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

Yusuf Yasa, Erkan Mese

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 2013 [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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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.

II. BRIEF INFORMATION ABOUT WIND TURBINE

A. Turbine Power

The kinetic energy of a mass is well known that,

$$E = \frac{1}{2}mv^2$$  \hspace{1cm} (1)

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

$$p = \frac{dE}{dt} = \frac{1}{2} \cdot \frac{dm}{dt} \cdot \frac{dv}{dt}$$  \hspace{1cm} (2)

The rate of change of mass in a time is

$$\frac{dm}{dt} = \rho A \frac{dv}{dt} = \rho A v$$  \hspace{1cm} (3)

where \( \rho \) 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]

$$P = \frac{1}{2} \rho A v^3$$  \hspace{1cm} (4)

with Betz Limit (\( C_p \)),

$$P = \frac{1}{2} \rho A v^3 C_p$$  \hspace{1cm} (5)

At room temperature (25°C), air density \( \rho =1.18 \text{ kg/m}^3 \).

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 \( v = 12 \text{ m/s} \). Then now it is time to find required rotor blade radius.

$$P = 2500 = \frac{1}{2} \rho A v^3 C_p = \frac{1}{2} (1.18)(\pi r^2)(12)^3(0.25)$$  \hspace{1cm} (6)

Turbine radius is found as \( r = 1.76 \text{ meter} \) for this application as shown below.

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. 4 Designed wind turbine blade geometry.](image)

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

![Table 1 Design Inputs](image)
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.

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>
<thead>
<tr>
<th>TABLE II</th>
<th>POWER LOSSES IN DESIGNED PMSG</th>
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</thead>
<tbody>
<tr>
<td>Power loss(W)</td>
<td>Copper Loss</td>
</tr>
<tr>
<td></td>
<td>183 W</td>
</tr>
</tbody>
</table>

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.
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

Erkan Mese received B.S. and M.S. degrees in electrical engineering from Istanbul Technical University, Istanbul, Turkey, and Ph.D. degree in Electric Power Engineering from Rensselaer Polytechnic Institute, Troy, New York, 1990, 1993, 1999, respectively. Between 1997 and 2005, he was with Advanced Energy Conversion, LLC, New York, USA. From 2005 to 2008, he was with General Motors in Michigan USA. He worked for AVL Powertrain as Consultant Engineer between 2008 and 2013. Since 2009, he has been faculty member in Yildiz Technical University Electrical Engineering Department. His research activities include Electric Machines, Electromechanical Systems, Power Electronics, Hybrid Electric Vehicles and Renewable Energy Systems.