Superconducting rotating machines: A review of the past 30 years and future perspectives

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Abstract. Research and development of superconducting rotating machines has a history spanning greater than 30 years. Earlier, superconducting homo-polar DC machines that used low temperature superconductors may have found the first practical applications in superconducting rotating machines; however, it cannot be said with certainty, given their use in secretive war ships. Superconducting synchronous generators cooled by liquid helium are well developed, particularly by the Super-GM project in Japan. The paper discusses fundamental subjects in the design, manufacture, operation, control, and performance in power systems. The development of oxide superconducting wires and bulks, has found applications in superconducting electric motors (mainly synchronous ones), the structures of which are very similar to the generators. The paper also discusses the power system problems addressed by superconducting equipment, which have arisen due to the increase in the number of renewable sources of energy. The paper assesses the solutions offered by superconductivity to the above mentioned challenges.

1. Introduction
Research and development on applied superconductivity to electric machines began in the 1960’s after researchers developed superconducting wires for direct current with stable performance.

In general, electrical machinery can be broadly classified into transformers and rotating machines. Alternating current flows in a transformer. On the other hand, direct current is used for field windings of DC machines and synchronous machines.

At the time, large capacity DC machines were required for ship propulsion, given that the technologies of power electronics were under development.

DC machines can be broadly categorized into homo-polar and hetero-polar machines. The hetero-polar machines, which are widely used for motion control such as in electric cars, have limitation for larger capacity due to problems on commutation. On the other hand, homo-polar machines require higher magnetic induction without the presence of magnetic material. This requirement led to the development and application of superconducting magnets.

A demand for large capacity synchronous generators, whose capacities at that time were less than those of steam turbines, let to the use of superconducting field windings.

In the early days, metal superconductors cooled by liquid helium were used to develop superconducting rotating electric machines such as DC homo-polar machines and synchronous generators.
At present, induction motors are being developed through the use of superconductor cooling systems that utilize the resistive states of superconductors. The items for obtaining the summaries of developing superconducting rotating machines are presented.

2. Rotating electric machine by use of low temperature superconductor [1]
This section introduces homo-polar DC machines and synchronous generators, whose application of DC superconducting magnets cooled by liquid helium produced successful results.

2.1 Homo-polar machines
The need for large capacity DC machines for electric ship propulsion systems led to the development of superconducting homo-polar DC machines. At present, several electric propulsion ships are operated by induction motors with power electronics devices. However, the superconducting homo-polar machines are considered because of their characteristics from an electrical machinery perspective.

2.1.1 Structure
Figure 1 and 2 illustrate two types of superconducting DC homo-polar machines, that is, disc type and drum type, respectively.

In the disc type homo-polar machine, the induced voltages are applied to the armature disc using superconducting magnets. The schematic of the armature disc is illustrated in Figure 1 (right inset). The use of superconducting magnet provides higher magnetic flux density than conventional magnets.

In rotating electrical machines, armature reaction phenomenon is an important problem. In particular, in homo-polar machines, the magnetic flux due to the armature current near the armature can be cancelled by the armature current flowing through the reaction torque disc. Such machines developed to overcome armature reaction have exhibited good performance. However, the disc type structure can lead to problems associated with mechanical vibration.
2.1.2 Properties
The homo-polar DC machine behaves as current source. A critical aspect is the performance in terms of armature current collection. Significant research efforts have been focussed on developing brushes for current collection; however, an optimal solution has not been found as yet.

These machines have been used for the electrical propulsion of war ships. Then, there are not so many papers opened.

In the early 1980’s, a production line of the disc type-machines was observed at the International Research and Development facility in Newcastle upon Tyne, UK.

However, in present day, large capacity DC machines are much less desired. Instead, large capacity machines that facilitate speed control are being developed through the use of induction motors with power electronic technologies. Even to this day, there are several electric propulsion ships, such as MS Queen Elizabeth. However, the newer applications of these machines will not be developed unless characteristics, such as current source and armature reaction, are not addressed.

2.2 Synchronous generator
Synchronous generators were developed by improving cooling methods for field and armature windings. However, conventional cooling methods did not suffice for the cooling requirements of large capacity machines. In such cases, the application of superconducting technology could realize better machines from not only a capacity point of view but also others. This potential was further explored by electric and power system engineers. Subsequently, research and development of this technology was actively pursued in the 1970’s in USA, USSR, Germany, France, and so on. However, these research projects have been pretty much terminated. The national project in Japan (also known as Super-GM) (1988–2004) may in fact be the last such research project. The developments in the design, manufacturing, and operation have matured. The following structure and the properties are based mainly on the research and development of Super-GM.

2.2.1 Structure
In the field of rotating metal superconducting winding cooled by liquid Helium and the armature of conventional winding without magnetic materials, the fundamental structure has been defined as shown in Fig. 3.

Liquid He is supplied through the transfer coupling to the rotor. The evaporating He from the rotor cools the torque tube and the radiation shield (cold damper). Subsequently, the gas escapes through the transfer coupling. The rotor comprises space to accumulate He, winding retaining cylinder, vacuum space, radiation shield, vacuum space, and room temperature (warm) damper. The stator consists of an air gap armature winding and a magnetic shield.

Helium transfer coupling is achieved through the use of a fluid magnetic seal. Thus, liquid He can be supplied stably and efficiently from the stationary part to the rotating parts. Thus, the He gas evaporating in the rotor is transferred from the rotating part to the stationary part through the coupling. Let us consider the behaviour of liquid and gaseous helium in the rotor. Inside the rotor, the liquid He flows to the outer part due to the density gradient and gaseous He flows towards the inner part due to the centrifugal force. This phenomenon is referred to as the “thermal siphon effect”. Thus, the pressure of gaseous He in the inner part of rotor is reduced, thereby enabling the supply of liquid He to the inside of the rotor. This effect is called the “self-pumping effect”. The discovery of above effects have led to the simplification of the interior structure of the rotor.

On the other hand, the torque tube shrinks due to the difference between room temperature and cryogenic temperature. The resultant shrinkage exerts stress on the tube. To address this issue, two shrink relaxation methods have been developed—the double bearing method and the flexible support method.

As illustrated in Figure 3, the superconducting field winding is affixed on the cylinder of the nonmagnetic material using slots. The shape is of the saddle is similar to that of a conventional machine. The rotor has two shields, referred to as called cold damper and room temperature damper (warm damper). The cold damper, which is affixed in the vacuum space between room temperature and cryogenic temperature, has two functions. First, it acts as a radiation shield. In addition, it also shields the field winding from the magnetic flux generated by armature current. It is cooled by the evaporated

![Figure 3 Cross section of superconducting generator cooled by liquid He](image-url)
He gas in the rotor. The room temperature damper is affixed to the surface of the rotor. The damper plays the same role as a damper winding in a conventional machine.

The armature winding consists of copper winding. The winding is affixed onto the cylinder of non-magnetic material by using slots. This reduces the synchronous impedance.

Field winding and armature one are directly in magnetic flux, then, stand for the magnetic strength. The mechanical support system of the winding is critical to the functioning of the machine.

2.2.2 Properties

As mentioned earlier, the superconducting synchronous generator provides has several advantages over conventional generators, such as larger capacity, Higher efficiency, particularly for partial loads, Improved power system stability, Larger capacity in reactive power supply, and smaller size and lighter weight. In addition, the superconducting synchronous generator provides larger capacity during imbalanced load operations, including a larger capacity to absorb harmonic currents and improved voltage regulation. It also exhibits higher terminal voltage and an improved ability to handle sub-synchronous resonance in power systems. Moreover, the simulations are in better agreement with experimental results.

Table 1 Characteristics of superconducting synchronous generator developed by Super-GM.

| Specifications | Slow-response-excitation type (0.1 p.u./s) | Quick-response-excitation-type (1.0 p.u./s) |
|----------------|------------------------------------------|------------------------------------------|
|                | A            | B            |                            |                            |
| Capacity (MVA) | 83           | 83           | 73                         |                            |
| Voltage (kV)   | 10           | 10           | 10                         |                            |
| Current (A)    | 4,792        | 4,792        | 4,215                      | 0.9                        |
| Power factor 0.9 | 3600        | 3600        | 3,600                      | 3,600                      |
| Rotation speed (m/s) | 0.35       | 0.35        | 0.45                       | 0.45                       |
| Synchronous reactance (p.u.) | 3,000 | 3,000 | 3,200                      | 3,200                      |
| Field current (A) Rated | 3,600 | 3,600 | 4,500                      | 4,500                      |
| Maximum (A)    | 3,600        | 3,600        | 4,500                      | 4,500                      |

| Rotor structure | Slow-response-excitation type | Quick-response-excitation-type |
|------------------|-------------------------------|-------------------------------|
| Room temperature damper | Single layer type | Squirrel cage type |
| Cold damper/Radiation shield | Three-layer type | Single layer type |
| Thermal shrink relaxation | Double bearing | Flexible disc |
| Property superconductor | High stability | High current density |
| Stator structure | Air-gap winding | Low AC loss |
| | Double transposed conductor | |
| | Water cooled | |
Given that the synchronous reactance is very small, it was pointed out that the short circuit current is relatively large. However, the large current at short circuit occurs only at the instance of the short circuit occurrence. At that instance, the generator reactance is transient or sub-transient, the value of which is almost identical to that in conventional generators.

Moreover, it has been pointed out that the larger time constant of the field winding of superconducting generators may negatively impact power systems. However, the role of time constant in field windings of conventional generators is that of a cold damper in a superconducting generator. Under fault conditions in power systems, a larger time constant prevents a significant reduction in the field current. The characteristic is rather suited for power systems.

In addition to the above, a full superconducting generator with both superconducting field winding and armature winding was examined; however, such a generator does not have the above mentioned features. This may be attributed to the poor characteristics of the AC superconductor developed at that time.

2.2.3 Concluding remarks

As part of the Super-GM project (1988-2004), long-term operation \(^4\) with refrigerator, and synchronous condenser operation were successfully carried out using 70-MW class superconducting generators.\(^5\) In these developments, three types of rotors and a stator were manufactured (Refer to Table 1). The small generator was used to carry out power operations in real power systems.\(^6\) These generators do not face issues in practical implementation; however, there is scope for further improvements. It should be noted that a synchronous condenser operation was successfully carried out using a high temperature superconductor in a real power system.

The characteristics of superconducting synchronous generators can be obtained by the structures. Conversely the structure may be determined by characteristics requested.

3. Present and future scope for development of superconducting rotating machines\(^7\)

Now that superconductors that can operate at rather high temperature have been discovered, the applications for rotating electric machines are increasing. These include, synchronous generators and motors, induction machines, and new concept machines. In use of superconductors, wire, bulk, thin film and so on have been examined. Research studies are also investigating several types of refrigerants, including liquid He, liquid N\(_2\), liquid H\(_2\), gaseous He, and gaseous Ne. Therefore, summarizing all these advances is beyond the scope of this paper. Before considering the summaries, the present state of electrical rotating machines must be considered. It is known that more than 50% of electric energy is consumed by motors. This percentage is expected to increase in the future. Therefore, more efficient motors must be developed, for example, by using permanent magnets as well as achieving elegant control through power electronics technologies. Therefore, the pressing question then becomes that of “can superconducting rotating machines provide solutions to these problems”? The answer might actually be “yes”. It is well known that the nature of electric power supply is rapidly changing, with an increase in renewable energy sources. This poses new challenges to existing power systems such as power system stability, voltage stability, and harmonic current. Can rotating superconducting machines provide solutions to the newly developing challenges? The answer might actually be “yes”.

Synchronous machines, induction machines, and DC machines have found wide and diverse applications. Large capacity DC machines were replaced by AC machines (synchronous and induction machines). The machines whose capacities are less than 100 W are used widely in electric and electronic devices. On the other hand, synchronous generators are applied in power stations. Similarly, induction motors works have found widespread applications. Small motors have almost been replaced by DC motors. Similarly, large motors have been replaced by synchronous motors owing to their higher efficiency and power factor, particularly in large power applications owing to features such as,
simplistic structure, low cost, and robustness. Similarly, synchronous machines have been adopted for large power applications.

From the above, it is evident that summarizing the research and developments is exhaustive.

In this paper, we have summarized the scope and applications for both generators and motors. The cryogenic temperature in rotors and stator have been discussed, both for wire and bulk. In addition, synchronous motors and induction motors have been discussed in terms of capacity and type of magnets for both AC or DC. Moreover, the cooling method have been discussed including pool and forced conduction. Similarly, the discussion has encompassed cryogen, for liquids, gas or others, and their application purpose, including in air crafts, ships, and wind powers.

At present, several feasibility studies have been conducted on the application of superconductivity to rotating machines like in the earlier phase of development. These developments are important. However, it may need to determine the goal of the studies. What characteristics are good for practical uses?

For example, generators, except those used in the generation of wind power, constant speed generators. These are suitable for the cooling systems of the cryogenic rotor.

As regards motor applications, changes in the motor speed are critical challenges, (as in the case of wind power generators), particularly with cryogenic rotors, where controlling the temperature can prove to be quite challenging. Therefore, AC homo-polar generators with cryogenic stator can find potential application in wind power generation.

On the other hand, induction motors that use superconducting squirrel-cage rotors are attractive given their nonlinear resistance characteristics and the high temperature superconductors. The subject is in completion for conventional ones. Therefore, current research and developments in superconducting rotating machines are beginning to attract the attentions of electrical and power system engineers.

4. Conclusions
The paper sought to describe the developments in the application of superconductivity to rotating electric machines. The paper also comments on their scope for future development. Thus, taking into account the changing needs of society and the developments in the features of rotating superconducting machines, such machines continue to be developed. Conversely, the developments of those machine has the potential to lead or change the world.

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