also high energy density. At present, the main types of batteries that are used in EVs consist of lead-acid batteries, nickel-metal hydride (Ni-MH) batteries, and lithium-ion batteries. [9-10].

2.1.1.1 Ni-Mh batteries

These nickel-metal hydride batteries (Ni-Mh) are manufactured by using nickel hydroxide (made as a positive electrode) and different materials as negative electrodes, with potassium hydroxide solution as an electrolyte. Some of the different negative electrode materials for nickel batteries include Nickel Cadmium (Ni-Cd), Nickel Iron (Ni-Fe), Nickel Zinc (Ni-Zn), Nickel Hydrogen (Ni-H₂), Nickel Metal hydride (Ni-Mh), which are the different types of batteries. In all of the above batteries, the nickel metal hydride batteries were mostly used in the electric vehicle sector in the early starting years. *Figure 3* shows some of the available Ni-Mh batteries that are currently used in electric vehicle applications, which are GM Ovonic USA and Varta Germany. The electromechanical reaction in these batteries is given below,



In contrast with lead-acid batteries, these Ni-Mh batteries have advantages like having more specific energy and a larger energy density. These batteries have disadvantages like lower charging efficiency and a high self-discharge rate in high-temperature environments. In recent years, the application of Ni-MH batteries has been stagnant and stable [10-11].

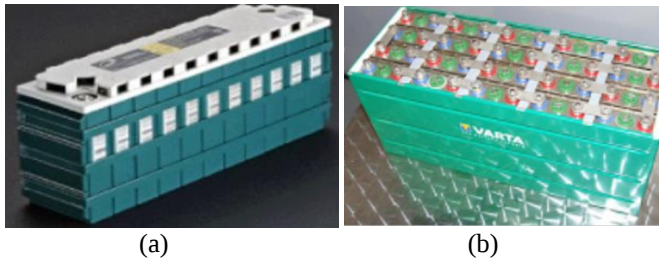


Figure 3: Ni-Mh batteries for EVs GM (a) Ovonic USA and (b) Varta Germany

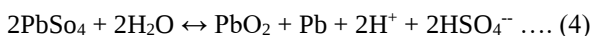
The literature has found that the static design of the load balancing algorithms, the lack of scalability and durability are some of the limitations. In addition to literature review, it was found that artificial intelligence systems such as genetic algorithms, honeybee algorithms, game theory and intelligent agents were used as load balances in cloud computing. Therefore, an effective load balancing system is urgently required in cloud computing.

2.1.1.2 Lead acid batteries

The lead-acid batteries consist of positive plates made up of lead dioxide and the negative plate consists of lead metal, and both the plates are put in an electrolyte made up of diluted Sulphur acid. *Figure 4* shows some of the lead-acid batteries. The *equation 4* for a chemical reaction in lead-acid batteries is given as bellows. There are many categorizations of lead acid batteries. Lead acid batteries are mainly classified into two main categories: flooded (or wet) cells and maintenance-free sealed lead-acid batteries (SLA).



Figure 4: Lead-acid batteries



These batteries have advantages such as low cost, high reliability, and high availability, making them the most extensively used rechargeable batteries. Lead-acid batteries have low specific energy and density, hence they are not used in large-scale EV production. The researchers had done a comparison between lithium-ion and lead-acid batteries and concluded that the latter one stores less energy than the previous one with the same mass.

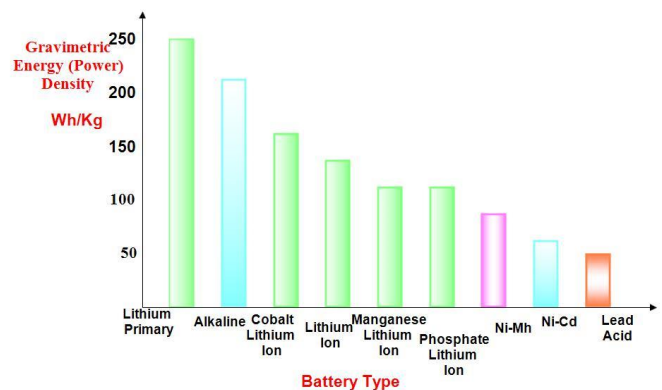


Figure 5: Comparison between battery type and power density [6]

The mass and volume of batteries are important for electric vehicle production. If the battery pack were smaller and lighter, then the weight of the vehicle would be decreased, and hence the travel range would increase. Recently, lead-acid batteries are mainly used for low-speed electric vehicles with a low travel range. *Figure 5* shows the comparison between battery types and power density for different batteries on the aspect of energy density and specific energy concerning battery capacity. Batteries such as lithium primary and alkaline batteries are non-rechargeable batteries, whereas other batteries such as lithium-ion and lead-acid batteries are chargeable batteries.

2.1.1.3 Lithium-ion batteries

Sony was the first company to introduce lithium-ion batteries in 1991. As compared with other types of batteries, these batteries have advantages such as large power carrying capacity, long life cycles, small size and lightweight in nature, better energy efficiency, lower memory effect, and more power density as compared with other types of batteries. Hence, because of the advantages, they are the best choice for the large energy storage devices for EVs. Hence, these batteries dominate the battery market currently. *Figure 6* shows some of the available lithium-ion batteries on the market.

Figure 7 shows the classification of lithium-ion batteries based on the types of positive electrodes. The LiFePO₄ batteries are widely used in EVs currently because they have advantages as compared with other lithium-ion batteries available, such as low cost of production, better chemical stability, and better thermal stability. The drawback of LiFePO₄ is that of high discharge current, which is negligible. The other batteries for manufacturing EVs are also used, such as NCA and NMC. These batteries also have certain disadvantages like barriers to battery charging rates, lifespan, and reliability. Hence, these batteries need to improve further and researchers are doing well in this sector [9, 12].



Figure 6: Lithium-ion batteries

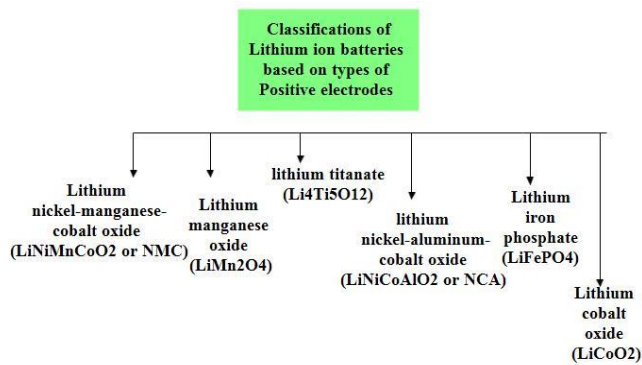


Figure 7: Classifications of lithium-ion batteries

2.1.2 Recent development in fuel cell technology

The fuel cell device consists of components such as electrolytic material, cathode, and anode. The chemical reaction occurs between hydrogen ions and oxygen ions in the electrolytic material and produces electricity, vapor, and heat in a fuel cell device. The reaction between hydrogen ion and oxygen ion occurs at 800 °C, hence called "cold combustion." The generated electricity from this reaction is stored in the battery pack and then given to the electric motor through inverter operation. The thickness of an individual fuel cell is nearly 2 mm, and it can generate a voltage of 1 volt because of that fuel cell. An electric vehicle uses a fuel cell stack, which consists of an array of hundreds of fuel cells. The advantage of FCEV is low greenhouse gas emissions; hence, there is a low pollution effect. The FCEV doesn't store energy like a battery, instead it constantly supplies fuel and oxygen through a chemical reaction. If unpolluted hydrogen is used in a chemical reaction, then fuel cells release only heat and water. The FCEV does not have to be plugged in all of the time, and both the BEV and the FCEV have a longer travel range of up to 300km with a full tank of H₂ gas. FCEV has more efficiency as compared with other energy sources with traditional combustion technologies, and the H₂ gas in the tank is filled up just like other petrol and diesel filling up.

There is a disadvantage to FCEV, such as hydrogen being more explosive as compared with petrol and diesel. The chemical reaction in fuel cells needs energy, which is taken from fossil fuel, and hence greenhouse gas emissions take place. The price of FCEV is also high [12, 13]. Table 1 shows the classification of fuel cell technology, lithium-ion battery, lead-acid battery, and ultra-capacitor based on self-discharge rate, energy density, efficiency, and life cycle.

Table1 Classifications of Storage System [3]

Energy source	Ultra Capacitor	Lithium-ion Battery	Lead Acid Battery	Fuel Cell
Life Cycles	1000-8500	700	500-1000	NA
Self-discharge rate (% per month)	0.5-1.5	3-5	5	NA
Energy Density (Wh/kg)	1000-8500	90	30	NA
Efficiency (%)	90	80-90	50-95	40-60

2.2 Development in electric motor drives technology for EV

Development of Electric motor drives consists of the Electric motor, development in power converters, development in controllers, recent development in battery chargers and charging stations, and different software simulating devices for EV analysis. [12-14]

2.2.1 Development in power electronics converters

The electric motor plays an important role in EVs as their efficiency, performance, and maintenance are directly dependent on the motor. The speed control of the electric motor is carried out by controlling the voltage, current, and frequency of the supply from the power electronic converter, which takes power from the battery pack. Again, the inverter operational performance directly affects the EV performance. Hence, the proper selection of an inverter with an appropriate rating is a crucial part of designing the EV. *Figure 8* shows the advantages of power electronic converters for EV applications. There are various types of converters available currently, such as AC-DC Rectifiers, DC-AC Inverters, DC-DC Buck-Boost converters, and AC-AC Cyclo-converters [15, 16]. As a result, the performance of the EV will be determined by the performance of the inverter. The DC-DC converter converts DC power from the onboard high-voltage battery into lower DC voltage to power fans, window motors, pumps, power headlights, and interior lights.

The DC-DC converter is used for getting higher voltage levels from the battery to the DC-AC three-phase inverter level. The DC-DC converter matches the battery voltage level with the electric motor voltage level. The major applications of bidirectional DC-DC converters are battery charging stations with chargers for EVs. They are also used in hybrid EVs for bidirectional power flow operation. The various types of multilevel inverters (MLI), such as cascaded type MLI, diode clamped type MLI, and flying capacitor type MLI, which are now under consideration for EV applications, Other unidirectional converters consist of the unidirectional DC-DC converters in EV applications, which include conventional boost converters, interleaved boost converters, modified boost converters, 4-leg floating interleaved boost converters, multiphase interleaved boost converters, capacitor clamped H-type converters, and isolated full-bridge converters. In battery chargers and charging stations, for securing the battery energy

storage system part from the electric motor drive part, the isolated bidirectional DC-DC converter plays an important role for safe operation. Hence, currently, these converters are very popular in use for EV applications [14–17].

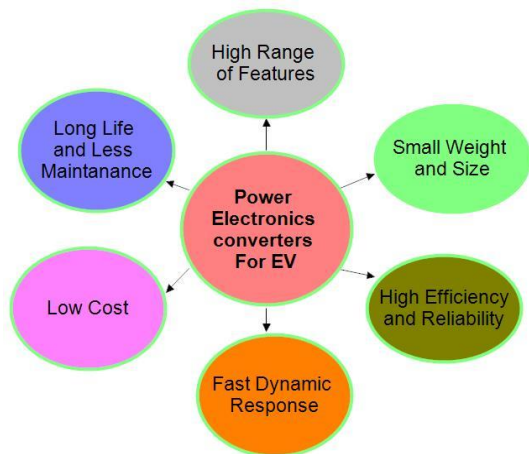


Figure 8: Advantages of power electronic converters for EV

2.2.2 Electric motor drive technology

The EV performance is mainly dependent upon the selection of the electric motor. *Figure 9* shows the different classifications of electric motors. Basically, the requirements of electric machines for EVs are much more onerous than those for industrial or any other application. These requirements are outlined as high torque and power density, extensive speed coverage, covering low-speed creeping or accelerating and high-speed cruising, high efficiency over an extensive torque and variable speed range operation, and a wide constant-power operating capability. Some other things that electric cars need to have are high torque for electric start and hill climbing, high random overload for overtaking, high reliability and robustness for the road, low noise, and probably a reasonable price.

The machines required in EVs are divided into two major groups, which are commutator and commutatorless. The major classifications are AC motors and DC motors. Each one has certain advantages and disadvantages. AC motors are generally classified into induction motors, Vernier motors, doubly salient motors, and synchronous motors. DC motors are generally classified into self-excited (series and shunt) and separately excited DC motors. The synchronous motors are of different types, such as wound rotor synchronous motors, permanent magnet synchronous motors (PMSM or BLAC), brushless dc motors (BLDC), and synchronous reluctance motors (SyRM) [15,18]. Permanent magnet synchronous motors (PMSM) have more efficiency as compared to conventional motors with wound field windings. According to the placement of the permanent magnets, the doubly salient motors are classified into doubly salient permanent magnet machines (DSPM), flux-reversal permanent magnet machines (FRPM), and flux-switching permanent magnet machines (FSPM). With the help of the addition of independent copper field windings in the stator for magnetic flux control, the classification can be further divided into the flux-controllable machines (FC) types, such as FC-DSPM machines, FC-FRPM

machines, and FC-FSPM machines. There are two main classifications of Vernier machines, which are Vernier permanent magnet machines (VPM) and Vernier reluctance (VR) machines.

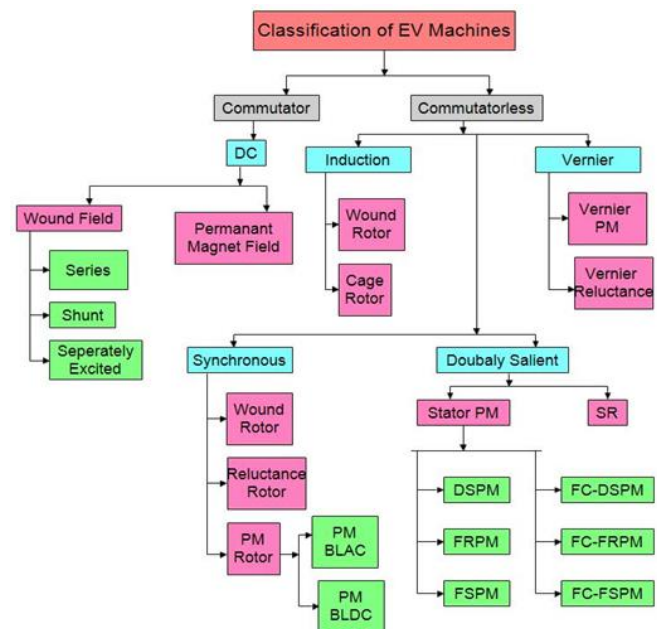


Figure 9: Classifications of electric motors

2.2.1.1 DC motor drive technology

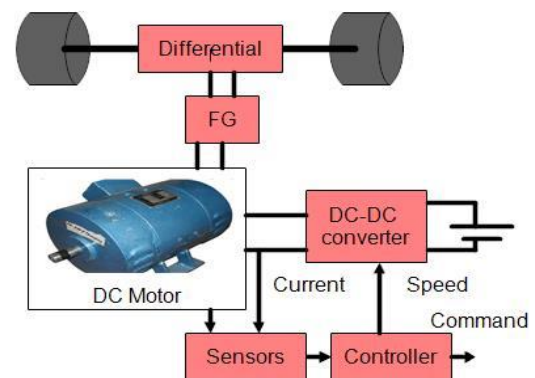


Figure 10: Block diagram of dc motor drive technology

The DC machine drive uses power converters and various controllers and is a very full-grown and well-advanced technology for industry and EV applications. It also possesses the advantage of simple control, which can be used for EV propulsion. *Figure 10* shows the block diagram of DC motor drive technology for EV propulsion. The most required features for EV applications are higher efficiency, maintenance-free operation, high power density, and various power quality concerns. Because of the above factors, DC machine drives have been a physically feasible and attractive choice for EV propulsion in recent years. Another major reason for the lack of attraction for DC drives in EVs is the technological development in AC motor drives. In recent years and the future, it might be observed that the DC machine drive

technology will be replaced by AC permanent magnet, PMSM (BLAC, BLDC), or reluctance motor drives for EV propulsion applications and various industrial applications because these ac machines give performance equivalent to DC machine drives.

2.2.1.1 Induction motor drive technology

Commutator-less motor drives have several advantages over conventional direct-current motor drives for EV propulsion when compared to commutator motors. In recent years, induction machine drives are the most developed technology amongst the various commutator-less machine drives. Induction motors are classified into two types: wound-rotor (slip ring) induction motors and squirrel-cage induction motors. Because of the moderate cost, frequent maintenance required, and lack of ability to withstand force or stress without being distorted, dislodged, or damaged, the slip ring induction motor is less attractive than the squirrel-cage induction motors for application of EV propulsion. Figure 11 shows the block diagram of induction motor drive technology for EV applications. The induction motor drive has advantages over DC and PMSM motors, such as low cost and ruggedness. It also has disadvantages in control complexity, but their advantages are more significant than their disadvantages, hence this is being generally adapted for EV applications.

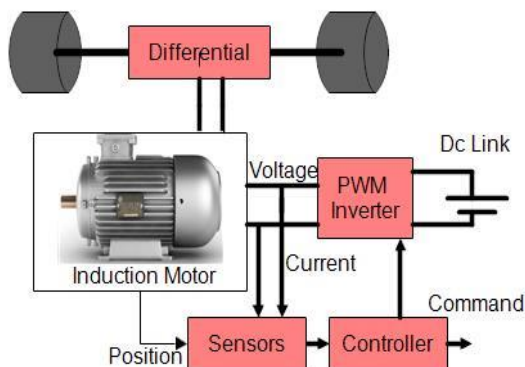


Figure 11: Block diagram of induction motor drive technology

2.2.2.3 Permanent magnet brushless motor drive technology

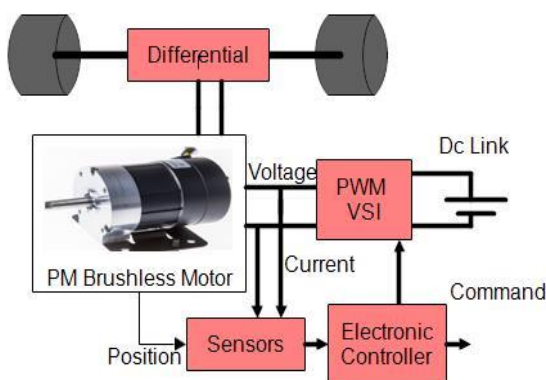


Figure 12: Block diagram of PM brushless motor drive technology

Permanent magnet brushless machines are classified into two parts: BLAC and BLDC, and these machines are widely used in EV applications. Figure 12 Block diagram of PM brushless motor drive technology for EV application. A brushless DC motor is an ideal option for the industry that requires characteristics such as high-reliability, high efficiency, and high torque to weight (volume power) ratio. The BLDC drives are a serious competitor to the DC motor drive. BLDC has the same speed and torque performance curve characteristics as compared with the brushed DC motor, which has certain additional advantages like long life, fast response, and maintenance, no sparking, near-consistent performance, and higher reliability. The PMSM has a lower electromagnetic time constant, hence better dynamic performance, because of the no presence of copper windings in the rotor. Due to the lower availability of rare earth PM materials, the cost of a permanent magnet as well as PMSM drive subsystems increases as compared with electromagnetic motor drives. This is the major disadvantage of PMSM drives.

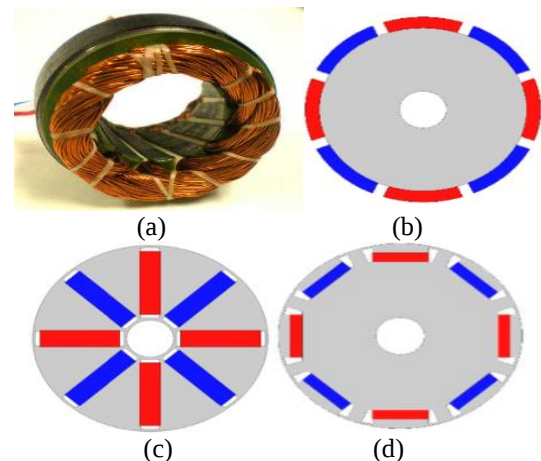


Figure 13: Stator distributed winding for PMSM (a), surface PM rotor (b), interior PM rotor (c) and inset PM rotor (d)

The permanent magnet synchronous motor (PMSM) and brushless DC motor can be the same or different, which depends upon the researcher's point of view. Both the motors are synchronous motors with a permanent magnet fitted to their rotors. Certain researchers call it PMSM with sinusoidal back EMF for PMSM drive and PMSM with trapezoidal back EMF for BLDC drive. Basically, in PMSM, the stator winding is sinusoidal distributed, and hence the stator current is sinusoidal, and also the back EMF is sinusoidal. Figure 13 shows the stator distributed winding for PMSM, which includes the surface PM rotor, the interior PM rotor, and the inset PM rotor. In the BLDC machine, the stator winding is concentrated, and hence the stator current is in a square waveform and the back EMF is trapezoidal. This is the major difference between the two motors. Table 2 shows the comparison between induction motors and permanent magnet synchronous motors based on efficiency, controllability, reliability, power density, and overall cost [19–22]. Figure 14 shows the trapezoidal SPM or BLDC motor with its stator and rotor windings arrangement. The various control algorithms

for EV control, such as path following control strategy, model predictive control, [18,22,30,33,34]



Figure 14: BLDC concentrated stator winding and PM rotor (Trapezoidal SPMSM)

Table 2 BLDC and IM comparison

Electric Motor	Efficiency	Controllability	Reliability	Power density
BLDC	High	Low	Low	high
I'M	Low	high	high	low

Among the three main types of commercially available EV motor drives, namely the DC, induction, and PM brushless, the PM brushless motor drives take the definite advantages of higher efficiency, higher power density, and higher torque density, which are highly desirable for EV propulsion.

2.2.2.4 Switched reluctance motor drive technology

Switched reluctance motors are getting a lot of attention from industry, electric vehicles, and other applications because they are durable and strong, can run at high speeds, don't care about temperature changes, and can handle small problems. Figure 15 shows the block diagram of switched reluctance motor drive technology for EV applications. Although they have various advantages, these motors have some limitations as well as drawbacks, which are as follows: SR motors are complex to design because of the saturation of pole tips and the fringing effect in the magnetic circuit of the machine. Creating torque ripple at high-speed operations, and the noise level and vibrations are high. The design of SR motors for the applications of EVs requires some rigorous criteria, such as less weight and size of the machine, high torque density, high efficiency, lower torque ripples as well as noise at higher speeds, better dynamic response, and good performance.

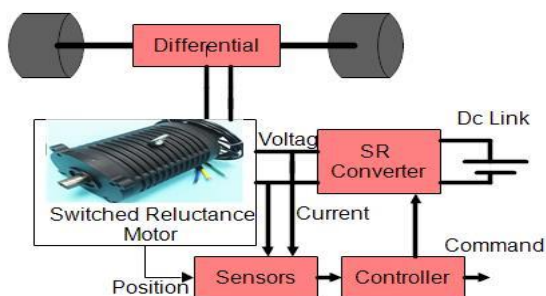


Figure15: Block diagram of switched reluctance motor drive technology

2.2.2.5 Stator permanent magnet motor drive technology

The stator permanent magnet motor drive technology is most significant for EV applications because of its robustness, higher stability at high speeds, and thermal stability. And these advantages are highly valuable for machine drives used in EVs, which need to operate effectively in critical working environments. Recently, various stator PM machines have been available that are most suitable for EV applications, such as the DSPM machine, FRPM machine, and FSPM machine. Figure 16 shows the block diagram of doubly-fed stator permanent magnet motor drive technology, which consists of the stator permanent magnet motor, pulse width modulated (PWM) inverters, sensors, and controllers. The doubly-fed has more cost as compared with the singly-fed stator PM drive but has the advantage of superior controllability, which gets better performance. The stator permanent magnet motor has some advantages, such as operating capacity at high speeds and high centrifugal forces withstanding capacity because of the placement of permanent magnets on the stator in the head of the rotor. The cooling arrangement required for the machine is also easy, which resolves the thermal instability problem.

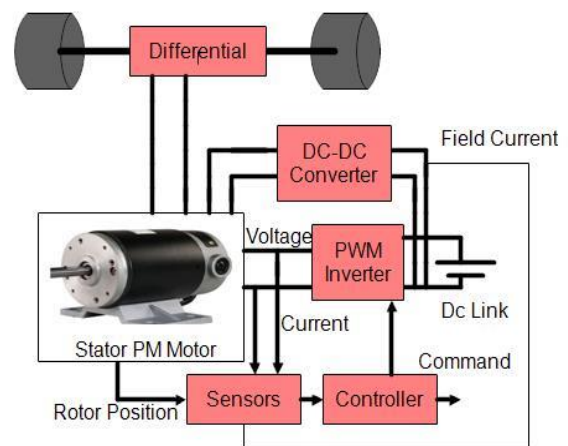


Figure 16: Block diagram double-fed fed stator PM motor drive technology

2.2.2.6 Advanced magnet less motor drive technology

There are various rare earth and precious permanent magnet materials such as neodymium, samarium, cobalt, nickel, magnetite, gadolinium, erbium, etc. The main advantages of the permanent magnet over an electromagnet are that it does not need a continuous supply of electric current, the motor has a small size and light weight, good dynamic performance, large overload capacity, wide speed variable operation, etc. The rare earth permanent magnet materials have varying limited supply, as well as the corresponding market price of these materials, which is volatile. Hence, in recent years, the advanced motor drive has become the more attractive option for electric vehicle applications because of its cost-effectiveness.

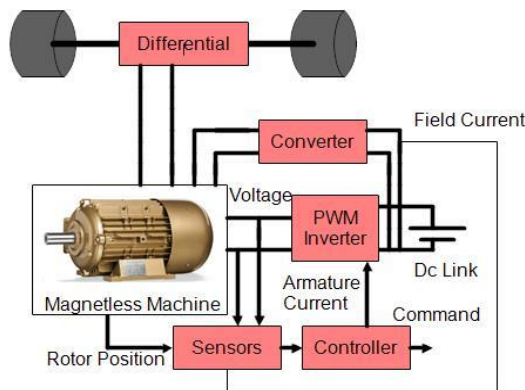


Figure 17: Block diagram of doubly-fed advanced magnet less motor drive technology

Figure 17 shows a block diagram of doubly-fed advanced magnet-less motor drive technology for an EV application. Singly fed motor drives have lower costs and are simple to implement but have low operating performance. The doubly-fed motor drives are moderately priced, complex to implement, but have better operating performance. Some of the permanent magnet-less machines are induction machines and switched reluctance machines because they do not have any permanent magnets in their construction. These two machines are well developed and mature technologies, having individual families with their specific advantages and disadvantages.

2.2.3 Development in processing and controlling devices

Recently, many specialists and research scholars around the world are doing significant research on electric vehicle transportation systems, different advanced control algorithms for enhancing performance, and battery chargers and charging stations. The controller plays an important role in the safe and efficient operation of any electric vehicle. The controller works on a control algorithm designed, tested, and implemented by the researcher or user. The controller must be designed by considering factors such as loss, overall efficiency, drive performance, and robustness of the drive [23].

Figure 18 shows the hardware in loop (HIL) simulations of electric drives for an electric vehicle. Field-programmable gate array (FPGA)-based controllers make every complex control algorithm implementation possible for power electronics and drive applications. It implements the control algorithm designed and developed by researchers on a specific hardware or software architecture to get the required best performance in terms of execution time. The major manufacturers of FPGAs are Xilinx, Altera (Intel), Microchip, Achronix, and Lattice Semiconductor. At that time, the first two manufacturers controlled more than half of the market [24-25].

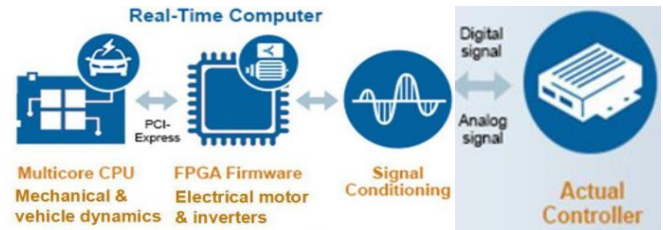


Figure18: HIL simulations of Electric drives for EV [34]

2.3 Development in battery charging methods

According to the various factors, such as charger placement, which can be on the vehicle or external, and power flow, which can be unidirectional or bidirectional, The cost of the EV, hence, depends on the above-mentioned factors with their advantages and disadvantages [24,26,27]. Generally, the off-board chargers require the charging station facility, which onboard chargers don't. Classifications of battery charging methods are given below:

2.3.1 Conductive type charging

The cable connection is required before charging as the conductive charging method is the wired method. There are various conductive charging methods that are currently used in the EV market, such as constant power charging, constant current charging, constant voltage charging, taper, and trickle charging methods. There are advanced control methods that are also available, which are combinations of the different conventional methods [13, 26].

Table 3 shows the charging standards for different charging levels with their different specifications such as voltage current and power ratings. Constant current and constant voltage charging methods are most commonly used in charging lithium-ion batteries because of their advantages, such as protection under low thermal stress and overvoltage [25,26].

Table 3. Charging Standards with Specifications [1]

Charging level	AC Level 1	AC Level 2	AC Level 3	DC charging
Max power(KW)	1.44	11.5	96	240
Voltage (volt)	120	208-240	208-240	208-260
Current (Amp)	12	48	400	400





Figure 19: J1772 connector and J1772 combo connectors for EV battery charging [6]

AC battery charging methods are classified as AC Level 1 charging, AC Level 2 charging, and AC Level 3 charging, with their respective different voltage and current specifications. The DC charging methods have also become very popular in recent years as they require very little time for battery charging. All the AC charging methods require an onboard charger, but in the DC charging method, an off-board charger is required. The DC charging methods are classified as DC level 1 charging and DC level 2 charging. Various countries, like India, the USA, and China, have their own battery charging standards. There are some globally accepted standards such as IEC (International Electro-technical Commission), SAE (Society of Automotive Engineers), GB (Chinese National Standard), and JEVs (Japan Electric Vehicle Association Standards). Table 3 shows the charging standards that are usually adopted in different countries [30-31]. The connector J1772 and the J1772 combo connector are the two connectors used in AC and DC level charging battery storage systems as per the Society of Automotive Engineers (SAE), which is shown in Figure 19.

2.3.2 Inductive or wireless charging

The name for this charging method is given because of the characteristics of transferring energy through an inductive type of coupling, resonant inductive coupling between two coils at a particular resonant frequency. Figure 20 shows the general inductive charging setup. Wireless charging is the latest technological development for electric vehicle charging done by researchers and EV manufacturing industries. The specific frequency is selected based on wireless charging distance and maximum efficiency. There are several advantages to the wireless charging method, such as the elimination of sparking while plugging and unplugging the charger, and the ability to use the EV in gas stations, airports, and other applications. The technological concept of wireless power transfer was first introduced in the late 19th century and the beginning of the 20th century. Initially, it is classified based on methods of charging, such as inductive power transfer (IPT), which is applied for high power ratings and high air gap distance, and capacitive power transfer (CPT), which is used for low power ratings and low air gaps between two coils [25].

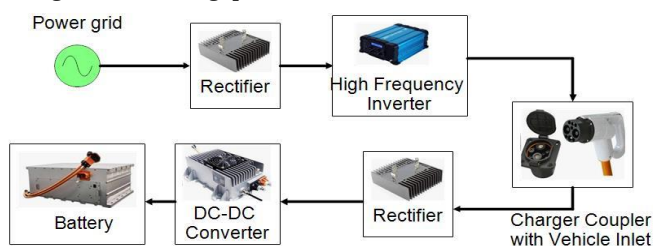


Figure 20: General inductive charging setup

2.3.3 Battery exchange method

In the battery exchange method, the discharged battery in an electric vehicle is simply exchanged with the other charged battery. Hence, this method is one of the quickest methods of electric vehicle charging. The various factors that should be considered for setting up the EV battery-swapping station are: demand estimation, site selection, swipe station setup, battery replacement mechanism, security of the station, and payment methods. The whole process of battery swapping for an EV requires only two to three minutes, so it is the most time-saving method as compared with all other methods. It is necessary to install the battery swapping station where there is a demand, such as the number of batteries, types of power supplies. In the battery replacing station, there are six parts: the battery handling mechanism, the power supply and maintenance systems; the battery charging and payment systems; the control system; and the battery maintenance and control systems.

3. TYPES OF EVS

EVs are classified based on the power supply systems required and the propulsion devices required for the EV. The major classification of EVs is issued to ground vehicles, electrically powered spacecraft, seaborne EVs, and airborne EVs. It's shown in Figure 21. It shows the different types of ground-operated electric vehicles based on their energy source and how they move.

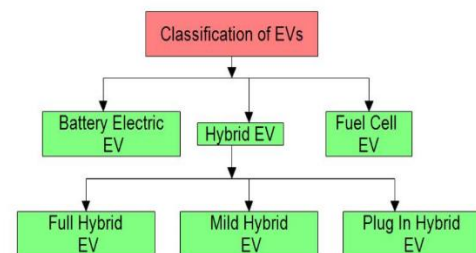


Figure 21: Classifications of Electric Vehicles

3.1 Hybrid electric vehicles (HEV)

A hybrid electric vehicle (HEV) is a merger of a conventional internal combustion engine and an electric powertrain. Countries like Japan, the USA, and Europe are the market leaders for hybrid electric vehicles. Some of the global hybrid electric vehicle manufacturing brands are Toyota Motor Company, Hyundai Group, and Suzuki Group. Generally, hybrid electric vehicles are classified as either grid-connected HEVs or conventional HEVs. The types of grid-connected HEVs are plug-in hybrid electric vehicles (PHEV) and range-extended electric vehicles (REV). The types of conventional HEV are: full HEV, micro HEV, and mild HEV. Figure 22 (a) shows the block diagram of a hybrid electric vehicle and (b) shows the PHEV [39-41]. Lexus ES, Toyota Camry, Porsche Cayenne, BMW 7 Series, and MG Hector: Hybrid electric vehicles are classified as full hybrid electric vehicles, mild hybrid electric vehicles, and plug-in hybrid electric vehicles [42]. Most of the vehicles used in the world already use internal combustion engines that consume either gasoline, petrol, or diesel as a fuel for their work.

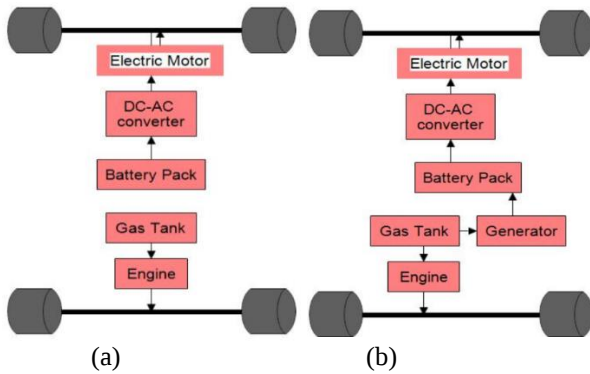


Figure 22: Hybrid Electric (a) Vehicle and (b) PHEV

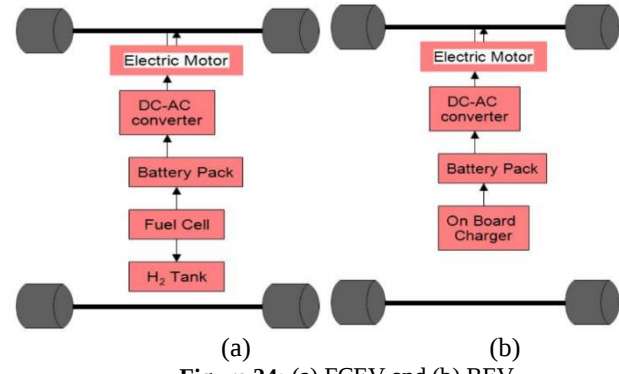


Figure 24: (a) FCEV and (b) BEV

A full hybrid electric vehicle (HEV) consists of a minimum of two sources of power for its appropriate operation, such as an internal combustion (IC) engine and an electric motor propulsion system. In mild hybrid vehicles, the electric motor assists the IC engine in the overtaking of the vehicles [43-44]. The plug-in hybrid electric vehicle (PHEV) consists of an onboard arrangement of battery charging methods. PHEVs generally consist of a gas tank with a generator as well as an IC engine, hence they are called "plug-in hybrid electric vehicles." *Figure 22 (b)* shows the diagram of the plug-in hybrid electric vehicle [45-49]. In terms of battery charging, the PHEV is charged by using conventional battery charging methods and it has a bigger battery as compared with full hybrid EVs.

3.2 Fuel cell electric vehicles (FCEV)

FCEVs have nearly zero CO₂ emissions. Fuel cell electric vehicles operate on an electric powertrain that takes power from fuel cells. This fuel cell generates electricity with the help of oxygen, which is taken from air, and hydrogen, which is in compressed form [50-51]. Fuel cells generate electricity by using an electrochemical process. *Figure 23* shows the classifications of fuel cell electric vehicles, which consist of the different combinations of fuel cell electric vehicles such as type 1, type 2, type 3, type 4, type 5, type 6, and type 7. *Figure 24 (a)* shows the block diagram of the electric powertrain diagram of FCEV, which consists of the electric motor, power converter, battery pack, fuel cell, and hydrogen tank. FCEVs do not have any movable parts, hence the higher efficiency and reliable operation. FCEVs do not store total energy; instead, they constantly generate energy, similar to the petrol engine [52-53].

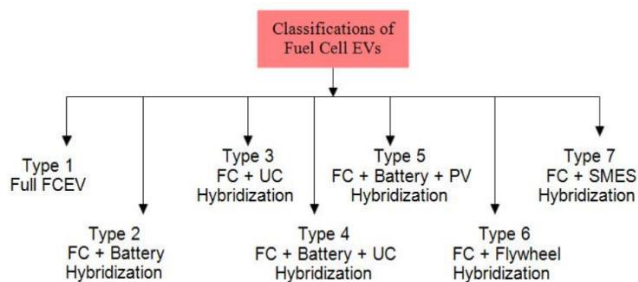


Figure 23: Classifications of FCEV

3.3 Battery operated electric vehicle (BEV)

The battery-operated electric vehicle is powered by a battery energy storage system. Currently, the demand for various hybrid electric vehicles is increasing, but in the future, the demand for battery-operated electric vehicles will also increase because of the recent advancements in the various types of batteries, which are covered previously in this paper. *Figure 24 (b)* shows the electric powertrain for battery electric vehicles (BEV) [54-57].

4. ELECTRIC VEHICLE MARKET

4.1 Challenges for EV market in India

Even though the electric vehicle sector promises lots of advantages, it is facing several impediments in its way. Considering conventional vehicles and gas-powered vehicles, EVs have a shorter range, which is a technological challenge and causes pain for the long drive. The full recharge of the battery pack in an EV generally takes eight hours. A similar battery pack can take nearly one hour. The range of the EV generally depends on the KWh capacity of the battery pack. For making the EV successful on Indian roads, there are several obstacles such as lack of charging infrastructure in India, large dependence on battery imports from other countries like China, the initial high cost of the EV, unavailability of consistent energy supply in India, and high cost of maintenance and repair [58-59].

4.2 Various factors driving the EV market

Some of the various driving factors for the EV market are given below

1. Government grants and subsidies
2. Increasing requirement for EVs
3. Large investment from Automakers into EV Industry
4. Increasing Environmental concerns
5. Battery material and their cost

Auto experts in India state that if the shift of transportation is moved to EV then dependence on oil imports from different gulf countries (Iran and Saudi) will be decreased. The government can use funds reserved for oil purchases in different sectors for the nation's development. Demand for EVs is driven by increased demand for fuel-efficient high performance and low vehicle emission. Currently, EVs constitute less than one percent of all the conventional vehicles sold in India. There are more than 400000 units of EVs (2

wheelers) and only a few thousand EVs (4 wheelers) are running on Indian roads. Manufacturers sector and industries are demanding for the government to reduce regulatory difficulties and promote infrastructure developments to boost the market growth.

4.3 Government initiative to magnify EV manufacturing and sale

By 2030, it is mediated that the trading of internal combustion engine vehicles will be prohibited by the government of India. In this scenario, the overall market size of global EVs is projected to expand from US \$12967156 million in 2018 to US \$35985456 million by the end of 2025 at a CAGR of 15.69% (Source: Global EV outlook 2021). The government of India has increased investment from foreign firms in the Indian automobile sector. And it permits 100% foreign direct investment (FDI) under the automatic route. Reports also surfaced that to boost the automobile industry according to global standards, the government is aiming to commence new R&D at a cost of US \$388.5 million under the national automatic testing and research and development infrastructure project (NATRIP). Increasing EV-related training courses in institutes and universities will result in magnifying EV research and development in India. The tax concession given by the Indian government for purchasing new EVs will increase the market adaptability of EVs in the market.

4.4 Opportunities for the EV market

The WEF (World Economic Forum) revealed that India has the potential to develop the EV ecosystem if the government acts appropriately. Transportation is majorly responsible for scalding pollution and global warming at a massive level. To combat pollution and the greenhouse effect, auto companies and scientists have come up with the concept of electric and hybrid vehicles, which have gained massive traction globally. According to auto experts, electric cars have zero carbon emissions, and with on-road augmentation, there can be a clear atmosphere, thereby leading to fewer pollution-based diseases in the world. Though there will be fewer greenhouse gas emissions, this will still protect the ozone layer and have a lesser carbon footprint. Another uniqueness of all the EVs on the market is that they are all connected digitally with the servicing and charging centers using the internet.

4.5 How ready are Indian cities for EVs

It is very important to know the requirements of a particular city for the design and development of the EV infrastructure, such as charging stations, public transport based on EVs, and battery swapping stations, under the policies of the state and central government for EV consumers and manufacturers. The best example is Nagpur, where the Maharashtra state government launched a mega-project in collaboration with the private sector. Under this scheme, 200 EVs such as buses, taxis, and E-Rickshaws are running in the city. While considering a particular city for the EV model, various factors should be considered, such as charging infrastructure, monthly or annual sales of EVs, total project cost, and policies of the

state and central government. The utilisation of green energy for feeding power to EV infrastructure in the city can further reduce the hazardous effects on environmental stability. The various EV manufacturing companies plan to install millions of EVs for daily mobility across cities by 2022 [59-65].

5. FUTURE TRENDS

With the advancement of technology, it can be easily speculated that this sector will continue to grow. It also means that the number of EV charging stations will grow across the country, which is currently very low. Research is ongoing for different battery manufacturing materials to improve efficiency, increase KWh capacity and reduce cost, which will result in the expansion of the travel range of EVs. After the expansion of charging stations, there will need to be an advancement in the public transportation system based on EVs that will work on existing charging stations.

6. CONCLUSION

The article proposes a review of electric vehicle technology development in key sectors such as EV types, EV markets in India with future trends, energy storage system development, fuel cell technology development, and motor drive for EVs with power converters, electric motors, processors, and controllers. Different battery charging methods are elaborated upon in this paper, such as conductive type charging, inductive type charging, and battery exchange methods. The different attributes of various classes of EVs have been reviewed in this paper. These classifications are HEVs, FCEVs, and BEVs. The EV market section consists of challenges for the EV market in India, various factors driving the EV market, government initiatives to magnify EV manufacturing and sales, opportunities in the EV market, and the readiness of Indian cities for EVs. India wants the EV industry to grow in the country. The government is working on a strong charging infrastructure, a policy for universal charging standards, consumer awareness about EVs, and new technology that will make EVs cheaper to make. Based on the review in this paper, the following necessary and important conclusions are given below:

- Electric cars are needed all over the world because people are worried about climate change. This is true for India and for the rest of the world.
- Battery technology is the bottleneck for EVs, as well as the performance of the PWM converter technology, which is required for EV propulsion, should also be further extensively researched to improve the overall efficiency.
- Air pollution in India led to a lot of different types of transportation vehicles, like two-four-wheelers and goods vehicles.
- With the right control and communication with the utility power grid, electric cars could be made to work with a smart grid.
- The incentives for vehicle owners need to be customised to suit their socio-economic needs.
- Power network development moves slowly compared to EVs. Also, the associated cost required to modernize

electric networks to accommodate EVs' additional loading is so large that it makes it impractical.

The review of this paper was developed for researchers and industry people who are implementing EVs in the Indian market and is relevant to the global acceptance of EVs.

7. ACKNOWLEDGMENT

As an author, I mostly have to thank the AICTE for starting a scholarship program called the ADF (AICTE Doctoral Fellowship). This program helps improve the research environment in the country. I am also grateful to the research Centre at the Government College of Engineering Aurangabad for the valuable support.

REFERENCES

- [1] Kong, Fanxin, and Xue Liu. "Sustainable transportation with electric vehicles." *Foundations and Trends in Electric Energy Systems* 2.1 (2017): 1-132.
- [2] Texas instrument, "Driving the green revolution in transportation," from www.ti.com.
- [3] Ashish Tiwari, Om Prakash Jaga, "Component Selection for an Electric Vehicle: A Review" in *IEEE International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC)* India, March 2017.
- [4] Krause, Paul C., et al. Analysis of electric machinery and drive systems. Vol. 2. New York: *IEEE Press*, 2002.
- [5] Zhang, Fan, et al. "Literature review of electric vehicle technology and its applications." 2016 5th *International Conference on Computer Science and Network Technology (ICCSNT)*. IEEE, 2016.
- [6] Sun, Xiaoli, et al. "Technology development of electric vehicles: A review." *Energies* 13.1 (2020): 90.
- [7] IRENA (2017), Electric Vehicles: technology brief, International Renewable Energy Agency, Abu Dhabi.
- [8] Feng, Sida, and Christopher L. Magee. "Technological development of key domains in electric vehicles: Improvement rates, technology trajectories, and key assignees." *Applied Energy* 260 (2020): 114264.
- [9] L. Lu, X. Han, J. Li, J. Hua, and M. Ouyang, "A review on the key issues for lithium-ion battery management in electric vehicles," *Journal of power sources*, vol. 226, pp. 272–288, 2013.
- [10] Ranawat, Daisy, and M. P. R. Prasad. "A Review on Electric Vehicles with the perspective of Battery Management System." 2018 *International Conference on Electrical, Electronics, Communication, Computer, and Optimization Techniques (ICECCOT)*. IEEE, 2018.
- [11] Bai, Yunfei, et al. "Optimal design of a hybrid energy storage system in a plug-in hybrid electric vehicle for battery life improvement." *IEEE Access* 8 (2020): 142148-142158.
- [12] M. Ehsani, Y. Gao, and A. Emadi, "Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory, and design." *CRC Press*, 2009.
- [13] Texas instrument, "Intelligent battery management and charging for electric vehicles," from www.ti.com.
- [14] Joseph, J. Jency, J. L. Juliha, and F. T. Josh. "Review on the recent development of the power converters for an electric vehicle." 2017 2nd *International Conference on Communication and Electronics Systems (ICCES)*. IEEE, 2017.
- [15] Zhu, Z. Q., and S. Cai. "Hybrid excited permanent magnet machines for electric and hybrid electric vehicles." *CES Transactions on Electrical Machines and Systems* 3.3 (2019): 233-247.
- [16] Kaname Sasaki, Hideaki Ishikawa, Kinya Nakatsu, Kenji Kubo, Ryuichi Saitou, and Takashi Kimura, "High-power density Inverter Technology for Hybrid and Electric Vehicle Applications," *Hitachi Review* Vol. 63, 2014.
- [17] H.-J. Chiu and L.-W. Lin, "A bidirectional dc-dc converter for fuel cell electric vehicle driving system," *Power Electronics, IEEE Transactions on Power Electronics*, vol. 21, no. 4, pp. 950–958, 2006.
- [18] İnci, Mustafa, et al. "A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing, and future aspects." *Renewable and Sustainable Energy Reviews* 137 (2021): 110648.
- [19] Guo, Ningyuan, et al. "A Computationally Efficient Path-Following Control Strategy of Autonomous Electric Vehicles with Yaw Motion Stabilization." *IEEE Transactions on Transportation Electrification* 6.2 (2020): 728-739.
- [20] Xiong, Huiyuan, et al. "A New Dual Axle Drive Optimization Control Strategy for Electric Vehicles Using Vehicle-to-Infrastructure Communications." *IEEE Transactions on Industrial Informatics* 16.4 (2019): 2574-2582.
- [21] Ding, Xiaolin, et al. "Longitudinal Vehicle Speed Estimation for Four-Wheel-Independently-Actuated Electric Vehicles Based on Multi-Sensor Fusion." *IEEE Transactions on Vehicular Technology* 69.11 (2020): 12797-12806.
- [22] Oncken, Joseph, and Bo Chen. "Real-time model predictive powertrain control for a connected plug-in hybrid electric vehicle." *IEEE Transactions on Vehicular Technology* 69.8 (2020): 8420-8432.
- [23] Sreehari, M. D., et al. "Design and Analysis of E-Bike with Electrical Regeneration and Self-Balancing Assist." 2020 4th *International Conference on Trends in Electronics and Informatics (ICOEI)*(48184). IEEE, 2020.
- [24] Xiong, Rui, et al. "Critical review on the battery state of charge estimation methods for electric vehicles." *IEEE Access* 6 (2017): 1832-1843.
- [25] Teng, Fei, et al. "Technical Review on Advanced Approaches for Electric Vehicle Charging Demand Management, Part I: Applications in Electric Power Market and Renewable Energy Integration." *IEEE Transactions on Industry Applications* 56.5 (2020): 5684-5694.
- [26] Wolbertus, Rick, and Robert van den Hoed. "Fast Charging Systems for Passenger Electric Vehicles." *World Electric Vehicle Journal* 11.4 (2020): 73.
- [27] Yilmaz, Murat, and P. Krein. "Review of charging power levels and infrastructure for plug-in electric and hybrid vehicles and commentary on unidirectional charging." *IEEE International Electrical Vehicle Conference*. 2012.
- [28] Said, Dhaou, and Hussein T. Mouftah. "A novel electric vehicles charging/discharging management protocol based on queuing model." *IEEE Transactions on Intelligent Vehicles* 5.1 (2019): 100-111.
- [29] Wang, Bo, et al. "Electrical safety considerations in large-scale electric vehicle charging stations." *IEEE Transactions on Industry Applications* 55.6 (2019): 6603-6612.
- [30] Zhang, Wenliang, et al. "Evaluating Model Predictive Path Following and Yaw Stability Controllers for Over-Actuated Autonomous Electric Vehicles." *IEEE Transactions on Vehicular Technology* 69.11 (2020).
- [31] Schuss, Christian, et al. "Impacts on the Output Power of Photovoltaics on Top of Electric and Hybrid Electric Vehicles." *IEEE Transactions on Instrumentation and Measurement* 69.5 (2019): 2449-2458.

- [32] G. Putrus, P. Suwanapongkarl, D. Johnston, E. Bentley, and M. Narayana, "Impact of electric vehicles on power distribution networks," in *Vehicle Power and Propulsion Conference*, 2009. VPPC'09. IEEE, 2009, pp. 827–831.
- [33] Bayati, Mahdi, et al. "Sinusoidal-Ripple Current Control in Battery Charger of Electric Vehicles." *IEEE Transactions on Vehicular Technology* 69.7 (2020): 7201-7210.
- [34] W. Price and A. Botelho, "Protodrive: Rapid prototyping and simulation for EV powertrains," *University of Pennsylvania*, 2012.
- [35] Now, Aiman, et al. "ELEVES: A new software tool for electric vehicle modeling and simulation." *World Electric Vehicle Journal* 1.1 (2007): 236-243.
- [36] Ding, Ning, K. Prasad, and T. T. Lie. "The electric vehicle: a review." *International Journal of Electric and Hybrid Vehicles* 9.1 (2017): 49-66.
- [37] Mohd, T. A. T., M. K. Hassan, and W. M. K. A. Aziz. "Mathematical modeling and simulation of an electric vehicle." *Journal of Mechanical Engineering and Sciences* 8.1 (2015): 1312-1321.
- [38] Singh, Krishna Veer, Hari Om Bansal, and Dheerendra Singh. "A comprehensive review on hybrid electric vehicles: architectures and components." *Journal of Modern Transportation* 27.2 (2019): 77-107.
- [39] Zhu, Z. Q., and S. Cai. "Hybrid excited permanent magnet machines for electric and hybrid electric vehicles." *CES Transactions on Electrical Machines and Systems* 3.3 (2019): 233-247.
- [40] Bai, Yunfei, et al. "Optimal design of a hybrid energy storage system in a plug-in hybrid electric vehicle for battery life improvement." *IEEE Access* 8 (2020): 142148-142158.
- [41] Shafiq, Saifullah, et al. "Reliability Evaluation of Composite Power Systems: Evaluating the Impact of Full and Plug-in Hybrid Electric Vehicles." *IEEE Access* 8 (2020): 114305-114314.
- [42] Yoshihara, Shigeyuki, et al. "Development of technology for electrically driven powertrains in hybrid electric vehicles." *Hitachi Review* 58.7 (2009): 325.
- [43] Shafiq, Saifullah, et al. "Reliability Evaluation of Composite Power Systems: Evaluating the Impact of Full and Plug-in Hybrid Electric Vehicles." *IEEE Access* 8 (2020): 114305-114314.
- [44] Kumar, Siddhant, and Adil Usman. "A review of converter topologies for battery charging applications in plug-in hybrid electric vehicles." 2018 *IEEE Industry Applications Society Annual Meeting (IAS)*. IEEE, 2018.
- [45] Zhang, Yuanjiang, et al. "A Cyber-Physical System-Based Velocity-Profile Prediction Method and Case Study of Application in Plug-In Hybrid Electric Vehicle." *IEEE transactions on cybernetics* 51.1 (2019): 40-51.
- [46] Fouladi, Ehsan, et al. "Power Management of Microgrids including PHEVs based on Maximum Employment of Renewable Energy Resources." *IEEE Transactions on Industry Applications* 56.5 (2020): 5299-5307.
- [47] Oncken, Joseph, and Bo Chen. "Real-time model predictive powertrain control for a connected plug-in hybrid electric vehicle." *IEEE Transactions on Vehicular Technology* 69.8 (2020): 8420-8432.
- [48] Yilmaz, Murat, and P. Krein. "Review of charging power levels and infrastructure for plug-in electric and hybrid vehicles and commentary on unidirectional charging." *IEEE International Electrical Vehicle Conference*. 2012.
- [49] Taherzadeh, Erfan, Hamid Radmanesh, and Ali Mehrizi-Sani. "A Comprehensive Study of the Parameters Impacting the Fuel Economy of Plug-In Hybrid Electric Vehicles." *IEEE Transactions on Intelligent Vehicles* 5.4 (2020): 596-615.
- [50] Kang, Young-Rok, Ji-Chang Son, and Dong-Kuk Lim. "Optimal Design of IPMSM for Fuel Cell Electric Vehicles Using Autotuning Elliptical Niching Genetic Algorithm." *IEEE Access* 8 (2020): 117405-117412.
- [51] Huangfu, Yigeng, et al. "An Advanced Robust Noise Suppression Control of Bidirectional DC-DC Converter for Fuel Cell Electric Vehicle." *IEEE Transactions on Transportation Electrification* 5.4 (2019): 1268-1278.
- [52] Jin, Jian Xun, et al. "Cryogenic power conversion for SMES application in a liquid hydrogen-powered fuel cell electric vehicle." *IEEE Transactions on Applied Superconductivity* 25.1 (2014): 1-11.
- [53] Reddy, K. Jyotheeswara, and N. Sudhakar. "High voltage gain interleaved boost converter with neural network-based MPPT controller for fuel cell-based electric vehicle applications." *IEEE Access* 6 (2018): 3899-3908.
- [54] Dusmez, Serkan, and Alireza Khaligh. "A supervisory power-splitting approach for a new ultracapacitor-battery vehicle deploying two propulsion machines." *IEEE Transactions on Industrial Informatics* 10.3 (2014): 1960-1971.
- [55] Xiong, Rui, et al. "Critical review on the battery state of charge estimation methods for electric vehicles." *IEEE Access* 6 (2017): 1832-1843.
- [56] Lehtola, Timo, and Ahmad Zahedi. "Electric Vehicle Battery Cell Cycle Aging in Vehicle to Grid Operations: A Review." *IEEE Journal of Emerging and Selected Topics in Power Electronics* (2019).
- [57] Xiong, Rui, et al. "Lithium-ion battery health prognosis based on a real battery management system used in electric vehicles." *IEEE Transactions on Vehicular Technology* 68.5 (2018): 4110-4121.
- [58] Bayati, Mahdi, et al. "Sinusoidal-Ripple Current Control in Battery Charger of Electric Vehicles." *IEEE Transactions on Vehicular Technology* 69.7 (2020): 7201-7210.
- [59] Vidhi, Rachana, and Prasanna Shrivastava. "A review of electric vehicle lifecycle emissions and policy recommendations to increase EV penetration in India." *Energies* 11.3 (2018): 483.
- [60] Alshahrani, Salem, Muhammad Khalid, and Muhammad Almuhamini. "Electric vehicles beyond energy storage and modern power networks: Challenges and applications." *IEEE Access* 7 (2019): 99031-99064.
- [61] Patil, Harshavardhan, and Vaiju N. Kalkhambkar. "Grid Integration of Electric Vehicles for Economic Benefits: A Review." *Journal of Modern Power Systems and Clean Energy* (2020).
- [62] Alizadeh, Mahnoosh, et al. "Retail and wholesale electricity pricing considering electric vehicle mobility." *IEEE Transactions on Control of Network Systems* 6.1 (2018): 249-260.
- [63] Singh, Shakti, Prachi Chauhan, and Nirbhaw Jap Singh. "Feasibility of grid-connected solar-wind hybrid system with an electric vehicle charging station." *Journal of Modern Power Systems and Clean Energy* 9.2 (2020): 295-306.
- [64] Abas, AE Pg, et al. "Techno-economic analysis and environmental impact of an electric vehicle." *IEEE Access* 7 (2019): 98565-98578.
- [65] Wang, Lu, et al. "Grid Impact of Electric Vehicle Fast Charging Stations: Trends, Standards, Issues, and Mitigation Measures-An Overview." *IEEE Open Journal of Power Electronics* (2021).



© 2022 by Sachin B. Shahapure, Vandana A. Kulkarni (Deodhar) and Sanjay M. Shinde. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).