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# A Comprehensive Review on High Speed Permanent Magnet Motors and their Modern Applications

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## Abstract

Synchronous speeds in all types of alternating current machines depend on the frequency of the power grid, and performance at higher speeds at steady conditions requires higher frequency feeds. The development of speed control drive technology in recent decades has prompted renewed attention to high-speed engines. Important advantages of using high speed electric motors include higher density (and smaller dimensions) and greater torque generation capability. Also, the use of these motors enables the removal of the gearbox and lubrication system, which reduces maintenance costs. Nowadays, surface-mounted PMSMs are increasingly used for high-speed applications, because of the merits of simple structure and high-strength of the rotor. This paper first discusses the fundamental differences in the configurations of ordinary and high-speed permanent magnet motors, considering their specific characteristics. The specimens and their properties, have been discussed. Finally, the modern applications of high-speed permanent magnet motors have been introduced. also, the main manufacturers of high speed synchronous motors have been presented.

***Keywords:*** Synchronous Motor; Permanent Magnet; High Speed.

## 1. INTRODUCTION

With the availability of high specification materials, development of power electronic converters and improvement in the manufacturing methodologies, high
power density, high speed electrical machines are becoming increasingly popular in numerous applications, such as automotive [1]-[3], aerospace [4], compressor [5] and tool applications[6]. Permanent magnet synchronous motor (PMSM) offers the advantage of high efficiency compared to other types of motors since there is no excitation power loss in the rotor, and low eddy current loss in the stator and rotor for slotless structure. Therefore, there is an increasing interest to consider PMSM for super-high speed applications. Generally speaking, there are two kinds of rotor topologies for the permanent magnet (PM) machines, the surface-mounted PM (SPM) one and the interior PM (IPM) one. Nowadays surface-mounted PMSMs are increasingly used for high-speed applications, because of the merits of simple structure and high-strength of the rotor [4, 5]. The number of poles is usually designed as two or four to reduce the iron losses at high operating frequency [6].

## 2. High Speed PMSM structures

The design of high-speed permanent magnet synchronous machines is carried out with the purpose of reduction of the optimum flux density of the machine relative to similar machines at synchronous speeds. This reduction strategy is helps to control the machine's speed and results in designing machines with larger effective airgaps and lower power densities. Slotless stators can be utilized to stop power density drop. In this stator's structure, teeth on the stator are replaced by conductors. By using slotless stators, the rated current of rotor increases and the loss of power density causing by flux drop is compensated [7]. The cross section and conductor layout of slotted and slotless machines are shown in figure 1.

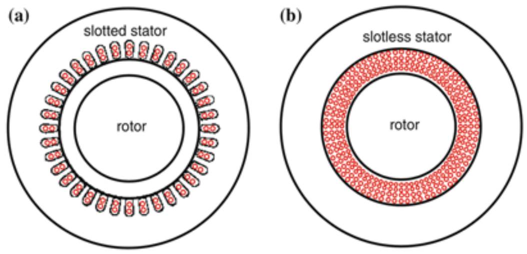


**Fig. 1:** conductor installation in stator: a) slotted, b) slotless

In the following section high speed IPM and SPM machines will be compared with regard to their mechanical and electromagnetic performance, weight, and cost.

## 3. The comparison between IPM and SPM machines

The main part of SPM machine which bears the mechanical stress is the rotor sleeve, while in IPM machines this stress is commonly withstood by rotor laminations and shaft. The sleeve stress increases as the rotating speed goes up due to the increasing centrifugal force, and decreases as the rotor temperature goes down due to the higher thermal expansion coefficient of the sleeve. Both the stress in the IPM rotor laminations and that in the IPM shaft goes up as the rotating speed increases. However, as the temperature goes up, the stress in the rotor laminations increases while that in the shaft decreases. Under similar working conditions, IPM machines are under a larger stress than SPMs, which may lead to break and fatigue.

Apparently, the IPM motor has more harmonics in its air gap flux density waveform, which is caused by the rotor openings and the smaller air gap compared to SPM with similar rated power.

The maximum torque for the SPM is achieved when the stator armature reaction field is ahead of the rotor magnet field by 90◦. In this situation the stator current and flux vectors are aligned and copper losses is minimum. However, the maximum torque for the IPM is achieved when the current vector have two non-zero perpendicular components. As a result, the maximum torque in IPMs will result in flux drop and copper losses in stator.

Apparently, the most expensive material in the motors is the rare-earth PMs. The SPM motor uses more copper while the IPM motors uses more steel, and the total weight of the two motors are almost the same. The magnets used in the IPM motor is much less than that of the SPM one. Meanwhile, the IPM motor is exempt from high strength alloy, which is considerably expensive and hard to process. Therefore, both the material costs and the processing costs of the IPM motor are much lower than that of the SPM motor.

Table 1, compares the information of some high speed PMSMs, sorted by their speed [8].

**Table 1:** specification of manufactured high speed PMSMs

| No. | Speed (rpm) | Power(KW) | Sleeve material | topology | application |
|---|---|---|---|---|---|
| 1 | 500,000 | 1 | titanium | SPM | Micro turbine |
| 2 | 500,000 | 0.1 | titanium | SPM | Micro turbine |
| 3 | 240,000 | 5 | Inconel | SPM | - |
| 4 | 220,000 | 2 | Carbon fiber | SPM | Turbo charger |
| 5 | 200,000 | 2 | titanium | SPM | - |
| 6 | 200,000 | 2 | titanium | SPM | - |
| 7 | 150,000 | 1.5 | Carbon fiber | SPM | Spindle motor |
| 8 | 150,000 | 1.5 | Glass fiber | SPM | Super charger |
| 9 | 120,000 | 22 | titanium | SPM | - |
| 10 | 120,000 | 5 | Inconel | SPM | - |
| 11 | 60,000 | 0.5 | Carbon fiber | SPM | - |
| 12 | 50,000 | 11 | SiFe | IPM | Spindle motor |
| 13 | 40,000 | 40 | Carbon fiber | SPM | - |
| 14 | 40,000 | 40 | Carbon fiber | SPM | - |
| 15 | 40,000 | - | SiFe | IPM | - |
| 16 | 40,000 | 1 | None | SPM | - |
| 17 | 28,000 | 1 | Inconel | SPM | Turbo compressor |

## 4. 250 KW, 20000 rpm high speed PMSM

MEIDENSHA CORPORATION[1], which is a major manufacturer of power equipment such as switches, relays, electronic power converters, railroad equipment, turbines, power supplies, and etc. in Japan, has developed a high speed PMSM machine with the speed and power of 20000 RPM and 250 kW. In this machine, active magnetic bearing is utilized as the levitation system [9]. By bringing this machine into service, conventional speed-increasing gearbox systems can be replaced by direct-drive ones. This replacement have some advantages such as decreasing system size, increasing system efficiency, less maintenance (oil-free), decreasing vibration and noise.

The rated machine's efficiency is 96.6 % and its maximum value in the whole motor operation range is 97.5.
This motor's specifications are shown in table 2.

**Table 2:** specifications of prototype of 20000 rpm, 250 KW high speed PMSM.

| Item | Specifications |
|---|---|
| No. of poles | 2 |
| Rated output | 250kW |
| Rated rotational speed | 20,000min$^{-1}$ |
| Frequency | 333.3Hz |
| Rated torque | 119.4N·m |
| Cooling system | Forced air cooling |
| Bearings | Magnetic levitation type |

Figure 2, shows the Cross sectional configuration of this motor.

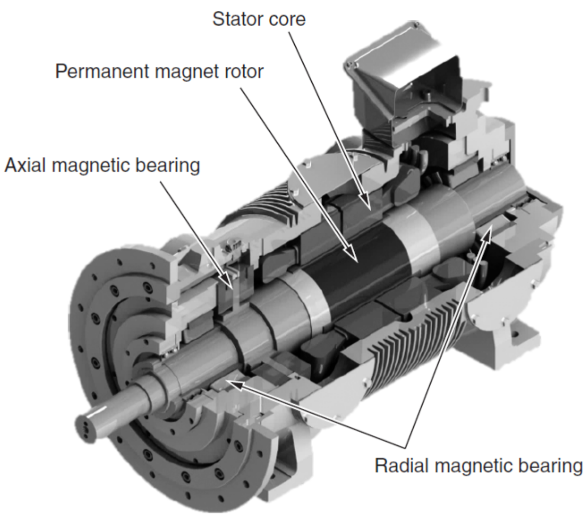


**Fig. 2:** Cross sectional configuration of prototype of 20000 rpm, 250 KW high speed PMSM.

## 5. Applications and manufacturers of high speed PMSM

One of the most important applications of high speed electric drives is to upgrade or replace gas drives in industry. A gas turbine is the main component in gas drives, and gas compressors are the most widely-used gas-turbine-based industrial equipment.
Flywheel is one of the most common tools to store electric energy. Flywheel-based storing systems, save energy in the form of kinetic in rotating wheels. In this technology, the stored energy is proportional to the square of the rotating wheel's speed.
Spindle motors are widely used in high speed industrial machinery. This type of electrical machines have high speed with high precision, low vibration, and a large power density.

### *A. Compressors and blowers*

In recent years, the need for clean, dry air has increased in many industrial applications. The desire to increase the safety of the production line as well as improving energy efficiency has forced manufacturers to the eliminate the lubrication system in compressors and air blowers. As a result, induction motors and mechanical bearings are replaced with high speed PMSMs and air or mafnetic bearings, respectively. Not only minimizes the oil leakage, lubrication system elimination also increases the drive's efficiency and reduces its size. As mentioned above, improving energy efficiency, is one the most important breakthroughs of these machines. For example, by using PMSM-based blowers in some wastewater refineries, the energy consumption has decreased by 35 percent [10].
The information of the main manufacturers of high speed drives for compressors and blowers is shown in table 3. Figure 3, shows a K-Turbo compressor in which a surface-mounted PMSM is utilized.

**Table 3:** manufacturers of high speed drives for compressors and blowers

| No. | name | Motor type | Power (KW) | Speed (rpm) |
|---|---|---|---|---|
| 1 | K-Turbo | PMSM | 400 | 65,000 |
| 2 | SKF | PMSM | 300 | 30,000 |
| 3 | Suzler | PMSM | - | 50,000 |
| 4 | Corac | PMSM | 150 | 45,000 |

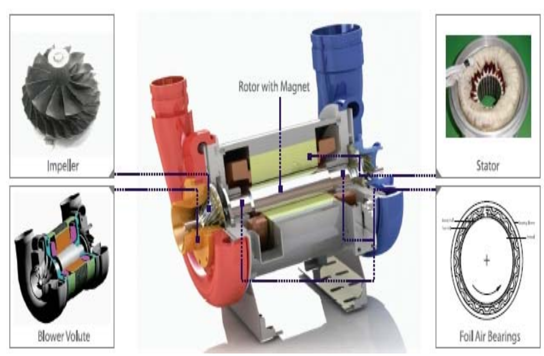


**Fig. 3:** air compressor produced by K-Turbo

### *B. Spindle motors*

Nowadays, Spindle motors have numerous applications especially in industrial fields. They are used in a variety of applications such as turning, milling, delicate drilling, CNC machines, dentistry and circuit printing. They are also one the most important elements in computer hardware. High speed and precision, very low vibration, and high power density are some of this motors' advantages. The speed and power of the commercial spindle motors are of great variety. These motors are used at speeds ranging from 6 to 300,000 rpm and powers from 24 kW to 200 watts [11].

Among the latest applications of high speed spindle motors, the tools for printing electronic boards could be mentioned. The use of high-speed and high-power spindle motors for this application is rapidly growing. The spindle motor has also been manufactured at a speed of one million rounds per minute for the drilling of printed circuit boards [12] [13]. A new field to apply high speed spindle motors is dentistry, where dentists utilize them to perform surgeries. Small wind turbines (supplies by high pressure air) have been used in dentistry tools. As a result, each tool is able to operate at a constant speed. By replacing wind turbines with drive-based high speed electrical motors, the precise control of speed and torque could be obtained which will result in reducing the number of required dentistry tools [14]. Table 4, prepares the information of spindle motors producers.

**Table 4:** manufacturers of spindle motors based on high speed electrical motors

| No. | company | Motor type | Power (KW) | Speed (rpm) |
|---|---|---|---|---|
| 1 | Servax | PMSM | 53 | 30,000 |
| 2 | Siemens | PMSM | 18.5 | 24,000 |

*C. Ship propulsion*

PMSM technology developments along with its long term advantages, have triggered many scientist to perform researches and examinations about this motors to be applied as ship propulsion systems. Compared to conventional motors, this type of motors have higher efficiency in high speeds, much lower weight, and smaller size. In [15], a 20 MW, 10000 rpm motor have been designed for propulsion application.

The largest and the most powerful PMSM motor for ship propulsion, manufactured by JEUMONT Electric, has been delivered to the Brazilian Navy. This motor is 6 meters long, 3 meters wide, and 4.5 meters high with a weight of 72 tons (figure 4). The details of this project have not been released yet.


**Fig. 4:** The largest and the most powerful PMSM motor for ship propulsion

*D. Rotary-based Energy Storages*

An electromechanical battery or flywheel is one of the most widely used technologies for storing electrical energy. A flywheel is a high-mass rotating wheel (rotor) held by a magnetic bearing on a floating stator. The wheel may be made of a disc or cylinder. Wheel-based storage systems store energy in the spinning wheel. In these systems, the electrical energy is stored in kinetic energy by an engine responsible for spinning the wheel. When power is required, the electric motor reduces the speed of rotation. As a result, some of the mechanical energy is converted to electrical energy again.

In rotary-based storage, an electronic power converter is used as an interface for connecting electrical and mechanical components. Energy efficiency in a grid-based rotary-based storage is about 90 to 95 percent. Today, these storage units are built to power up to 50 MW. Rotary-based storage devices can be divided into two groups based on rotational speed [16]:

1) Low-speed storage, at speeds below 10,000 rpm, used across the global network (and micro-networks) and a variety of industrial applications. They use a high-inert steel disc.
2) High-speed storage devices, with speeds exceeding 10,000 rpm, used in a variety of mobile systems such as electric cars and satellites. The disk or cylinder used in these storages is often made of composite material.

In Table 6, the basic characteristics of the two groups are compared.

The major limitation in rotary-based storage is their low energy density (despite high power density). Therefore, they are used in cases where the system's output power over a short period of time experiences

a large fluctuation. The use of high-speed electric motors in the storage structure has many advantages. Replace Battery-Based Storage with this Technology:
1) Reduces the physical dimensions of the system. 2) Increases the efficiency and useful life of the system. 3) Allows to operate at a wider temperature range.

**Table 6:** Properties of Rotary-based Energy Storage

| property | High Speed | Low speed |
|---|---|---|
| Disc Material | Composite | Steel |
| Used Electric Machinery | Permanemt Magnet Synchronous<br><br>Switched Reluctance | Induction Permanemt Magnet Synchronous<br><br>Switched Reluctance |
| Bearing | Magnetic | Mechanical Magnetic |
| Application | Transportation Industry Aerospace Industry | Power Quality Improvement |
| Cost | High | Low |

For example, the new generation of these storage devices has higher power density (and lower energy density) than metallic nickel-hydride batteries used in electric cars [8]. A rotary-based energy storage system is shown in Figure 6. Developed by Williams Hybrid Power for use in the Porsche 911 GT3R. Its rated speed is 40,000 rpm and its rated power is 120 kW. The equipment is designed to be able to absorb or inject power at its rated capacity over and over again, so that acceleration and successive brakes during the race are associated with less fuel consumption. As a result, it has a high power density (and low energy density) and its ability to store energy is very limited (6-8 seconds).

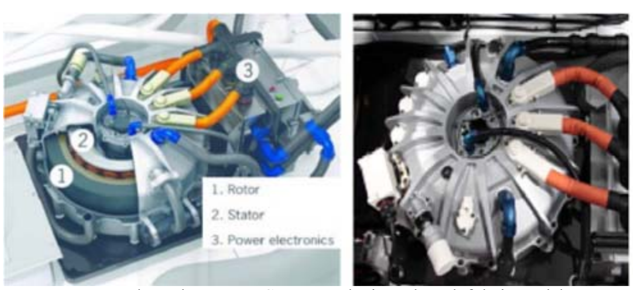


**Fig. 6.** Rotary-based Energy Storage, designed and fabricated by Williams Hybrid Power

*A. E. Microturbines*

Gas turbines of small physical size with an approximate capacity of 30 to 330 kW are called microturbines. Business prototypes of this technology have also been developed in the form of one megawatt capacity packages with high speed generators (up to 120,000 rpm) [8] [13]. Like large gas turbines, the basis of microturbines is based on Brighton's thermodynamic cycle. Small size and light weight make this technology a viable option for a variety of applications with limited occupancy. Microturbines are highly fuel-efficient and can use a variety of liquids or gases such as natural gas, propane, butane, diesel, kerosene and biogas. They are often used in heat and power co-generation systems and in places where space is limited for the installation of power generation equipment [17]. Therefore, a high power density is essential for a generator connected to a microturbine.

Using a high speed electric car as a generator is inevitable to provide the power required without significantly increasing the dimensions. In most commercial cases, high speed permanent magnet synchronous machines are used. A microturbine made by Bladon is shown in Figure 7. This microturbine has a capacity of 50 kW and can rotate at a speed of 80,000 rpm. Information on several important microturbine manufacturers is presented in Table 7.

**Table 7:** Manufacturers of gas microturbines

| Manufacturer | Speed (rpm) | Power (kW) |
|---|---|---|
| Capstone | 120,000 | 30 |
| Ansaldo | 70,000 | 100 |

**Fig. 7.** Microturbine manufactured by Bladon Co.

## 6. Conclusion

High power density, high speed electrical machines are becoming increasingly popular in numerous applications, such as automotive, aerospace, compressor and tool applications. Permanent magnet synchronous motor (PMSM) offers the advantage of high efficiency compared to other types of motors since there is no excitation power loss in the rotor, and low eddy current loss in the stator and rotor for slotless structure. Therefore, there is an increasing interest to consider PMSM for super-high speed applications. In this paper, PMSM topologies for high speed applications have been introduced and compared. Afterwards, the most important applications of high speed PMSMs have been presented, where the main producers with the specifications of their products have been prepared in detail.

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