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Review of Superconducting Generator Topologies for Direct-Drive Wind Turbines

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***Abstract*—Wind energy, as a clean and renewable energy, is now being widely developed to reduce the production of carbon dioxide from fossil fuels and mitigate the energy crisis. The urgent needs for wind energy motivate larger generators with lower cost, lower weight, and higher reliability. The most popular solution is the direct-drive generator concept, Permanent Magnet Generator (PMG) or superconducting (SC) generator. When referring to weight, volume, and cost, SC generators are superior to PMGs for wind turbines larger than 8 MW according to the report from the American National Renewable Energy Laboratory [1]. In order to find out the most suitable topology for megawatt-class direct-drive wind turbine generators, various designs of SC machines in literatures are carefully reviewed and advantages and disadvantages are concluded. Also promising ways to benefit from their advantages are also included. Electromagnetic, mechanical and thermotic structures, including excitation system, SC support system, cryogenic cooling system etc., are crucial for SC machines applied in wind markets. Therefore, design challenges and possible solutions are also proposed in this paper to guide designers in large wind turbine generators.**

***Index Terms*—Superconducting generator, direct-drive wind turbine, electromagnetic topology, cryogenic cooling system**

I. INTRODUCTION

WIND ENERGY has developed rapidly in the last 15 years, for rising fossil fuel prices and threat of climate change. The Global Wind Energy Council (GWEC) predicts that at the end of 2016, global wind capacity will be 493.3GW, up from 237.7GW at the end of 2011 [2]. The European Wind Energy Association's scenarios also show that the total installed wind energy should reach 230GW in 2020, and by 2030, 400GW [3]. The integrated Wind Turbine Design Upwind project in Europe has found that 20MW machines are feasible and is planning for a 20MW offshore wind turbine design [4]. In 2011, China has the largest installed wind power capacity country in the world with 62.4GW [2] and now plans for 10MW class offshore wind turbines [5].

Wind turbines with larger power capability, lower cost and higher reliability are required to meet the rapid development of wind energy. The most promising generator system is direct-drive generator, as direct-drive system simplifies the drive train, and improves the overall efficiency and reliability [6], [7]. The increase of output power per generator and power density are required to reduce the manufacturing difficulty and cost to construct wind farms. However, 10MW permanent magnet direct-drive (PMDD) generators are above 300ton and their diameters are larger than 10m [1], [7]. Heavy weight and large diameter always accompanies high cost, which limits the development from laboratory to factory.

Design of superconducting direct-drive (SCDD) generators is a new trend for above 10MW class wind generators. High temperature superconducting (HTS) machines are famous for low weight, small size, and high efficiency. American Superconductor (AMSC) has designed a 10MW SC direct-drive generator with about 160ton, which is roughly 50% of the PMDD generator's mass. When referring to weight, volume and the overall drive train cost, HTS generator concept is much superior to PMDD generators for above 8 MW wind turbines [1]. Moreover, HTS generators can obviously save energy consumption. An economic analysis has been made by Converteam showing that the reduction in the cost of energy could reach up to 17% from a 500MW offshore wind farm by use of 10MW HTS direct-drive turbines when compared with the baseline case of 4MW conventional DFIG turbines, while PMDD 8MW generators actually increase the cost [8].

The cost of HTS materials is the main disadvantage of HTS generators, which is about 90% of the total active materials cost. If the generator can reduce the cost, then the HTS direct-drive generator will be the most suitable topology for wind turbines. It is expected that the 1G HTS wire could be 50$/kAm and the lowest cost of 2G HTS materials could be 10~15$/kAm, but no one knows when the day comes [8]. At present, the prices of HTS materials are still high. The price of HTS materials sometimes might be too expensive for the HTS generators to reach the market. Applying low temperature superconducting materials might be a solution to reduce the price of the SCDD wind generator.

II. TOPOLOGIES

Low weight, small size and high efficiency are the characteristics of SC generators. Various types have been studied since 1960s and this paper adopts rotating armature versus rotating fields as well as radical versus axial flux to identify the promising HTS generator topology for the megawatt class direct-drive wind turbines, as these topologies are widely depicted in literature. In addition, some new and

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special topologies are also included. There needs to be a balance among electrical, magnetic, thermal, mechanical and economic factors for an optimized SC generator. These factors are always conflicting with each other. No matter what kind of methods designers use to optimize, the key criteria are the reliability and availability of the generator system. Moreover, cost always prevents generators from commercialization.

A. Rotating Armature Versus Rotating Field Concept

It is believed that the first work on SC alternators was conducted in 1966, which is designed with rotating armature [9]. After that, some other models with rotating armature were made. The models are mainly designed for small motors or to investigate the feasibility to apply SC materials in alternators [10], [11].Obviously, it's easy to access the SC magnet when the SC field coils are in stator, as the cryogenic system is stationary. Without rotation, problems of mechanical vibrations on SC coils which may cause quench can be avoided as well as the continuous transfer of refrigeration coolant to a rotating system. It can also eliminate the need for a reliable rotating seal in the rotating field machines. Moreover, rotating armature concept makes it possible to apply LTS materials to reduce cost. It has been concluded by GE that HTS wires, cryogenic cooling system and the HTS support are among the highest costs for HTS machines [12].Therefore, by using the rotating armature concept, the SC generator can cost less.

However, the armature construction will be more critical requiring cooling and electrical circuits to operate under increased forces and vibration due to rotation. That is to say, the mechanical, thermal and electric structures of the armature need to be carefully designed [9]. In addition, the difficulty of transferring large amounts of power through sliding contacts will be a disadvantage [13]. The positive side is that the performance of the sliding contacts has been advanced and the peripheral speed is not high in direct-drive wind generators, which improves the reliability of the sliding contacts. J. T. Erisson et al points out that it will be easier to transfer electric power than cryogenic fluids to the rotor [14]. At present, the rotating armature concept is a competitive candidate for SCDD wind generators.

Rotating field concept is the most popular concept in SC generators. In particular, most of the projects on SCDD generators are designed in this concept with HTS materials, for example, the 10MW wind generator designed by AMSC. It seems that SC generators historically choose this direction. Mario Robinowitz et al believed that the rotating field and stationary armature is more feasible, though it will bring the problems associated with the rotating SC field coils [9], [13]. This configuration makes armature design easier and permits higher current density and magnetic flux density. The problems brought by the slip rings in the armature can be avoided. It can also improve the performances of fault conditions, as it is easier to make the reinforcement of the stationary armature to endure high transient forces and torques. Thermal structure of armature such as cooling system can also be simplified.

Moreover, the technology of SCDD wind generators with rotating field concept is more mature. The problems associate with this configuration has already been researched and possible solutions have come up. Even offshore wind generators with this concept are being designed and are planned for commercialization [8]. There is a trend to develop the on board refrigeration system for the SC field coils, which means the refrigeration system is rotating with the rotor and transfer coupling will be removed as well as the problems associating with it [15]. Therefore, this configuration can highly improve the reliability, which is the crucial to wind generators, especially offshore wind generators. Rotating field concept can be superior to rotating armature concept with the rotating cryogenic refrigeration technology advanced. It is the most promising candidate for SCDD wind generators in the future.

B. Axial Versus Radical Generator Concept

Axial HTS machines are mainly used in vehicles, ship and aircraft propulsion. As far as I know, there's no project on axial SCDD wind generators. However, Gieras believes that axial HTS machines will find potential applications in wind generators, for they are characterized by low noise, low leakage magnetic flux and low cogging torque [16]. Many works has done on axial permanent magnet wind generators [6], [7] and the electromagnetic theory of the SC alternators is much similar to the surface permanent-magnet (SPM) synchronous machine [17]. Therefore, the characteristics of axial SC generators are similar to that of SPM machines. Its output power per unit volume is higher and its axial length is shorter than radical machines [7], [18], which make the axial generator compact. Moreover, SC field coils can be made in circular shape, which gives them the best performances as there's no concentration strain like in the racetrack type coils [18], [19].

However, compared to radical machines, axial machines have lower torque to mass ratio and will be structural instable with large diameter [6], [7].They will be heavier than radical machines. In megawatt class direct-drive wind generators, the diameter usually large to produce enough torque. It may increase the complexity to make mechanical structure strong and robust, which increases the cost and difficult to manufacture. The demerits must be overcome or greatly improved before axial machines find their application in direct-drive wind turbines.

Radical topology is most popular with designers for SC machines, especially for wind turbine generators. It seems that the radical topology is better, as most SC wind generator projects are focused on it. The methods to design, analysis and manufacture of radical machines are advanced and the mechanical structure is easy to make stable enough. Besides, designers can refer to existent theoretical and empirical experiences on SC wind turbine generators, especially experience on mechanical structure and the cryogenic refrigeration system.

Though the torque to volume ratio is smaller, the torque to mass ratio is usually larger than axial topology [6]. It has been

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concluded that radical machines are better than axial machines in terms of cost, when the output is more than 100kW [20], which makes radical topology more suitable for megawatt wind generators. Moreover, Andrea Cavagnino et al pointed out that axial topology is attractive when the number of poles is high and the axial length is short [21]. In direct-drive wind generators, though the diameter is large, it is difficult to make a design with high number of poles like in SPM machines for the restriction of minimum bending diameters as well as the limitation of mechanical supporting system and cryogenic cooling system. Therefore, radical topology is superior to axial topology in SCDD wind turbines, when taking cost and reliability into consideration.

As a whole, the best topology of SCDD wind generators has the maximum output, minimum expenses and highest reliability. At present, rotating armature with radial flux topology is competitive and rotating field with radical flux topology is most promising.

C. *Other Innovative Topologies*

Some other special topologies are put forward in direct-drive wind generators. Swarn Singh Kalsi believes the SC homopolar DC generator may have potential for direct-drive wind generators, because its SC field winding can be stationary and it is simple in theory [22]. However, there are many thorny problems with it. The slip rings to collect large current and the complex mechanical and electrical structure to improve output voltage are all fatal for it to apply in wind generators.

A SC homopolar inductor alternators topology is put forward by GE and other researchers [22]-[24]. In this topology the SC field coils are stationary in the stator with armature, which simplifies the SC support system, cryogenic refrigeration system and excitation system. The field coils in this configuration are more reliable for there are no large centrifugal forces. However, the design and manufacture of stator structure are complicate. Besides, SC field coils are in the stator and they occupy part of axial space, which would decrease the torque density and increase the copper ends in the armature. What is worse, it only uses about 50% of the magnitude of magnetic flux density and the leakage magnetic flux is high. Those drawbacks make it less attracting to designers.

A transverse flux topology for SCDD wind generators is proposed by M. R. Quddes et al in Japan [19]. It takes the advantage of circular SC field coils and transverse magnetic flux help to increase the output power. In addition, the volume of the generator and magnetic flux leakage are smaller. However, it needs many SC wires which are expensive and the structure of the generator, either thermal or mechanical, is more complicate. It still needs further study for this topology.

III. DESIGN CONSIDERATION

Electromagnetic, thermal and mechanical structure need carefully designing to achieve the most suitable direct-drive generator system for wind markets, including cooling system, superconducting support system, excitation system etc. All of them are crucial for a superconducting generator operates well.

A. *Superconducting Support System*

A SC support system includes SC winding assembly and torque transfer assembly. SC winding assembly is cooled with cryogenic refrigeration system while torque transfer assembly operates at ambient temperature. The SC support system must be capable of withstanding the torque in the normal operation and even in short circuit fault. In addition, the SC support system should be able to handle the thermal stress in the cooling process. Moreover, if the SC field coils are mounting in the rotor, the SC support system is required to withstand large centrifugal force. When designing the SC support system, designers have to keep all mechanical stresses and thermal stress in mind.

The SC winding assembly mainly includes support components of SC wires at cryogenic temperature. Besides the torque, thermal stress and centrifugal force, the support components also need to withstand the ovalization forces. Also the support components must have good thermal conductivity to cool down the SC field coils. The conduits for the cryogenic coolant always exist in the support components or around them.

The torque transfer assembly usually consists of the driven shaft, iron core body, torque tube and interconnection assembly, for example fasteners. The most important and difficult part is the torque tube, by which torque from the warm shaft to the cryogenic winding assembly is transferred. In order to reduce the heat leakage, the materials of the torque tube are poor in thermal conductivity. Flanges, protruding parts or other mechanical structures are used in the torque tube to provide a vacuum space between the warm and cryogenic parts to further reduce heat leakage [25]-[27]. Moreover, the torque tube may consist of some discrete rods to decrease heat leakage [28]-[30], for the heat flow will be reduced if the total crossing area of the heat flow is reduced.

However, James F. Maguire et al [31] point out that metallic material may not provide the level of thermal insulation, while composite material may not provide the shear stress needed to handle the torque. They proposed a method to take advantages of the two materials, in which the metallic material is put in a shear configuration and the composite materials in a tangentially loaded configuration.

B. *Cryogenic cooling system*

Cryogenic cooling system is essential to SC wind generators for it cools the SC field coils and maintains a stable cryogenic environment. The heat load it needs to remove mainly consists of heat generated in the SC coils, radiated heat through the cryostat, conduction heat through the current leads and mechanical support system [22]. The time to cool the SC field coils from ambient temperature to operating cryogenic temperature should be reasonable [32]. The requirement of the cryogenic system is to be “invisible”, which means the vibration, input power, maintenance, failure, cost etc. should have few influences on the whole generator system [33]. In

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SCDD wind generators, 20K~30K is preferred to obtain the merits in weight and size reduction derived from high current of SC field coils [34]. Therefore, gas He and liquid Ne are suitable coolants for the cryogenic cooling system. Conventional pool boiling method is not suitable for large SC generators for it needs continuous replenishing [35] and requires plenty of fluid to immerse the whole rotor.

Another method is a stationary cryocooler with recuperative refrigeration cycle, for example Reverse Brayton cycle [12], [36]，which is simple in concept [15]. The cooling power and efficiency of the system are relatively high [37]. As it has a moving expansion engine, it will cost more and has potential reliability problems [33]. Therefore, the system is expensive and needs much effort to maintain, which makes it less attractive.

In order to make the cryogenic cooling system less expensive and less complicated, a stationary cryocooler with regenerative refrigeration cycle, for example Gifford-McMahon (G-M) cycle, is put forward. G-M cryocooler is most popular for cooling HTS magnets [22].The main advantage is that it is an industrially established technology and has been commercially available [34]. However, the efficiency is not high [38] and it needs maintenance every 9~18 months [8]. Multi-cryocoolers are used in one cryogenic cooling system to improve the reliability and capability, which offers redundancy for the system [39]. Stirling cryocoolers and pulse tube cryocoolers are also under development and they will gradually replace the G-M cryocoolers [38]. They are beginning to be available in larger SC machines [8]. Stirling cryocoolers have higher efficiency and longer lifetime than G-M cryocoolers, but they are much more expensive [22]. The pulse tube cryocooler has a longer lifetime [34], but its lower efficiency, smaller cooling capacity and higher cost than the G-M cryocoolers limit its application at present.

Stationary cryocoolers are chosen for their undesirable high gravity heat transfer in the cold head when rotating [40]. The critical component is the transfer coupling, which connects the rotating rotor with the stationary cryocooler. Though the cryogenic cooling system with stationary cryocoolers is viable in commercial, the reliability of the transfer coupling is still a problem [41]. In addition, the heat losses to the coolant and coolant leakage should be minor in the transfer coupling [42]. Gregory Snitvhler proposes a cooling system by mounting the cold heads on the rotor for the low speed wind turbine application [39]. Without the transfer coupling, the efficiency and reliability will be increased [43]. However, it still needs much more studies and experiences.

C. Excitation System

Some special requirements exist in the excitation system of SC generators. The resistance in the SC generator is relatively low and a small change in voltage will have a great impact on the field coil current [44]. In addition the inductances of the SC field coils are relatively high. Low resistance and high inductance will lead to a long time constant. In order to change the field current within a reasonable period of time, a relatively higher voltage is required to the SC field coils [34]. Moreover, the quality of the DC current applied to the field coils is essential, as the AC loss of the SC materials increases with the low quality DC current. Therefore, current rather than voltage is more suitable as the control parameter in the excitation system. In addition, the heat leak to the cryostat should be minor [45]. As excitation with slips and rings, which are common in hydroturbines, has reliability and heat leakage problem [46], [47], designers focus on brushless excitation system and have proposed two methods. One is a rotating transformer with complex control system; the other is a flux pump. As a result of negligible resistance, the SC field coils work in current persistent model to reduce heat loads to the cryostat in either method.

The rotating transformer excitation system employs switching devices to work in a switching model. This excitation system only appears in some patents [45], [48] and there is no common development effort [34]. The main advantage is less heat loads as the current leads only carry current intermittently. However, the reliability and availability of the switching devices in the cryogenic environment is a problem. The maintenance of the switching devices is difficult as the whole cryostat should be open. Moreover, the quenching protection should also be paid attention in the rotating transformer system.

Flux pump system can offer high field current to the SC field coils with low heat leak to the cryostat [49]. The efficiency of flux pump is higher and it is more robust by removing the switch devices needed in the rotating transformer excitation system. In addition, the flux pump can reduce the synchronous reactance in the wind generator, which can improve the voltage regulation as well as the output power of the wind generator [50]. Moreover, flux pump provides a simple way to ensure the dynamic stability of SC wind generator in the power system [51]. No matter the rotating transformer excitation system or the flux pump excitation system, more efforts are needed to find access to successful application in SCDD wind turbine generator system.

IV. CONCLUSION

This paper mainly reviews different topologies for superconducting direct-drive wind generators and discusses their advantages and disadvantages. Rotating armature with radial flux topology is competitive in nowadays and rotating field with radical flux topology is most promising. As design consideration, including the superconducting support system, the cryogenic cooling system and the excitation system, is crucial to a successful SCDD wind generator, it is also described in the paper.

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