International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:9, No:8, 2015

Thermal Assessment of Outer Rotor Direct Drive Gearless Small-Scale Wind Turbines

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***Abstract*—**This paper investigates the thermal issue of permanent magnet synchronous generator which is frequently used in direct drive gearless small-scale wind turbine applications. Permanent Magnet Synchronous Generator (PMSG) is designed with 2.5 kW continuous and 6 kW peak power. Then considering generator geometry, mechanical design of wind turbine is performed. Thermal analysis and optimization is carried out considering all wind turbine components to reach realistic results. This issue is extremely important in research and development (R&D) process for wind turbine applications.

***Keywords*—**Direct drive, gearless wind turbine, permanent magnet synchronous generator (PMSG), small-scale wind turbine, thermal management.

I. Introduction

WIND energy usage is rapidly rising worldwide in last decade. This energy source existence is the same with the world. However in a long time, human did not effectively use this energy source to get a power. The main reason is well known that the absence of power converters. Before enabling power converters in wind turbine applications, fixed speed wind turbines were used and this type of turbines only generates electrical power at specific speed. Hence the efficiency was low and speed range was very limited. But now thanks to power converters existence, variable speed wind turbines are used to generate electric power. This also provides to produce wind turbines in more powerful sizes.

U.S. department of energy renewable energy data book shows the trend of renewable energy last decade from 2000 to 20013 [1]. Renewable energy usage itself is rising every year. But this is the point that should be stated here the growth of wind energy in renewable energy sources has extremely high potential as shown in Fig. 1.

The cost of producing energy from wind is quite comparable with other energy sources. Fig. 2 indicates that after hydropower, the wind turbine energy cost has the second lowest energy cost [2].

Wind turbine technology requires multidisciplinary study during R&D process. Electrical, electromagnetic, mechanical, thermal, and structural [3] issues are mixed together in wind turbine applications [4]-[6]. Hence it requires very high engineering skills and professional vision.

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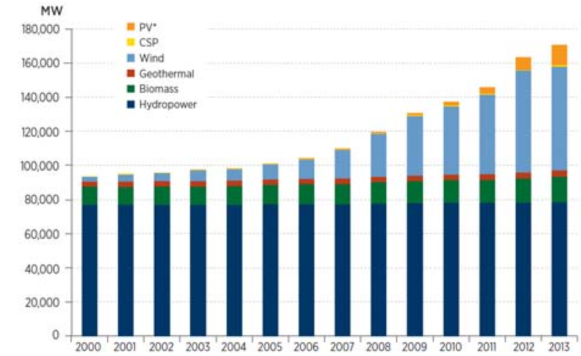


Fig. 1 U.S. renewable electricity nameplate capacity by source

In wind turbine technology, mainly two variable speed generator types are frequently used; doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG). Wind turbine applications now is tended to use PMSG recently especially at small scale power. It has some advantages such as high power density (W/kg), low noise, ability to operate direct driving without using gear, thus high efficiency, low manufacturing cost etc.

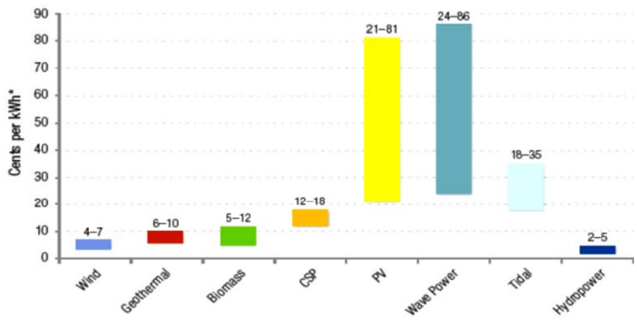


Fig. 2 Average energy costs in renewable energy sources

Permanent Magnet Synchronous Generator (PMSG) can be manufactured either interior or exterior rotor as shown in Fig 3. Outer rotor PMSG has relatively low cogging torque. It allows a high number of magnet poles in rotor due to the high rotor radius, permanent magnets are more attached to the rotor yoke as speed increases and the last but most significant advantages is that this type of generator is quite suitable for wind turbine applications due to the structural and mechanical aspects. The hub can be directly fixed to the rotor [2]. The most significant drawback is that it is vulnerable to the high temperature. Because of the inner stator winding, the dissipation of power losses from stator is not very easy. Inner rotor PMSG has more ability to dissipate heat. Thus relatively current density of this machine can be kept higher. This will be resulted with higher generated torque. Drawbacks; needs more challenges in terms of cogging torque and centrifugal forces on magnets. Also limited area is another concern that limits the number of poles.

This paper mainly consists of thermal study. Electrical, electromagnetic and some part of mechanical issues/their results about designed generator were previously presented and published in conference [7]. So this paper evaluates the designed PMSG from thermal-outer rotor geometry has thermal behavior drawback as mentioned.

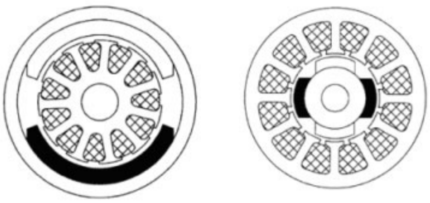


Fig. 3 Outer rotor and inner rotor geometries of PMSG

II. Brief Information about Wind Turbine

A. Turbine Power

The kinetic energy of a mass is well known that,

$$E = \frac{1}{2}mv^2 \tag{1}$$

From energy, the power of this mass can be found as,

$$P = \frac{dE}{dt} = \frac{1}{2}v^2\frac{dm}{dt} \tag{2}$$

The rate of change of mass in a time is

$$\frac{dm}{dt} = \rho A\frac{dx}{dt} = \rho.Av \tag{3}$$

where ρ is density of air (kg/m^3), A is area wind passing through perpendicular to the wind (m^2) and v is wind velocity(m/s). All together the total wind power is [8]

$$P = \frac{1}{2}\rho.Av^3 \tag{4}$$

with Betz Limit (C_p),

$$P = \frac{1}{2}\rho.Av^3C_p \tag{5}$$

At room temperature (25°C), air density ρ =1.18 kg/m^3.

In (5), C_p coefficient depends on turbine design. But roughly C_p = 0.25 is assumed. Wind speed at maximum continuous power rating (2.5kW) is selected as v=12 m/s. Then now it is time to find required rotor blade radius.

$$P = 2500 = \frac{1}{2}\rho.Av^3C_p = \frac{1}{2}(1.18).(\pi r^2).(12)^3(0.25) \tag{6}$$

Turbine radius is found as r=1.76 meter for this application as shown below.

Fig. 4 Designed wind turbine blade geometry.

B. Designed Generator

Outer rotor PMSG is designed and its details are mentioned in [7] so just brief information about it will be given here. In [7], optimization of PMSG is done aiming of low cogging torque which enables to generate electrical power even in low wind speed. In addition, magnet thickness, torque angle, flux density and efficiency optimizations are done. The final geometry of PMSG is shown in Fig. 5. In design process, base speed is selected as 150 rpm. Some design criteria are given in Table I.

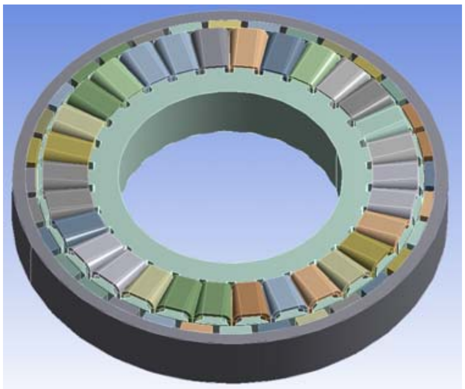


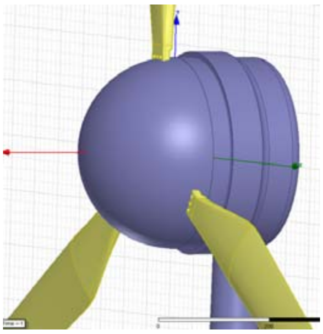
Fig. 5 Final version of designed permanent magnet synchronous generator

TABLE I
Design Inputs

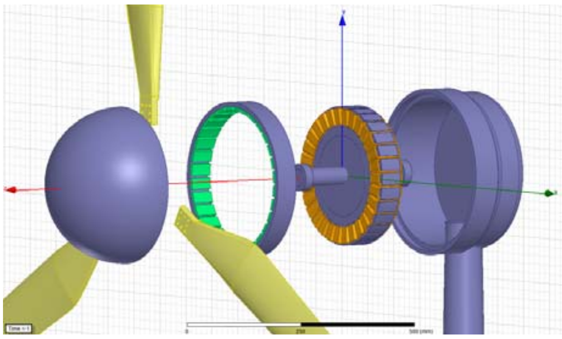
Parameter	Value
Rated power (kW)	2.5
Rated speed (rpm)	150
Rated torque (Nm)	159
Maximum allowed weight (kg)	25
Maximum allowed generator diameter (mm)	350
Grid frequency (Hz)	50
Number of phases and connection type	3/Y
DC Bus voltage (V)	400

III. Thermal Analysis of Wind Turbine

Thermal analysis of wind turbine is carried out to see the behavior of designed PMSG at nominal conditions. In first step, the case of the PMSG is roughly designed as shown in Fig. 6.



(a)



(b)

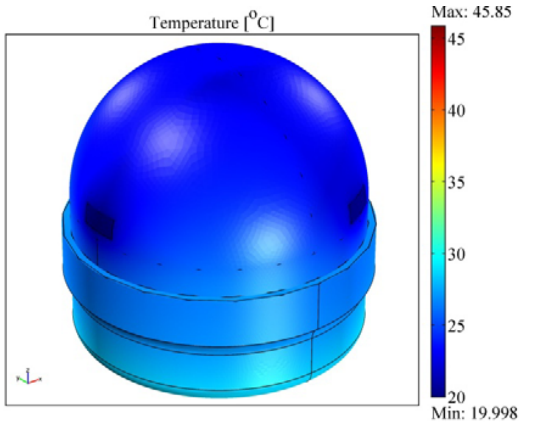
Fig. 6 Designed wind turbine hub-geometry (a) and its exploded picture (b)

As can be seen from Fig. 6, stator is inside the cage and there is only shaft to dissipate the power losses of stator with conduction. Convection heat dissipation is not easy with this geometry for stator. However for magnets, it has advantage to dissipate the power loss. But this is the problem that majority of the power losses in low speed PMSG is copper losses. Core losses are very low because of the low electrical frequency and laminated steel of stator. Power losses in PMSG are listed in Table II. Consequently coils can be considered as heat source.

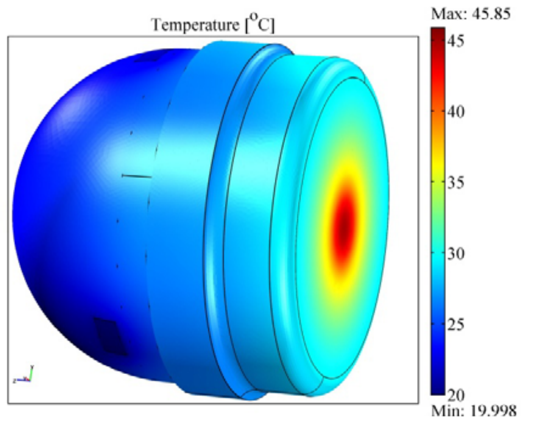
TABLE II
Power Losses in Designed PMSG

	Copper Loss	Core Loss
Power loss(W)	183 W	38 W

The first results of wind turbine thermal analysis are given in Figs. 7 and 8 which show the hub-cage temperature and stator core temperature, respectively. Analysis is carried out using COMSOL based Finite Element Analysis (FEA) software. The results indicate that coils are heat source. Thus the highest temperature occurs in coils and stator core. This can be expected because the stator is inside the geometry and there is even no conduction heating transfer so all heat is dissipated in closed cage of hub as shown in Fig. 9. Designed PMSG with this geometry cannot be operated with continuous 2.5 kW power because of the high temperature.



(a)



(b)

Fig. 7 Wind turbine hub-cage temperature distribution

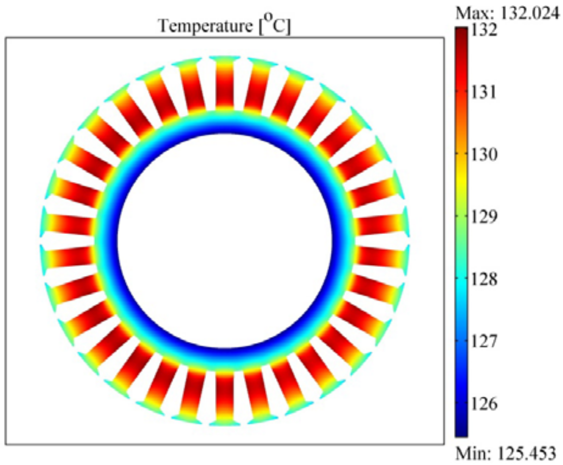


Fig. 8 Stator temperature distribution

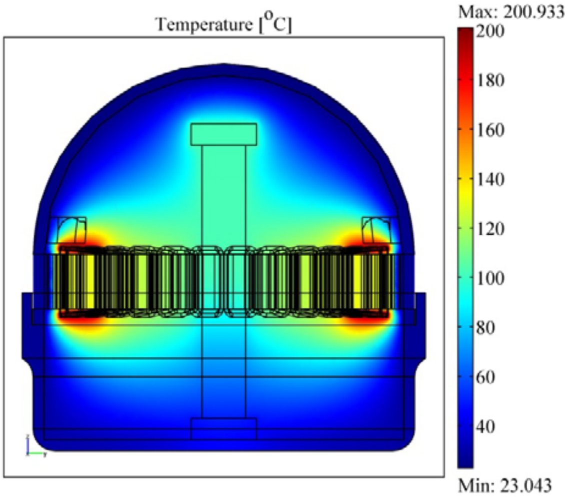


Fig. 9 Inner side temperature distribution of wind turbine hub-cage

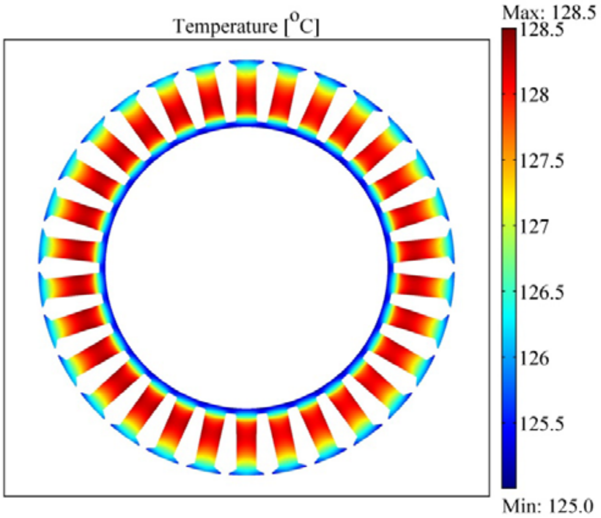


Fig. 10 Stator temperature distribution - epoxy applied

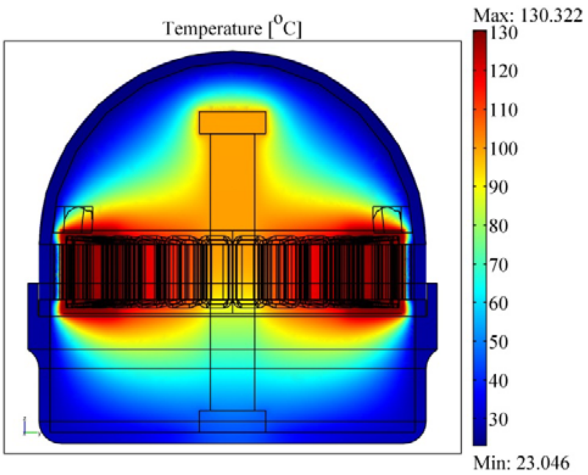


Fig. 11 Inner side temperature distribution of wind turbine hub-cage-epoxy applied

The high temperature problem is solved using high thermal conductivity material-epoxy in stator coils. The epoxy was applied between whole stator slots and hub-cage. The related results are given in Figs. 10 and 11. Epoxy is frequently used in industrial applications which reduces the temperature and also make the coils more durable. The wind turbine will be also more robust with epoxy. With epoxy applied, max temperature in wind turbine is now around 130°C in coils. This is the worst condition analysis result that the wind turbine generates 2.5 kW power in a long time.

IV. Conclusion and Future Work

This paper investigates the thermal issue of permanent magnet synchronous generator which is frequently used in direct drive gearless small-scale wind turbine applications. Permanent magnet synchronous generator (PMSG) is designed with 2.5 kW continuous and 6 kW peak power. Then considering generator geometry, mechanical design of wind turbine is performed. Thermal analysis and optimization is carried out considering all wind turbine components to reach realistic results. The results show that designed PMSG can be operated at 2.5 kW rated continuous power without damaging. The thermal issue is extremely important in research and development (R&D) process for wind turbine applications.

Future work will be vibration/noise study of this designed wind turbine. After that whole designing processes will be ended and it will be ready to do experimental study.

References

[1] Energy efficiency & renewable energy, Renewable Energy Data Book, 2013, U.S. Department of Energy.

[2] Florence Libert, "Design, optimization and comparison of permanent magnet motors for a low-speed direct-driven mixer" Master thesis, Royal Institute of Technology, Departement of Electrical Machines and Power Electronics, 2004.

[3] George Robert Katsanis, "Transient small wind turbine tower structural analysis with coupled rotor dynamic interaction" Master thesis, The faculty of California Polytechnic State University, 2013.

[4] Chad Van der Woude and Sriram Narasimhan "Dynamic Structural Modelling of Wind Turbines Using Comsol Multiphsics", COMSOL conference Boston, 2010.

[5] J. Peeters, D. Vandepitte and P. Sas, "Structural Analysis of a Wind Turbine and its Drive Train Using Flexible Multibody Simulation Technique", International Conference on Noise and Vibration Engineering (ISMA), 2006.

[6] L. Jian, G. Xu, Y. Gong, J. Song, J. Liang and M. Chang, "Electromagnetic Design and Analysis of a Novel Magnetic-Gear-Integrated Wind Power Generator using Time-Stepping Finite Element Method", Progress in Electromagnetics Research, Vol. 113, 351-367, 2011.

[7] Y. Yasa and E. Mese, "Design and Analysis of Generator and Converters for Outer Rotor Direct Drive Gearless Small-scale Wind Turbines", International Conference on Renewable Energy Research and Application (ICRERA), 2014.

[8] Wind Turbine Power Calculations, Technical Paper, The Royal Academy of Engineering.

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