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# Synchronous reluctance generator with ferrite magnets for wind turbine

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**Abstract**. Synchronous reluctance generators with ferrite magnets in the rotor (PMSynRG) are a good alternative to synchronous generators (SG) with rare-earth magnets. The comparison between a SG with rare-earth magnets and a PMSynRG with ferrite magnets of the same diameter, stack length, power and speed is given in the paper. Twice as less magnets are required for the PMSynRG with ferrite magnets than for the SG with rare-earth magnets. The cost of the ferrite magnets is 4.4 times less than of the rare earth magnets. Also, the PMSynRG with ferrite magnets has much higher efficiency than the SG. The half-integer slot number per pole and phase is chosen to achieve rather low torque ripple without skewing the rotor.

## 1. Introduction

In variable-speed wind generators, synchronous generators (SG) with rare-earth magnets in the rotor are widely used. Such SGs are connected to the grid through a frequency convertor. The energy generation principal in these machines is in inducing the electromotive force (EMF) in the stator winding by moving the magnetic flux of the magnets mounted on the rotating rotor. A large amount of the expensive rare-earth magnets is required to achieve the necessary EMF for effective electric energy generation.

Synchronous reluctance machines without magnets are similar to three-phase inductors: both of them have the winding and the magnetic cores. The winding current induces the magnetic flux which induces the self-inductance EMF. Three-phase inductors are used to produce reactive power. In contrast to three-phase inductors, synchronous reluctance machines without magnets have a rotor with anisotropic magnetic permeance which shifts the flux with respect to the current. As a result, the most part of reactive power becomes active power. Hence, synchronous reluctance machines can be used for energy transformation between electric and mechanical energies, or in other words, both as motors and as generators. However, reactive power of synchronous reluctance generator is rather high (power factor is approximately equal to 0.7) which increases frequency converter cost, the rotor and stator saturation and the winding current. As a result, the efficiency and the specific power are decreased.

Reducing the reactive power of a synchronous reluctance generator (SynRG) can be achieved by adding cheap ferrite magnets in the rotor. Also these ferrite magnets produce some EMF generating active power directly as in SG. As a result of the reactive power reduction, the saturation and the winding current decrease and the efficiency and specific power increase.

Synchronous reluctance generator with ferrite magnets in the rotor (PMSynRG) is a good alternative to SG with rare-earth magnets. The main advantages of the PMSynRG with ferrite magnets compared to SG with rare-earth magnets are:

- Low cost, since ferrite magnets are about five times cheaper than rare-earth magnets.
- Lack of technological dependence on Chinese suppliers; 95% of the rare-earth elements are extracted in China [1], while ferrite magnets are produced in different countries.

- The stability of prices for ferrite magnets, while due to the monopoly of China, prices for rare-earth magnets can change by 2-3 times in several years [2].
- Absence of eddy current losses in ferrite magnets because of their high electric resistance. In contrast, the electric resistance of the rare-earth magnets is low. The eddy-current losses in rare-earth magnets in synchronous machines can be significant [3] and several times higher than the core losses in the rotor core and the stator core [4].
- The possibility of the operation of synchronous reluctance machines with ferrite magnets in applications with a high specific power and temperature, while the characteristics of synchronous machines with rare-earth magnets are significantly deteriorated when the generator runs with high specific power and heats [5].
- The required magnetic flux density of ferrite magnets in PMSynRG much less than that in SG with rare-earth magnets which decreases the stator and rotor cores remagnetization at underload and increases the PMSynRG efficiencyat wide range of power and speed. In other words, PMSynRG has high efficiency in wide range of powers and speeds.

In this paper, a new design of a PMSynRG for a wind turbine developed according to [6] is described. The new design differs from the synchronous reluctance machine described in [5], [7], [8]. One of the features of this design is the double-layer fractional-slot winding with number of slots per pole and phase $q = 2.5$. The use of the winding with a fractional q makes it possible to reduce the torque ripple. As a result, low the torque ripple without skewing the rotor was achieved.

The rotor design [6] has the advantage of increased mechanical strength because the maximum radial force and torque is concentrated at the thick cross-like base of the rotor. Hence, the thickened rotor cross [6] provides an increase in the mechanical power compared to the rotors in [7], [8].

Recently, synchronous reluctance machines with ferrite magnets have attracted attention of many researchers as a good alternative of synchronous machines with rare-earth magnets [9]. A PMSynRG with ferrite magnets is considered as a generator of the wind turbine in [10],[11] but the papers [10],[11] do not present any comparison of PMSynRGs with ferrite magnets and synchronous motors with rare-earth magnets. In [12], the PMSynRG with the number of slots per pole and phase $q$=3 and the number of pole $p$=4 is compared tothe interior permanent magnet synchronous generator for a 5 MW wind turbine. However, the issue of the comparison of PMSynRGs with various types of SGs with ferrite magnets is not investigated thoroughly. In this paper, the PMSynRG with half-integer $q$=2.5 and $p$=3 is compared to the widely spread synchronous generator with magnets on the stator surface.

In this paper, a mathematical model for designing the PMSynRG on the basis of the finite element method in case of half-integer $q$ is described. Also, comparison between the SG described in [13] with rare-earth magnets and the PMSynRG with ferrite magnets of the same diameter,stack length, speed and power is given.

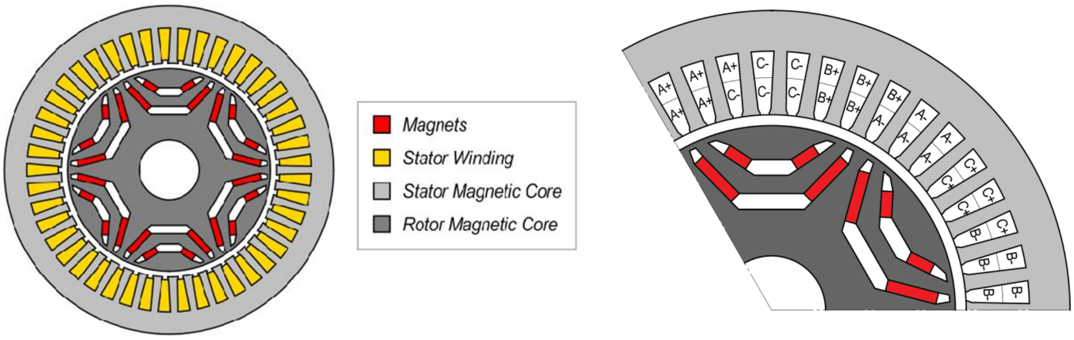
## 2. Mathematical model

Mathematical modeling the four-pole PMSynRG with ferrite magnets, with integer number of slots per pole and phase $q = 3$, and running in the motor mode is given in [5]. Unlike [5], this paper describes the six-pole PMSynRG with half-integer $q = 2.5$. The number of pole pairs $p$ is 3. The machine is shown in Figure 1.

The supply currents are supposed to be sinusoidal. The mathematical model is based on the set of the magnetostatic boundary problems for various rotor positions and corresponding to supply currents. No losses are taking into account in the stage of solving the boundary problems. The winding losses and the stator and rotor core losses as well as the motor efficiency are calculated in the postprocessing.

The 2D magnetostatic model is used for the FEM calculation of the magnetic field. In this case the vector magnetic potential can be chosen so as to have only the perpendicular to the plane z-component $A$.

Zero conditions $A = 0$ are used on the outer stator and inner rotor boundaries which means magnetic insulation.




a) b)

**Figure 1.** a) The machine scheme with $p$ = 3, $q$ = 2.5; b) The winding distribution in its slots.

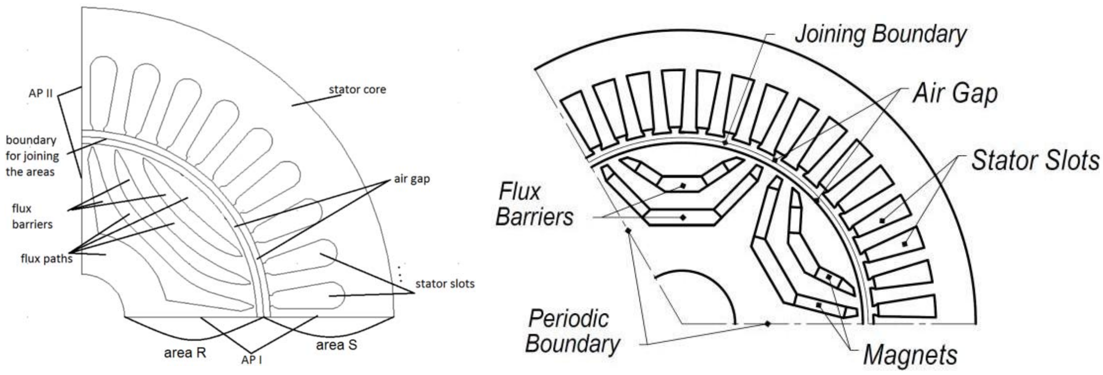
Two symmetries can be used to reduce calculating areas and to minimize number of boundary problems and the calculation efforts for PMSynRG either with integer q or with half-integer q.

The calculation area of the SynRG with $q$ = 3 and $p$ = 2 is shown in Figure 2a. At any rotor position and at any winding current, the PMSynRG with integer $q$ is symmetric with respect to the motor rotation by a pole pitch as a whole with simultaneous changing the current signs and magnetization directions of the magnets. The aperiodic boundary condition is to be applied to join the radial boundaries of the sector-like calculation area. These boundaries are denoted as *API* and *APII*. The symmetry allows reducing the calculation area of the four-pole SynRM by four times.

The calculated area of the PMSynRG with $p$ = 3 and $q$ = 2.5 is shown in Figure 2b. The motor with half-integer q is symmetric only in respect to the square of the described above operation. That is two-pole (120 degrees for a six-pole machine) sector is to be considered. Also, the periodic boundary condition is to be applied to join the radial boundaries of the sector-like calculation area. The symmetry allows reducing the calculation area of the PMSynRG by only three times.

Another symmetry operation of the PMSynRM with integer $q$ is a simultaneous rotation by sixth of electric period and the phase current permutation $I_A \to -I_C, I_B \to -I_A, I_C \to -I_B$. The motor with half-integer q is symmetric only in respect to the square of this operation because of lower symmetry of the winding. So, the boundary problems for the rotor positions from interval of third of the electric period are to be considered in the case of half-integer q, while sixth of the electric period is sufficient in the case of integer q. That is, the number of the required boundary problems is doubled compared to the PMSynRM with integer $q$.

Hence, modeling the PMSynRG with half-integer $q$ is more resource consumptive than that with integer $q$.




a) b)

**Figure 2.** Calculation areas a) $q$ = 3; b) $q$ = 2.5.

As follows from the above, the mathematical model is based on the set of $n + 1$ boundary problems with the rotor position $\varphi$ (angle between d-axes and the fundamental current harmonic direction when $I_A = 2A; I_b = -1A; I_c = -1A$) and the phase currents $I_k$ given as:

$$\varphi = \varphi_e / 3,$$

$$\begin{aligned} I_A &= \sqrt{2} I \sin(\varphi_e + \theta), \\ I_B &= \sqrt{2} I \sin(\varphi_e - 120° + \theta), \\ I_c &= \sqrt{2} I \sin(\varphi_e - 240° + \theta), \end{aligned} \tag{1}$$

$$\varphi_e = 0; \frac{120°}{n}, 2\frac{120°}{n}, ..., 120°,$$

where I is rms of the phase current, $\varphi_e$ is electrical angle, $\theta$ is control angle.

Not depending on whether $q$ is integer or $q$ is half-integer, one and the same calculation area can be used for all boundary problems describing the various rotor positions. To model the rotation, the computational area is cut by the circle in the centre of the air gap into two areas: the area I includes area of the stator and a half of the air gap area; the area II covers the rotor area and the other half of the air gap. Each area is considered in the reference frame related to it.

The coordinate system related to area II is not inertial. Maxwell's equation, however, in quasi-stationary approximation possesses a property of additional symmetry – invariance with respect to the transition into the revolving reference frame. Thus, the electromagnetic field, both in the area I and in the area II, is described by the same partial differential equation.

On the common boundary of areas I and II, joining the field $A$ is performed. On the area boundaries, values $A$ belonging to area I are independent degrees of freedom. These values at the point $(x, y)$ define values $A$ at the point on the area II boundary having the following coordinates:

$$\begin{aligned} x' &= x \cos\varphi + y \sin\varphi, \\ y' &= -x \sin\varphi + y \cos\varphi, \end{aligned}$$

Points $(x', y')$ on the area II boundary are not necessarily the discretization points. The values $A_z$ at the discretization points of the area II are defined by the polynomial interpolation. Joining the field $A_z$ normal derivative is automatically performed in the finite element method.

When the boundary problems are solved, the flux linkages can be calculated:

$$\Phi_k = pL \iint \Xi_k A dxdy, \tag{2}$$

where $L$ is the stack length and $p = 3$ takes into account that the calculation area is reduced by three time, $\Xi_k(x, y)$ are the current density fields when only the $k$-th current $I_k$ is nonzero and equal to 1A. $\Xi_k(x, y)$ can be nonzero only in the stator slot areas.

Since the inner stator surface and the outer rotor surface are concentric, the following integral over the air gap can be used to find the PMSynRG torque:

$$M = pL \iint_{S_{air}} \frac{xy(B_y^2 - B_x^2) + (x^2 - y^2)B_x B_y}{\delta_{air}\mu_0\sqrt{x^2 + y^2}} dxdy \tag{3}$$

where $\delta_{air}$ is the air gap thickness and $\mu_0$ is the magnetic constant.

The PMSynRG instantaneous power can be found in two ways: having instantaneous fluxes $\Phi_k$ and currents and having rotational speed and instantaneous torques $M$. As any losses are not taken into account in this stage, these power values averaged over electric period should coincide. However, it is not so because of computational errors of FEM method but the difference in the calculation results presented below is not higher than 0.1 %.

The winding losses can be easily calculated using the Joule–Lenz law. The estimation of the losses in the stator and rotor cores is more complicated and is done in the postprocessing.

During the calculation of the core losses it should be taken into consideration that the magnetic flux is not sinusoidal. So the harmonics contribution should be evaluated.

The averaged magnetic loss density in steel is supposed to be given by the expression:

$$p_{st} = \frac{\alpha}{\omega^2} < \left( \frac{d\mathbf{B}}{dt} \right)^2 >= \frac{\alpha B_{equ}^2}{2}, \quad (4)$$

where $\alpha$ is the proportionality factor determined on the basis of empirical data, $\omega = 2\pi f$ is the angular frequency of the supply, $< >$ is averaging over the interval of rotor position for which the boundary problems is solved, $f$ is frequency and the equivalent flux density is

$$B_{equ} = \sqrt{2 < \left( \frac{d\mathbf{B}}{d\varphi_e} \right)^2 >} \quad (5)$$

Having $B_{equ}$, the C. Steinmetz expression was assumed for calculating the core losses:

$$p_{st} = \rho p_{50} \left( f / 50 \right)^s B_{equ}^2 \quad (6)$$

where $\rho$ is the steel density, $p_{50}$ is losses in 1 kg of steel at 50 Hz and 1T; $n$ is the parameter which is taken as $s$ = 1.3 for the majority of electrical steels.

This approach makes it possible to evaluate the core losses at any frequency when the steel losses at 50 Hz and 1 T are given in the datasheet of the steel.

The stator and rotor core losses can be found with integrating the expression (7). Due to consideration the rotor and the stator in their own reference frames, the total derivatives in (5) is equal to the partial ones which significantly simplify calculations of the equivalent flux density $B_{equ}$. The stator and rotor core losses can be found by integrating (6).

It could seem that according to (1), the last boundary problem duplicates the first one because of the motor symmetry. However, the last boundary problem is very useful for calculating the derivative $\frac{d\mathbf{B}}{d\varphi_e}$ by expression $\frac{\mathbf{B}_{i+1} - B_i}{\varphi_{e\ i+1} - \varphi_{e\ i}}$ at all sections of the rotor position interval.

## 3. Designing PMSynRG and its comparison to SG

The PMSynRG has been designed on the basis of the developed mathematical model. The efficiency calculation was done with the assumption that the mechanical losses are assumed to be equal to 2% at the rated speed.

Table 1 shows that the main characteristics of the designed PMSynRG with ferrite magnets and of the SG with rare-earth magnets described in [13]. The rated speed of both machines is 4500 rpm, their rated power is 15kW, their rated torque is approximately 35 N*m. Also, the SG is claimed to operate as a starter which rated speed is 800 rpm and rated power is 1.2 kW. So, the torque at the starter mode is only approximately 15 N*m. Therefore, the starter mode was not investigated in [13] and the synchronous machine was designed mainly as a generator. Although the SG with rare-earth magnets [13] is designed for electric vehicle, the similar SGs are used in wind turbines [14]. The PMSynRG was compared to the SG from [13] but not from SGs from [14] because the paper [13] contains a detailed information on the SG mass and the cost of its active materials.

**Table 1**. Comparison of the parameters of the 15 kW, 4500 rpm generators.

| Parameter | PMSynRG | SG [7] |
|---|---|---|
| Rated power, kW | 15 | 15 |
| Rated speed, rpm | 4500 | 4500 |
| Rated efficiency, % | 93.9 | 90.4 |
| Number of poles | 6 | 10 |
| Current density, A (RMS)/mm$^2$ | 2.1 | - |
| Rated frequency, Hz | 225 | 375 |
| Remanence of magnets, T | 0.4 | 1.1 |
| Type of magnets | ferrites | rare-earth |
| Stator outer core diameter, mm | 200 | 200 |
| Stack length of stator core, mm | 110 | 110 |
| Copper mass, kg | 5.3 | - |
| Stator and Rotor Steel mass, kg | 38.6 | - |
| Magnet mass, kg | 0.8 | 1.8 |
| Magnet estimated cost, $ | 20 | 198 |

According to [6], the cost of the ferrite magnets (remanence is 0.4 T) is 25$ per kg. The cost of the rare-earth magnets (remanence is 1.1 T) is 110$ per kg.

Compared to the SG, the PMSynRG efficiency is increased by 3.5%, which corresponds to decreasing the losses by more than one third. Moreover, decreasing the operational power decreases the switching losses in the frequency convertor. The PMSynRG mass could be reduced by designing it with higher current density. In this case, the copper losses would increase and the efficiency would become lower.

Figure 3 shows the calculated magnetic flux density field in the developed PMSynRG. The most saturated parts of the machine is the rotor ribs providing its integrity which ensures high magnetic saliency required for achieving high efficiency and high power density.

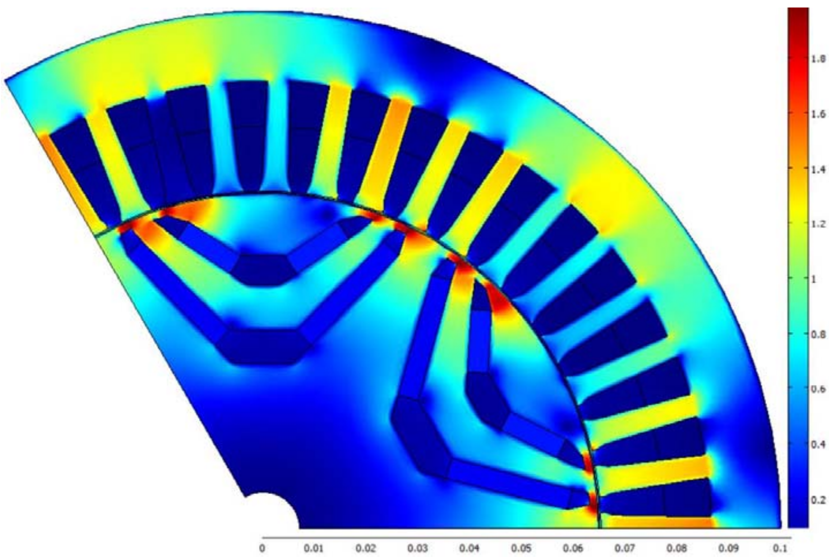
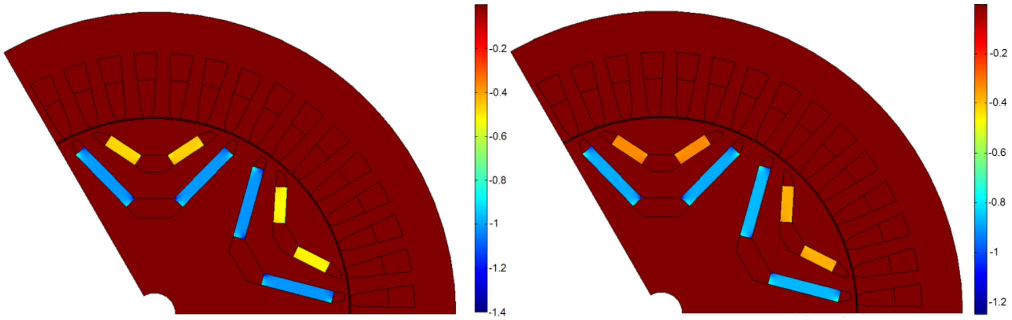



**Figure 3.** Magnetic field density in the PMSynRG (T).

The demagnetization field in the magnets does not exceed 140 kA/m at the rated mode (Figure 4a) and 125 kA/m at the emergency short circuit (Figure 4b). The coercitivity of most grades of ferrite magnets is much higher than those values. The threat of demagnetization of ferrite magnets in traditional SGs arises from the fact that it is only magnets that induce the useful flux and interact with the field of the winding strongly. But in the PMSynRG, the magnets play an auxiliary role. Also, adding ferrite magnets improve the characteristics of the synchronous reluctance machine significantly. Therefore, the ferrite magnets are often used in synchronous reluctance machines [15].



a) b)

**Figure 4.** The magnetic field projection on the magnetization direction of the magnets ($10^5$ A/m).

Figure 5 shows the PMSynRG with ferrite magnets has high efficiency not only at the rated point but also in wide range of speeds and torques.

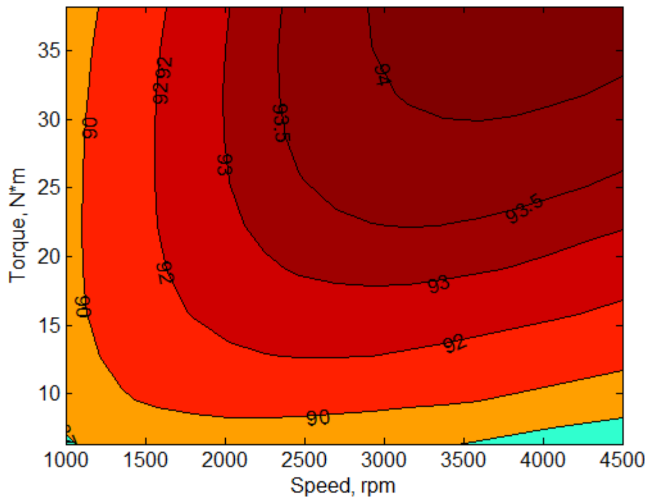



**Figure 5.** The PMSynRG efficiency map.

Figure 6 shows one the period of the calculated torque ripple waveform. Since the machine has three pairs of poles, the electric period is 120°. The period of the torque ripple waveform of PMSynRG with half-integer $q$ is equal to third of electric period and equal to 40° in the considered case. Applying the winding with half-integer $q$ allows achieving rather low torque ripple without skewing the rotor. The peak to peak torque ripple value of the developed PMSynRG is 5.3% of the average torque.

Figure 7 shows the torque ripple harmonics. The period of the first harmonic is 40 degrees (third of the electric period). The main contribution in the torque ripple is made by second (even) harmonic. The spectrum contains, however, odd harmonics as well. This demonstrates that considering sixth of the electric period as it could be done in the case of integer $q$ is not sufficient. Third of the electric period should be taken into consideration.

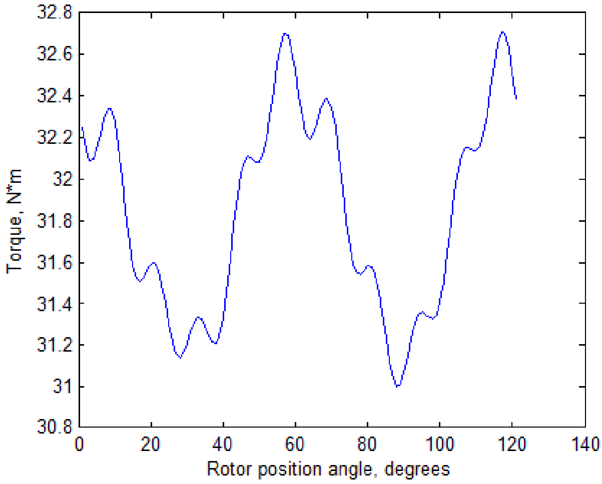



**Figure 6.** The PMSynRG torque ripple.

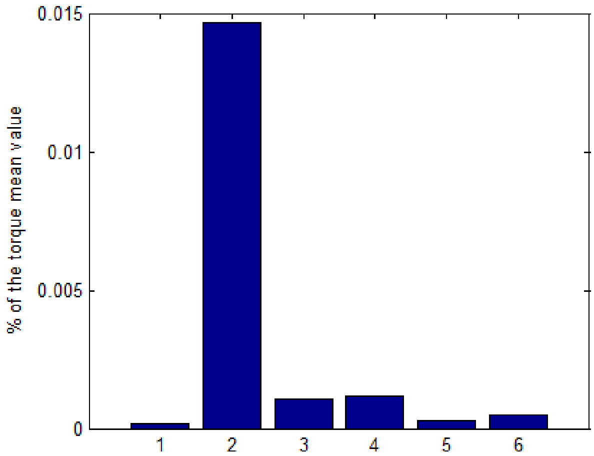



**Figure 7.** The torque ripple harmonics.

## Conclusions

The mathematical model for designing a PMSynRG with the half-integer slot number per pole and phase is described. The half-integer slot number per pole and phase is chosen to achieve rather low torque ripple without skewing the rotor. However, the model requires more calculations than that for designing a PMSynRG with the integer slot number per pole and phase because of decreasing the machine symmetry.

The comparison between the SG with rare-earth magnets and the PMSynRG with ferrite magnets of the same diameter, stack length, power and speed is given. Twice as less magnets are required for the PMSynRG with ferrite magnets than that for the conventional SG. The cost of the ferrite magnets is 4.4 times less than of the rare-earth magnets. Therefore, the PMSynRG is much cheaper than the SG with rare-earth magnets.

There are no eddy current losses in PMSynRG with ferrite magnets. And ferrite magnets are more thermostable than rare-earth magnets. Compared to the SG, the PMSynRG efficiency is increased by 3.5%, which corresponds to decreasing the losses by more than one third.

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