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Chapter 3
Analysis of the Different Types of Electric Motors Used in Electric Vehicles

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1 Introduction

The principle supply of electricity in an electric vehicle is the electric powered strength that proves to be an impetus part of the development of electric vehicles in the automobile industry. This electrical strength is focused on the electric-powered vehicle wherein it is converted into mechanical energy in the form of rotations. This strength is carried forward to the wheels of the vehicle using an optimal transmitting device, enabling movement of the vehicle. The electric motor serves as the backbone of the electric vehicle, providing the power to drive. Depending on the type of electric vehicle and its functionality, an electric motor is chosen. Electric vehicles might ignite DC/AC [1] motors based on the configuration or dependent on the utilization of the electric vehicle. An electric motor is a mandatory part of any electric vehicle. This has paved the way to creating a large market for electric vehicle parts [2], primarily the motors [3], which contribute toward improving the performance and affordability of the vehicle. In 2013, 44.6 million electric motors were required for building electric vehicles while in 2023, about 129 million electric vehicles are estimated to be used and 158.8 million

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are expected to be used in 2023 [4]. The motors that are generally used today in air and through water are mostly brushless since the exit of DC brushed motors. The importance of brushless traction motors is indicated by the sinusoidal output with permanent magnet AC [5] and the trapezoidal output in the brushless DC motor. However, both motors show outstanding performance with the inclusion of additive measures like regenerative and reverse braking. These dynamics have however been shaken due to the in-wheel motors that are used in today's large vehicles (electric vehicles) [6] to make movement simple, comfortable, and adaptable. In today's scenario, the average money used on electric motors in electric vehicles deal with the use of smaller motors in smaller vehicles such as the mobile household robots built in Japan, power chairs for the disabled, and mobility scooters that are commonly used in the United States and Europe, two-wheelers in China, sea scooters, motorized lifters and stair walkers, walkies (popularly used in Japan as golf caddies), golf-cars, go-karts, all-terrain vehicles (ATVs), and tiny quad bikes [7]. These small vehicles require about 60% traction motors that are available in the market. However, with the increase in larger electric vehicles, the market for electric motors [8] has also increased substantially. In the near future, these electric vehicles powered by electric motors will dominate the streets, replacing the age-old fuel-based vehicles [9].

For example, as the military decides to buy battlefield hybrids instead of the stereotype electric tools, the value for military electric vehicles begins to increase many-fold [10]. Another example is executed in China where hybrid versions of buses are bought, in line with the national transportation system resulting in a higher market value. Similarly, the electric vehicle market is bound to grow leaps and bounds in the years ahead, leading to a demand for traction motors [11]. The electric motors that are used in electric vehicles are reaching higher values of torque and power. A low-cost electric bike will be utilizing a 0.25 kW motor, cars will require a power of 70 kW per motor while a large bus or forklift will need a motor with 250–350 kW and an AUV will require 400 kW [11]. By and large, the torque for the motor will be about 6000 Nm though only about 0.4 Nm of torque will be required by most vehicles used by the disabled. Based on the analysis of asynchronous motors, it has been observed that about 52% of buses use this motor apart from about 65% of military vehicles. One of the biggest vehicle builders [12], Toyota, uses asynchronous motors for many of its buses and forklifts.

An electric vehicle motor works based on a physical process introduced during the 1900s [13]. It is made up of a stator (fixed part of the motor) and rotor (rotating part of the motor) which operates in a magnetic field created, using current. There are two terms that are used in an interchangeable fashion: "Motor" and "Engine." It is crucial to know the difference between the two as used in the automotive industry. An engine refers to a machine that converts thermal energy into mechanical energy while a motor refers to the machine that converts energy into mechanical energy [14]. Since thermal energy is involved in an engine, it refers to the process of combustion. This means that an engine is also one type of motor although not all motors are engines. In motors, electricity is used to create mechanical energy [15] that drives the electric vehicle. Similarly, electric motors also find application in many devices. When it uses Direct Current (DC) [16], it can perform certain basic operations. In this case, the motor is directly connected to the source of energy and subsequently, the speed of rotation will depend on the intensity of the current. Though these motors enable easy rotation, they cannot produce the required amount of power, are unreliable, and relatively large to be used in an electric vehicle [17]. However, they find application in devices such as windows, windshield wipers, and other similar simpler mechanisms used in the car.

2 Electric Motor in Electric Vehicle

2.1 Progress of the Electric Motors

In [18], Thanh Anh Huynh analyzed some traction motors to determine the thermal execution and electromagnetic field generation. The motor examination was performed using two driving cycles: one for freeway driving and the other for urban driving. Assessment of electromagnetic execution took place using the flux weakening capacity and the estimation of torque output for accelerating vehicle speed. Similarly, in [19], the authors have discussed the different machine techniques that are used such as DC, switched reluctance, permanent magnet, and induction machine techniques for high-speed traction implementation. Based on the HST zone, correlation varies with respect to power density, fault torque, proficiency, quality, cost, and adaptability to non-critical failure capacity. Dr. Sab Safi in [20] has determined that critical research is carried out in HEVs and EVs due to the need for ecological vehicles to effectively utilize power. In his research work, Dr. Sab Safi has contemplated the idea of using induction machines instead of PMSMs. He also found that some portions of the IM are related to SRM and PM synchronous machines. Authors in [21] observed the capacity of the motor to save energy by decreasing the power loss using wheel torque designation. Loss of power in slope steer move as well as when driving straight occurs for different motors along with power loss for different wheel torque are investigated using identical methods. In [22] Juan de Santiago and other researchers have examined the drivelines of the various electric vehicles (EVs). In his work, the author has discussed the different EVs and the choice of the motor based on the type of framework used. The authors of [23] show the use of electric motors and their applications in hybrid electric vehicles by means of the outcome. In 2009, Gianmario Pellegrino [24] introduced three electric traction motors that had high proficiency and power with respect to inverter estimate and drift measurements. Based on the vehicle, internal permanent magnet (IPM), surface mounted permanent magnet, and inductor motors are analyzed.

2.2 Working of an Electric Motor

For easy understanding of the electric motor consider a 4-pole 3-phase AC induction motor [25]. The motor is connected to a battery which supplies electrical energy to the stator. A typical magnet is concocted with the help of a stator using the coils arranged in the core's opposite sides. Hence, when the battery supplies electrical energy the coils in the motor create a magnetic field that is capable of tugging the conducting rod at the rotor outside. This enables the rotor to spin, creating the necessary mechanical energy that turns the gears resulting in a tire rotation. In general, a non-electric vehicle will contain both an alternator and an engine. It works in a cycle wherein the wheels and gears are powered by the engine which in turn is powered by the battery [26]. The alternator present in non-electric vehicles is powered by the rotation of the wheels and will contribute to recharge the battery. This is also the reason why a small electric vehicle like a car that remains idle for a prolonged period of time needs to be jumped, i.e., the battery needs to be recharged for the car to start properly. However, there is no alternator in an electric car. Then how does the battery recharge? Though an electric vehicle does not have an alternator, the electric motor will act as both the alternator and a motor. An alternating current characterizes electricity using a variation of current and voltage with respect to time. The alternating nature of a typical AC signal results in stepped-up or stepped-down voltage at different time intervals. This makes the use of an AC motor unique in an electric vehicle. As mentioned earlier the motor is started using the battery which passes this energy to the gear, enabling rotation of the tires. This process is initiated when the driver steps on the accelerator, initiating the rotor to move with respect to the rotating magnetic field. However, when the foot is removed from the accelerator, the rotating magnetic field stops and the rotor begins to decrease its speed of rotation, contrary to stopping along with the magnetic field [27]. Thus the battery is recharged by the motion of the rotor to spin quicker than that of the magnetic field, making it behave as an alternator.

2.3 Alternating Current or Direct Current

The basic difference between the two currents is a known fact: while one is consistent (DC), the other is intermittent (AC) [28]. However, when choosing an electric motor, there are more factors that need to be taken into consideration.

- Direct current: The direct current is a unidirectional and constant flow of electricity when the polarity of the voltage is maintained with respect to time. For example, the positive and negative poles are marked in a battery. A unidirectional current is produced using the constant potential difference. Apart from batteries, solar and fuel cells also produce direct current.
- Alternating current: An alternating current characterizes electricity based on the variation of current and voltage following a sinusoidal pattern. Because of the

shape of the waveform, both current as well as voltage alternates between negative and positive polarity, with respect to time. This shape of the waveform also indicates the generation of electricity.

The best choice among these two forms of current for transferring useable energy over a large distance is AC electricity.

2.4 Hierarchy of Electric Motors

The hierarchy of electric motors is represented in Fig. 3.1. wherein the EVs are generally classified according to the presence and absence of commutators.

2.5 Electric Vehicle Industries and the Environment

As the performance of the electric motors improves, the performance of electric vehicles also elevates substantially so much so that they outperform their counterparts. Though the use of electric cars is not as prominent as expected, the exploration of various companies like Toyota and Tesla has instilled hope for the future of transportation with electric motors at the core. Companies like Alphabet, US Cobalt, Tesla Motors Inc., Albermarle, and Ford motors are some of the renowned companies that have revolutionized electric vehicles all around the world. Electric engines

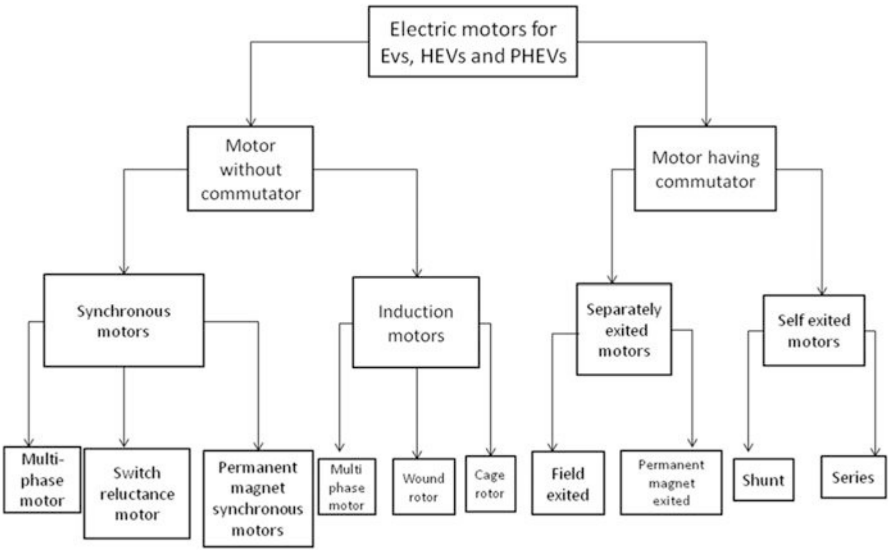

Fig. 3.1 Hierarchy of electric motors

have a direct as well as an indirect impact on the environment. The invention of electric cars has liberated buses from the use of gasoline and fuel-based cars resulting in a pollution-free atmosphere across the highways and cities. It resolves the strain of toxins in the air due to harmful emissions [29]. However, this in turn has created an additional problem of electricity production demand. Since electric engines do not emit much noise when compared with other gas or fuel-powered engines, it results in a significant reduction in noise pollution. Similarly, maintenance, as well as lubricants expense for a typical motor, is not essential for an electric motor, saving oils and chemicals used at the auto-shops.

3 Motors in Electric Vehicles

In general, most of the electric cars that are in use today operate using DC motors with a power of 4 kW or lesser. For Electric Vehicles that use advanced power, the induction motor serves as an apt choice of AC motor. Normally a vector drive is used to provide acceleration and torque management. A Brushless DC (BLDC) motor is commonly used in low power applications. Almost all EVs use batteries as the primary energy depository system. In recent years, a vast amount of research is being carried out in using in-battery improvements (such as lithium particles) for electric vehicle. The motors used, show diverse characteristics which make it crucial to assess the different motors based on certain guidelines to help determine the apt motor that can be used for the EV [30]. Electric vehicles use electric motors that possess important characteristics such as great control, low upkeep cost, high vitality, and easy plan. In general, the motors that are used by the EV manufacturers are Permanent Magnet Brushless Motors, Switched reluctance motors, Synchronous motors, Induction Motors, and DC motors. Table 3.1 gives an overview of the motors used in different electric vehicles built over the years.

Table 3.1 Motors used in electric vehicles

Product Name	Manufacturer	Types	Year
Toyota Prius	Toyota	Permanent magnet motor	1997
Tesla Model S	Tesla	Induction motor	2012
Fiat 500e	Fiat	Permanent magnet motor	2014
Volkswagen Golf Electric	Volkswagen	Permanent magnet motor	2014
Nissan Leaf	Nissan	Permanent magnet synchronous motor	2017
Mitsubishi i-MiEV ES	Mitsubishi	Permanent magnet synchronous motor	2017
Focus Electric	Ford	Permanent magnet motor	2018
Chevrolet Bolt EV	Chevrolet	Permanent magnet motor	2018
Audi E-Tron	Audi	Permanent magnet synchronous motor	2019
Kia Niro	Kia	AC synchronous permanent magnet	2020
Nissan Leaf	Nissan	Permanent magnet motor	2021

3.1 Direct Current Motors

The DC motors or Brushed DC motors were widely used during the 1990s. Brushed DC motors have the ability to have a high torque value at low velocities, resulting in appropriate output. But, this brushed DC motor has poor power density making it unsuitable to be used in electric vehicles. On the other hand, the use of a brushless DC motor will prove to be less maintenance and better efficiency. A Direct Current (DC) drive is used conspicuously in electric vehicles because of its impeccable torque speed and control over speed. There are two sections aligned using excursion motor namely: motors without communication and switching motors. A typical switching motor is a DC motor that uses both shunt and series excitation. They are also great contenders for applications that require low power. In a DC motor, the commutator acts as a strong inverter and is hence recommended to be used in gadgets, as they are economic and simple to build. However, the major drawback when using this motor is the high maintenance caused by both the commutators and brushes (hence also knows as Brushed DC Motors). The DC motors are still used in the Indian Railways.

3.2 Induction Motors

In general electric vehicles make use of three-phase induction motors because of their great speed control, high proficiency, and absence of a commutator. The three-phase AC supply is related to the winding of the stator which results in the development of a rotating magnetic field. The lack of a commutator has resulted in the maintenance-free tasks as well as high reliability and hence this motor is ideal for electric vehicles. Moreover, to uplift the dynamic execution of the electric drive framework, vector control is utilized in this motor. This inclusion provides a variety of speed range when using this motor. Overall, the three-phase AC induction motor (IM) is low accelerated and leads to better productivity and quality.

3.3 Permanent Magnet Synchronous (PMS) Motors

In general, the rotor moves at a synchronous speed in a synchronous motor. Though the stator uses a three-phase AC supply the rotor is powered by a DC supply. Brushless AC motors are commonly called permanent magnet synchronous (PMS) motors. In terms of vitality productivity, the PMS motor is found to be more effective and is comparable to that of the induction motor. Many renowned electric vehicle makers like Toyota, Honda, and Nissan have chosen PMS motors for their efficiency and effectiveness. Powerful dissemination of warmth, higher proficiency, and higher power thickness are some of the promising aspects of this motor. Due to the immense energy thickness of the magnets, agitation is confined to a smaller space resulting in higher profits for the machine. Since excitation current is not necessary it is possible to improve the speed proficiently. The losses involved while using the PMS motors are iron losses which can be easily overcome using an air conditioning framework. Thus PMS motors are found to be more efficient than induction motors in terms of productivity and control thickness. The biggest drawback is the cost of NdFeB in the magnets used in the motor. Another aspect of weakness is the requirement for additional current segment used for field debilitating, which results in lower productivity at large speeds and losses at the stator.

3.4 Permanent Magnet Brushless DC and AC Motors

Another type of motor that can be used in electric vehicles is the permanent magnet brushless DC (PM-BLDC) motor. These motors are used for many purposes by transforming the rotor and stator of the permanent magnet DC motor. Though this motor's setup is similar to that of a permanent magnet synchronous motor, the BLDC motor is powered by an AC supply with a waveform that is rectangular instead of the typical sinusoidal shape. The major advantage of the PM-BLDC motor is its ability to provide higher torque in line with voltage and current level. Because of these characteristics, the PM BLDC motor proves to be a compatible electric vehicle motor.

3.5 Switched Reluctance Motor (SRM)

The SRMs make use of the switching of rotor position to align the different phase windings in a sequence. It is possible to develop a wide speed using this methodology. Torque is induced in this manner based on the movement of the rotor toward the slightest reluctance. SRM is used in electric vehicles due to its ability to adapt in times of failure and large beginning torque.

3.6 Comparison of All the Motors Used in EVs and HEVs

The motors that are used in the electric motors are compared in Table 3.2 based on their power, efficiency, and other characteristics to determine the best electric motor based on the vehicle.

Table 3.2 A comparison of the motors using EVs and HEVs

	Induction motor	Switched reluctance motors	Permanent magnet motors	Brushless DC motors
Type	AC	AC	DC	AC
Family	Induction slip ring squirrel cage	Synchronous unexcited	Separately excited	Synchronous excited PM
Power to stator	AC	Pulsed DC	PM	Pulsed DC
Power to rotor	Induced	Induced	DC	PM
Weight	Medium	Medium	Medium	Low
Overall	Medium	Medium	Medium	High
Commutation method	External electronic	External electronic	Mechanical commutation	Internal electronic
Controller cost	High	High	Medium	Very high
Speed range	Controllable	Controllable	Limited by brushes, easy control	Excellent
Starting torque	High	Up to 200% of the rated torque	>200% of the rated torque	>175% of the rated torque
Speed control method	Frequency dependent	Frequency dependent	PWM	Frequency dependent
Maintenance requirement	Low	Low	Brushes wear	Low
Efficiency	High	Less than PMDC	High	High
Application	ICVs, EVs, and HEVs	ICVs	ICVs, EVs, and HEVs	ICVs, EVs, and HEVs
Efficiency with motor and power	85	86	91	79
Efficiency with power electronic devices only	94	91	94	98.5
Efficiency with motors only	91	95	97.5	81
Pros	High efficiency	Low inertia that can be modified according to the application	High starting torque	Long-life, tremendous power, fast responses, outstanding speed, and torque
Cons	Expensive controller	Requires power sensing, has ripples in torque, and is not very powerful	Limited rotation speed, bulky, requires maintenance, susceptible to damage if dropped	High cost, limited economy to small motor size
Examples	Chevrolet/ Siverado (USA)	Holden/ ECOmmodore	Honda/insight (Japan)	Peugeot Citroen/ Berlingo (France)

4 Parameters Considered in Selecting the Electric Motors

This chapter aims to establish a correlation between the various electric motors that are available in the market and the various factors considered by the electric vehicle manufacturers to find the apt electric motor. The following are specific parameters that have been observed while choosing the electric motor.

4.1 Power Density

The motor apex power is used to calculate the power density of an electric motor in relation to capacity-to-weight proportion. The apex power yield (kW) divided by mass (kg) gives the power density of any motor. Hence power density holds the measuring unit kW/kg. As observed in Fig. 3.2, the power density appears stronger in PM motors due to the newness of the permanent magnets' high power density. It has been observed by Thomas Finken et al. [31] that the highest power thickness is possible in a PMS machines, enabling them to establish the essential field within the confined motor cell. Putting this advantage to better use, the PM brushless motor provides the highest power density while closely followed by SRM and induction motors. On the other hand, the DC motors are said to exhibit low power density. Higher power in city motor is better suited for EV applications.

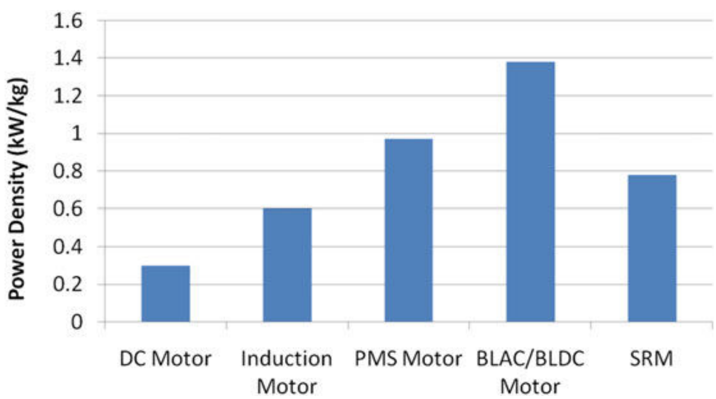

Fig. 3.2 Correlation of DC motor, induction motor, PMS motor, BLDC motor, and SRM with power density

4.2 Energy Efficiency

The efficiency of the electrical motor establishes a connection between the mechanical and electrical yield. Every electric motor manufactured is built to perform with optimal efficiency at the measured output. Based on the experimental analysis, it is observed from Fig. 3.3 that the induction motors show 91% efficiency while the BLDC motors show greater than 95% efficiency. This is mainly due to the lack of rotor losses in the BLDC motor, deeming it to be the most efficient and productive motor. On the other hand, DC motors contribute only 78% efficiency and are not preferred by electric vehicle manufacturers.

4.3 Reliability

As indicated by authors in [32], when comparing the different motors based on fidelity such as support and breakability, the most reliable electric motors would be the SRM and induction motors. The DC motors are found to be slightly dependable while the PM motors pursue reliability as shown in Fig. 3.4. DC motor switches and brushes allow entry of current in the armature and are found to be ill-equipped and are hence not suitable for tasks that are maintenance-free [33].

4.4 Cost Factor

One of the biggest problems faced by electric vehicle manufacturers is providing the customers, electric vehicles which fit their moderate expense and are also

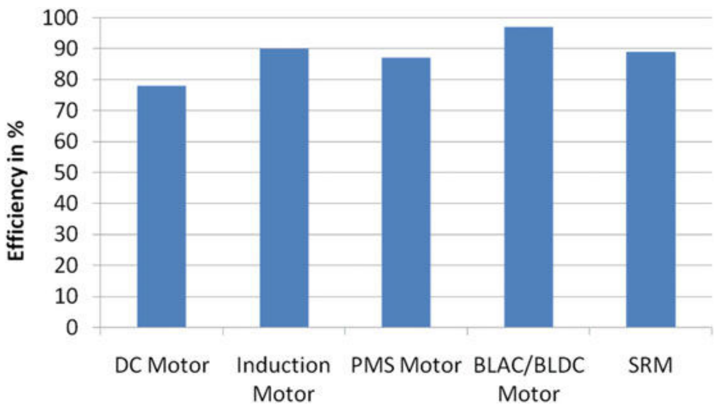

Fig. 3.3 Correlation of DC motor, induction motor, PMS motor, BLDC motor, and SRM with efficiency

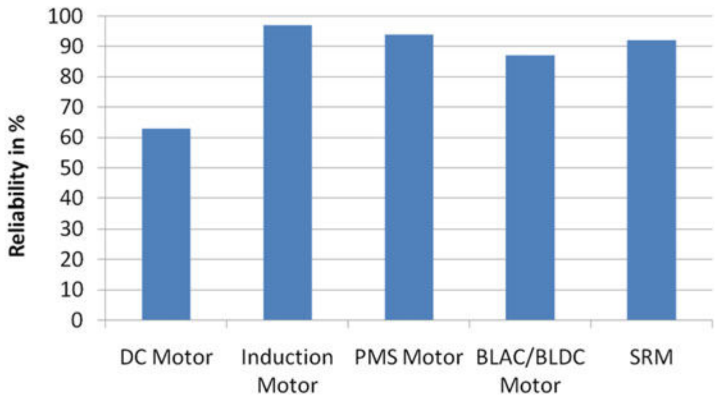

Fig. 3.4 Correlation of DC motor, induction motor, PMS motor, BLDC motor, and SRM with reliability

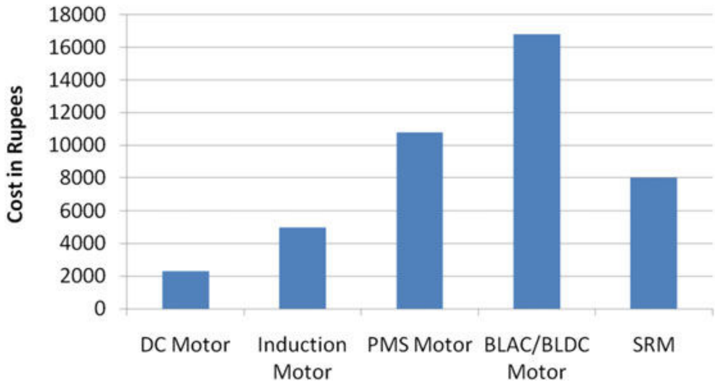

Fig. 3.5 Correlation of DC motor, induction motor, PMS motor, BLDC motor, and SRM with cost

competitive with similar class fuel vehicles. Taking the cost factor into consideration the IM would be the best match, followed closely by SRM and DC motors as shown in Fig. 3.5. Due to their economic rate, the induction engine is commonly used by many manufacturers in electric vehicles. As the capacity of the motor increases, the cost of a DC motor will be more than that of a similar capacity AC motor. If one has to pick one of the two motors holding the same power capacity, a motor with high torque and low speed will cost more than a motor with low torque and high speed. Similarly, a motor with a high current and lower operating voltage will cost more than that of a motor with the low occurrence and higher operating voltage. However, it is the design of the rotor that will play a crucial factor in increasing the cost of a typical DC motor. In fact, analysis indicates that an AC motor that is considered to be less expensive will be of low quality when compared with a high power-rating DC motor. The use of permanent magnets in PMDC motors makes it more expensive and the amount of magnet used is related to the power. On the other hand, iron pole pieces and copper windings are used in induction motors.

5 Conclusion and Future Scope

This chapter attempts at analyzing the diverse electric motors that are used in electric vehicles. Based on the observation, the following conclusions are drawn regarding the different motors examined: The DC motors are not easy to control but at capable of producing large torque at less speed. However, they have deficient efficacy, have an expansive structure, and possess large support costs. The BLDC motor is small in size, can generate high productivity, and has advanced power density. The drawback is the expensive control requirements. An Induction motor is capable of yielding productivity of over 90%. They exhibit substantial area, low power density, fidelity, and average acceleration. At lesser accelerations, synchronous machines are observed to be more proficient and can improve the usage of batter and have a propulsive extent. When steady torque was needed, the synchronous motor is preferred. SRMs are more suitable when the cost is a factor (as it is very economical), adapt to the internal failure capacity, have good efficiency and high reliability. Based on the type of electric vehicle and the characteristics of the vehicle built, the choice of the motor could be either of the five motors surveyed to yield the best results.

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