Design of a six-phase asymmetrical permanent magnet synchronous generator for wind energy applications

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Abstract: The electromagnetic design of a six-phase permanent magnet synchronous generator (PMSG) for application in medium/high-speed wind energy conversion systems (WECS) is studied in this work. The dynamic model and the analytical design process of the six-phase PMSG are presented and some design aspects, such as the winding configuration and the geometry of the permanent magnets are discussed in order to improve the performance of the generator in both healthy and fault-tolerant conditions, i.e. when only one set of three-phase windings is connected to the grid. Finally, several simulation results obtained through finite element analysis are presented in order to validate the proposed design.

1 Introduction

The permanent magnet synchronous generator (PMSG) combined with full-scale power converters is increasingly being used to equip multi-megawatt wind energy conversion systems (WECS) [1]. Although the use of a very low-speed PMSG enables the elimination of the gearbox in WECS, the large number of poles of such a generator increases its size, weight and cost [2]. Hence, an intermediate solution combining a simpler gearbox with a medium-speed generator is expected to be the future trend in PMSG-based WECS [3].

The growth in size and rated power of WECS has led manufacturers to commercialise wind turbines (WTs) based on multiphase generators, i.e. with a number of phases m higher than three [4]. In comparison to three-phase counterparts, multiphase generators not only reduce current ratings per phase but also improve the fault-tolerant capability of WECS, which is an important feature for remote offshore applications [5]. In order to take advantage of the existing power converter technology for three-phase systems, the WT industry adopted the use of generators with multiple sets (k) of three-phase windings (m = 3k), electrically isolated, where each set is connected to the grid by means of a back-to-back converter [6]. In the event of a fault, in either the converter or the generator, the simplest and usual procedure is to disable the affected three-phase winding set and continue to operate the WT with a reduced power rating [7].

Nowadays, the six-phase PMSG, with two sets of three-phase windings, is one of the most used topologies in multi-MW WECS [8]. The two sets of windings can be displaced apart by either 30° or 60° electrical degrees and are usually classified in the literature as asymmetrical or symmetrical six-phase windings, respectively [9]. The asymmetrical configuration provides some advantages over the symmetrical counterpart, such as the elimination of torque harmonics of order h = 6n, with n being an odd number, and the minimisation of rotor losses, as a consequence of the reduction of the harmonic content of the stator magnetomotive force (MMF) [10].

In this paper, the electromagnetic design of a 4 kW six-phase asymmetrical PMSG with distributed windings is studied. The main purpose of the designed prototype is to implement a medium/high-speed WECS in a laboratory environment. Firstly, the dynamic model of the six-phase asymmetrical PMSG is presented in both abc and dq reference frames and the relation between the inductance parameters in both frames is derived. Then, the electromagnetic analytical design process is presented and some design aspects regarding the stator winding configuration and the geometry of the permanent magnets (PMs) are discussed and analysed in order to improve the performance of the six-phase PMSG in both healthy and faulty operating conditions. Finally, the designed prototype is validated by finite element analysis (FEA).

2 Dynamic model of the six-phase PMSG

Assuming that the airgap flux distribution is sinusoidal, the magnetic saturation is negligible and the symmetry between the different phases, the dynamic model of a six-phase PMSG with surface-mounted permanent magnets (PMs) is given by

\[
\begin{align*}
\frac{d}{dt} \mathbf{u}_{abc} &= \mathbf{R}_s \cdot \mathbf{i}_{abc} + \frac{d}{dt} \mathbf{\psi}_{abc} \\
\frac{d}{dt} \mathbf{\psi}_{abc} &= \mathbf{L}_s \cdot \mathbf{i}_{abc} + \mathbf{\psi}_{PM}
\end{align*}
\]

where \( \mathbf{R}_s \) is the stator resistance matrix in diagonal format, \( \mathbf{R}_s = \mathbf{R}_s \cdot \mathbf{I}_s \), variables \( \mathbf{u}_{abc}, \mathbf{i}_{abc}, \mathbf{\psi}_{abc}, \mathbf{\psi}_{PM} \) correspond to the stator voltage, current, flux linkage and no-load flux linkage created by the permanent magnets (PMs), respectively, written in the vector format \( \mathbf{f}^{abc} = [i_{a1} i_{b1} i_{c1} i_{a2} i_{b2} i_{c2}]' \). Finally, the inductance matrix \( \mathbf{L}_s^{abc} \) is defined as

\[
\begin{align*}
\mathbf{L}_s^{abc} &= \begin{bmatrix} L_s & M_{sa} & M_{sb} \\ M_{sa}^T & M_{s} & M_{sb} \\ M_{sa} & M_{sb} & L_s \\
\end{bmatrix} \\
\mathbf{L}_s &= \begin{bmatrix} L_s & M_{sa} & M_{sb} \\ M_{sa}^T & L_s & M_{sb} \\ M_{sa} & M_{sb} & L_s \\
\end{bmatrix} \\
&= \begin{bmatrix} M_1 & M_2 & M_3 \\ M_3 & M_1 & M_2 \\ M_2 & M_3 & M_1 \\
\end{bmatrix}
\end{align*}
\]

where \( L_s \) is the phase self-inductance, \( M_{sa} \) is the mutual inductance between phases within the same set of windings and \( \{M_1, M_2, M_3\} \) are the mutual inductances between phases of different sets of windings. The phase self-inductance is defined as

\[
L_s = L_{sh} + L_{slm} + L_{sw}
\]

where \( L_{sh} \) is the leakage inductance, \( L_{slm} \) is the mutual leakage inductance and \( L_{sw} \) is the magnetising inductance. The mutual inductances depend on the angular displacement between the different phases and are defined by...
\[ M_s = \cos\left(\frac{2\pi}{3}\right) \cdot L_{in} \]
\[ M_i = \cos\left[\frac{\pi}{6} + (i-1) \frac{2\pi}{3}\right] \cdot \left(\frac{2}{3} L_{dm} + L_m\right). \quad (4) \]

The vector space decomposition (VSD) transformation is capable of separating the variables responsible for the production of flux and torque from the remaining ones [9]. The amplitude invariant form of the VSD transformation for six-phase asymmetrical machines is defined as follows:

\[ T_s = \frac{1}{3} \begin{bmatrix} 1 & -1 & -1 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 & 1 & 1 & -1 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (5) \]

By using the rotation matrix

\[ T_{rot} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 & 0 & 0 & 0 \\ -\sin(\theta) & \cos(\theta) & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \]

in conjunction with (5) the variables in the natural reference frame can be mapped into the \( d-q \) rotor reference frame.

The VSD model of the asymmetrical six-phase PMSG, in a rotor reference frame is then given by

\[ u_{sq} = R_{sq} i_{sq} + L_{sq} \frac{di_{sq}}{dt} + \omega_0 L_{pm} i_{pm} + \alpha_0 J_{pq} \psi_{pmq}^q + a_0 J_{pmq}^q \]

(7)

where \( L_{pq} \) is the inductance matrix, \( \omega_0 \) is the rotor angular frequency and variables \( \psi_{pm}^q \) and \( \psi_{pmq}^q \) correspond to the stator voltage, current and no-load flux linkage, respectively, and are expressed in the vector format \( f^q = [f_d, f_q, f_s, f_z, f_s, f_z]^T \). The matrix \( J_{pq} \) is defined as

\[ J_{pq} = \begin{bmatrix} J & 0_{6 \times 3} \\ 0_{3 \times 6} & 0_{3 \times 3} \end{bmatrix}. \]

Finally, the inductance matrix \( L_{pq} \) is defined as follows:

\[ L_{pq} = \begin{bmatrix} L_{dq} & 0 & 0 & 0 & 0 \\ 0 & L_{dq} & 0 & 0 & 0 \\ 0 & 0 & L_{sv} & 0 & 0 \\ 0 & 0 & 0 & L_{sv} & 0 \\ 0 & 0 & 0 & 0 & L_{sz} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \]

(9)

It can be demonstrated that only the fundamental component and the harmonics of the current of order \( h = 12n \pm 1, n = \{1, 2, 3, \ldots\} \), which are mapped into the \( d-q \) subspace, contribute to the flux and torque production. On contrary, the current harmonics of the order \( h = 6n \pm 1, n = \{1, 3, 5, \ldots\} \), are mapped in the \( x-y \) subspace and contribute to neither the flux nor torque production, when assuming a sinusoidal airgap flux distribution [9].

### 3 Analytical design of the six-phase PMSG

#### 3.1 Main parameters

The design process is initiated with the selection of the main parameters of the PMSG [11], which are presented in Table 1.

#### 3.2 Stator windings

Since the required prototype has a high rated speed, a distributed winding is chosen instead of a concentrated winding configuration. In order to obtain a number of slots per phase per pole \( q > 1 \) with \( q \in \mathbb{N} \), a number of stator slots \( Q_s = 48 \) is selected.

Considering that the resultant MMF wave for each set of three-phase windings is defined by

\[ \Phi_r(\theta_s, t) = \sum_{i=0, \text{odd}}^{\infty} \Phi_{s,i} \sin(\theta_s - \frac{2\pi}{3} i) \cos(\omega_0 t - \frac{2\pi}{3} i) \]

\[ \Phi_r(\theta_s, t) = \sum_{i=0, \text{odd}}^{\infty} \Phi_{s,i} \sin(h(\theta_s - \frac{2\pi}{3} i) - \alpha_0 t) \cos(\omega_0 t - \frac{2\pi}{3} i - \alpha) \]

(10)

where \( \Phi_{s,i} \) is the \( h \)-order harmonic of the MMF, \( \theta_s \) is the electrical angular position along the stator inner periphery, \( \omega_0 \) is the stator angular frequency and \( \alpha \) is the angular displacement between both sets of windings. The resultant MMF wave of the two sets of windings becomes

\[ \Phi_r = \sum_{h=-\infty}^{\infty} \Phi_{s,i} \{\sin((6h + 1)\theta_s - \alpha_0 t) + \sin((6h + 1)\theta_s - \alpha) \}

(11)

From (11) it is possible to observe that when \( \alpha = \pi/6 \) rad (asymmetrical configuration), the MMF harmonics of order \( 6n \pm 1 \) \( (n = 1, 3, 5, \ldots) \) are cancelled and do not contribute to either flux or torque production. In opposition, if \( \alpha = \pi/3 \) rad (symmetrical configuration) the harmonic content of the MMF remains the same as in a three-phase machine.

The prototype is also designed with the objective to operate with good performance in fault-tolerant mode, i.e. when only one set of windings is connected to the grid. In this case, the PMSG operates as a three-phase generator and is subjected to the sixth harmonic of the torque caused by the MMF harmonics of order 5 and 7. A double-layer winding along a coil pitch of 5π/6 is then selected to minimise this problem [11]. The parameters of the designed winding are given in Table 2.

| Parameter Value Parameter Value |
|---------------------------------|
| Parameter Value Value |
|-------------------------|-----------------------|
| rated power \( P_r \) | 4 (kW) efficiency \( \eta \) 95 (%) |
| rated speed \( n \) | 1500 (rpm) phases \( m \) 6 |
| rated torque \( T_n \) | 26.8 (N.m) pole pairs \( p \) 2 |
| rated voltage \( U_r \) | 340 (V) IEC frame size 132M |
| tang. force \( c_f \) | 21 (kPa) — — |

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3.3 Permanent magnets

According to [11], the time harmonics of the electromotive force (EMF) in a phase of the stator windings can be related to the spatial harmonics of the airgap flux density created by the PMs by

$$\dot{E}_{ph,k} = \frac{2}{\alpha} n_{t} B_{ph} r_{id} N_{k} B_{h}(r_{id})$$

where $N_{k}$ is the number of turns series-connected per phase, $l$ is the rotor axial length and the variables $B_{ph}$, $r_{id}$ and $k_{h}$ are the $h$-harmonic component of the no-load flux density in the airgap, pole pitch and winding factor, respectively.

Since, in six-phase machines, the currents in the $x$–$y$ subspace are only limited by $R_{t}$ and $\lambda_{x} = \sigma_{i} L_{sh}$, the EMF harmonics of order $h = 6n \pm 1$ with $n = \{1, 3, 5, \ldots\}$ need to be minimised in order to avoid the circulation of large currents in this subspace. The dependence on $B_{ph}$, normalised by $B_{ph}$, as a function of the PM span ratio [12] is shown in Fig. 1. A ratio of $5/6 - 0.83(3)$ is then selected to minimise the fifth and seventh harmonics in both the flux density and EMF.

Moreover, the PM in one pole is divided into $3 \times 3$ segments not only to reduce losses, but also to implement a skew of one stator slot pitch ($\pi/24$ rad) in order to minimise the effect of spatial harmonics ($h = 1 \pm 2mn$, with $n \in \mathbb{N}$) [11]. The value of $k_{h}$ is only slightly decreased to $k_{h} = 0.956$ with the implementation of skewing.

3.4 PMSG geometry

The internal geometry of the PMSG is designed according to the reference values shown in Table 3.

An estimate for the rotor axial length is obtained from the relation:

$$l = \frac{2T_{n}}{\sigma_{i} \pi D_{ro}}$$

where $D_{ro}$ is the rotor outer diameter. To simplify the design process, $D_{ro}$ can be initially fixed and $l$ can be obtained from (13). Since the external diameter of the stator ($D_{so}$) is limited by the selected IEC frame, if at the end of the design process $D_{so}$ is incompatible with the frame size, the design process is re-started and $D_{ro}$ is adjusted. In this case, $D_{ro} = 107$ mm is chosen and the airgap length ($g$) is fixed at 1.5 mm.

From (12) with $h = 1$, it is possible to calculate the required $N_{k}$ for the selected values of $k_{h}$ and $U_{e}$:

$$N_{k} = \frac{\sqrt[3]{2/3}}{2} \sqrt{\frac{3}{2}} k_{h} U_{e} \frac{r_{o}}{\alpha} B_{r} \gamma \lambda_{k}$$

### Table 2 Six-phase asymmetrical winding parameters

| Parameter               | Value | Parameter | Value |
|-------------------------|-------|-----------|-------|
| stator slots ($Q_{o}$)  | 48    | coil pitch ($r_{g}$) | 5m/6 (rad) |
| slots/pole/phase ($q$)  | 2     | set displacement ($\alpha$) | $\pi$/6 (rad) |
| number of layers        | 2     | wind. factor ($K_{wl}$) | 0.958 |

### Fig. 1 Normalised no-load flux density harmonics as a function of the PM span ratio

The stator slot geometry, presented in Fig. 2, is developed using an approach similar to the one found in [11], according to the target values established in Table 3.

The height of the rotor and stator yokes can be estimated with

$$h_{r} = \frac{\psi_{PM}}{2k_{r} j B_{r} m} - h_{r} = \frac{\psi_{PM}}{2k_{r} j B_{r} m}$$

where $\psi_{PM}$ is the peak value of the no-load flux linkage and $k_{r}$ is the stacking factor of the material used in both the rotor and stator yokes (M400–50A). The PM height necessary to induce $B_{f}$ = 0.9 T in the airgap is obtained by

$$h_{P} = \frac{U_{m,gt} + U_{m,dt} + (U_{m,y}/2) + (U_{m,y}/2)}{B_{PM} - B_{f}}$$

where $B_{PM}$ and $\mu_{PM}$ are the residual flux density and the relative permeability of the PM material (N33H), respectively. The variables $U_{m,gt}, U_{m,dt}, U_{m,y}$ and $U_{m,y}$ are the magnetic voltages across the airgap, tooth, stator and rotor yokes, respectively.

Once the slot geometry and PM dimensions are established, the values of both the stator outer diameter $D_{so}$ and the rotor inner diameter $D_{ri}$ can be calculated by

$$D_{so} = D_{ro} + 2(h_{r} + h_{s}) D_{ri} = D_{ro} - 2(h_{PM} + h_{ro})$$

The flowchart of the design procedure of the PMSG is shown in Fig. 3 and the final parameters, adjusted with the aid of the FEA are given in Table 4.

### Table 3 Reference values for the PMSG geometry [11]

| Parameter                  | Value, $T$ | Parameter | Value |
|---------------------------|------------|-----------|-------|
| airgap flux density ($B_{f}$) | 0.9         | tooth flux density | 1.6 (T) |
| rotor yoke flux density ($B_{y}$) | 1.4         | current density ($J$) | 4 (A/mm$^2$) |
| stator yoke flux density ($B_{s}$) | 1.4         | ratio of E/U ($k_{e}$) | 1.1 |

### Fig. 2 Stator slot geometry

The performance of designed six-phase PMSG is validated through the use of FEA. Due to the periodicity of the generator, only one pole of the PMSG is modelled in Cedrat Flux 2D. The results obtained through FEA are presented, for different modes of operation, and some design choices are compared in this section.

In order to assess the performance of the PMSG, the total waveform distortion (TWD) is used to evaluate the harmonic content of the current, EMF and torque, being given by

$$TWD(f) = \frac{\sqrt{f_{RMS}^2 - f_{1}^2}}{f_{1}} \times 100\%$$

### 4 FEA results

In order to test the PMSG under no-load conditions, the phase currents are set to zero and the rotor speed is fixed at the nominal value, $n = 1500$ rpm. The waveforms of the flux density along the airgap and the line-to-line EMF, along with their spectra are shown in Fig. 4.
The obtained no-load flux density has a fundamental component of 0.91 T, which is very close to the reference value in Table 3, while the EMF has a fundamental component with a RMS value of 375.17 V, which complies with the selected value for $k_e$.

The normalised amplitudes of the fifth and seventh EMF harmonics are very small, 1.15% and 0.44% of the fundamental, respectively, due to the selected PM span ratio.

### 4.2 Rated operation

In order to test the PMSG with rated conditions, the rotor speed is fixed at 1500 rpm and the stator windings, Y-connected with isolated neutrals, are fed by sinusoidal voltage sources with rated amplitude and frequency. The waveforms of stator currents, electromagnetic torque and their respective spectra, under rated conditions and with a load angle of $\delta = 15.95^\circ$, are shown in Fig. 5.

As seen in Fig. 5, the torque only contains harmonics of order $h = 12n$ ($n \in \mathbb{N}$), while the current contains a high amount of fifth and seventh harmonics, with normalised amplitudes of 20.57% and 3.91%, respectively. The same test presented in Fig. 5 is replicated in Fig. 6, but with a PM span ratio of 2/3 and $\delta = 18.25^\circ$.

While the spectral content of the torque in Fig. 6 remains unaltered, the amplitude of the fifth and seventh current harmonics increases to 39.19% and 15.14%, respectively. Although these harmonics can be compensated by the control system, an oversized dc-link voltage is required [13]. In order to compare both designs at rated conditions, the efficiency and the TWD of current, EMF and torque are given in Table 5.

### 4.3 Fault-tolerant operation

In order to test the PMSG in fault-tolerant conditions, only the first set of three-phase windings is fed by the sinusoidal voltage sources, while the phase currents of the second set of windings are forced to zero. The waveforms of stator currents, electromagnetic torque and their respective spectra under fault-tolerant operation with $\delta = 8.25^\circ$ are shown in Fig. 7.

The spectral content of currents in Fig. 7 has decreased, mainly the fifth and seventh harmonics, while the harmonic distortion of the torque has increased and now contains harmonics of order $h = 6n \pm 1$. A similar test to the one displayed in Fig. 7 with a full-pitch winding configuration and $\delta = 9.15^\circ$ is shown in Fig. 8.

Although the use of full-pitch winding enables an increase in the fundamental component of the EMF by 3.36%, the use of a...
4.4 Inductance parameters

The inductances of the PMSG windings as a function of the rotor position, obtained through FEA, are given in Fig. 9.

Despite the fact that the short-pitch windings improve the performance of the six-phase PMSG, mainly in fault-tolerant operation, the inductance of the subspace \( x-y \) is greatly reduced [14]. The inductances in the different subspaces are given in Table 7 in order to compare both winding configurations.

5 Conclusion

In this paper, the electromagnetic design of a 4 kW six-phase asymmetrical PMSG with distributed windings for application in a medium/high-speed WECS has been developed. The influence of the design choices such as the coil pitch and the PM span ratio in the performance of the six-phase PMSG has been studied for both healthy and fault-tolerant modes of operation.

As for the selection of the coil pitch, the results obtained through FEA show that there is a trade-off between the performance of the PMSG in fault-tolerant operation and the value of \( L_{ab} \), important to filter high-frequency current harmonics. The use of passive generator-side filters can also be employed to overcome this limitation. Moreover, the results demonstrate that the PM span ratio can have a great impact in the spectra content of the current, mainly in the fifth and seventh harmonics. Although it is possible to compensate them with the injection of current harmonics, an oversized dc-link is mandatory and this may not be reasonable in wind energy applications.

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short-pitch winding greatly reduces the fifth and seventh space harmonics in the airgap flux, leading to a reduction in the fifth and seventh harmonics of the EMF and in the sixth harmonic of torque. A comparison of the performance between PMSG designs with short-pitch and full-pitch windings is provided in Table 6.