Received: 2 February 2019 | Accepted: 24 February 2020 | Revised: 2 December 2019

IET Electrical Systems in Transportation

DOI: 10.1049/els2.12018

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH PAPER

New trends in electric motors and selection for electric vehicle propulsion systems

Sreedhar Madichetty[1] | **Sukumar Mishra**[2] | **Malabika Basu**[3]

[1]Mahindra Ecole Centrale, Hyderabad, India

[2]IIT Delhi, New Delhi, India

[3]Technological University Dublin, Dublin, Ireland

Correspondence
Sreedhar Madichetty, Mahindra University- Ecole Centrale School of Engineering, Department of EEE, Survey No 62/1A, Near Tech Mahindra Campus, Hyderabad, 500043, India.
Email: sreedhar.803@gmail.com

Funding information
SERB/NPDF/2017/000568

Abstract

The increase in the numbers of electric vehicles (EVs) is seen as an upgrading of the existing vehicles for various reasons. This calls for an in-depth analysis of the heart of these vehicles—the motor. A motor in an electric vehicle propulsion system is a crucial component that has the ability to affect the efficiency, weight, cost, reliability, power output and performance. Hence a detailed comparative study, that compares the existing types and topologies of various motors, is the need of the hour. The various motors that can be used in electric traction, namely DC, induction, switched reluctance, permanent magnet brushless AC motors and permanent magnet brushless DC motors, are reviewed in view of their capabilities with respect to EV propulsion. A detailed review is presented of existing motors and the application of power electronic techniques to EVs, and recommendations for some new designs of brushless DC motors. These include permanent magnet hybrid motors, permanent magnet spoke motors and permanent magnet inset motors.

1 | INTRODUCTION

The increasing inclination towards electric vehicles has been due to a large number of factors. The greatest advantage of electric vehicles over fossil fuel-powered vehicles is the increased efficiency from the source of energy to the wheel. Some of the other factors that have caused an increase in trends towards electric vehicles include better torque–speed capabilities, ability to operate without any transmission, low maintenance, zero emissions and noiseless operation. These vehicles can also be described as green vehicles if the source of electricity is a renewable source such as solar, hydro, wind, etc. Hence, electric vehicles are seen as the future of transportation.

There are three main stages in the history of EVs. Electric motors during the 1900s had a market penetration equivalent to that of the steam and internal combustion (IC) engine-powered vehicles. At that time, long journeys were infrequent and so the short range of electric vehicles was not a huge limitation [1, 2]. The first hybrid electric vehicle was created by Porsche in the 1989. The intention was to improve the efficiency of the IC engine by operating it along with an electric traction motor. With the advancement in power electronics a lot was made possible in terms of power conversion and motor control. This lead to the resurgence of electric vehicles in the automotive industry [3]. The low power density and the high cost of batteries caused electric vehicles to lose competition against the IC engine powered vehicles [4]. In the present scenario electric vehicles and hybrid electric vehicles are re-entering the market with advanced technologies such as high-density batteries, high power density motors, and more efficient power converter technologies [5].

The motors that are used in electric vehicles are quite different to the motors used in other applications. These motors require certain specifications to be fulfilled and need to be in alignment with the traction effort of the vehicle. Also, these motors cannot afford to be heavy as the range of the vehicle depends on the weight. High efficiency, high power density, efficient regenerative braking, robustness in harsh conditions, low maintenance and reliability are the main criteria sought after in an electric traction motor [5].

The most common types of electric vehicles are battery electric vehicles and hybrid electric vehicles. The commonly used motors in these vehicles are DC, induction, permanent magnet AC motors and permanent magnet DC motors (brushless DC motors) [6]. There is also mention of switched reluctance motors in electric vehicles due to their excellent torque–speed characteristics that are very much in alignment with the demands of traction. Permanent-magnet (PM) motors, which have the highest efficiency, appear to be one of the best options. However, the market is dominated by asynchronous machines. The explanation for this paradox can be expressed in terms of the low utilisation factor of the motor in vehicles and the cost of materials [7].

A study is presented herein of the above-mentioned motors and their new trends that have arisen due to significant improvements are also discussed. With respect to the direction of flux, brushless DC motors can be categorised as axial and radial flux motors, whereas with respect to the rotor position, the motors can be classified as surface permanent magnet and interior permanent magnet motors. These different classifications of the brushless DC motors are discussed. Some new trends in the brushless DC motors, namely the permanent magnet hybrid motor, permanent magnet spoke motor and the permanent magnet inset motor are described, including their advantages with regards to their use in electric traction. Data for electric motors in the most representative electric cars are also presented. Finally, the trends of electric vehicles around the world are briefly discussed.

2 | MOTOR TOPOLOGIES

There are different types of electric motors that can be found in modern electric vehicles [8]. There are also a great number of motor topologies possible, with various specifications that can be used to power an EV. This results in market segments having DC motors, induction motors, brushless AC motors (BLAC) and brushless DC (BLDC) motors [9].

Motors that do not run at a constant speed do not have either nominal speed or nominal power [5]. The design of the motor is done by making trade-offs between weight and efficiency. Usually, motors are rated at lower values than their peak power capability. The peak power capability of a motor can vary between a few kilowatts for electric cycles to 200 kW in electric cars. Market demands play a key role in deciding the power of the machine.

The efficiency rating for a variable-speed motor can be characterised by power–speed or torque–speed efficiency maps. Electric motors have an optimal working condition and efficiency decays when the working points are out of the optimal region, depending on the type of motor [5]. The different points that each driving cycle applies to the motor decide the efficiency of the traction motor, as the efficiency depends on the working points. Hence, the performance of a motor for a wide range of speeds and powers is defined by the design. The efficiency of a motor also depends on the voltage level at the input. The high-voltage-rated machines are inherently more efficient. When a motor is operated at voltages below the rated voltage, then the efficiency of the motor is decreased. This mainly happens at low state of charge [5].

3 | MOTOR CHARACTERISTICS

The major requirements of an electric vehicle propulsion system, as mentioned in the literature, are summarised as [10, 11]:

1. High instant power and high power density.
2. A high torque at low speeds for starting and climbing, as well as high power at high speed for cruising.
3. A very wide speed range, including constant torque and constant power regions.
4. A fast torque response.
5. A high efficiency over wide speed and torque ranges.
6. A high efficiency for regenerative braking.
7. A high reliability and robustness for various vehicle operating conditions and
8. A reasonable cost.

Apart from these, the electric propulsion system must be fault tolerant [12, 13]. Market acceptance is the final criterion based on which the type of motor to be used for electric traction is decided. This acceptance is decided based on the comparative availability and the cost of the power converter technology [14].

Figure 1a shows the typical characteristics of the electric motor used in electric vehicles. As can be observed from the figure, the motor operates at a constant torque for the entire speed range until the base speed is achieved. After attaining the base speed, the motor then reduces the torque in a proportion of the speed and hence maintains a constant power until the maximum speed. Beyond the maximum speed, the constant power region eventually degrades at higher speeds. In this region, the torque decreases in proportion to the square of the speed [14].

The characteristics of the traction effort with respect to speed are also similar to those of electric motors. There is a short constant torque range for low speeds and a wide constant power region for higher speeds. This can be seen in Figure 1b. This profile is derived from the basic characteristics of the power source and transmission [14].

This means that for any source of electric vehicle propulsion the profile of traction effort versus speed must always be a constant torque region followed with a constant power region with respect to speed.

4 | COMPARATIVE STUDY

4.1 | DC motors

The brushed DC motors are known to have high torque at low speeds and easy control. They also have torque–speed characteristics suitable for the traction environment [15] but not for EVs.

The main advantages of these type of motors are their low cost, well established technology, simple yet robust control and reliability. These motors were earlier preferred for use as traction motors but due to the advancement in power

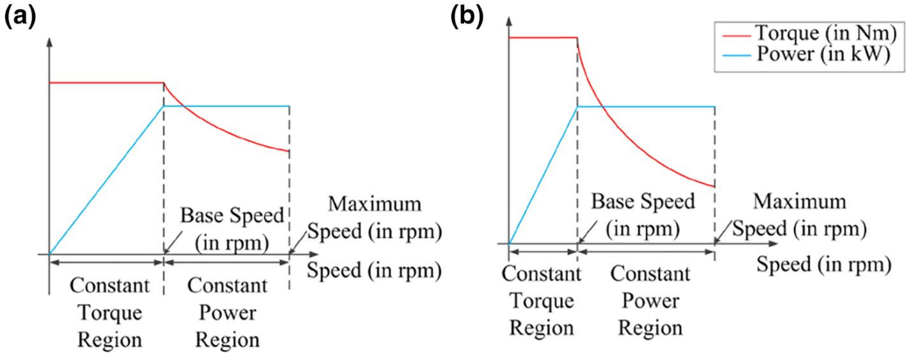

FIGURE 1 (a) Typical characteristics of an electric motor. (b) Characteristics of the traction effort [14]

electronics there has been a shift towards the AC motors, namely induction and synchronous motors. This is due to the fact that the inversion of current that is done using commutators in the DC motors is now being done by highly efficient and controllable inverters.

The main disadvantages of these motors have been their low power density, requirement of maintenance of the coal brush (about every 3000 h), and low efficiency [5]. It is also difficult to reduce the size of DC motors, which makes them heavy and expensive. Along with this, the maximum motor speed is also restricted by the friction between brushes and commutator [15].

4.2 | Induction motors

Induction motors are the most mature technology amongst the various commutator-less motor drives. The squirrel cage type induction motors are the most acceptable motors for use in electric propulsion. They have advantages such as reliability, low maintenance, low cost and robustness [14]. The typical characteristics of an induction motor are shown in Figure 2a.

The critical speed of an induction motor is around twice the synchronous speed and can be written as [14]:

$$N_c = 2 * N_s \tag{1}$$

where N_c is the critical speed in rpm and N_s is the synchronous speed of the machine in rpm.

It is this speed at which the motor reaches breakdown torque limit. If the motor is attempted to be operated at speeds beyond the critical speed and at maximum current, it will begin to stall due to the breakdown torque [14]. Hence, the breakdown torque of the motor is a limitation to the constant power operation. The larger the value of breakdown torque, the wider is the constant power region. From Figure 2a it can be seen that, on increasing the speed beyond the critical speed, the rotor stalls and this makes the slip unity.

Apart from this, there are other disadvantages of induction motors. These include high losses, low efficiency, low power factor, and low inverter usage factor which is dominant at high speeds [14]. The efficiency of induction motors is inherently lower than that of permanent magnet motors due to the presence of rotor bars. This means higher rotor copper losses, due to which the efficiency of the motor at high-speed ranges is low [14]. Some of the newly proposed techniques have attempted to overcome these disadvantages. These are vector control, multiphase pole-changing IM drive, and use of dual inverters. There is also mention of a new type of design of induction motors known as axial flux induction motors. The above-mentioned techniques and axial flux induction motors are discussed subsequently.

4.2.1 | Vector control of induction motors

To improve the dynamic performance of the induction motor drive vector control technique is preferred. Vector control of IMs is a technique which allows the decoupling of the torque control from field control. This requires coordinate transformations on the line to provide fast torque control of the induction motor. A method called direct torque control is employed. [15] Direct torque control consists of three parts: hysteresis control for controlling torque and flux, an optimal switching vector look-up table and a motor model. The motor model estimates the developed torque, stator flux and shaft speed based on the measurements of two stator phase currents and battery voltage. Torque and flux reference signals are produced by using a torque and flux hysteresis control method. A switching vector look-up table gives the optimum selection of the switching vectors for all the possible stator flux-linkage space-vector positions. Speed is controlled using a PI speed controller [14]. The advantages of using the direct control method are that the system gives a quick response and is a simple configuration for control of induction motors. This is capable of working in all four quadrants and includes regenerative braking. This thereby improves the overall efficiency of the system [14].

Vector control of induction motors is a variable-frequency drive control method, also known as the field-oriented control. In this method, the stator currents of the three-phase induction motors are split into two orthogonal components. These components are then mathematically manipulated as two vectors. One of the vectors identifies the magnetic flux of the motor and the other identifies the torque of the motor [16].

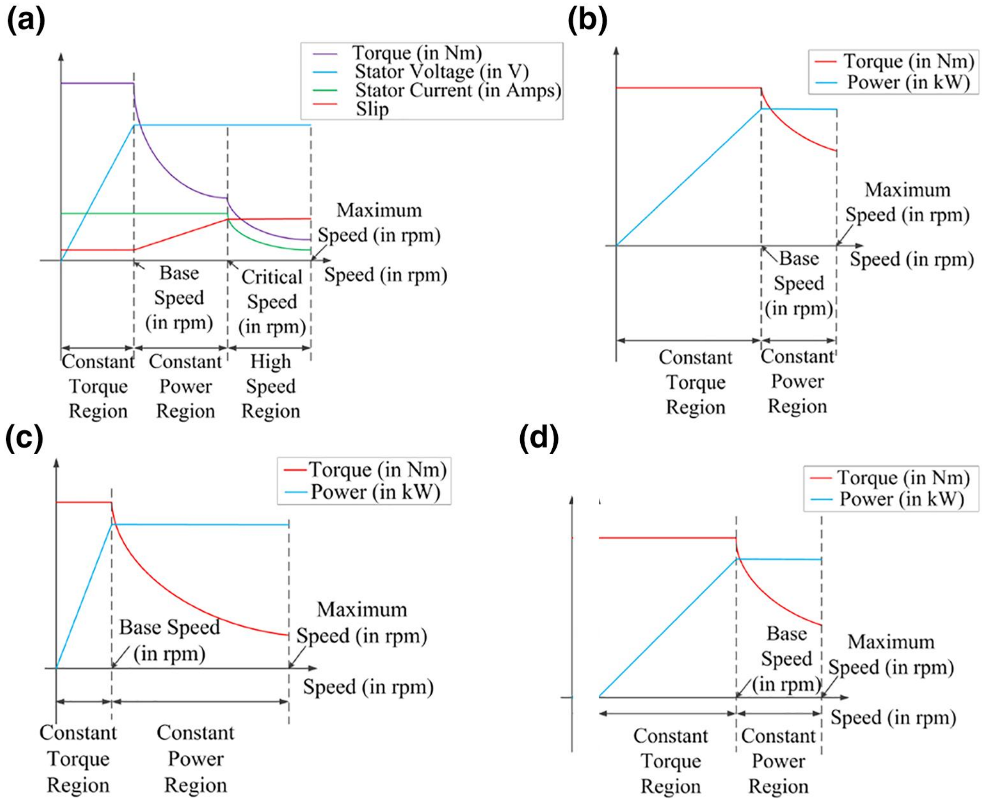

FIGURE 2 (a) Typical characteristics of an induction motor [14]. (b) Torque–speed characteristics of a brushless AC (BLAC) motor [6]. (c) Torque–speed characteristics of a switched reluctance motor [14]. (d) Torque–speed characteristics of a brushless DC (BLDC) motor [14]

For this reason, vector control is said to decouple torque control from flux control [17]. This can be seen in the equations below [18]:

$$\overline{\lambda}_r = L_m \overline{I}_{s\phi} \tag{2}$$

$$\overline{I}_r = -\frac{L_m}{L_r}\overline{I}_{sT} \tag{3}$$

where $\overline{\lambda}_r$ is the rotor flux vector, $\overline{I}_r$ is the rotor current vector, L_m and L_r are the mutual and rotor inductances, respectively, $\overline{I}_{s\phi}$ and $\overline{I}_{sT}$ are the projections of stator current $\overline{I}_s$ onto $\overline{\lambda}_r$ and $j\overline{\lambda}_r$. $\overline{I}_{s\phi}$ is the component of the stator current $\overline{I}_s$ that identifies magnetic flux and $\overline{I}_{sT}$ identifies the toque of the motor.

The need for vector control arises due to the limiting nature of the breakdown torque which causes stalling of the motor, when it is operated at speeds higher than the critical speed [17]. The vector control of the induction motor makes the control of the motor similar to that of the separately excited DC motor. In the separately excited DC motor the field flux and armature flux linkages are independent of each other [19].

This means that the control of torque is possible without changing the field flux. This helps the motor increase the breakdown torque limit and hence increases the constant power region of the motor. In this method, the flux and torque reference values are sent by the drive's speed control to a control system. This control system then calculates the required values of current components and the speed is varied by changing the flux and the torque. The proportional integral controller is usually used to control the measured signals according to the reference values [16].

4.2.2 | Multiphase pole-changing IM drive

There are mainly two techniques to change the number of poles of an induction machine. The first technique requires a specially designed induction motor. The coils of windings are rearranged to change the number of poles of the stator. The second technique also requires a specially designed machine. This machine has two stator windings. For low-speed operations, one winding is used and other winding is used for high-speed operations [20]. The main flux of pole changing induction motors can be visualised as in Figure 3d.

The synchronous speed of the induction motor is inversely proportional to the number of poles of the motor.

$$N_s = \frac{120 * f}{P} \Rightarrow N_s \propto \frac{1}{P} \tag{4}$$

where N_s is the speed of the induction motor in rpm, f is the frequency of supply in Hz and P is the number of poles of the machine.

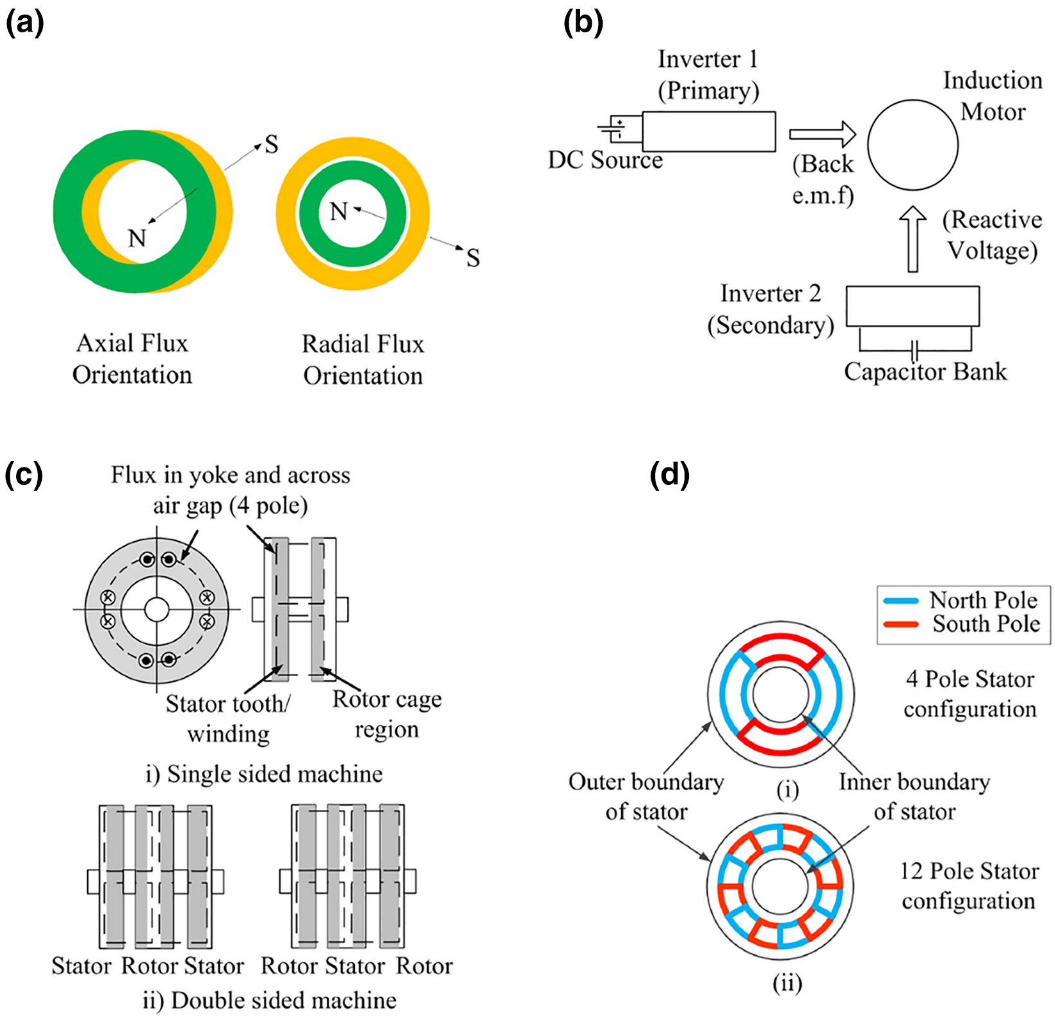

FIGURE 3 (a) Flux orientation in axial and radial flux motors [21]. (b) Basic idea showing the dual-inverter control scheme: Inverter 2 only takes care of the reactive voltage component [22]. (c) Designs of single- and double-sided axial-flux induction motors [21]. (d) Main flux of a pole-changing IM drive [20]: (i) four-pole configuration; (ii) twelve-pole configuration

Increasing the synchronous speed will lead to an increase in the critical speed, which is around twice the synchronous speed. The breakdown torque, which is dependent on the critical speed, also increases now and hence the constant power region of the motor is increased. This means that reducing the number of poles using multiphase pole-changing drives, at high speeds, will widen the constant power region. A six-phase pole-changing squirrel cage induction motor is presented in [16]. The research proposes a new sinusoidal pulse width modulation (PWM) strategy in a way that the two carriers of the six-phase inverter are out of phase during four-pole operation and are in phase during two-pole operation. With the use of double Fourier series, it is possible to eliminate the dc-link harmonics centred on the odd multiples of the carrier frequency. The use of this new PWM strategy can significantly reduce the DC-link harmonic currents, which can improve the battery lifetime also. Figure 3 shows the main flux of a pole-changing IM drive. The multiphase pole-changing IM drive is able to extend the constant power region without oversizing the motor to solve the problem of breakdown torque [13].

4.2.3 | Dual inverters

The reactive voltage and the back electromotive force (emf) of an induction motor increase with an increase in electric angular speed. This is shown by the following equations [18]:

$$\overline{V_s} = R_s\overline{I_s} + j\omega_e\sigma L_s\overline{I_s} + j\omega_e\frac{L_m}{L_r}\overline{\lambda}_r \tag{5}$$

$$V_r = j\omega_e\sigma L_s\overline{I}_s \tag{6}$$

$$e = j\omega_e\frac{L_m}{L_r}\overline{\lambda}_r \tag{7}$$

where $\overline{V_s}$ is the source voltage, V_r is the reactive voltage, e is the back emf, R_s is the stator resistance, ω_e is the electric angular frequency, σ is the total leakage coefficient, L_s, L_m and L_r are the stator, mutual and rotor inductances, respectively, $\overline{I}_s$ is the stator current, and $\overline{\lambda}_r$ is the rotor flux.

Thus, the reactive component of voltage for an induction motor becomes high during high-speed operation. This leads to a poor power factor of the motor. If two inverters are used instead of one to supply power to the motor, the decrease in power factor can be compensated. This can be done using a floating DC-link capacitor bank to supply the required reactive power. The advantages of this system are that it provides reactive voltage support for the main DC-link that is connected to the battery and also allows voltage boosting to enhance the motor terminal voltage [18]. At high speeds when the requirement for reactive power increases, the secondary inverter connected to the capacitor bank compensates for the reactive power requirement. This helps to maintain the unity power factor of the main DC-link connected to the source. As the floating DC-link capacitor bank only supplies reactive power to the induction motor, no power source is required to be connected to it. When the power factor is maintained at unity, it is possible to extend the constant power region of the motor. This is because the floating DC-link is actually supplying voltage boost to the motor [18]. Figure 3b shows the basic idea of such a dual converter scheme.

4.2.4 | Axial flux induction motors

Axial flux machines are more common in the brushless permanent magnet types of motors. Axial flux induction motors could play a role in the electric propulsion as the rare Earth magnets are limited. The work in [23, 24] proposed that light construction, excellent mechanical and dynamical performance are properties that make the axial flux induction machine well adaptable to medium-speed operations in the range of 3000–15,000 rpm.

The axial flux induction motor can have better cooling due to a greater diameter-to-length ratio. These motors also allow inner diameter to be much larger than the shaft diameter. This is a great advantage in cases such as the in-wheel motors where the diameter-to-length ratio is high, as the axial flux IM can significantly increase the torque density where the length of the machine is a limiting design constraint [24]. The different topologies in which axial flux induction motors can exist are:

(i) Single-sided machines
(ii) Double-sided machines.

Single-sided rotor axial flux induction motor

This type of machine contains one stator and one rotor, and the stator can be slotted or slot-less. The flux in these machines flows in the circumferential direction. This means that the flux enters and leaves the stator and rotor on the same side.

Double-sided rotor axial flux induction motor

Double-sided axial flux motors can have two configurations. In one configuration it can have one rotor and two stators on each side. In the other configuration, it can have one stator in the centre and two rotors on two of its sides. This can be seen in Figure 3c.

The radial length from the stator inner radius to the outer radius is the active part of the motor which produces torque in the axial motors. The axial length is dependent on the proper yoke design of the stator and rotor. As the number of poles increases, the active radial part of the machine remains unchanged and the axial length depends on the flux density in the stator yokes [25]. The flux path in a radial flux machine is relatively long compared to the axial flux equivalent. The larger the flux path the greater is the requirement for magnetising current and hence the power factor drops. A large fraction of the length of a radial flux machine is in the end turn region of the windings. This makes the axial flux motors have a shorter profile in terms of length of the rotor [21].

The axial flux machines are not used very commonly because of the large attraction forces that exist between the stator and the rotor. This causes difficulties in manufacturing. The difficulty in maintaining the air gap uniform along with the high cost of the manufacturing for the laminated stator core is another hurdle in their adoption [21].

4.3 | Permanent magnet synchronous (PMS) motors (or brushless AC)

The brushless AC motor is another type of AC motor used in electric vehicle propulsion. There have been many car manufacturers using this technology to power their vehicles.

These motors are fed sinusoidal AC current which produces a sinusoidal field. The interaction between the sinusoidal field and sinusoidal current produces a constant and a smooth torque. This is the inherent property of BLAC motors that differentiates them from BLDC motors. In contrast, brushless DC motors are fed rectangular currents, which produces a rectangular field. Though the torque produced by the interaction of rectangular field and rectangular current is higher than that produced by the sinusoidal field and current, the torque is not smooth and has ripples [26].

BLAC motors have advantages such as better efficiency, higher power density and better heat dissipation to the environment [6]. Better heat dissipation make these motors suitable for operation in harsh environments. The disadvantage of these motors is that they have a narrow constant power region. The constant power region must be wide enough to accommodate higher speeds. Thus, this calls for a need of power converters that can widen the speed range above the base speed. These converters control the conduction angle at higher speeds and help in improving the efficiency of these motors. Figure 2b shows the torque–speed characteristics of the brushless AC motor [6].

4.4 | Switched reluctance motor

The switched reluctance motors have emerged as a new competitor to the existing types of motors used in electric traction. This has mainly been due to the rising concern about the magnetic material [27]. The use of rotor salient poles is the main characteristic feature of this motor. The difference between the direct axis and quadrature axis synchronous reluctance is the cause for the torque production in these motors, as there is no excitation field in the rotor [5]. The rotor is cheap, robust and insensitive to temperature [28, 29]. The peak efficiency of the reluctance motor is comparable to the induction motor but the efficiency remains high for a large range of speed. The efficiency of the hybrid switched reluctance motors can go as high as 95% [30].

The advantages of this type of motor are its simple yet rugged construction, ability to tolerate faults, simple control, and outstanding torque–speed characteristics. The switched reluctance motor's greatest advantage lies in the large constant power region. This is usually inherently small in the other motors and power electronics or other means are used to extend this region [14]. Apart from these advantages, the high rotor inductance ratio makes the sensorless control easier to implement [30, 31]. Switched reluctance motors are also easy to cool when compared to the other types of motors. This is again advantageous, as it can be used in harsh ambient conditions [15].

However, even after these advantages the switched reluctance motor is not extensively used in electric vehicles due to certain disadvantages [31, 32]. These disadvantages include high acoustic noise that is due to the high torque ripple, need of special converter topology, excessive bus current ripple, and electromagnetic interference noise generation. However, all these disadvantages and advantages are crucial for EV applications. Figure 2c shows the typical torque–speed characteristics of the switched reluctance motor [14].

4.5 | Brushless DC motor

The brushless DC motors are one of the largest competitors to all the existing types of motors used in electric vehicle propulsion. They can be imagined as a reversal of the stator and rotor in the permanent magnet DC motors. Also, the inversion from DC to AC is done with the use of power electronic converters instead of a mechanical commutator. In contrast to brushless AC motors, these are not fed sinusoidal current waves. Instead, they are fed rectangular waves due to the sequential commutation of winding currents. This is one reason why they are called brushless DC motors [33–35].

There are quite a few advantages to these motors, these include high power density, which means that the weight and volume are reduced for the same amount of output power; higher efficiency intrinsically, which is due to the use of permanent magnets that eliminate the rotor excitation currents which account for half of the losses in the form of Joule losses for non-self-excited synchronous motors; efficient and reduced dissipation of heat to the surroundings, which means that the temperature increase does not handicap the performance of the motor [14]; reduced maintenance, as there is no need for replacement of brushes; and high torque due to the interaction between the rectangular flux and the rectangular current. This torque is higher than the torque due to the interaction between the sinusoidal flux and sinusoidal current motors in BLAC motors. The recent trends in electric vehicles have shown the use of direct-drive motors and in-wheel motors. The permanent magnet brushless DC motors are well suited for these type of applications also [5, 14].

The main disadvantage of these motors is that the constant power region is narrow due to the limited field weakening capabilities which come from the presence of permanent magnets [10]. This is because, at high speeds, there is a risk of permanent demagnetisation of the PMs [11]. Figure 2d shows the typical torque–speed characteristics of a brushless DC motor [14].

There exist various topologies in which PM brushless motors can be configured. If the position of the magnets is considered, they can be classified as surface permanent magnet (SPM) and interior permanent magnet (IPM) brushless DC motors. If the direction of flux is considered, they can be classified as axial flux and radial flux motors. Figure 4 shows one of the many possible arrangements of magnets in the surface and interior permanent magnet motor designs. A type of hybrid permanent magnet brushless motors are known to exist in which the air gap field that is provided by the permanent magnets is weakened by the DC field excitation during high-speed operation. The direction and magnitude of this DC field excitation determine the strengthening or weakening of the PM magnetic field. Another type of hybrid motor uses SPM and IPM magnet arrangements in its rotor sections. The PM inset motor is one type of BLDC motor that has characteristics of both BLDC motors and multi-phase reluctance motors. A novel design of BLDC motors, known as the spoke motor, is also present in the recent trends due to its high torque and power density. These types of BLDC motors are discussed subsequently.

4.5.1 | Axial flux and radial flux motors

When compared to radial flux motors, axial flux motors are well suited for applications where the axial length is limited and a very flat profile is required. Figure 3a shows the direction of

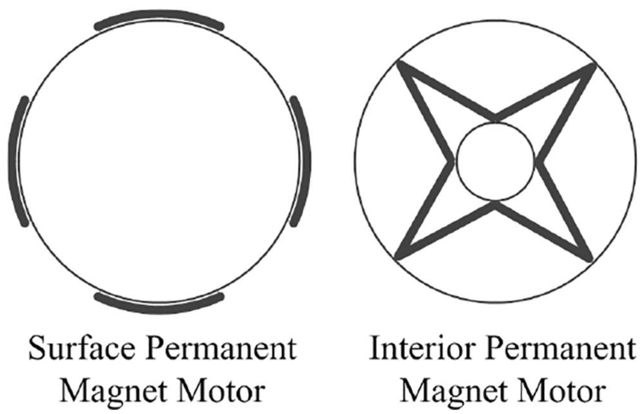

FIGURE 4 Rotors of radial flux motors with surface-mounted and interior permanent magnet designs [5]

flux in the axial as well as radial flux motors. Also, in applications where rapid acceleration or deceleration is required, axial flux motors are preferred over the radial flux motors [36].

There are various configurations in which the axial flux motors can exist. Based on the type of the stator these motors can be classified as slotted or slotless (Figure 5). Based on the number of air gaps they can be classified as single gap or double gap. According to these criteria, the axial flux motors can be classified as:

1. Single-gap slotted axial machine
2. Dual-gap slotted axial machine
3. Single-gap slotless axial machine
4. Dual-gap slotless axial machine

The radial flux motors occupy a volume larger than any of the axial flux motors. The diameter of slotless motors is greater when compared to the slotted type of motors, but the length in the axial direction is the smallest for the slotless motors. This leads to the flattest profile amongst all the types. The radial field motor has the maximum moment of inertia when compared to any axial motor at all power levels. All the axial flux motors have almost the same moment of inertia, with the dual-gap slotless motor having the least. This is because the dual-gap slotless motor does not contain any steel in the rotor and the density of the magnetic material is slightly lower than that of steel. Both axial flux slotless machines require the maximum magnet volume. This increases the weight of these motors. Slotted axial flux motors require less magnetic material than radial flux motors, for all power ratings [36].

In terms of copper losses in these machines, the radial motors and the slotted axial flux motors require a lower number of turns per coil for the same generated back emf, when compared to the slotless motors. Hence the copper losses are lower in radial and slotted axial motors. All the machines, axial or radial, slotted or slotless, have similar iron losses. At high power levels the axial single-gap slotless has the least amount of iron losses due to the least weight of steel used. If sufficient cooling is available then the single-gap slotless axial motor can be used when minimum weight is required for a given power rating. Both the iron and copper losses can be reduced by increasing the amount of iron and copper, but this will increase the package size and the weight of the motor. When the sums of copper and iron losses are compared, the radial flux and the dual-gap axial motors have similar values. Also, the friction and the preload losses will be lower in the dual-gap and the radial flux machines due to the high attractive forces between the rotor and the stator. A low speed of operation can lead to windage losses [36].

An important indicator of the acceleration of the rotor is the torque per unit moment of inertia. The radial flux motor has the lowest torque for a given moment of inertia. This is due to the longest rotor for any power rating. The dual-gap slotless axial motor has the largest value for the torque per unit moment of inertia. In this case, the slotted motors come between radial and slotless motors [36].

Active weight in the motor is the weight of the copper and the iron that is required by the magnetic circuit. Active volume is the volume of the active weights. The power per unit active weight of axial and radial motors are similar except at higher power levels, when it is less for the radial flux motors. The power per unit active volume of the radial flux motors is significantly low for all power levels [36].

4.5.2 | Surface permanent magnet (SPM) and interior permanent magnet (IPM) motors

When performances of the SPM and IPM motors are compared, it is observed that the IPM can have a higher loading capacity, both at low and high speeds (Figure 6). This is not true in the case of SPM motors. This overload capacity of IPM motors is much higher in the case of higher saliency motors. The saliency ratio (ε) defined as below [38]:

$$\varepsilon = \frac{L_q}{L_d} \tag{8}$$

is the ratio between the quadrature axis inductance (L_q) and the direct axis inductance (L_d). A high saliency ratio value means high anisotropy of the machine.

The SPM motor is not able to go beyond the continuous power rating, independent of the current load that is applied. The important fact to be considered is that the IPM motor has a superior overloading capacity when compared to the SPM, only for the designs where rotor anisotropy is maximum [38]. For enhancing the overload capacity of the IPM motor at high speeds a higher value of PM flux can be set according to the following equation [38]:

$$\lambda_m = L_d \cdot \frac{1}{2} \cdot (i_1 + i_0) \tag{9}$$

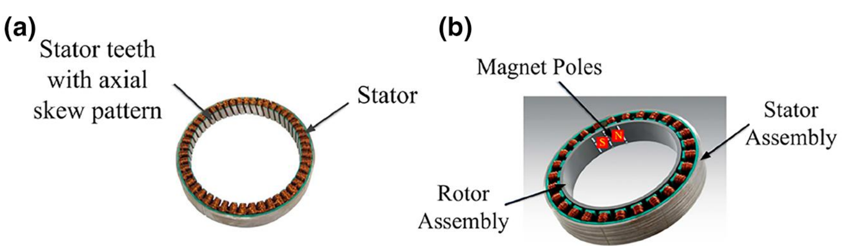

FIGURE 5 a) A slotted machine rotor and (b) a slotless machine rotor [37]

where λ_m is the PM flux linkage, L_d is the direct axis inductance, i_1 is the rated current and i_0 is the overload current.

When the motors are supplied by the same current and maximum voltage, the two motors have very similar power outputs. Saturation, in both the motors, has the ability to affect the rated torque. Overload torques, however, are different because of saturation and cross-saturation effects. These effects are more pronounced in the case of the SPM motor. Due to this, the SPM motor has a lower overload torque at low speed [38].

When compared with SPM motors, the IPM motors tend to have higher copper losses and lower iron losses. At base speed, the SPM motor tends to have lower overall losses, but at higher speed there exist losses due to permanent magnets. The PM losses in the SPM motor can be reduced by axial segmentation. Increasing the number of poles is advantageous to the SPM motor as it helps to improve continuous power density. However, even after the addition of poles, the IPM motor tends to have a greater overload capacity than the SPM motors. The IPM motors, on the other hand, are also more susceptible to the losses due to harmonics. Hence, it is required to have a calculated number of stator slots and rotor segments in this motor. The SPM motor is more subject to PM losses [38].

The SPM and IPM motors both give the same continuous power for the same size of inverter and active parts. When manufacturing is considered, the SPM motor is easier to manufacture than the IPM motor [38].

4.5.3 | Spoke motor

Recent trends in electric motor design have shown a drift towards the spoke brushless DC motor. These motors are known for their high power density. The design of a spoke motor is of an interior permanent magnet motor. The superiority of this motor is due to the higher saliency ratio, which concentrates the magnetic flux generated. This concentration of flux is the reason for higher torque density per unit volume [39]. The spoke BLDC motor is inherently an IPM motor, where the magnets are arranged at both sides of the rotor pole, as shown in Figure 6a. This is the reason for flux concentration [39].

The spoke BLDC motor has an average back emf that is about 34% higher than the SPM motor [39]. This back emf has severe harmonics in its spatial distribution, when compared to SPM motors. The inductances in an SPM motor are constant on positions of rotor and otherwise. However, in the case of the spoke motor, the inductances are highly variable with respect to rotor position. The variation of inductances in spatial distribution leads to the generation of the reluctance torque. These inductances have a value that is larger than that in the SPM motors. The reduction in the reluctance in the case of the spoke motor is the reason for the larger value of inductances [39].

In a brushless DC motor there is always an incoming phase and an outgoing phase. Due to the phase inductance there is a commutation torque ripple that is generated in the motor. The spatial distribution of harmonics in the back emf and varying inductances in the spoke motor have a direct consequence on the phase current and the instantaneous torque. The phase current ripple is the cause for commutation torque. The reluctance torque hardly contributes in the effective torque. When the phase current has an advanced phase angle, then the phase current increases, due to constructive addition of two consecutive peaks. The increase in current then leads to an increase in the electromagnetic torque and also the reluctance torque. This reluctance torque is now able to contribute to the output torque [39].

The leakage flux is generated between the magnets because the magnets are inside the rotor. This leakage flux leads to a

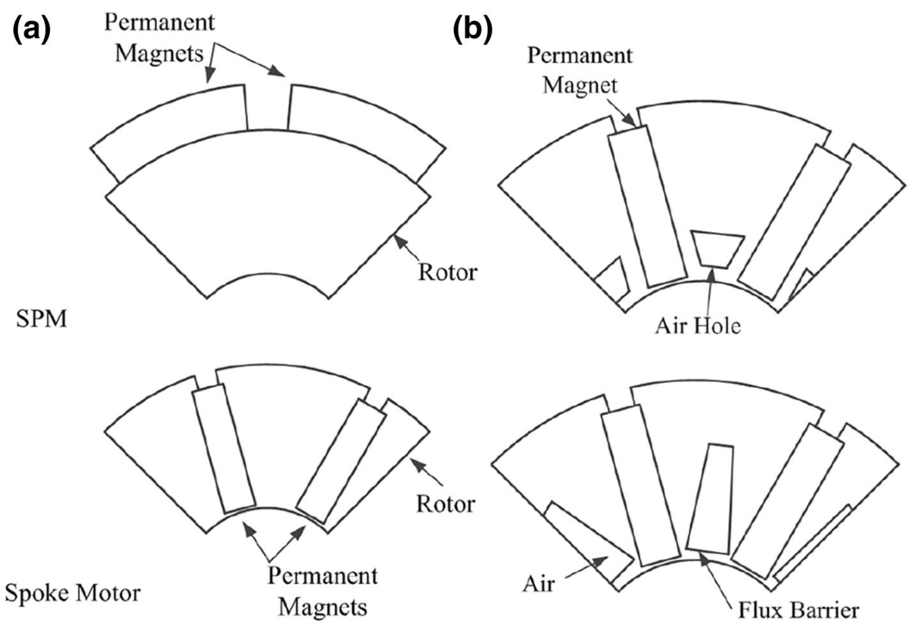

FIGURE 6 (a) The rotor design of SPM and spoke motor [39]. (b) Air hole and flux barrier design of the spoke motor [39]

reduction in the torque and output power density. Reducing the leakage flux can increase the torque further [39].

When irreversible demagnetisation analysis is performed on the SPM and spoke motor, it is observed that the SPM motors are only partially demagnetised, whereas the spoke motors are completely demagnetised by external fields. This shows that the spoke motor has weak resistance to the external demagnetising field [39].

In order to reduce the effect of the demagnetisation in spoke motors, two designs, namely the air hole type and flux barrier type rotor designs, are proposed [39]. These are shown in Figure 7(b). If the reference model is considered to have a rotor without any air hole or flux barrier design, then it can be said that the air hole and the flux barrier type rotors perform better than the reference model. Both the air hole and the flux barrier type designs have better torque characteristics, but the flux barrier type design has more torque when compared to the air hole type design. In terms of back emf, it can be seen that the flux barrier type rotor exhibits better resistance to external demagnetising fields. The back emf reduction is about 18% in the case of the air hole design and it is about 5.3% in the flux barrier type design. This shows that the flux barrier type spoke BLDC motor is more robust to the external demagnetising fields [39].

4.5.4 | Permanent magnet hybrid motor

The permanent magnet hybrid motor is composed of segments of the surface and interior permanent magnet arrangements on a stepped skewed rotor shaft. Placement of the rotor segments is done in such a way that the average output torque is maximised [40]. This arrangement is shown in Figure 7a.

When compared to the SPM motors of the similar torque density, the hybrid PM motor has a wider constant power region. This motor also has 21.9% reduced magnet weight compared to conventional SPM motors [40].

When compared to the IPM, the SPM has greater maximum torque, maximum back emf and also maximum cogging torque. Although it is preferred to have high values of back emf and torque, a high value of cogging torque is not preferred. The greatest advantage of the IPM motor that is added to this hybrid motor is the wide constant power region [40].

Hence, the hybrid motor that combines the designs of SPM and IPM motors, will have properties that are almost an average of the two motors. This helps to reduce disadvantages of one type and add advantages of another type in properties such as the back emf, torque, etc. [40].

Figure 7b shows that the torque–speed characteristics of the hybrid BLDC motor are an average of that of the SPM and IPM motors, thus extending the constant power region of the SPM motor [40].

4.5.5 | Permanent magnet inset motor

The PM inset motor utilises the advantages of the high power density and efficiency of the brushless DC motor and advantages of high starting torque and wide constant power range of DC series motor. The originality of this motor is that the generation of the PM excitation is both by PM and by the specially controlled stator currents (two particular phases), that are under the same stator pole. This causes torque of the motor to be generated in two parts. By the interaction between the PM excitation and the two phase stator currents, one part of torque is generated. The other part is the electromagnetic torque that is generated due to the interaction between the magnetic field generated by the two stator currents and the stator currents of the other phases. This second part of the torque is proportional to the square of the phase currents, which is the characteristic of the DC series motor [41].

The design of the inset motor draws inspiration from the multiphase reluctance motor. An inverter-fed multiphase reluctance motor operates similarly to the DC motor with the only difference being that both the field and the armature windings are inside the stator. The armature reaction field (F_a) is produced by the stator currents of the phases that are under the rotor pole faces. These currents act as armature currents (i_a). The field excitation (F_f) is produced by the stator currents that flow in the phases that are in the interpole region. These currents act as field currents (i_f). The use of a multiphase inverter allows control of each phase current of the multiphase motor. This makes it possible to control the field and the armature currents independently. This is the characteristic feature of the separately DC motor. The rectangular distribution of field and current gives high power density to the multiphase reluctance motor [41].

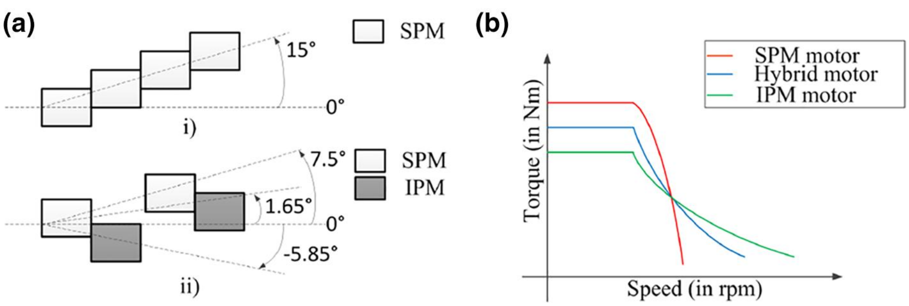

FIGURE 7 a) Arrangement of (i) conventional stepped skew of SPM motor and (ii) unconventional stepped skew of permanent magnet hybrid motor [40]. (b) Torque–speed characteristics of SPM, IPM and permanent magnet hybrid motor [40]

There are two types of torques that can be produced by this motor. One of the torques, T_a is a positive torque that is produced due to the interaction of F_f and i_a. The other torque is undesirable and is called the negative torque T_f. This torque is generated by the interaction between F_a and i_f [41].

The PM inset motor is designed by placing the permanent magnets in sunken spaces in a specific way such that the rotor has a PM magnet width less than half the pole pitch. Such an arrangement produces two positive torques. This means that the stator field current is now used to create two positive torques, instead of a positive and negative torque. One of the positive torques is the reluctance torque that equals the difference between T_a and T_f. The other positive torque is the PM torque, T_m. This torque is produced by the interaction of i_f and permanent magnet field F_m.

The torque of the PM inset motor is given by the equation below [41]:

$$T = [i]^T \frac{d}{d\theta}[L][i] + [e]^T[i] \Big/ \omega \tag{10}$$

Here, T is the motor torque, $[i]$ represents the matrix of phase currents, $[L]$ represents the matrix of phase inductances, where L_{ii} is the self-inductance of phase i, and L_{ij} is the mutual inductance between phases i and j, θ is the angle between rotor axis and stator winding axis, $[e]$ represents the rotational back emf due to the PM material and ω represents the angular speed.

The first term in the above equation represents the reluctance torque component and the second term represents the PM torque component of the inset motor.

Figure 8 shows the different torques, stator poles and the excitations in the permanent magnet inset motor during clockwise and anticlockwise rotation of the motor [41].

The PM inset motor has two specialties. Firstly, these are fed by multiphase rectangular waves to give high power density. Secondly, the rotor has PM magnet width that is less than one-half of the pole pitch, giving it the ability to perform field regulation for constant power operations at high speeds. Also, the salient rotor pole surfaces are eccentric, thereby reducing the armature reaction [41].

Thus the PM inset motor has the powerful torque of the PM brushless motor and controllable reluctance torque, which is proportional to the square of the phase current. Hence, this motor is able to offer high power density, high starting torque and high efficiency [41].

4.5.6 | Trends of motors used in electric vehicles

Table 1 shows the recent trends in the electric motors used in some of the most representative electric vehicles in the market [5]. It can be seen that induction motors and permanent magnet motors are the most commonly used type of motors in recent times. DC motors were more prevalent during earlier times when the electric vehicle technology was evolving. There are numerous electric vehicles coming into the market. The electric vehicle market includes electric cars, hybrid electric cars, electric scooters and motorcycles, electric cycles and also electric pickup trucks and three wheelers. Table 2 shows the different electric vehicles, specifying the type and power of their motors.

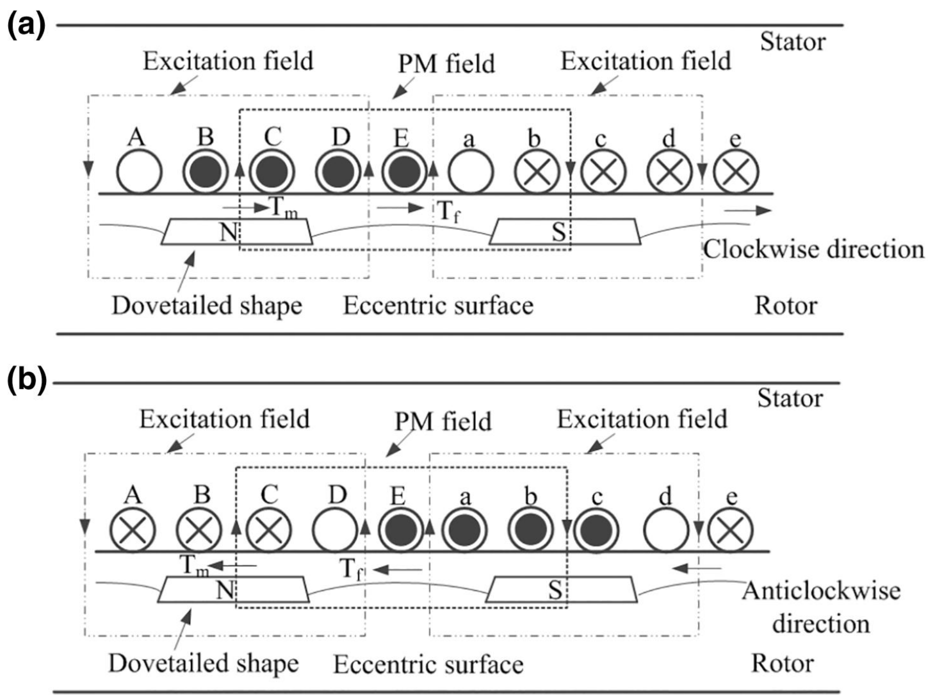

FIGURE 8 (a) Clockwise and (b) anticlockwise rotation of the inset motor [41]

TABLE 1 Types of motors used in the most representative models in the market

Sl. No.	Name	Year	Power (in kW)	Motor type
1	Audi e-tron Quattro	2019	300	IM[a]
2	Mercedes-Benz EQC (N293)	2019	300	IM[a]
3	Hyundai Kona	2018	150	PM[b]
4	Mahindra eVerito	2017	31	IM[a]
5	MW Motors Luka EV	2016	50	IM[a]
6	Tesla Model X	2015	245	IM[a]
7	Kia Soul EV	2014	81.4	PM[b]
8	Volkswagen e-Up	2013	60	PM[b]
9	Tesla Model S	2012	215	IM[a]
10	Hyundai Blue ON	2012	212	PM[b]
11	Ford Focus Electric	2011	110	IM[a]
12	Volvo C30 DRIVe	2011	89	PM[b]
13	Tata Indica Vista EV	2011	55	PM[b]
14	Ford Turneo Connect EV	2011	50	IM[a]
15	REVA NXR	2011	13	IM[a]
16	BYD F3M	2010	125	PM[b]
17	Fiat Doblo	2011	43	IM[a]
18	Peugeot iOn	2011	35	PM[b]
19	Nissan Leaf	2010	80	PM[b]
20	Ford Transit Connect EV	2010	50	IM[a]
21	BYD e6	2009	115	PM[b]
22	Mitsubishi i MiEV	2009	47	PM[b]
23	Tesla Roadster	2008	215	IM[a]
24	REVAi	2008	13	IM[a]
25	AC Propulsion eBox	2007	150	IM[a]
26	Ford Ranger EV	1999	67	IM[a]
27	Peugeot Partner	1999	28	DC[c]
28	Toyota RAV4 EV	1998	50	PM[b]
29	GM S-10	1997	85	IM[a]
30	Nissan Altra	1997	62	PM[b]
31	Honda EV Plus	1997	49	DC[c]
32	GM EV-1	1996	102	IM[a]
33	Ford Ecostar	1992	56	IM[a]
34	Bertone Blitz	1992	52	DC[c]
35	City EI	1987	4	DC[c]
36	Lucas Chloride	1977	40	DC[c]
37	Citicar	1974	6	DC[c]
38	Enfield 8000	1969	10	DC[c]

[a]Induction motor.
[b]Permanent magnet motor.
[c]DC motor.

TABLE 2 Types of motors used in the most representative electric vehicles in India

Vehicle type	Model name	Power (in kW)	Motor type
Car	e2o Plus-2016	19	IM[a]
Car	e-Verito-2017	30.5	IM[a]
Car	Tigor-2017	30	IM[a]
Car	Tiago-2017	85	IM[a]
Car	Prius (Hybrid)-2018	55	PMSM[b]
Car	Camry (flex-fuel Hybrid)	105	PMSM[b]
Motorcycle	T6X-2019	6	BLDC[c]
Scooter	S340-2018	4.5	BLDC[c]
Scooter	High Speed-2019	0.6	In-hub BLDC[c]
Scooter	Economy-2019	0.25	In-hub BLDC[c]
Scooter	Flow-2019	2.1	BLDC[c]
Scooter	V48-2017	0.25	BLDC[c]
Bus	K7	2 × 90-2017	PMSM[b]
Bus	K9	2 × 100-2019	PMSM[b]

[a]Induction motor.

[b]Permanent magnet synchronous motor.

[c]Brushless DC motor.

5 | CONCLUSION

The DC motors appear to be one of the best choices according to the traction profile of an electric vehicle. They have excellent torque speed characteristics and are simple and robust in their construction. However, these motors require maintenance and have low power density. The induction motors have easy control due to the flux-weakening capabilities, are robust and require low maintenance. These motors are restricted in their constant power region by their breakdown torque. They have low efficiencies and operate at poor power factors at high speeds. The vector control of induction motors helps to improve the dynamic performance of the motor and also its constant power region. The pole-changing induction motors are capable of operating with high efficiency at low and high speeds due to the different windings that are used in low-speed and high-speed operations. The dual-converter strategy can be used to enhance the power factor of the induction motors at high speeds. Axial flux induction motors have light construction, excellent mechanical properties and dynamic performance. This makes them adaptable to medium-speed operations. These new advances on the induction motor add advantages to the motor, but at the same time increase the cost and size of the system.

The other type in AC motors are the brushless AC motors (or permanent magnet synchronous motors). They have better efficiency, smooth torque, high power density and better heat dissipation to the environment. They lack a wide constant power region and hence require power converters. A switched reluctance motor is also a type of synchronous motor. These motors, in contrast to the brushless AC motors, have a wide constant power region and have the most suitable characteristics for an electric vehicle. However, these motors suffer from torque ripple that causes acoustic noise. In addition, they have excessive current ripple.

The brushless DC motors have been in recent trends due to the high power density and high torque capabilities. These motors have undergone and are still undergoing a lot of research. This has led to the development of various types of brushless DC motors. Although a very suitable choice, this motor does also lack the wide constant power region due to its limited flux-weakening capabilities.

Axial flux BLDC motors can be used in designs where the length of the rotor is a constraint. The radial flux motors have the lowest copper losses when compared to the axial flux motors. With increasing output power, the radial flux motor has overall losses close to those of the single air gap slotted type axial motor, which has the least overall losses. The main advantage of axial flux motors is their significantly high power per unit active volume for all power levels.

If the mounting of permanent magnets is considered, the interior permanent magnet motors have a higher overload capacity when compared to the surface permanent magnet motors. Spoke motors have recently come into the picture, in which the permanent magnets are arranged as spokes of a wheel. These motors pack a high power per unit active volume and have greater values of back emf and torque than conventional SPM motors. The flux barrier type rotor design of these motors is superior in resisting demagnetisation due to external fields. Another new type of permanent magnet motor that is a hybrid of SPM and IPM motors has been designed. This motor exhibits the advantages of both SPM and IPM motors and has fewer disadvantages when compared to SPM motors. The permanent magnet inset motor is a new design of the BLDC motor that has PM magnets sunk into the rotor surface. This motor has the advantage of using both the PM torque and the reluctance torque additively.

REFERENCES

1. Sulzberger, C.: An early road warrior: electric vehicles in the early years of the automobile. IEEE Power Energy Mag. 2(3), 66–71 (2004)
2. Situ, L.: Electric Vehicle development: the past, present & future. In: 3rd International Conference on Power Electronics Systems and Applications (PESA), Hong Kong, pp. 1–3 (2009)
3. Hesla, E.: Electric propulsion [history]. IEEE Ind. Appl. Mag. 15(4), 10–13 (2009)
4. Rajashekara, K.: History of electric vehicles in general motors. IEEE Trans. Ind. Appl. 30(4), 897–904 (1994)
5. de Santiago, J., et al.: Electrical motor drivelines in commercial all-electric vehicles: a review. IEEE Trans. Veh. Technol. 61(2), 475–484 (2012)
6. Hashemnia, N., Asaei, B.: Comparative study of using different electric motors in the electric vehicles. In: 2008 18th International Conference on Electrical Machines, pp. 1–5 (2008). https://doi.org/10.1109/ICELMACH.2008.4800157
7. Vägverket: Presentation of the Swedish National Road Administration (SNRA). www.vv.se
8. Thiemer, H.: Influence of automotive 42 V powernet on small PM DC motors. In: IEEE International Electric Machines and Drives Conference (Cat. No.01EX485), pp. 591–593 (2001)
9. Chan, C.C., Chau, K.T.: An overview of power electronics in electric vehicles. IEEE Trans. Ind. Electron. 44(1), 3–13 (1997)

10. Rahman, Z.: An investigation of electric motor drive characteristics for EV and HEV propulsion systems. SAE Technical Paper Series. Paper no. 2000-01-3062 (2000)
11. Chan, C.C.: The state of the art of electric and hybrid vehicles. Proc. IEEE. 90(2), 247–275 (2002)
12. Diallo, D., Benbouzid, M.E.H., Makouf, A.: A fault-tolerant control architecture for induction motor drives in automotive applications. IEEE Trans. Veh. Technol. 53(6), 1847–1855 (2004)
13. Jack, A.G., Mecrow, B.C., Haylock, J.A.: A comparative study of permanent magnet and switched reluctance motors for high-performance fault-tolerant applications. IEEE Trans. Ind. Appl. 32(4), 889–895 (1996)
14. Zeraoulia, M., Benbouzid, M.E.H., Diallo, D.: Electric motor drive selection Issues for HEV propulsion systems: a comparative study. IEEE Trans. Veh. Technol. 55(6), 1756–1764 (2006)
15. Xue, X., Cheng, K.W., Cheung, N.: Selection of electric motor drives for electric vehicles. In: 2008 Australasian Universities Power Engineering Conference, Sydney, pp. 1–6. (2008)
16. Zambada, J.: Field oriented control for motors. (2007) https://www.machinedesign.com/news/article/21816702/fieldoriented-control-for-motors
17. Singh, B., et al.: Direct torque control: a practical approach to electric vehicle. In: 2006 IEEE Power India Conference, p. 4 (2006)
18. Haque, R.U., et al.: PWM control of a dual inverter drive using an open-ended winding induction motor, In: 2013 28th Annual IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 150–156 (2013)
19. Texas Instruments, Field Orientated Control of 3-Phase AC-Motors (1998)
20. Kelly, J.W., Strangas, E.G., Miller, J.M.: Control of a continuously operated pole-changing induction machine. In: IEEE International Electric Machines and Drives Conference. 1, 211–217 (2003)
21. Mushid, F.C., Dorrell, D.G.: Review of axial flux induction motor for automotive applications. In: 2017 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), 146–151 (2017)
22. Kim, J., Jung, J., Nam, K.: Dual-inverter control strategy for high-speed operation of EV induction motors. IEEE Trans. Ind. Electron. 51(2), 312–320 (2004)
23. Valtonen, M.S.M., Parviainen, D.S.A., Pyrhonen, J.: Electromagnetic field analysis of 3D structure of axial-flux solid-rotor induction motor. In: International Symposium on Power Electronics, Electrical Drives, Automation and Motion, pp. 174–178 (2006)
24. Jussila, H., et al.: Concentrated winding axial flux permanent magnet motor for industrial use. In: The XIX International Conference on Electrical Machines - ICEM 2010, Rome, pp. 1–5 (2010). https://doi.org/10.1109/ICELMACH.2010.5608168
25. Honsinger, V.B.: Sizing equations for electrical machinery. IEEE Trans. Energy Convers. EC-2(1), 116–121 (1987)
26. Korkmaz, F., Topaloglu, I., Mamur, H.: DTC control of BLAC and BLDC motors for pure electric vehicles. Int. J. Instrum. Control Syst. 6(2/3), 9–17 (2016)
27. Takano, Y., et al.: Design and analysis of a switched reluctance motor for next generation hybrid vehicle without PM materials. In: The 2010 International Power Electronics Conference - ECCE ASIA, pp. 1801–1806 (2010)
28. Chen, H., Gu, J.J.: Implementation of the three-phase switched reluctance machine system for motors and generators. IEEE/ASME Trans. Mech. 15(3), 421–432 (2010)
29. Moghbelli, H.H., Rashid, M.H.: Performance review of the switched reluctance motor drives. In: Proceedings of the 34th Midwest Symposium on Circuits and Systems, 162–165 (1991)
30. Qianfan, Z., Shumei, C., Xinjia, T.: Hybrid switched reluctance motor applied in electric vehicles. In: 2007 IEEE Vehicle Power and Propulsion Conference, pp. 359–363 (2007)
31. Haataja, J.: A Comparative performance study of four-pole induction motors and synchronous reluctance motors in variable speed drives. Lappeenranta Univ. Technol. (2003)
32. Malan, J., Kamper, M.J.: Performance of hybrid electric vehicle using reluctance synchronous machine technology. In: Conference Record of the 2000 IEEE Industry Applications Conference. Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No.00CH37129), Rome, pp. 1881–1887 (2002)
33. Gieras, J.F.: Permanent magnet motor technology: design and applications. CRC Press (2010)
34. Demerdash, N., Nehl, T.: Dynamic modelling of brushless dc motors for aerospace actuation. IEEE Trans. Aerosp. Electron. Syst. AES-16(6), 811–821 (1980)
35. Deng, F.: Commutation-caused eddy-current losses in permanent-magnet brushless DC motors. IEEE Trans. Magn. 33(5), 4310–4318 (1997)
36. Sitapati, K., Krishnan, R.: Performance comparisons of radial and axial field, permanent-magnet, brushless machines. IEEE Trans. Ind. Appl. 37(5), 1219–1226 (2001)
37. Motion, C.: Comparison of slotless and slotted motors. https://www.celeramotion.com/applimotion/support/technical-papers/slotless-vs-slotted-motors/
38. Vagati, A., Pellegrino, G., Guglielmi, P.: Comparison between SPM and IPM motor drives for EV application. In: The XIX International Conference on electrical machines - ICEM 2010, p. 1 (2010)
39. Byoung-Kuk, L., Jin, H., Dong-Wook, Y.: Sign of spoke type BLDC motors with high power density for traction applications. In: Conference Record of the 2004 IEEE Industry Applications Conference. 39th IAS Annual Meeting. 2, 1068–74 (2004)
40. Ocak, O., Aydin, M.: New hybrid permanent magnet synchronous motor with two different rotor sections. IEEE Trans. Magn. 53(11). 1–5 (2017)
41. Gan, J., et al.: A new surface-inset, permanent-magnet, brushless DC motor drive for electric vehicles. IEEE Trans. Magn. 36(5), 3810–3818 (2000)

How to cite this article: Madichetty, S., Mishra, S., Basu, M.: New trends in electric motors and selection for electric vehicle propulsion systems. IET. Electr. Syst. Transp. 11(3), 186–199 (2021). https://doi.org/10.1049/els2.12018