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Development scheme and key technology of an electric vehicle: An overview

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ABSTRACT

Environmental protection and energy conservations are the main concern of 21st century which has now accelerated the pace to plan and develop electric vehicle technology. The electric vehicles (EVs) offer a zero emission, new automobile industry establishment, and economic development, efficient and smart transportation system. Also EVs equipped with artificial intelligence system will also improve the present traffic safety and road utilization. The EV system consist of energy storage devices such as various types of batteries, fuel cells, ultra-capacitors along with electric propulsion, body of the vehicle and energy management system with the diversified technology of electrical, electronics, mechanical, automotive and chemical engineering. The objective of electric vehicle is to produce commercial viable range, efficient performance, and comfort with safety and reliable operations at cheaper price than its counterpart the internal combustion EV. Currently the permanent magnet brushless direct current motors are the present choice of automobile industries and researchers because of its high power density, compact size, reliability, and noise free and minimum maintenance requirements. In this paper an overview of electric vehicle technology and key strategy is presented. The present state of art permanent magnet brushless DC motor drive for the electric vehicle application is also presented in this paper. In addition the energy storage devices, smart energy management system unit for EV and commercial aspects and benefits of EV are highlighted.

1. Introduction

Earliest Electric Vehicles (EVs) were available since 1918 [1–5]. Since then, because of the rapid development and viability of Internal Combustion Engines [ICE], the usage of electric vehicle for road transportation was substantially reduced. But, present factors like environmental pollution problems, shortage of petroleum products and its sharp rise in cost along with energy independence has encouraged to re-organize the electric vehicles as an alternative mode of transportation. In the past 20th century the Direct Current (DC) and Alternating Current (AC) variable speed drives were commonly used for electric vehicle applications. But in this 21st century because of the availability of high quality rare earth permanent magnet materials like samarium cobalt (Sm-Co) and Neodymium-Iron-Boron (Nd-Fe-B), the Permanent Magnet Brushless Direct Current (PMBLDC) motors were introduced which has high power density and high efficiency [6–9]. The PMBLDC motor uses electronic commutation instead of brushes as in that of DC motor. But control algorithm is complex because of electronic commutation [10–12]. However, the few advantages of PMBLDC motor are increase in efficiency, high-quality Torque Vs Speed characteristics, high output power to size ratio, fast dynamic response and noise free operations. Hence, PMBLDC motor drives have become highly attractive for EV applications [13–16].

The most important issue of EV design is System Integration (SI) and Optimization. This is required to accomplish reliable performance and low cost of EVs. The design concept of Electric Vehicle (EV) consists of three parts, namely, (1) Advance technologies which are capable to increase the performance of the EV. However, these technologies are to be selected from state of art electrical, electronics, mechanical, automotive and chemical engineering. (2) Adoption of unique design specially applicable for EVs, and (3) Automobile industry techniques suitable for EV [17].

Presently the automobile industries show great deal of interest in In-wheel technology of Electric Propulsion System (EPS) applicable to Modern Electric Vehicles (MEVs). The main objective of MEVs is to provide wide speed range, high efficiency, controllability and safety. Therefore presently PMBLDC motors are extensively used than other different types of electric motor.

The PMBLDC motor drive system consists of both motor design and control strategy. In addition because of the advancement of microelec-

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tronics and control systems the PMBLDC drives has become has more reliable and categorized in to IE 4 efficiency (super premium efficiency) classification.

The study presents the understanding of PMBLDC drive system for EV applications and with recent advancements in the development of PMBLDC drive has been provided. Paper also high lights EV commercialization, along with the key issues and overall strategy.

The organization of the paper is as follows: - Section 2 provides informative details on trend related to EV which consists of Commercialization of EVs, key issues and overall strategy, International Energy (IE) Standard and key technology. EV Motors and Propulsion System Technology, Study and progress of EV, Comparisons between of EVs and ICEs, Comparison between different types of motors used for EV application and Architecture of EV, Motor drive theoretical and practical requirements are presented in Section 3. Section 4 explains the different types of energy storage systems like Battery, Fuel Cell (FC), Flywheel, Hybrid Energy System and Ultra Capacitor (UC). Smart Energy Management System of the EV is mentioned in Section 5. Finally in Section 6 commercial aspects to populate the EV and the benefits of EV is summarized.

2. Trend for EV

The present state of affairs of Electric Vehicle (EV) development depends on various factors that affect its progress and implementation. The development of swift trade and industry, labor costs, availability of natural resources, and constraints for new infrastructures determine the pace of the EV development and implementation. The performance requirement of EVs will be directly tied to clean energy demands. Hence, EVs also provide additional innovative transportation system along with replacement of conventional ICE vehicles [18]. From environment aspect, EV provide zero emission transportation and from energy point of view it is eco-friendly and efficient because it offers secure, comprehensive and energy balance spectrum. From transportation point of view, EVs provide intelligent transportation system that will improve road utilization and safety.

The motor required for electric scooter applications should be compact, small axial length, less weight with high efficiency. The aerodynamic drag, tractive force of the load, i.e. the road should be overcome by the torque developed by PMBLDC motor propulsion. Higher motor driving current is the major limitation of the PMBLDC motor [19,20].

2.1. Commercialization of EV

The commercialization of EV is happening currently but at low pace. It is expected to grow in this decade and the growth can accelerate with crisis in the reduced supply and increased cost of fossil fuel. The commercialization of EV in developed countries will be followed by the developing countries and especially in China and India where pollution from fossil fuel based IC engine will be major concern. Beside pollution and dwindling fossil fuel issues, advances in technology and economic reason can drive early implementation of EV in large scale. It is expected that EV would both cover public and private transport. The auto industry, government and environmental agencies would work together in this venture.

2.2. Key issues and overall strategy

Production of low cost and high performance EV is the main issue in successfully commercializing and promoting the EV. The overall strategy involves multiple stakeholders, countries, and methodologies. Sharing of the resources and the market between the countries will provide key information in advancement of the commercialization of EV. Some of these aspects include identification of standards and technical specification suitable for each country, availability of natural resources, economic development and cost effective labor. These steps enable establishment of information centers. Extensive database pooled at information centers would promote exchange of knowledge and experience between the countries. Government incentives and promotions would encourage commercialization of EV at rapid pace.

2.3. International Energy (IE) standard

The increase in electric motor efficiency contributes to the worldwide energy savings. To make this possible International Electrotechnical Commission (IEC) has made International Energy (IE) to develop the standards and performance of the motor drives [21]. The main concern of IE standards is efficiency which can be categorized as.

- Standard Efficiency, IE 1
- High Efficiency, IE 2
- Premium Efficiency, IE 3
- Super Premium Efficiency, IE 4
- Ultra-Premium Efficiency, IE 5

Currently this classification run from IE 1 to IE 4, but at present stage IE 3 is made mandatory in some countries so that performance can be increased. IE 4 standard is still not legally applied, but the regulation and specification are defined. The manufacturers use IE 4 as the readiness for implementation. The IE standards are already designed for the motor ranging from 0.5 to 375 kW, within which the motor of 7.5–375 kW mandatory rule for some application is made to follow from 2015 and for low power of 0.5 kW is from 2017. With the up gradation to IE 4 standards efficiency can be brought up for the machines of 120–500 kW.

2.4. Key technology

Key technology in EV consists of (a) Motor drive technology, (b) Power electronic technology (c) Micro-electronic and control technology, (d) Automotive technology, (d) Material Technology, and (d) Energy storage technology. Integration of all these technology is the key of success of an EV [22–27].

The EV Propulsion system of the EV converts the electrical power in to the mechanical power. This is re4quired to propel the vehicle to overcome the aero dynamic drag, rolling resistance drag and kinetic resistance as shown in Fig. 1.

3. The EV motors and propulsion system technology

EV propulsion system design is of flexible nature. It can be either single motor drive or multi motor drive with or without gears. The power ratings, Torque Vs Speed characteristics, reliability, high efficiency over wide speed and torque ranges and cost effectiveness are the main requirements of EV Motors. Classification of EV Motors required for electric propulsion is shown in Fig. 2.

Electric Machines (EMs) used in EV propulsion system have to operate at higher current density than conventional EMs of the same

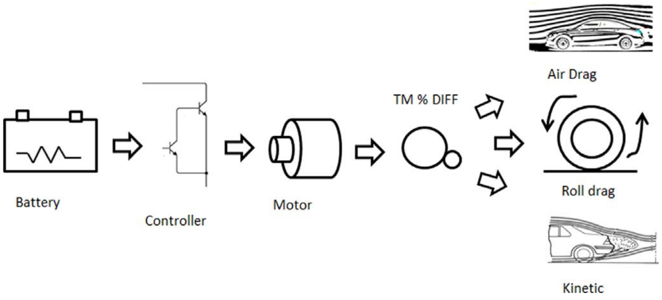


Fig. 1. EV propulsion system.

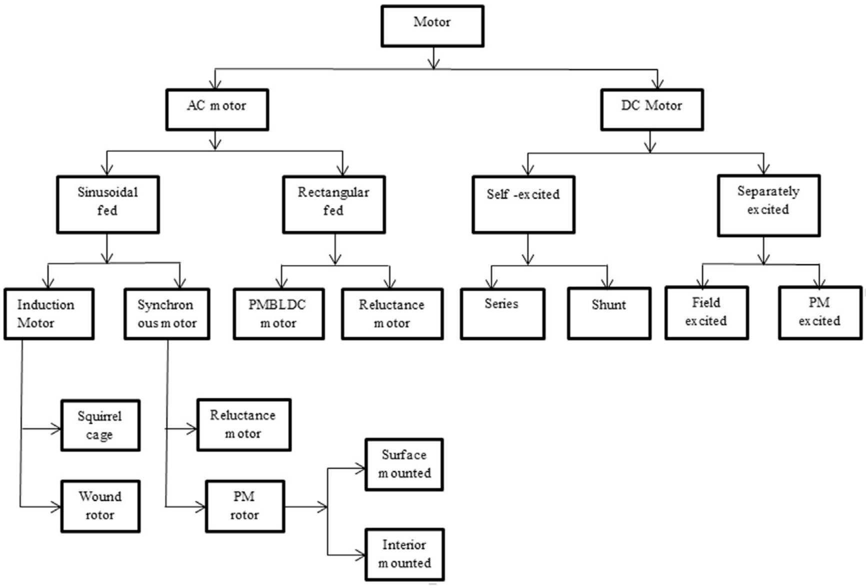


Fig. 2. Classifications of EV motors.

power rating and should have following special requirements [28–34]:

1. High efficiency over wide speed - torque ranges, especially for regenerative braking (maximizing efficiency is one of the most important challenges).
2. High torque/power density and high starting torque for high acceleration and deceleration rates. High torque at low speeds (starting and hill climbing) and High power at high cruising speeds.
3. Wide operating speed range including constant torque and power operations.
4. Easy-to-perform field-weakening at high speeds.
5. Small size and volume, lighter weight with high power and frequent starts/stops.
6. Good voltage regulation over a wide speed range and fast dynamic response.
7. High intermittent over load capability, typically twice the rated torque.
8. High reliability, robustness for harsh operating environments.
9. High fault tolerance operation and robust control.
10. Cost Economic and Rugged with simple maintenance
11. Low torque ripple, cogging torque and acoustic noise.
12. Minimum cooling requirements.
13. Mature technology, structural integrity and modular design.
14. Low level of electromagnetic interference (EMI) noise, minimum total harmonic distortion factor.
15. Water proof, shock proof, and dust proof.
16. Motor drive needs high controllability, steady-state accuracy, and good transient performance.

Induction motors (IM) are as 'work horse' of the industry, and presently vector controlled IMs are accepted but it has low efficiency at light loads as a result it does not perfectly match the requirement of EV propulsion system. While PM Brush less DC motors enjoy highest power density, its control algorithm is complex. The PM Hybrid motors (PMH) offer optimum efficiency over wide speed range because it has auxiliary field winding, hence the air gap flux is the sum of the permanent magnet flux and field winding flux and these flux have their individual magnetic path. Switched Reluctance Motor (SRM) is robust because of its reliability, simplicity in construction [35–38]. It offers high starting torque, wide speed range at constant power region and good thermal distribution. The Sliding Mode Control SRM drives are applicable for EV Propulsion System. The Table 1 shown below gives the basic comparison of the motors on the basis of grading from 1 to 10 points for each parameter in which 1 is the worst and 10 is the best.

Table 1
Parameter comparison of EV motors.

Parameters	IM	PMBLDC	PMH	SRM
Torque Vs Speed Characteristics	10	10	10	10
Density of Power	5	10	8	6
Efficiency	6	8	10	6
Robustness	8	8	8	10
Thermal Management	8	10	8	10
Status	10	8	6	6
Total	47	54	50	48

3.1. Electrical machine models and comparisons

An accurate model of the magnetic field of an electrical machine is required to know the performance capability such as torque, back E.M.F and also parasitic effects which consists of eddy current and iron losses, cogging torque and noise [39]. For analysis and computation of parameters and performance characteristics many electrical machine models have been reported in the literature. Analytical models make use of equivalent circuit parameters [40–43] and support fast simulation. But the limitations are accuracy and flexibility [44,45]. It is a useful tool for initial assessment of magnetic performances and considered as the first step of design optimization [46,47]. Finite element analysis (FEA) is a numerical tool to solve magnetic fields and the model is based on FEA. This method delivers precise results if all the characteristics of the material including time irreversibility are incorporated on a point-by-point basis within the FEA mesh [48]. But the limitations are all the material characteristics are rarely addressed. FEA is usually formulated to produce flux information, while torque requires analysis of local energy gradients and time derivatives. If the formulation is not considered with care, the gradients will be much less accurate than the flux values and torque errors will be large. Another model which is becoming more popular is Magnetic Equivalent Circuit (MEC) model. It is also based on physical geometry and material characteristics [49–51].

The results of two analytical models, a 2D FEA model and the 3D MEC model are compared to actual measurements, shown in Fig. 3. The error appears that 60% on torque between FEA and test, 40% on

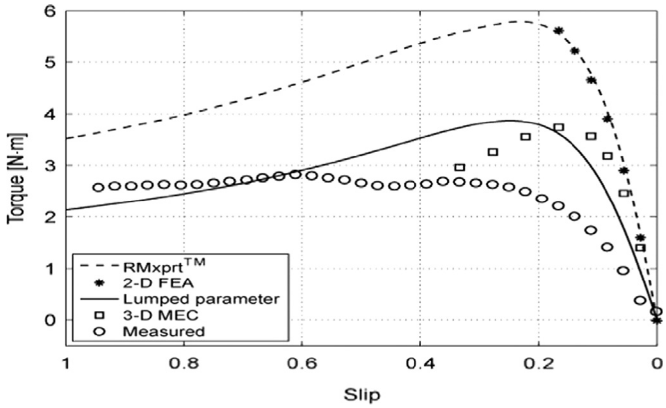


Fig. 3. Comparison of steady-state torque values of the IM.

torque between MEC and test results. At larger slips, MEC model values follow the measured characteristic more closely than the others [52].

3.2. Comparative case study of steady-state characteristics of induction motor

The steady-state characteristics of the three-phase induction motor (30 kW, 2890 rpm, 400 V, 50 Hz) have been obtained in order to compare results with measurements. Steady-state measurement results are compared to 2D FEA (Ansys Ansoft Maxwell and Magsoft's Flux software) and an analytical model results. FEA models of the induction motors take in to account rotor end-rings, stator end-wings, skin effects and leakage paths. Fig. 4 shows the simulated and measured steady-state torque and current characteristics of the three-phase IM. At greater speeds, torque and current values of all models are very similar and follow the measured values. But, at slower speeds, the error appears that 29% on torque between Maxwell FEA and measured results, 23% on torque between analytical and measured results, and 12% on torque between Flux FEA and measured results. The error appears that 21% on current between Maxwell FEA and measured results, and 13% on current between Flux FEA and measured results. The analytical model agrees well with measured current results.

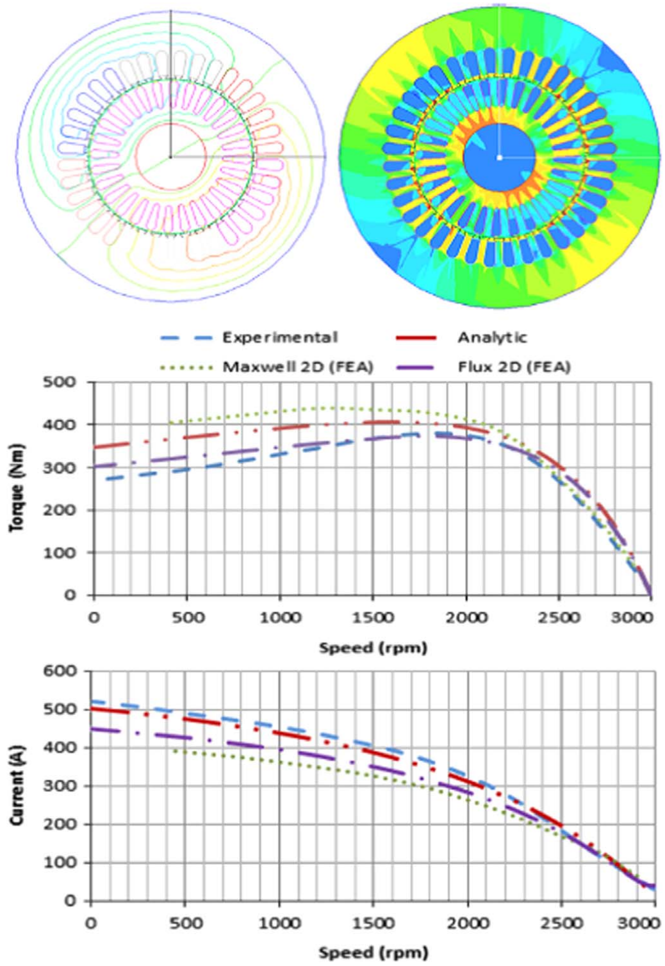


Fig. 4. Magnetic analysis of the three-phase IM and comparison of analytic-2D FEA torque- current simulated results with measured results.

3.3. Electric vehicle study and progress

The electric vehicles are zero emission vehicles. The possible Research and Development (R & D) activities in electric vehicles are: Stored Energy Electric Vehicle and Hybrid Electric Vehicle which are further classified as below:-

3.3.1. Stored energy electric vehicle

i. EV propulsion scheme by means of Battery
ii. EV propulsion scheme by means Battery and Ultra-Capacitor (UC)

3.3.2. Hybrid electric vehicle

i. EV propulsion scheme by means Fuel Cell (FC)
ii. Hybrid Electric Vehicles

The R & D activities carried out in the above field has yielded many solutions to environmental pollution problems and also raised questions owing to the initial cost of its development.

Based on the design characteristics Hybrid Electric Vehicles (HEVs) are classified into three categories namely series, parallel and power-split series-parallel [53]. The main concern in the development of HEVs is the management of the power flow between fuel and energy storage system (ESS) which contributes to the vehicle motion. It is a challenging task to satisfy the constraints and the requirements simultaneously to obtain an optimal solution [54]. The performance of the vehicle in terms of fuel economy depends heavily on the energy management strategy (EMS) which has been the topic of interest for many researchers. A number of the most recent approaches to the EMS problem are provided in the literature [55–63].

3.4. Comparison between EV and conventional vehicle

Comparison between electric vehicles and conventional vehicles (IC Engine vehicle) in given in Table 2 [64]. The IC engine efficiency is low because of heat loss also its cooling system is of intricate process. On the other hand electrical machines have higher efficiency than ICE.

Table 2
Comparison between electric vehicle and IC Engine vehicle.

Feature	Electric Vehicle	Automotive Vehicle
Prime mover	Electric motor	IC Engine
Source of Energy	Battery, Ultra capacitor Fuel Cell	Petroleum products
Mass	High	Low
Transmission scheme	Both electrical and mechanical	Mechanical
Braking scheme	Regenerative braking	Frictional brakes
Efficiency	Low	High
Zero emission	Yes	No
Capital cost	High	Standard
Running cost	Less	High

Table 3
Vehicle specifications used in powertrain models.

	Scooter	3-Wheeler	Low power 4-wheeler	High power 4-wheeler
Base vehicle mass (kg)	150	500	898	1493
Motor max power output (kW)	1.5	5.46	19	80
Final drive ratio	6.3805	6.3805	6.8737	7.9377
Usable battery capacity (kWh)	2.16	4.25	6.54	16.7
Tire size	1000 Â 300	1000 Â 4.500	P155/70R13	P205/55 R16
Drag coefficient	0.60	0.35	0.335	0.28
Frontal area (m2)	1.25	2.40	2.0	2.50
Baseline electrical accessory & AC load (W)	50	100	200	200
Estimated range in City (km)	64–71	60–80	117	123–138
Estimated range on Highway (km)	N/A	N/A	70–95	73–136
Top speed (km/h)	50	73	34–76	120

Electrical consumption data for scooters, 3-wheelers, and small 4-wheelers has previously been unavailable in the literature, particularly for the Indian context where driving conditions will be different than in developed countries including modern comfort like air conditioning load will be a significant factor [65].

A detailed vehicle powertrain model is used to estimate electrical consumption for four types of vehicles, with specifications for each vehicle listed in Table 3. The powertrain models are created in the industry standard Autonomie powertrain modeling platform. A vehicle powertrain model was constructed with specifications resembling a Nissan Leaf, and electrical consumption model estimates were compared against published measurement data [66] for the EPA UDDS, Highway, and US06 drive cycles over a range of total vehicle mass.

3.5. Comparison between different types of motors used for EV applications

The characteristics of the DC motors are suitable for EVs. But its limitations are the commutator and brushes. However the cost of Power Processing Unit (PPU) used for DC motor drive is much cheaper than that used for three phase induction motor [67–69]. The purpose of the commutator and brushes are now implemented by means thyristors. As a result zero maintenance motors were developed which are known as brush less dc motors. Since, these PMBLDC motors are without commutator and brushes their maintenance is very low also there is increase in efficiency and power-to-weight ratio. Hence, present trend is to use PMBLDC motor drive for electric vehicles.

The cost of PMBLDC motor drive has two main components, namely motor and the controller. The ease of control of the motor has made the researchers to take up the motor to work at efficiency and cost reduction and commercialize the application of the motor. Due to these features PMBLDC motor drives finds the wide application in low power drives and automotive. PMBLDC motors are well known for less maintenance, long life, low EMI and quiet operation [70]. The output power of these motors produce more output power per frame than other motors.

Table 4
Comparison between different types of DC and AC Machines used for EV applications.

Features	BLDC motor	DC motor	Induction motor
Speed -Torque Characteristics	Linear.	Quite flat.	Non-Linear.
Commutation	Electronic	Brushed	NA
Rating / size	High	Low	Moderate / low
Efficiency	High	Moderate	Low
Maintenance	Less	frequent	Frequent
Speed range	High	Low	High
Electric Noise	Low	High	Moderate
Control	Complex and expensive	Simple and cheap	Simple and cheap
Operating Life	Longer	Short	Moderate
Slip	No slip	No slip	Present
Starting Current	Rated	Twice the rated current	5–7 times rated current

Speed -Torque Characteristics of PMBLDC motor is linear. Hence operation with rated load at different speeds is achievable. In the case of DC Motor the speed -torque Characteristics is approximately linear. As a result Torque developed is decreased at high speeds due to friction of the brushes [71–73]. In Induction motors this speed – torque characteristic is noon linear. Therefore at low speeds developed torque is less.

Comparison between different types of DC and AC machines used for EV applications in given in Table 4.

3.6. Vehicle architecture

Electric Propulsion System (EPS) of an Electric vehicle is an integration of Mechanical, Electrical, Control, Magnetic, Electrochemical, Thermal, Chemical engineering [74–76]. Hence it is a complex assembly. The fuel tank of the conventional vehicle is replaced by the battery bank in EV. Single Phase or three phase AC mains or fuel cell is used charge the batteries [77]. The power controller is provided to control the power supply to the motor. To supply the power to auxiliaries and peripheral devices a separate 12 V battery is provided.

The EPS of an electric vehicle is combination of the electric motor, controller and the storage devices like battery. The batteries deliver the power to the motor via power controller. The accelerator knob is coupled to a pair of potentiometers (variable resistors). This provides the signal to the controller estimating the power to be delivered for the particular load condition. By varying the accelerator knob the controller can deliver zero to full power or any power level in between to the motor [78–80]. The vehicle is at rest when the controller delivers zero power and the vehicle is at full speed when the accelerator knob is fully raised. By varying the battery voltage with the application of semiconductor devices variable power can be applied to the EV Motor. Electrical Propulsion System of an Electric scooter is shown in Fig. 5.

3.7. Motor drive

Generally electric motors used for industrial application should be capable for long time run at constant speed and also at variable loads etc. But for electric vehicle application the motor needs to start, stop frequently, periodic acceleration and deceleration which cannot be compared with industrial electric motors. In order to suit the motor for electric vehicle application some of the key features have to be satisfied to operate at good performance and efficiency [81,82]. The motor for electric vehicle should have high torque for starting and uphill propulsion, higher power density for acceleration and speeding, capacity to bear over load for certain interval of time, reliable, efficient and cost affordable. The speed-torque characteristics of the motor will decide the appropriate motor. Figs. 6 and 7 shows the speed- torque

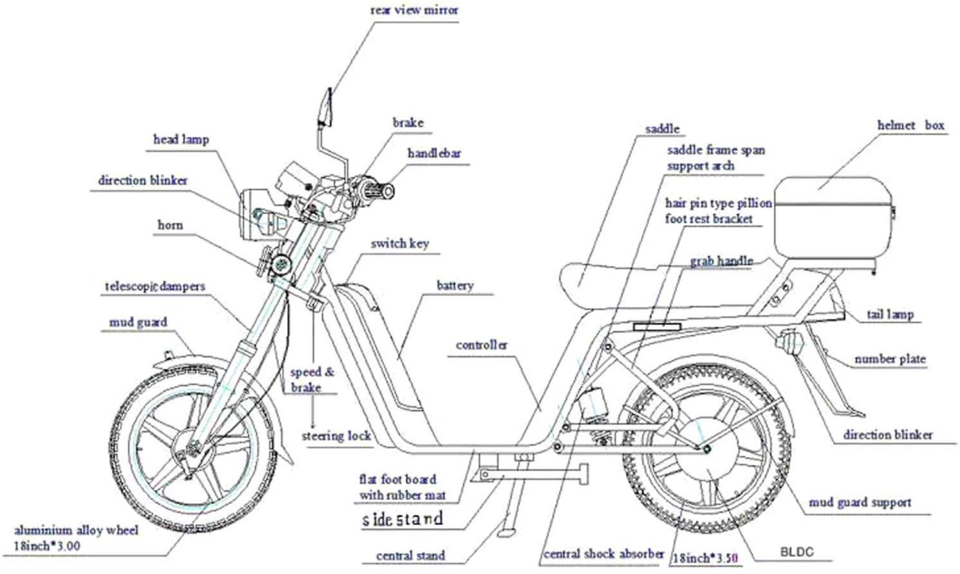


Fig. 5. Electric scooter.

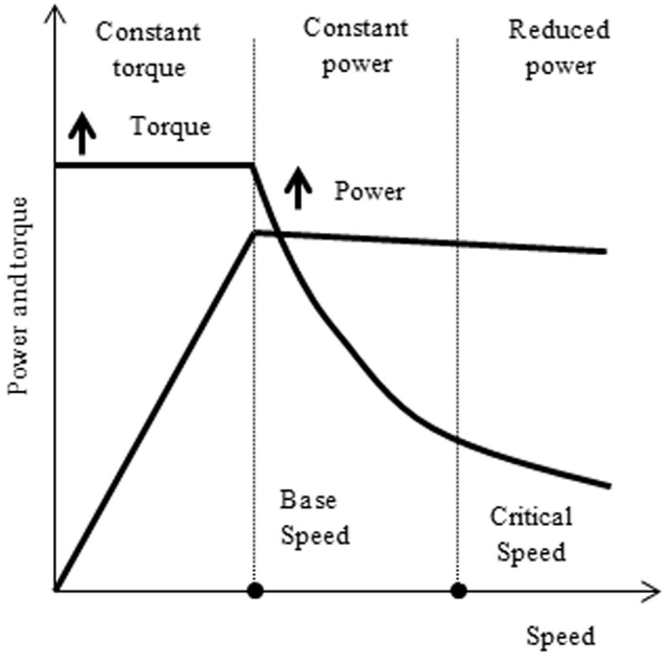


Fig. 6. Speed- torque characteristics of desired electric vehicle motor.

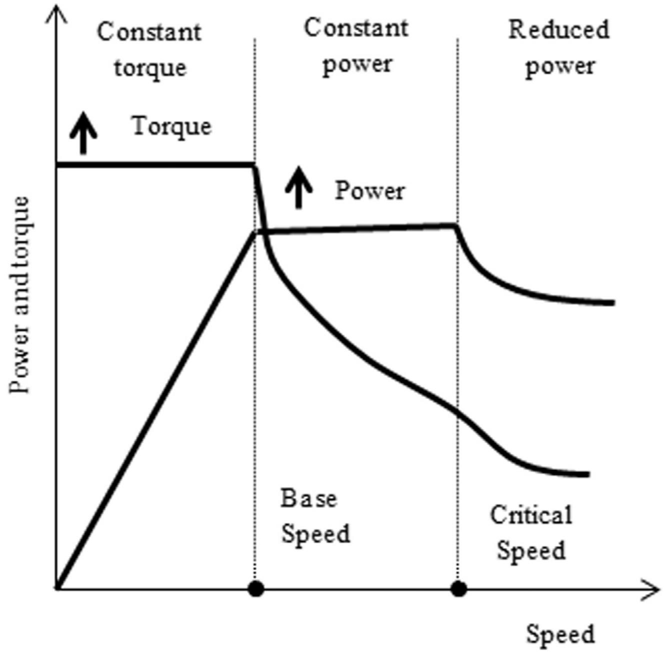


Fig. 7. Speed- torque characteristics of standard electric motor.

characteristics of the desired electric vehicle motor [83] and standard electric motor [84].

3.8. Motor drive requirement

The comprehensive mechanical parameters required for the Electric Scooter is given in Table 5.

To meet these limitations PMBLDC motor parameters provided in Table 6 is required. These values are necessary to calculate torque, power and speed of the PMBLDC motor drive. The electric motor for this application should be small in size, light weight and higher efficiency. In order to fit the motor into the scooter it should have a short axial length. Sufficient torque has to be generated to overcome the rolling resistance, drag, tractive force against gravitation during locomotion. The other constraints such as the size of the motor, size of the tire, driving current and output power are also to be taken into consideration [85].

Table 5
Required scooter parameters.

Sl. No	Parameter	Values	Unit
1	Total weight of the vehicle including people and luggage	200	Kg
2	Maximum acceleration	0.65	M/s^2
3	Coefficient of normal type rolling resistance	0.013	
4	Density of air	1.23	Kg/m^3
5	Drag coefficient	0.6	
6	Frontal area	0.8	M^3
7	Angle of slope	12	Degree

Hence, the feasibility of PMBLDC motor drive is studied from the technical specifications as mentioned in Table 6.

The design philosophy of EV PMBLDC motor drive is mainly based on the technical parameters like: high power density; high efficiency and wide speed range [86–88]. The two novel approaches of design

Table 6
Technical specification of the PMBLDC motor drive.

Sl. No	Parameter	Values	Unit
1	Rated voltage	48	Volts (DC)
2	Rated power	500	Watts
3	Rated torque	1.27	Nm
4	Rated speed	3000	Rpm
5	Rated current	11.4	Amps
6	Peak current	34.2	Amps
7	Peak torque	3.81	Nm
8	Resistance	0.94	Ohms
9	Inductance	1.19	mH
10	Electrical time constant	1.26	ms
11	Mechanical time constant	4.91	ms
12	Voltage constant	10.1	V/k rpm
13	Torque constant	0.128	Nm/A
14	Rotor moment of inertia	0.51	Kg cm^2
15	Motor length	130	Mm
16	Motor weight	1.6	Kg

philosophy are (A) Development of novel control strategy for specially designed PM BLDC motor drive and (B) Development of Permanent Magnet Hybrid (PMH) Brushless DC Motor Drive which consists of permanent magnets and the field winding.

3.8.1. Permanent magnet brushless motor drives

The PMBLDC motor is more suitable for EV application due to their inherent features like high power density and efficiency, but further improvement in design is required thus to fulfill the necessary constraint for EV [89–92]. The novelty of the PMBLDC drive has special distinct features as listed below;

- Pair of poles formed by two adjacent poles such that flux path per pole-pair is independent; hence these motors are motors are inherently de-coupled. Also the magnetic circuit arrangement reduces volume and weight due to this reduced magnetic iron yoke [93].
- The stator winding is designed in such a way that the coil span of the stator winding is made equal to the slot pitch which results in saving of copper. This will result in further reduction in volume and weight the machine.
- The cogging torque is eliminated by using fractional number of slots per pole per phase.
- Since these motor has phase-decoupling nature, the dynamic performance is outstanding. Therefore field-weakening control method for constant power operation is not suitable. For constant power-operation at high speeds the transformer EMF has to counter act with the rotational EMF. To achieve this novel control strategy is developed [94,95].
- On the basis of type of input PM BLDC motors are classified as sinusoidal-fed or rectangular-fed. For the same RMS values the sinusoidal input type motor develops smooth torque whereas rectangular input type develops high torque.
- The permanent magnets of the motor can be either housed on the rotor surface or buried inside the rotor. The effective air gap is large in case of surface mounted rotor and in case of permanent magnets buried inside the rotor, the permanent magnets are protected.

The unique wide speed control of PMBLDC Motors is as shown in Fig. 8.

3.8.2. Permanent magnet hybrid BLDC motor drives

This type of motor drive consists of both permanent magnets and field winding. The Permanent Magnets are incorporated into the rotor and the field winding is located at the stationary angular region which is formed by the inner and outer parts of the rotor as shown in Fig. 9. This combination provides the wide speed range operation and the air-gap flux is flexibly controlled by adjusting the DC field current [96–100]. To attain the constant-power operation, field weakening at high

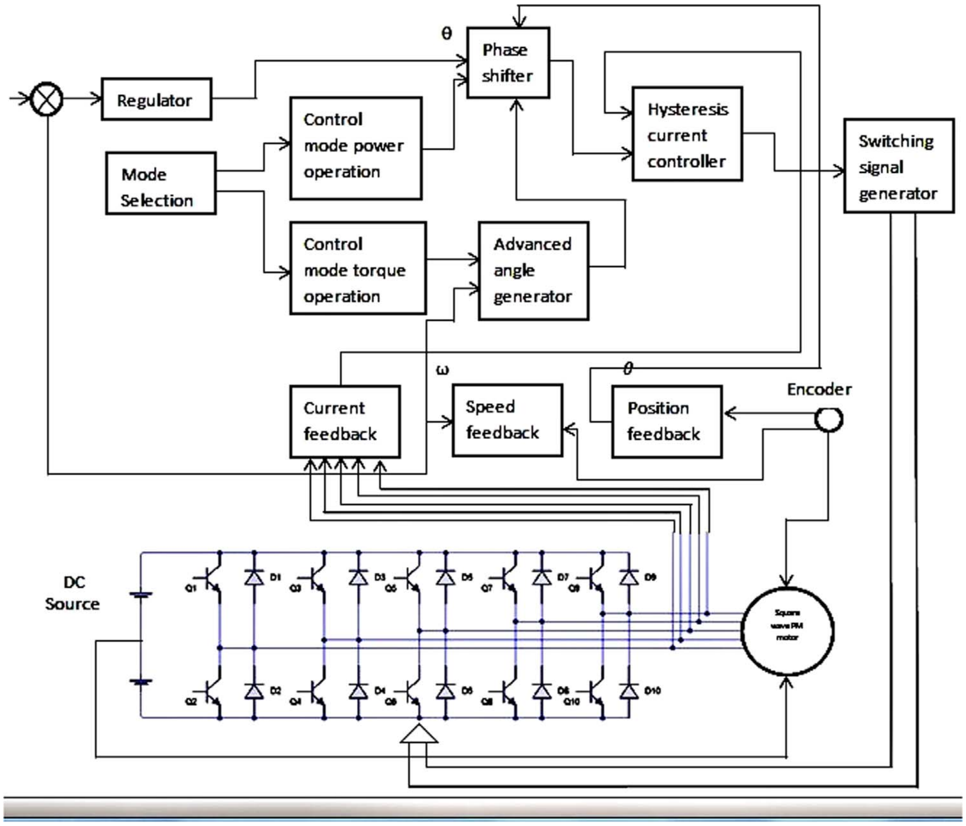


Fig. 8. Wide speed control of PMBLDC Motor Drives.

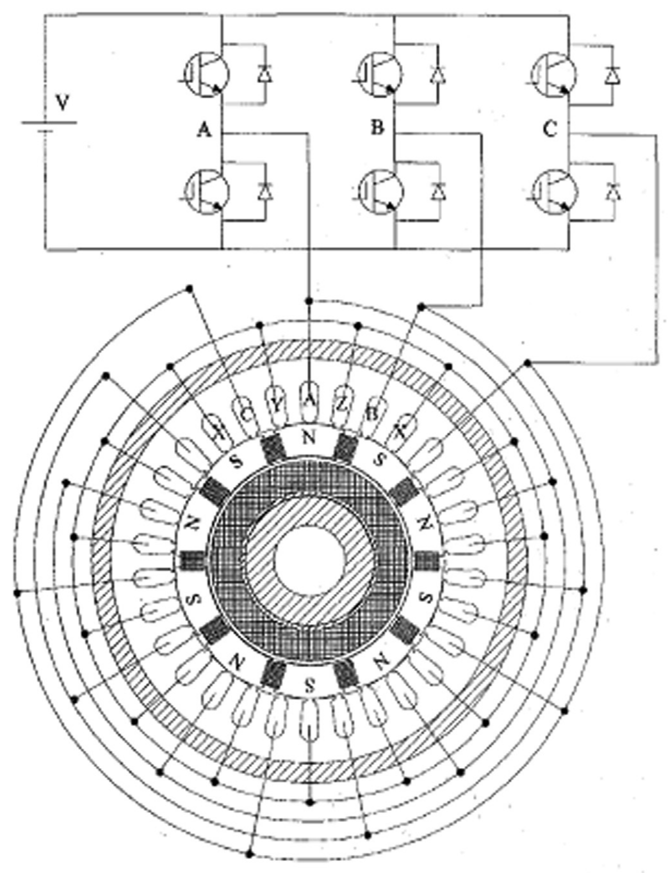


Fig. 9. Novel permanent magnet hybrid brushless motor drive.

speed is desirable which is possible by the flexibly field control. The advantages and key features of this type of drive are as below:

- The leakage flux is minimized by claw-type rotor structure arrangement. By placing the filed winding in the internal stator, the motor axial length can be decreased thus reducing the volume and weight of the motor.
- The existence of both permanent magnet and field windings results high air-gap flux density and high power density.
- The air-gap flux density can be flexibly adjusted by controlling the magnitude and direction of field current, thus the speed - torque characteristics meet the requirement of the electric propulsion system [101].
- The efficiency mapping of the motor can be optimized by sensibly controlling the input voltage and DC field current. Thus, efficiency for high- toque low-speed, low-torque high-speed operations can be enhanced [102].

3.9. Case study

3.9.1. The Finite Element Method (FEM) based design and analysis of PMBLDC motor

The Finite Element Method (FEM) based design and analysis of radial flux Permanent Magnet Brushless DC (PMBLDC) motor for electric scooter application with an objective develop high power density and high efficiency is presented in [103]. The motor considered for FEM design is a 3-phase, 8 pole rectangular waves, which replaces the conventional Internal Combustion Engines (ICEs). The distinct features of this motor design are: (1) The magnetic yoke reduction, which will decrease the weight and size, (2) Coil span equal to one slot pitch which will result in saving of copper and (3) elimination of cogging torque because of fractional number of slots per pole. The outer rotor configuration of PMBLDC motor has been considered in this design. The spokes of the wheel is directly fitted into the outer rotor of the motor. The simulation has been carried out by Pre-flux software. The electromagnetic field analysis is used for the design and optimization of the motor which is based on FEM.

The poly-phase, multi-pole construction of a PMBLDC motor reduces length of the winding as a result copper loss will be decreased. The height of the yoke and volume of the motor is also reduced because of decrease in magnetic circuit length. It also produces large torque in comparison to that produced by the interaction of sinusoidal current and the sinusoidal magnetic field [104–108]. This type of PMBLDC motor inherently exhibits superior dynamic performance. FEM is used for the analysis of electromagnetic field by which design and optimization of the proposed motor is carried out. The advantages of FEM are that a solution to the field is obtained even for the time-variable fields [109]. The computational time is reduced and accurate data are obtained because air gap is also considered for the analysis [110–112]. Simulation results are compared with analytical results in order to verify its suitability for electric scooter application. Simulation results show that the proposed motor is suitable for high performance Electric Scooter.

The design and optimization process of the proposed PMBLDC motor requires electromagnetic field analysis. This process is summarized as below:

- Initialize motor design configuration and geometry.
- Develop the meshes automatically for the area of involvement.
- Electromagnetic field analysis by FEM.
- Evaluation of performance parameters of the PMBLDC motor.
- Modification of the motor geometry by iteration.

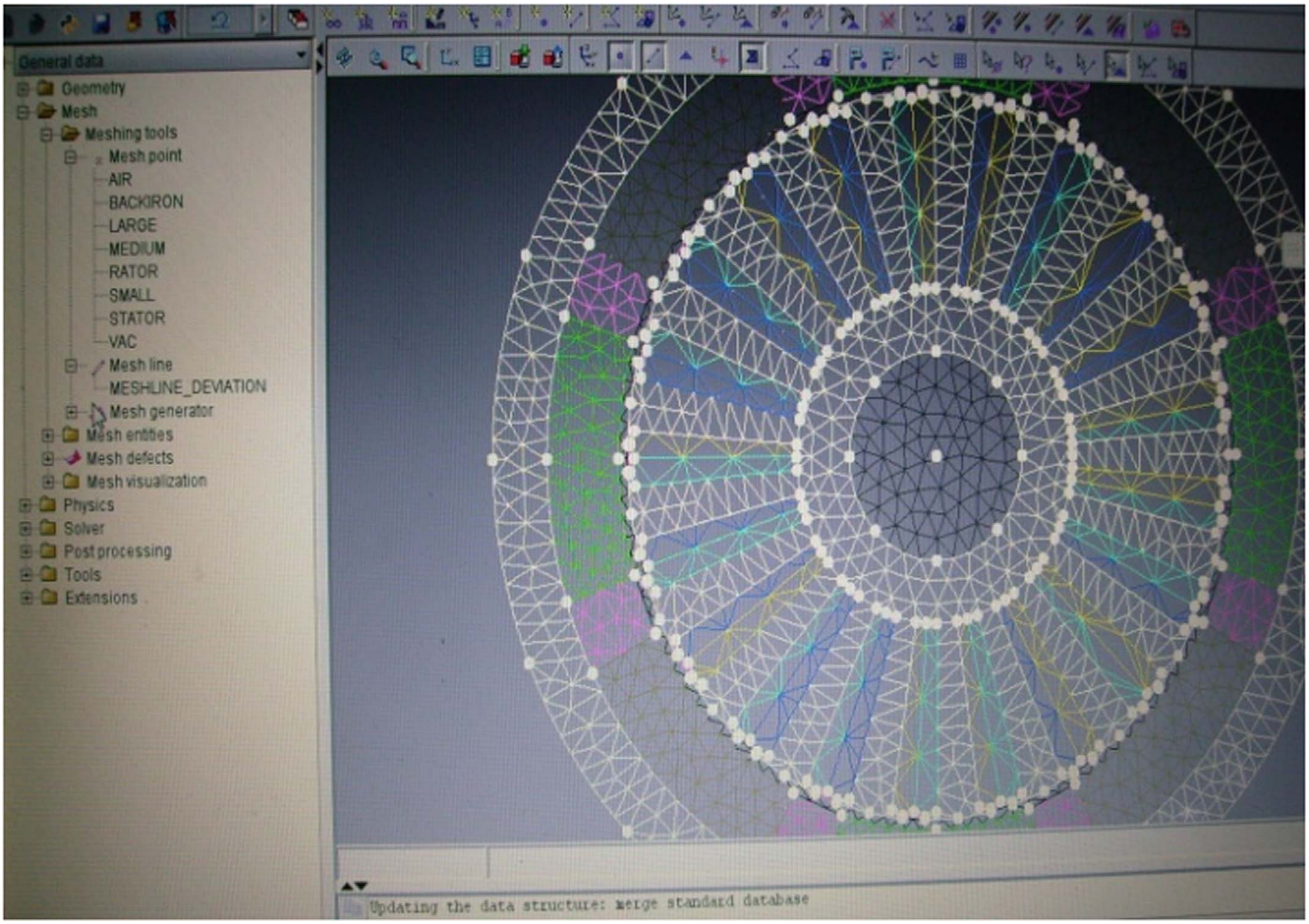
Brushless PM motor operation relies on the conversion of energy from electrical to mechanical. As magnetic energy plays vital role in the production of torque, it is necessary to formulate methods of computing it. A 2D FEM is suitable for this type of geometry and has lot of advantage over 3D calculation, such as lower memory storage and reduced time computation. In order to find motor performance FEM using Preflux is carried out. Generated mesh for the Finite element analysis of this motor is as shown in Fig. 10.

From the flux density distribution it is observed that at no-load condition flux distribution is symmetrical and at full load condition the flux distribution is un-symmetrical this is because of armature reaction. Since energy conservation is processed through the air gap, the air gap flux distribution is necessary. Fig. 11 illustrates the normal and tangential components of flux density and force density along the air gap periphery at full load condition. The desired optimization of the motor geometry can be adjusted based on this result.

Back EMF waveforms are shown in Fig. 12 in which line values of back EMF, V_{LL}=30.173 volts and phase value of back EMF, V_{ph}=17.39 V. It is observed that the analytical values of back EMF and FEM result of back EMF are almost equal.

The comparative results of FEM and analytical method of flux density distribution are shown in Table 7 which indicates that the results are much comparable. Prophy for torque calculation, phase currents and the load torque waveform are shown in Figs. 13–15 respectively.

The case study reveals that the multi-pole magnetic circuit with fractional slot is capable to achieve a high power density, high efficiency with negligible cogging torque. FEM has been carried out to know flux distribution at various parts of motor. This scheme focuses on magnetic and electrical design aspects of motor. Radial flux PMBLDC motor with outer rotor configuration has compact arrangement with high efficiency and low power to weight ratio that can be easily integrated with direct drive system of the electric scooter.

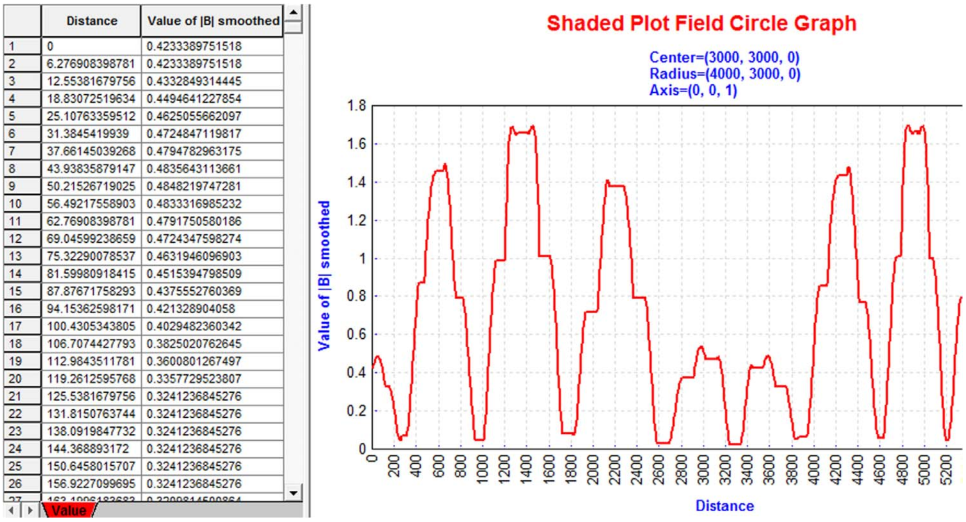


Updating the data structure: merge standard database

Fig. 10. Finite Element mesh of the motor.

3.9.2. Stability analysis of PMBLDC motor drive

Stability analysis of high power density and high efficiency Permanent Magnet Brushless DC (PMBLDC) Motor drive suitable for light electric vehicle application is presented in [113]. The motor used is poly-phase, multi-pole, rectangular wave Permanent Magnet motor with outer rotor configuration. The spokes of the wheel is directly fitted in to the outer rotor of this proposed motor. In comparison to the conventional PMBLDC motor this motor has special features namely, reduction in volume and weight, saving in copper and elimination of cogging torque. The motor operates at high starting torque and high cruising speed. Hence the proposed PMBLDC drive will have high power density, high efficiency and fast dynamic performance which will be best suited for gearless electric vehicle application. The design and stability analysis are carried out on 3-phase, 8 pole PMBLDC motor



	Distance	Value of |B| smoothed
1	0	0.4233389751518
2	6.276908398781	0.4233389751518
3	12.55381679756	0.4332849314445
4	18.83072519634	0.4494641227854
5	25.10763359512	0.4625055662097
6	31.3845419939	0.4724847119817
7	37.66145039268	0.4794782963175
8	43.93835879147	0.4835643113661
9	50.21526719025	0.4848219747281
10	56.49217558903	0.4833316985232
11	62.76908398781	0.4791750580186
12	69.04599238659	0.4724347598274
13	75.32290078537	0.4631946096903
14	81.59980918415	0.4515394798509
15	87.87671758293	0.4375552760369
16	94.15362598171	0.421328904058
17	100.4305343805	0.4029482360342
18	106.7074427793	0.3825020762645
19	112.9843511781	0.3600801267497
20	119.2612595768	0.3357729523807
21	125.5381679756	0.3241236845276
22	131.8150763744	0.3241236845276
23	138.0919847732	0.3241236845276
24	144.368893172	0.3241236845276
25	150.6458015707	0.3241236845276
26	156.9227099695	0.3241236845276

Fig. 11. Flux density at the teeth.

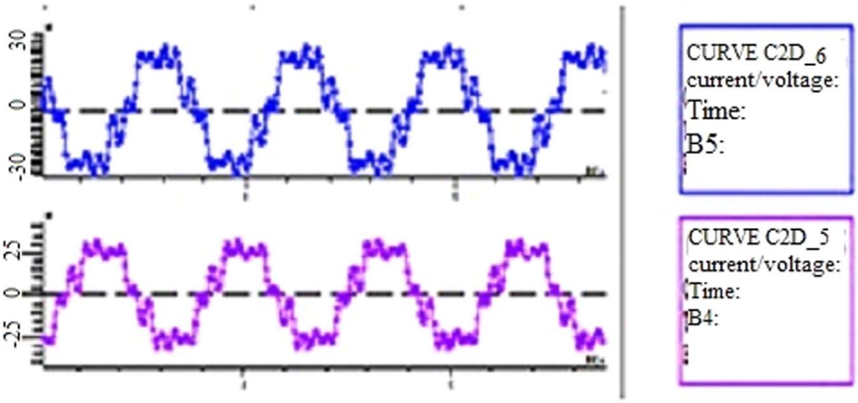


Fig. 12. Back emf waveforms.

Table 7
Comparison of analytical and FEM results.

	Calculated	FEM Method
Flux density at rotor back iron	0.557 wb/m^2	0.77865 wb/m^2
Flux density at Stator back iron	1.7 wb/m^2	0.65 wb/m^2
Flux density at teeth	1.854 wb/m^2	1.74 wb/m^2
Flux density at air gap	0.88 wb/m^2	0.69 wb/m^2
Torque	8.879 N-m	7.38 N-m
Emf (L-L)	31.2 V	30.173 V

drive. Simulation results are obtained with Matlab.

The electric vehicle configuration can be implemented with two different controls namely- open loop control and closed loop control. An open loop electric scooter configuration consist of a battery, accelerator, PMBLDC motor drive within built hall sensors and an electronic commutator to produce gate signals for the inverter.

In closed loop control technique, in addition to the open loop configuration the feedback signals from the hall sensors are considered. Fig. 16 shows the Block diagram of open loop control system of EV and Fig. 17 shows closed loop control technique of the EV. The closed loop

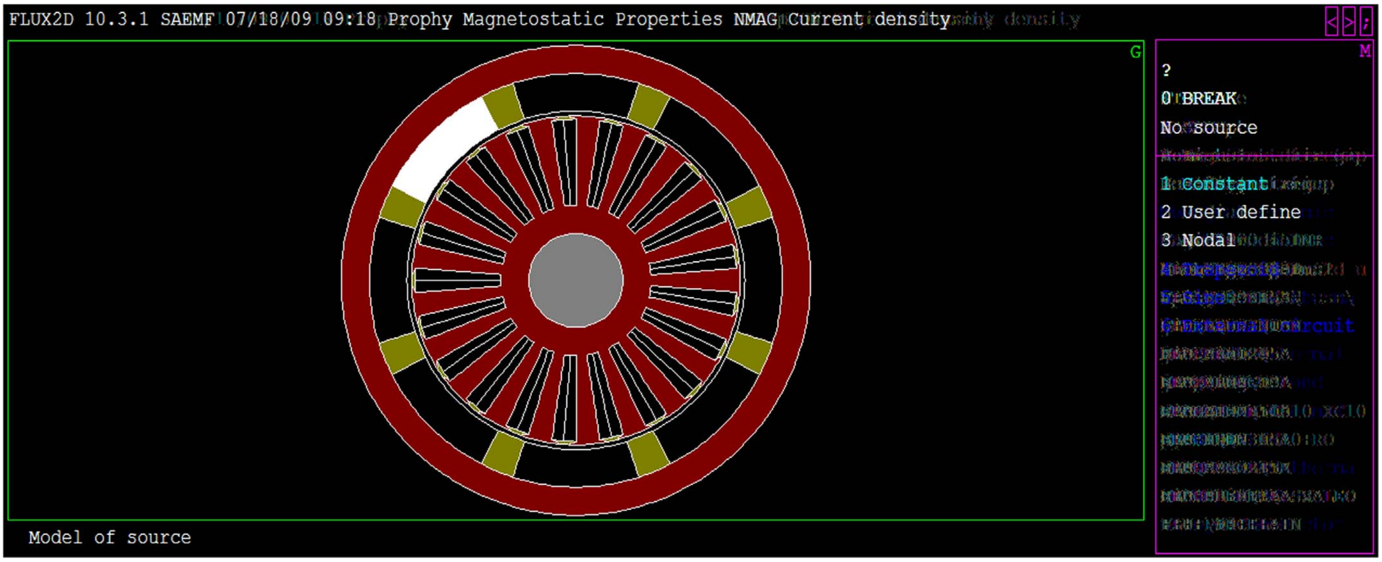


Fig. 13. Prophy for torque calculation.

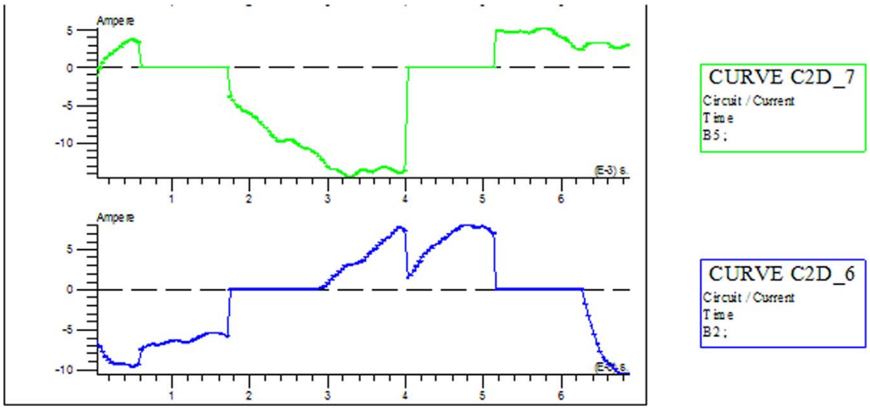


Fig. 14. Phase currents.

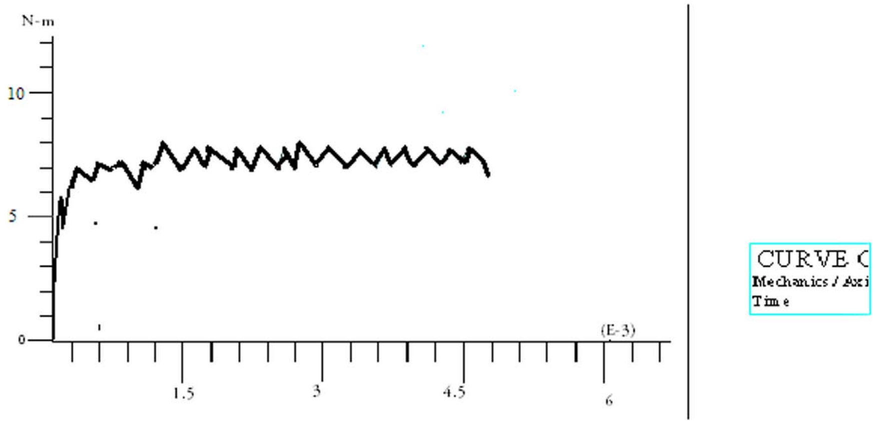


Fig. 15. No load torque.

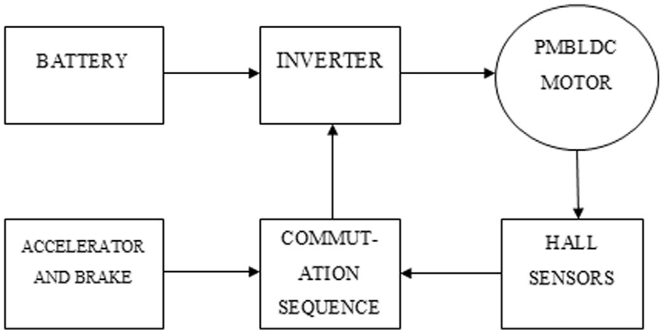


Fig. 16. Block diagram of open loop control for electric vehicle.

control technique of the proposed system is as shown in Fig. 18 which consists of speed feedback and current feedback signals. This control technique is much simpler when compared to that of the three phase vector control of the induction motors drives.

The control operation is as follows: When the set reference speed ω_{ref} is changed from zero to one, the motor starts rotating and the speed feedback steadily increases. The relative speed between reference speed and the speed feedback is fed into the Speed Controller (SC). The current reference for the inner current loop is I_{ref}. Per phase current feedback is compared with current reference and the difference between these two currents is fed into Current Controller (CC). The output of the CC and the signals from the hall sensors provide triggering signals to the thyristors of the inverter circuit. The current control in each phase is implemented by using hysteresis loop and Proportional Integral (PI) controller is used for speed control of the proposed PMBLDC motor. Simulation model of the PMBLDC motor drive shows that the stator current is sinusoidal in nature and the trapezoidal form of back emf generated from the mathematical model of the PMBLDC motor is shown in Fig. 19.

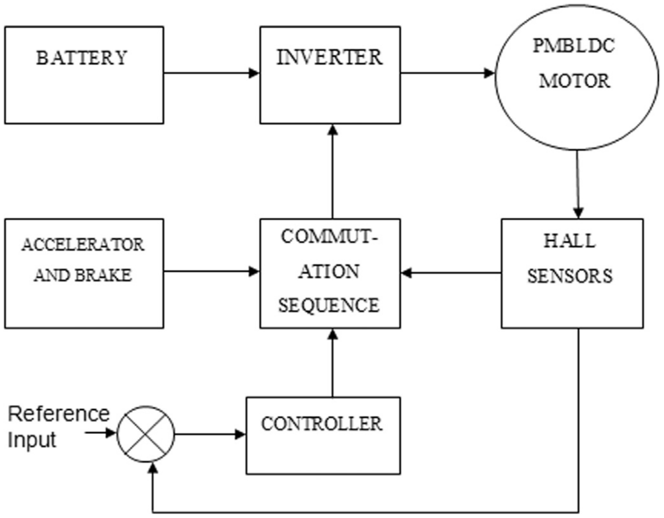


Fig. 17. Block diagram of closed loop control for electric vehicle.

The closed loop control system model of PMBLDC motor has been simulated using Matlab/ Simulink. In this model a PI control is been used in order to regulate the speed. The parameters of the PI controller are shown in Table 8. From the Simulink model of closed loop system of PMBLDC motor, a constant speed with increase of time with load is as shown in Fig. 20. The stability analysis of the PMBLDC motor is obtained from the derived transfer function equation and the stability plot is as shown in Fig. 21. Since the plot lies on the left and side of the S plane the motor is in stable state. The step response of the system is obtained from the derived transfer function [114]. The transient analysis of the motor without the controller is shown in Fig. 22. It is observed that without the controller the system takes 0.12 ms to settle down. In order to reduce the settling time and rise time a PI controller is cascaded with the PMBLDC motor system. The Fig. 23 shows the transient analysis with controller [115]. Table 9 shows the characteristics of the motor with and without controller for the step response. Performance analysis of the PMBLDC motor is as shown in Tables 10 and 11 respectively. Table 10 provides the readings of DC input, V_{dc}, input DC current I_{dc}, Motor input voltage V_{rms} and Motor input current I_{rms} respectively for different load conditions. The corresponding output readings namely speed (N) in RPM, Force (F) in Newton, Torque (T) in N-m, Power output of the motor (P_o) and Power input to the motor (P_{in}) in Watts and controller and motor efficiencies are as shown in Table 11.

From the case study of the stability analysis of the PMBLDC motor drive it is found that the special features of the proposed motor like arrangement of permanent magnets with outer rotor configuration and fractional number of slots per pole are capable of achieving high power density, high efficiency with elimination of cogging torque. It is found that design configuration with performance requirement of the EVs motor are different from that of the industrial drive motor. From the steady state and dynamic analysis it is found that the designed PMBLDC motor drive is suitable for EV application with high starting torque and high cruising speed.

4. Energy storage technologies for EV

4.1. Battery

The EPS requires two types of batteries namely deep-cycle group and high-power group. Deep-cycle group is mainly used for extended battery storage and requires deep discharging capabilities [116,117].

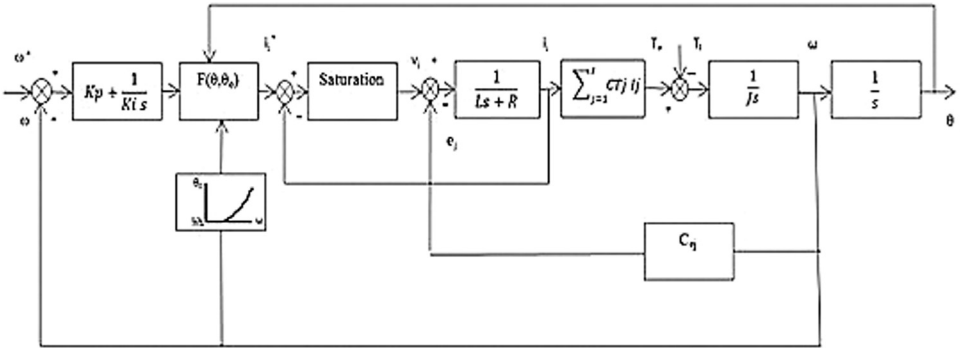


Fig. 18. Control block diagram of the PMBLDC motor.

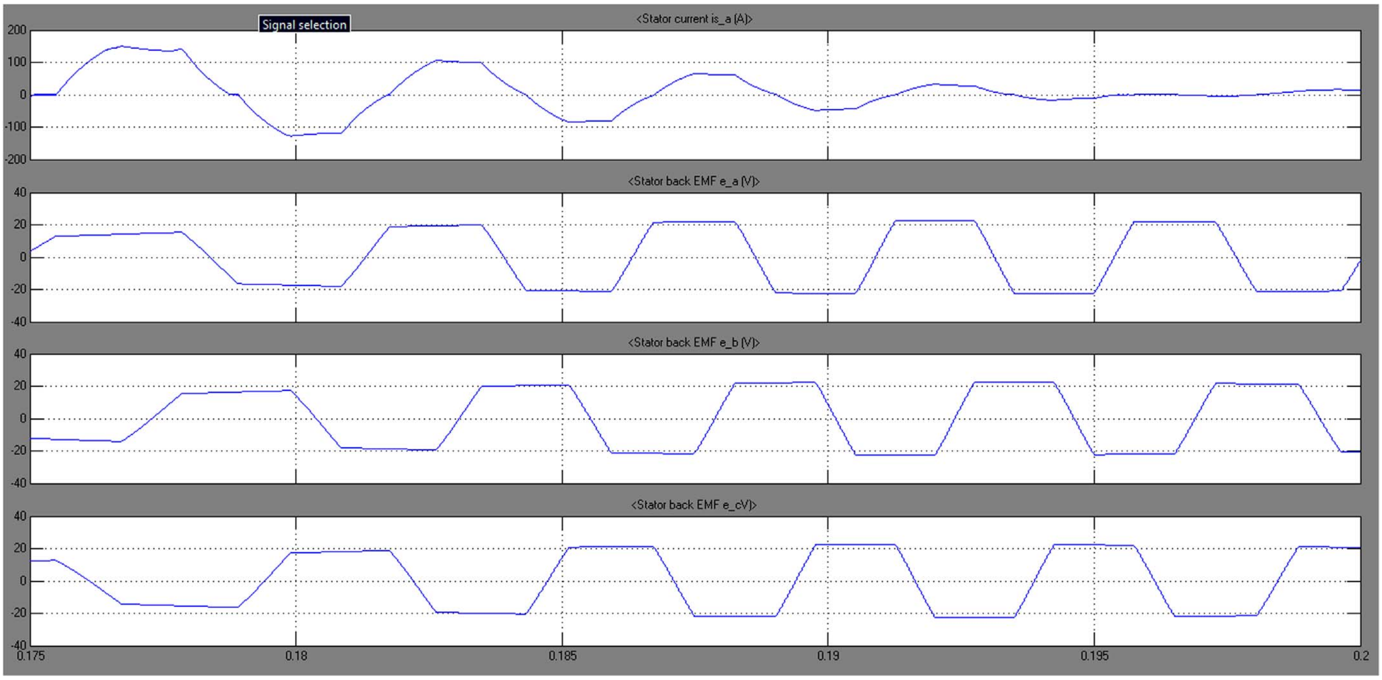


Fig. 19. Stator Current and Back-emf generated by the PMBLDC motor with respect to time.

The high-power group type of battery is mainly used in hybrid vehicular technology suitable for rapid discharge and swift multiple cycling.

The suitable batteries for EV propulsion system are described below.

4.1.1. *Lead acid battery*

The lead oxide is the positive active material, Soft lead acts as negative active material of the battery, and dilute sulfuric acid is the electrolyte. For discharging purpose, both materials are to be transformed into lead sulfate [118]. These are sealed batteries which come in different configurations, namely, gelled electrolyte, starved electrolyte and flooded electrolyte. The flooded type has higher energy density, long-term application and maintenance free, less expensive in comparing to the other configuration batteries and hence commonly used in EVs but clean-up and adding water are some of the drawbacks. Lead acid batteries were replaced by nickel based batteries [119].

Table 8
Parameters of the speed controller.

PI parameters	K_p	K_i
Values	2	666

4.1.2. *Nickel based battery*

The aqueous, room temperature batteries such as nickel iron (Ni-Fe), Nickel Cadmium (Ni-Cd) and Nickel-metal hydride (Ni-MH) finds higher advantages due to high peak power and higher energy density. Also these batteries are made of safe materials and are known as Sealed Maintenance Free (SMF) batteries.

Ni-MH batteries remove Cadmium from the negative electrode and lastly from entire cell. The positive electrode of Ni-MH battery is made up of nickel hydroxide and its negative electrode is made of an alloy of vanadium, titanium, nickel and other metals. The range of operating temperature of Ni-Cd batteries is superior.

Sodium-nickel chloride (Na–NiCL2) or ZEBRA (Zero Emissions Batteries Research Activity) batteries were introduced into EV field about the same time as Ni–MH battery. This type of battery uses sodium salt as electrolyte and has an (Ni–MH) and has very high operating temperature ranges from 245 to 350 °C. Because of high operating temperature stress on thermal management and safety concerns are the main issues of Sodium-nickel chloride (Na–NiCL2) or ZEBRA batteries [120].

4.1.3. *Nickel-Iron battery*

These types of batteries were invented by Thomas A Edison. These have iron as anode and nickel (III) oxide-hydroxide as cathode and, with potassium hydroxide as electrolyte. In lead acid batteries the

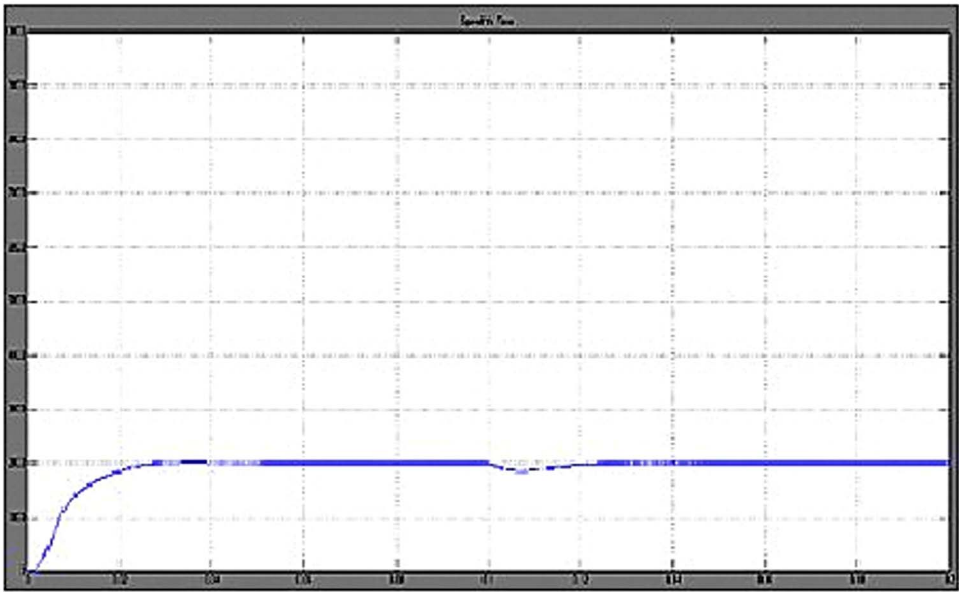


Fig. 20. Speed -Time for closed loop system.

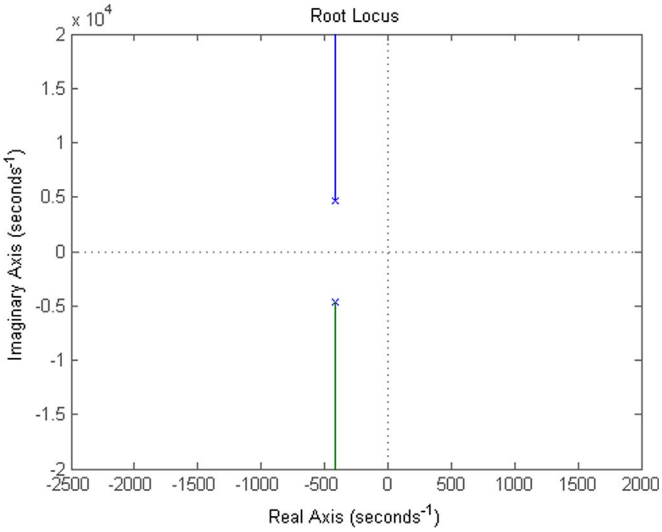


Fig. 21. Stability analysis using Root locus plot.

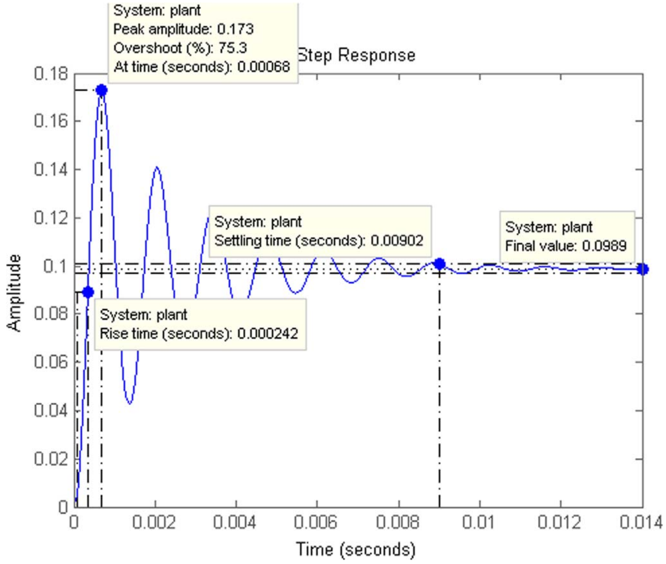


Fig. 22. Transient analysis of the motor without controller.

acidic electrolyte interacts with the plates during charging and discharging which leads the plates to shed-off and reducing the life of the battery, but in Nickel-Iron battery it does not occur. It is a very robust battery with very long life span. It is often used in backup situations where it can be continuously charged and can last for more than 20 years.

The disadvantages of nickel based batteries are efficiency of charge and discharge is less, self- discharge rate is high and operating performance in cold weather conditions is poor [121].

4.1.4. *Lithium based battery*

Presently the lithium content batteries are used in electric vehicle battery technology. The advantages of lithium- based batteries are very high energy density, fast charge, light weight, cost economic and non-toxic. The top electric vehicle manufacturing companies namely Mitsubishi i-MiEV, Tesla Model S and Chevrolet Volt and Nissan Leaf uses lithium based batteries and have invested heavily in this technology.

Types of lithium - based batteries are (a) lithium-ion (Li-ion) battery, (b) lithium-ion polymer (LiPo) battery and (c) lithium-iron phosphate (LiFePO4) battery. In lithium-ion (Li-ion) battery, positively charged lithium ions travel between the anode and the cathode in the electrolyte. It primarily uses graphite or silicon anodes and a liquid electrolyte. Drawback is lithium heats up and expands during charging, causing leaked lithium ions to build up on a battery's surface. These growths short-circuit the battery and decrease its overall life.

The positive electrode of this type of battery is composed of an oxidized cobalt material, the negative electrode is of carbon material and lithium salt in an organic solvent is the electrolyte. These batteries are of light weight, high efficiency and energy density. The self-discharge rate is of superior-quality.

Carbon nanotube electrodes increases the lithium battery capacity, the researchers at Massachusetts Institute of Technology have found that with the application of specially treated thin layer of carbon nanotubes in batteries can bring up the power delivery up to ten times which need still more researches and development. The electrode is fabricated with a layer-by-layer technique where the base material is dipped in the solution containing treated carbon nanotubes either to have slightly negative or slightly positive charge, when the two layers

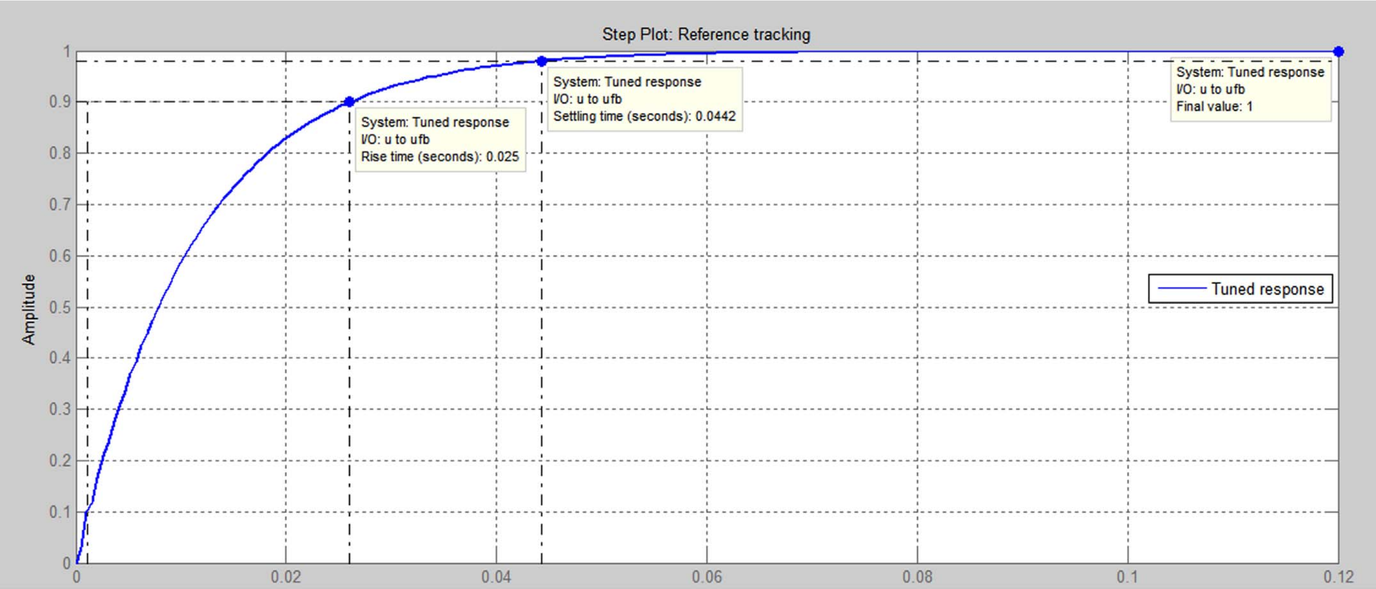


Fig. 23. Transient analysis of the motor with controller.

Table 9
Characteristics of the motor with and without control.

Specifications	Without controller	With controller
Rise Time	0.00178 s	0.001 s
Peak Over Shoot	82.6%	0%
Settling Time	0.12 s	9 ms

Table 10
Motor power controller readings.

Sl. No	V_{dc} (V)	I_{dc} (A)	V_{rms} (V)	I_{rms} (A)
1	48.1	9.2	37.0	7.5
2	48.2	10.0	35.9	8.1
3	48.2	10.5	35.8	8.1
4	48.0	11.5	37.0	10.0
5	48.1	12.8	37.0	11.6
6	48.2	13.5	36.0	13.0
7	48.0	15.5	36.2	15.8
8	46.8	21.0	35.0	20.1
9	44.9	21.6	33.0	20.1
10	48.1	9.2	37.0	7.5

Table 11
Motor drive output readings.

Sl. No	N (RPM)	F (N)	T (N-m)	P_0 of motor (W)	P_{in} to motor (W)	Controller η (%)	Motor η (%)
1	155	0	0	0	338.55	76.5	0
2	152	9.8	1.17	18.71	354.76	73.6	05.20
3	150	19.6	2.35	36.94	353.77	69.9	10.44
4	148	49	5.88	91.13	370.00	67.02	24.62
5	140	98	11.76	172.41	429.20	69.71	40.10
6	142	147	17.64	262.31	570.96	87.74	45.94
7	133	196	23.52	327.58	571.96	76.87	57.17
8	110	294	35.28	406.40	703.50	71.58	57.76
9	101	343	41.16	435.33	663.3	68.39	65.50
10	155	0	0	0	338.55	76.5	0

are brought together, the magnetic forces of opposite sides pulls each other with self-assembling of the electrodes, thus these batteries can be subjected to thousands of charge-discharge cycles. Present inventions found the electrodes with few microns but with development still thinner electrodes are desirable for better performance.

Lithium-iron phosphate (LiFePO4) battery has high power density, more life cycle and better safety and the disadvantage of lesser energy density when compared to Li-ion battery [122]. The limitations of lithium-based batteries are fire risk and explosion during malfunction of the battery [123]. Battery technologies in the experimental stage are (a) lithium–sulfur (Li–S) battery, (b) zinc-air (Zn-air) battery and (c) lithium-air (Li-air) battery. These batteries offer better quality performance [124].

4.1.5. Silicon air battery

The Technion-Israel Institute of Technology has developed an eco-friendly silicon-air battery which is capable of deliver non-stop power for thousands of hours without replacement. These batteries are made from oxygen and silicon. The materials used are non-toxic, safe, and stable. The built-in cathode is eliminated in this type of battery hence cost and weight is reduced. This made the battery more suitable for electric vehicle. The special features of Silicon-air batteries are unlimited shelf-life, high tolerance for humid and dry conditions. It is estimated that within four years silicon air battery can be built commercially and applied for electric vehicular propulsion system.

Table 12 shows the emerging battery technologies and characteristics [125–128]. The battery characteristics such as nominal voltage (V), energy density(Wh/kg), specific power (W/kg), life cycle, percentage of self-discharge per month, operating temperature and production cost ($/kWh) have been provided.

Technology development in batteries will not only transform the transportation industry, but it would also significantly affect global energy markets. The combination of batteries with renewable energy sources would drastically reduce the need for oil, gas, and coal. In spite of the existing deficiency of batteries, the potential global impact that even comparatively reasonable improvements can have is amazing.

4.2. Fuel cell

The electric vehicle using fuel cell instead of battery is called fuel cell electric vehicle in which electricity to power the wheels of vehicle is supplied by fuel cell. But a battery must be recharged once all the fuel is reacted; a fuel cell is a refillable battery [129–131]. The fuel cell generates power from the fuel on the anode and oxidant on the cathode and the reaction takes place in the presence of electrolyte. The reactants flows into the cell during the process of generation mean

Table 12
Comparative chart of electric vehicle batteries.

Type of Battery	Nominal voltage (V)	Energy density (Wh/kg)	Specific power (W/kg)	Life cycle	Self discharge (% per month)	Operating temperature (°C)	Production cost ($/kWh)
Lead acid (Pb-acid)	2.0	35	180	1000	< 5	−15 to +50	60
Nickel- cadmium (Ni-Cd)	1.2	50–80	200	2000	10	−20 to +50	250–300
Nickel- metal hydride (Ni-MH)	1.2	70–95	200–300	< 3000	20	−20 to +60	200–250
Nickel- iron (Ni-Fe)	1.2	60	100–150	2000	20	−10 to +50	150–200
ZEBRA	2.6	90–120	155	> 1200	< 5	−245 to +350	230–345
Lithium-ion (Li-ion)	3.6	118–250	200–430	2000	< 5	−20 to 60	150
Lithium-ion polymer (LiPo)	3.7	130–225	260–450	> 1200	< 5	−20 to 60	150
Lithium-iron phosphate (LiFePO4)	3.2	120	2000–4500	> 1200	< 5	−45 to 70	350
Zinc-air (Zn-air)	1.6	460	80–140	200	< 5	−10 to 55	90–120
Lithium-sulfur (Li-S)	2.5	350–650	–	300	8–15	−60 to 60	100–150
Lithium-air (Li-air)	2.9	1300–2000	–	100	< 5	−10 to 70	–
Ultra capacitor – Double layer capacitor	–	5–7	1–2 M	40 years	–	–	–
Lead acid (Pb-acid)	2.0	35	180	1000	< 5	−15 to +50	60
Nickel- cadmium (Ni-Cd)	1.2	50–80	200	2000	10	−20 to +50	250–300
Nickel- metal hydride (Ni-MH)	1.2	70–95	200–300	< 3000	20	−20 to +60	200–250
Nickel- iron (Ni-Fe)	1.2	60	100–150	2000	20	−10 to +50	150–200
ZEBRA	2.6	90–120	155	> 1200	< 5	−245 to +350	230–345
Lithium-ion (Li-ion)	3.6	118–250	200–430	2000	< 5	−20 to 60	150
Lithium-ion polymer (LiPo)	3.7	130–225	260–450	> 1200	< 5	−20 to 60	150
Lithium-iron phosphate (LiFePO4)	3.2	120	2000–4500	> 1200	< 5	−45 to 70	350
Zinc-air (Zn-air)	1.6	460	80–140	200	< 5	−10 to 55	90–120
Lithium-sulfur (Li-S)	2.5	350–650	–	300	8–15	−60 to 60	100–150
Lithium-air (Li-air)	2.9	1300–2000	–	100	< 5	−10 to 70	–
Ultra capacitor – Double layer capacitor	–	5–7	1–2 M	40 years	–	–	–

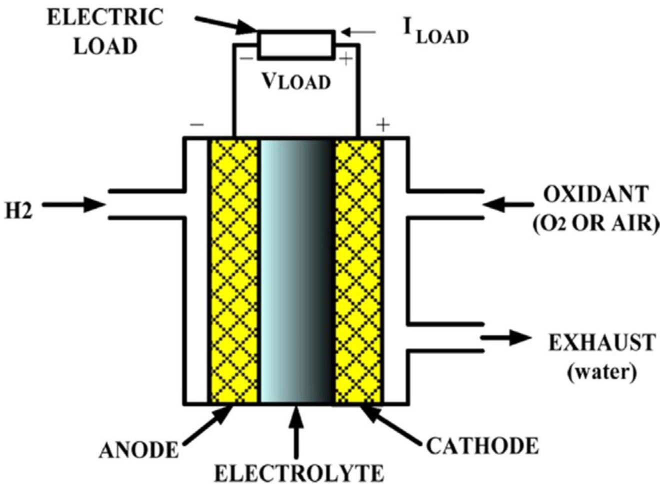


Fig. 24. Arrangement of a hydrogen FC.

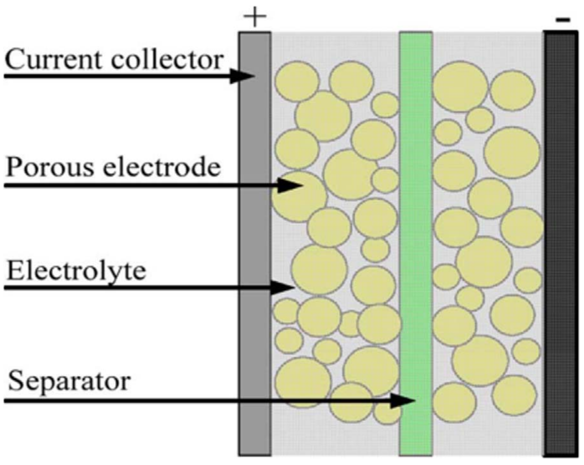


Fig. 25. Internal arrangement of an ultra-capacitor cell.

while the products flows out, the generation continues as far as the process is maintained. The major advantage of fuel cell is higher efficiency in conversion, quit operation, fuel flexibility, durability and reliability.

Various combinations of fuel and oxidant is possible, hydrogen is a non-polluting fuel for fuel cell that after reaction it liberates water and it has the highest energy density. Other fuels are hydro-carbons and alcohols and oxidants being chlorine and chlorine oxide. The efficiency of the fuel cell depends on the power drawn, higher the power drawn, lower is the efficiency. Losses occur due to the voltage drop on the internal resistance and the fuel cells have relatively longer response

Table 13
Energy Storage System (ESS) specifications required for various types of vehicles.

Electric Vehicle (EV) Types [19]	System voltage (V)	Battery (kWh)	Ultra Capacitor (UC) Energy (W h)	Fuel cell (FC) Energy (kW h)	Electric Motor (EM) (kW)
Conventional ICE	12	–	–	–	–
Micro-Hybrid EV	12–42	0.02–0.05	30	–	3–5
Mild-Hybrid EV [13]	150–200	0.125–1.2	100–150	–	7–12
Full-Hybrid EV [20]	200–250	1.4–4	100–200	–	40
Plug in Hybrid EV [21,22]	300–500	6–20	100–200	–	30–70
All EV [22]	300–500	20–40	300	150–200	50–100

time [132]. Also, fuel cells are more expensive than the other batteries. Fig. 24 shows the arrangement of a hydrogen fuel cell.

Heat and water are the byproduct of FC. Hence fuel cell technology reduces the dependence of oil resources and hazardous CO_2 emissions [133,134]. Types of fuel cells are Direct Methanol Fuel Cells (DMFC), Proton Exchange Membrane Fuel Cells (PEMFC), Alkaline Electrolyte Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cells (SOFC) [135]. Because of fast recharge, high energy capacity and low operating temperature DMFC are currently used in portable electronic items such as mobile phones, tablet, laptop, etc. Methanol has energy density of 4390 Wh/L when compared with a Li-ion battery with an energy density of 620 Wh/L. DMFC, PEMFC, AFC and PAFC are classified as in low operating temperature fuel cell and re presently used in electric vehicle application such as Citaro fuel cell bus and Honda FCX Clarity (passenger vehicle). The MCFC and SOFC are high operating temperature fuel cell, which are normally used in electric utility and distributed generation due to its high power output. The main advantage of the fuel cell in electric vehicle application is the capability of operating in high efficiency, low emissions, silence, and the FC system is simple [136].

4.3. Flywheel

Flywheel is a device that stores and delivers the energy in the mechanical motion due to size and weight problem, the use is being reduced in electrical vehicle application as these require minimal size and weight [137]. Flywheel energy storage takes place when flywheel is accelerated to high speed and rotational energy is maintained. As and when the energy in the flywheel is extracted, the rotational speed reduces as a consequence of principle of conservation of energy. The energy storage in flywheel is directly proportional to its mass and square proportional to velocity from supply and delivers to the load as per the requirement [138].

Due to the advancement in bearing, carbon-fiber composite materials, micro-electronics and controls has made the wide application of flywheel [139]. As a result of these improvements numerous advantages are added to this category i.e., efficiency, reliability, high speed at lower weight and size, thus made the storage system more suitable for electric vehicular propulsion system. The recent flywheels can store more power and energy when compared to the conventional batteries. These are independent of in-depth discharge thus does not alter the life cycle of the system.

There are two types of Flywheel energy technologies, (a) kinetic energy (rotational energy) as output and (b) electric energy as output energy. According to the business manager from Torotrak, the energy efficiency from braking to flywheel energy storage is 70% which is the double of the efficiency of energy transformed from braking to electric energy and then to flywheel energy storage [140]. If magnetic bearings and vacuum are used then overall mechanical efficiency of the flywheel energy storage can increase up to 97% and round-trip efficiency up to 85%. Presently, research agencies (such as Lawrence Livermore National Laboratory (LLNL) in US, Ashman Technology, AVCON, Northrop Grumman, Power R & D, Rocketdyne /Rockwell Trinity Flywheel US Flywheel Systems, Power Center at UT Austin and so on) have developed an ultra-high-speed flywheel system for electric vehicle. Typically, the system can achieve 10–150 Wh/kg energy and 2–10 kW/kg power. For example, LLNL built a proto type which can achieve 60,000 rpm, 1 kWh and 100 kW in a 20 cm diameter and a 30 cm height. Compared to Ultra Capacitor (UC), flywheel energy storage has a higher energy density and power density. But the disadvantages are the safety issues and gyroscopic forces [141,142].

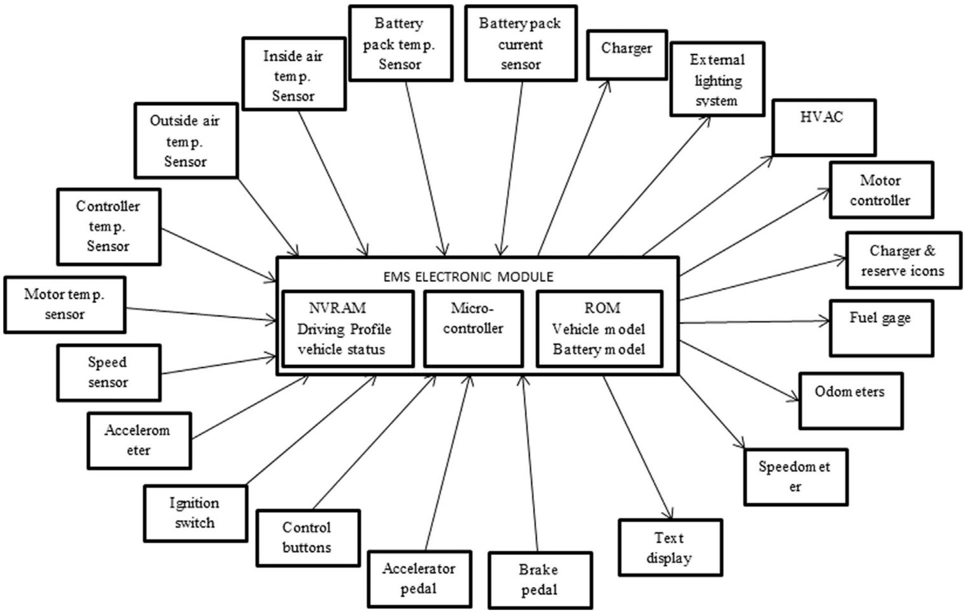


Fig. 26. Block diagram of energy management system.

The advantages are swift power response and less recharge time, minimum maintenance, longer life of more than 15 years, wide operating temperature and minimum damage to the environment [143,144].

4.4. Hybrid energy system

The battery and fuel energy systems have high specific energy but less specific power when compared to flywheel. It can be said that apart from energy density, voltage and current characteristics of the different energy storage system are different. Combination of the energy system with proper calculation and placing can improve the performance of the system [145]. This condition is called hybrid energy system. The combination depends on the type of vehicle and the required output.

With the combination of storage system, both energy density and power density could be enhanced. The application of only system for higher power density like flywheel increases the cost, weight and size but with combination, the problem could be solved. The overall efficiency, reliability, durability can be improved with this storage system and also concern the cost and weight [146–148].

4.5. Ultra capacitor

The Ultra Capacitor is an energy storage device. It stores energy by actually separating positive and negative charges. The charges are stored on two parallel plates separated by an insulator. The applied potential on the positive electrode attracts the negative ions in the electrolyte, whereas the potential on the negative electrode attracts positive ions. Fig. 25 shows the arrangement of an ultra-capacitor cell.

The Ultra Capacitor (UC) has long life and its power density is greater than that of the battery because the charges are stored physically on the electrodes. Also terminal voltage of UC is directly proportional to the State of Charge (SOC) [149]. Further the advancements and developments in the field of micro-electronics and control makes the UC to operate at variable voltage range. UC is used as a secondary energy storage device for HEVs. Because of their fast charging and discharging rates, in EVs they are useful in regenerative braking and swift discharge of power during acceleration.

There are five types of UC technologies in development, namely: (a) Carbon/metal fiber composites, (b) Foamed carbon, (c) Carbon particulate with a binder, (d) Doped conducting polymer films on a carbon cloth, and (e) Mixed metal oxide coatings on a metal foil. Also researchers are exploring the different type of techniques to further increase the surface area of the electrodes such that energy storage handling capacity of the UC can be further increased [150].

Ultra capacitor (UC) or super capacitor has high capacitance (high energy capacity with factor of 20 times) than the standard capacitor. Its characteristics are maintenance - free operation, longer operation cycle life and in sensitive to environment temperature variation. Table 13 shows the Energy Storage System (ESS) specifications required for various types of vehicles [151–156].

5. Smart energy management system

Satisfactory performance of the EVs depends upon the utilization of maximum power and supervision of the power capacity. Functional block diagram of Energy management System (EMS) is shown in Fig. 26. This EMS system make use of sensor signal inputs from the subsystems of the EVs to achieve standard driving profile, controls the power requirement of the subsystems of the EVs, and thereby proposes energy efficient driving techniques, Directs the regenerated braking power from to energy storage system, necessary signal for battery charging and light intensity of the EV etc. Also when EMS coupled with navigation system suggests safety and energy efficient routes on the basis of road traffic and its status [157–159].

6. Commercial aspects to populate the electric vehicle in rural area

Presently global community is aware of conventional fuel crisis and its ever increasing fuel cost. Hence there is lot of opportunities for EVs development and commercialization. This is possible with few minor mandatory changes by the statutory bodies will ease in reaching the people more effectively and also efficiency standards can be upgrade to IE 3 and further to IE 4.

Two wheeler vehicles are popular for short distance commutes Most of the time, about 80–90% of the rider travel with another seat empty. One person ride two wheeler electric scooter will have high speed and high torque compared to two person ride electric scooter. Presently commercial automotive vehicles have high speed and high torque and battery operated electric scooters are now considered as the alternative for bicycles. The low speed, low torque and high initial costs are the main demerits in popularizing the electric scooter. If high speed, wide range, high torque and low initial costs EVs are developed which will be in par with ICEs then undoubtedly EVs can be popularized there by it can contribute to the conventional fuel crisis.

Safety: The fire hazardous and highly inflammable industries like chemical, explosive and petroleum battery operated EVs can be utilized.

Air Pollution: The food processing and pharmaceutical industries in which the process has be carried in complete air conditioning environment without gas emissions, the EVs can be used for transportations.

Noise Pollution: EVs are also useful at hospitals, wildlife sanctuaries and Holiday resorts, where patients, tourists and people are expected to maintain peace and calm without any delay for transport.

Hence from safety, air and noise pollution point of view EVs can also be popularize in the above mentioned Industries and customer places.

6.1. Benefits of electric vehicle

Since EVs are used in day time and the batteries are charged during off-peak hours of night, the generated power during days can be used for the development of renewable energy sources. Electric Vehicle works at higher efficiency compared to conventional IC engine vehicle. EVs reduce air pollution and global warming problems with no emissions during their use. Use of renewable energy sources in the EVs systems reduces the use of depleting fossil fuels. The EVs provide flexibility in terms of use of primary energy as long as electricity is produced from any primarily energy sources and preferably renewables.

7. Conclusions

Development Scheme and Key Technology of an Electric Vehicle is discussed in this paper. The electric vehicle design philosophy, its motor drive operating conditions and the desired performances are different from that of standard industrial drives. Electric vehicle technology is an interdisciplinary technology. It is found from the review that for the enhancement of the performance of the electric vehicle the state of art technologies are to be selected from electrical, electronics, automobile and material engineering. Electric vehicle technology including EPS and Energy storage systems has been reviewed. Electrical propulsion system design should be more flexible and user friendly. PMBLDC motors have high power density when compared with that of other AC motor drives. Poly phase, multipole PMBLDC motor configuration has short winding lengths as a result there will be reduction in copper, decrease in copper loss. It also has short magnetic circuit length; hence height of the yoke and volume of the motor is reduced. Cogging torque is eliminated by making use of fractional number of slots/pole/phase. It is found that advanced

PMBLDC motor with novel microelectronics and control technique along with the advanced batteries are progressively being acknowledged.

Microelectronics and control technique is emerged to provide intelligent algorithm for high dynamic performance of the drive. This new intelligent control algorithm is useful in increasing the speed range of the PMBLDC motor over constant power region. The design such as saving in weight, saving in energy, reliability and good safety are to be adopted in modern electric vehicles. Smart Energy Management System of the EV is vital in order to attain the desired performance of the EV by monitoring the energy capacity and increasing the usage of energy and hence suggest energy efficient driving behavior. It is viewed that Fuel cells has high energy efficiency. Hence, Fuel cells are considered as a likely technology to overcome the drawbacks of electric vehicle such as long recharge time and short range per charge. It is confirmed that Electric vehicle is zero emission, highly energy efficient alternative urban transportation system. For promoting the EV, standardization and infrastructure developments are necessary. Finally, it is viewed that PMBLDC motor drive has high power density, high efficiency and first-rate dynamic performance compared to any other motor drive and is best suitable for Electric Vehicles.

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