Application and Market of High-Speed Electrical Machines

Do Hyun Kang*, and Strete Larisa**

* Mechatronics Research Group, Korea Electrotechnology Research Institute, Changwon, Korea
(Tel : +82-55-280-1480; E-mail: dhkang@keri.re.kr)
**University of Science and Technology, Daejon, Korea
(E-mail: stretelarisa@yahoo.com)

Abstract: The technology of high-speed electrical machines is particularly relevant to applications involving electrical power generation and high-speed motors with high power density and high efficiency.
Due to the development of improved materials for electrical machines, power electronic elements and design technology, the high-speed electrical machines are being rapidly introduced into industrial applications. The introduction of high-speed electrical machines has created a new market for electrical machines and will, as an application, contribute to the development of modern electrical machines. This paper deals with applications and market trends and KERI's activities in high-speed electrical machines.

Keywords: High speed rotating machines, Magnetizer, Motors, Generators, High efficiency, High Power density.

1. INTRODUCTION

According to [1] the power output of an electrical machine can be written:

$$P = \frac{\pi^2}{\sqrt{2}} \cdot \frac{n}{60} \cdot D^2 \cdot L_c \cdot A \cdot B_g \cdot k_w, \qquad (1)$$

where: n is the speed of rotation in rpm; D is the diameter of stator bore, L_c is the effective length of machine; A is the number of amp.cond./meter; B_g is the amplitude of air-gap magnetic flux density and k_w is the winding factor. It can be seen that the output power is proportional with the product of geometrical dimensions of machines (D^2L_c), material parameter (B_g) and the speed of rotation n [rpm].

It is clear that the high rotating speed led to small sizes of electrical machine at the same power and hereafter to the small weight. This is the reason for the large development of such kind of applications in the last time.

The following researches will be included to realize the high-speed rotating machines:

1) Magnetization of rotor with surface mounted magnets:

The rotors of large synchronous motor with surface mounted magnets are usually assembled with magnetized magnets. This assembly is very dangerous and hard work because of very strong repulsive or attractive forces between magnets. When permanent magnet rotors of large synchronous motors with surface-mounted rare-earth magnets are magnetized as a whole unit with special magnetizing coils, the danger of assembling magnets and the hard work are avoided.

During magnetization, the magnetic induction within the magnets rises up to typically 4 to 6 T peak value to ensure that their specified values of remanence induction and coercive field are reached, yielding a very high saturated iron circuit.

The magnetization of magnet segment is carried out with a special magnetizing coil and an impulse current. These coils are loaded with peak currents of several thousand Ampere.

2) Design of electro-magnetic system:

The voltage, current, power factor, electrical input, mechanical output, efficiency and temperature are calculated by electro-magnetic system designs at high speed operating conditions with new materials (permanent magnet and low loss iron steel). The more detailed machine dimensions are decided by FEM analysis.

3) Power conversion system:

To supply sinusoidal 3-phase electrical power with variable frequency and voltage up to 1,000Hz, the low loss switching, V/F constant control, field weakening control, DSP control are required.

4) Mechanical dynamics:

Mechanical design is important due to the high mechanical stress placed on the rotor components. The modeling and simulation of the dynamic analysis of the rotor assembly, including shaft, core stack, bearing sleeves and critical speed should be carried out with great detail.

5) Test and evaluation:

To verify the designed high-speed permanent magnet motor and drives, the measurement of voltage, current, power factor, electrical input, mechanical output, efficiency, noise, vibration and temperature is performed for all required load conditions and speeds.

2. APPLICATION OF HIGH-SPEED ELECTRICAL MACHINES

2.1 Flywheel

Flywheels are kinetic energy storage devices, the amount of energy stored being given by:

$$E_k = \frac{1}{2} I\omega^2, \qquad (2)$$

where I is moment inertia, a function of mass and geometry, and ω is the angular velocity. It is easily seen that the energy is direct proportional with the second power of angular velocity, thus the need of high-speed electrical machine with high efficiency.

Flywheels became a viable technical option only recently, due to new composite materials with increased strength and low loss bearings techniques, like HTS.

Some of the reasons for which flywheels are considered one of the most promising technologies: they are environmentally safe, reliable, fully bidirectional, modular; they have a long life cycle, a very high specific power capability limited only by the electrical machine and ability to withdraw large amounts of energy in a very short time.

The next figure is showing the specific energy and specific short-time peak power for various energy storage devices:

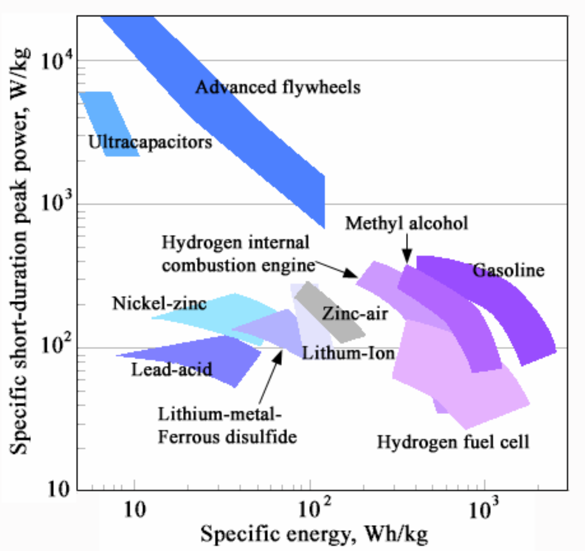

Fig. 1 Specific energy vs. specific peak power for various technologies

From the above picture the advantages of flywheels over other technologies can be easily depicted.

Due to all these factors, flywheels can be applied to increase efficiency and reliability in mainly two areas: load leveling and uninterruptible power systems (UPS).

As load leveling they are used in hybrid vehicles to deliver the peak power and allow the main energy source to operate in narrow rpm band, where it has the highest efficiency. They can fill in the peaks and valleys of electrical load by charging during off-peak hours and delivering energy in peak-hours, saving energy costs.

The dynamic UPS system consists of generators which produce power and assure electrical isolation between mains and load. They provide short-time power in events of grid failure.

Depending on customer requirements and the desired bridging time, the UPS system is fitted with a kinetic energy storage device (POWERBRIDGE dynamic storage module) or a battery storage system.

In Fig. 2 can be seen such a dynamic UPS, flywheel generator, manufactured by Piller GmbH Germany [2]

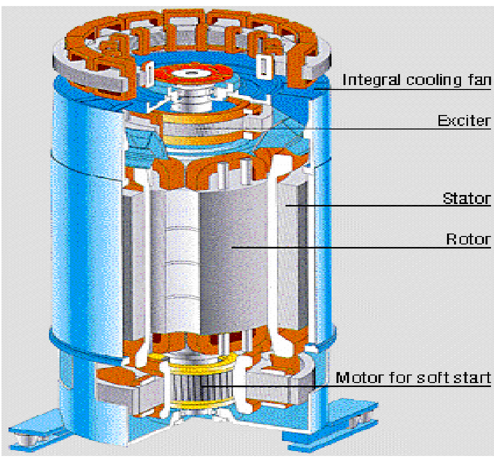

Fig. 2 Dynamic Uninterruptible Power System

The UNIBLOCK-System [3] has already proved itself in a large number of installations, for example in a 30 MW co-generation station of the Dresden power supply centre, which supplies a microchip factory with high-quality power, in Berlin.

2.2 Micro-turbine

High-speed alternators [4] have become feasible with the advent of high magnetic field strength rare-earth magnetic materials. For electrical power generation, they have been integrated with small gas turbine engines to produce a turbo genset, capable of using different forms of fuel.

The concept of distributed power is seen as a major advance in improving electrical power generation efficiency, thus minimizing the emissions of greenhouse effect gases and atmospheric pollutants. Conventional power stations are often situated in remote locations, where the waste heat they produce may not be effectively utilized.

There are also considerable power losses associated with the electrical distribution networks which they employ. By contrast, the distributed power concept enables the local generation of electrical power to minimize power distribution losses and local utilization of waste heat to maximize overall thermal efficiency. Waste heat may be diverted to a boiler that provides hot water and heating for a building or to a heat exchanger for air conditioning or refrigeration applications.

Gas turbine engines are particularly well suited for these applications because of the high temperature exhaust heat they produce, unlike conventional piston engines where the exhaust heat is of a lower temperature.

The basic diagram of a microturbine is shown in Fig. 3 [5].

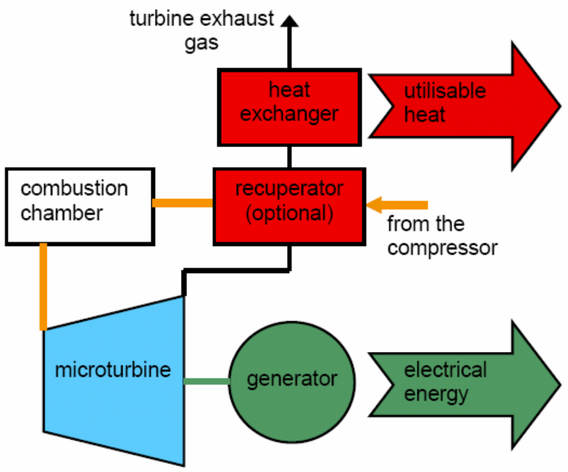

Fig 3 Diagram of a microturbine

Other important advantages offered by gas turbines include reliability, long operating life, ease of installation and ease of maintenance. The high speed alternators developed in the last time have been designed to be directly powered by a gas turbine, while the power electronics are designed to ensure the quality of the electrical power output.

By the super speed operation, the system can be much smaller and lighter for the same power level.

2.3 Aircraft Power System

Recent advances in power electronics and electric drives are making their way in aerospace industry. A dominant trend in aircraft power systems is increasing the use of electric power over the conventional mechanical, hydraulic and pneumatic systems, which include gearboxes, hydraulic pumps, electrical generators, flight control actuators. The concept is known as MEA, more electric aircraft.

New concepts like electric environmental control and electric fuel pumps, along with magnetic bearings for generators and eventually more electric turbine engines, are in the works. They promise simplifications in aircraft system design, while improving reliability and maintainability.

Immediate benefits derived from the wider application of electrical power and electronics include performance as well as savings in weight, space, and overall life-cycle costs. Another important demand is the reduction of emission as well as noise reduction.

Growing technologies will help the development of this concept from more powerful starter/generators that start turbine engines to high specific power density batteries.

A full-operating-speed demonstration was completed of an integrated power unit (IPU) rotor system at speeds in excess of 61,000 rpm, [6]. The IPU uses magnetic bearings rather than traditional lubrication systems reducing maintenance and saving energy and space.

Another success is the electric flight control system, or power-by-wire, incorporated into the F-35 [6]. As part of the JSF demonstration program, electric actuators, or motors, replaced hydraulics in an Advanced Fighter Technology Integration F-16 tested at Edwards Air Force Base, California. The testing proved electric flight controls could be transparent to the pilot.

A similar program is initiated by the European Union, Power Optimized Aircraft (POA) involving 40 partners. POA aims at identifying, optimizing, and validating innovative aircraft component designs that reduce nonpropulsive power consumption.

The project is aimed at demonstrating the feasibility of a 25% reduction in non-propulsive peak power consumption while reducing weight and operational maintenance.

Another concept is of "all-electric" airplane which would still rely on a fuel-burning jet engine for thrust. Most other systems would be electric, relieving demands on the engine.

3. KERI'S ACTIVITIES IN HIGH SPEED MACHINES

The Mecatronics Research Group in Korea Electrotechnology Research Institute is researching and developing high-speed machines to cope with the industrial demand using the mechanics and electronics. The Mecatronics Research Group in KERI has developed the Magnetizer of entire rotor with surface-mounted NdFeB PMs for a 200 kW, 30,000 rpm PM-motor, 200kW 30,000rpm Induction motor, 100kW 15,000rpm PM-motor and 65kW, 61000rpm micro-turbine Starter/Generator.

3.1 Magnetization of rotor with surface mounted magnets

The magnetization of PM magnet segment was carried out with a special magnetizing coil and an impulse current in KERI. The rotors of large synchronous motor with surface mounted magnets are usually assembled with magnetized magnets. This assembly is very dangerous and hard work because of very strong repulsive or attractive force between magnets. When permanent magnet rotors of large synchronous motors with surface-mounted rare-earth magnets are magnetized as a whole unit with special magnetizing coils, the danger of assembling magnets and the hard work are avoided.

During magnetization, the magnetic induction within the magnets rises up to typically 4 to 6 T peak value to ensure that their specified values of remanence induction and coercive field are reached, yielding a very high saturated iron circuit.

The entire rotor with surface-mounted NdFeB PMs of a 200 kW, 30,000 rpm PMSM was directly magnetized by KERI magnetizer as shown in Table 1.

Table 1 The components of power pulse magnetizer.

CH (Charger):voltage reg.+transf.+rectifier	10 kVdc, 50 kVA
DS (Disconnecting Switch)- magnetic	220 V, 10 kgf/cm^2
ES (Earth-connect. Switch)-magnetic type	220 V,10 kgf/cm^2
C (Capacitor bank)	150 μF // 200 = 30,000
MS (Making Switch)	24 kV, 20 kArms
ACB (Auxiliary Circuit Breaker)	38 kV, 31.3 kA
VD (Voltage Divider)	600 kV, 500:1
Sh (Shunt)	0.63 mΩ, 65kA$_{rms}$,450
OSC (Digital memory oscilloscope)	multichannel

3.2 65kW, 61000rpm PMSM (permanent magnet synchronous machine). for Micro-turbine

The PMSM (permanent magnet synchronous machine) for Micro-turbine with 65kW, 61000rpm is working as starter for micro-turbine to 24,000 rpm and is generating a maximum electrical energy of 65kW.

The stator has very thinly laminated silicon steel (0.35mm) and is directly cooled by air.

The two pole rotor is installed on the same shaft as the gas turbine and is air cooled by gas-turbine inlet air.

The rotor consists of an iron core, the surface mounted magnets and a stainless steel to support the magnet by high centrifugal force at high rotating speed. The entire rotor with surface-mounted NdFeB PM was directly magnetized by KERI's magnetizer. The air bearings operate free of contact with the shaft, eliminating the need for lubrication and resulting in great reliability and lower maintenance.

Fig. 4 is showing the stator and motor elements of the PMSM, while Fig. 5 is showing the microturbine with permanent magnet synchronous machine.

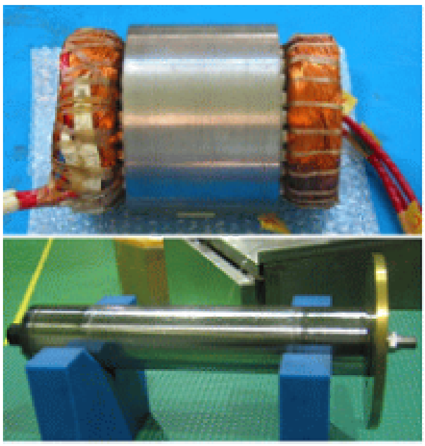

Fig. 4 Stator and Rotor with permanent magnets.

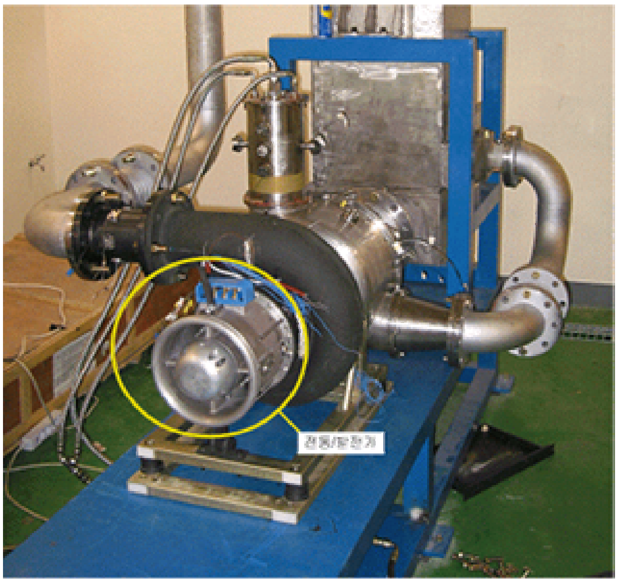

Fig.5 Microturbine with PMSM

3.3 200kW 30,000rpm Induction motor and drive

The high-speed induction motor and drive are composed of stator with windings, rotor, inverter which supply variable voltage and variable frequency power to motor, and other mechanical components like magnetic bearing. The stator of high-speed motor is essentially identical with that of an induction motor with comparable rating. The stator has very thinly laminated silicon steel (0.35mm) and is directly cooled because of very high iron loss at high frequencies.

The rotor consists of a very thinly laminated silicon steel (0.35mm) and cooper bar. The rotor is levitated by magnetic bearing.

Fig. 6 Stator and rotor for induction motor.

3.4 100kW 15,000rpm PM motor and drive

The stator has very thinly laminated silicon steel (0.35mm) and is directly cooled by water.

The rotor consists of an iron core, the surface mounted magnets and a stainless steel to support the magnet by high centrifugal force at high rotating speed. The entire rotor with surface-mounted NdFeB PM was directly magnetized by KERI's magnetizer.

Fig. 7 Stator and Rotor with permanent magnets

4. MARKET TRENDS

This kind of high-speed electrical machines has created a new market for electrical machines with a large development in the future years [7].

According to [8] a Japanese source of information, the future market for high-speed electrical machines is presented in Table 2.

Table 2 New market for high-speed electrical machines in 21st century

List	Application	Function	World market in 2,020 (trillion yen)
22	Electric vehicle	Propulsion system	19
25	Direct injection vehicle	Starter/Alternator	17.1
30	Fuel cell vehicle	Propulsion system	13.9
32	Electric ship	Propulsion system	12.5
47	Energy saving electrical machine	High efficient motor	7.4
65	High efficient generation	Generator	4.4
85	Secondary battery car	Propulsion system	2.5
90	Hybrid vehicle	Propulsion/ braking	2.4
113	Machine tool	Spindle motor	1.5
164	Electrical mover	Propulsion system	0.4
179	High precision grinder	Propulsion system	0.2
186	Methanol vehicle	Propulsion system	0.1
191	Hydrogen vehicle	Propulsion system	0.1
198	Fly wheel	Energy storage	0.1
Sum	14 item		81.6

5. CONCLUSIONS

High-speed rotating machines (motor and generator) can be used to rotate apparatus directly without speed reducing/increasing gearboxes, meaning considerable savings in investments and maintenance costs. Due to the development of improved materials for electrical machines, power electronic elements and design technology, the high-speed electrical machines are being rapidly introduced into industrial applications.

The Magnetizer of entire rotor with surface-mounted NdFeB PMs for a 200 kW, 30,000 rpm PM-motor, 200kW 30,000rpm Induction motor, 100kW 15,000rpm PM-motor and 65kW, 61000rpm micro-turbine Starter/Generator by the Mecatronics Research Group in Korea Electrotechnology Research Institute are introduced.

A new 81.6 trillion yen market in 14 applications will be opened for high-speed electrical machine until in 2020.

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