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Chapter 5

Design of a Low-Cost Permanent Synchronous Machine for Isolated Wind Conversion Systems

Florin-Nicolae Jurca

Additional information is available at the end of the chapter

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Abstract

The chapter deals with the theoretical analysis of two configurations of low-cost permanent synchronous generator (PMSG), suitable for small rating, direct driven applications, such as small- and microscale wind power plants. The first structure is a permanent magnet claw-pole synchronous generator (PMCP SG) to be used in an isolated microwind power plants with installed power around few hundred Watts. A permanent magnet synchronous machine with outer rotor (PMSMOR) is the second presented structure, suitable for small wind system with installed power between 2 and 5 kW. In order to obtain the optimal value of the main geometric dimensions of the generators, an optimization procedure, based on Hooke-Jeeves method, was implemented for all the considered structures.

Keywords: permanent synchronous machine, low-cost permanent magnet, small-scale wind power plants, direct-driven, optimization

1. Introduction

Wind turbines are widely used as a pollution-free and renewable source in order to supplement other electricity generators. Wind power technology has developed remarkably during the latest decade. Due to its flexibility, it can be used practically anywhere.

Small wind turbines have been used to generate electricity for rural farms or others remote buildings which do not have the possibility to connect to a main power supply. The increasing demand in recent years for clean and affordable energy will lead without doubt to a wider use of the small turbines for urban area.
The technology of the generator system in small wind turbine can be classified into direct drive and the geared technology concepts. The geared generator system has the advantages in terms of the cost, size, and weight. The direct-drive generator system is superior in terms of efficiency, reliability, and maintenance problem [1]. Because in direct drive generator technology it is necessary a high number of poles, accordingly with a big weight, the permanent synchronous machine (PMS) have the advantages of comparing to other machines of being robust in construction, very compact in size, not requiring an additional power supply for magnetic field excitation [2]. One problem of this generator is the cost, especially when the permanent magnet is neodymium, because in the last years its price is continuously increasing. The solution is to use low-cost permanent magnets, such as ferrites and alnico. These materials are reasonably easy to find [3]. Usually, the performances of electrical machines with low-cost permanent magnets are lower comparative with the same machines using neodymium magnet. In order to keep the generator with low-cost permanent magnet feasible, more attention is necessary in design and optimization procedure. So, the challenge for small- and microscale wind power plants is to find a solution to maintain the lower costs of systems (e.g., generator) in conditions of reliability and the high value of efficiency.

This is the motivation of this research work. For that, two configurations of low-cost PMSG suitable for direct drive in wind power applications will be studied from the theoretical point of view.
hundred Watts. A permanent magnet synchronous machine with outer rotor (PMSMOR) is the second presented structure (see Figure 2), suitable for small wind system with installed power between 2 and 5 kW. Hence in this chapter, an exhaustive approach will be presented by going through all the phases in the development cycle of special topologies of low-cost permanent magnet synchronous machine.

Figure 2. The PMSMOR topology.

2. Design and optimization of the studied electrical machines

2.1. Design of PMCPSG

The objective of the present subchapter was the design and optimization of a three-phase PMCPSG, driven by a small wind turbine with the following set of key parameter: $s_N = 180$ apparent power (VA); rated phase voltage $u_{N} = 100$ (V); rated speed $n_{N} = 750$ rpm; pole pair number $p = 4$; permanent magnet-type Alnico. In addition, several constraints must be met such as limited size, low weight, and low torque ripple content.

The analytical procedure includes the following topics: analysis of the specifications, selection of the topology and of the active and passive materials, dimensioning of the geometry, parameter and performance calculation, choice of the manufacturing technologies, and cost prediction.

For the given output power and operating speed, the PMCPSG main dimensions may be determined using the output power equation, based on specific magnetic and electric loads [4]. The inner stator diameter results as follows:
with \( D_n \) — the stator inner diameter; \( C \) — machine constant; and \( \lambda \) — geometrical form factor. For PMGPSG, the machine constant could be written as:

\[
C = \frac{\pi^3}{2\sqrt{2}} \cdot k_w \cdot \alpha_i \cdot A \cdot B_g
\]

with \( A \) — electrical load (between 30 and 80 kA/m for indirect air cooling); \( B_g \) — magnetic load (0.4…0.8 T for machines using Alnico); \( k_w \) — winding factor; and \( \alpha_i \) — pole pitch coverage coefficient [the ratio between the rotor pole width (\( b_{pr} \)) and the rotor pole pitch(\( \tau_r \))] [4]. As a starting point, due to the special configuration of the rotor, the values for \( k_w \) (0.92… 0.966) and \( \alpha_i \) (0.6…0.9) were chosen according to [4, 5] for a permanent magnet synchronous machine with rotor salient poles and single-layer fractional windings (see Figure 3).

![Figure 3. Stator winding of PMGPSG.](image)

The lamination stack length results as follows:

\[
l_{fe} = \lambda \cdot D_n
\]

Computation of the rotor outer diameter gives:

\[
D_r = D_n - 2 \cdot g
\]

with \( g \) — air-gap length.

Due to fault tolerance consideration and the fractional number of slots per pole and phase (\( q = 1.5 \)), a single-layer fractional winding was chosen. The rms value of the phase electromotive force (emf) is given by [6]:

\[
D_n = \frac{60 \cdot S_N}{C \cdot n_N \cdot \lambda}
\]
with \(w_1\) — number of turns per phase, \(p\) — number of pole pairs, and \(B_{g\,av}\) — average magnetic load.

Starting from the geometric dimensions of the stator and the electrical parameters of the generator, we will obtain from the winding design algorithm, the winding connection diagram (see Figure 3), the number of turns per phase \(W_1\), the area of the wire cross section \(S_c\), the number of turns per slot \(n_c\), and the number of parallel current paths \(a\) \[4\].

![Figure 4. Stator slot geometry.](http://dx.doi.org/10.5772/62817)

For the stator slot a trapezoidal cross section was chosen (see Figure 4). Its dimensions are derived from the slot area:

\[
A_{\text{slot}} = \frac{n_c \cdot S_c}{k_{\text{fill}}} = b_0 \cdot h_0 + \frac{b_1 + b_2}{2} \cdot h_1 + \frac{b_3}{2} \cdot h_2
\]

with \(k_{\text{fill}} = 0.36…0.55\) and \(b_w\) — the stator tooth width:

\[
b_w = \frac{\pi \cdot D_A \cdot B_{g\,av}}{Q_L \cdot B_{g\,av}}
\]
with $B_{ts\_av}$ — average flux density in stator tooth, usually between 0.8 and 1.2 T according to [5, 7]. Finally, choosing the values for the slot opening, tooth tip height, fixing wedge height [4], the stator slot, and tooth dimensions can be computed. The width of the stator yoke results as follows [6]:

$$b_{ys} = \frac{\pi \cdot D_{a} \cdot B_{ys\_av}}{2 \cdot p \cdot B_{ts\_av}}$$  \hspace{1cm} (8)

with $B_{ys\_av}$ — average flux density in stator yoke, usually between 0.6 and 1 T according to [5, 7]. Thus, the outer stator diameter results as follows:

$$D_{o} = D_{a} + 2 \cdot (h_{ts} + h_{ys})$$  \hspace{1cm} (9)

with $h_{ts}$ — the stator tooth height and $h_{ys}$ — the stator yoke height.

The rotor steel plate carrying 4 claw poles and its dimensions to be computed are shown in Figure 5.

![Figure 5. Rotor geometry: (a) claw-pole structure, (b) permanent magnet.](image)

For reducing the leakage flux between two claw poles, the rotor claw-pole width value is given by:

$$b_{pr} = (0.6 \ldots 0.8) \cdot r_{r}$$  \hspace{1cm} (10)

The height of the rotor pole tip:
\[ h_{p_2} = (2...4) \cdot g \]  

(11)

The length of the rotor pole should be smaller than the rotor length:

\[ l_p = (0.85...0.95) \cdot l_{Fe} \]  

(12)

As the permanent magnet will be accommodated between the two steel plates, its length can be computed as:

\[ l_m = l_{Fe} - 2 \cdot b_{wedge} \]  

(13)

with \( b_{wedge} = 3.5 \text{ mm} \).

Considering the average value of the magnetic field density in the air-gap, the average value of the magnetic field density in different parts of the machine (\( B_x \)) is calculated as [6]:

\[ B_{x_{av}} = \frac{k_x \cdot \pi \cdot D_s \cdot l_{Fe} \cdot B_{x_{av}}}{2 \cdot p \cdot A_x} \]  

(14)

with \( A_x \) the average area of the cross section of the x part of the machine (stator teeth and yoke, rotor claw poles, rotor steel plates, etc) and \( k_x \) a coefficient giving the percent of the air-gap magnetic field that is crossing the x part of the machine [8].

2.1.1. Steady-state parameters and losses computation of PMCPG

The d-q model of the generator is characterized by the synchronous reactance defined on direct and quadrature axis, \( X_d \) and \( X_q \) respectively. The d-q reactance’s are given as:

\[ X_d = \omega_1 \cdot L_d = \omega_1 \cdot (L_{md} + L_{me}) \]

\[ X_q = \omega_1 \cdot L_q = \omega_1 \cdot (L_{mq} + L_{me}) \]  

(15)

with \( \omega_1 \) the rotor electrical speed, \( L_d \) and \( L_q \) the direct and quadrature axis corresponding synchronous inductances [8], given as the sum between the corresponding magnetizing inductances, \( L_{md} \) and \( L_{mq} \) and the stator leakage inductance, \( L_{me} \). Simplified formulae for the magnetizing inductances were derived as [8]:
The magnetizing inductance of the three-phase PMCPSP was computed [4]:

\[ L_m = \frac{3 \cdot D_o}{\pi \cdot p \cdot g_{ef}} \cdot \mu_0 \cdot l_c \cdot (k_d \cdot W_1)^2 \]  

where \( g_{ef} \) is the effective air-gap, including the Carter factor [4]. The Carter factor was calculated considering both the stator and rotor Carter factors [9]. The expressions for the coefficients in [Eq. (16)] correspond to the ones presented in [10].

Stator leakage inductance was calculated for the stator slot geometry shown in Figure 3 as the sum of four main components [4]: air-gap leakage inductance, slot leakage inductance, tooth tip leakage inductance, and end-winding leakage inductance. The phase resistance can be computed with the formula [4, 11].

\[ R_s = \frac{W_1 \cdot l_c}{\sigma \cdot a \cdot S_y} \]  

Next, the losses and efficiency can be determined. The main losses of the PMCPSP [8] are as follows:

\[ P_{\text{inside}} = P_{\text{hyst}} + P_{\text{eddy currents}} + P_{\text{mech}} \]  

where \( P_{\text{mech}} \) are mechanical losses (can be approximated at 1%, as a starting point). Iron losses are the sum of hysteresis (\( P_{\text{hyst}} \)) and eddy current (\( P_{\text{eddy currents}} \)) for stator and rotor cores and the claw-pole surface (\( P_{\text{scwp}} \)) losses. The losses can be computed considering the general expression [4]:

\[ P_{\text{hyst/eddy currents}} = C_{\text{mat}} \cdot f^{0.5} \cdot B^{2.0} \cdot G \]  

\[ P_{\text{mech}} = 2 \cdot p \cdot S_{\text{exp}} \cdot k_p \cdot f^{1.5} \cdot B_{g_{\text{av}}}^{2.0} \]  

\[ P_{\text{scwp}} \]
where $a_f$ and $a_B$—material empirical constants than can be determinate from curve-fitting the losses for a wide range of “f” (frequency) and B values; $k_{cp}$—a factor dependent on the claw-pole material and machine Carter factor; and $G$—the weight of the considered part of the machine [6].

Thus, the efficiency of the machine can be written as:

$$\eta = \frac{P_N}{P_N + P_{loss}}$$  \hspace{1cm} (21)

with $P_N = S_N \cdot \cos \phi$.

After, the designing process, the following results have been obtained, see Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PMCPSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power (W)</td>
<td>150</td>
</tr>
<tr>
<td>Rated speed (rpm)</td>
<td>750</td>
</tr>
<tr>
<td>Phase voltage (V)</td>
<td>50</td>
</tr>
<tr>
<td>Number of phases ((\cdot))</td>
<td>3</td>
</tr>
<tr>
<td>Number of pole pairs ((\cdot))</td>
<td>4</td>
</tr>
<tr>
<td>Number of slots</td>
<td>36</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>145</td>
</tr>
<tr>
<td>Stator inner diameter (mm)</td>
<td>95</td>
</tr>
<tr>
<td>Rotor pole width (mm)</td>
<td>29</td>
</tr>
<tr>
<td>Rotor pole length (mm)</td>
<td>105</td>
</tr>
<tr>
<td>Rotor pole base height (mm)</td>
<td>15</td>
</tr>
<tr>
<td>Steel plate radius (mm)</td>
<td>31</td>
</tr>
<tr>
<td>Rotor pole tip height (mm)</td>
<td>21</td>
</tr>
<tr>
<td>Permanent magnet diameter (mm)</td>
<td>60</td>
</tr>
<tr>
<td>Residual flux density—Alnico 8 (T)</td>
<td>0.9</td>
</tr>
<tr>
<td>Coercive force—Alnico 8 (kA/m) [11]</td>
<td>115</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>1</td>
</tr>
<tr>
<td>Losses (W)</td>
<td>81</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 1. Obtained results for the designed PMCPSG.
2.2. Design of PMSMOR

The dimensioning procedure was applied for the following set of key parameters: \( P_{\text{out}} = 3 \text{ kW} \) (estimated); rated phase voltage \( u_N = 220 \text{ (V)} \); rated speed \( n_N = 500 \text{ rpm} \); pole pair number \( p = 10 \).

By neglecting the leakage reactance and for a certain number of phases \( m \), phase current \( i(t) \), and induced emf \( e(t) \), we obtain the output power of an electrical machine [13]:

\[
P_{\text{out}} = \eta \cdot \frac{m}{I} \int_0^T e(t) \cdot i(t) \, dt = \eta \cdot m \cdot k_p \cdot E_{\text{max}} \cdot I_{\text{max}}
\]

where \( T \) is the period of one cycle of emf, \( E_{\text{max}} \) is the peak value of the emf, \( I_{\text{max}} \) is peak value of the phase current, \( k_p \) is the power coefficient, and \( \eta \) is the estimated efficiency. The peak value of the emf is expressed by introducing the electromotive force coefficient, \( k_E \)[13]:

\[
E_{\text{max}} = k_E \cdot W_i \cdot B_g \cdot D_g \cdot I_{\text{rms}} \cdot \frac{f}{p}
\]

with \( D_g \) - air-gap diameter.

By introducing a geometric coefficient, \( k_L = L_m/D_g \) and a current coefficient (related to its wave form) \( k_i = I_{\text{max}}/I_{\text{rms}} \) and defining the phase load ampere-turns:

\[
A = \frac{2}{\pi} \cdot W_i \cdot \frac{I_{\text{rms}}}{D_g}
\]

it is possible to define the air-gap diameter of the machine [13]:

\[
D_g = \frac{2 \cdot p \cdot P_{\text{out}}}{\sqrt{\pi \cdot m \cdot A \cdot k_E \cdot k_L \cdot k_i \cdot \eta \cdot B_g \cdot f}}
\]

The height of the permanent magnet results as follows:

\[
h_m = \frac{\pi \cdot D_g \cdot B_g}{2 \cdot p \cdot B_{\text{in}}}
\]
with $B_m = 0.405\ T$ (for permanent magnet type: ferrite) and interior diameter of rotor: $D_r = D_g + g$.

Using Eq. (16), the dimensions of different parts of the rotor (permanent magnet width, rotor pole width, air barrier width) are calculated (see Figures 6, 7). All the other stator geometric parameters will be computed based on air-gap diameter, as for conventional synchronous machine. Thus, the performances of the generator will be determined with conventional equations [4]. All results after the designing process and the performances obtained are presented in Table 2.
Table 2. Obtained results for the designed PMSMOR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PMSMOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power (W)</td>
<td>3000</td>
</tr>
<tr>
<td>Rated speed (rpm)</td>
<td>500</td>
</tr>
<tr>
<td>Phase voltage (V)</td>
<td>220</td>
</tr>
<tr>
<td>Number of phases (•)</td>
<td>3</td>
</tr>
<tr>
<td>Number of pole pairs (•)</td>
<td>10</td>
</tr>
<tr>
<td>Number of slots</td>
<td>39</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>248</td>
</tr>
<tr>
<td>Stator inner diameter (mm)</td>
<td>202</td>
</tr>
<tr>
<td>Rotor outer diameter (mm)</td>
<td>290</td>
</tr>
<tr>
<td>Rotor pole height (mm)</td>
<td>21</td>
</tr>
<tr>
<td>Rotor pole base width (mm)</td>
<td>5.2</td>
</tr>
<tr>
<td>Rotor pole top width (mm)</td>
<td>10.5</td>
</tr>
<tr>
<td>Permanent magnet base width (mm)</td>
<td>18</td>
</tr>
<tr>
<td>Permanent magnet top width (mm)</td>
<td>13</td>
</tr>
<tr>
<td>Residual flux density—Ferrite Y30BH (T)</td>
<td>0.405</td>
</tr>
<tr>
<td>Coercive force—Ferrite Y30BH (kA/m) [12]</td>
<td>230</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>5</td>
</tr>
<tr>
<td>Losses (W)</td>
<td>500</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>86</td>
</tr>
</tbody>
</table>

2.3. Optimization of PMCP SG and PMSMOR

The influence of different geometrical dimensions on the PMCP SG and PMSMOR performances can be done by using 3D and 2D, respectively. Despite the fact that the results provided by finite element method (FEA) are accurate and can be very useful in for the optimization of the main geometric dimensions, this approach is highly time-consuming [6]. Hence, in order to reduce the time cycle and the number of iterations, a better solution is to use an optimization based on an analytical algorithm. Due to technological and cost constraints, two available stator laminations with the geometry given in Figures 3 and 4, respectively, and the dimensions given in Tables 1 and 2, respectively, were chosen.

The optimization of electric machine is a multivariable, nonlinear problem with constraints. To treat problems with constraints is necessary to transform them in unconstrained ones. This can be done, for example, by embedding the constraints in the objective function [6]. The so-called direct search optimization methods fulfill these requirements. Hooke-Jeeves, one direct search method, was selected for the optimization of the presented generators [6, 14]. The main steps in the optimization algorithm are as follows (see Figure 8): the choice of the optimization
variables, input of the constraints, the definition of the objective function, objective function calculation, the computation of the main parameters (geometrical and electromagnetic), and the visualization of the obtained result.

For the studied machine, a set of 4 variables ($x_i, i = 1 \ldots 4$) for each structure were selected (see Table 3). In order to keep the topology, functional limits are set for each variable and specific constraints are set, together with a penalty coefficient for including in the objective function.

The following constraints were considered:

a. The output power has to be greater or equal to the design specified value.

b. The air-gap magnetic flux density has to be closed to the specified value.

c. The stator teeth magnetic flux density has to be closed to the specified value.

d. The stator lamination geometry remains unchanged.

![Optimization algorithm](http://dx.doi.org/10.5772/62817)

Figure 8. Optimization algorithm.
### Table 3. Optimization variables: initial values and boundaries.

<table>
<thead>
<tr>
<th>PMSMOR parameters</th>
<th>Initial value</th>
<th>Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor pole width ( b_{rp} ) (mm)</td>
<td>29</td>
<td>[25......35]</td>
</tr>
<tr>
<td>Rotor pole length ( l_{pr} ) (mm)</td>
<td>105</td>
<td>[55......110]</td>
</tr>
<tr>
<td>Rotor pole base height ( h_{sp} ) (mm)</td>
<td>15</td>
<td>[10......20]</td>
</tr>
<tr>
<td>Rotor pole to height ( h_{p2} ) (mm)</td>
<td>2.5</td>
<td>[1......3.5]</td>
</tr>
<tr>
<td>PM base width ( b_{rp1} ) (mm)</td>
<td>18</td>
<td>[14......22]</td>
</tr>
<tr>
<td>PM top width ( b_{rp2} ) (mm)</td>
<td>13</td>
<td>[10......16]</td>
</tr>
<tr>
<td>Height of the PM on magnetization direction ( h_{m} ) (mm)</td>
<td>21</td>
<td>[18......23]</td>
</tr>
<tr>
<td>Rotor barrier width ( b_{air} ) (mm)</td>
<td>6</td>
<td>[5......8]</td>
</tr>
</tbody>
</table>

**Figure 9.** Optimization results of PMCPG: efficiency and losses.

For the generators dedicated to microwind and small wind conversion systems, some optimization issues (objective functions) are important: low-cost, maximum generated voltage, and maximum efficiency. The maximum efficiency \( f_1(x_1) \) for the maximum generated voltage \( f_2(x_2) \) was selected as multi-objective optimization function. The chosen multi-objective function is mathematically expressed as [6]:

\[
f(x) = w_1 f_1(x_1) + w_2 f_2(x_2)
\]

where \( w_1 \) and \( w_2 \) are the weights assigned to each objective function.
The iterative process has reached its optimum after 60 steps, the simulation time being 1.26 s. The efficiency and the losses have been plotted in Figure 9, while the evolution of the geometric parameters of PMCP SG has been plotted in Figure 10. It can be seen that some parameters presented a low variation, but the length of claw pole presented a high variation around a mean value.

It is obvious that if the geometrical parameters will decrease, the iron losses will decrease too. This is the normal behavior; thus, the efficiency of the generator will increase. For the PMCP SG, the efficiency of the machine will increase with 8%.

$$f(x_i) = w_1 \cdot f_1(x_i) + w_2 \cdot f_2(x_i)$$  \hspace{1cm} (27)

In Figure 11, the evolution of efficiency and losses of PMSMOR during the optimization process have been plotted. For this machine, the efficiency increase with decrease of losses due
Figure 11. Optimization results of PMSMOR: efficiency and losses.

to changes of geometrical parameters is shown in Figure 12. Here, only the permanent magnet dimensions and rotor flux barrier width are presented as a sample. It can be seen that the value of geometrical parameters of permanent magnet is reduced, consequently barrier rotor width increased. The efficiency of the machine has globally increased with 3%.

Figure 12. Optimization results of PMSMOR: evolution of geometrical parameters.
### PMCP SG parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial value</th>
<th>Final value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor pole width $b_{rp}$ (mm)</td>
<td>29</td>
<td>27</td>
</tr>
<tr>
<td>Rotor pole length $l_{rp}$ (mm)</td>
<td>105</td>
<td>60</td>
</tr>
<tr>
<td>Rotor pole base height $h_{sp}$ (mm)</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Rotor pole to height $h_{p2}$ (mm)</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>Losses (W)</td>
<td>60</td>
<td>38</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>0.695</td>
<td>0.78</td>
</tr>
</tbody>
</table>

### PMSMOR parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial value</th>
<th>Final value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM base width $b_{rp1}$ (mm)</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>PM top width $b_{rp2}$ (mm)</td>
<td>13</td>
<td>12.5</td>
</tr>
<tr>
<td>Height of the PM on magnetization direction $h_m$ (mm)</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Rotor barrier width $b_{air}$ (mm)</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Rotor outer diameter (mm)</td>
<td>290</td>
<td>288</td>
</tr>
<tr>
<td>Losses (W)</td>
<td>502</td>
<td>384</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>85.8</td>
<td>89.1</td>
</tr>
</tbody>
</table>

**Table 4.** Main optimization results, at rated operating point, for both considered topologies.

The resume of the optimized results of the PMCP SG and PMSMOR are given in **Table 4**.

### 3. Magnetic field analysis of the studied electrical machines

The magnetic flux density distribution in the electrical machines’ core is very important because this affects the voltage waveform, the iron losses, and the efficiency. The finite element method (FEM) is a simple, robust, and efficiently widely used method of obtaining a numerical approximate solution for a given mathematical model of the machine [6]. This analysis has been carried out by using Flux software (2D for PMSMOR and 3D for PMCP SG).

#### 3.1. Magnetic field analysis of PMCP SG

Due to the complex three-dimensional structure of claw pole, the magnetic field inside the claw-pole generator needs to be treated as a 3D problem, using 3D module of Flux software [14]. In the case of 3D simulations, high memory resource of computer is necessary. However, they are much time-consuming. In order to reduce this, considering the symmetry of the machine structure, the analysis will be carried out for one pole pair. In the first steps of the analysis, the geometry of the structure was introduced and the mesh was generated. Next, if the previous steps are correct, the solution will be generated. After that, in post-processing stage, the data about magnetic behavior (map of flux density in the stator and rotor core, air-gap flux density distribution) and other performances (induced emfs, cogg ing torque, etc) of the generators will be computed [6].
The no-load regime for the rated speed was simulated, in order to present the maps of the magnetic flux density in the stator and rotor core (Figure 13).

It has been observed that in Figure 13, the value of magnetic flux density is very close to the saturation level of the considered steel, especially at the base of the claw pole, where the direction of the flux density is changing. Since due to its complex three-dimensional structure, the rotor claws are usually press-formed out of solid metal or pressed in a die of iron powder [14], magnetic flux density distribution along the radial and axial length of the air-gap obtained in load condition are very useful in order to develop an optimum design in terms of low eddy current losses (Figures 14, 15).
Figure 15. Magnetic field distribution along the axial air-gap.

The wave depicted in Figure 14 shows maximum values when the air-gap is minimum and minimum values when the air-gap is maximum. As it can be noted that the flux density under each rotor pole has the same value, the peaks corresponding to the four stator teeth overlapped with one rotor pole.

The obtained voltage and axis torque in load condition are shown in Figures 16 and 17, respectively. It can be observed that the waveform of voltage is slightly deformed due to the shape of the claw poles. In this case, a further optimization of the shape of the claw poles can be achieved, but this involves a supplementary cost in manufacturing. For the structure of PMCP SG presented in this chapter, a supplementary optimization of the shape of the claw poles is not necessary in the context of the considered application (isolated microwind power plants with installed power around few hundred Watts).

Figure 16. Computed voltage (rms value) in load condition.
The axis torque is obtained based on rated current (1 A). Also, the torque ripple is 15.7%. In this context, no strategy to reduce the torque ripple was adopted.

Figure 17. Axis torque in generator regime.

3.2. Magnetic field analysis of PMSMOR

Due to configuration of PMSMOR, the numerical computation has been carried out by using Flux 2D. In order to obtain the map of magnetic flux density distribution in the stator and rotor core and its distribution in air-gap the FEM analysis, in no-load condition, this generator regime is employed at rated speed (500 min\(^{-1}\)).

Figure 18. Magnetic field distribution in the air-gap.
Figure 19. Flux density and field lines for studied PMSMOR.

The saturation level can be shown in Figure 19. It can be observed that the maximum value is almost 1.3 T in stator teeth. Because this value is below the maximum saturation level, more optimization can be performed in order to reduce the stator and rotor core.

In the next step of the simulation, the generator has been tested in load condition at rated power (3 kW) and speed.

Figure 20. Computed voltage (rms value) at rated power.
The generated phase voltage and obtained phase current using resistive load have been plotted in Figures 20 and 21, respectively. The average values of voltage and current are 223 V and 5.12 A, respectively, very close to the ones obtained from the analytical approach. The rated torque depicted in Figure 22 is obtained for the rated current. Also, thanks to the proper winding–slots–poles combinations, the torque ripples are significantly reduced. In fact, the ratio of torque ripple is 6.6% (maximum at 52.5 Nm and minimum at 49.1 Nm).

3.3. Generators steady-state performances

In order to obtain the complete evaluation of performances of considered generators, an analysis in load condition was carried out for three different driven speeds for each generator.
3.3.1. Steady-state performances of PMCPSG

The simulation of PMCSPG has been performed for three different speeds: 500, 750, and 1000 rpm. The efficiency, the generated voltage, and the electric power have been computed, but the additional losses were neglected.

![Figure 23. Steady-state performance of PMCPSG: phase voltage and output power.](image)

![Figure 24. Steady-state performance of PMCPSG.](image)

Figures 23 and 24, respectively, show the steady-state performance (terminal voltage, output power, and efficiency) of the PMCPSG supplying a resistive load. The voltage–current characteristics are approximately linear from no load to rated load. Due to the rather high armature impedance, the voltage drop difference between no load and rated load is of 57% at
750 rpm. As it can be noted, for low speeds, the maximum efficiency occurs at rather low values of load current. For higher speeds, the load current for which the maximum efficiency is obtained is increasing.

### 3.3.2. Steady-state performances of PMSMOR

The simulation of PMSMOR has been performed for three different speeds: 250, 500, and 750 rpm.

The voltage–current characteristics of PMSMOR are depicted in Figure 25. Also, the voltage drop difference between no load and rated load at 500 rpm is of 42%. The efficiency of the

**Figure 25.** Performance of PMSMOR: phase voltage.

**Figure 26.** Performance of PMSMOR: output power and efficiency.
generator can be shown in Figure 26. It can be observed that the maximum value is 0.92 for 3.62 A and 1000 rpm.

4. Conclusions

This chapter presents the main steps to be followed in the design of a low-cost permanent magnet synchronous machine suitable for small rating, direct driven applications, such as small- and microscale wind power plants. The analytical approach contains the major elements which need to be discussed. Detailed equations are presented for the calculation of geometrical parameters corresponding to the chosen special topologies of the rotor (claw pole and outer rotor). Also, the output performances (generated voltages, efficiency, losses) of the generators were computed. After preliminary design of the generators, the optimization procedure was performed using Hooke-Jeeves algorithm, in order to obtain the final topologies of the rotor in condition of maximum: efficiency, terminal voltage, and optimum weight.

The static performance of the machine, phase voltage, output power, and efficiency at different values of speed in order to obtain more detailed information, was studied through numerical analysis using Flux 3D for PMCSFG and 2D for PMSMOR.

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