Simulation of Magnetic Flux Distribution of Stator and Rotor Coil of Superconducting Air Cored Wind Turbine Generator Using COMSOL Multiphysics

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Abstract: Direct drive wind turbine generators are gaining importance for light weight, compact design in wind power generation. A new design approach of superconducting wind generator having both axial and radial air gaps between stator and superconducting rotor winding is selected for this simulation work. This paper deals with the simulation of magnetic flux distribution in stator and rotor coil of the same using the sliding mesh tool of COMSOL Multiphysics.

In this work, the model geometry of the wind turbine generator is drawn using 3D CAD tool of COMSOL Multiphysics. AC/DC module has been chosen for the simulation of this HTS generator. Parametric sweep is incorporated in study portal, which evaluates field distribution of the model for every angular position of the rotor with respect to the stationary axis and stores the results. Combining all the results, an animation in motion is also made for the realization of flux distribution during rotation.

Keywords: Direct-drive, superconducting wind-turbine-generator, parametric sweep, magnetic flux distribution.

1. Introduction

Energy is considered to be indispensable for the existence of mankind. It controls the social and economical growth of any nation. Renewable energy based systems became more attractive worldwide because of the continuous reduction of installation costs of solar and wind power systems since last 30 years [1]. Wind is a renewable resource because it is inexhaustible and naturally existing. It is a result of uneven incident of sun light on the earth. Uneven temperature on the earth's atmosphere causes pressure difference in air which results in flow of wind.

It is obvious that among all the form of energy, electricity is the most compact and clean form of energy in terms of usability and transmission. So many attempts have been made globally to generate electricity from various sources adopting various power generation methodologies. In recent years interests are shown in producing electrical energy from the different available renewable energy sources, like wind and solar [2]. The main reasons for using them are to save fuel, to supply electricity to remote places and to meet the environmental consideration.

Wind energy is the fastest growing source of renewable, clean, reliable, and pollution free source for generation of green electricity [2]. A demand for 300 GW of installed wind power is predicted by 2030 in European countries [3]. In India, wind power occupied considerable share in total electricity generation from different renewable energy resources in last two decades. In 2011 India had an installed capacity of 14158 MW [4]. Now India is in the 5th position in the world in wind energy production [5].

Compared to the onshore-wind-energy production, researches are emphasizing on large scale offshore wind energy because of higher wind speeds and higher capacity factors [6]. The optimal size of offshore wind turbine depends on the local wind, water conditions of the installation site. From preliminary analysis based on these criterions, it is found that 10 MW offshore turbine will be of optimum size [7]. The global demand for large size offshore wind turbine generator invites the application of high temperature superconductors in wind generators. High torque and the direct drive facilities of HTS drive trains provide mechanical simplification eliminating the need for gearbox.

The market conditions predict that the generators rated above 5 MW are preferred for increased wind power generation (Figure 1) [8].

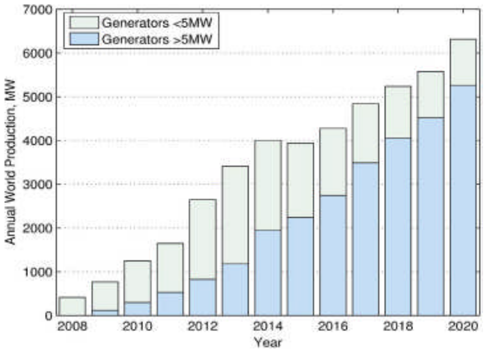

Figure 1. Emerging market projection for offshore wind-energy converters [8].

Nowadays superconducting generators are in operation for loss free power generation. Conventional generators operate with considerable losses at an efficiency of around 80 percent. Compared to theses conventional counterparts, superconducting generators are highly capable to meet the huge electricity demand [9,10] having lightweight, compact design, high current carrying capability, high reliability, direct drive configuration etc. The basic constructional difference between the conventional and superconducting generators lies in the use of superconducting tapes/wires instead of the conventional copper wires. Superconductors are preferred over the copper wires in this type of generators because of high power density, high amperage, enhanced strength and electrical stability etc.

Recently, superconducting wind turbine generators are getting an enormous attention [8-14]. However, a typical model of a 10 MW High Temperature Superconducting Generator [19] has been chosen here for numerical simulation using FEM based software COMSOL Multiphysics and MATLAB.

2. HTS wind generator model

In this work, a model of circular coil, air cored superconducting generator [19] is selected for simulation work.

2.1 Uniqueness of the selected HTS Generator

Superconducting circular coils used in this design are better compared to other shapes of superconducting coils. The direct drive arrangement reduces the total weight of the machine. Its circular field coil design with 2G high temperature superconducting wires (YBCO) provides uniform stress and magnetic force around the coil [15]. This design requires long length of superconducting wires which is difficult to manufacture commercially. Its high magnetic field incorporates additional cost for expensive non-magnetic structural supporting materials [15] required for shielding.

2.2 Generator model and design description

Figure 2 describes a wire frame view of stator and rotor coils having both axial and radial air gaps of a direct drive synchronous superconducting wind turbine generator. This figure is drawn in AUTO-CAD 2010.

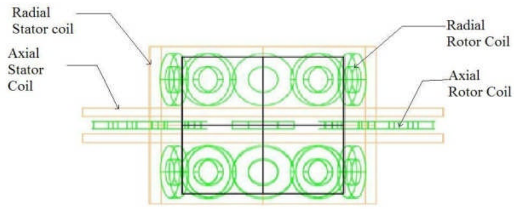

Figure 2. 3D wire frame view of a 10-pole wind turbine generator model.

The geometry of superconducting rotor of the same drawn in CAD module of COMSOL Multiphysics is shown in Figure 3. Two sets of radial flux type circular coils, and one set of axial flux type coils in between them are arranged as shown in Figure 3. The axial coil is needed for the enhancement of the transverse flux component among three superconducting coils under a single pole [15]. The air gap is considered to be 10 cm. The operating temperature of 20 K with rotational speed of 10 rpm [19] is maintained for the HTS rotor of this machine. According to chosen HTS wire properties, the current density in the field coils is assumed 1.68×10^8 A/m^2 for 10 T [16,17,18]. Coil is 100 mm in width and 200 mm in height. HTS rotor with 5 m diameter assumed to be the most appropriate one to realize 10 MW generator along with a compact size [19] having 10 poles.

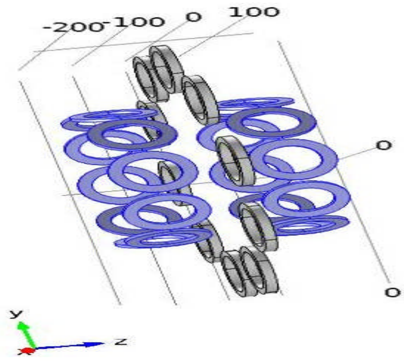

Figure 3. Rotor coil of a 10-pole generator.

Stator winding being the conventional one, no cryocoolers are required there. It is designed as an air core machine for making it light weight. For higher induced voltage, air gap is designed to be 10 cm between the air cored stator and rotor windings [15]. 3 phases concentrated stator windings are of 160 mm width.

3. Use of COMSOL Multiphysics

COMSOL Multiphysics is a finite element based solver software package for various applications in physics and engineering [20,21]. Here, the simulation of magnetic flux distribution of stator and rotor coil of the superconducting wind generator is performed using the sliding mesh tool of COMSOL Multiphysics. The 3D model geometry of the 10 MW class, 3-phase, 5m size, 10-pole induction generator having circular field coil is shown in Figure 4.

In AC/DC module, the magnetic and electric field section (mef of COMSOL Multiphysics) is chosen for setting the physics of the model. It is followed by the proper assignment of material properties of the coils and core. The main purpose of this work is to implement the rotational effect of the rotor coil on the stator magnetic field using sliding mesh concept. Incorporation of parametric sweep in study portal evaluates field distribution of the model for every angular position of the rotor with respect to the stationary axis and stores the results.

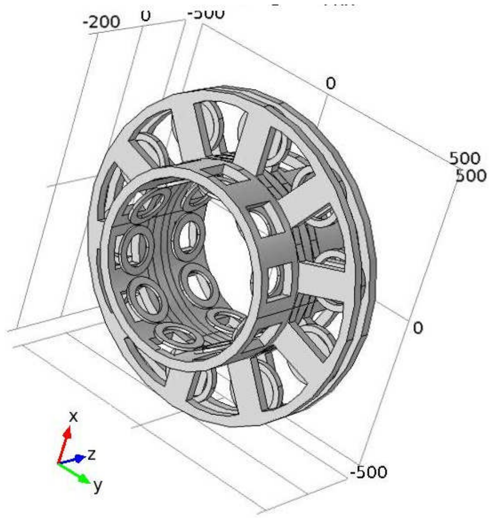

Figure 4. 3D model geometry of the HTS generator

The simulation problem is formulated in terms of the electric scalar potential V and magnetic vector potential **A**. This technique is known as *A-V* formulation, where the magnetic vector potential (A) is a depended variable. The equations were formulated in differential form so that the finite element method can handle them. In the *A-V* formulation (Equation 1), different variables like conductivity of the HTS material, permeability of vacuum are defined.

$$\frac{1}{\mu o}\nabla^2 . A + \sigma\frac{\partial A}{\partial t} = -\sigma.\nabla.V \qquad ...1$$

where **A** is the magnetic vector potential, ∇.V is the voltage gradient, σ is the conductivity of HTS and μ_o, is the permeability of vacuum.

Another fundamental relationship (2) is used as the equation of continuity.

$$\mathbf{\nabla}.\mathbf{J} = -\frac{\partial \rho}{\partial t} \qquad ....2$$

Where J is the surface current density which is assigned to the coil. The boundary conditions at material interfaces and at physical boundaries are specified using Equation (3) and (4).

$$n \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{J}_s \qquad ...3$$

$$n.(\mathbf{B}_1 - \mathbf{B}_2) = 0 \qquad ...4$$

were *n* is the outward normal vector from medium 2 and *H*, *B*, *J* represents the magnetic field intensity, The magnetic flux density, and the current density respectively of medium 1 and 2 as denoted by suffixes.

4. Results and Discussions

The simulation software COMSOL Multiphysics is used for the numerical computation of the magnetic fields of this circular superconducting air core coil of direct drive off-shore wind turbine generator. A three-dimensional model of the HTS wind generator is created with the help of the CAD tools of COMSOL Multiphysics. The optimization of the mesh size is done based on the model geometry. The magnetic field simulation of the AC/DC module of COMSOL Multiphysics is chosen for a static as well as dynamic analysis of the model.

The problem has been solved on an Intel Core i5 processor with six cores and a clock frequency of 3.8 GHz and memory of 32 GB, 1600 MHz, in 64 bit Windows 7 platform.

4.1 Mesh generation

COMSOL Multiphysics supports automatic mesh generation with a given level of element size. Alternatively, the size of the elements and further parameters can be manually defined for domains and edges [21].

Here, at first the superconducting coil, which is the most significant part of this work, has been meshed with extra fine size of elements. After that normal size of the elements are chosen for the small air gap between the superconducting coils and copper coils. The copper coils are meshed with a fine element size. Finally, the surrounding air has been meshed with coarse elements. Figure 5 shows the complete meshed model.

Figure 5 Model of the generator with finite element mesh (surrounding air cylinder hidden)

4.2 Post processing plots and discussions

Magnetic vector potential (MVP) plot of the model is reported in Figure 6. Its maximum value of A obtained is 0.84 tesla-meters. Here in this simulation the critical electric field is 10^{-4} Volts/meter. The maximum MVP occurs at the axial coils and at the exo-surface of the axial coils.

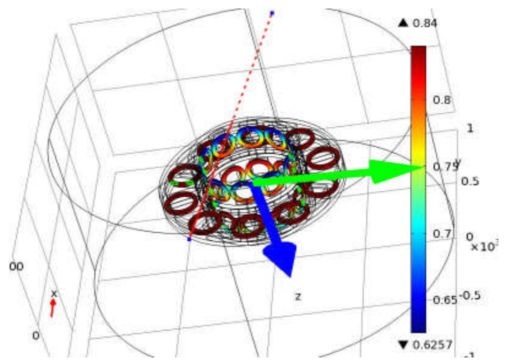

Figure 6. MVP plot (circular coils only).

Flux distribution in the rotor coil is realized here using volume plot of magnetic flux density (normal). The simulated magnetic field is distributed almost uniformly throughout the outer part of the stator and the same varies gradually with the distance from the centre in each coil of the rotor. It is visualized in Figure 7 and Figure 8 in full and zoomed views respectively.

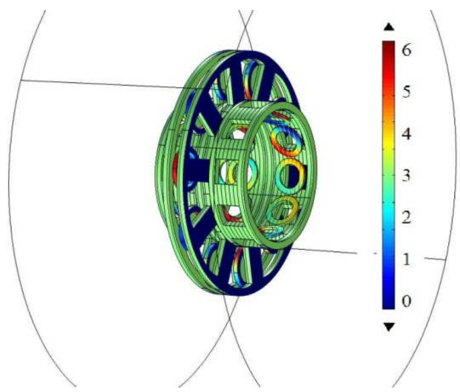

Figure 7. 3D plot of flux distribution (whole length view)

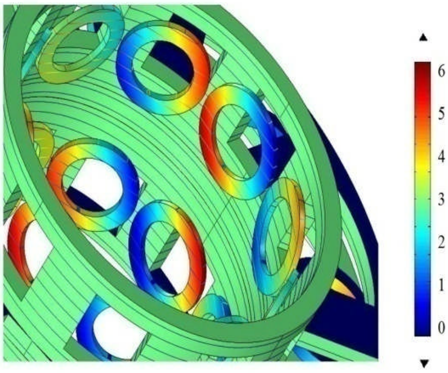

Figure 8. 3D plot of flux distribution (closer view)

Furthermore, the study of the flux distributions on the rotor coil more precisely is done by plotting magnetic flux density vs distance of a single superconducting rotor coil using static analysis. The flux density of rotor coil is also calculated using MATLAB code developed in-house and the results are compared with the same obtained using COMSOL Multiphysics. These two results are verified with the published data [19] in Figure 9. From the plots it is obvious that the flux density reduces from the surface to the centers of a single coil. Near the surface, all the plots render almost same values whereas towards center they differ by 1T.

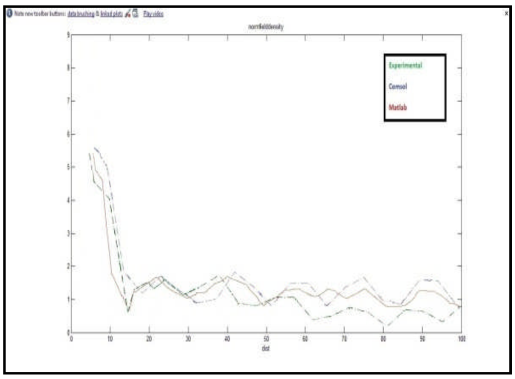

Figure 9. Combined plot of Flux density distribution on a single coil.

5. Conclusions

Here finite element analysis has been performed using two different softwares, COMSOL Multiphysics and MATLAB. Satisfactory plots have been obtained while simulating in COMSOL Multiphysics. The simulation software COMSOL Multiphysics has been also used to simulate a parametric model of the superconducting air core wind turbine generator. The solution has been efficiently computed using the built-in tools and solvers of COMSOL Multiphysics. Sliding mesh technique incorporating parametric sweep gave the realistic effect of rotation of the rotor with respect to the stator on flux distribution. The results obtained from the COMSOL are verified by MATLAB code and both of these are compared with a reference plot of same. In summary, 3D model geometry has been efficiently constructed in 3D CAD tool of COMSOL Multiphysics and it is found to be a very flexible and efficient tool for numerical field computations.

8. References

1. Antonia V. Herzog, et al. ‘Renewable Energy Sources’, *Encyclopedia of Life Support Systems (EOLSS). Forerunner Volume-‘Perspectives and Overview of Life Support Systems and Sustainable Development.* Part 4C. Available: http://www.eolss.com
2. www.beyondcoal.org/solutions/renewable-energy
3. A B Abrahamsen, N Mijatovic, et al, 'Superconducting wind turbine generators’, *Superconductor Science and Tecnology*, **Volume 23**, 034019 (2010).
4. Nitin Sethi, ‘1GW solar power in 2013' TNN, 18 November 2009’.
5. www.indianwindpower.com
6. Bonnie Ram, et al, 'Energy from Offshore Wind', *2006 Offshore Technology Conference, U.S.A.*, 18355 (2006). Available: http://www.ntis.gov/ordering.htm
7. N Mijatovic, et al, 'Superconducting wind turbine generators.' *Supercond. Science & Technology*, **Volume 23**, 034019 (2010).

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8. Ozan Keysan, Markus, et al,'A Homopolar HTSG Topology for Large Direct-Drive Wind Turbines', *IEEE transactions on applied superconductivity*. **Volume 21**(5), 3523-3531 (2011).
9. M. Lesser and J. Muller, 'Superconductor technology generating the future of offshore wind power', *Renewable Energy World Conf., Cologne, Germany*, 1-10 (2009).
10. 'American Superconductors Corporation.' Available: http://www.amsc.com
11. 'Enercon Wind Turbines Technology & Service.' Available: http://www.enercon.de/
12. G. M. Joselin Herbert, et al, 'A review of wind energy technologies.' *Renewable and Sustainable Energy Reviews*, **Volume 11**, 1117–1145 (2007).
13. N. Maki, "Design study of high-temperature superconducting generators for wind power systems," *IOP Science,J. Phys.: Conf. Ser.*, **Volume 97**, 012155 (2008).
14. C. Lewis and J. Muller, 'A direct drive wind turbine HTS generator.' *IEEE Power Engineering Society General Meeting*,1-8 (2007).
15. M.R. Quddes, et al, 'Electromagnetic Design Study of 10 MW-class Wind Turbine Generators using Circular Superconducting Field Coils', *Electrical Machines and Systems (ICEMS), 2011 International Conference*, 1-6 (2011).
16. D. W. Hazelton and V. Selvamanickam, 'SuperPower's YBCO coated high-temparature superconducting (HTS) wire and magnet applications.' *Proceedings of the IEEE*, **Volume 97**(11), 1831-1836 (2009).
17. V. Selvamanickam, et al, 'High performance 2G wires: from R&D to pilot-scale manufacturing.' *IEEE transactions on applied superconductivity*, **Volume 19**(3), 3225–3230 (2009).
18. X. Li, et al, 'The development of second generation HTS wire at american superconductor.' *IEEE transactions on applied superconductivity*, **Volume 19**(3), 3231–3235. (2009).
19. M. R. Quddes, M. Sekino, 'Electromagnetic Design Study of Transverse Flux Enhanced Type Superconducting Wind Turbine Generators' *IEEE transactions on applied superconductivity*, **Volume 21**(3), 1101 (2011).
20. www.comsol.com
21. Hanke Michael, 'Short Introduction to Comsol Multiphysics' ,1-6 (2006).