International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

Comparative analysis of electric motor drives employed for propulsion purpose of Battery Electric Vehicle (BEV) systems

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International Journal of Science and Research Archive, 2023, 10(02), 1097–1112

Publication history: Received on 11 November 2023; revised on 22 December 2023; accepted on 25 December 2023

Article DOI: https://doi.org/10.30574/ijsra.2023.10.2.1074

Abstract

This paper presents an analysis of electric motor drives for the propulsion system of a battery electric vehicle (BEV). It offers a comprehensive review and mathematical analysis of both AC and DC motor drives commonly used in electric vehicle (EV) applications. Various types of electric motor drives have been utilized for EV propulsion, and among them, the Permanent Magnet Synchronous Motor (PMSM) drive stands out as the optimal choice. The PMSM drive demonstrates superior performance and numerous advantages, including a robust structure, high efficiency, compact size, reduced maintenance costs, and minimal torque ripple. These characteristics make it a more suitable option for EV propulsion compared to other motors. This study investigates the performance of the PMSM drive in comparison to other competitive electric motor drives used in EV propulsion systems, namely the Brushless DC Motor (BLDCM), the Induction Motor (IM), and the Switched Reluctance Motor (SRM). The evaluation focuses on key criteria for electric motors—output power and torque densities, essential for effective application in EV propulsion systems. The paper introduces novel mathematical and analytical relationships between two prominent PM motor families: the PMSM and the BLDCM. Both motors are highly competitive in terms of power and torque output. The mathematical analysis and graphical plot simulation results demonstrate that the PMSM drive offers the highest power and torque densities among the three motor drives. Specifically, the PMSM drive exhibits 29.90% greater power and torque densities than the BLDCM drive, 88.68% greater than the SRM drive, and an impressive 200% greater than the IM drive, all under the same operating parameters such as power factor, size, rating, and efficiency. These findings highlight the significant advantages of the PMSM drive, positioning it as a superior choice for electric vehicle propulsion systems.

Keywords: BEV; PMSM drive; BLDCM drive; SRM drive; IM drive; Power density; Torque density

1. Introduction

Electric motors are the brain and core element of an EV. The electric motors that are used for automotive purposes need to meet certain characteristics like high power density, high efficiency, high speed ranges, low torque ripple, high starting torque, high reliability, and reduced weight. Hence, all available electric motors for EV propulsion do not have equal importance, as all have their own merits and demerits. Regarding applications for EV propulsion systems, PMSM drive, BLDC motor, Induction motors, Reluctance motors, and Brushed DC motors are widely used.

1.1. Brushed DC Motor

A brushed DC motor is an internally commutated electric motor that uses a mechanical commutator and an electric brush for contact and is powered by a direct current power source. Brushed motors were the first commercially important application of electric power to drive mechanical energy, and DC distribution systems have been used to power motors in commercial and industrial facilities for more than a century. The speed and torque characteristics of a brushed motor can be changed depending on how the field is connected to the power supply to produce a constant

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speed or a speed that is inversely proportional to the mechanical load. This makes them able to achieve high torque at low speeds. Brushed motors are still applicable in electric propulsion (traction) systems, massive cranes, paper machines, and steel rolling mills. Even though they have good speed torque characteristics, these motors suffer from wear and tear due to the presence of brush contacts. The wearing of the commutator segments occurs because of the continuous cutting with brushes, and hence the friction between the brushes and commutator segments limits the maximum speed of the motor. Thus, brushed DC motors have low efficiency, low reliability, and a higher need for maintenance and repair, mainly due to the presence of the mechanical commutator segments and electrical brushes, even if interesting advancements have been made with slippery contacts. Furthermore, brushed DC motors have a lower power density when compared to PMSM, BLDC motor, SRM, and induction motors for use in electric vehicles [1] [2].

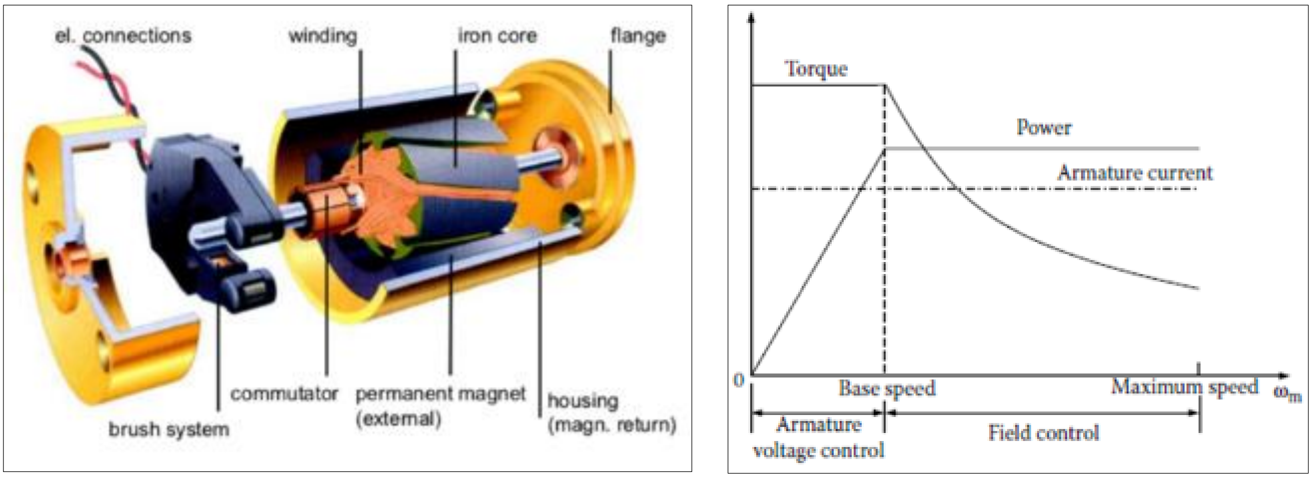

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Figure 1 (a) Cut-away view of Brushed DC Motor [3] (b) Speed Vs Torque Vs Power curve [4]

1.2. Switched Reluctance Motor (SRM)

The switched reluctance motor (SRM) is a special-purpose electric motor family designed to run by reluctance torque, i.e., torque is produced in such motors by a variable reluctance technique. Unlike the conventional brushed DC motor types, electric power is delivered to the stator windings rather than the rotor conductors. When stator coils (windings) are energized, variable reluctance is set up in the air gap between the stator and the rotor. Hence, the rotor tends to move to a position of least reluctance, thus causing torque. This significantly simplifies mechanical design as electric power does not have to be delivered to the moving part (rotor). However, it complicates the electrical design as some sort of switching system needs to be used to deliver power to the different windings. SRM can be applied for different purposes, like robotic control applications, washing machines, vacuum cleaners, and automobiles. But, due to its electrical design complexity, high torque ripple, audible acoustic noise and vibration problems, lower power density, and lower efficiency, SRM is mostly applied to electric vehicle propulsion systems due to its high starting torque [5] [6].

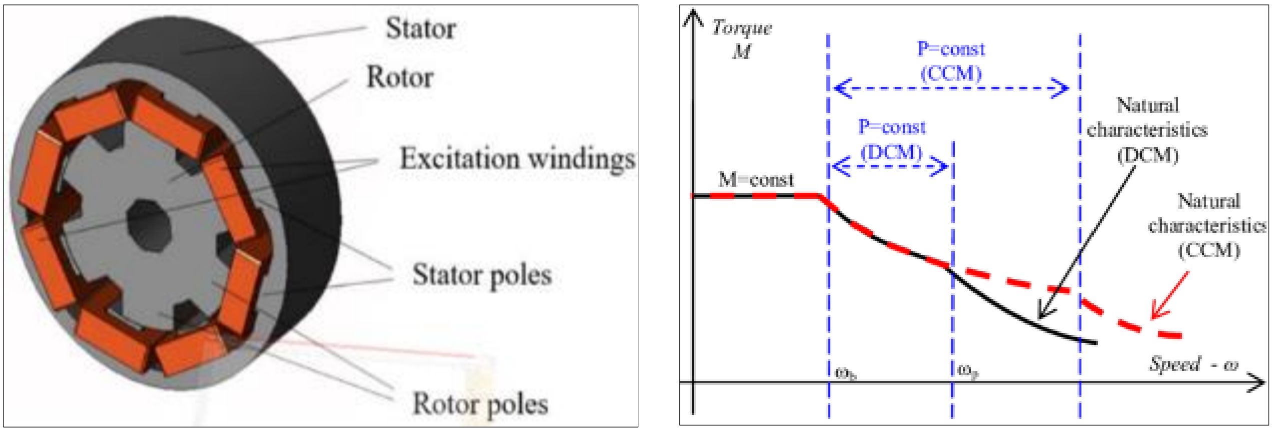

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Figure 2 (a) Appearance of switched reluctance machine 8/6. [7] (b) Torque speed characteristics of SRM [8]

1.3. Induction Motor

An induction motor, also known as an asynchronous motor, is a type of AC electric motor in which the electric current in the rotor required to develop torque is generated by electromagnetic induction from the revolving magnetic field of the stator winding [9]. Because of its high efficiency, superior speed control, lack of commutators and low cost, three-phase induction motors are commonly utilized in electric vehicles [10]. But, compared to the PMAC motor families, they have large rotor inertia, higher torque ripple, lower power and torque density, and hence lower speed dynamic response [11].

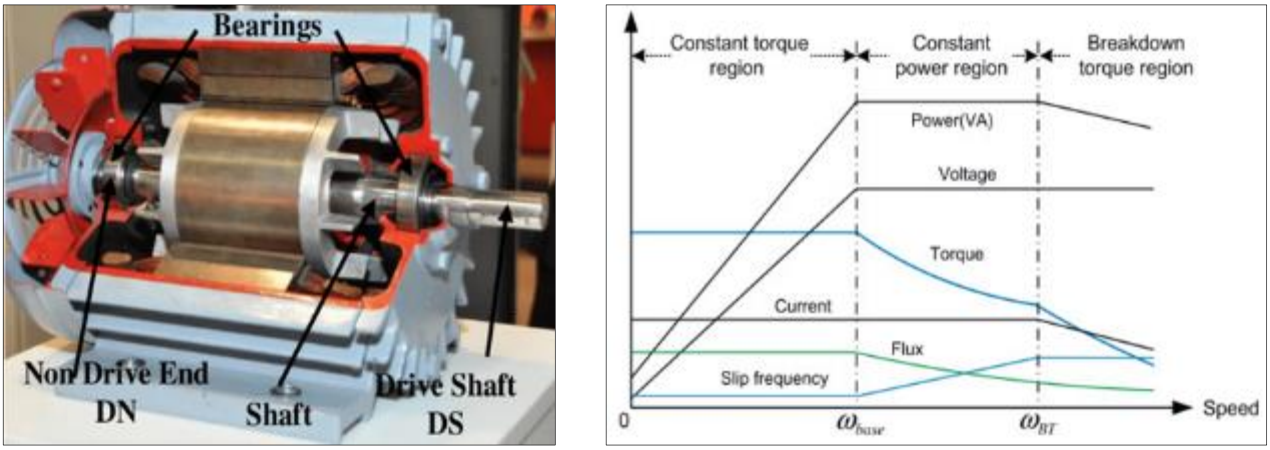

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Figure 3 (a) Cut-away view of squirrel cage IM [12]; (b) Speed Vs Torque Vs Power curve of IMs [13]

1.4. BLDC Motor

BLDC motor is an AC permanent magnet motor family with a trapezoidal back EMF waveform. Unlike the brushed DC motor, the BLDC motor doesn't have brushes, slip rings, and field windings, and the mechanical commutation is replaced by electronic commutation, which makes it have higher efficiency, less maintenance, reduced weight, and a compact size [14]. In comparison to the above three motors, the BLDC motor offers higher power density, higher dynamic response, larger torque output, lower torque ripple, high speed ranges, higher reliability, and less maintenance needs. Hence, the BLDC motor is suitable for EV propulsion systems.

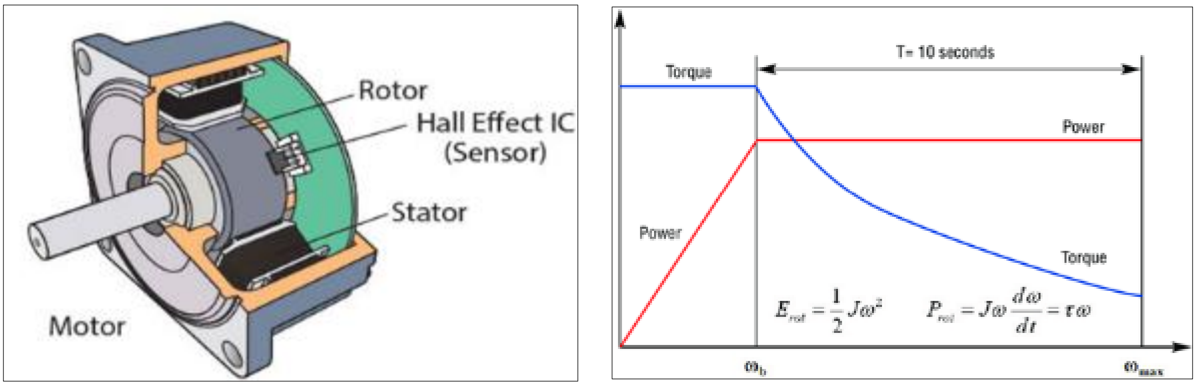

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Figure 4 (a) Cut-away view of BLDC motor (b) Speed versus Torque versus Power curve [15]

1.5. PMSM Drive

A permanent-magnet synchronous motor (PMSM) is an AC motor family that uses permanent magnets instead of electromagnets, which are embedded in the steel rotor to create a constant air gap magnetic field. The stator carries windings connected to an AC power supply to generate a rotating magnetic field (as in the case of asynchronous motors). It has a multiphase stator (usually three phase and/or, in some cases, five phase), and the stator electrical frequency is directly proportional to the rotor speed in steady state. At synchronous speed, the rotor poles lock onto the rotating magnetic field. PMSM has the same principle of operation as that of the classical synchronous machine except that it has permanent magnets in place of the field winding and has no rotor conductors, which leads it to have zero copper loss in the rotor. The adoption of permanent magnets in the rotor dynamics improves efficiency, avoids the requirement for brushes and slip rings, as well as alleviates the complications associated with control techniques, especially vector control. In such motors, neodymium magnets are the most widely employed magnets. Although, in recent years, due to the significant volatility in the pricing of neodymium magnets, much study has focused on ferrite magnets as an alternative [16] [17] [18]. The combination of an inner permanent magnet rotor and outer windings offers the advantages of low rotor inertia, reduced motor size, compact structure, efficient heat dissipation, high power density, high efficiency, high torque inertia ratio, high speed range, high air-gap flux, and no conversion spark (since there are no brushes) over other kinds of electric motors [17]. Thus, PMSM drive tops all the electric motor preferences available for EV propulsion systems.

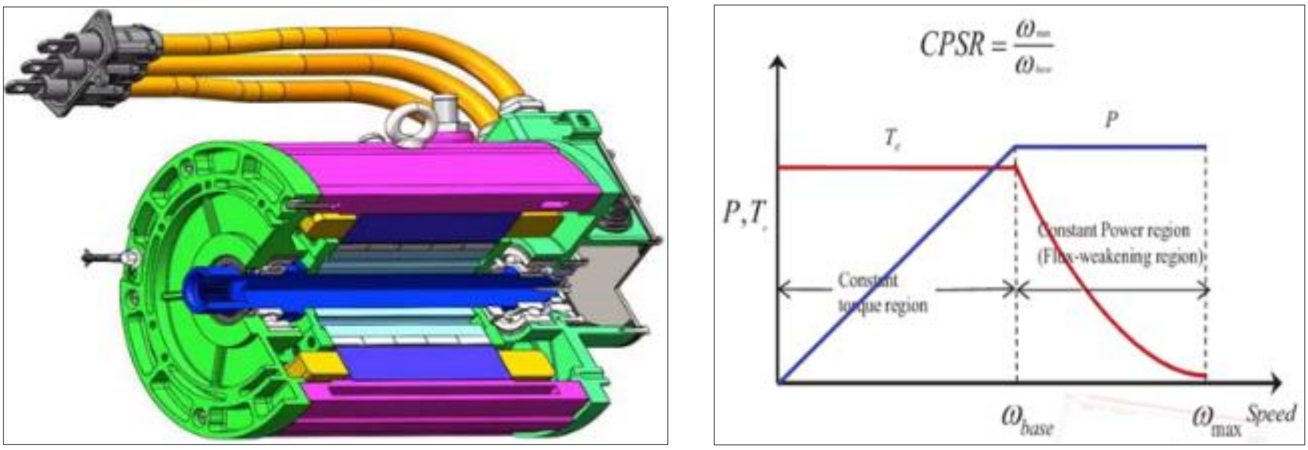

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Figure 5 (a) Cutaway view of PMSM [19] (b) Speed vs Torque vs Power graph [20]

The internal parts of the stator and rotor along with the permanent magnet can be seen as in figure (6):

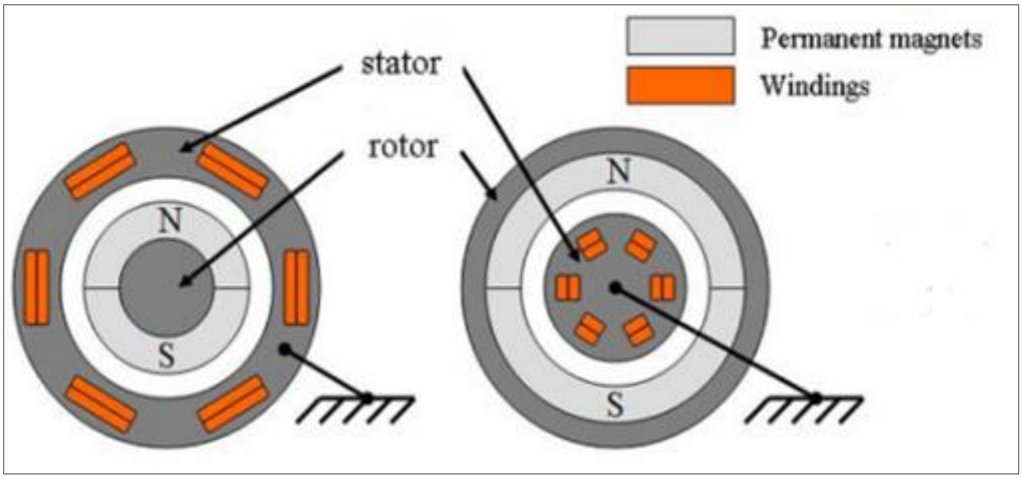

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Figure 6 Constructions of a PMSM (a) Standard (b) Inside-out [21]

2. Drivetrain of electric vehicles

The electric vehicle drivetrain requirements and specifications available in the world market are given in tables 1 and 2 [22] [23]. From these tables, it could be observed that PMSM, BLDC motor, and induction motor are the most popular from the manufacturer's vantage point. An overall comparison of electric motors based on EV requirements is required to select an appropriate motor that can mostly fulfill the EV motor technology requirements. The following are the most important criteria and required features of electric vehicle motor drives:

- High dynamic performance;
- High power density;
- Fault tolerance capability;
- Reduced power loss and high overall efficiency;
- Reduced size and weight;
- Cost-effective;
- Reduced maintenance and operating costs;
- Electromagnetic interface (EMI) suppression capability in motor controllers;
- Low/reduced torque ripples;
- High produced torque at low speed,
- Enhanced energy management system for regenerative braking system;
- High reliability and robustness of the motor at different operating states;

Table 1 Available Electric Vehicles in the world market [24]

No	Name of EV	Electric Motor type	Manufacturer Company	Passenger/seat capacity	Country
1	Fiat Panda Elettra	Brushed DC motor	Fiat	5	Italy
2	Buddy	Brushed DC motor	Buddy electric	3	Norway
3	PSA Peugeot-Citroën/ Berlingo	Brushed DC motor	PSA Group	5 or 7	France
4	Tesla Model S	Induction motor	Tesla	5	USA
5	Tesla Model X	Induction motor	Tesla	5	USA
6	Toyota RAV4	Induction motor	Toyota	5	Japan
7	GM EV1	Induction motor	General Motors	2	USA
8	ZeCar	Induction motor	Stevens Vehicles	5	UK
10	Toyota Prius	PMSM	Toyota	5	Japan
11	Nissan Leaf	PMSM	Nissan	5	Japan
12	Kia Soul EV	PMSM	Kia	5	S/ Korea
13	Honda Insight	PMSM	Honda	5	Japan
14	Lucas Chloride	SRM/ SynRM	Lucas chloride EV systems	5	UK
15	BYD E6	BLDC	BYD Auto	5	China
16	Mitsubishi i-MiEV	BLDC	Mitsubishi	4	Japan
17	BMW-i3	BLDC	BMW	5	Germany

Table 2 Requirements of electric motors used in EV [23]

Type of Motor	Max. Speed (Km/hr)	Advantages	Disadvantages
Brushed DC motor	Up to 80	Maximum torque at low speed	Bulky structure Low efficiency Heat generation at brushes
Induction motor	Up to 160	The most mature commutator-less motor drive system Can be operated like a separately excited DC motor by employing field orientation control	Complicated control Always lagging power factor Low efficiency with lighter loads
PMSM	Up to 160	Operable in different speed ranges without using gear systems Highly Efficient Compact size Suitable for in-wheel application High torque even at very low speeds High power density	Huge iron loss at high speeds during in-wheel operation
SRM/ SyrnRM	Up to 160	Simple and robust construction Low cost High speed Less chance of hazard Long constant power range High power density Fault tolerant Efficient Small	Very noisy Low efficiency Larger and heavier than PM machines Complex design and control Problems in controllability and manufacturing Low power factor
BLDC motor	Up to 160	No rotor copper loss More efficiency than induction motors Lighter Smaller Better heat dissipation More reliability More torque density More specific power	Short constant power range Decreased torque with increase in speed High cost because of PM

2.1. Advantages of PMSM drive over the corresponding motors:

The advantages of PMSM drive over the corresponding alternative motors types for EV propulsion applications are: [25] [26] [27]

Advantages of PMSM drive over Brushed DC motor

- Lighter in weight and smaller (compact) size;
- Have less audible acoustic noise;
- Spark-less and no fire hazards due to the elimination of carbon brushes;
- Higher torque and power densities;
- Comparatively negligible torque ripples;
- Better heat regulation and dissipation;
- Longer life span; and

- Higher dynamic response;

Advantages of PMSM drive over IM

- Better dynamic performance characteristics, for it has lower rotor inertia;
- Higher power and torque densities for medium power applications like EVs, resulting smaller and compact size;
- Due to its higher torque to volume ratio it has better geometrical integration in to the engine cabinet, hence reduces the overall curb weight of the vehicle;
- Has the ability to maintain full torque at low speeds;
- Lower current rating for inverter and improved battery utilization;
- Due to its higher efficiency at low speeds, it is suitable for city automobiles, where frequent start-stop at low speed. Hence, improving battery energy utilization and driving range;
- Higher power factor;
- Better heat dissipation; and
- Less noisy and more reliable.

Advantages of PMSM drive over BLDC motor

- Reduced current and torque ripple.
- Higher power to weight ratio.
- Higher and smooth torque and low noise due to lower ripples.
- Highly efficient and more reliable.
- Higher power density that would help in reducing the size and weight of the motor. Thus, PMSM drive gets better than BLDC motor in terms of dynamic performance to use in EVs.

In general, the performance comparison of PMSM drive with the possible electric motors used in EV propulsion systems can be summarized as shown in figure (7) based on ten motor performance characteristics, each with a maximum of ten points, for a total of one hundred points [28]. Higher values indicate better performance. According to the findings, PMSM drive is the best option for high-performance electric vehicles as a drivetrain.

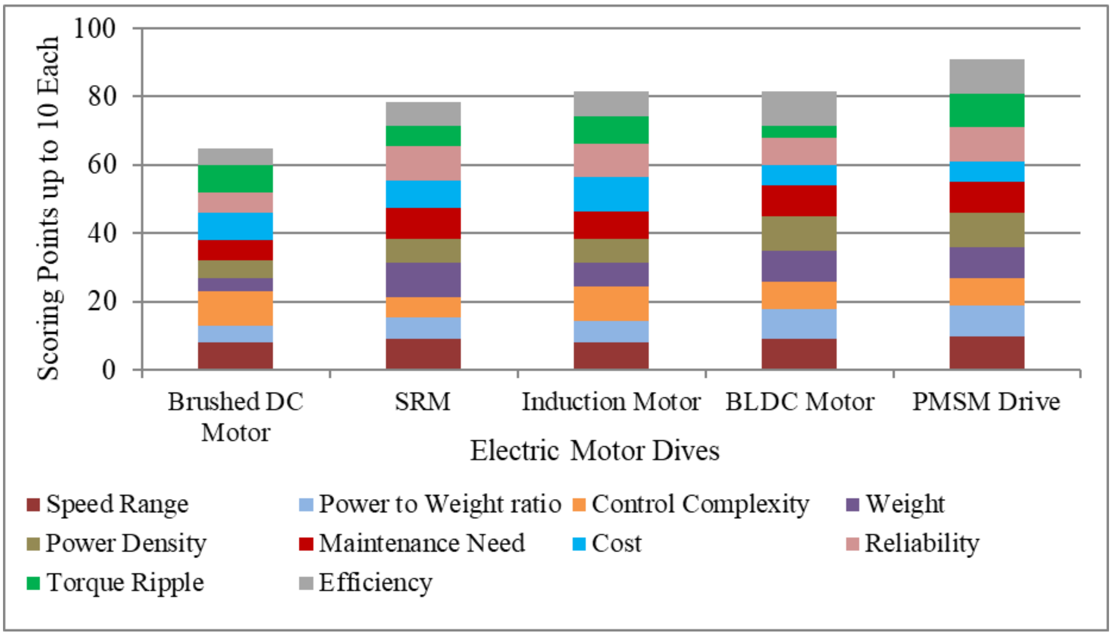

Figure 7 Performance comparison of electric motors out of 100 points

3. Methodology

The methodology generally consists of the type and specifications of the Battery Electric Vehicle (BEV) chosen for comparison, overall assumptions, and the major points considered to proceed with the comparison of the available electric motor drives employed for the propulsion of the BEV system.

3.1. Type and specification of the EV

To pursue with the performance analysis of the motors, a specific type of EV has been chosen (i.e., Nissan Leaf S Plus BEV) and the motor rating requirements of the EV is given in table 3 [33] [34]:

Table 3 Motor specification for Nissan Leaf S Plus EV [33] [34]

Parameters	Description/Values
Model Type	EM57
Company	Nissan
Electric Motor Type	3 phase AC synchronous/ Permanent Magnet
Voltage rating	360 V-
Rated Power	80 kW
Rated Current	223 A
Rated Speed in rpm/ Base Speed	4600 r.p.m and base speed of the EV 320 rad/sec
Maximum Torque @ 80 kW	250 Nm

3.2. Assumptions Made

The general assumptions made to make comparisons b/n the motor drives are:

- Electrical and mechanical loading of each motors under comparison are kept the same.
- The same machine design and construction is considered.
- The size, rating, power factor, and efficiency of each motor drive are considered to be the same.

The major comparing points this paper addresses are the power and torque density of each motor, which are required to be as high as possible for EV applications. Therefore, each motor is compared based on its output power and torque.

4. Mathematical analysis, result and discussion

This section includes the mathematical and analytical analysis performed between the Permanent Magnet Synchronous Motor (PMSM) and the other three motors. Subsequently, MATLAB simulation plots are generated from the mathematical relations, and discussions are made accordingly.

4.1. PMSM Vs BLDC

In the above sections , it is shown that PMSM drive is the best selection for EV compared to Brushed DC motors, SRM, Reluctance motors, Induction motors and BLDC motors. However, the ac synchronous family, i.e., the BLDC motor, is highly competent with the PMSM drive, specifically in terms of its simple controllability and cost. Although the two motors are highly competent to each other, PMSM has better features in terms of having a higher power output and higher torque density. In this section a novel mathematical relationships b/n the two motors is addressed, hence the power output ratio for the two motors is derived as follows, which is based on the equal cupper loss principle of their stators. Let $I_{m(PMSM)}$ and $I_{m(BLDC)}$ be the peak value of PMSM stator currents and the peak values of BLDCM stator currents respectively. The rms values of these currents can be calculated using equation (1):

$$I_{BLDC} = I_{m(BLDC)} \times \sqrt{\frac{2}{3}} \text{ and } I_{PMSM} = \frac{I_{m(PMSM)}}{\sqrt{2}} \text{………..} (1)$$

By equating the cupper losses of the two motors and substituting for the currents in terms of their peak currents, would yield:

$$3 \times I_{BLDC}^{3} \times R_A = 3 \times I_{PMSM}^{3} \times R_A \text{ ………..} (2)$$

Substituting the rms currents in to equation (1) and solving for the peak current of PMSM drive in terms of the peak current of BLDC motor gives:

$$\mathrm{I}_{\mathrm{m(PMSM)}} = \mathrm{I}_{\mathrm{m(BLDC)}} \times \frac{\sqrt{3}}{2} \text{ …………(3)}$$

The maximum values of the induced EMF in BLDC motor and PMSM drive are equal and denoted by E_m. In the case of BLDC motor, only two phases conduct at the same time, and output power is contributed by the two phases only. On the contrary, the PMSM drive has currents in all its phases and, hence, power output is contributed by all three phases. Considering power angle β at 90° for maximum power, where sin β becomes unity; the output power of the two motors is given as:

$$\mathrm{P}_{\mathrm{BLDC}} = 2 \times E_m \times \mathrm{I}_{\mathrm{m(BLDC)}} \text{ ………… (4)}$$

$$\mathrm{P}_{\mathrm{PMSM}} = 3 \times E_m \times \mathrm{I}_{\mathrm{m(PMSM)}} \text{ ……………(5)}$$

$$\text{Output Power Ratio} = \frac{\mathrm{P}_{\mathrm{BLDC}}}{\mathrm{P}_{\mathrm{PMSM}}} = \frac{2}{3} \times \frac{2}{\sqrt{3}} = 0.7698 \text{ ……… (6)}$$

The above relationship shows that the output power density of the PMSM drive is much greater than that of the BLDC motor, i.e., considering a unity power factor for the BLDC motor, the PMSM drive output power density is superior by over twenty percent, to be exact, 29.90%.

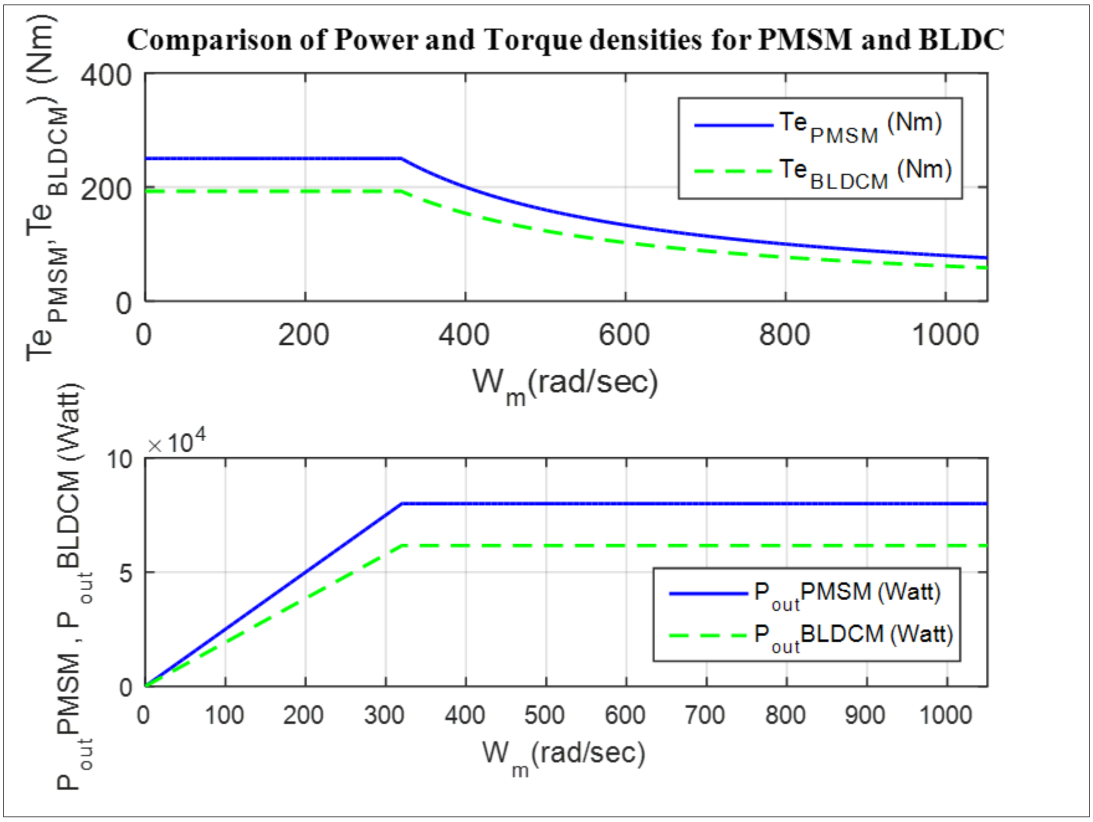

Figure 8 Output torque density and output power of PMSM drive and BLDC motor

If a base speed of 320 rad/sec with rated power of 80 kW and a maximum torque of 250 Nm of PMSM drive with the same cupper loss compared with its counter BLDC motor is considered, the output torque and output power of the two motors can be summarized as in figure (8). From this figure, it can be observed that the power output and torque density of the PMSM drive is larger than that of the BLDC motor by 29.90%, which makes it suitable for applications that require larger torque outputs like EVs, aircrafts, train, aerospace and industries.

4.2. PMSM Vs SRM

The performance comparison between PMSM drive and doubly salient SRM, in terms of power and torque density for EV propulsion system applications, is done by considering the same size, rating, and design for the two machines. Hence, the following equations are given to pursue the comparison.

The electrical and mechanical output power of PMSM drive is determined using equations (7) and (8) [29].

$$\mathrm{P_{PMSM(Elec.)}} = \eta_1 \left(\frac{m_1}{2}\right) \hat{E}_1 \hat{I}_1 \cos\varphi_1 \quad \ldots\ldots\ldots\ldots (7)$$

$$\mathrm{P_{PMSM(Mech.)}} = \eta_1 \left(\frac{\pi^2}{8}\right) k_{w1} \hat{\beta}_{g1} \hat{A}_1 D^2 L\, \omega \cos\varphi_1 \quad \ldots\ldots\ldots\ldots (8)$$

Where η_1 is the efficiency of the PMSM drive, m_1 is the number of stator phases, $\hat{E}_1$ is the maximum phase air-gap EMF (volt), $\hat{I}_1$ maximum value of the stator phase current (Amp), k_{w1} is the winding distribution factor of the motor which is given to be 0.9, $\hat{\beta}_{g1}$ is the fundamental air-gap flux density (Tesla), $\hat{A}_1$ is the peak current density or loading (A/m^2), D is stator inner diameter or air-gap diameter (mm), L is the effective stack length (m), ω is angular speed (rad/sec) and $\cos\varphi_1$ is the power factor of the motor.

The power developed by the corresponding SRM drive is deduced using equation (9). The equation is a simplified form that is done considering that only one phase conducts simultaneously ($m_1 = 1$) [30].

$$\mathrm{P_{SRM(Mech.)}} = \eta k \hat{\beta} \hat{A}_s D^2 L\, \omega \cos\varphi = \eta \frac{3\pi}{16} \hat{\beta} \hat{A}_s D^2 L\, \omega \cos\varphi \quad \ldots\ldots\ldots\ldots (9)$$

Where η is the efficiency of the SRM drive, k is global coefficient which is deduced to be ($3\pi/16$), $\hat{\beta}$ is the air-gap flux density of the motor (Tesla), $\hat{A}_s$ is current density or loading (A/m^2), D is stator inner diameter or air-gap diameter (mm), L is the effective stack length (m), ω is angular speed (rad/sec) and $\cos\varphi$ is the power factor of the motor.

The relative power density ratio ρ_P between the two machines topologies can be determined if the linear current density A, the air gap flux density β, power factor, rotational speed and the mechanical parameters are the same for both machines PMSM and SRM:

Hence, the ratio of the power densities for the two motors are obtained as [30]:

$$\rho_P = \frac{P_{PMSM}}{P_{SRM}} = \frac{\eta_1\left(\frac{\pi^2}{8}\right)(0.9)\hat{\beta}_{g1}\hat{A}_1 D^2 L\, \omega \cos\varphi_1}{\eta\left(\frac{3\pi}{16}\right)\hat{\beta}\hat{A}_s D^2 L\, \omega \cos\varphi} \quad \ldots\ldots\ldots\ldots (10)$$

$$\rho_P = \frac{P_{PMSM}}{P_{SRM}} = \frac{\eta_1\left(\frac{\pi^2}{8}\right)(0.9)\cos\varphi_1}{\eta\left(\frac{3\pi}{16}\right)\cos\varphi} \quad \ldots\ldots\ldots\ldots (11)$$

In accordance with the general assumptions made and for the sake of simplicity, it is considered that the motors have the same efficiency and power factor. As a result, the power density ratio is determined as follows:

$$\rho_P = \frac{P_{PMSM}}{P_{SRM}} = 1.88 \text{ or } \frac{P_{SRM}}{P_{PMSM}} = 0.5319 \quad \ldots\ldots\ldots\ldots (12)$$

$$P_{PMSM} = 1.88 P_{SRM} \quad \ldots\ldots\ldots\ldots (13)$$

Equations (12) and (13) denote that the power density of the PMSM drive is 1.88 times the power density of the SRM drive, or that the power density of the SRM drive is 0.5319 times the power density of the PMSM drive.

To compute the torque density of the motors, the general equation (14) can be used [31]:

$$T = \frac{n_p}{D^2 L \omega} \quad \ldots\ldots\ldots\ldots (14)$$

For the PMSM drive, the torque density can be obtained using equation (15) [32]:

$$T_{PMSM} = \left(\frac{\pi^2}{8}\right) k_{w1} C_{PMSM}\left(\beta_{g1} \hat{A}_1\, \eta_1 \cos\varphi_1\right) \quad \ldots\ldots\ldots\ldots (15)$$

$$= \left(\frac{\pi^2}{8}\right)(0.9) C_{PMSM}\left(\hat{\beta}_{g1} \hat{A}_1\, \eta_1 \cos\varphi_1\right) \quad \ldots\ldots\ldots\ldots (16)$$

For the SRM drive, the torque density can be obtained using equation (17) [31]:

$$T_{SRM} = k\, C_{SRM}\left(\hat{\beta}\hat{A}_s \eta \cos\varphi\right) = \frac{3\pi}{16}\, C_{SRM}\left(\hat{\beta}\hat{A}_s \eta \cos\varphi\right) \qquad \text{…………}\ (17)$$

The ratio of the torque densities for the two motors can be obtained by using equation (18).

$$\rho_T = \frac{T_{PMSM}}{T_{SRM}} = \frac{\left(\frac{\pi^2}{8}\right)(0.9)\, C_{PMSM}\left(\hat{\beta}_{g1}\hat{A}_1\, \eta_1 \cos\varphi_1\right)}{\frac{3\pi}{16} C_{SRM}\left(\hat{\beta}\hat{A}_s \eta \cos\varphi\right)} \qquad \text{…………}\ (18)$$

$$\rho_T = \frac{T_{PMSM}}{T_{SRM}} = 1.88 \text{ or } \frac{T_{SRM}}{T_{PMSM}} = 0.5319 \qquad \text{…………}\ (19)$$

In short, once the power density is obtained the torque density can be deduced using the relation:

$$T = \frac{P}{\omega} \qquad \text{…………}\ (20)$$

Since the motors are considered to have the same speed, the ratio of torque density will be the same as the ratio of power density of the motors.

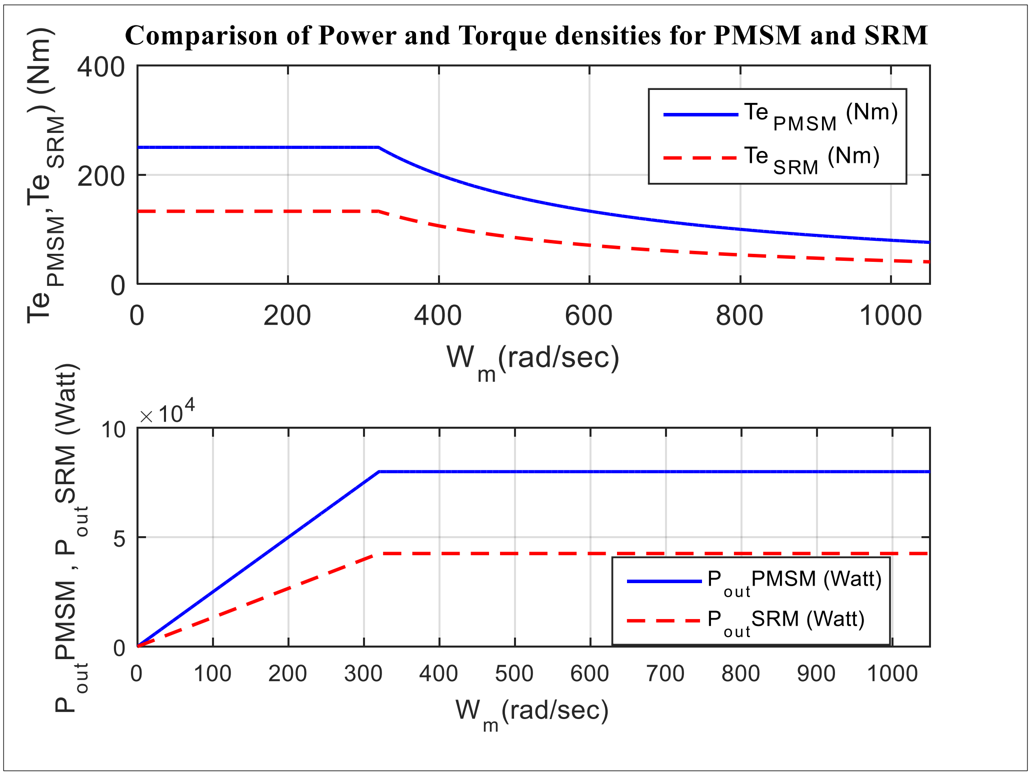

Figure 9 Output torque density and output power density of PMSM drive and SRM drive

For a base speed of 320 rad/sec with rated power of 80 kW and a maximum torque of 250 Nm of PMSM drive with the same efficiency, power factor and mechanical parameters compared with its counter SRM drive is considered, the output torque and output power of the two motors can be summarized as in figure (9). From the figure, it can be noted that the power output and torque density of the PMSM drive is larger than that of the SRM drive by 88.68 %. As a result, the PMSM drive is superior compared to SRM drive for EV propulsion systems, which require higher torque and power densities.

4.3. PMSM Vs IM

The power density of a PMSM drive is two to three times the power density of an induction motor for the same rating, size, and design of the two motors [25] [26].

Hence, considering the power density of the PMSM drive to be twice that of the induction motor, the corresponding power and torque densities will become:

$$P_{PMSM} = 2 \times P_{IM} \qquad \text{............} (21)$$

$$\rho_P = \frac{P_{PMSM}}{P_{IM}} = 2 \text{ or } \frac{P_{IM}}{P_{PMSM}} = 0.5 \qquad \text{............} (22)$$

To pursue the performance comparison between the two motors, the rotational angular speed is considered to be the same for the two motors, which results direct relationship b/n the power and torque densities. Thus, the torque density of the PMSM drive will be twice that of the induction motor.

$$T_{PMSM} = 2 \times T_{IM} \qquad \text{............} (23)$$

$$\rho_T = \frac{T_{PMSM}}{T_{IM}} = 2 \text{ or } \frac{T_{IM}}{T_{PMSM}} = 0.5 \qquad \text{............} (24)$$

For a base speed of 320 rad/sec with rated power of 80 kW and a maximum torque of 250 Nm of PMSM drive with the same efficiency, power rating, power factor and mechanical parameters compared with its counter IM drive is considered, the output torque and output power of the two motors can be summarized as in figure (10). From this figure, it can be noticed that the power and torque density of the PMSM drive is larger than that of the IM drive by 200%. Consequently, the PMSM drive is superior compared to IM drive for EV propulsion systems, which require higher power and torque densities.

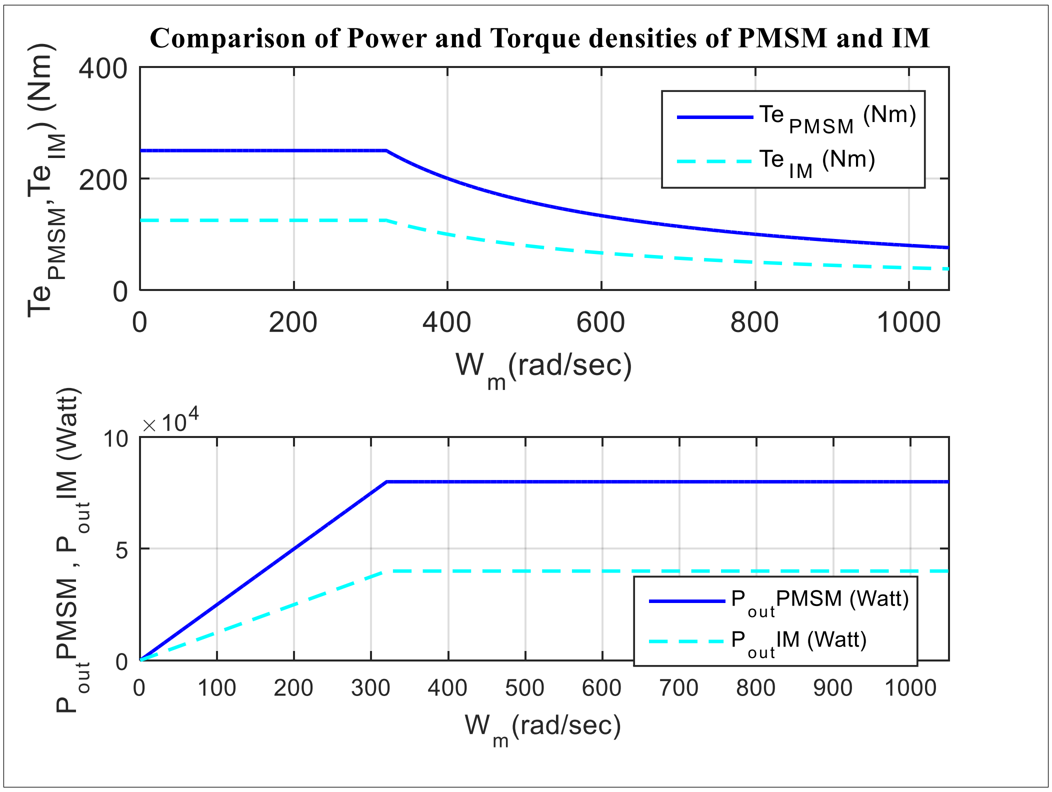

Figure 10 Output torque density and output power of PMSM drive and IM drive

Generally, the performance comparison of the PMSM drive with BLDCM, SRM, and IM in terms of torque and power densities is given in figure (11). The maximum possible output power and torque densities of the four motors when chosen to be applied to the selected EV (i.e., the Nissan Leaf S Plus) is summarized in table 4. From figure (11) and table 4, it can be concluded that the PMSM drive is the best choice for electrical systems that require high power and torque densities, like for EV propulsion systems.

Table 4 Summary of the power and torque densities of the four motors for the same physical parameters

Motor type	Max. Power Density	Max. Torque Density
PMSM drive	80 kW	250 Nm
BLDCM drive	61.6 kW	192.5 Nm
SRM drive	42.552 kW	132.975 Nm
IM drive	40 kW	125 Nm

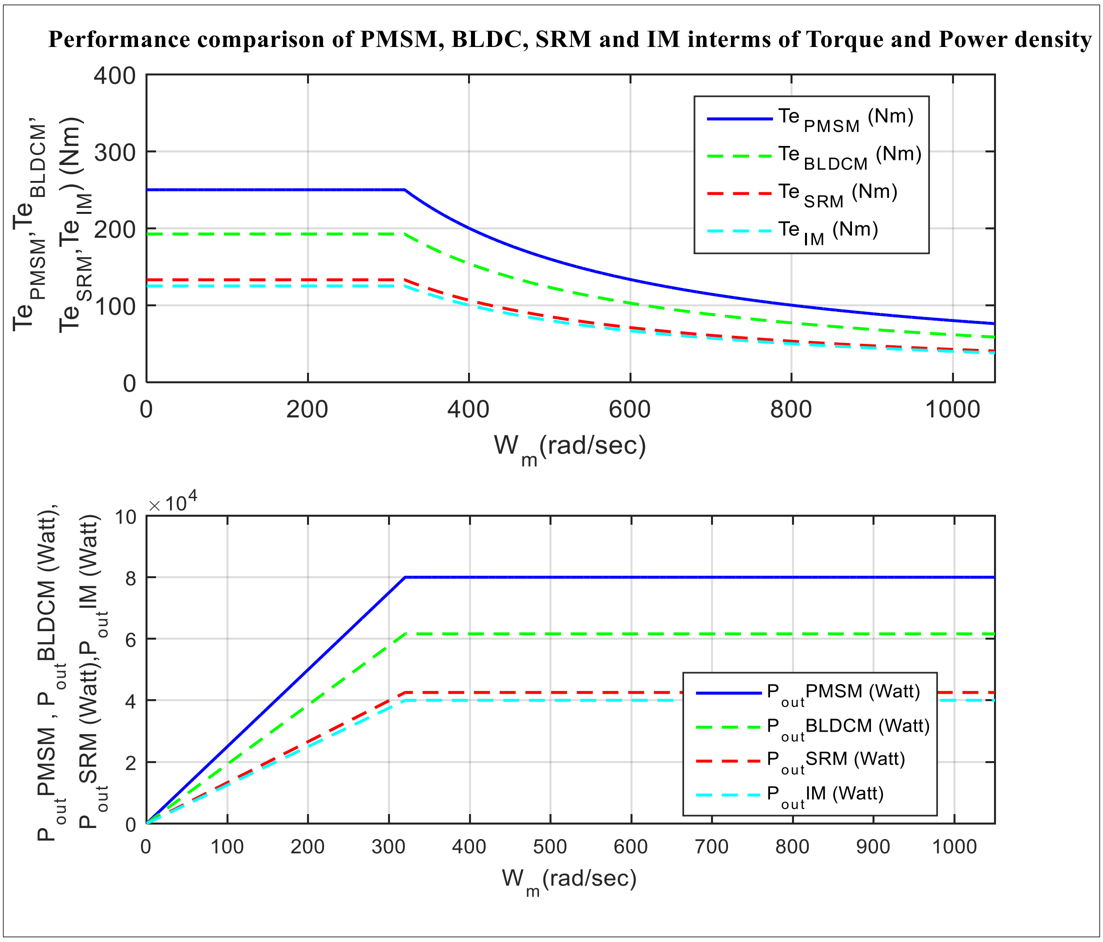

Figure 11 Performance comparison of PMSM, BLDCM, SRM and IM drives in terms of Power and Torque densities

Figures (12) and (13) depict the comparison chart of the four motor drives in terms of power and torque densities, where PMSM drive is superior of the three motor drives. The power and torque density of the PMSM drive is 29.90 % superior than the BLDCM drive, 88.68% superior than the SRM drive and 200% superior than the IM drive.

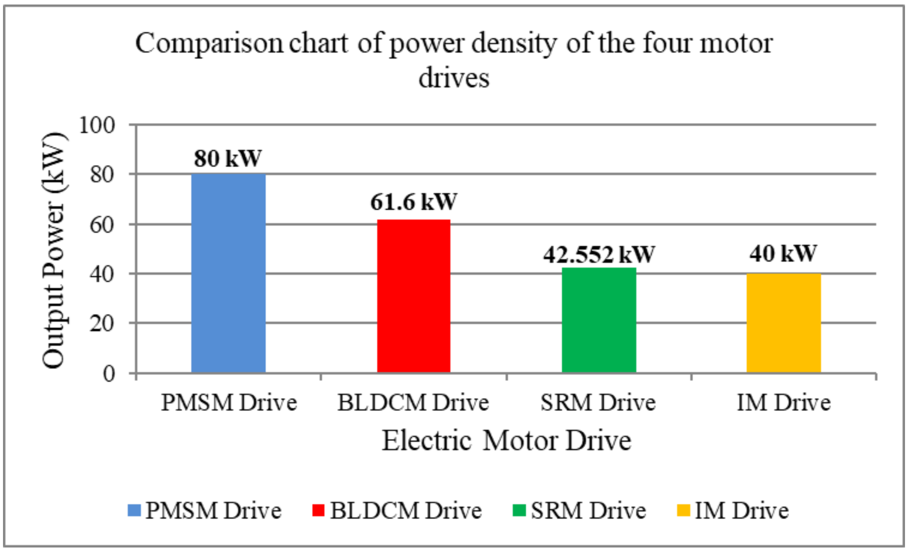

Figure 12 Comparison chart of the four Motor drives in terms of Power densities

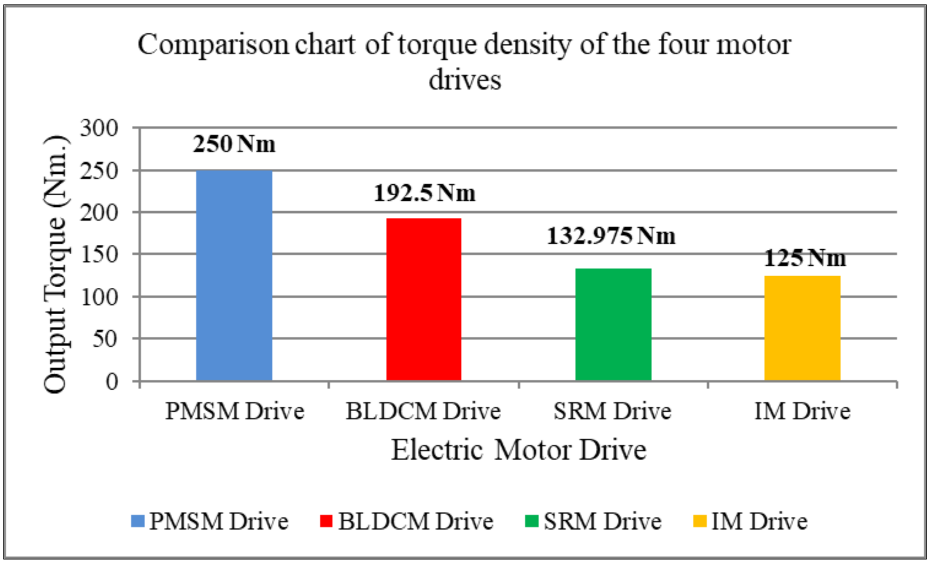

Figure 13 Comparison chart of the four Motor drives in terms of torque densities

5. Conclusion

In this paper, a comprehensive investigation and analysis of electric motor drives employed for electric vehicle (EV) applications has been conducted. The paper addresses the advantages and drawbacks of each motor drive, providing a detailed comparison. Analytical and mathematical relationships between the Permanent Magnet Synchronous Motor (PMSM), Brushless DC Motor (BLDCM), Switched Reluctance Motor (SRM), and Induction Motor (IM) drives have been established for the purpose of comparison. Operational characteristics, specifically power and torque densities have been subjected to mathematical and graphical analysis and simulation to establish a hierarchy among the electric motors. The paper also delves into the mathematical and graphical analysis to demonstrate the superiority of the PMSM drive over BLDCM, SRM, and IM in terms of power and torque densities—crucial factors determining the suitability for electric vehicle propulsion systems. According to the findings, the PMSM drive exhibits a significant advantage and preference over the other three motors in terms of power and torque output. To further illustrate the comparison, the Nissan Leaf S Plus BEV with a rated power and torque of 80 kW and 250 Nm, respectively, is considered. Based on the mathematical relations indicating that the BLDCM has 0.7698 of the power and torque output of the PMSM, the SRM has 0.5319, and the IM has 0.5, it is evident that the PMSM emerges as the top choice for the propulsion of EV systems.

Therefore, considering the comprehensive analysis and the specific comparison with the selected EV, the PMSM drive has been identified as the number one choice for electric vehicle propulsion systems.

Compliance with ethical standards

Acknowledgement

We express our gratitude to everyone who supported and encouraged us in pursuing this research. Additionally, we extend our thanks to IJSRA for their continuous and steadfast communication, as well as their valuable feedback, which contributed to the publication of this research article.

Disclosure of conflict of interest

The authors declare no conflict of interest.

References

[1] Wikipedia free encyclopedia https://en.wikipedia.org/wiki/Brushed_DC_electric_motor

[2] S. R. Jape, Comparison of electric motors for electric vehicle application, 'IJRET: International Journal of Research in Engineering and Technology, vol. 06, no. 09, p. 2, september 2017.

[3] Link reference https://www.monolithicpower.com/en/brushless-vs-brushed-dc-motors

[4] Mehrdad Ehsani, Yimin Gao,Sebastien E. Gay and Ali Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles Fundamentals, Theory, and Design, United States of America : CRC PRESS, 2010.

[5] Cheng He, Chen Hao, Wang Qianlong, Xu Shaohui and Yang Shunyao, Design and Control of Switched Reluctance Motor Drive for Electric Vehicles, 14th International Conference on Control, Automation, Robotics & Vision Phuket, Thailand (ICARCV), November 2016.

[6] Wikipedia free encyclopedia SRM,https://en.wikipedia.org/wiki/Switched_reluctance_motor

[7] Link reference https://iopscience.iop.org/article/10.1088/1755-1315/84/1/012031/pdf

[8] Link reference https://www.researchgate.net/figure/Torque-speed-characteristics-of-SRM-when operated-in-CCM-and-in-DCM_fig2_304012280

[9] Wikipedia free encyclopedia IM, https://en.wikipedia.org/wiki/Induction_motor

[10] X. D. Xue, K.W.E.Cheng and N. C. Cheung, Selection of Electric Motor Drives for Electric Vehicles, Australasian Universities Power Engineering Conference (AUPEC), vol. 08, 2008.

[11] Ektesabi and N. Hosseinzadeh, CHARACTERISTICS OF SUITABLE DRIVE TRAIN FOR ELECTRIC VEHICLE, International Conference on Instrumentation, Measurement, Circuits and Systems, 2011.

[12] Link reference https://www.researchgate.net/figure/Cutaway-view-of-an-AC-motor-Adapted-from-5_fig3_311334077

[13] Link reference https://www.sciencedirect.com/topics/engineering/induction-motor

[14] GAGANDEEP LUTHRA, Comparison of characteristics of various motor drives currently used in electric vehicle propulsion system, International Journal of Mechanical And Production Engineering, vol. 5, no. 6, 2017.

[15] Link reference https://www.orientalmotor.com/brushless-dc-motors-gear-motors/technology/brushless-dc-motors-servo-motors-inverter.html

[16] S Eriksson and P Eklund, Effect of magnetic properties on performance of electrical machines with ferrite magnets Journal of Physics D: Applied Physics, Volume 54, 2021

[17] Mahlet Legesse Gebresilassie, Speed Control of Vector Controlled PMSM Drive using Fuzzy Logic-PI Controller, thesis for the degree of Master of Science in Electrical and Computer Engineering Addis Ababa Institute of Technology (AAiT) ,August, 2011.

[18] S.-K. Sul, Control of Electric Machine Drive Systems, 1st Edition, John Wiley & Sons, Inc., Hoboken, New Jersey, 2011.

[19] Link reference https://www.hiboriddhn.com/showroom/50ktyz-permanent-magnet-synchronous-motor-ac-220v-speed-reducer-motors-6w-10w.html

[20] Link reference https://www.researchgate.net/figure/Typical-characteristic-curves-of-torque-power-vs-speed-of-IPMSMs_fig1_263272422

[21] Link reference https://en.engineering-solutions.ru/motorcontrol/pmsm/

[22] A. Tashakori and N. Hosseinzadeh, Characteristics of suitable drive train for electric vehicle, Proceeding of the International Conference on Instrumentation, Measurement, Circuits and Systems , 2011.

[23] Fuad Un-Noor , Sanjeevikumar Padmanaban, Lucian Mihet-Popa , Mohammad Nurunnabi Mollah and Eklas Hossain, A Comprehensive Study of Key Electric Vehicle (EV) Components, Technologies, Challenges, Impacts, and Future Direction of Development 2017

[24] GAGANDEEP LUTHRA, Comparison of characteristics of various motor drives currently used in electric vehicle propulsion system, International Journal of Mechanical And Production Engineering, vol. 5, no. 6, 2017.

[25] M. Karamuk, A Survey on Electric Vehicle Power Train System, Electro motion, Istanbul, pp. 315- 324, Septemper 2011.

[26] Q. Guo, C. Zhang, L. Li, D. Gerada, J. Zhang, M. Wang,, Design and implementation of a loss optimization control for electric vehicle in-wheel permanent-magnet synchronous motor direct drive system, Applied Energy, p. 1317–1332, 2017.

[27] S.Sakunthala, R.Kiranmayi, P.Nagaraju Mandadi, A Study on Industrial Motor Drives : Comparison and Applications of PMSM and BLDC Motor Drives, IEEE, International Conference on Energy, Communication, Data Analytics and Soft Computing, pp. 86- 89, 2017.

[28] Mounir Zeraoulia, Mohamed El Hachemi Benbouzid, Demba Diallo, Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study, IEEE Transactions On Vehicular Technology, vol. 55, no. 6, pp. 1756-1764, November 2006.

[29] R. Krishnan, Switched reluctance motor drives: modeling, simulation, analysis, design, and applications, Magna Physics Pubishing, 2001.

[30] J. G.W. West, DC, induction, reluctance and PM motors for electric vehicles, Power Engineering Journal, vol. 8, no. 2, April 1994.

[31] A. G. Jack, B. C. Mecrow, and J. A. Haylock, Acomparative study of permanent magnet and switchedreluctance motors for high-performance fault-tolerant applications IEEETrans. On Industry Applications, vol. 32, No. 4, July/August 1996

[32] Ritu Tak, Sudhir Y Kumar and B.S.Rajpurohit, Speed Control Schemes of Four Quadrant Operating PMSM Drive For Electric Vehicles Applications

[33] evspecifications.com/en/model/68ad67

[34] en.wikipedia.org/wiki/Nissan_EM_motor