Trends and Challenges in Electric Vehicle Motor Drivelines - A Review

Review Paper

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Abstract – *Considering the need to optimize electric vehicle performance and the impact of efficient driveline configurations in achieving this, a brief study has been conducted. The drivelines of electric vehicles (EV) are critically examined in this survey. Also, promising motor topologies for usage in electric vehicles are presented. Additionally, the benefits and drawbacks of each kind of electric motor are examined from a system viewpoint. The majority of commercially available EV are powered by a permanent magnet motor or single induction type motors and a standard mechanical differential driveline. Considering these, a holistic review has been performed by including driveline configurations and different battery types. The authors suggest that motors be evaluated and contrasted using a standardized driving cycle.*

Keywords*: Electric vehicles, motor drivelines, electric vehicle propulsion, traction motor, power systems*

1. INTRODUCTION

Electric vehicles are gaining large-scale acceptance, because of which there has been growing interest in optimizing driveline topologies for hybrid and fully electric vehicles. Studies on common motor drive for EV and HEV have been presented in [1, 2]. The article examines the development of the EV with a focus on commercially available and upcoming electric motors. The study covers the benefits and drawbacks of current technological advances and describes the automatic components of the EV driveline.

The automotive sector has been a key force in research since the Ford T began to be produced in large quantities. Currently seen as the car of the future, electric vehicles (EVs) are rapidly acquiring industrial traction [3]. The history of the EV may be divided into three major phases. IC motors gained initial momentum. Steam cars were risky, unclean, and costly to repair. There were several technological benefits to electric vehicles. Since only major cities had fully paved roads and those lengthy trips were unusual, the limited range of EVs was less of a restriction [4].

The improvement of internal combustion (IC) and the decline in pricing due to mass manufacturing made IC automobiles the favored and only technology for years. Early in the development of the HEV, it was recognized that better efficiencies might be attained if IC motors were used in permutation with electric traction motors. The development of power electronics led to the second surge of EVs. It is also vital to note that the automotive industry was the first to study motor control for electric vehicles. The oil crisis helped to preserve interest and funding for EV development. Modern electric cars are built on the foundation of prototypes created during this time [5, 6].

The poor energy density and increase in cost of battery made EV less viable in comparison with IC automobiles [7]. However, in the current transportation landscape, HEVs and EVs are gaining traction owing to rising pollution. Additionally, there is legislative support for eco-friendly transportation, as seen by the subsidies and tax breaks for HEVs and EVs [8]. The appeal of EVs is increased by social and economic aspects. This achievement reveals resurgence in interest for effective electric drives. Specific criteria for vehicle propulsion set stationary and on-board motors apart [9]. Every kilogram carried aboard causes the system to lose energy due to friction and increases the structural stresses. High efficiency equates to lower energy requirements, which reduces battery weight. The most effective alternative would thus seem to be Permanent Magnet (PM) motors. If PM motors are made of rare earth elements, it is hypothesized that a switch to EVs and HEVs for all developed nations might result in a rise in pricing and a lack of raw materials [10].

This paper introduces different models of the motors in section 2. Survey on models of motors, followed by a study on drivelines and its configuration in section 3. Driveline Configuration, 4. Battery and a brief overview in section 5. Overview of Market and 6. Electric Vehicle Machine Trends. Finally summarizing and concluding in section 7. Conclusion.

2. SURVEY ON MODELS OF MOTORS

Modern vehicles have over 100 distinct types of electric motors [11]. While only traction motors are addressed here, it is necessary to note that the subject matter is quite broad. With direct current (DC) motors, Synchronous Permanent Magnet (PM), Induction machine (IM), and Synchronous Brushed (SB) motors, currently available; the market for electric vehicles is fragmented due to the wide range of motor architecture and requirements. The Reluctance motor (RM) is a suggested fifth architecture with promising attributes but has not seen widespread commercial use in EVs. Both the nominal speed and power of variable-speed motors are artificial constructs [11]. A vehicle's catalog power is equal to its maximum power output from the drive system, or the upper limit set by the control system as a compromise among production and battery life. The motor strikes a balance between lightweight and powerful. The peak power capacity of the motor exceeds the rating of the system. Electric vehicles' power ranges from a kilowatt (kW) for mini quads to well over three hundred kW for higher production. As the electric vehicle market expands, the number of available niches increases, but the industry is still a long way from standardization. Early prototypes' power was governed by technical specifications, but it is today driven by market demands [12]. Fig. 1 depicts the time-dependent development of the power placed in the traction motors.

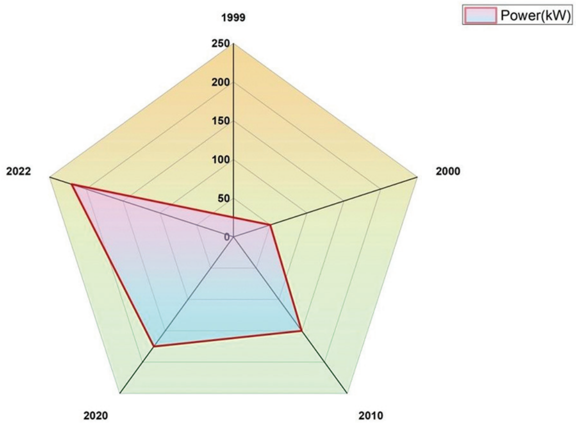


Fig. 1. Representation of power rating in EV

The operational point that every drive cycle imparts to an electric motor determines its efficiency, as is the case with IC motors. Variable speed motors do not have an industry-standard definition for efficiency rating. Efficiency maps for power and torque are used to describe them. Based on the motor type, the efficiency goes down at working points outside of the optimal region [13]. The design determines the motor's execution throughout a broad variety of speeds and powers, even though every kind of motor has a unique torque-speed relationship. For motors of similar peak efficiency, it is found that PM motors are more efficient in overload transients at constant speed, whereas RM motors perform better under high-speed overloads. The control of RMs enables for high-speed operation, but at low speeds, efficiency quickly degrades. Despite being less efficient overall than PM motors, SB motors are nonetheless highly efficient across a large operating range and can operate at high speeds because of its control. The different motor types and options for EV applications are shown in Fig. 2.

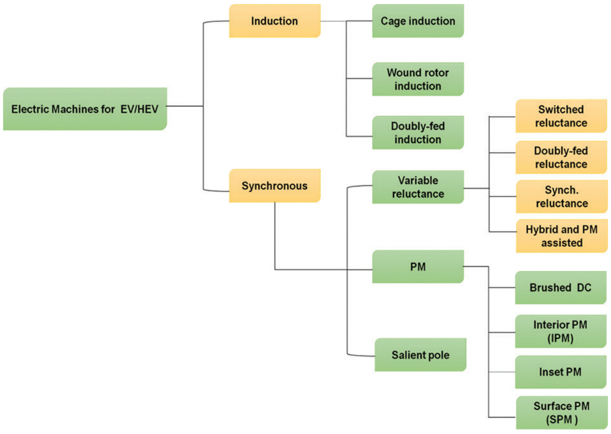


Fig. 2. Available motor types for EVs and HEVs

There are many different machine options in Fig. 2. Double-fed, wound rotor induction motors are not presently used in any automotive application within the IM category [14]. Doubly fed induction machines are often employed in wind energy production. The barrier to entry into automotive application is due to comparatively lower efficiency and power density. High peak torque, strong dynamic responsiveness, and minimal maintenance requirements across the board are some other significant benefits of these machines. It has been determined that wound-field synchronous machines might provide the increase in specific power requirement for electric propulsion. Despite being explored for several prospective uses, machine topologies such as doubly fed reluctance are not being used in any vehicles [15].

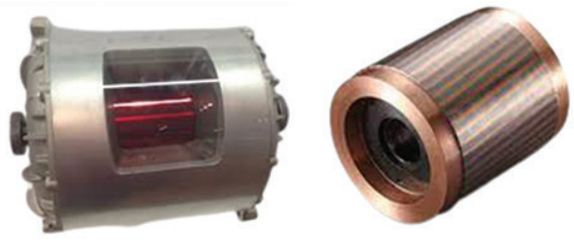
2.1. DC MOTOR

DC motors have a wound rotor and a stator. The rotor is equipped with a brush commutation mechanism and the stator possesses a stable field. Although tiny machines may have a permanent magnet excitation, the field in the stator is often produced by coils. Depending on the desired characteristics, the field winding may be linked to the rotor coils in series or shunt. The copper segments that make up the commutator create greater friction than the slip rings, which results in the production of dust. The technology is well established, the motors are reliable, affordable, and offer an easy-to-use control system as its key benefits [16].

Prior to the development of sophisticated power electronics, DC motors were the chosen choice for variable speed operating applications. Low power density (PD) in comparison to competing technologies and expensive maintenance of the coal brushes are the primary drawbacks. The coal brushes practically need no maintenance because of the low use rate of private automobiles. Lower and intermediate power range commutation vehicles are still a significant market for DC motors [17].

2.2. INDUCTION MACHINES

The most popular devices in industry are squirrel cage induction machines. They are a solid choice including traction, owing to the simple yet robust design. The features of high peak torque, strong dynamic responsiveness, and minimal maintenance requirements across the board are some of these machines' other major benefits. The technology for induction machines is old [18]. Fig. 3 shows an example of the parts of an induction machine.



Tesla Motor Cut-Out   Die-Cast Cooper Rotor

Fig. 3. Components in induction machine [16]

This technology is seen on initial Tesla car models and General Motors (GM) EV-1. Die-casting techniques that made copper rotors more affordable and gave these machines a big boost. Copper die-cast rotors have an increase in electrical conductivity than aluminum die-cast rotors, by about 60%. This means that overall motor losses are reduced by about 15–20%. Die-cast copper rotor technology may boost machine efficiency due to decreased rotor losses, reducing cooling requirements. [19]. Copper gives weight and strength to machines. Copper rotor innovation does not overcome the fundamental difficulties of the IM as a vehicle technology, especially given increased economy and PD [20]. Graphical representation of torque and power in IM as depicted in Fig. 4.

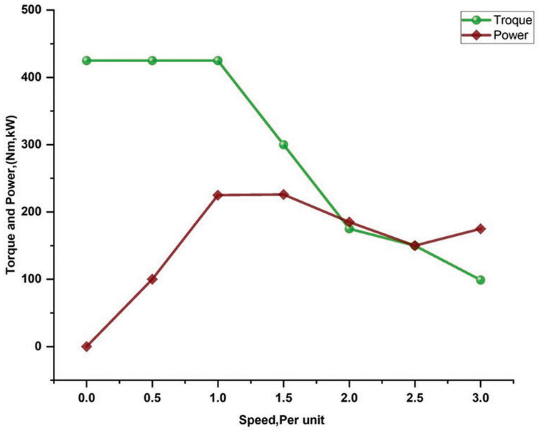


Fig. 4. Graphical representation of torque and power in IM

2.3. PERMANENT SYNCHRONOUS MAGNET MACHINE

PM machines are used in most of the machines in cars and trucks today. Most car machines employ permanent magnets. Increasing demands for high efficiency, specific power, and power density led to a move toward PMM, such as the Tesla Model 3's switch from IM to PM as shown in Fig. 5.

2010 Prius V-Shaped rotor   2017 Prius double U rotor

2016 Chevy Volt IPM rotor

Fig. 5. Rotor's IPM design for production traction motors [21]

There are many different architectures and types of PMM, but the rotor design serves as a fundamental characteristic of categorization into two major categories: permanent and surface magnet machines. Numerous crucial aspects of the machinery that have the fixed power speed range, are influenced by the rotor design [22]. The rotor design affects the fixed power speed range. Synchronous permanent magnet machines (SPMM) have a basic design/structure, however the rotor magnet causes a wider air gap, affecting performance, notably constant power speed range (CPSR).

Even though SPMM may be constructed with focused windings to increase CPSR, their use in automobiles is restricted due to the trend toward high torque, high PD machines with decreased magnet content. Interior permanent magnet (IPM) stators for traction machines can either have focused winding or scattered winding [23]. Concentrated windings feature fewer end turns, which reduces Joule loss and copper loss.

The dispersed windings might be randomly woven using strands or hairpin-wound bars. Comparing this winding design to the random wound, it is said to have greater slot fill, shorter end turns, and better production in thermal. Axial flux machines (AxFM) are a sort of PM machine that is receiving more and more negative press. For traction applications, the AxFMs offer qualities like high power density, high efficiency, small and modular construction, low weight, and high fault tolerance. They may take benefits of torque generation on numerous surfaces and have least current routes inside the machines [24].

2.4. RELUCTANCE

Synchronous reluctance machines (SyRMs) and the switching reluctance machine are two significant machine architectures that use the reluctance principle to generate torque. Both machines have a simple architecture with a rotor made simply of thin steel laminations and devoid of magnets. The SRM has relevant pole formation, but the SyRMs is normally non-salient, though it may be constructed with saliency [25]. Fig. 6 depicts the development of the SyRMs.

Original Kotsko rotor

Rotor adapted from an induction motor rotor

Rotor with Multiple Barriers

Rotor with saturable bridges

Segmented Rotor

Axially laminated V Rotor

Axially laminated U Rotor

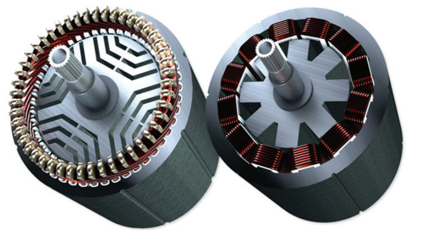
Modern transverse laminated rotor

Fig. 6. Development of the SyRMs [43]

SyRMs are desirable because of their dependability, high efficiency, little torque ripple, and ease (cheap cost) of control. Due to their popularity as a perfect substitute for variable speed-controlled induction machines, and recently, these devices became available for industrial use [26].

While trying to improve their performance, SRMs are being evaluated for vehicle industries. These machines have high CPSR and great efficiency, but noise and transient response are still hurdles [27]. Low torque ripple (TR) is critical for EVs, especially in EV designs where the electric motor serves as the primary propulsion source. Significant study has been done in recent years on decrease in TR designs, including their eradication via the design of power electronic controllers. There have been several efforts made to improve the efficiency and PDof the SRM, including the usage of double stator and double-sided architectures.

By inserting magnets into stator poles, a new generation of machines is researched. It has been suggested that SRMs be used for traction drives, and several manufacturers have reportedly used or planned to employ SRMs in their drive trains. Prototypes for traction have been created. [28]. Fig. 7 shows an SRM built to match a Prius IPM. SRM may be a potential rival for applicant motors as magnet-free devices are in demand. These machines are now used in trucks and heavy machinery, and it is anticipated that they will eventually be used in light cars [29].



Rotoe inside Stator Assemble Motor

Fig. 7. SRM in traction [30]

2.5 IN WHEEL

The space available within the wheel places a restriction on the outside diameter of in-wheel motors (IWMs). Some designs use a planetary gear and a brake disc, IWMs may also be operated directly [31]. The space available within the wheel places a restriction on the outside diameter of in-wheel motors (IWMs). Some IWMs employ a planetary gear and brake disc, whereas others are actuated directly. In concept, any architecture may be used, however PM motors with outer rotors or axial flux have higher PD and volume usage. There are several variants for reluctance and in wheel induction motors [32]. Table 1 indicates the benefits and drawbacks of various motors.

Table 1. Benefits and Drawbacks of Various Motors

No.	Motors	Benefits	Drawbacks
1	DC motor	Affordable speed controls	Excessive starting torque may harm reducers
2	Induction Machines	Induction motors function efficiently	The motor can't be used for traction or lifting when strong beginning torque is required
3	Permanent synchronous magnet	Power supply not required	No ability to regulate field strength
4	Reluctance Machines	These motors work at very high speeds.	It has High TR and low power factor
5	In-wheel	The response of the accelerator is great.	The life expectancy is reduced.

3. DRIVELINE CONFIGURATION

Compared to IC engines, electric motors provide greater configuration flexibility. One electric motor per wheel provides a simple, lightweight, and more effective transmission without a differential. New automobile body shapes are possible because of the great variety of geometries in which electric motors may be built. Single traction motor, single speed gear reduction, and differential are employed for propulsion [33]. A different setup would have a motor in each wheel. In-wheel motors save transmission area, weight, and friction losses.

When turning, the interior wheel moves more slowly than the exterior wheel [34]. Fig. 8 displays inlet and outlet wheel trajectories during a turning regime. To prevent slide and provide stability, drivelines with 2 motors need separate control and an electronic differential. Induction motors are also affected, even though it is clear for synchronous motors.

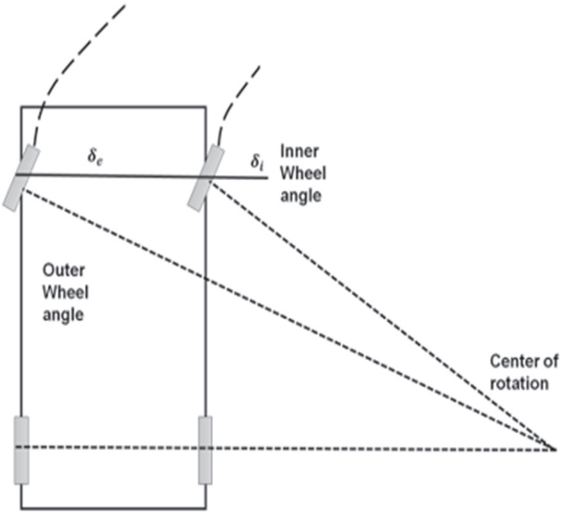


Fig. 8. Various trajectory of the inlet and outlet wheel

Induction motors' torque/slip characteristics point to a turning regime behavior that is unstable. The slower wheel has higher torque but risks losing grip, whereas the rapid wheel has less slip and consequently less torque [35]. Concept automobiles have been suggested using in-wheel engines. In particular at high speeds, the in-wheel motor has inferior dynamic performance than conventional power trains. The vehicle's unsprung mass is significantly increased by the in-wheel motor. In-wheel motors are more efficient and weigh less than mechanical drive systems. In-wheel motors are used in situations where performance is valued above comfort, like as sport automobiles, and unbeatable in solar car racing [36].

4. BATTERY

The battery selection for HEVs and Plug-in Hybrid Electric Vehicles (PHEVs) has been evaluated to achieve the appropriate balance between the electric drive and the range-extending IC motor. The mechanical design and overall cost of the vehicle are both compromised by the battery's size. According to economic research, the ideal battery size correlates to a limited range of electric battery [37]. For EVs, a variety of battery technologies are available. Before lithium-ion technology was developed, nickel metal hydride (NMH) was the favored choice for higher performance when compared to lead acid batteries.

According to the market overview, the current market is practically divided into lead-acid and lithium batteries. This battery is inexpensive and safer, but they have a lower PD. They are becoming less common, and their current uses are limited to small vehicles. Lithium-ion batteries require extensive charging cycles and are highly combustible, but their greater PD makes them the preferred solution for most general and superior efficiency vehicle producers [38].

The battery's chemistry results in nonlinear equivalent circuit behavior. Power transients significantly shorten life duration. The PD of batteries built to tolerate power transients is lower. EV batteries have longer operational cycles than identical HEV batteries [39]. Table 2 summarizes the energy and PD achieved for various methods.

Table 2. Features of Several Battery Types

Battery	Application	Wh/kg	$/kW	W/kg
Nickel Metal			1500	usage dependent
Shin-Kobe	EV	140	usage dependent	3920
Shin-Kobe	HEV	77	usage dependent	1344
Saft	EV	105	usage dependent	1550
Saft	HEV	56	usage dependent	476

Battery	Application	Wh/kg	$/kW	W/kg
Lithium ion			2000	usage dependent
Ovonic	EV	45	usage dependent	1000
Ovonic	HEV	68	usage dependent	200
Panasonic	EV	68	usage dependent	1093
Panasonic	HEV	46	usage dependent	240
Lead acid			150	usage dependent
Panasonic	EV	34,2	usage dependent	250
Panasonic	HEV	26,3	usage dependent	389

The battery's capacity is the only determinant of an EV's range. As a result, the vehicle's application and a safety buffer must be considered while choosing a battery. A key influencer of consumer attitudes regarding EVs is the driver's concern that the battery would run out before arriving at the destination. From quadricycles to very capable sports automobiles, there are many different values [40].

5. OVERVIEW OF MARKET

Environmental concerns and strict emission regulations focus research on low emission and fuel-efficient automobiles. The hybrid arrangements have re-emerged in this situation. The electronic industry's leadership in the development of battery technology has revived interest in fully electric automobiles. With a limited market for zero-emission vehicles, the sector has become more established [41]. The biggest technological drawbacks of electric automobiles compared to ICs are their short range and lengthy recharging times. Combining electric and IC propulsion, manufacturers strive to make EVs more appealing from a business standpoint.

With a high efficiency hybrid powertrain and a limited electric range, PHEVs are possible. The Extended Range Electric Vehicle (EREV) includes an all-electric driveline and a small IC engine that only kicks in when the battery is running low. As a result of drivers' concern of the electric range, the EREV IC engine has benefits. Two market trends apply to pure EVs. Commuter devices have light batteries and restricted ranges [42]. Two market trends apply to pure EVs. On the one hand, models made for commuting have a light battery and limited range. These city automobiles are lightweight and have a limited maximum speed.

Electric cars with a long range and large batteries are available. This product is targeted at the high-performance market because of the batteries' weight and cost [43].

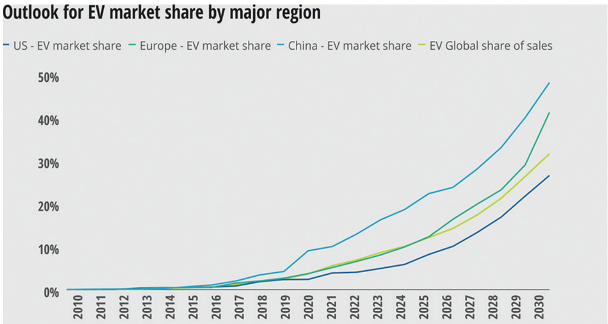


Fig. 9. EV market share projection by region [44]

In recent times, the EV market is booming with multiple alternatives in terms of range, efficiency and utility, with many products from established automakers and startups. This is further affirmed by market study and projections [44].

6. ELECTRICAL VEHICLE MACHINE TRENDS

This part includes some of the electric machine trends and challenges in electric vehicles.

6.1. ABSENCE OF RARE EARTH MAGNETS IN TRACTION MACHINES

The concurrent development of non-rare earth machine replacements is a significant trend in the development of machines for EVs. In addition to improving motor cost reduction, removing the rare-earth magnets also eliminates the reliance on this essential component. Induction machines have a decent chance of filling this requirement; however, the rising needs for high specific power and PD requirements make induction machines no longer a choice. The SRM and SyRMs machine topologies are two more crucial ones. Both machines feature a simple design with rotors made entirely of thin steel laminations. SRM controls are difficult and costly [45].

SyRMs are resilient, efficient, have minimum torque ripple, and are simple (cheap) to regulate. However, they have a decreased power factor, which impacts converter cost and size and a limited CPSR. Higher saliency ratios may mitigate these disadvantages. SynRM without magnets may be a low-cost motor and inverter if developed appropriately. SynRM and SRMs may allow for very efficient traction machines without rare earths. For non-rare-earth or reduced rare-earth drivetrains, improve SRM and SynRM [46].

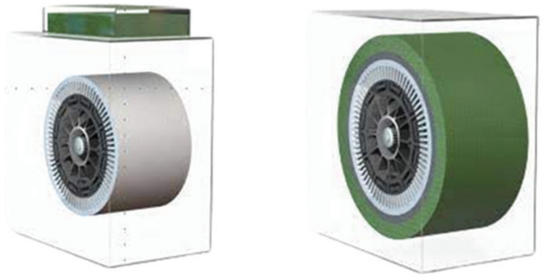
6.2. IPM DEVICES USING RARE-EARTH MAGNETS

Motors with substantial rare-earth content may fulfill critical traction motor performance parameters, and most of these machines include rare earth magnets. IPM machines' ability to generate reluctance and permanent magnet torque and perform a broad operation has increased for traction drive systems. IPM can produce reluctance torque between 40 and 50% or higher [46]. This feature makes IPM ideal for certain applications. With the ability to extract high resistance torque, one would think magnet utilization in these machines would have stabilized over time, particularly as magnets make about 20–30% of a motor's cost and manufacturers would want to reduce that cost. However, it was stated that the usage of magnets has not reduced through time and may have even risen [47].

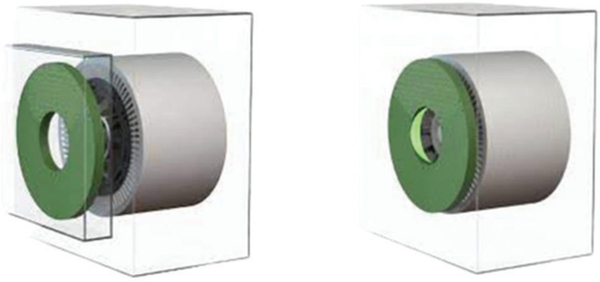
6.3. THERMAL MANAGEMENT SYSTEMS AND INTEGRATION OF MACHINERY

Another growing trend that will persist is the integration of power electronics and machines. Innovative integration approaches become increasingly crucial as space requirements for vehicle comfort rise, needing powertrain systems to become more compact. Advantages of density or reduced size, reduction in number of parts, shortened cable runs and busbars, and lower electromagnetic interference, and significant cost savings can be realized by enclosing power electronic drive and electric machine into a single compartment [48].

Integrated motor and power electronics may increase PD by at least 10% and reduce manufacturing and installation costs 30–40%. However, enclosing the electric machine and power electronics in the same compartment gives rise to system issues. Compound thermal management concerns are a challenge. Electronic boards are fragile and less tolerant to movement and roughness than motors. Combining them is difficult. Considering this, several tradeoff studies have been conducted to produce solutions that maximize integration advantages while decreasing system faults. Study [49] described four integration techniques and captured in Fig. 10.



a) Radial housing mount b) Radial stator mount



c) Axial endplate mount d) Axial stator mount

Fig. 10. Option for motor and inverter integration [50,51]

The methods basically include attaching the power electronics to the axis of the motor utilizing radial and axial mounting approach in Fig. 9. Fig. 9(a) displays the power electronic inverter on the motor's casing, whereas Fig. 9(c) displays it on the motor's end shield. Fig. 9b shows the motor stator's perimeter fitted with power electronics, while Fig. 9d shows the stator's end attached with power electronics. For instance, the more typical technique depicted in Fig. 9a is straightforward to construct but only partially capable of providing high PD. The IM is mounted on the motor housing in this form, or on the side of the housing in other versions of the same idea [52]. Additionally, the motor and drive might employ a combined or independent cooling system [53].

The cooling system may be separate in certain circumstances, which results in less than ideal system volume utilization. The cooling system may be separate in certain circumstances, which results in less than ideal system volume utilization [54]. Although the stator curvature prevents these other designs from simply providing a flat surface to install electrical components, they do provide superior integration. The design of the EV, such as the number of motors and axles, will determine the integration method and degree of integration. The Chevy Volt serves as a typical illustration of radial housing implementation in study [55,56].

To create a longitudinal instead of a vertical layout, the Tesla cars with 2 axle motors and rear motor combinations toward the axial end plate mount [57,58]. Due to the significant benefits already described, it is generally anticipated that ever-tighter integration will be sought. Advanced thermal management systems are needed to maintain the increase in PD and specific power of vehicle traction drive systems. The paper provides a thorough examination of the cooling techniques used with traction motors, their analyses, and the calculation techniques. The study gave a description of the transmission approach used in vehicle traction motors, along with their advantages and disadvantages, as well as the conditions needed to optimize cooling performance for each method discussed.

The study examined the transmission approach used in vehicle traction motors, their trends and limits, and the conditions needed to maximize cooling efficiency. As machine power and vehicle range expand, efficient cooling systems become increasingly vital. Recent trends of compact motor drive integration make the adoption of contemporary thermal management systems that can cool motor drive components and other powertrain and automotive parts sensible.

7. CONCLUSION

This study provides a summary of significant advances toward high-PD machines used for traction in vehicles, with an emphasis on existing technology and the trends that are expected in future. Since most traction machines are currently PMM and the development of devices with high specific power and PD is a major focus. The development of permanent magnet machines that produce greater reluctance torque appears to be a suitable field of work since this trend is predicted to continue in the future.

Alternative traction devices made without rare earth materials are becoming more popular. Based on the data, permanent magnet reluctance machines (switching and synchronous type) are preferred.

Based on motor performance, it can be concluded that PM motors are better than RMs, SBMs and IM, with IM being the least efficient in terms of performance. The cost of PM motor raw materials will decide whether PM motors become the industry standard or RM and SBM achieve a breakthrough in the market. The right choice of electric motor helps make design and packaging of the powertrain components easier owing to the size and lack of extensive thermal constraints. In-wheel motors make cars lighter and free up space inside, which allows for new body styles. This research can be further extended to include power converter components, as modern-day skateboard architecture encompasses drives, motors, and power management as a single unit. An integrated skateboard architecture in an electric vehicle, has closer integration with the power and thermal management system.

8. FUTURE WORK

This manuscript provides a review of motors and driveline topology used in electric vehicles. This study can be used for off-road vehicles, utility and long-haul vehicles as well. Based upon the traction, power and torque needed the use case of the motors can vary. The study can be extended to combine alternate energy sources such as hydrogen fuel cells. This review paper can be converted to a research study where different drivelines and configurations are modeled based on the physical parameters and the results can be documented.

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