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Design and Analysis of Interior Permanent Magnet Motor for Hybrid Electric Vehicles

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***Abstract*— Because of the need for clean energy and the requirement to lower carbon dioxide emissions from internal combustion engines, researchers and engineers are studying and creating novel driving systems. Vehicle emissions have been drastically cut thanks to the invention of hybrid automobiles. This, though, falls short. Being completely clean, the implementation of the all-electric vehicles is crucial. As a result, an electric motor is used in place of the internal combustion engine typically seen in cars and other vehicles. Researchers in the field are therefore concerned about the need for significantly improved motors that can function at their best. A review of various electric motors is provided in this document along with information on their affordability, efficiency, durability, and design simplicity.**

***Index Terms*— Electric motors, EVs, Internal Combustion Engines.**

I. INTRODUCTION

A road vehicle that is powered by electricity is known as an electric automobile. With this broad definition, EVs might also encompass fuel-cell electric vehicles(FCEVs), hybrid electric vehicles, and battery electric vehicles (BEVs). EV is an interdisciplinary discipline that covers a variety of complex subjects. However, it does have some fundamental technologies, including technology for the chassis and body, propulsion, and energy sources [1]. Energy and environmental issues have arisen as a result of the growing use of internal combustion (IC) cars, which burn non-renewable conventional fuels and produce pollutants such carbon dioxide, hydrocarbons, and nitrogen oxides. In an effort to address the issues that conventional cars exacerbate, hybrid electric vehicles (HEVs) have been developed and put to use recently [2–3].Many countries have devised electric vehicle (EV) development policies to ensure sustainable energy usage [4]. Electric vehicles are seen as a solution to the problem of greenhouse gas (GHG) emissions and, more broadly, global anthropogenic emissions, which are primarily, produced by the transportation and energy sectors. They also provide new commercial opportunities and diversify the energy sector [5]. Recent technological developments have led to the introduction of electric automobiles. Because the range of an electric bus is severely limited by the battery capacity, we cannot ignore the need for daytime refueling for these new vehicles [6].EVs need 59–62% less electrical power from grid to drive the wheels than gasoline-powered cars do. Without an exhaust, EVs accelerate more quickly, produce fewer pollutants, and require less maintenance. EVs have a few drawbacks in addition to their many benefits. Driving distances for EVs are not that far (defined as the entire distance in miles that an electric vehicle can go after having a full charge). They normally have a range of 62 to 107 miles, with the exception of Tesla models, which can go between 234 and 270 miles on a single charge. It can take an EV between 30 minutes and many hours to fully recharge, therefore having access to a charging station is always required. More people live near gas stations than electric vehicle charging points. There were more than 15,943 publicly accessible charging stations with more than 42,550 outlets in the US as of 2017 [7]. Since before 2000, electric vehicles (EVs) have been around. They sold reasonably well and were generally well-liked up until roughly 1918. However, when gasoline-powered internal combustion engines (ICEs) developed, EV use for transportation decreased. By 1933, there were hardly any EVs left because they were slower and more expensive than ICEs. The revival of EVs is mostly fueled by factors such as rising energy prices, energy independence, and environmental protection. Due to their increased cost and supply-restricted nature, EVs are being looked at as a potential alternative mode of transportation in light of the imminent shortage of gasoline-based products. Given that electricity can be generated from a wide range of alternative energy sources, EVs are the ideal variable fuel vehicle. Additionally, when energy suppliers have surplus capacity, they are frequently refilled. The environmental advantages of electricity over gasoline are the key considerations that have renewed interest in electric vehicles. Electric vehicles (EVs) can dramatically lower air pollution in heavily populated urban areas. [8]. As a result, the annual cost of operating electric vehicles is very low.

II. NEED OF ELECTRIC VEHICLES

Transport is a vital component of modern life, yet the traditional combustion engine is increasingly becoming less efficient. Automakers are quickly replacing the highly polluting gasoline and diesel vehicles with all-electric vehicles. Fully electric cars (EVs) are significantly better for the environment than conventional automobiles because they emit no pollution. Because of the advantages listed below, electric vehicles are absolutely important for day-to-day transportation.

A. Lower Operating Costs

Compared to a fuel- or diesel-powered car of comparable value, an electric vehicle's operating costs are far lower. Electric vehicles recharge their batteries using electricity rather than fossil fuels like gasoline or diesel. Electric vehicles are more cost-effective than others because charging one costs less than buying gasoline or diesel to power it for your travel needs.

B. Cheap Maintenance Costs

Electric vehicles have a lot fewer moving parts than internal combustion vehicles, which leads to very low maintenance costs. Electric cars require less maintenance than conventional gasoline or diesel vehicles. As a result, running an electric vehicle has a relatively low annual cost. Since there are only so many fossil fuels available, including gasoline and diesel, their consumption is destroying our planet. Unpleasant emissions from gasoline and diesel automobiles have a long-term harmful impact on public health. Electric vehicles produce significantly less pollution than those driven by gas or petrol. Electric vehicles are more efficient than gasoline or diesel vehicles, which can only transfer 17 to 21 percent of the energy from the fuel to the wheels. The wheels of electric vehicles could be powered by about 60% of the grid's electrical energy. Eighty percent of that was wasted. Even if power output is taken into consideration, gasoline or diesel vehicles emit nearly three times as much carbon dioxide as the average EV. Pure exhaust is produced by fully electric vehicles.

C. No Noise Pollution

Due to the absence of an engine, electric vehicles may operate quietly. An automobile without an engine is silent. To find out if the electric motor is on, you must look at the instrument panel because it operates so quietly. Manufacturers must create fake sounds for electric vehicles because they are so silent in order to safeguard pedestrians. [9].

In the next 50 years, there will be an increase of 2.5 billion automobiles on the road and a growth of 6 billion people to 10 billion. Where will the oil come from if all of these automobiles have internal combustion engines (ICEs)? Where should the emissions be released? Will the ominous sky remain there always? People are inspired to strive towards 21st-century sustainable road transportation by the gloomy replies to these questions.

The advancement of EV technology has sped up to meet these objectives in a society where preserving the environment and reducing energy use are top considerations. The emission-free urban mobility that EVs may provide will be advantageous to the environment. Using electric vehicles (EVs) can dramatically lower global air pollution, even when the radiations from the power stations required to fill up cars are taken into consideration. Electric vehicles can provide a secure, complete, and fair power solution that's effective and beneficial for daily life, such as the use of a variety of renewable energy sources. Consequently, EVs could have a significant impact on energy, transportation, and the environment as well as on the development of hi-tech, the emergence of new industries, and economic growth. Let's start by examining the population and automobile growth shown in Fig. 1 to get things started. [10]

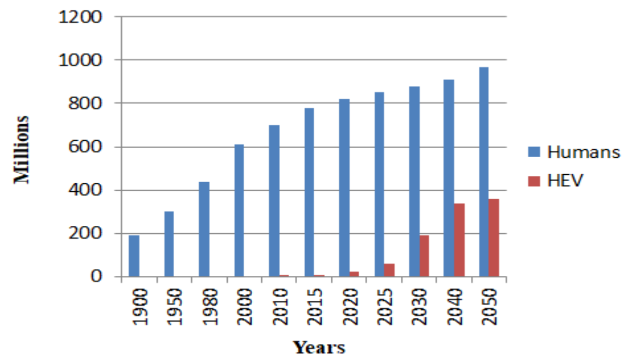


Fig: 1Growth of population and vehicles

III. RECENT TRENDS IN EVS/HEVS

The current stage of electric vehicle (EV) development is influenced by a variety of factors that have an impact on its creation and use. How quickly EVs are produced and deployed is influenced by a variety of factors, including labor costs, the availability of natural resources, and restrictions on new infrastructure. The need for renewable energy will directly affect what an EV must be able to do. Consequently, EVs offer another cutting-edge mode of mobility in addition to replacing conventional ICE vehicles [11]. The PHEV is the most recent HEV advancement to garner international attention. By restoring the most sought aspect of pure EV on top of the benefits of HEV that are already there, it is thought to be one near to entirely emission-less vehicles. This feature enables use of the all-electric mode, enabling an initial few kilometers of entirely fuel- and emission-free driving [12].

IV. EVS (MENTIONED OR LISTED HERE ARE CURRENT EVS AND HEVS)

Figures 2 through 5 show how the BMW-El [16], IZA [15], Nissan FEV [14], and GM Impact [13] look.

Fig.2 GM EV1

Fig.3 Nissan FEV

Fig. 4.lZA, TEPCO and Tokyo R &D.

Fig.5 2022 BMW iX – Electric SUV

V. MOTORS IN EVs (RECENT TRENDS)

Electric vehicles and drive propulsion systems employ a variety of motor types. As indicated in Fig. 6, different electric motors utilised in electric vehicles can be categorised [17].

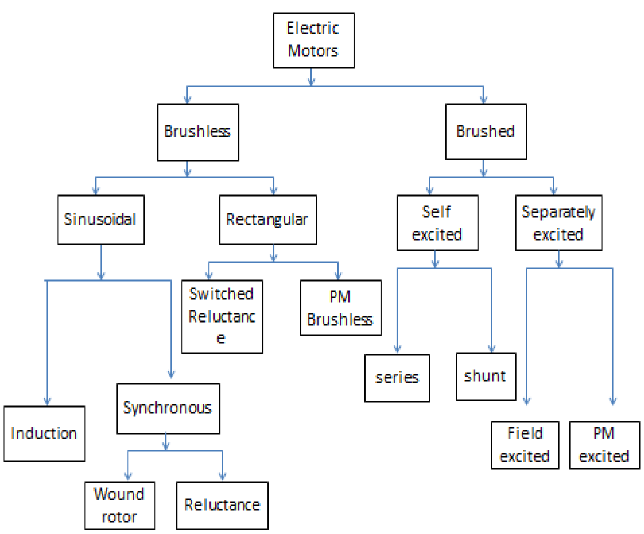


Fig.6 Classification of electric motors

VI. MOTORS IN EVs (MENTION/ ENLIST THE PRESENT DAY MOTORS USED IN EVS/HEVs)

Electric motors and drives have a big impact on whether EVs, HEVs, and FCVs are successful. For electric vehicles, hybrid electric vehicles, and fuel cell vehicle applications, there are three standard classifications of electric motors that are appropriate: Switching reluctance motors, permanent magnet synchronous motor (PMSM) or permanent magnet brushless dc (PMBLDC) motors, and induction motors round out the list. Common needs for motor and drive technologies contain large torque and power thickness, a extensive speed range, continuous torque and power working, high capability throughout a large speed range, high durability and robustness, and an affordable price.

A. *Permanent Magnet Synchronous Motor*

Success or failure of EVs, HEVs, and FCVs is heavily influenced by electric motors and drives. There are three primary kinds of electrical motor that can be installed in electric vehicles, hybrid electric vehicles and fuel cell vehicles.The list is completed by induction motors, permanent magnet synchronous motors (PMSMs) or permanent magnet brushless dc (PMBLDC) motors, and switching reluctance motors (SRMs). Automotive applications frequently use permanent magnet synchronous machines (PMSMs), which offer a high power density, high efficiency, and quick dynamic performance. Excellent performance and dependability PMSM drives are essential for electric vehicle (EV) applications. The permanent magnet's temperature has a significant impact on how well PMSMs work and are controlled (PM). This is becausethe problem of rising temperature is unavoidable. because PMSMs require a significant amount of current to supply the propulsion thrust in EV applications [20]. Due to their high dependability and power-to-weight ratio (up to a few kW/kg), permanent magnet synchronous motors (PMSM) are being installed more and more in a variety of technological domains (transport: AGV trains; aeronautical: aeroplanes, as in our case; etc.) [21]. The most effective option is considered to be an inside permanent magnet synchronous motor (IPMSM), due to its efficiency, power density, and broad speed operating range. Because the resistance torque may be used in the field weakening zone, the speed range of an IPMSM can be increased while retaining constant power [22].

Permanent magnet synchronous motors have been frequently applied in the automotive sector for the propulsion systems of electric vehicles (EV) and hybrid electric vehicles (HEV), where there is a tendency to achieve high mechanical speeds [23]. Surface-mount permanent magnet synchronous machines (SM-PMSM) are commonly utilised in specialised applications or in applications where efficiency is of the utmost significance as exceptionally accurate positioning systems. SM-PMSMs offer a favourable power-to-weight ratio, low rotor inertia momentum, and high dynamic performance [24]. The use of permanent magnet synchronous motors (PMSMs) in hybrid and electric vehicle (EV) applications is widespread. These motors, however, depend on permanent magnets, which are made up of rare-earth components. Because of their expensive price, limited supply, and negative environmental impact, rare-earth metals are not widely used in mass-produced EVs [25]. Interior permanent magnet synchronous motor IPMSM is depicted in fig. 7 [26].

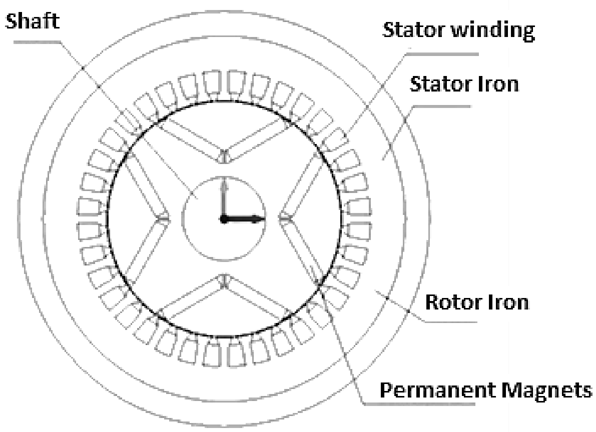


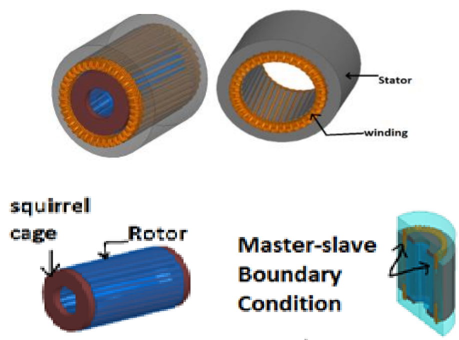
Figure.7, Cross section of IPMSM under construction

Table 1 SPECFICATIONS OF PROPOSED IPMSM

Attribute	Value
Rated Power	30Kw
Rated speed	2500 rpm
Number of poles	4
Frequency	83.33 Hz
Voltage & Phase	415 V & 3Φ
Efficiency	80%
PM thickness	8millimeter
No. of stator slots	36
Angle of V type PM/ °	120
Outer diameter of a stator	210 millimeters
Inner diameter of a stator	136 millimeters
Outside diameter of a rotor	135 millimeters
Inside diameter of a rotor	48 millimeters
Air gap length	0.5 millimeter
PM width	28 millimeters
No. of turns in slot	54
Stack length	100 millimeters

B. Induction Motor

The stator winding's magnetic field is utilized in this motor's electromagnetic induction to draw current. The rotor current is now used to generate torque. The most popular asynchronous motor on the market is the induction motor. [27]. The IM has numerous default scenarios because of the sensitivity of its operation modes to a wide range of unfavorable situations [28]. Ac drives utilizing induction machines are currently rising in popularity in a range of industrial variable-speed applications due to the performance they can provide [29]. Induction motors (IMs) are a common commutation-less motor for electric vehicle propulsion due to their robustness, high level of dependability, and absence of maintenance requirements [30].The choice of flux level has a direct impact on the minimizing of the induction motor. As the flux level rises, the iron losses also climb. On the other hand, severe reduction causes substantial copper losses. The ideal flux level guarantees the smallest possible loss. The induction motor of an EV encounters four types of losses: First, copper is lost in the stator, followed by core loss in the rotor, copper loss in the rotor, and core loss in the rotor. Since the slip frequency at the rated speed is too low, core loss in the rotor is commonly ignored [31]. Table 2 contains the parameters for3Φ, 7.5 kilowatt, 400 volts, 2 pole induction motor (IM) illustrated in the 3D model in Figure 8. [32].



Fig; 8 Structure of induction motor

Table2 Designed Specifications of motor

Parameter	Value
Outer diameter of a stator	240 mm
Inner diameter of a stator	135 mm
Length of stator	210 mm
Air gap	0.35 mm
Number of slots in stator	36 mm
Skew	1 slot
Material of Rotor and Stator	M350-50A
Outer diameter of a Rotor	134.3 mm
Inner diameter of a rotor	30 mm
No. of rotor slots	28
Stacking factor	0.95

C. Switched Reluctance Motor

A switched reluctance motor (SRM), a doubly important electric device, turns utilizing reluctance torque rather than electromagnetic torque. The employment of power switching transistors in the motor's operation is referred to as being "switched" in this context. But because power electronics had not developed at all, this was the reason that hampered the development of SRM. One of the key selling aspects of SRM is how straightforward its structure is. The rotor is nothing more than a stack of ferromagnetic material laminations; the windings and/or permanent magnets are only found in the stator. In addition, the windings are distributed in nature. SRM is relatively straightforward to build from a manufacturing standpoint. The core laminations of conventional designs are formed by stamping there, and the windings of the stator may be quickly attached. The coil's placement, which when operating produces a lot of heat, is advantageous for cooling. SRM, however, has a number of well-known flaws in its design, such as high torque ripple and acoustic noise, which are now popular research subjects [33]. The switching reluctance motor has been in operation for more than 150 years; therefore the idea is not new. In 1842, SRM was first employed to drive a locomotive. When Nasar introduced a variable reluctance motor for variable speed applications in 1969, interest in SRM was rekindled. The following events and characteristics have made a big difference in the reinvention.

1) High-power semiconductor engineering made its debut.
2) Knowing that the application of magnetic saturation can boost the efficiency of energy conversion.
3) Understanding the energy savings that variable speed drives can provide.
4) The development of affordable microcomputers.

Switching reluctance motors have the advantage of being manufactured with minimal complexity. Their toughness and quick operating are further advantages. The 2-D computer-aided design (CAD) model in Figure 9[34] shows how simple a doubly salient, singly stimulated switching reluctance motor can be designed.

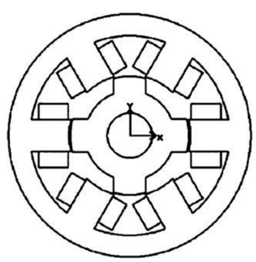


Figure 9, CAD Model of SRM

DESIGNED SWITCHED RELUCTANCE MOTOR

The design of this motor, which has a rated speed of 110 000 rpm and a rated output of 1.5 kW, was inspired by the articles Kozuka (2008) and Chayopitak (2012) as well as current high-speed motors used in the automobile sector. Tables 1 and 2 summaries, respectively, the mechanical and electrical properties of the envisaged motor. A list of the complicated designs was provided in the article Koan (2018) [35].

D. Permanent Magnet Brushless DC (PMBLDC) Motor

Permanent-magnet brushless dc (PMBLDC) motors use permanent magnets on the rotor and an electrically commutated winding on the stator to excite the magnetic field. These motors are more efficient and smaller than induction motors because rare earth magnets are used and manually commutated dc motors. Despite being less efficient, single-phase PM BLDC motors are less expensive and simpler to produce in large quantities than three-phase PM BLDC motors. They are utilized when the required output power is between a few watts and less than 100 watts. Cogging and excitation torques are applied to the rotor in non-salient permanent magnet motors. Cogging torque is produced by the contact of the stator tooth and permanent magnet, However, excitation torque is created when the permanent magnet field and winding current interact. Single-phase, homogeneous air gap PM BLDC motors cannot start on their own because the excitation and cogging torque levels coincide at zero torque. To separate the cogging torque's zero torque point from the excitation torque and enable self-starting, an asymmetric air gap is created. However, a large torque ripple can be produced by such an asymmetric air gap. A tapered air gap design delivers the least torque ripple, according to previous studies [36]. Compared to traditional brushed DC motors and induction motors, BLDC motors have a few advantages. Some of these are wider speed ranges, high dynamic responsiveness, high efficiency, extended service life, superior speed vs. torque characteristics, silent operation, and longer service life. BLDC motors are also dependable, affordable, and simple to use. BLDC motors are frequently used in servo applications such as automotive, aerospace, medical, instrumentation, actuation, robotics, machine tools, and industrial automation equipment due to their better electrical and mechanical features. The functioning of BLDC motor drives has been enhanced using a variety of machine design and control strategies.

DIAGRAM OF PERMANENT MAGNET BRUSHLESS DC MOTOR

Figure 10 shows structure of brushless DC motor. Stator windings resemble those in a poly-phase AC motor, and the rotor is made up of permanent magnets. Brushless DC motors (BLDC) have fixed stator windings and a strong permanent magnet rotor. Static stator windings are typically 3-phase, which implies that a different voltage is applied to each of the three sets of windings [36]. Unlike AC synchronous motors, which detect the rotor's position (or magnetic poles), brushless DC motors have a system for sensing the rotor position and using that information to generate signals that control the electronic switches, as can be seen in figure 11.

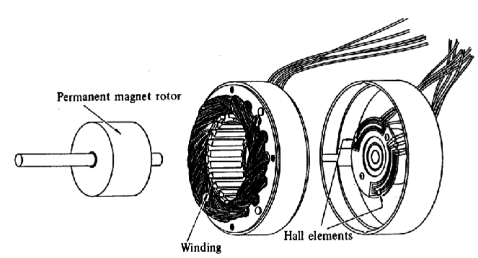


Figure 10 shows a brushless DC motor in disassembled form.

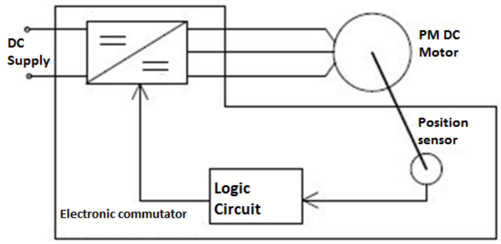


Figure 11 shows a BLDC motor diagram.

VII. IPM MOTORS (PAST PRESENT FUTURE)

IPM motor development history is closely related to the 50-year development of high-energy permanent materials. Fig.12 gives a short history of advancement of PM materials. A great potential existed in an Alnico (Aluminum Nickel Cobalt) magnet in the 1950s with a (BH) maximum of about 5 MG Oe. After that, in 1960s, barium ferrite magnets and samarium cobalt magnets were developed; with (BH) maximum values of around four and six MG Oe., respectively. A big shift happened when Neodymium Boron Iron (NdBFe) magnets with (BH) maximum at 14 MGOe. were commercially existed in the early 1980s.Today, Japanese producers such as Neomax Co, Japan Magnets Inc., Aichi Steels Co, TDK Co, etc. regularly produce and market NdBFe magnets with (BH) maximum at 57 MG Oe. For IPM motors, permanent magnets must have the highest (BH) max, energy product, the largest coercive force H, and the highest residual magnetic flux density Br. All PM materials have been shown to be insufficient for high efficiency IPM motor drives, with the exception of NdBFe magnets. Merrill revealed an early interior permanent magnet motor using Alnico-5 in 1955. On the basis of ferrite PM, Binn, Barnard, and Jabbar created many flux-focused IPM motors in 1978. Rahman created the first significant 45 kilowatt high efficiency interior permanent magnet motor in 1982 by utilizing NdBFe magnets. IPM analytical frameworks were first proposed by Rahman, Little, and Slemon in 1985. Jahns began putting the flux-weakening regime in place in 1987.In 1994, Zhou and Rahman introduced the first finite element analysis of an interior permanent magnet motor combining field and circuit coupling. Over the past ten years, IPM motor design, analysis, control, and application have steadily advanced—Merrill even exceeding Merrill and Alger's projections [38].The evolution of permanent magnet materials is seen in Figure 12 [39].

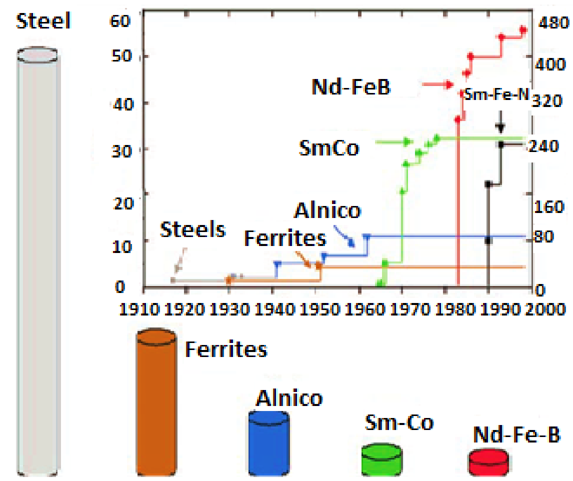


Figure 12; development of permanent magnet materials

VIII. IPM MOTOR (RECENT TRENDS, ISSUES, APPLICATIONS IN PROPULSION SYSTEM)

A stator with a distributed multi-phase winding, typically a three phase winding, and a rotor with permanent magnets (PMs) make up permanent magnet (PM) motors. When PMs produce the primary magnetic flux for the machine, there are two substantial benefits. First, the motor design has a variety of degrees of freedom due to the little amount of space that the PMs need for magnetization. The PM motors offer an exceptional efficiency and a high torque density since there are no magnetization losses. The rotor iron contains PMs with alternating polarity [40].

A. *Analysis*

The operating principle of any rotary electrical motor is based on the Lorenz force. A wire having current experiences a force in a magnetic field, which can be described by the BLI principle. In typical synchronous motor, stator is powered by a three-phase balanced voltage source, and slip rings provide dc excitation current to the rotor field winding. The dc excitation current is turned on when the machine is moving near to synchronously. The device initially functions as an induction motor. The rotor spins at synchronous speed after being brought into synchronism. The need for two power sources—dc from the rotor using brushes and slip rings and ac from the stator—is the motor's glaring weakness. In contrast to an induction motor, a synchronous motor's speed remains constant regardless of the load. An induction motor, however, is a single-fed motor. The rotor is a reliable, uncomplicated squirrel cage. The drawback is that it does not function at synchronous speed Ns since the rotor speed Nr reduces with load [41].

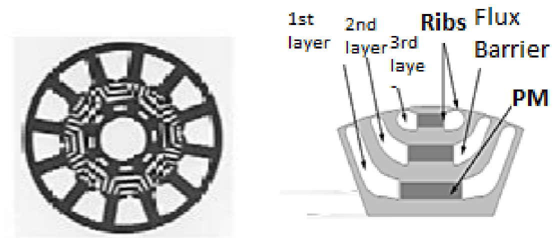
B. *Issues*

The design, research and optimization of a distinctive electrical motor drive for vehicle usage will be the study's primary area of focus. The hybrid electric vehicles appear to be a temporary fix. The directions are in the overall design and optimization of EVs. Small vehicles, mostly electric scooters and bicycles pre-dominated the development of full EVs until a few years ago. Now, larger EVs are in demand, particularly for automobiles, but also for buses and lorries. Various power-train solutions are currently being sought after by the car industry.

The trend among automakers is to provide electric motors more features. Maximum power and torque are always increasing. This shows that the optimization of machine geometry, taking into account thermal capacities as well as electromagnetic and mechanical performance, is given more consideration. In truth, synchronous permanent magnet (PM) machines are at the heart of technology, with the interior permanent magnet (IPM) motor emerging as its most formidable rival. Due to its greater torque and power density compared to other motor types, it is used in more than 80% of automobiles. Most motors use NdFeB, a rare earth PM, in conjunction with dysprosium to improve thermal stability. To create the purported IPM rotor, the PMs are put into the rotor iron. Both advantages and downsides apply to this solution. The motor's constant-power speed range has increased significantly, and its torque density is superb. However, utilizing rare earth PMs will cost the motor dearly. Automotive makers are interested in exploring alternatives without compromising actual performance [42].

C. Design And Optimization

Electric vehicle (EV) and hybrid electric vehicle (HEV) advancement is dependent on the motor design industry, which has recently received more focus. IPM motors benefit from both permanent magnet (PM) and reluctance torque, providing advantages such as high torque density and efficiency. However, IPM motor has a significant drawback in that high-speed operation makes it difficult to attain required flux-weakening abilities and low vibration. To increase torque and reduce torque ripple, further optimization is carried out according to the suggested motor specifications given in Table 2. First, finite element methods of three motors with different rotor structures are created and solved (FEM). The objective functions, constraints, and design parameters are chosen in the second stage. The GA is then used to determine the optimal placements for the design variables [43]. The PMs are located within the rotor of the internal permanent magnet (IPM) motor. They have better demagnetization protection than SPMs because of the stator current, which also increases safety and overload capacity. The modern hybrid automobiles are increasingly using this motor architecture because of its well-known advantages. The torque component produced by the PM can be combined with a torque component from the rotor's anisotropy by carefully designing the rotor's lamination. Variations in the d-axis and q-axis reluctances may result from the flux barriers' precise design. Generally speaking, thickness of torque has been greater than that of an SPM motor. The proper flux-weakening control and the reluctance torque component enable an effective CPSR. In [44] figure 13 shows the laminations of a 12-slot, 8-pole machine utilized for an ISA.



(i) (ii)

Fig. 13, IPM motor: (i) Laminations of a 12-slot 8-pole machine, (ii) Design of poles in rotor

IX. Conclusion

IPM (Interior Permanent Magnet) motor is a type of electric motor that uses permanent magnets placed on the rotor and high-frequency power electronic devices on the stator to achieve high efficiency, high torque, and low noise operation. IPM motors have become increasingly popular in various applications such as electric vehicles, industrial drives, and household appliances due to their improved performance and energy efficiency. By carefully controlling the magnetic fields generated by the permanent magnets, IPM motors can achieve high torque with low heat generation, making them a reliable and efficient choice for many applications.

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