Grenze International Journal of Engineering and Technology, Jan Issue

Electric Motors for Electric Vehicles - Comprehensive Review based on Various Performance Parameters

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***Abstract*—The main focus areas in the field of EVs has always been in regards to designing higher energy density motors (with minimum usage of PM material by improving performance parameters). In this paper, different types of electric motors are reviewed and associated to verify the benefits of each motor to find most suitability in the EV application. Comparison of different electric motors used in EVs are carried out based on various performance parameters. In this paper, authors provide comparative analysis of PM motors and Non-PM motors with advantages and disadvantages. Each motor has its own limitations and based on that the best motor candidate would be select by designer base on requirement and operating condition. FE analysis of PMBLDC motor is represented. Selection criteria and performance of the different materials used for PM motors is also discussed.**

***Index Terms*— Electric Vehicles, Electric Motors, FE analysis, PM motors, PMBLDC.**

I. INTRODUCTION

The fossil fuels proved out to be the base of energy source in the early 1970s. EVs are preferred over conventional IC engine driven vehicles because of the benefits of EVs such as efficiency and eco-friendly design. Despite being easily controllable, the commutator and brushes present in the DC machines may demand frequent maintenance. The reluctance motors show fluctuations in torque produced, which is not advisable in such applications. The power density of asynchronous motors is lesser than that of permanent magnet brushless motors, thereby, limiting the use of these machines for high power density applications [3]. The advancements in the PMSM is accelerated with the developments in the field of power electronics and the permanent magnet materials. Higher efficiency, lower volume and higher torque/weight ratio are some of the major advantages of these motors which magnifies the use of these motors [4]. The papers [5-7] compare the PMSM with different topologies used for electric vehicles. In [8], it was concluded that V-shape rotor structure is better as compared to the other rotor structures being examined by the author. Also, it was observed that the V-shape structure has the lowest magnet consumption. According to the study in [9], the W-shape rotor structure has higher efficiency. In terms of magnet placement technology, the overload capacity of surface mounted permanent magnet motors (SMPMSM) is lesser than that of the buried ones. Interior permanent magnet (IPM) motors need a higher number of stator slots in order to mitigate harmonic losses, due to which it is disadvantageous in terms of production costs [10]. In [11]. It is proved that for lower speeds, IPM machines have high efficiency and for higher speed applications, surface mount machines have high efficiency.

Grenze ID: 01.GIJET.7.1.6_2

II. COMPARATIVE STUDY AND ANALYSIS

A majority of motor selection rely on permanent magnet (PM) technology using rare-earth magnets. It offers a balance between high specific torque and low losses, which is the most desired scenario for most of the applications. Table 1 summarizes the existing electric vehicles in the European & US markets, specifying the technological solution for the traction motors.

TABLE I. TRACTION MOTORS

Vehicle	Motor Type	Material used
BMW i3	Interior PM	Rare-earth
Chevrolet Volt	Interior PM	Ferrite/ Rare-earth
Hyunday Sonata	Surface PM	Rare-earth
Mitsubishi PHEV	Interior PM	Rare-earth
Nissan Leaf	Interior PM	Rare-earth
Porsche Panamera	Surface PM	Rare-earth
Tesla S	Induction motor	Copper cage
Toyota Prius	Interior PM	Rare-earth

As per the survey carried out in [14], different motor types and configurations are used for EV applications as alternatives to the baseline PM machines that use high-strength sintered neo magnets. Instead of comprehensive comparisons, the focus is maintained on the discussion of the underlying advantages and limitations of these alternative machines suitable for electric traction applications.

A. DC Series Motor

DC series motor has a high starting torque which makes it suitable for traction applications. The benefits of the motor include easy speed control and its capability to withstand a sudden increase in load. All these characteristics make it an ideal traction motor. The main disadvantage of this motor is the need for high maintenance due to brushes and commutators. This motor lies under the category of DC brushed motors. [**]

B. Brushless DC Motors or PMBLDC

PMBLDC is similar to DC motors with Permanent Magnets instead of windings. The absence of commutator and brushes make it a brushless machine. Since the commutation is achieved electronically, the BLDC motors are maintenance free. BLDC motors possess traction characteristics like high starting torque, high efficiency (around 95-98%), etc. BLDC motors are suitable for high power density design approach. These characteristics make BLDC the most preferred motors for the electric vehicle application. Out-runner type BLDC motor (Hub motor) is widely preferred by electric cycle manufacturers like Hullikal, Tronx, Spero, light speed bicycles, etc. It is also used by two-wheeler manufacturers like 22 Motors, NDS Eco Motors, etc. Many three- wheeler manufacturers like Goenka Electric Motors, Speego Vehicles, Kinetic Green, Volta Automotive use In-runner type BLDC Motor BLDC motors. Generaly its available in power rating of 10 to 20 kW with operating voltage of 48 V-96 V. Features and Limitations are mentioned in table given below:

TABLE II. FEATURES AND LIMITATIONS OF PMBLDC

Features	Limitations
• It does not have the commutator and brush arrangement. Less maintenance • High starting torque • High efficiency • Can also operate at unity power factor • Much less rotor heat is generated. • Energy efficiency for a dc brushless drive will typically be a few percentage points higher than for an induction drive. • Compact and low weight. (Small Rotor) • No rotor winding (better heat dissipation being stationary armature) • Noiseless operation • High torque and power density	• High cost due to permanent magnet • Overloading the motor beyond a certain limit reduces the life of permanent magnets due to thermal conditions. • Produces no starting torque. • Require an absolute position sensor and requires complex power electronics • There is no easy way of changing b with permanent magnets. • Because of the nice set up of the ac system, it's capable of taking energy back from braking and giving it out under acceleration. So, a huge amount of battery power can be recovered during the normal driving process. Though a few dc systems can also do that, it makes them more expensive and complex.

C. Induction Motor (IM)

Unlike DC series, the induction motors don't have high starting torque under fixed-frequency operation and voltage. For altering this characteristic, FOC or v/f methods like techniques are used. For traction applications, the suitable maximum torque at the starting of the motor is made available through these control techniques only. Since the maintenance required in Squirrel cage induction is less, they have a long life. 92% - 95% is the efficiency up to which the induction motors can be designed. The requirement of a complex inverter circuit and difficult control is responsible for the drawback of the induction motor. In induction motors, it's high-performance capability can be proven by the Tesla Model S, as it's the best example to prove it compared to its counterparts. For eliminating the dependencies on permanent magnets, Tesla might have used induction motors. For propelling, the Mahindra Reva e20 also uses the three-phase induction motor. Manufacturers like TATA motors, which are among the major in the automotive industry, have been planning to introduce Induction motors in the cars and buses manufactured by them.

TABLE III. FEATURES AND LIMITATIONS OF INDUCTION MOTOR

Features	Limitations
• Complete elimination of all rotor magnets, avoiding one of the highest machine cost contributors. • Rotor losses can be significantly reduced by adopting copper squirrel cage instead of aluminium. • Drive-cycle efficiency of well-designed induction machine can challenge that of an IPM machine in some applications. • Magnetic field strength in machine can be lowered via stator current to reduce losses under light-load condition; valuable for extended high-speed cruise. • Absence of magnets reduces induction machine's vulnerability to damage caused by short circuit faults.	• Rotor losses are generated whenever torque is being produced, even if Fe is lossless. • Requires small air gap to minimize reactive current and maximize efficiency. • Induction machines are generally not well suited to high pole numbers, making them less desirable for lower-speed, direct-drive applications. • Constant-power speed range is more limited than IPM machines; increasing CPSR requires reduced leakage reactance, generating additional PWM losses. (Narrow operating region) • Generally a poor candidate for rotor position self-sensing at low speeds due to absence of rotor saliency.

D. PMSM

The permeability of the magnet is similar to the air in SPMSM, thus making it a non-salient machine. Now the permeability of iron parts and magnet parts of the rotor are different which results in the salient pole machine nature of IPMSM. The saliency in the machine lets us utilize the reluctance torque instead of electromagnetic torque. A PMSM is used in the GM Chevrolet Bolt where inside the rotor, the magnets are placed. A similar motor type is also used by the Toyota Prius, Nissan Leaf, BMW i3, etc.

TABLE IV. FEATURES AND LIMITATIONS OF PMSM

Features	Limitations
• Higher power Density • Higher efficiency • More effective heat distribution of heat into the environment • Speed range can be extended to 3 or 4 times the base speed. • Dynamic speed control possible • Fast reaction to load change • Small installation space, low weight • Ability to maintain full torque at low speeds.	• A short coming is that these motors is that they can be demagnetized due to the heat or armature reaction. • Narrow constant power region. • To widen speed range and increase the efficiency, conduction angle of converter can be controlled at higher speeds than base speed. • More expensive due to permanent magnet. (Cost) • Difficult to start (Initial Magnetization and difficulty in handling magnet) • Speed control is difficult. (To estimate speed and rotor position)

E. PM Assisted Synchronous Reluctance Motors (PMASyRM)

Having a low power factor is the main disadvantage of the reluctance machine. It indicates that a high volt-ampere rating is required for the inverter to produce the desired motor output power. Assisting the machine by a proper volume of permanent magnet can overcome this drawback. In general, ferrite PM is introduced in the rotor flux barriers. [16] Due to instability and increase in the price of rare earth magnets, ferrite based PMASR motors are gathering more attention by the researchers. The ferrite PMs possess excellent reluctance features which improves the flux weakening (FW) operating range with respect to other PM machines. In contrast, the surface-mounted PM machines use expensive rare earth PMs to achieve a high torque density. Also, rare earth PMs do not exhibit a wide constant power speed range, as required in traction applications. [17] The dual-motor versions of the Tesla Model S have an induction motor in the front and a permanent magnet synchronous reluctance motor in the back. The Model S and Model X switch this around, putting an induction motor in the back and a PMSRM in the front which boosted the range by more than 10 percent to 370 miles (595 km).

TABLE V. FEATURES AND LIMITATIONS OF PMASYRM

Features	Limitations
• There is no concern with demagnetization; hence SyRM are inherently more reliable than PM machines. • (Due to any problem in magnetization, the motor will not perform well or stop. These motors undergo irreversible magnetization due to changes in temperature. At extreme low and high temperatures, the magnets are irreversibly demagnetized.) • The main advantage of the SyRM relies on the absence of rotor copper losses that permits continuous torque that can be higher than an IM of the same size. • The rotor is potentially less expensive than both PM and IM motors due to cancelling cage, winding, and magnets from its structures. • The torque per ampere is acceptable and unlike the PM and IM motors it does not depend on the rotor temperature. (High Temp. Operational Capability) • High torque-to-volume ratio • Torque improvement of about 20% respect to the SyRM. (Moern ferrite PM-assisted SyRM produce 75% of the torque *wrt* interior PMSM.) • The control system is simpler than that of the field-oriented IM drives. However, rotor position information is necessary. Sensor less rotor position detection capability. • Manufacturability is easy except rotor, as all other parts are similar to IM parts. • PF is improved, large constant power speed range, and High motor efficiency. • Improved PF, so required VAr is less, so reducing inverter power rating. • Robustness and reliability • Low manufacturing cost.	• Most important **drawback** is the intrinsically higher torque ripple. • (which **can be reduced** by means of different strategies, such as an optimization of the shape of the flux barriers and skewing) • Vibration and noise •

III. FE ANALYSIS OF PMBLDC

Based on the analytical design parameters, simulation of PMBLDC motor is carried ot in MAGNET and MOTORSOLVE software. Design data is mentioned here. Achieved results by both the software are compared and minor errors are fond due to software accuracy.

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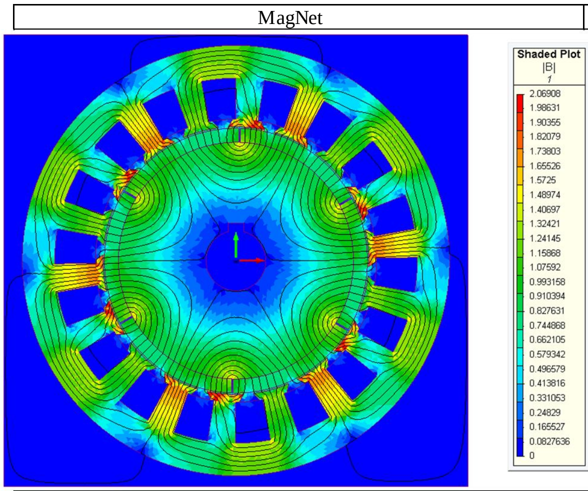
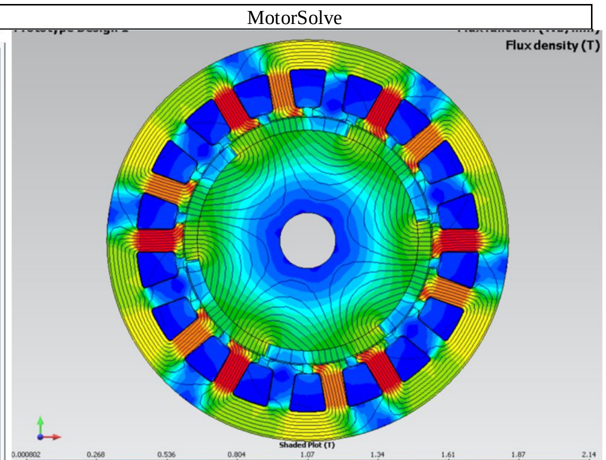
<tr><td>
</td><td>
</td></tr>
<tr><td>The Slots are square shaped and tooth width isn't uniform. So, maximum instantaneous flux density is 2.06T at tooth edge.</td><td>The slots aren't in square shape and tooth width is uniform. So, maximum instantaneous flux density is 2.14T throughout the tooth.</td></tr>
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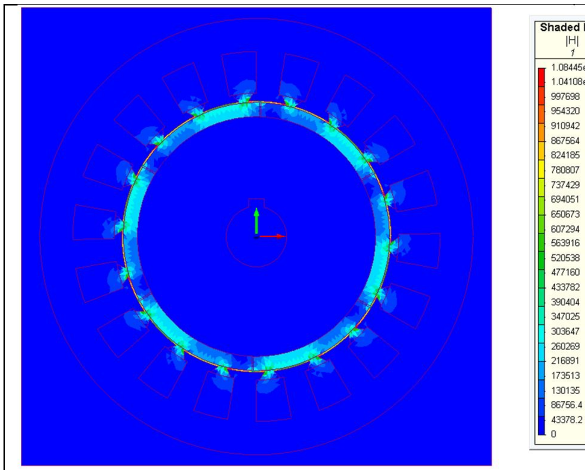
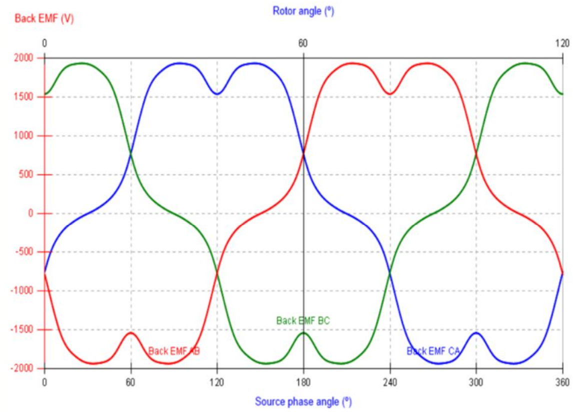
<td></td>
<td>
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<tr>
<td>Field Strength H</td>
<td>Back EMF vs Rotor angle</td>
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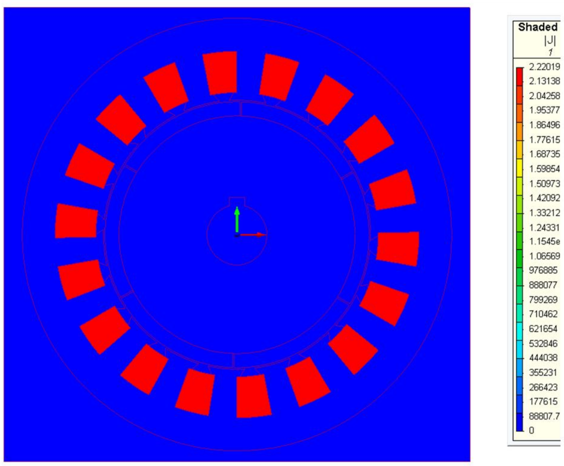
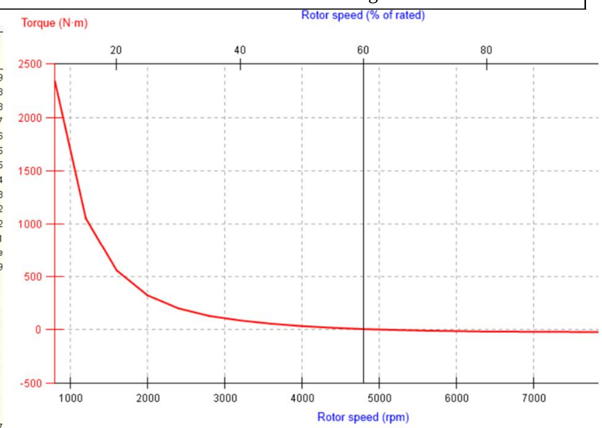
<td></td>
<td>
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<tr>
<td>Current density (J)</td>
<td>Torque vs Speed
As drive system is open loop, at higher speed, rotor's speed is more than RMF. So, torque is becoming 0/negative after 5000 rpm. MotorSolve doesn't provide close loop drive facility. To overcome this, Hall effect sensor/ floating coil feedback is compulsory.</td>
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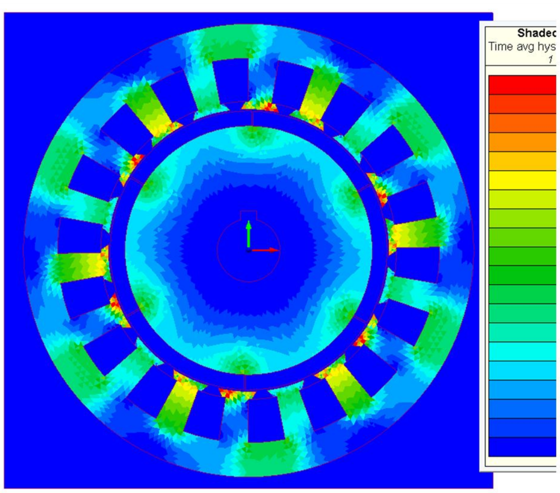
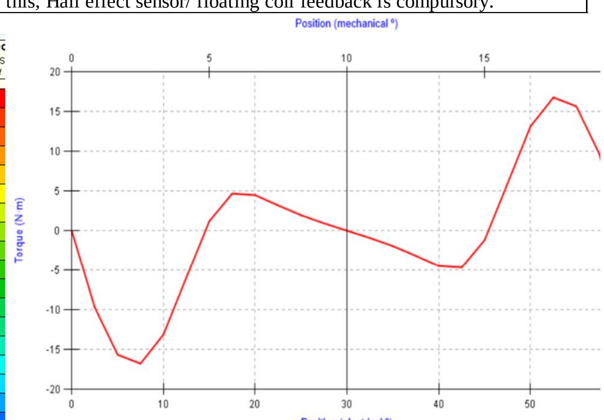
<td></td>
<td>
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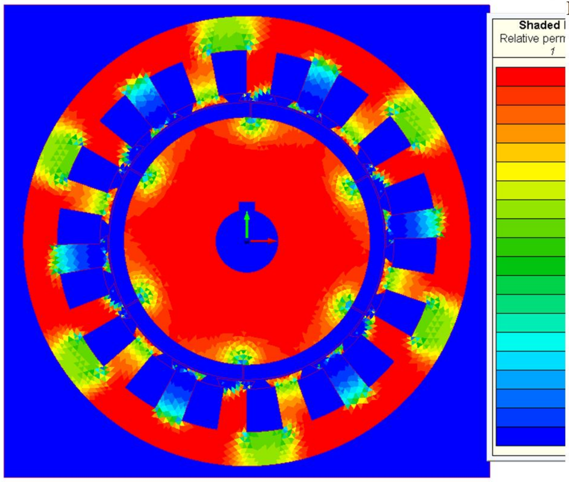
Hysteresis loss

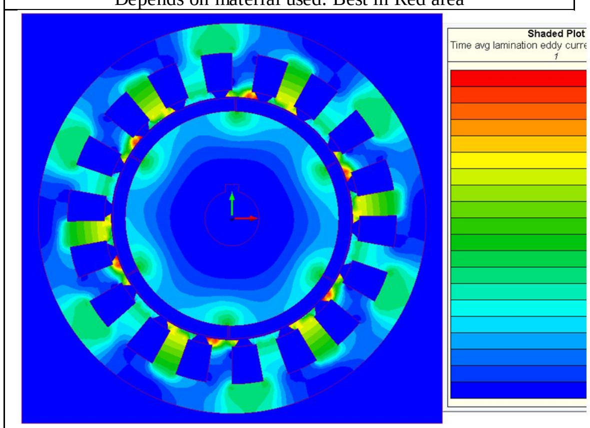
Cogging torque vs Rotor angle
+/- 17 Nm. Compare to motor rated torque (298.41Nm), it is very small.



Design parameters

- Single PMBLDC motor to drive vehicle
- P = 250kW, V = 1000V, 6 pole, 8000 rpm,
- Assumptions: η=0.8, K_{TRV} = 50 kNm/m^3, B_g = 0.8T, A_r = 1.3, S_r = 0.55, δ = 5 A/mm^2
- P = ω T T= 298.41 Nm
- L = 0.3717m D_{so} = 0.2859m D_{ro} = 0.1572m
- I_{ph} = 312.5A ac=31250A/m Z_{ph} ~ 24 Z_s = 72
- No. of conductors per slot = 4 (No. of slots =18)
- Area of each conductor = 62.5 mm^2 ~62 mm^2 standard
- Slot area = 620 mm^2 (S_f = 0.4) d = 27.27 mm w = 22.73 mm
- W_{bi} = 0.02183m (B_{st} = 1.2T, k_{st} = 0.8)

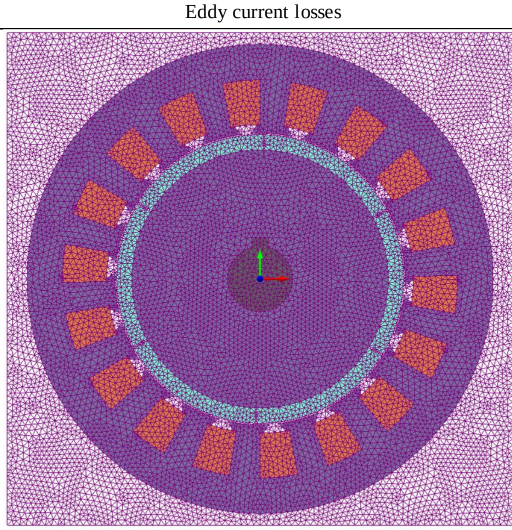
Relative permiability
Depends on material used. Best in Red area



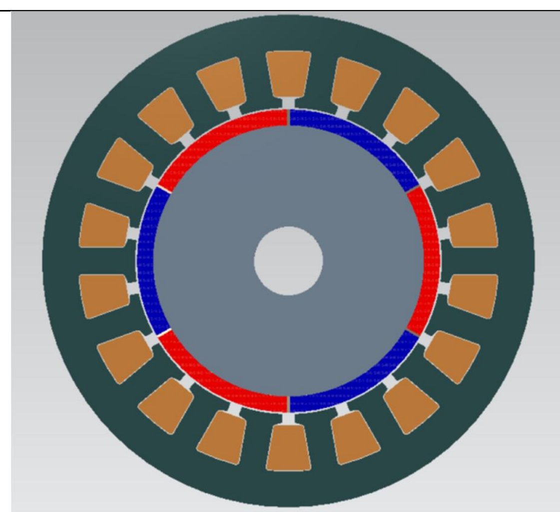
Material used:

Rotor and Stator core: M-19 29 Ga
Magnets: NdFeB
Conductors: Copper 100% IACS
Shaft: 304 Non magnetic Stainless steel

Eddy current losses



Design of Motor



Design of Motor

IV. CONCLUSIONS

As per the details given in this paper, characteristics, application, advantages and disadvantages of all motors which can be suitable for EV application are discussed in detail by considering various performance parameters. After reviewing related literature, it was found that EV manufacturer can use motor based on the requirement of power and ease of control. For low power application i.e. two wheeler or three wheeler PMBLDC is best option. For high power requirement in EVs, PMSM and Induction motor are preferred. SRM is not preferred in passenger EVs due to its significant disadvantages as discussed. Due to non-availability of PM material, high cost, less temperature handling capability researcher and manufacturers are moving towards motor in which use of PM will be eliminated or very less amount of PM material will be required. For this, PMASyRM is best candidate, and in details discussion is included in this paper. At the end, the best motor suitable for EV, is the trade-off between the various performance parameters and also type of driving cycle.

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