RECENT TRENDS IN MOTOR DEVELOPMENT FOR ELECTRIC VEHICLES (EVs)

Electric Vehicles (EVs) continue to gain larger market share in different markets across the world. The earlier generation of EVs used traction motors based on induction machine technology comprising a stator with distributed winding and either a die-cast squirrel cage rotor or, less frequently, a wound rotor. Over the recent years, increasing requirements of high efficiency, high specific power, and high-power density has caused a shift for electrified drivetrains to use Motors based on Permanent Magnet Synchronous Machines (PMSM).

Surface Permanent Magnet vs Interior Permanent Magnet Motors

The permanent magnet motors are broadly classified into two categories - surface permanent magnet (SPM) and interior permanent magnet (IPM) machines based on the rotor design, which influences several important features of the machine, including the constant power speed range (CPSR). Though SPM machines have a relatively simple design/structure, they pose a challenge with lower CSPR as the position of the magnets are located on the surface of the rotor, which results in a larger airgap thus impacting the performance of the machine. The application of SPM machines in automobiles requiring high torque and high-power density machines with reduced magnet content has been on decline, even though they can be designed with concentrated windings to achieve significantly improved CPSR.

The electromagnetic torque generated by PMSM motors have two components, viz, magnet torque and reluctance torque. Increasing the magnet torque comes with increased iron losses at no load conditions and has implications for flux weakening operation. By designing a machine with significant reluctance torque in lieu of magnet torque, the permanent magnet volume in the machine can be reduced while the machine is still capable of achieving high CPSR. As reluctance torque plays a critical role for automotive traction, IPM motors are a favoured choice over SPM motors which do not have reluctance torque component by design.

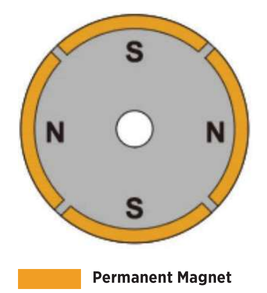


FIG 1 (A). SURFACE PERMANENT MAGNET MOTOR [REF. 1]

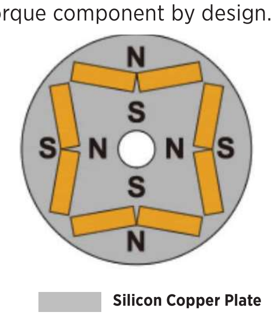


FIG 1(B). INTERIOR PERMANENT MAGNET MOTOR [REF. 1]

Interior Permanent Magnet Motor Design Trends

The rotor design, which is critical to IPM motor performance, has progressed from basic flat magnets through various configuration of U-, V-, W-, and double V-shaped magnets including variations in magnet sizes from pole to pole. The magnet volume per Nm of torque has progressively increased over the last decade with change in design from single V to double V to multiple V magnets, with significant consumption of high strength rare earth materials used for the magnets.

FIG 2(A). V-SHAPED ROTOR [REF. 2]

FIG 2(B). U-SHAPED ROTOR [REF. 2]

The stators for IPM traction motors are wound with either concentrated windings or distributed windings. The advantage of concentrated windings is they have shorter end windings leading to lower copper losses. The distributed windings typically have longer end turns leading to higher energy losses. The distributed windings on stators can be random wound with strands or bar wound in the hairpin fashion. Of late, hair pin winding on stators is gaining more attention as it has been reported to exhibit higher slot fill, reduced end turn length, improved thermal performance and possibility to have robotic and highly automated manufacturing process.

Radial vs Axial Flux Machines

Another emerging trend in permanent magnet motors is the design of axial flux machines (AxFM), which have high-power density, high efficiency, compact and modular structure, low weight and high fault tolerance characteristics that are highly desirable for EVs. Typically, electric motors are designed and constructed in order to use the radial flux distribution, where rotor and stator have a small radial air gap between them whereas the structure of axial flux motors (AxFM) trades length for diameter which allows to take advantage of torque production on multiple surfaces. Axial Flux Machines, with shorter current paths in the machine, are versatile and the winding can be varied by geometric arrangement according to the design specific diameter, making it possible to considerably reduce the total volume occupied by the machine. The axial flux motors have specific positioning of their magnets in planes parallel to the coils, which allows generating magnetic flux over a smaller rotary volume resulting in a decrease in the moment of inertia and the overall mass of the rotor. Owing to large diameter and short length, axial flux motors, with power range of 100-260 KW and specific power density of 5 KW/kg are well suited as in-wheel hub motors.

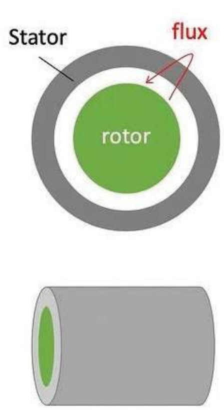


FIG 3(A). RADIAL FLUX MACHINE [REF. 3]

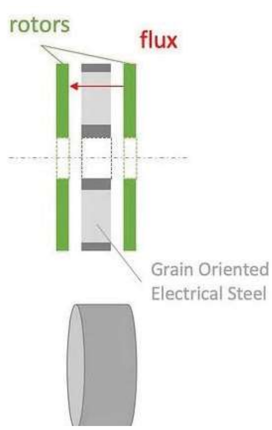


FIG 3(B). AXIAL FLUX MACHINE [REF. 3]

IPM Machines with and without Rare Earth Magnets

The ability of IPM machines to develop permanent magnet torque and reluctance torque in 40-50% range and to achieve a wide CPSR operation has dramatically increased their appeal for traction drive systems. Most of the IPM machines over the last decade have used rare-earth magnets because alloying rare earth materials such as Neodymium (Nd) and Dysprosium (Dy) into iron creates magnets with much greater magnetic strength than standard iron magnets. The magnets alone contribute approximately 20–30% of the cost of the overall motor and over the last 15 years, the cost of Nd has increased by a factor of 20 (~$10/kg to ~$200/kg) while the cost of Dy increased by a factor of 40 (~$50/kg to ~$2000/kg). This created a need for IPM design without rare earth magnets.

The usage of magnets without rare earth materials not only leads to reduced overall motor cost but also reduced mining of these materials and associated environmental impacts. Though Induction machines have been around for almost 100 years, the increasing demands on high specific power and power density requirements are eliminating induction machines as viable options for EV traction applications. Recently, two viable alternatives of machine topologies have emerged that eliminate magnets on the rotor composed of only thin steel laminations, viz., Synchronous Reluctance (SynRM) machines and Switched Reluctance Machine (SRM). The disadvantages with SRM range from significant noise and vibration issues and high torque ripple to significant complexity and costs in controls. While SynRMs have advantages such as robustness, high efficiency, low torque ripple and simplicity through low cost of control, they also have major disadvantages such as limited CPSR and lower power factor which impacts converter sizing and cost. With proper design, SynRM with no magnets can be a very attractive low-cost machine from both motor and inverter perspective and can also overcome the above disadvantages through significantly improved saliency ratios. With continued research, SynRMs and SRMs can provide a path to obtain high performance traction machines without rare earth content that will not only be cost effective but also environmentally friendly.

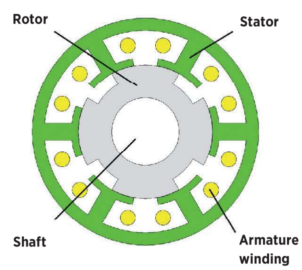


FIG 4(A). SWITCHED RELUCTANCE MOTOR [REF. 4]

FIG 4(B). SYNCHRONOUS RELUCTANCE MOTOR [REF. 2]

Integrated Motor and Inverter

Integration of Motor and Inverter and associated power electronics (PE) is another emerging trend that will call for innovative integration techniques as space requirements for vehicular comfort increase, forcing the design of more compact PE devices. The integration of motor and PE devices into one enclosure (package) not only provides benefits of compactness and reduced size but also ease of installation, reduced number of parts, shortened cable runs and busbars, all of which in turn translate into desirable technical benefits including reduced electromagnetic interference, reduced voltage overshoots on motor drive terminal as well as significant cost savings. A major advantage of integrated motor and power electronics is that it can achieve 10–20% improvement of power density and 30–40% reduction in manufacturing and installation costs. However, a major problem posed by the co-location of electric machine and power electronics in the same package is the compounded thermal management issues of the system. Another issue is that, though the motor is designed to be more tolerant to vibration and harshness the integrated power electronic boards that experience the same vibration are fragile and less tolerant to vibration. These problems have been the subject of research with the view to developing practical and innovative solutions that harness the advantages of integration while minimizing the problems of the system.

FIG 5(A). INTEGRATED MOTOR INVERTER [REF. 5]

FIG 5(B). INTEGRATED MOTOR INVERTER [REF. 6]

Four major types of integration techniques comprising radial and axial mounting approaches are available which primarily involve mounting the power electronics on either the motor housing as in Figure 6a and 6c or on the stator as in Figure 6b and 6d. In Figure 6a, the power electronic inverter is mounted on top of the housing of the motor while the same component is mounted on the end shield of the motor in Figure 6c. In Figure 6b, the power electronics is mounted on the periphery of the motor stator, while it is mounted on the end of the stator in Figure 6d. Each of these mounting variants have advantages and disadvantages. For example, the more common approach shown in Figure 6a is simple to implement but has limited capability of achieving high power density. In this design, the inverter package is placed on the housing of the motor or in some variations of the same concept, on the side of the housing. Furthermore, a shared or separate cooling system for the motor and drive can be used. In some cases, the cooling system is separate, leading to sub optimal utilization of system volume. The other designs where the power electronics is fitted to the stator periphery yield a better integration but due to stator curvature, they do not easily lend a flat surface to mount electronics components.

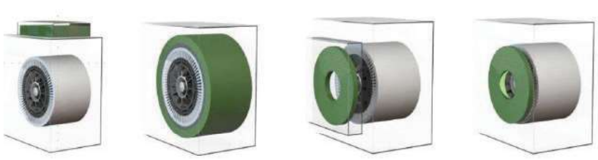
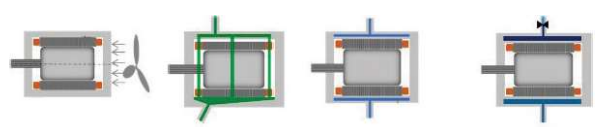


FIG 6. MOTOR & INVERTER INTEGRATION OPTIONS: A) RADIAL HOUSING MOUNT, B) RADIAL STATOR MOUNT, C) AXIAL ENDPLATE MOUNT, AND D) AXIAL STATOR MOUNT [REF. 2]

The integration strategy and the level of integration will be dependent on the configuration of the vehicle, including number of motors and axles. In general, vehicles with a front motor may be integrated differently than those with rear motor or both and even then, the arrangement of the motor drive will depend on the size of the vehicle, battery footprint and other factors. For example, compact front axle vehicles would most likely opt for radial housing mount. Vehicles that feature two axle motors and rear motor configurations have leaned toward the axial end plate mount in these vehicles, creating a longitudinal instead of vertical arrangement. In-wheel type integrated motor drives are most likely to be configured as in Figure 5b or Figure 5d. In general, it is expected that tighter and tighter integration will be pursued due to the important advantages mentioned previously. Tight integration will become even common as drivetrains converge toward mass market skateboard platforms.

Advanced Thermal Management Systems

For continued improvement in power density and specific power of vehicular traction drive systems, advanced thermal management systems are required (Ref [7]). Various cooling technologies and computation methods have been developed for automotive traction motors including the natural, forced air, forced liquid and phase change types. In a forced air-cooling system, a fan or a blower is employed to generate the continual passage of air through a motor or over its exterior. The forced air-cooling system can be segregated into two different varieties depending on the enclosure of a motor: an enclosed fan cooled (EFC) motor and an open fan cooled (OFC) motor. A major challenge associated with fan cooling is the emission of acoustic noise, especially at high speed fan operation. This forces the motor design engineers to move towards more effective liquid cooling systems, which are found to be suitable especially for high-power electric motors, where the requisite outputs cannot be attained by EFC or OFC motors. Majority of traction motors use housing jacket cooling with water or oil in addition to other forms of cooling. In this cooling system, the forced liquid passes through the housing jacket, stator channels and/or rotor channels of the motor. The most common liquid coolant in thermal management of electric motors is water due to its high relative heat capacity and less susceptibility to stains, corrosion, leakage and contamination though liquid ethylene glycol and water (EGW) in 50:50 ratio and engine oil are also used in select applications (Ref. [7, 8]).



AIR COOLING OIL COOLING WATER COOLING REFRIGERANT COOLING

FIG 7. MOTOR & INVERTER COOLING METHODS [REF. 8]

As machine power requirements and vehicle range continue to increase and as multiple applications of tight motor drive integration are introduced into the market, there is an increasing need for advanced cooling systems such as active cooling based on water glycol or oil or R134a refrigerant, passive cooling, and integrated thermal management systems. The advanced thermal management systems can simultaneously provide the needed cooling of motor drive components as well as other power train and vehicle components. Recent launches of popular Electric Vehicles indicate different levels of integration and correspondingly different interconnections between components, thus needing different thermal management systems. While in one EV, the cooling is interconnected between all drive train components and the battery, in another EV, tighter integration is observed in the second generation of the vehicle compared to the first – thus reconfirming the trend that most of the future Electric Vehicles will follow a tighter integration with a common thermal management system that interconnects all drivetrain components and the battery.

In conclusion, this article presented an overview of recent trends in traction motors in Electric Vehicles with notable shift towards high specific power density and high-power density machines and the technological trends that are likely to be pursued in near future. The major directions likely include the development of permanent magnet machines with high specific power and high-power density, since majority of the traction motors are currently permanent magnet machines. This trend is expected to continue into future. In particular, the development of permanent magnet machines developing increased amounts of reluctance torque seems a natural area of activity. The multi-fold increase in cost of rare earth materials over the last 15 years is forcing non-rare earth alternative traction machines to gain significant ground, which is likely to continue into future. For PM machines without rare earth magnets, synchronous reluctance and permanent magnet assisted reluctance machines as well as switched reluctance machines have been favoured by many researchers. It is also becoming a trend to integrate the machines and drives and the thermal management system in one package, and to transition from Si-based to SiC-based devices, and these trends obviously will impact the choices made in machine design. It is also expected that, as a future trend, most vehicles will follow a tighter integration to a common thermal management system that interconnects all drivetrain components and the battery.

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