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# DESIGN AND COMPARISON OF PERMANENT MAGNET MOTOR TOPOLOGIES FOR DIFFERENT APPLICATION SECTORS

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# DESIGN AND COMPARISON OF PERMANENT MAGNET MOTOR TOPOLOGIES FOR DIFFERENT APPLICATION SECTORS

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# ABSTRACT

Induction motors are commonly coupled to a gearbox when an application requires a low speed and a high torque. The gearbox is costly, needs maintenance and decreases the efficiency of the drive. Therefore, taking away the gearbox is very advantageous. This can be made possible by using a permanent magnet (PM) synchronous motor running directly at low speed, so called direct-drive PM synchronous motor.

In this thesis, low-speed direct-drive and high-speed direct-drive PM motors are investigated. The thesis begins with an overview of different existing PM direct-driven applications. It concentrates then on a few topologies that are promising for the considered application: five different radial-flux PM machine configurations with surface-mounted, buried permanent magnets, axial-flux and transverse-flux PM machine configurations.

The design of the different PM motors is realised by solving an optimisation problem, using Sequential Quadratic Programming methods. Firstly, to design the low speed machines requires stator and rotor design based on material, weight and pole number. Secondly, Low-speed PM machines, advantages and disadvantages of the SPM, Inset, V-type and tangentially magnetised PM machine configurations are summarised in detail.

For high-speed permanent magnet (HSPM) machines, firstly, accounting for stator structures of both slotted and slotless, rotor structure of interior PM (IPM), surface-mounted PM (SPM), and solid PM including retaining sleeves and their geometric designs are investigated based on choice of material, weight and pole number with. Secondly, HSPM machines, applications, advantages, and disadvantages of slotted/slotless stator configurations and IPM, SPM and solid PM rotor configurations.

In this thesis, Wind turbine and ship propulsion systems applications of PM machines are explained and comparison between RFPM and AFPM were seen.

A comparison among permanent magnet (PM) wind generators for different topologies of both HSPM and LSPM were chosen based on criteria that are identified for deployment of generators in wind turbines mainly for radial and axial-flux machines.

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1 INTRODUCTION

**6 Application**

# 1 INTRODUCTION

## 1.1 Permanent magnet synchronous machines:

Nowadays, electrical motors account for 65% of the worldwide energy consumption. As environmental concern increases, electrical drives with higher efficiency are desirable. Permanent magnet is becoming one of the key components used in a wide range of electric motors for electromechanical actuation and traction applications in modern automotive industry. Due to ever-demanding fuel efficiency, zero-emission and more vehicle electrification, electric motoring and generating components and systems have been finding their ways into vehicle traction, electric power steering, drive train actuation, engine cooling fan, HVAC, electric braking, oil and water pumps, to name a few.

Regarding the Electric Drive, Permanent Magnet Synchronous Machines (PMSMs) and induction machines are generally concerned for commercial EVs. By replacing conventional induction machines with Permanent Magnet (PM) synchronous machines has recently gained great interest, as the price of PM materials decreases.

Indeed, PM machines have no rotor winding resulting in lower copper losses, and therefore, they feature a higher efficiency than the induction machines.

For low-speed applications, PM machines may further eliminate the need of a gearbox. The dynamic problems can be neglected when the electrical machines operate below 100,000 rpm. Electrical machines with a value of more than this could be defined as high-speed machines.

The tip speed, i.e., the rotor surface linear speed, is presented as a better way to define high speed electrical machines, since the rotor surface speeds can be used as the critical speeds. To adapt the speed and torque of the machine, a gearbox is traditionally coupled to a standard induction machine. It is advantageous to take away this mechanical element, because it is costly, decreases the drive efficiency and needs maintenance.

Compared with induction machines (IMs), and switched reluctance machines (SRMs), permanent magnet machines (PMMs) have the highest power density and efficiency, lowest mass, and shortest stator active length.

## 1.2 Low – speed direct drive:

Low-speed (or high-speed) drives without gearbox are called direct drives, Since the gearbox is costly, decreases the efficiency of the drive, and needs maintenance, a direct-driven PM machine is an attractive solution that can compete with the induction motor and the gearbox. since the machines are directly coupled to the load.

low speed applications, using PM machines may further eliminate the need of a gearbox, which is traditionally coupled to a standard induction machine.

Low-speed PM direct drives are mostly used for two applications, wind turbines and boat propulsion. Direct drives are also successfully used for elevators[4] to get rid of whole room.

In conventional wind power plant [1] [2], the generator is coupled to the turbine via a gear so that it can typically rotate at a speed of 1000 or 1500 rpm. The wind power plant can be simplified by eliminating the gear and by using a low-speed generator, the rotor of which rotates at the same speed as the rotor of the turbine. The generator-gear solution in the wind power plant can be replaced by a low-speed PM synchronous generator. Some wind turbines with direct-drive generators, such as Lagerwey, Jeumont Industry as shown in figure 1.1.

Figure 1.1: Wind turbines from Jeumont Industry

Synchronous machines used in boat/ship propulsion motor drives[3] as shown in figure.1.2 are generally high-speed machines compared with the low speed required for the propellers. Thereby, a speed reduction gear is required in the drive train, and the use of such a large-power device affect negatively cost, weight and efficiency of ship propulsion motor drives.

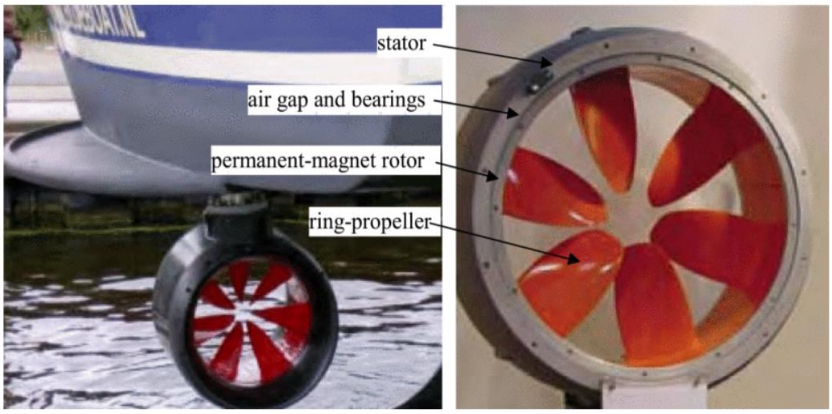


Figure 1.2. PM synchronous rotor with ring propeller in the rotor

Hence, a great improvement would result from the use of low-speed high torque electrical motors which allow the direct driving of the ship propellers.

## 1.3. High-speed direct drive:

High-speed motors[5] usually refer to motors with speed exceeding 10000r/min or difficulty value (product of speed and square root of power) exceeding 1 x $10^5$. At present, high-speed motors are mainly used in industry, medical treatment, energy and aerospace.

Compared with low-speed and moderate-speed conventional electrical machines, high-speed electrical machines offer advantages such as high-power density, small size, and light weight. More importantly, high-speed electrical machines can be directly connected to high-speed loads, and conventional gear boxes are no longer needed, which avoids complex gear box systems, improves system efficiency and reliability, and reduces system vibration, noise, and cost. With the evolution in the field of power electronics converters, the problems of high frequency supplies, required for high-speed operation, is no longer a restriction. The development of high-speed electrical machines is also supported by the development of high-speed bearing systems with high robustness, fewer losses, and longer lifetime. With the increasing applications of high-speed PMSM systems and the pursuit of high-performance motors, high speed PMSMs and their drive control technologies have become a new hotspot in electrical field. They also used as wheel-hub drives for traction drives in electric cars.

Direct drive as a wheel-hub-drive[7] no gearbox is needed, and therefore no related energy conversion losses are occurring as shown in figure 1.2. The mechanical power is directly generated, where it is needed – at the wheel.

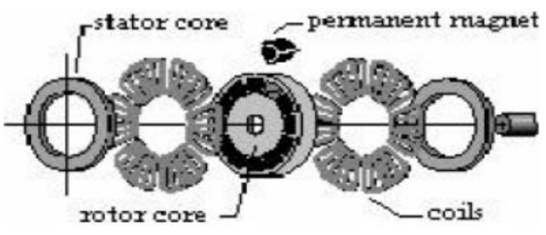
Figure 1.2: Direct-drive brushless permanent magnet with external rotor

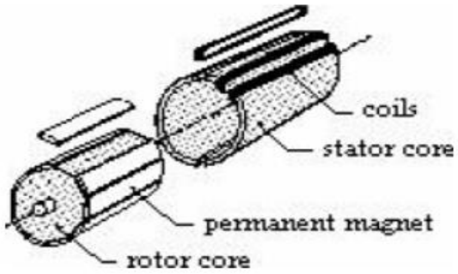
## 1.4. Goal of a project:

The main goal of the project is to define suitable PM drives for low-speed and high speed applications. In this we have seen types of motor topologies of PM, design of low speed and high speed and losses occurred, and comparison of motor topologies. And we have seen the applications of high speed and low speed direct drives.

# 2 PM machines for Low speed direct-drive:

As with the long and thin structure of high speed machine, the low speed machine usually has a short and fat structure like a disc in order to use effectively the rotating speed of the rotor. Permanent magnet machines are divided into three categories—axial, radial, and transverse machines—depending upon the direction of flux through the air-gap as shown in Fig. 2. In synchronous PM machines, the stator is the same of the induction machines. The rotor can assume different topologies, according to how the PM is placed in it. The inner rotor or outer rotor structure can be adopted for these kinds of PM machines are distinguished in three classes: surface–mounted PM (SPM) machines, inset PM machine, and interior PM (IPM) machine





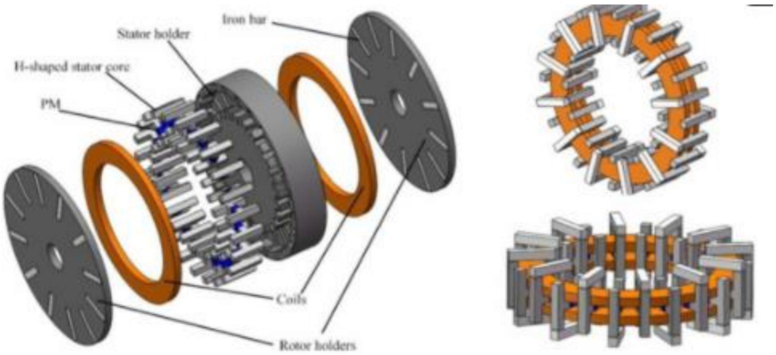


Figure.2: Axial flux PM machine, Radial flux PM machine and transverse flux PM machine

## 2.1 Radial- Flux PM Machine:

Radial-flux PM synchronous machines (RFPM) are the most conventional PM machines. The RF structure is the common one with one external cylindrical stator and one internal cylindrical rotor. They are widely used for direct-drive applications.

Figure 2.1 shows two views of a RFPM machine with the direction of the flux and current flows. The flux flows radially in the machine while the current flows in the axial direction.

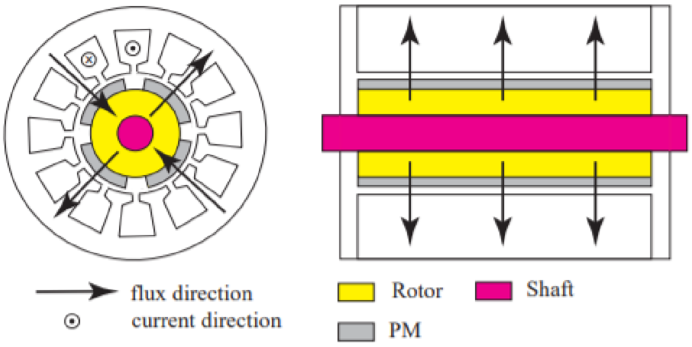


Figure 2.1: RFPM machine with flux and current flows.

RFPM machines are the easiest and cheapest to manufacture among the PM Machine. However, they are much bigger than the axial-flux and transverse flux machines in terms of active weight and axial length[9]. Surface mounted permanent-magnet (SMPM) motors are the most common configuration of radial-flux PM motors for direct-drive application. Both inner rotor and outer rotor motor are explained below.

## 2.2 Surface-mounted PM machines with inner rotor:

SPM machines offer relatively easier manufacturability, since the magnets are adhesively bonded to the rotor surface as shown in figure 2.2. However, this also results in potential flying-off of the magnets during high-speed operation. This is the most commonly used configuration**.**

The main direct-drive application of the inner-rotor SMPM machine is wind turbines, ship/boat propulsions[10][11].

They have also lower increase in machine outer diameter when number of poles increases. In low speed applications, this can become a critical issue. Therefore, the cost of active material, especially permanent magnet, in the bulky machine has to be minimized in the design stage.

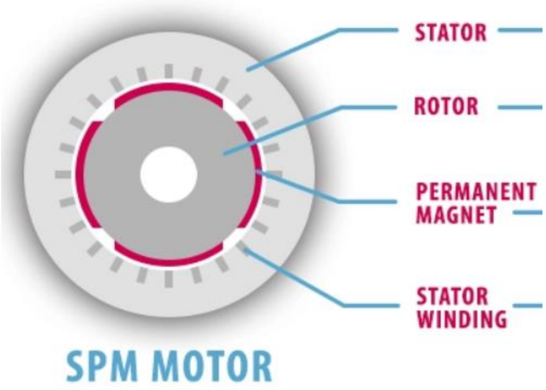


Figure.2.2 SPM motor with inner rotor

## 2.3 Surface-mounted PM machines with outer rotor:

The machine consists of a stationary wound stator located in the centre of the machine while the magnets are mounted along the inner circumference of the rotor as shown in figure 2.3.

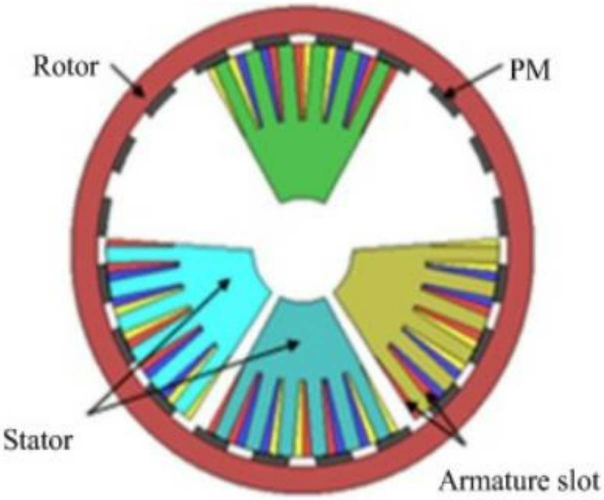


Figure 2.3. Surface mounted PM motor with outer rotor

Outer-rotor generators are commonly used in small wind turbines (up to 30 kW). The advantages of this type are: The rotor diameter is larger than for conventional radial-flux machines, which allows a higher number of poles.

During the rotation of the outer rotor, the centrifugal forces exert a pressure on the permanent magnets making their detachment more improbable. The structure is well adapted to wind turbines, as the hub carrying the blades can be fixed directly to the outer rotor.

## 2.4 Inset PM machines

As the SMPM machines[12], the inset PM machines have permanent magnets mounted on the rotor surface. However, the gaps between the permanent magnets are partially filled with iron, as shown in figure 2.4.

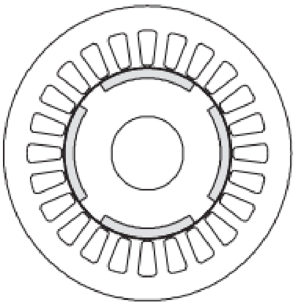


Figure 2.4. Inset PM machine

This configuration is referred to as inset PM machine. The iron between the permanent magnets creates a saliency and gives a reluctance torque in addition to the torque from the magnets.

## 2.5 Interior PM machines

Another way to place the permanent magnets by burying the magnets inside the rotor of the IPM synchronous motor as shown in fig 2.5.1 has several important effects on the machine's electromagnetic characteristic. An advantage of the buried PM machine configurations compared to the surface PM machines is the possibility to concentrate the flux generated by the permanent magnets in the rotor and thus achieve high air gap flux densities. Moreover, the buried permanent magnets are well protected against demagnetisation and mechanical stress. Features of the IPM drive include high motor and inverter efficiency, high motor power density, low magnet weight, fast dynamic response, and flexible torque-speed envelopes, including high-speed constant horse power operation. These features make the IPM drive an appealing candidate for a wide variety of applications, ranging from high-performance machine tool servos and robot actuators to high-power traction and spindle drives demanding wide speed operation.

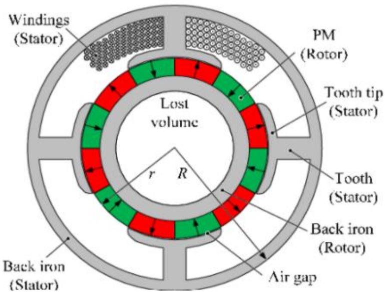


Figure 2.5.1. Interior PM machine

Permanent magnet synchronous machine has five different rotor topologies[13] as shown in fig 2.5.2 including a surface mounted PM rotors, V-shape single-layer interior PM, W-shape interior PM, segmented and conventional interior PM rotor.

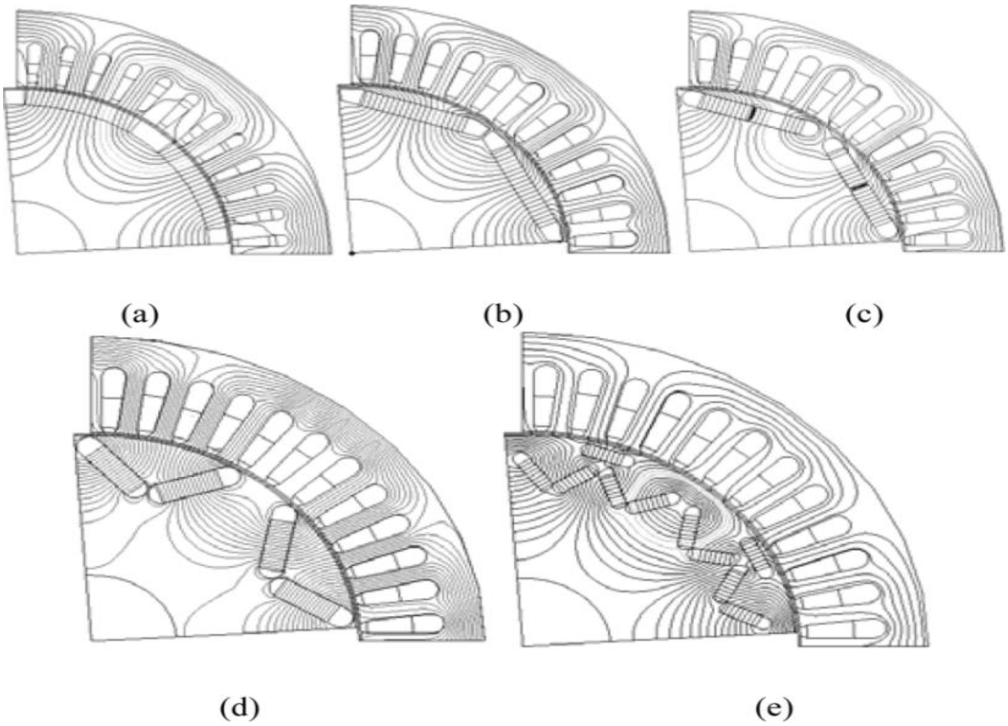


Figure 2.5.2. Cross sections and no-load flux distributions of the five machine designs. (a) Surface PM rotor. (b) Conventional PM rotor. (c) Segmented PM rotor. (d) V-shape PM rotor. (e) W-shape PM rotor.

Few observations of PMSM rotor topologies are:

1. The V-shape PM rotor has the lowest magnet mass.
2. The W-shape PM rotor has the largest d- axis and q-axis inductances, followed by the V-shape PM and the surface PM rotor.
3. The W-shape PM machine has excellent flux-weakening performance and has high efficiency over a wide speed range.
4. The segmented PM motor has a wider range of constant power speed operation than the conventional PM motor since its capacity for flux

weakening is increased because of the greater leakage inductance produced by the path between the two permanent magnets.

## 2.6 Axial Flux PM machines

The axial-flux PM (AFPM) machine is another possible solution for low speed direct-drive applications. This machine features a large diameter and a relatively short axial length compared to a radial-flux PM machine. As suggested by its name and fig 2.6.1, the flux from the PMs flows axially while the current flows in the radial direction.

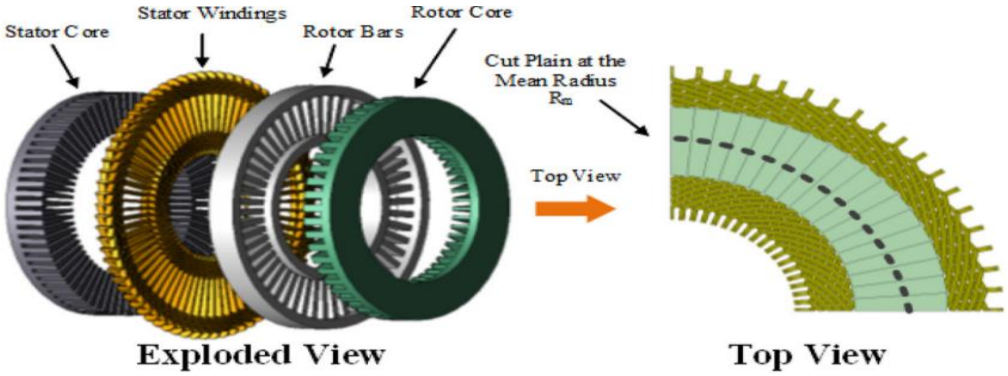


Figure 2.6.1. Axial Flux PM machine

The AFPMG has two rotors and one internal stator. The two rotors carry surface mounted NdFeB48 magnets on their inner surfaces which are axially magnetized. The machine has coreless stator in trapezoidal shape by means of concentrated coils. The two rotor discs with central-stator act naturally act as fans, thereby the heat produced by copper coils and iron losses are removed.

Axial-flux PM machines have the advantages such as compact structure, high aspect ratio, planar structure, and short axial length. The applications for this type of PM machines are small wind turbines, ship propulsion and elevators.

Axial flux machines[15] can be classified according to the rotor and stator structure or according to the number of stators and rotors in the machines. The machine is said to be axial flux induction machine if the rotor is squirrel cage and if the magnets are mounted on the surface of the rotor it is said to be axial flux surface mounted PM machine as shown in fig 2.6.2, and if the magnets are integrated/buried inside the rotor the machine is then called axial flux interior PM machine meanwhile the stator structure has only three types slotted, non-slotted and coreless as shown in fig 2.6.3. All these machine can single, double or multistage depending upon the number of rotors and stators.

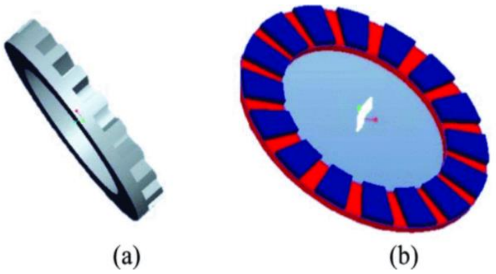


Figure 2.6.2. (a) Squirrel cage rotor, (b) Surface mounted PM rotor

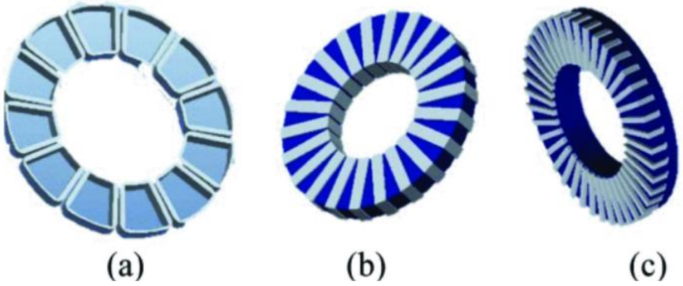


Figure 2.6.3. (a) Coreless Stator, (b) Non-Slotted Stator, (c) Slotted Stator

Low-speed applications are most commonly use the Torus type machine[16]. In which, the stator is placed between the two external rotors that are rigidly connected to the mechanical shaft. The permanent magnets are placed opposite to each other on the two rotors and the stator windings are toroidal figure 2.6.4. The stator can be slot less. The main benefits of the Torus machine are:

1. The machine is compact and lightweight with a short axial length.
2. Good ventilation and cooling of the stator windings.
3. Absence of slots and large effective air gap, which leads to a negligible cogging torque, reduced high-frequency losses and also a low acoustic noise.
4. Possibility to stack together many stator and rotor discs, which gives a higher effective air gap surface.

The main drawback of this kind of machine is its complex assembly due to axial forces.

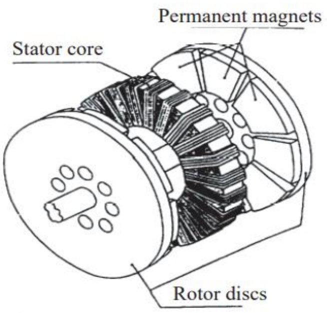
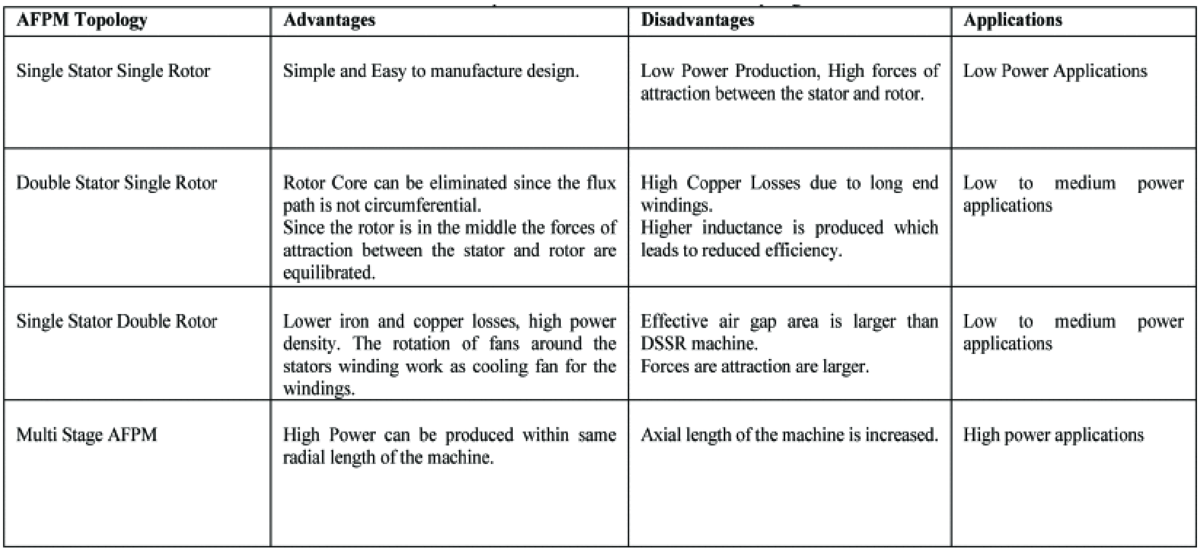


Figure 2.6.4 Torus machine

Other AFPM machine configurations are the double-sided with internal PM disk machines, single-sided machines, ironless double-sided machines, and multi-disk machines. The different configurations with advantages and disadvantages are shown below.



| AFPM Topology | Advantages | Disadvantages | Applications |
|---|---|---|---|
| Single Stator Single Rotor | Simple and Easy to manufacture design. | Low Power Production, High forces of attraction between the stator and rotor. | Low Power Applications |
| Double Stator Single Rotor | Rotor Core can be eliminated since the flux path is not circumferential.<br>Since the rotor is in the middle the forces of attraction between the stator and rotor are equilibrated. | High Copper Losses due to long end windings.<br>Higher inductance is produced which leads to reduced efficiency. | Low to medium power applications |
| Single Stator Double Rotor | Lower iron and copper losses, high power density. The rotation of fans around the stators winding work as cooling fan for the windings. | Effective air gap area is larger than DSSR machine.<br>Forces are attraction are larger. | Low to medium power applications |
| Multi Stage AFPM | High Power can be produced within same radial length of the machine. | Axial length of the machine is increased. | High power applications |

Table 1. Comparison between different AFPM Topologies

The application of axial flux machines, including vehicle wheel motors, electrical scooter motor drive adjustable speed pump, small wind turbines, propulsion dive for ship motor, direct drive elevator, small size generator for hybrid vehicles.

## 2.7 Transverse Flux PM machines

Transverse flux PM machines have become popular due to the use of lower strength ferrite magnets. The significant difference between TFPM machines and conventional machines is that the TFPM machine[17] permits an expansion of space for the armature windings without diminishing the available space for the main magnetic flux.

The simplest topology of the TFPM machine is a single-sided surface-mounted TFPM machine shown in Fig. 2.7.

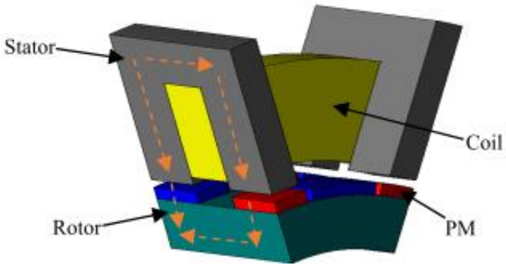


Figure 2.7. Transverse flux PM machine (one pole pair).

This machine performs like a synchronous machine. The TFPM machine has a higher torque density, separate electrical and magnetic loadings, modular structure, fault tolerance, and simple windings. The TFPM machine can also be made with an exceptionally small pole pitch compared with other machines.

Based on electromagnetic configuration, the TFPM machines can be categorized as follows:

- Surface-mounted and flux concentrated;
- Single-sided and double-sided;
- Single winding and dual winding;
- Inner rotor and outer rotor;
- Stator type: C/U-core, Z-core, E-core, claw pole

The disadvantages related to TFPM machines incorporate a complicated 3-dimensional structure, low power factor, and high cogging torque. However, they suffer from high leakage flux and high inductance, which lead to low power factor, high core loss, and saturation, and on top of that, it is difficult to construct. Rotating structures of both axial and transverse flux PM machines have complex 3-dimensional magnetic flux paths, compared to the traditional radial flux machines. Additionally, as these topologies are difficult to construct from lamination iron, their core material has a lower permeability and saturation flux density. As a result, radial flux PM machines are more suitable for analytical design studies in which the field variables are 2-dimensional.

# 3 PM machines for high-speed direct drive:

Permanent magnet (PM) synchronous motors have been widely used in various industrial applications due to their compact size and high efficiency. When the high-speed motor is utilized in such a way, the system can be replaced by using a speed increasing gear with the direct drive system to eliminate the gear. Thus, in this way, the system size can be made compact, costs can be lowered, system efficiency can be improved, and maintenance time can be reduced.

Like low-speed direct drive permanent magnet machines are divided into three categories—axial, radial, and transverse machines—depending upon the direction of flux through the air-gap as shown in Fig. 3.1. The rotor can assume different topologies, according to how the PM is placed in it.

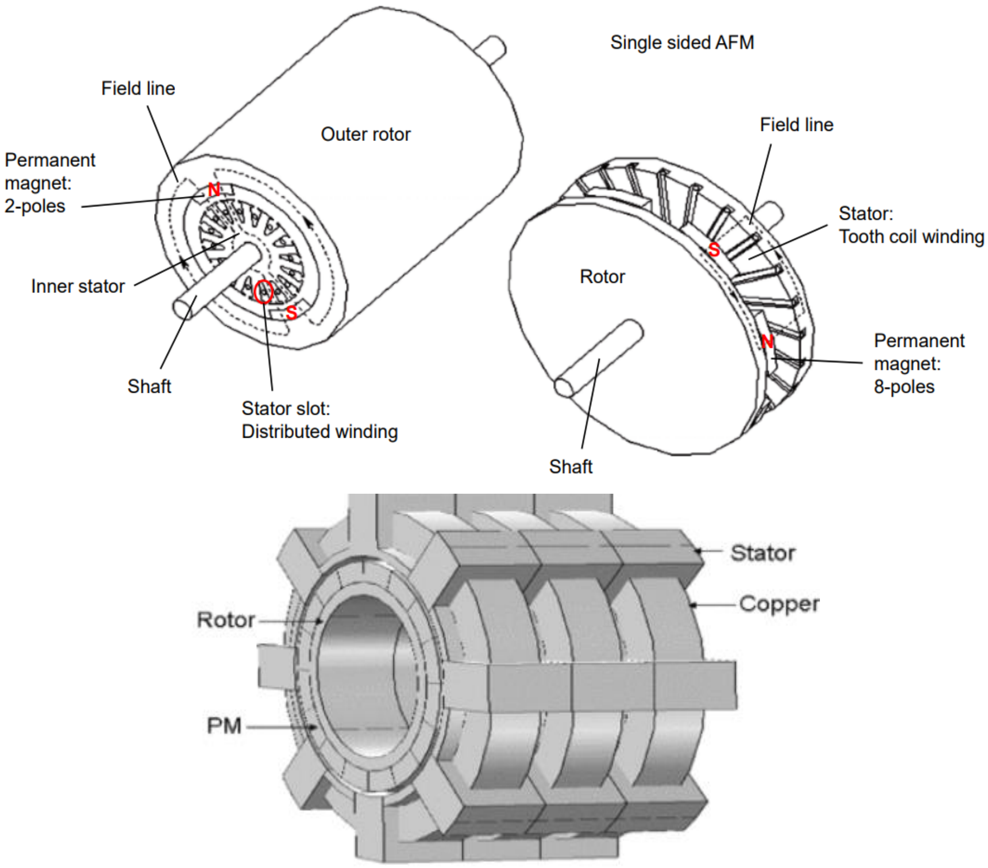


Figure 3.1. Permanent magnet radial flux machine(RFM), Axial flux machine(AFM) and Transverse flux pm machine(TFPM)

PMs have the advantages in terms of their high power factor, high efficiency and high power density. Therefore, PMs are good candidates for wheel motor, wind turbines, ship propulsion systems, EVs etc.

The stator structures of high speed direct drives can be classified[18] into slotted and slot less topologies, and the winding configurations can be divided into overlapping and non-overlapping layouts. In general, the stator structures of slotted HSPM machines can be separated into multi-slot (>6-slot) and minimal-slot (6-slot; 3-slot), Fig 3.2. The multi-slot stator structure is widely used for high power (>10 kW) requirements.

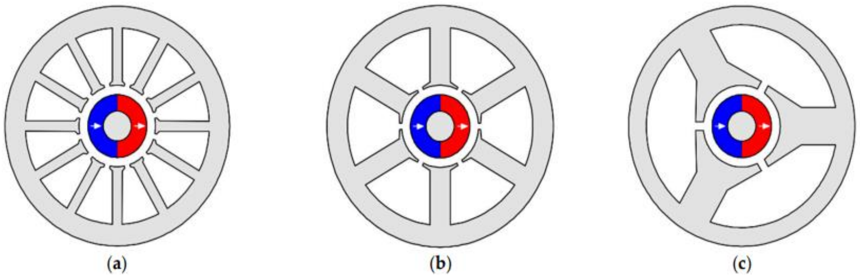


Figure 3.2 HSPM machines with multi-slot and minimal-slot stator structures. (a) Multi-slot (12-slot). (b) Minimal-slot (6-slot). (c) Minimal-slot (3-slot)

The slot less stator structures with large air gaps and flux leakages have relatively small output torque, and are rarely used for conventional low-speed and moderate-speed PM machines. For high-power, large-size HSPM machines, although the high speed can increase the power, the critical speed is limited by the rotor mechanical strength and dynamic characteristics. Therefore, a relatively large torque is required for these machines; therefore, the slot less stator structure is not a suitable choice. For low-power, small-size HSPM machines, the critical speed is higher than that of high-power, large-size HSPM machines due to smaller rotor diameter. Therefore, the slot less stator structures with relatively small torque can be accepted in low-power, small-size HSPM machines, Fig 3.3.

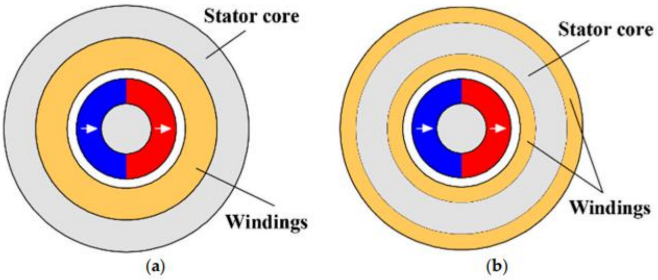


Figure 3.3. Slot less high-speed PM machines. (a) Air-gap windings. (b) Toroidal windings

The different applications for HSPM, such as electric vehicles and electric-turbo compounding systems. In addition, HSPM machines are employed in industrial applications are centrifugal turbo-compressors, air blower cooling etc.

For high-speed applications, the PM machines mainly employ three different rotor structures, i.e., IPM, SPM, and solid PM, Fig 3.4. Those different rotor designs affect the electromagnetic performance, thermal aspect, mechanical strength, and dynamic characteristic of HSPM machines.

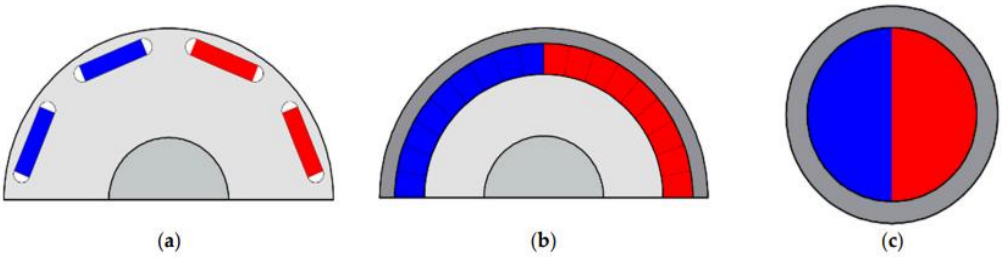
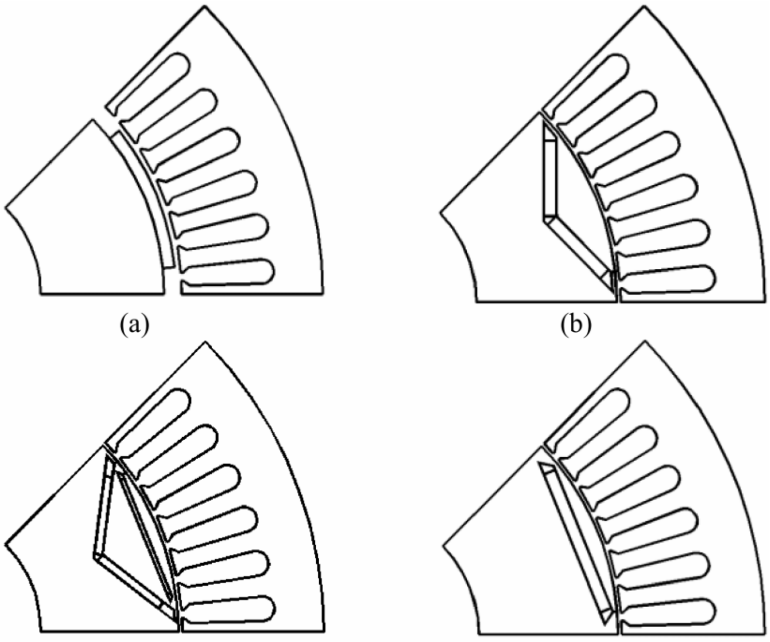


Figure 3.4. High-speed PM machines with IPM, SPM, and solid PM rotor structures. (a) IPM. (b) SPM.
(c) Solid PM

All these types offer high power density. In terms of speed range, IPM offer extended speed range owing to both of the magnetic torque and reluctance torque. Depending on the different placement ways of permanent magnet, IPMs can be divided into many kinds. Different kinds of IPM with various rotor topologies [19] have different salient rate and torque characteristic. Four types of PMs are:

SPM, V-shape IPM (V-IPM), delta-shape IPM (D-IPM) and flat-shape IPM (F-IPM), respectively as shown in fig 3.5.



(a) (b)

(b) (d)

Figure 3.5. (a). SPM. (b). V-IPM. (c). D-IPM. (d). F-IPM

Few observations from above topologies are:

- IPMs have higher starting torque than SPM at the same current. Reluctance torque plays an important role in increasing the electromagnetic torque for IPM.
- Among IPMs, D-IPM and V-IPM have the highest output torque due to the higher salient rate.
- Besides, IPMs have better performance in torque ripple, efficiency and demagnetization than SPM.
- In terms of demagnetization, SPM is confronted with serious demagnetization risk at high peak current.
- SPM with smaller d-q inductances tends to produce higher torque in high-speed region than IPMs.

For high-speed applications, the sleeve is the most important part and has a close relationship with machine performance. Different sleeve materials, such as stainless steel, carbon fibre, copper iron alloy, and copper.

# 4 Design of low speed PM machine:

To design a low speed direct drive PM machine[12], the following problem, need to be considered.

## 4.1 Stator design:

The coreless nature of the stator eliminated the lamination stamping during the manufacturing process of the stator winding. The absence of the iron core for the coils of the stator winding creates a low flux density in the magnetic circuit of the coil, resulting in a low value of inductance for the coil in the coreless stator. In this design, the stator windings are concentrated coil non-overlapping winding, connected in series and the star connection because of avoiding of the circulating currents as shown in fig 4.1.

Figure 4.1. design of stator(slotless)

The outer diameter of the stator core is the most important dimension of PM generator:

$$D_{out} = \sqrt[3]{\frac{\varepsilon P_{out}}{\pi^2 k_D k_\omega n_s B_g A_m \eta \cos\varphi}}$$

Where ε = the constant for generator>1.

$K_w$ = the winding factor.
$A_m$ = the electromagnetic loading.
$n_s$ = the speed (rev/sec).

The inductance of the non-overlapping winding, $L_c$ is:

$$L_c = \frac{q(2l_a + l_{ec})^2 N_t^2}{h_a} \cdot 10^{-7} K_n$$

Where q = no. of stator coil per phase = $\frac{Q}{3}$
Q = the total number of stator coil,
$I_a$ = active length of the stator winding,
$I_{ec}$ = the end winding length of the stator winding,
$h_a$ = the axial height,
ω = the coil side width of the stator,
$K_n$ = the Nagaoka constant, and
$N_t$ = the number of turns in one coil.

During operation the coil is magnetized, which results in the magnetic field no longer being uniform in the winging and therefore a correction factor, refer to as the Nagaoka constant, $K_n$ is required. The $K_n$ constant can be express as:

$$K_n = \frac{1}{1+0.9\frac{2l_a+l_{ec}}{2\pi h_a}+0.32\frac{2\pi\omega}{2l_a+l_{ec}}+0.84\frac{\omega}{h_a}}$$

## 4.2 Rotor design:

The permanent magnets in the internal rotor of a double sided structure may be located on the surface or inside the rotor disk as shown in fig 4.2. The main flux may flow axially through the rotor disk or flow circumferentially along the rotor disk. With the permanent magnets located at the surface of the rotor disk, it is not necessary a ferromagnetic rotor core and the axial length is substantially reduced, which improves the power density of the machine. The places in between the windings are filled with epoxy resin to increase robustness and provide better conductor heat transfer.

Figure 4.2. design of rotor.

The effective air gap is defined as:

$$I_{geff} = 2I_g + \frac{2\,I_m}{\mu_{rm}} + h_{sy}$$

Where $I_g$ = the physical gap between magnet and stator disk.

$I_m$ = the magnet length in magnetization direction.

$\mu_{rm}$ = the relative recoil permeability of the magnets and

$h_{sy}$ = the stator thickness.

The air gap flux density can be written as:

$$B_g = \frac{2\,B_{rm}I_m}{\mu_{rm}I_{geff}}$$

Where $B_{rm}$ = the remanent flux density of the magnets.

Similarly, the constant $k_D$ is calculated by,

$$K_D = \frac{1}{8}(1+k_d)(1-k_d)^2$$

Where $K_d$ = optimal value of coefficient.

The design of the different PM motors is realised by solving an optimisation problem, using Sequential Quadratic Programming[20] methods as shown in fig 4.3. The designs are conducted by solving an optimization problem. The objective function is the active weight of the motor. The parameters to be optimised are: the number of poles, some geometrical parameters that define the stator teeth and the magnets, the air-gap length and the machine length. These parameters are subject to some non-linear inequality constraints that should guarantee the mechanical, thermal, and magnetic behaviour expected. The outer stator diameter is limited. The copper losses are set to a value that guarantees a better efficiency and lighter weight than the induction motor with its gearbox. The magnet weight is also limited to set a constraint on the cost of the machine.

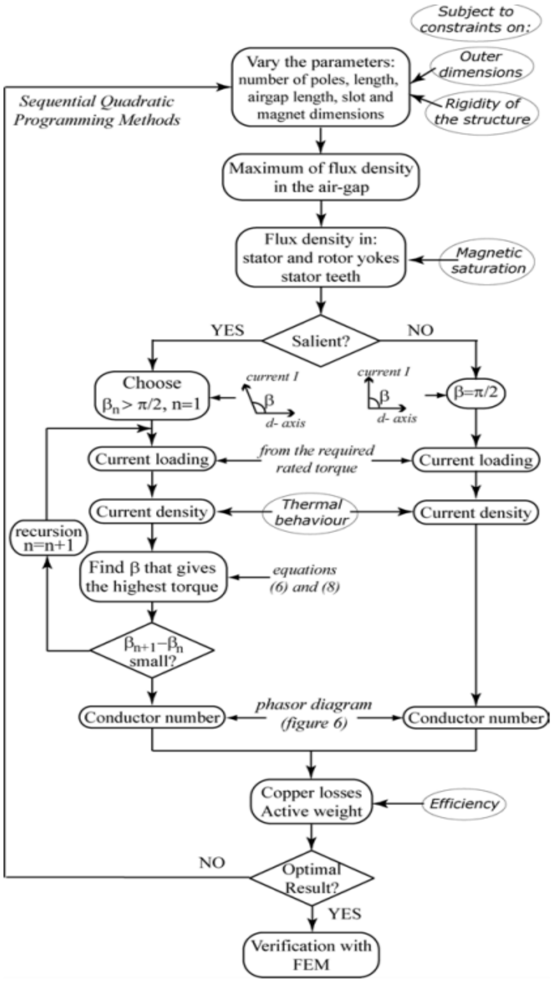


Figure 4.3. Procedure followed for the design of a low speed PM motor

The design process differs between the investigated rotor configurations in mainly two points: the analytical calculation of the flux-density in the air gap and the calculation of the inductances and currents.

1. **Flux density in the air gap:** The flux-density in the air gap has to be calculated with accuracy since the design procedure relies on above fig 4.3

For the surface mounted PM motor the waveform is assumed to be rectangular as in fig 4.3.1.

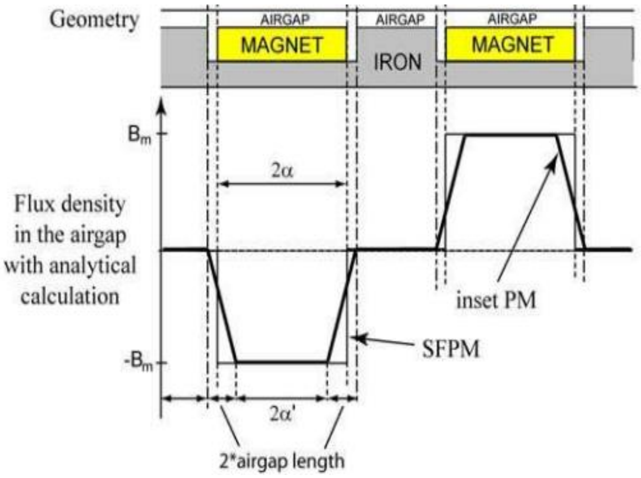


Figure.4.3.1. Method to calculate analytically the flux density in the air gap.

For different types of rotor, the maximum value of air gap flux density $B_m$ changes. For instance, the maximum value of the air gap flux-density $B_m$ for surface mounted pm motor is computed as,

$$B_m = \frac{B_r}{1 + \frac{\delta . \mu_r . k_c}{l_m}}$$

where $B_r$ = the remanence flux density of the magnet,

$\mu_r$ = the magnet relative permeability,

$k_c$ = the carter factor,

$\delta$ = the air gap length and

$l_m$ = the magnet thickness.

**Observations:**

- For the inset PM designs, $B_m$ is calculated the same way. However, there is more flux leakage between the magnets than for the SMPM. It because a part of the flux created by the magnets can go directly from the magnet to the iron pieces.
- For buried PM designs, the flux leakage through the iron piece is negligible if the distance between the magnet and the iron piece is more than twice the air gap length.
- The maximum of the air gap flux-density $B_m$ for the V-shape PM motor is calculated as follows,

$$B_m = \frac{B_r - B_{sat}\frac{w_{Fe}}{w_m}\left(1 + \mu_r \frac{l_i}{l_m}\right)}{\left(\frac{2\alpha D_r}{p w_m} + 2\frac{w_{Fe}}{l_{Fe}} \cdot \frac{k_C \delta}{w_m}\right)\left(1 + \mu_r \frac{l_i}{l_m}\right) + \mu_r \frac{k_C \delta}{l_m}}$$

Where $B_{sat}$ = the flux density in the saturated iron bridge.

- For the design with tangentially magnetized PM, the derived formula is:

$$B_m = \frac{B_r \alpha_m l_m \frac{D_r}{p}}{\mu_r l_m k_c \delta + \alpha_{iron} \alpha_m \left( \frac{D_r}{p} \right)^2}$$

**2. Saliency and inductances:** The second main difference between the designs is due to the saliency of the inset and buried PM structures, whereas the SMPM is non-salient. The inductances in the direct and quadrature axis ($L_d$ and $L_q$) are not equal and therefore a reluctance torque is created. In order to utilise this additional torque, a d-axis current $i_d$ is added as written in below equation.

For the SMPM, the d-axis current is equal to zero.

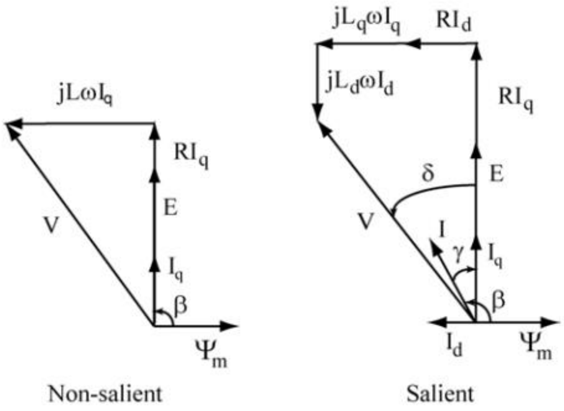
$$T = \frac{3}{2}\frac{p}{2}\left[\Psi_m i_q + \left(L_d - L_q\right) i_d i_q\right]$$

with p = the pole number,

$i_q$ = the q-axis current,

$\Psi_m$ = the flux from the magnets.

The phasor diagram of salient and non-salient motor is as shown in fig 4.3.2.



Non-salient Salient

Figure 4.3.2. Phasor diagram at rated speed for salient and non-salient PM Machines

The angle ϒ (or β = -ϒ + π/2) is chosen so that it gives the maximum torque for a given current as

$$\frac{dT}{d\square} = 0$$

We know that, $I_d = I \sin \Upsilon$

$I_q = I \cos \Upsilon$

And by substituting these in Torque equation and by differentiating we get a second order equation i.e.

$$2(L_d - L_q)I^2 . \sin^2 \Upsilon + \Psi_m . I . \sin \Upsilon - (L_d - L_q)I^2 = 0$$

Different values of β are tested using a recursion, in order to find the minimum current together with the angle β that gives the required torque. The recursion is described on fig.4.3. Knowing the angle β and the d- and q- current, the number of conductor per slot can be calculated using the phasor diagram at base speed. The procedure can be continued as for a SMPM (figure 4.3).

### Choice of material:

There are typically four categories of permanent magnets: neodymium iron boron (NdFeB), samarium cobalt (SmCo), alnico, and ceramic or ferrite magnets. Known as third generation of Rare Earth magnets, Neodymium Iron Boron (NdFeB) magnets are the most powerful and advanced commercialized permanent magnet today. So NdFeB magnets are used for this permanent magnet generator.

Usually the following factors are considered for the choice of PM material:

- For the high power density and high efficiency of the machine, the PM material should have good magnetic properties normally including remanence $B_{r,}$ coercive force $H_c$ and maximum energy product $(BH)_{max}$.
- The magnetic properties of the PM should be stable, and the demagnetization curve is expected to be linear within the operation temperature range. Therefore, the PM material should withstand high operation temperature.
- The price of the PM material should not be too high.

Combining the above considerations, the sintered Nd-Fe-B material would be the best candidate.

### Weight and pole number:

Since the price of PM material is high compared to the rest of the machine materials, the weight of the permanent magnets should be limited as much as possible. However, the lower their weight, the higher will be the total active weight (fig 4.4). A lower flux from the permanent magnets is indeed compensated by a higher armature reaction, resulting in bigger slots and consequently a bigger stator. The flux concentration is therefore a non-negligible advantage.

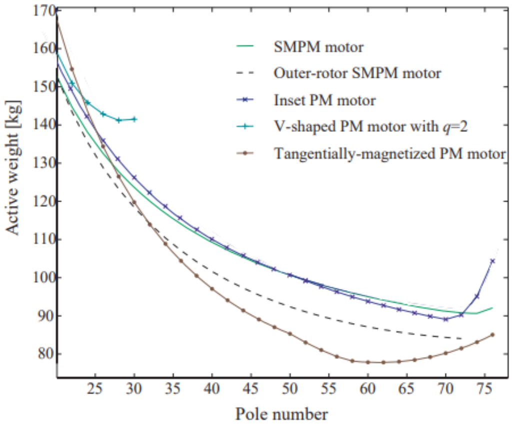


Figure 4.4. Active weight as a function of the number of poles for different optimized designs.

It should be kept in mind that the number of permanent magnets and the production cost increase with a higher pole number. Therefore, a compromise should be found between the weight and the number of magnets. For pole numbers higher than 50, the active weight decreases slower due to the constraints on the structure.

**Observations:**

- For the inset PM designs, the tooth width reaches its lower limit. The length of the motor is then increased to fulfil the torque requirement and the weight therefore increases.
- From fig 4.4 it is clear that the outer-rotor SMPM configuration is lighter than the SMPM. It because an outer-rotor geometry allows a larger bore diameter and thus a lower current loading is needed to obtain the same torque.
- It also reveals that the SMPM and the inset PM configurations have almost the same weight for the same value of magnet weight and copper losses.
- The inset PM rotor is heavier than the SMPM due to the iron pieces between the magnets. However, the reluctance torque that represents more than 5% of the required nominal torque allows a lighter stator, giving a motor that can be lighter than the SMPM.
- The configuration that is the lightest for a pole number over 34 is the one with tangentially magnetized PM rotor because the flux concentration in the rotor allows a high flux density in the air gap and thus the machine length is lower.

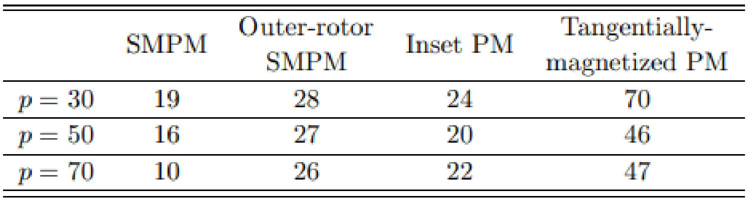
**Torque ripple:**

Torque ripple is mainly caused by the harmonics in the air-gap flux density. Harmonics in the air-gap flux are introduced by the slot openings of the stator and the magnet flux-barrier of the rotor.

The torque is pulsating because of:

- The variation of permeance in the air gap, generating the cogging torque.
- The interaction between the air gap flux and the space harmonics in the magneto-motive force (MMF) depending on the winding layout.
- The interaction of the air gap flux with the current harmonics. The current harmonics generated by voltage harmonics are neglected here, as the supplied voltage is assumed to be ideally sinusoidal.

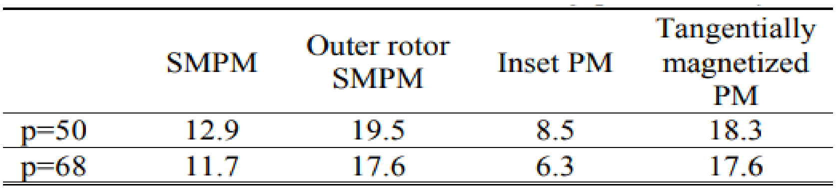
The torque ripple differs between the configurations and the pole numbers table 4.1. gives the ratio between the torque ripple and the mean torque for 3 different pole numbers and for the different rotors.



| | SMPM | Outer-rotor SMPM | Inset PM | Tangentially-magnetized PM |
|---|---|---|---|---|
| $p = 30$ | 19 | 28 | 24 | 70 |
| $p = 50$ | 16 | 27 | 20 | 46 |
| $p = 70$ | 10 | 26 | 22 | 47 |

Table 4.1: Ratio between the torque ripple and the mean torque in %.

As can been seen, the torque ripple for the buried PM and outer PM are very high. The cause of this high ripple can come from the harmonics in the air gap flux density. The harmonics 5 and 11 for the outer PM and buried PM designs are indeed very high as shown in table 4.2.



| | SMPM | Outer rotor SMPM | Inset PM | Tangentially magnetized PM |
|---|---|---|---|---|
| p=50 | 12.9 | 19.5 | 8.5 | 18.3 |
| p=68 | 11.7 | 17.6 | 6.3 | 17.6 |

Table 4.2. Relative value of harmonic 5 in the air gap flux density

By finding a half pole angle that decreases both the 3rd and 5th harmonics can decrease the torque ripple. Another solution is to use a concentrated winding with a good combination between the pole number and the slot number or to have stator teeth with different widths.

## Advantages and Drawbacks of the configurations:

- The advantages of the buried magnet configurations compared to the surface PM designs are the possible flux concentration generated by the magnets in the rotor, the protection of the magnet against demagnetisation and the mechanical strength.
- The centrifugal forces on the surface mounted PM are very low because the nominal speed is low.
- The property that differs between the rotors is the saliency of the buried PM designs and of the inset PM designs. A reluctance torque can be produced in addition to the torque produced by the magnets.
- The drawbacks of the rotors with V-shape magnets are the iron bridges that cause a high leakage flux.
- Furthermore, the V-shape rotor is not very adapted for high pole numbers because higher the pole number, the smaller the place for the magnets in V-shape, and the smaller the angle between the two magnets. It can therefore easily get saturated between the magnets if the angle is too little.
- Another drawback of the V-shape configuration is the high number of magnets that increases the production cost.
- The tangentially magnetised PM rotor presents the drawback of many iron and magnet pieces to be manipulated if the number of poles is high.

# 5 Design of high speed PM machine:

The actual trend in high speed electromechanical drives technology is to use PM brushless motors[22], solid rotor induction motors or switched reluctance motors. The highest efficiency and highest power density is achieved with PM brushless motors.

Design guidelines for high speed PM motors include are:

- Compact design, high power density and minimum number of components;
- High efficiency and power factor close to unity over the whole range of variable speed and variable load;
- Ability of the PM rotor to withstand high temperature (losses in retaining sleeve and PMs);
- Active and passive materials used for the rotor should be thermally compatible, i.e., with similar coefficient of thermal expansion;
- SmCo PMs rather than NdFeB PMs should be used if the PM rotor is integrated with turbine rotor;

- Optimal cost-to-efficiency ratio to minimize the cost-to output power ratio of the system;
- High reliability (failure rate < 5% within 80,000 h);
- Low cogging torque and vibration level;
- low total harmonics distortion (THD).

It is apparent that the PM rotor is a key part and more attention should be paid to the mechanical consideration for the design of a high-speed motor or generator. Figure 5. shows a (a) stator and (b) rotor for the reference motor. For the stator, three coils are designed with concentrated windings. By contrast, the rotor contains one pole pair magnet where the copper sleeve is included on the rotor to fix the magnet.

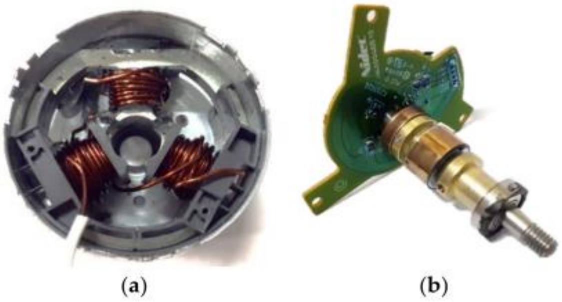


Figure 5. Reference motor (a)stator and (b)rotor

### 5.1. Stator Design and material:

The stator core is stacked of slotted or slotless laminations. For input frequencies 400 Hz and lower, 0.2 to 0.35-mm thick laminations are used. For higher frequencies, 0.1-mm laminations are necessary. Vacuum impregnated coils made of stranded conductors are inserted into slots.

To minimize the space harmonics, the stator winding is made as a double layer winding with shorted coils. For very high speeds and low voltages, when the EMF induced in single turn stator coils is too high, small number of coils, single layer winding or parallel paths (not recommended) must be used.

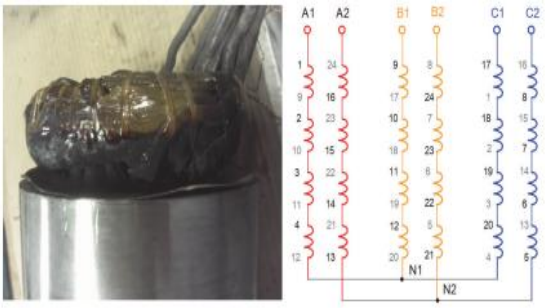
Hollow conductors and direct water cooling are too expensive for machines rated below 200 kW. The stator volume is affected by winding losses and heat dissipation.

In order to avoid circulating currents, excessive winding losses and hot spots in the stator winding[21], it is necessary to avoid:

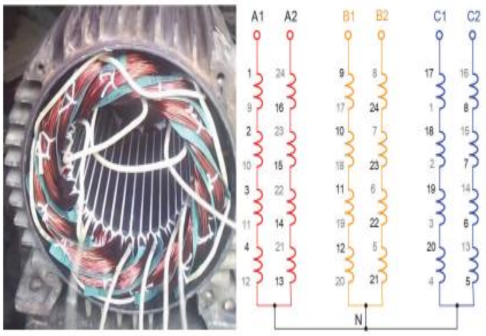
- Duplex windings (Fig. 5.1.1(a)): Duplex winding works well for induction machines, but it is not acceptable for high speed PM machines.

- Parallel paths (Fig. 5.1.1(b)): There are circulating currents in parallel paths of the auto-wound stator due to random position of conductors in coils.
- Concentric winding (Fig. 5.1.1(c)): Concentric double-layer winding with coil groups containing different number of coils is not recommended. It is much better to use double-layer lap winding instead. Double-layer lap winding can be auto wound.
- Deep slots (Fig. 5.1.1(d)): Deep slots for auto wound double layer windings with parallel paths are not recommended. Winding asymmetries due to coil side location in the slot, lead to unequal impedances and unequal induced EMFs. This causes circulating currents and more importantly, very uneven distribution of the currents within the strand conductors (parallel wires) of the same phase.

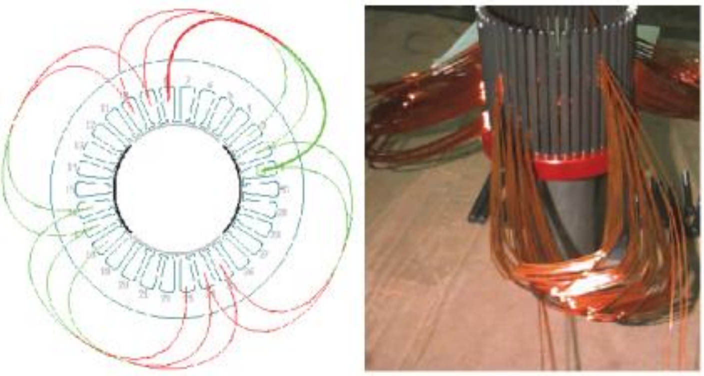
(a)



(b)



(c)



(d)

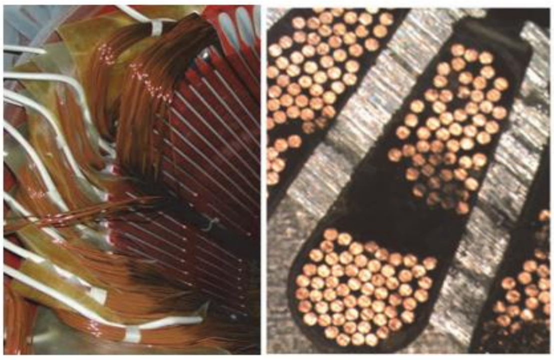


Figure 5.1.1. (a). Duplex winding. Unavoidable small phase shift between two systems of windings can arise high currents that can damage thermally the stator winding (damaged end turns are shown).
(b). Parallel paths can cause circulating currents in the auto wound stator due to random positions of conductors in coils.
(c). Concentric double-layer winding with coil groups containing different number of coils is a wrong solution. Double-layer lap winding is recommended. It can be auto wound.
(d). Deep slots for auto wound double-layer windings with parallel paths are not recommended. Winding asymmetries due to coil side locations in the slot lead to unequal impedances and unequal induced EMFs.

To minimize the losses in the retaining sleeve and PMs, torque ripple and vibration, the stator slots should have very narrow slot openings or be closed. In the case of closed stator slots, the slot closing bridge should be highly saturated under normal operating conditions.

The stator of HSPMM plays a significant role in cooling the whole machine. In addition, most of the losses including the losses generated by HSPMM rotor are all directly related to the structure and material of stator.

**1. Material:**

To improve the machine electromagnetic performance and to reduce iron loss a non-oriented silicon steel sheets are usually used for HSPMM stators. Recently, amorphous alloy and soft magnetic composite (SMC) materials are utilized in HSPMM stators.

Compared to silicon steel sheets, stators based on amorphous alloy can achieve a much lower iron loss. However, for amorphous alloy have complex shape result in such materials so they used only for the simple non-slot situations.

SMC may be suitable for the HSPMM stator cores due to the advantages including superior magnetism, low rotor eddy current losses (RECL) and cost.

## 2. Choice of pole number:

At present, the number of poles is usually fixed at 2 or 4 to realize high-speed operation. The 2-pole motors have strong integrity of magnetic poles, which can effectively reduce the winding current frequency as well as the magnetic field alternating frequency.

The 4-pole machines have a small winding length which can effectively save the space and cut down the copper loss. However, due to the change of motor main frequency, iron loss increases. Meanwhile, a higher number of poles can also be selected when the motor works with high power and low speed.

## 3. Stator core:

For the stator design, the main problem is the high frequency of the stator current and flux. It is well known that the stator core losses per kilogram can be expressed as:

$$P_{Fe} = k_0 (\frac{B}{B_0})^2 (\frac{f}{f_0})^{1.3}$$

Where B and f = are the density and frequency of the magnetic flux in the stator core,

$k_0$ = the loss coefficient per kilogram of the stator core material tested under the condition of the frequency $f_0$ and flux density $B_0$.

It can be seen that the stator core losses will be a serious problem for a high-speed machine due to the high frequency of the stator flux variation. The only method to cope this problem is to choose available materials with low core losses, such as special soft magnetic alloys, amorphous steel and powder ferrite cores. There are normally 3 different types of stator core structure: multi-slot, minimal slot and slotless, as shown in fig 5.1.2.

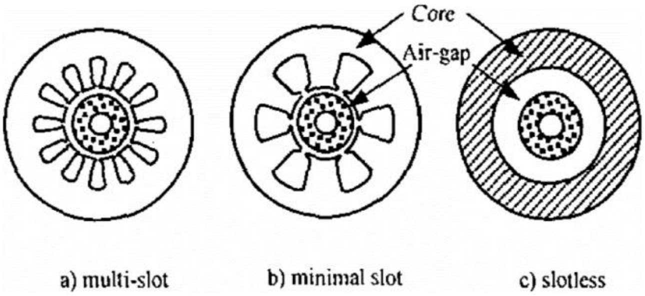


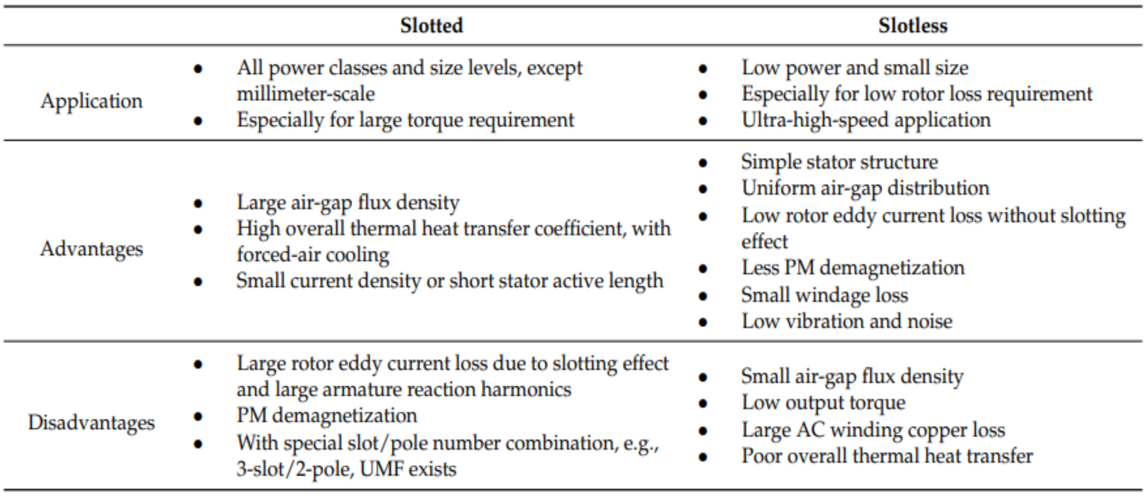
Figure 5.1.2. Three different structures of stator core

For the slotted core, the iron teeth are added in the stator for the arrangement of coil windings. Since the iron teeth are a magnetic material, the equivalent air gap can be reduced. By contrast, for the slotless core, the windings are directly attached on the surface of the stator back iron. Under this effect, the equivalent air gap is increased compared to the slotted core.

Brief description about three types of stator core:

- Multi-slot core has 12 even more slots. The advantage of the multi-slot core is that the stator winding can have distributed and short-pitch coils, which is helpful for eliminate some harmonic components of MMF. The pulsation frequency of magnetic field on the rotor surface produced by the stator slot opening due to the slot number increasing will increase, which will increase the losses of the rotor surface.
- The minimum number of slots for three-phase winding will be 6. Compared with the multi-slot structure, the 6-slot core is more effective for the winding availability. The pulsation frequency of magnetic field on the rotor surface is reduced due to the reduction of the slot number. The main drawback of the 6-slot core is the harmonic components of MMF cannot be eliminated.
- The slotless core, is a ring core with smooth surfaces. The large air-gap between the rotor and stator core is used for housing the stator winding.

Compared with the cores having slots, the magnetic field distribution in the air-gap is more uniform. Thus, the rotor losses produced by the magnetic field pulsation will be reduced. The axial length of the slotless core has to be larger than the slotted core to compensate the flux density reduction.



| | Slotted | Slotless |
|---|---|---|
| Application | - All power classes and size levels, except millimeter-scale<br>- Especially for large torque requirement | - Low power and small size<br>- Especially for low rotor loss requirement<br>- Ultra-high-speed application |
| Advantages | - Large air-gap flux density<br>- High overall thermal heat transfer coefficient, with forced-air cooling<br>- Small current density or short stator active length | - Simple stator structure<br>- Uniform air-gap distribution<br>- Low rotor eddy current loss without slotting effect<br>- Less PM demagnetization<br>- Small windage loss<br>- Low vibration and noise |
| Disadvantages | - Large rotor eddy current loss due to slotting effect and large armature reaction harmonics<br>- PM demagnetization<br>- With special slot/pole number combination, e.g., 3-slot/2-pole, UMF exists | - Small air-gap flux density<br>- Low output torque<br>- Large AC winding copper loss<br>- Poor overall thermal heat transfer |

Table 5.1. Application, Advantages and Disadvantages of slotted and slot less stator.

## 5.2. Stator geometric design:

In general PM motor losses consist of (a) copper loss, (b) iron loss, and (c) magnet eddy current loss. The stator design is then performed in order to minimize the motor loss balancing the torque output. Since the motor copper loss and iron loss can be minimized in slotted motors by the design of tooth depth ($t_d$) and tooth width ($t_w$). But, for slotless motors without an iron tooth, the parameters of slot span ($s_{spn}$) and slot depth ($s_d$) are selected to determine the slotless stator geometry. Similar to slotted stator motors, the balance design of copper loss and iron loss can be applied on slotless motors by adjusting $s_{spn}$ and $s_d$. Fig 5.2 illustrates both $s_{spn}$ and $s_d$ in a slotless motor.

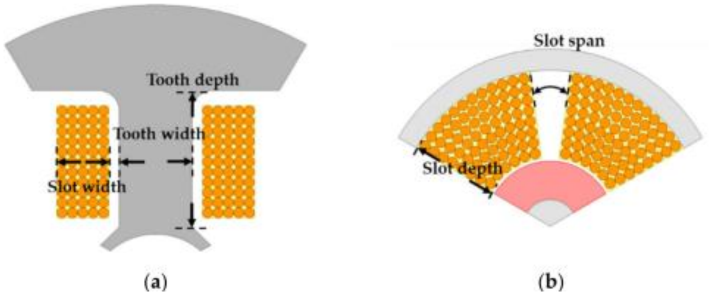


Figure 5.2 (a). slotted stator and (b). slotless stator

**Copper loss:**

The copper loss is induced by the winding resistances. The copper loss $P_{cu}$ can be estimated by:

$$P_{cu} = (N_{coil}.\ I\ )^2\ .\ \rho_{cu}\ .\ \frac{l_{slot}+l_{end}}{K_{ratio}*A_{end}}$$

where $N_{coil}$ = the number of turns per coil,

I = the phase current,

$\rho_{cu}$ = the resistivity of the copper conductor,
$l_{slot}$ = the slot axial end,
$l_{end}$ = the average length of end winding,
$K_{ratio}$ = slot ratio, and
$A_{end}$ = slot cross-section.

It is noteworthy that the copper loss causes additional heat when phase current passes through coil conductors. For slotless stators, more copper loss is expected because more windings are required to produce the same torque output. However, the low rotor iron loss is the design trade-off.

**Iron and Magnet loss:**

Different from copper loss, the iron loss and magnet loss are both induced by the variation of the magnetic field in the iron core. In general, the iron loss can appear in both the stator and rotor. However, for the surface PM motors, the rotor iron loss can be negligible due to the large air gap, including the magnet height.

The iron loss can be subdivided into hysteresis loss and eddy current loss. The hysteresis loss appears when the ferromagnetic material is repeatedly magnetized with the AC magnetic field. It causes mutual friction between two internal magnetic domains, resulting in the energy loss. On the other hand, the eddy current loss is caused by the local circulating current due to the armature reflected magnetic field. Considering both hysteresis loss $P_{hys}$ and eddy current loss $P_{eddy}$, the total iron loss $P_{iron}$ can be shown to be:

$$P_{iron} = P_{hys} + P_{eddy} = K_{hys} * B_{peak}^{2} f + \frac{\pi^2 d^2 \sigma}{6} (B_{peak} * f) + 8.67\, K_{eddy} (B_{peak} * f)$$

Where $K_{hys}$ = the hysteresis loss coefficient,
$B_{peak}$ = the peak flux density,
f = the rotor operating frequency,
d = the strip lamination thickness,
$\sigma$ = the strip lamination conductivity, and
$K_{mag}$ = the anomalous eddy-current loss coefficient.

It is noteworthy that, only the iron eddy current loss is considered in Peddy. In addition to iron, the eddy current also appears in magnets, e.g., magnet loss $P_{mag}$. For standard PM motors, $P_{mag}$ can be negligible at low speed. However, for high-speed motors, the magnet loss $P_{mag}$ must be taken into account to estimate the overall loss. $P_{mag}$ is mainly caused by air gap armature flux harmonics, which is formulated by:

$$P_{mag} = \int \rho_{Fe} * J^2 \, dV$$

where $\rho_{Fe}$ is the electric resistivity of the conduction body and

J is the armature current density.

Thus, by the geometric design, the copper loss $P_{cu}$ and iron loss $P_{iron}$ are both minimized by adjusting $t_d$ and $t_w$. For example, $P_{iron}$ decreases as $t_w$ increases due to more flux across the area. However, $P_{cu}$ might increase as $t_w$ increases because of less winding space. By contrast, for the slotless motors, the winding area instead of teeth area determines the magnitude of loss $P_{cu}$ and $P_{iron}$. The windings area can be designed through the parameters of slot span $s_{spn}$ and slot depth $s_d$.

## 5.3. Rotor structure and material:

There are two suitable materials (NdFeB and SmCo) for the HSPMM rotor to their high coercivity, compressive strength and flexural strength.

- NdFeB has a greater tensile strength than SmCo but it is susceptible to temperature.
- SmCo has a small temperature coefficient and performs better in high operating temperature, which means that this material is more suitable for HSPMMs considering the requirements of high temperature working stability.
- However, HSPMM needs to operate at a high speed range, which means that the SPM would suffer from a huge centrifugal force. Thus, sleeve equipment, installed on the surface of permanent magnet, is usually used to protect the rotor.
- Considering the satisfactory strength characteristics, alloy materials including Inconel718 and Ti6Al4V as well as fibrous composites such as carbon fiber and glass fiber can be used in the sleeve. Among these materials, fibrous composites are preferable in density and strength, but they have a low thermal conductivity.
- Alloy materials are proved to have better behaviour in terms of heat dissipation, temperature stability and stiffness.

### 1. Pole number:

There are normally two choices of the pole number they are 2 or 4 poles, which have both advantages and disadvantages as follows:

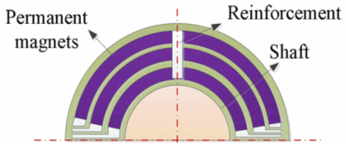
For a 2-pole machine, the rotor has the simple structure and good strength and rigidity. The permanent magnet can adopt the integral structure and be magnetized in whole, which insure the mechanical and electromagnetic symmetry of PM rotor.

Another advantage of the 2-pole machine is that the frequency of the stator flux sand current is only half the frequency of the 4-pole machine, which is beneficial to the reduction of the losses of stator core and copper.

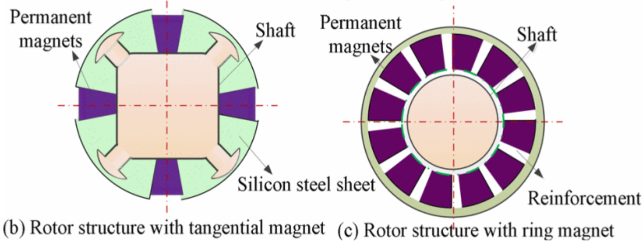
Compared with the 4-pole machine, the main drawbacks of the 2-pole rotor are that the endings of the stator winding will be longer and the sectional area of the stator yoke will be larger.

## 2. Rotor design:

PM rotor designs include [23]surface-type, inset-type bread loaf or interior-type PMs and solid PM. IPM performs well in terms of speed regulation range as well as overload capacity, and has low risk of demagnetization. Fig. 5.3.1 shows three different IPM rotor structures used in HSPMMs. The rotor in Fig. 5.3.1(a), have a small magnetic flux leakage coefficient. Then a novel tangential rotor structure, illustrated as Fig. 5.3.1(b) was proposed for not only effectively reducing the stress and magnetic flux leakage, but also providing the magnetic reluctance torque and reducing the permanent magnet usage. Moreover, a kind of ring permanent magnet segmented structure, shown as Fig. 5.3.1(c), was also proposed, which can efficiently reduce the sleeve thickness and equivalent air gap, and thus improve the permanent magnet utilization. However, the problems of air gap harmonics gradually hinder the extensive applications of IPM to HSPMM.



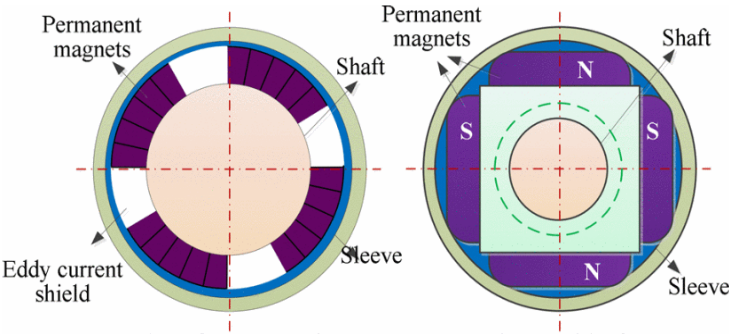
(a) Rotor structure with segmented magnet



(b) Rotor structure with tangential magnet (c) Rotor structure with ring magnet

Figure 5.3.1. Different IPM rotor structures used in HSPMM.

For SPM, the permanent magnet is mounted on the surface of rotor and protected by the sleeves made by composite materials or alloys as shown in fig 5.3.2. This kind of rotors are usually utilized in motor manufacturing companies like ABB and GE. For a bread-loaf permanent magnet structure, shown as Fig. 5.3.2(b) in which the motor performance in air gap magnetic flux density can be improved.



(a) Surface mounted (b) Bread-loaf

Figure 5.3.2. Two types of rotor structures

All surface-type PM rotors are characterized by minimal leakage flux. Bread loaf surface-type PM rotors provide, in addition, the highest magnetic flux density in the air gap (large volume of PM material). There are two solid PM rotor structures as shown in fig 5.3.3: a solid PM with a sleeve and solid PM with a hollow shaft. The design considerations mainly focus on the mechanical stress due to ultra-high-speed operation.

(a) (b)

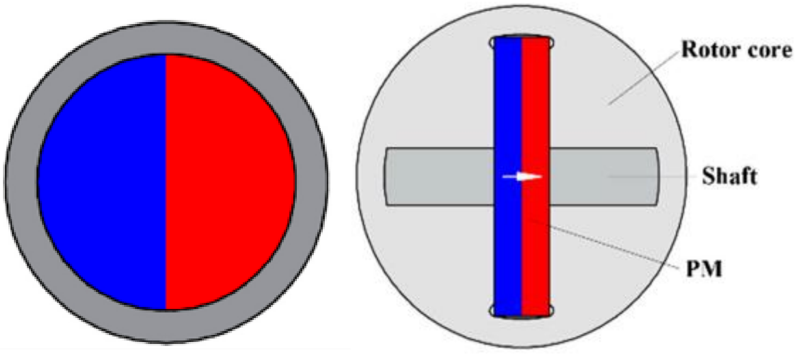
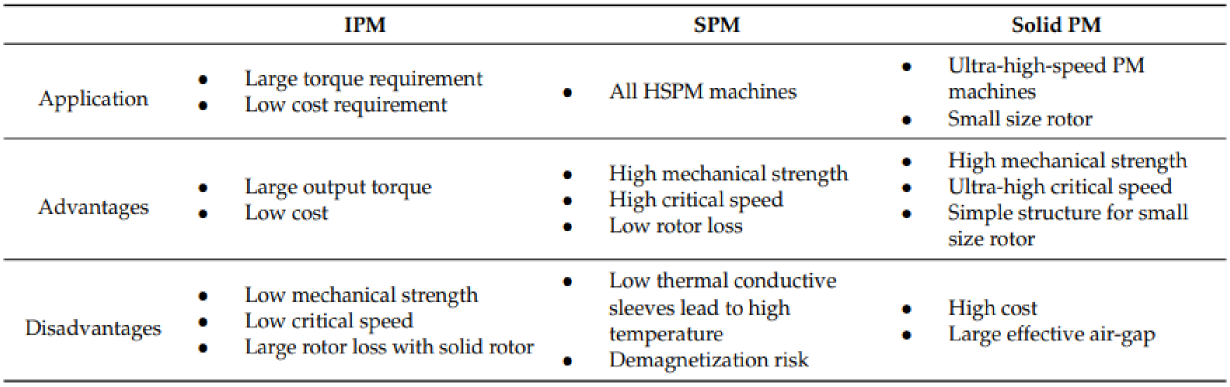


Figure 5.3.3. Solid PM rotor structure. (a) solid PM with sleeve. (b) solid PM with novel hollow shaft

The solid PM[5] with sleeve is commonly used due to its simple rotor structure and easy assembly process. In addition, the solid PM is segmented axially to reduce the rotor eddy current loss and to simplify the assembly process of the magnets, the high rotor mechanical strength and electromagnetic performance.

The novel solid PM rotor design with a hollow shaft, which consists of an amorphous rotor core, solid PM, and a hollow shaft, Fig 5.3.3. It should be noticed that epoxy is employed in the gaps between PMs and rotor core to improve the rotor mechanical strength. The advantage of the novel rotor structure is that since the PM is inserted into the rotor core, the manufacture and assembly are simple. This rotor structure can improve the rotor stiffness and significantly increase the first critical speed. However, this rotor structure will lead to a large shaft loss, which may increase the rotor temperature and the demagnetization risk.



| | IPM | SPM | Solid PM |
|---|---|---|---|
| Application | • Large torque requirement<br>• Low cost requirement | • All HSPM machines | • Ultra-high-speed PM machines<br>• Small size rotor |
| Advantages | • Large output torque<br>• Low cost | • High mechanical strength<br>• High critical speed<br>• Low rotor loss | • High mechanical strength<br>• Ultra-high critical speed<br>• Simple structure for small size rotor |
| Disadvantages | • Low mechanical strength<br>• Low critical speed<br>• Large rotor loss with solid rotor | • Low thermal conductive sleeves lead to high temperature<br>• Demagnetization risk | • High cost<br>• Large effective air-gap |

Table 5.2. Application, Advantages and Disadvantages of different rotor structure.

However,[24] at high speed, the rotor sleeve is required to maintain the magnets on the rotor surface. All surface-type, including bread loaf and inset-type PM rotors, can be used only with an external rotor retaining sleeve. In the case of an interior-type PM rotors the retaining sleeve is not necessary, but the ferromagnetic bridge in the rotor core between neighbouring PMs must be very carefully sized.

Firstly, although the increased sleeve thickness improves mechanical strength, the increased effective air-gap length due to the sleeve being nonmagnetic leads to a decrease in air-gap flux density and output torque. Secondly, sleeves made from non-conducting material with high mechanical strength have higher critical speed. However, their low thermal conductivity may lead to high maximum temperature concentration in the rotor and thus increase the demagnetization risk. Therefore, the sleeve thickness and sleeve material are widely researched in the rotor design for HSPM machines.

In general, the rotor sleeve is realized by a thin layer of non-magnetic material, e.g., titanium alloys, stainless steels, carbon graphite, carbon fiber, glass fiber and reinforced plastics.

The thin carbon-fiber bandage can make the air-gap smaller and the PM thickness larger, which are beneficial to the power density. However, the carbon-fiber acts like a thermal insulator and is an adverse factor for the watt dissipating of the rotor.

(c) (d) (e)

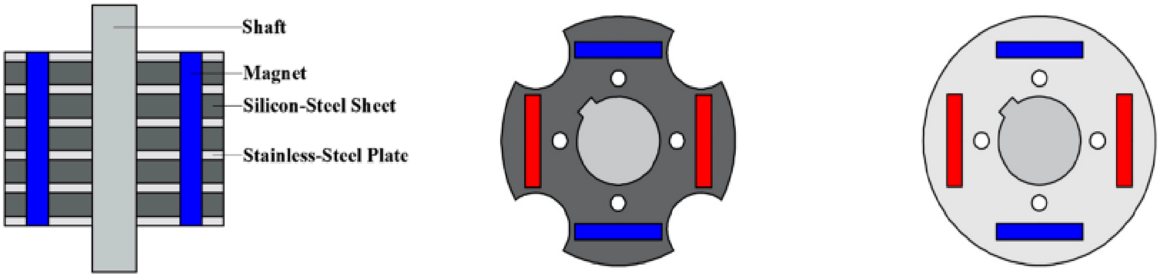


Figure 5.3.3. Retaining sleeves for high speed PM rotors: (a) Metal sleeve; (b) carbon-graphite sleeve. (c) Retaining shield rotor construction. (d) Silicon-steel sheet. (e) Stainless-steel plate.

- Maximum temperature for metal sleeves (Fig. 5.3.3(a)) is $290^0$C and for fiber sleeves (Fig. 5.3.3(b)) is $180^0$C.
- Maximum surface linear speed for metal sleeves is 240 m/s and for fiber sleeves is 320 m/s.
- There are no eddy current losses in fiber sleeves; however, it is more difficult to assembly the rotors with fiber sleeves than rotors with metal sleeves.
- If the magnetic saturation effect is used effectively, a thin steel sleeve in low power machines can sometimes be better than a sleeve made of non-ferro magnetic material.
- To prevent the magnets from exfoliating, initially, a non-ferro magnetic stainless steel sleeve is shrunk on the PMs to retain them. Although the stainless steel has low electric conductivity, the losses occurred in a relatively thick sleeve can be still quite large at the speeds over 100,000 rpm. Nonconductive fiber reinforced plastic at higher speeds is better.
- To increase the electromagnetic coupling between the magnets and the stator winding, the air gap should be made as small as mechanically possible. However, the use of a small air gap increases the tooth ripple losses in the retaining sleeve, if the sleeve is made of current-conducting material.

More importantly, although the rotor with a carbon fibre sleeve has the smallest rotor losses, the rotor with a copper sleeve has the lowest maximum temperature due to high thermal conductivity and relatively small eddy current losses. The glass fibre sleeve cannot withstand the centrifugal force when the rotor surface speed is larger than 150 m/s, so that the carbon fibre sleeve can allow higher critical speeds. Thus, a good material for retaining sleeves are non-ferro magnetic and have high permissible stresses, low electric conductivity, low specific mass density and good thermal conductivity. Since permanent magnet is not able to withstand large centrifugal forces and must be encapsulated in some high-strength material.

Recently, laminated sleeves stacked from non-ferro magnetic materials as shown in fig 5.3.4.

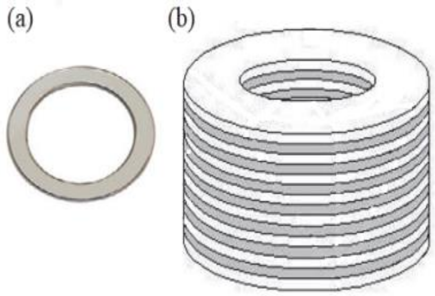


Figure. 5.3.4. Laminated retaining sleeve: (a) single non-ferromagnetic lamination; (b) stacked retaining sleeve.

They provide:

- significant reduction of eddy currents;
- simple manufacture using punching dies;
- can withstand high radial stresses.

The main drawback is the limit on the radial thickness of the laminated sleeve because the sleeve cannot be too thin.

Bearing support quality determines the operating stability and dynamic characteristics of HSPMM rotor to a large extent. At present, four kinds of bearings such as ball bearings, oil-filled bearings, air bearings and magnetic bearings can be applied to HSPMMs. Active radial and axial magnetic bearings or air bearing are frequently used. Accordingly, it is seen that ball bearings are mainly used in HSPMM with low rated power while air bearings and magnetic bearings can usually be employed for high power, high speed electrical machines High-speed PM motors integrated with magnetic bearings and solid-state devices are used in gas compressors providing a true oil free system, reduced maintenance and high efficiency. Recently, a kind of bearing less electrical machine was proposed, in which the rotor can be suspended through electromagnetic force. In summary, ball bearing possesses the advantages of space saving and lost cost, but it has relative high failure rate. Additionally, the operational stability of air bearing needs to improve while the force balance is a critical issue for the application of magnetic bearing. No auxiliary lubrication supply system is needed, eliminating hazardous waste disposal issues.

## 5.4 Rotor geometric design:

In PM synchronous and PM DC brushless motors the rotor core losses due to fundamental harmonic do not exist. The rotor core losses in PM machines are due to the pulsating flux produced by the rapid changes in the air gap reluctance as the rotor passes the stator teeth. These losses are negligible in surface-mounted PM motors, due to their large effective air gaps (including PM radial thickness). These rotor losses can sometimes be significant in buried PM motors, salient pole rotors and surface PM motors with mild steel pole shoes. The rotor core losses due to magnetic flux pulsations and higher harmonics can be calculated using various methods.

**A. Losses in conductive retaining sleeves:** The slot ripple losses in the retaining sleeve of the rotor can be calculated with the aid of the following simple analytical equation[25]:

$$\Delta P_{sl} = \frac{\pi^3}{2} * \sigma_{sl} * k_r * (B_{msl} * n)^2 * D^3_{sl} * l_{sl} * d_{sl} \ \ [W]$$

where n is the rotor speed in rev/s, $D_{sl} = D_{2out} - d_{sl}$, $D_{2out}$ is the rotor outer diameter, $D_{sl}$, $l_{sl}$, $d_{sl}$ and $\sigma_{sl}$ are the mid-diameter in meters, effective length in meters, thickness in meters and the electric conductivity in S/m of the retaining sleeve, respectively. For titanium alloy IMI250 the electric conductivity $\sigma_{sl} = 0{:}625 * 10^6$ S/m at $200^0$ C. The coefficient for increasing the sleeve resistance due to tangential sleeve currents is:

$$K_r \ \sim 1 + \frac{1}{\pi} * \frac{t_1}{l_{sl}}$$

The amplitude of the high frequency magnetic flux density due to slot openings (slot ripple) can be calculated as:

$$B_{msl} = 2\beta B_{mean} = 2\beta \frac{1}{k_C} \frac{2}{\pi} B_{mg}$$

$$\beta = \frac{B_{msl}}{2B_{mean}} = \frac{1 + u^2 - 2u}{2(1 + u^2)}$$

$$u = \frac{b_0}{2g} + \sqrt{1 + \left(\frac{b_0}{2g}\right)^2}$$

Where $B_{mean}$ = the mean value of the magnetic flux density in the air gap under the stator slot opening,

$B_{mg}$ = the peak value of the magnetic flux density in the air gap,

$b_0$ = the stator slot opening in m,

g = the air gap between the stator core and PM, and

$k_c$ = Carter's coefficient of the air gap.

Decrease in the slot opening and/or increase in the air gap reduce the slot ripple.

**B. Losses in permanent magnets:** Since the electric conductivity of rare earth PMs is only 40 to 96 times lower than that of a copper conductor, the losses in conductive PMs due to higher harmonic magnetic fields produced by the stator cannot be neglected in the case of high-speed motors. Similar to losses in a conductive retaining sleeve, the most important losses in PMs are those generated by the fundamental frequency magnetic flux due to the stator slot

openings. Slot ripple losses are only in motors with slotted armature ferromagnetic cores and do not exists in slotless machines.

The slot ripple losses in PMs can be approximately estimated by using slot ripple loss equation from conductive retaining sleeve, in which $\sigma_{sl} = \sigma_{PM}$, $l_{sl} = l_M$, $D_{sl} = D_{2out} - h_M$ and $d_{sl} = h_M$, where $\sigma_{PM}$ is the electric conductivity of PM, $l_M$ is the axial length of PM (usually $l_M = L_r$) and $h_M$ is the radial height of PM, i.e

$$\Delta P_{PM} = \frac{\pi^3}{2} * \sigma_{PM} * k_r * ( B_{msl} * n)^2 * (D_{2out} - h_M)^3 * l_M * d_M \quad [W]$$

Since the external surface area of PMs is smaller than that of the rotor, then slot ripple loss equation from conductive retaining sleeve should be multiplied by the factor $S_{PM} / (\pi * D_{2out} * l_M)$, where $S_{PM}$ is the surface area of PMs. For surface PMs,

$$S_{PM} = \alpha_i * \pi * D_{2out} * L_r$$

The magnetic flux density $B_{msl}$ can be estimated on the only if the rotor is not equipped with conductive retaining sleeve. Otherwise, the realistic peak value $B_{msl}$ will be much smaller. magnetic flux density from conductive retaining sleeve may give in this case too high value of slot ripple losses in PMs.

# 6 Applications

## 6.1 Wind Turbine:

Today, most of the low speed wind turbine generators are permanent-magnet (PM) machines[27]. As contrasted with the long and thin structure of high speed machine, the low speed machine usually has a short and fat structure like a disc in order to use effectively the rotating speed of the rotor. The permanent magnet (PM) machine is a favourite with the direct driven wind generator due to its high efficiency and simple structure although the conventional synchronous and induction machines can be used.

Since the machine will have lower copper losses due to the lower winding resistance and to some extent better fault tolerance. However, some slot-pole combinations in the machine will result in a low winding factor and excessive unbalanced radial magnetic forces. Furthermore, poorly chosen slot-pole combination will cause frequency alternating magnetic fields causing eddy current losses which may influence permanent magnets and stator windings. In order to avoid, the slot-pole combination has to be selected carefully. In a number of slot pole combinations with high winding factor and low radial magnetic force unbalance are suggested.

Small wind turbines can be categorized into two types: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs), as shown in Figs. 6.1, respectively.

Figure 6.1. Horizontal and Vertical axis small wind turbine

Vertical axis turbines[31] do not need to be pointed into the wind as they can access wind from all directions. However, the overall efficiency of the VAWT is not very impressive. Horizontal axis turbines have high overall efficiency compared with VAWT but they generally have difficulties operating near ground and in areas with turbulent winds because they require more laminar wind flows. In general, the efficiency of small wind turbines is low compared with large wind turbines which invariably leads to comparatively lower energy yield obtainable from Small Wind Turbines(SWTs). The low efficiency of SWTs is in part due to aerodynamics but also due to the lack of optimized designs.

The aerodynamic power of a wind turbine is given as,

$$P = \frac{1}{2}\rho\pi R^2 v^3 C_p$$

$$\lambda = \frac{R\Omega}{v}$$

Where ρ = air density,

R = turbine radius,

v = wind speed;

λ = the ratio of the tip speed of the turbine blade to the wind speed;

$C_p$ = the turbine power coefficient which represents the power conversion efficiency of the wind turbine, and is a function of the tip speed ratio λ as well as the blade pitch angle β for a pitch controlled turbine.

When the wind speed is lower than rated speed, the pitch angle β is usually taken as the optimal value in order to get the maximum power conversion efficiency. When the wind speed is larger than the rated value, the blade pitch angle should be adjusted to meet the requirement of the output power. The pitch angle β has strong effect on the tip speed ratio λ as well as the power coefficient $C_p$ of the wind turbine. The voltage and electromagnetic torque equations for a PM generator in the d–q axis synchronous rotational reference frame can be expressed as follows:

$$v_q = -(r + pL_q)i_q - \omega_r L_d i_d + \omega_r \lambda_m$$

$$v_d = -(r + pL_d)i_d + \omega_r L_q i_q$$

$$T_e = (\frac{3}{2})(\frac{P}{2})[(L_d - L_q)i_q i_d - \lambda_m i_q]$$

where $v_q$, $i_q$, $v_d$, $i_d$ and $T_e$ = are the q -axis voltage and current, d -axis voltage and current, and electromagnetic torque respectively;

r, $L_q$ and $L_d$ = are the resistance of q -axis and d -axis inductances;

$\lambda_m$ = flux linkage of the q -axis winding produced by the permanent magnets;

P and $\omega_r$ = are the pole number and angular rotor speed respectively;

p = d/dt is a differential operator.

In small-scale wind power plants very often low speed direct-drive synchronous generators are used. Due to low rotational speed of the synchronous generator directly connected to the mechanical shaft of the wind rotor, the generator has a multi-poles construction.

The use of a gearbox causes many technological problems in a wind power plant, as it demands regular maintenance, increases the weight of the wind plant, and generates noise and vibration level and then increases power losses. These problems may be avoided using a direct-drive low speed PM synchronous generator.

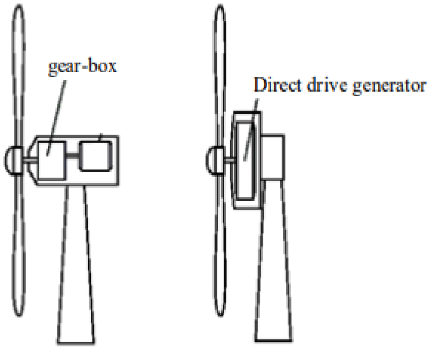
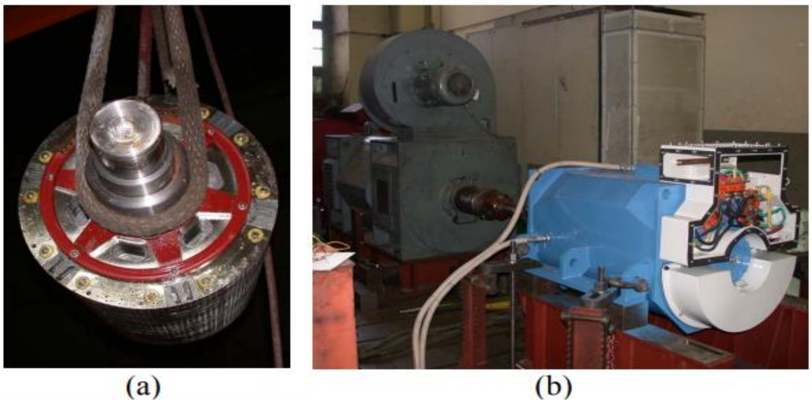


Figure. 6.1.2. Gear-Box and Direct-Drive Low Speed Wind Power Generator.

There are two basic flux types of direct-drive generator. Radial flux type (Cylindrical rotor structure) and Axial flux type (Disc type rotor structure). The length of the axial-flux machine is short compared to the radial-flux machine. Many axial-flux machines can easily be connected directly to the same shaft. The machine may have high axial force between the stator and rotor discs. This generator type is used the axial flux type.

## 6.2 Ship propulsion systems

In low-speed, high-power applications like electrical propulsion drives[32], development of motors towards higher specific outputs (power per volume unit) is going on. This is especially true in podded drives, where the motor is installed in the propeller pod, and where space savings can bring significant benefits. Manoeuvrability of the ship is greatly improved and control of propeller speed and ship direction are fast and smooth. Therefore, electric propulsion system is the advanced ship propulsion system that ensures high efficiency, flexibility and improves ship manoeuvrability, passengers comfort providing the complete environment harmonization. The PM motor has lower losses and higher torque density (smaller size) than induction or synchronous motor of the same power rating, which is important since space on the ship is always scarce. Although superconductive motor is the smallest in size, it remains currently reserved only for special applications due to its high cost.



(a) (b)

Figure 6.2. Prototype of the LPMR 750 IPM motor for ship propulsion. (a)assembled rotor, (b) preparation for testing

Guidelines for design optimisation are based on the specific machine application. In the first stage of the work, a comparison in terms of volume, cost and overall performance between direct drive solution and geared solution was carried out.

The second step was the choice of the rotor configuration. SPM rotors and Interior PM (IPM) rotors were considered. Application to ship propulsion does not require operation above base speed, in the high speed constant power region. Therefore, surface PM motors are adequate for such an application. However, IPM motors could allow smaller air-gap, easier and more reliable PM assembling and, in general, smaller volume. It was found that the direct drive motor has a weight, and then a cost, about 3 times that of the geared solution, the latter being designed with a lower iron and copper stresses and then with lower temperature rise.

**Comparison between SPM and IPM PM motor designs:**

For the purpose of ship propulsion[34] an SPM motor design is most often considered but IPM design offers several advantages over SPM design.

- The air-gap in an IPM motor is smaller and is limited by mechanical stiffness of the rotor structure and tolerances of the tools used for construction and fitting of the rotor.
- In an SPM motor the magnet protection against demagnetization can be achieved solely by increasing the thickness of the magnets.
- An IPM motor provides better protection against demagnetization since an additional path for the armature winding field is formed around rotor cavities in which the magnets are located.
- The field weakening capability of an SPM motor is very limited (around 20 % above rated speed for most designs).

- An IPM motor has a very good field weakening capability and can operate at speeds several times higher than rated speed depending on the configuration of the rotor cavities.
- The fitting of the rotor of an SPM motor into the stator bore is a complicated task since magnets on the surface can be easily damaged.
- The magnets in an IPM motor are fitted into cavities and are thus mechanically protected. The shape of the magnets can be made very simple (e.g. rectangular), which reduces cost.
- The magnets in an SPM motor cannot be further protected against corrosion in a manner other than initial galvanization.
- In an IPM motor an additional protection against corrosion can be achieved by pouring resin into the cavity prior to fitting the magnets.
- Besides producing torque originating from the interaction between permanent-magnet field and the armature current, an additional reluctance torque is produced in an IPM motor due to magnetic non-symmetry in d and q axes created by the presence of cavities in the rotor yoke.
- The rotor of an IPM motor is mechanically more robust thus allowing for higher rotational speed than an SPM motor of the same rotor size.
- The amount of permanent-magnet material required for the same power rating and the same level of demagnetization is smaller in an IPM motor than in an SPM motor.

For a given value of the machine outer diameter, $K_r$ is the important design parameter which greatly influences machine characteristics such as torque, ratio between torque and mass of the active materials and efficiency.

For given values of the magnetic and electric loadings the maximum torque is achieved, $K_r = 1/\sqrt{3}$.

However, the mass of the machine active materials also depends on $K_r$, and from design calculations it is found that the ratio between torque and mass of active materials is maximised with value of $K_r$ greater than $1/\sqrt{3}$, being this value a variable which depends on the machine pole number. If the machine design is specialised to ship propulsion drives, the machine weight is to be one major concern, as saving machine active materials may significantly reduce the machine cost.

The three main topologies of permanent magnet motors[33] are: axial flux, transverse flux and radial flux operation principle.

- **Axial Flux Machines:** The axial flux principle incorporates a disc type rotor and two-disc type Stators. The axially magnetized permanent magnets are located in the rotor disc. The flux produced by rotor poles flows through two annular air gaps into the stator core. A high pole number must be used to decrease the thickness of the flux carrying parts and to decrease the length of the winding overhangs. This allows a construction with many disc type stators and rotors within the axial length available and provides, as a consequence, a large air gap surface, which again means very high specific output (high torque/volume -ratio).
- **Transverse Flux Machines:** The transverse flux machine, also described as variable-reluctance permanent magnet machine, has a stator phase winding, usually having a simple circular form, exciting a homopolar mmf distribution in the air gap. This mmf is modulated by a pattern of stator teeth to produce a high order spatial harmonic of flux, which then interacts with a pattern of magnets on the rotor, with the same pole number, to produce torque. TF machines can efficiently have a very small pole pitch (high number of poles), which provides high specific output for the concept. The highest specific outputs can be achieved with multi-disc types.
- **Radial flux machines:** Radial flux flow is the traditional and conventional operation principle for rotating electrical machines. Radial flux machines can be built efficiently for low or for high pole numbers.

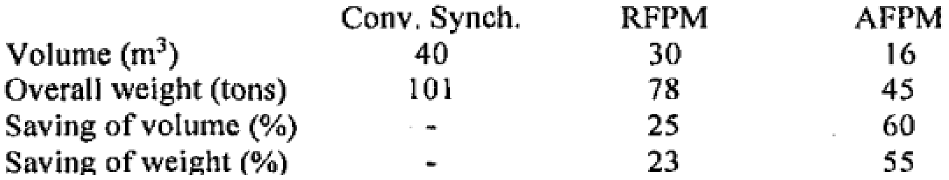
When optimising the permanent magnet motor construction in relation to the size and weight, a high pole number is favourable, in all the three topologies. A higher pole number means a shorter pole pitch, and because flux carrying parts are directly related to the pole pitch, smaller thicknesses of stator and rotor yoke can be used. A smaller pole pitch means generally also a smaller permanent magnet thickness, which is important thinking of material costs. A smaller thickness of flux paths allows using a bigger air gap diameter with the same external diameter. With a bigger air gap diameter, the motor can produce more torque.

- Since the gearless propeller motor drives have low rotational speed, employment of a fairly high pole number is natural.
- When increasing the pole number, the feeding frequency will also increase. The increased frequency combined with a typically small air gap length can present considerable eddy current losses on the rotor surfaces due to harmonic distortion of the air gap flux caused either by slot harmonics or by converter harmonics. This must be considered in the PM motor

dimensioning and design, especially in the case of surface mounted magnets.

- Achieving high specific torque with axial field and transverse field topologies will require a high pole number and fairly complicated multi-disc constructions. Another disadvantage of the transverse flux machine is the low inherent power factor at full load.
- A lower specific torque is suited for the conventional radial field motor.

**Comparison of motors for ship propulsions:** By concerning machine total weight and volume the comparison considered machines of a different type but having same rating of 14 MW, 195 rev/min and same nominal efficiency of 98% at a given working over temperature of the winding as shown in table.6.



|  | Conv. Synch. | RFPM | AFPM |
|---|---|---|---|
| Volume ($m^3$) | 40 | 30 | 16 |
| Overall weight (tons) | 101 | 78 | 45 |
| Saving of volume (%) | - | 25 | 60 |
| Saving of weight (%) | - | 23 | 55 |

Table. 6. Comparison of motors for ship propulsions.

# 7 Comparison of Low speed and high speed Wind generators of PM machines

Basically, PM generators [35]can be divided into radial-flux and axial-flux machines, according to the flux direction in the air gap. Transverse flux machines exist, but do not seem to have gained a foothold in wind power generation. The availability of modern high energy density magnet materials, such as NdFeB, has made it possible to design special topologies such as toothless stators with air gap windings.

A comparison of generator topologies for direct-drive wind turbines has been carried out, using torque density and cost/torque with respect to the machine outer diameter as the criteria. The machine topologies considered are the conventional inner rotor radial-flux construction, outer rotor radial-flux construction, double stator axial-flux construction, double rotor axial-flux construction, single sided axial-flux constructions with force balance stator and force balance rotor, and Torus toothless axial-flux construction.

All the machines compared are built with surface mounted magnets, NdFeB, and grouped into two categories. One has direct-driven generators operating at low speeds of 50 rpm or 100 rpm; the other has the machines rotating at a high speed of 1200 rpm, where gearboxes are needed.

The criteria used for comparison are torque density, active material weight, outer radius, total length, total volume and efficiency. These criteria are identified as being critical for the efficient deployment of generators in wind turbines.

**1. Torque/volume and Torque/weight:**

The torque/volume is defined as the ratio of the developed torque of the generator to the active volume of the machine. The active volume includes the volume of magnets, copper conductor, stator teeth and yoke.

The torque densities for low speed direct-drive machines are much better than that of high speed machines with gear boxes, which means that low speed, multi-pole PM wind generators are more suitable than the high speed machines with gear boxes.

**2. Magnet Weight:**

At low speed all the axial-flux configurations except the Torus machine, the use of the magnets is better than that for the radial-flux constructions. But the single sided axial-flux construction uses more magnet than the radial-flux construction.

As the price of NdFeB magnet is still high, axial-flux slotted wind generator designs can reduce magnet cost. Since the magnet weight change as a function of power rating for high speed machines at same output power, these machines use less magnet, as the speeds of these machines are much higher.

**3. Copper Weight:**

The maximum copper is required by the inner rotor radial-flux machine. This is due to the fact that the end length in the radial-flux construction is longer than that in the axial-flux construction. The single sided axial-flux configuration uses the least copper. The Torus machine uses more copper than the double sided axial-flux machines, as the air-gap flux density in the Torus machine is less than that of the axial-flux slotted machines.

For high speed machine, the use of copper in the Torus machine is much more than those used by other topologies. This means that the Torus machine can only be used in multi-pole configurations, as the magnetic path is shorter in these cases, resulting in the end turn length being shorter.

**4. Lamination Weight:**

The maximum value of lamination is used by the single side axial-flux machines. The torus machine uses the minimum amount of laminations because of the absence of the stator teeth. The double sided axial-flux slotted constructions make better use of the laminations than the radial-flux constructions.

For high speed machines the increase of the lamination use for axial-flux configurations because an enlarged axial length is needed to provide a path for the magnetic flux in the stator yoke, as the pole number is lower.

### 5. Total Volume:

The radial-flux configurations take the maximum space. The double stator axial-flux slotted machine requires the least space, as in this construction, no rotor back yoke is needed, and the axial length is very short.

For high speed machines, the single sided axial-flux constructions need more room, due to the lower pole number and the increased axial length.

### 6. Active Material Volume:

The maximum active materials are spent by single sided axial-flux machines. The double rotor axial-flux slotted machine uses the minimum amount of active materials, as the stator back of yoke in this construction is only used for mechanical strength and is very thin. The Torus machine uses almost the same active materials as those used by the double stator axial-flux machine, but less than that used by radial-flux machines.

For high speed machines, the increase of the active material for the Torus machine is because the enlarged axial length is needed to provide a path for magnetic flux in the stator yoke, as the pole number lower here.

### 7. Efficiency:

The highest efficiency exists in the double rotor axial-flux machine, as the iron loss in this construction is the least. The radial-flux configurations have the lowest efficiency. Apparently, the larger output power has higher efficiency.

For high speed machines, the single sided axial-flux constructions are not efficient, due to the lower pole number and the increased axial length.

### 8. Total Length:

It is very clear that the radial-flux constructions have a much longer axial length than axial-flux constructions, especially for multi-pole machines. The axial length for axial-flux machines is much shorter than the radius. That is why these configurations are referred to as pancake machines.

# 8 Conclusion

Different motor configurations have been investigated in an attempt to replace an induction motor and its gearbox with a competing direct-driven PM machine. A design procedure based on an optimization program has been developed, taking the particularities of each configuration into account.

Compared with low-speed and moderate-speed conventional electrical machines, high-speed electrical machines offer advantages such as high-power density, small size, and light weight. More importantly, high-speed electrical machines can be directly connected to high-speed loads, and conventional gear boxes are no longer needed, which avoids complex gear box systems, improves system efficiency and reliability, and reduce cost.

At first, the inner- and outer-rotor SMPM motors and of the tangentially-magnetized PM motors are the most promising however, the torque ripple of these machines is very high. The tangentially-magnetized PM motors are found to be the lightest, while the V-shaped PM motor designs could not compete with the other motor configurations.

The rotor with a carbon fibre sleeve has the smallest rotor losses, the rotor with a copper sleeve has the lowest maximum temperature due to high thermal conductivity and relatively small eddy current losses. Thus, a good material for retaining sleeves are non-ferro magnetic and have high permissible stresses, low electric conductivity, low specific mass density and good thermal conductivity.

From comparison between HSPM and LSPM, is that axial-flux slotted machines have a smaller volume for a given power rating, making the power density very high. However, it because that as the power rating increases and the outer radius becomes larger.

The two-sided axial-flux configuration is superior to the one sided axial-flux configuration. However, one sided constructions use less copper and has a lower conductor loss. This kind of construction is also simple in construction.

For all of the comparisons, the outer rotor radial-flux construction is superior to the inner rotor radial-flux construction. Therefore, the outer rotor construction is more suitable to be applied in wind energy systems.

The Torus construction is simple because the construction requires more magnet weight because of the presence of the additional air-gap for accommodating stator windings. Therefore, this construction is more suitable for low power rating wind generators.

For most of the comparisons, the low speed constructions are superior to the high speed constructions, which means that multi-pole PM generators are preferred in the application of small, gearless, low speed wind system.

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