Abstract — Direct-drive radial flux permanent-magnet generator (RFPMG) and Direct-drive permanent-magnet transverse flux generator (TFPMG) is discussed throughout the ranges of 10MW to 20MW. The radial flux generator is common and has been a target of several studies. The transverse flux generator is an interesting alternative due to his higher power-density comparing with conventional designs. The study of these generators is based in the weight optimization with electrical, mechanical and magnetic constrains. A thermal study after the weight optimization is done to evaluate the allowed current density in the generators.

Keywords: RFPMG, TFPMG, Wind Generators, Direct-drive, thermal circuit.

I. INTRODUCTION

Since 2006 global wind energy market grew 26% and is forecast to grow at double digit rates over the next 5 years [1]. Although onshore wind turbine installations have contributed with the biggest share for this growth and is expected that by 2020 it will be stagnated [2]. Offshore installation is more attractive due to constant and high wind speed, which can ensure a high power extraction and availability. However, the costs to install and O&M costs are higher than onshore [1]. In disagreement of this costs, offshore will have a higher grow until 2020 maintaining until 2050 [2]. Generator, gearbox and wind turbine blades are the main components that require O&M and this costs represents 80% of the total O&M costs [1]. The only possibility of reducing O&M costs is direct-drive generators application. Doubly-feed induction generator (DFIG) has been the most commonly used wind generator representing 50% of the wind generators market. The main drawbacks of the DFIG are the presence of a gearbox and a limited velocity. The presence of a gearbox implies higher operational costs due to maintenance which also means higher inactivity periods.

Synchronous Generator (SG) is the most-promising technology for wind energy as it can be designed without a gearbox. An SG can also be designed with rotor-windings or permanent magnets. The direct-drive SG with rotor-windings has more energy losses and it is also bigger than its counterpart with permanent magnets. Overall direct-drive SG wind generators are also bigger than other wind generators. Therefore, PM generators have more advantages for offshore wind application. RFPMG is the most conventional and is the first one to be implemented. Several works has showed that these generators are very expensive and heavy. TFPM is an attractive solution to direct-drive application due to is higher power-density, which can be a better solution. This work TFPMG and RFPMG will be compared and weigh results to these two generators are showed in order to confirm which a better solution is.

II. WIND TURBINE MODELING

For calculating the generators poles pairs \( P_p \), the turbine’s rotor size and speed must be found. The available shaft power \( P \) from a wind turbine can be calculated as

\[
P = \frac{1}{2} \rho_{\text{air}} C_p(\lambda, \beta) \pi r^2 V_w^3
\]

where \( \rho_{\text{air}} \) is the air density, \( V_w \) is the wind speed, \( r \) is the wind turbine radius and \( C_p(\lambda, \beta) \) is the power coefficient, which is a function of tip-speed-ratio \( \lambda \) and the pitch angle of turbine blades \( \beta \).

The turbine’s radius can be obtained through Equation (1). The first approximation of \( r \) is determined for a wind speed reference \( V_{\text{ref}} \) at a hub height \( h_{\text{ref}} \). Table I provides the other parameters values.

Since wind speed changes with hub height \( h \), using (2) a new value for the wind speed can be found. A new value for the radius can now be calculated using the wind speed in (1). The hub’s height will be 1.2 times the diameter of the turbine’s blades [3]. This process will be iterated until a difference of 1% is observed between the current value for the wind speed and turbine’s radius regarding the values in the previous iteration.

After the iterative process converges to the desired precision, the number of generators pole pairs \( P_p \) can be obtained from equation (3).
Table I – Wind turbine model values.

<table>
<thead>
<tr>
<th>Mean</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power coefficient $C_p$ [3]</td>
<td>0.48</td>
</tr>
<tr>
<td>Tip-speed-ratio $\lambda$ [3]</td>
<td>7</td>
</tr>
<tr>
<td>Hub height reference $h_{ref}$ [4]</td>
<td>125 m</td>
</tr>
<tr>
<td>Wind speed reference $V_{ref}$ [4]</td>
<td>11.5 m/s</td>
</tr>
</tbody>
</table>

\[
V_w = \frac{\ln \left( \frac{h}{z_0} \right)}{\ln \left( \frac{h_{ref}}{z_0} \right)} \times V_{ref}
\]  

(2)

where $z_0$ is the characteristic length of the roughness at sea.

\[
V_r = \lambda \times V_w
\]  

(3)

For a desired output power the evolution of the number of pole pairs $P_p$ can be seen in Fig. 1.

![Fig. 1 - Evolution of generators poles pairs.](image)

III. DESIGN AND GENERATOR MODELING

A. Design Considerations

In order to reduce the total weight (active and inactive material) of RPFM and TFPMG, the length $l_a$ and diameter $d$ of both generators have an aspect ratio $K_{ratio}$ between 0.15 and 0.3[5] given as

\[
K_{ratio} = \frac{l_a}{d}
\]  

(4)

However, the analysis of TFPMG is done for one phase and for optimization, the aspect ratio $K_{ratio}$ is dived by three.

Fig. 2 depicts the dimensions of RPFM with surface-mounted magnets used in the model.

![Fig. 2 – Definition of RFP MG dimensions](image)

The optimization and calculation of TFPMG has been made with two types of windings. A winding with one section, has showed in Fig. 4 and a winding with two sections Fig. 3. In the calculations procedures the winding width $b_{cu}$ for one section is the sum of the two sections width and in total, both have the same winding width $b_{cu}$.

Fig. 3 and Fig. 4 depict the dimensions of TFPMG and they are both the same in the two types of winding.

![Fig. 3 - Definition of TFPMG dimensions.](image)

![Fig. 4 – Definition of the rest TFPMG dimensions with three phases.](image)

B. Magnetic Circuits

The magnetic expressions of active parts can be obtained from the conventional magnetic circuits laws [6]. For flux density
expressions in each part of stator, the KCL is applied taking the air-gap flux density has reference. The air-gap flux density in RFP MG and TFPMG are given as

\[ B_{g_{\text{max}}} = \frac{h_m}{\mu_{\text{rm}} g_{\text{eff}}} B_{\text{rm}} \]  

(5)

where \( h_m \) is the magnet height in direction on magnetization, \( \mu_{\text{rm}} \) is the relative permeability of the magnets, \( B_{\text{rm}} \) is the remnant flux density of the magnets (1.2 T) and \( g_{\text{eff}} \) effective air-gap length which is different in both generators. For calculating the effective air-gap length \( g_{\text{eff}} \) Carter’s factor is used in both generators due to the stator slots (RFP MG) and rotor slots (TFPMG). Carter’s factor for RFP MG is calculated in [7] and for TFPMG is calculated in [8]. The fundamental flux density \( B_{g_{1h}} \) of the magnets is calculated with Fourier analysis [7].

C. Electric Properties

To express current density \( J (A/mm^2) \), the phase current \( I_{\text{phase}} \) is calculated with constant voltage of 6.6KV [9]. With no-load in generators, the induced voltage \( E \) is equal to the phase voltage. Therefore, the winding inductance, leakage inductance and electric resistance \( R_{\text{elec}} \) are neglected in electric calculation. However, the electric resistance \( R_{\text{elec}} \) is used to calculate copper losses for thermal analysis. The copper losses is given as

\[ P_I = R_{\text{elec}} I_{\text{phase}} \]  

(6)

The iron used for the RFP MG and TFPMG is the 25H230 [10] specific for large generators and the losses in stator teeth and stator yoke are given as [6]

\[ P_{\text{fe}} = k_{\text{sy}} p_{\text{fe}} \left( \frac{B_{\text{sx}}}{B_0} \right)^2 m_{\text{fey}} \]  

(7)

\[ P_{\text{fet}} = k_{\text{fet}} p_{\text{fe}} \left( \frac{B_{\text{tx}}}{B_0} \right)^2 m_{\text{fet}} \]  

(8)

where \( k_{\text{sy}} \) is the stator yoke correction coefficient, \( k_{\text{fet}} \) is the stator teeth correction coefficient, \( m_{\text{fey}} \) is the mass of stator yoke, \( m_{\text{fet}} \) is the mass of stator teeth, \( B_{\text{sx}} \) flux density in the stator yoke, \( B_{\text{tx}} \) is the flux density in stator teeth and \( p_{\text{fe}} \) is the specific iron losses (W/Kg) for an given flux density (1.5T) and a frequency (50 Hz).

The RFP MG no-load voltage induced can be calculated as

\[ E = \sqrt{2} \omega_m n l_s R_s B_{g_{1h}} \]  

(9)

where \( \omega_m \) is the mechanical angular speed of the rotor, \( n \) is the number of turns of the phase winding, \( l_s \) is the generator length in axial direction and \( R_s \) is the stator radius.

The TFPMG no-load voltage induced can be calculated as

\[ E = \frac{P_{\text{fe}} \omega_m n l_s R_s B_{g_{1h}}}{\sqrt{2}} \]  

(10)

where \( \tau_{\text{st}} \) is the sum of stator teeth length and stator slot length.

IV. OPTIMIZATION

To implement an optimization, several constrains must be applied to the weight functional that is given as

\[ V_T = \rho_{\text{cu}} V_{\text{cu}} + \rho_{\text{fe}} V_{\text{fe}} + \rho_{\text{mag}} V_{\text{mag}} \]  

(11)

where \( \rho_{\text{cu}} \) is the copper density, \( V_{\text{cu}} \) is the copper volume, \( \rho_{\text{fe}} \) is the iron density, \( V_{\text{fe}} \) is the iron volume, \( \rho_{\text{mag}} \) is the magnet density and \( V_{\text{mag}} \) is the magnet volume. The MatLab method is the \textit{fmincon} with non-linear constrains given by

\[ \min f(x) = \begin{cases} c(x) \leq 0 \\ c_{\text{eq}}(x) = 0 \end{cases} \]  

(12)

Electric constrains must respect the output power which is the voltage induced (9)-(10) and current density. Magnetic constrains are important due to the possibility of iron saturation and the maximum allowed flux density must be defined for the calculation of iron geometrical dimensions. For RFP MG the flux density for stator yoke must be less than 1.6 T and for flux density of stator teeth is less than 1.4 T. The flux density in air-gap is also considered to be less than 1.1 T.

In TFPMG all geometrical dimensions of the magnetic circuit depends of one single value. The flux density in the generator stator pieces are equal and must be less than 1.8 T. Due to TFPMG high leakage flux in air-gap, dimensions constrains is used to maintain low leakage flux [11].

The mechanical constrains implies a specific design for stator dimensions. The calculation of these implications is not a requisition in these work. Therefore, in RFP MG the mechanical constrains are given in [12] and for TFPMG given in [13].

With geometrical dimensions of the active material depending of magnetic, electric and mechanical constrains, the method converge for a minimum weight. In these calculations several current density’s has applied in order to obtained several weights and geometrical dimensions. With these results and with several current densities a thermal model is needed to verify the allowed temperatures in all active parts.

V. THERMAL ANALYSIS

The influence of temperature in permanent-magnet (PM) is important to guarantee generators durability. Generally, the remnant flux density \( B_{\text{rm}} \) decreases with temperature and higher temperatures demagnetization can occur. Although,
copper, iron and winding insulation can lose their properties due to higher temperatures. For this thermal analysis, RFPMG and TFPMG have the same materials, therefore, the same allowable maximum temperatures. The PM has demagnetizing temperature of 120°C and for the calculations 110°C is used. The allowed temperature in copper and iron is 130°C [15] and the winding insulation thickness $h_{Is}$ is 1 mm for both generators with a maximum temperature of 130°C. The ambient temperature is 40°C.

### A. Heat Transfer

The heat is removed by convection, conduction and radiation. The thermal resistances of conduction, convection and radiation are given as

$$R_{th} = \frac{l}{A \lambda_{th}}$$

$$R_{th} = \frac{1}{A \alpha_{th}}$$

where $l$ is the length of the bocy in the heat flow direction, $A$ is the cross-sectional area, $\lambda_{th}$ is the thermal conductivity and $\alpha_{th}$ is the convection coefficient. The thermal resistance of radiation is only used in RFPMG end-windings [6]. Thermal conductivity materials are in [14]. The heat convection is the most important method of generators heat transfer and occurs in the active material boundaries. There are two types of convection: natural (no coolant-flow) and forced (with coolant-flow). In RFPMG the windings are assumed to be cooled indirectly, by forced airflow at the outer surface of the stator. This means that end-windings have a majority of natural convection and heat radiation [6]. Although, is assumed that end-windings have 20% of forced convection. The RFPMG heat transfer coefficients are given as [6]

$$\alpha_{thn} \approx 1.32 \left( \frac{\Delta T}{d} \right)^{0.25}$$

$$\alpha_{thf} \approx 3.89 \left( \frac{V_{air}}{l} \right)$$

where $\Delta T$ the permitted temperature rise and $V_{air}$ is the cooling air velocity.

In TFPMG is assumed to be cooled directly and convection coefficients are different due to the interaction of with air the active material. For this generator Nusselt number is used to calculate the convection coefficient and is given by [6]

$$Nu = \frac{\alpha_{th} l}{\lambda_{air}}$$

where $\lambda_{air}$ is the thermal conductivity of the air at 40°C, with several surfaces the air will have an different interaction and different values. To calculate the Nusselt number, Reynolds number must be found in all surfaces with the respective length $l$ and kinematic viscosity $\nu$ at 40°C [6].

$$Re = \frac{V_{air} l}{\nu}$$

For different surfaces the number Nusselt is given as [16]

$$Nu = 0.664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}}$$

$$Nu = c Re^{m} Pr^{\frac{1}{3}}$$

The air-gap convection depends of the rotor velocity and the Taylor number $Ta$ that is given as [6]

$$Ta = \frac{\rho_{air} V_{air}^{2} r_{m} g^{3}}{\mu_{a}^{2}}$$

where $r_{m}$ is the air-gap average radius, $g$ is the air-gap length and $\mu_{a}$ is the dynamic viscosity of air at 40°C. The convection is calculated with Nusselt number (22) for several intervals of the average Taylor number $T_{am}[5]$

$$Nu = \begin{cases} 
2 & T_{am} \leq 1700 \\
0.128 T_{am}^{0.367} & 1700 < T_{am} \leq 10^{4} \\
0.409 T_{am}^{0.241} & 10^{4} < T_{am} \leq 10^{7} 
\end{cases}$$

### B. Cooling Method

To solve the thermal circuit an equivalent thermal resistance for the cooling must be considered. This resistance is given as

$$R_{th} = \frac{1}{2 q_{vc} \rho_{air} c_{th}}$$

where $q_{vc}$ is the volume flow rate, $\rho_{air}$ is the air density for 40°C and $c_{th}$ is the specific heat capacity for 40°C. Normally, this resistance is calculated for a specific power loss in generators. Although, in these PM generators the thermal resistance is obtained with a certain volume flow rate that depends of the main dimensions of the generators. The volume flow rate is given as [14]

$$q_{vc} = N_{air} V_{air} l_{th} h_{air}$$

where $N_{air}$ is the number of coolant circuits, $l_{th}$ is the length of the coolant and $h_{air}$ is the height of coolant. For TFPMG has considered 2 coolant circuits and for RFPMG the coolant circuit is given as [14].
where \( \tau_{air} \) is the length of the coolant circuit.

**C. Thermal Circuit**

Fig. 5 depicts the lumped-model used in several parts of generators active material. The negative thermal resistance in Fig. 5 takes account that real losses are distributed evenly not in the center of the cell has used in calculations. Stator and windings are divided in several cells, where the copper and iron losses are applied in each node.

With losses in the nodes and thermal resistances, the temperatures rises can be calculated as

\[ [P] = [G_{th}] [\Delta T] \]

where \( G_{th} \) is the conductivity and is given by

\[
[G_{th}] = \begin{bmatrix}
\frac{1}{R_{1,1}} & -\frac{1}{R_{1,2}} & \cdots & -\frac{1}{R_{1,n}} \\
-\frac{1}{R_{2,1}} & \frac{1}{R_{2,2}} & \cdots & \frac{1}{R_{2,n}} \\
\vdots & \vdots & \ddots & \vdots \\
-\frac{1}{R_{n,1}} & -\frac{1}{R_{n,2}} & \cdots & \frac{1}{R_{n,n}}
\end{bmatrix}
\]

**VI. RESULTS**

**A. RFPM Generator**

The weight of the optimized RFPMG is presented in Fig. 6 where these results respect the allowed temperatures in the active material. Has show, these weight are higher and the problems to manufacturing and install in wind turbines will be an obstacle.

For several current densities the temperature in the windings are different due to the copper and iron losses. In Fig. 8 the temperature in end-windings and windings slot are showed. The difference of these temperatures is due to the natural convection in end-windings and the slot is very important to the heat conduction. However, the diameters of these generators were obtained to able the possibility of an effective heat transfer.

**B. TFPM Generator**

The weight of the TFPMG with the two types of windings is showed in
Fig. 9. For the generator with one section winding, the weight is much higher than the outer. Its implicit in this result than sectional windings in this kind of generators is much better. This will traduce in less copper, iron and magnets with the advantage in price.

These results have been made with same allowed temperatures but with different cooling systems. In fact both PM generators are optimized due a termal analisys. The RPFPMG is much heavy than TFPMG and is obsivus the best choice in terms of weight, price and costs do install. However TFPMG must have sectional windings in order to reduce the temperatures in windings maintaining the same dimensions.

VII. CONCLUSIONS

REFERENCES


