Minimizing Cogging Torque in Permanent Magnet Synchronous Generators for Small Wind Turbine Applications

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Abstract- Permanent magnet synchronous generators have a wide usage among electric machines, especially in small wind turbine systems. However permanent magnet synchronous generators suffer from cogging torque due to the magnetic interaction between the poles of the rotor's permanent magnets and the steel laminations of the stator's teeth. The cogging torque drawback is a major problem in this kind of generators that affects its functionality negatively. In the literature many different approaches for reducing the cogging torque are proposed and each different approach achieves different amount of reduction in the cogging torque. In this study 6 different cogging torque reduction techniques are considered and with finite element simulations using the JMAG simulation software, they are compared with each other in terms of percent reduction in the cogging torque. Present simulations show that among the considered different approaches, continuous skewing technique reduces the cogging torque the most with respect to the each other techniques considered. Also using the step skewing of the rotor or stator, changing the slot opening width and having dummy slots techniques can decrease the cogging torque more or less the same amount in magnitude. Present results indicate that changing the radial shoe depth technique has almost no effect in reducing the cogging torque.

Keywords Cogging torque reduction, permanent magnet synchronous generator, finite element analysis, optimization

Nomenclature

T_{cog}: Cogging Torque
$\emptyset_g$: Permanent Magnet Flux
R: Reluctance
θ: Angular Position
T_{mk}: Fourier Coefficient
LCM: Least Common Multiple
θ_{skew}: Optimum Skewing Angle
N_s: Number of Stator Slots
N_p: Number of Poles
N_{period}: Period Number of Cogging Torque Waveform
HCF: Highest Common Factor
N_{notch}: Number of Notches
θ_o: Shifted Relative Angle

1. Introduction

Permanent magnet synchronous generators (PMSG) are preferred over other electrical machines due to their high efficiency, high torque to volume and torque to current ratio, power per volume and simple structure [1],[2]. For this reason, in small wind turbines PMSGs are preferred [3]. PMSGs are also used in large range of applications such as compressors and hybrid electric vehicles, industrial drive systems, electric propulsion systems, and fly-wheel energy storage systems and also in underwater applications [4],[5].

Among the renewable energy sources wind energy is one of the fastest growing energy source all around the world [6],[7],[8]. In wind energy systems it is always preferable that the wind turbines should have a low cut-in wind speed such that the wind turbine rotor should start spinning and therefore generate electricity at low wind speeds [9]. PMSGs often suffer from cogging torque which is due to the interaction between the permanent magnets and the slotted steel structure of the stator [10]. In wind turbines, the cogging torque of the generator directly affects the cut-in wind speed of the turbine. At the cut-in wind speed, the aerodynamic torque generated by the wind turbine rotor blades starts to overcome the cogging torque of the PMSG and rotor blades start spinning. If the cogging torque of the wind turbine PMSG is large, then the cut-in wind speed of the wind turbine will be higher. This will result in loss of energy output of the wind turbine at low wind speeds [11].

The cogging torque also creates torque ripple [12],[13],[14],[15] during operation which also leads to different drawbacks such as noises, vibrations on the wind turbine. Thus, in wind turbines PMSGs with low cogging torque are preferred.

In the literature there are many different approaches in order to reduce the cogging torque of PMSGs. One approach in cogging torque reduction is to modify the design parameters of the PM rotor. Continuous or step skewing of the permanent magnets and shifting the permanent magnets can be counted as examples for this approach. Another approach in cogging torque reduction is to modify the design parameters of the stator armature. Skewing the stator slots, notching the stator teeth, changing the slot opening width and changing the radial shoe depth can be counted as examples for this approach.

Each of the different cogging torque reduction techniques presented in the literature has a different effect on the PMSG and they have different effectiveness in reducing the cogging torque. In this study 6 different cogging torque reduction techniques are considered and they are compared with each other in terms of the amount of cogging torque magnitude each can reduce. For this a baseline prototype PMSG is considered and by doing finite element simulations using the JMAG simulation software, the cogging torque of the considered baseline prototype PMSG is calculated. Then one by one each cogging torque reduction technique is applied to the same baseline prototype PMSG respectively and a finite element simulation is performed afterwards. With this, the amount of reduction in the cogging torque is obtained when each different technique is applied to the same baseline prototype PMSG. Thus the effectiveness of the considered 6 different cogging torque reduction techniques is presented and compared with each other.

2. Cogging Torque

As the rotor rotates while the stator stays fixed, the permanent magnet flux travels through a periodically varying reluctance. During this action, permanent magnets tend to align themselves with the stator teeth and thus cogging torque is created. The cogging torque is the attraction between permanent magnets and stator teeth by a circumferential attraction force attempting to keep the alignment of the permanent magnets and the stator teeth [10]. The time average of this pulsating torque (cogging torque) is zero Nm [16]. The cogging torque can be represented by [16]

$$T_{cog}(\theta) = -\frac{1}{2}\emptyset_g^2 \frac{\partial R}{\partial \theta} \tag{1}$$

where, $\emptyset_g$ is the permanent magnet flux that crosses the air gap, R is the reluctance of air gap, (note that the iron core and permanent magnet reluctances are negligible compared to air gap reluctance) and θ is the angular position of the rotor. The periodicity of the varying air gap reluctance causes the cogging torque to be also periodic. Thus, cogging torque could be written as Fourier Series [16].

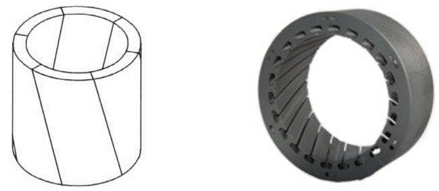
$$T_{cog} = \sum_{k=1}^{\infty}(T_{mk}\, sin(mk\theta)) \tag{2}$$

where k, is an integer, T_{mk} is the Fourier coefficient and m is the *LCM* (Least Common Multiple) of the number of slots and the number of poles. This equation clearly shows that cogging torque is directly related to stator slots and rotor poles numbers. Moreover, m is the cogging torque periods per the revolution of the rotor.

Among many different approaches for reducing the cogging torque in PMSGs found in the literature, the 6 different cogging torque reduction approach considered in this study are given below.

2.1. Stator or Rotor Skewing

Stator or rotor skewing, as shown in Fig. 1, is a well-known approach used to minimize the cogging torque. Although, skewing plays an effective role in cogging torque minimization, it has some drawbacks also. For example, if the stator is skewed then it will be difficult to do the slot filling automatically for mass production [17]. On the other hand, if the permanent magnets are skewed then this requires special magnets to be manufactured which increases the cost and the complexity of the PMSG [18]. In a PMSG, skewing can be applied as continuous skewing or else as step skewing.



(a) Skewing the rotor magnets **(b)** Skewing the stator

Fig. 1. Skewing the rotor or stator.

2.1.1 Continuous Skewing

In [19], it is stated that cogging torque is created when magnetic flux interacting with the changing magnetic reluctance. Skewing aims to decrease the net change of reluctance with the position. So, the axial dimension change decreases the circumferential direction change and thus cogging torque is decreased. Using the optimum skewing angle, cogging torque could be minimized to a negligible magnitude. The optimum skewing angle is given as [18]

$$\theta_{skew} = \frac{2\pi}{N_{period}N_s} \tag{3}$$

where N_s is the number of stator slots and N_{period} is the period number of cogging torque waveform during the rotor rotation and it is given as [18]

$$N_{period} = \frac{N_p}{HCF\,\{N_s, N_p\}} \tag{4}$$

where $HCF\,\{N_s, N_p\}$ is the Highest Common Factor of the number of slots (N_s) and the number of poles (N_p).

2.1.2 Step Skewing

Step skewing is arranging magnet slices in *z*-direction with each slice shifted by a skew angle as shown in Fig. 2.

Therefore, with this approach the magnets are not skewed continuously but skewed stepwise. Step skewing technique was studied also in [19],[20] and it is stated that step skewing is an effective technique used to reduce cogging torque. In step skewing, increasing the number of the magnetic slices in z-direction makes this technique more effective since in the limit when the number of magnetic slices in z-direction becomes infinite this method will be identical with continuous magnet skewing technique.

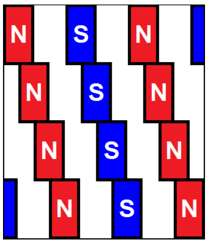


Fig. 2. Step skewing of the permanent magnets.

2.2. Decreasing Slot Opening Width

In a PMSG the cogging torque is created when the stator slots interact with the magnetic flux inside the air gap. Therefore, in a slotless PMSG there will be no cogging torque created. On the other hand in a PMSG, stator slots play the main role in the average torque and the machine performance. In [21], it is stated that increasing slot opening width leads to increase in average torque, but it produces a bigger cogging torque in magnitude. Decreasing the slot opening widths decreases both cogging and average torque. Making the slot openings narrower means allowing the pole to transit smoothly along the stator teeth and thus less cogging torque is produced. A drawback of having small slot openings is that it will be difficult to insert the windings into the slots in practice [22].

2.3. Having Dummy Slots

Another well-known and effective technique to reduce cogging torque is to have dummy slots. In this approach the teeth are notched with the same width of the stator slots as shown in Fig. 3. The space between the notches should also be the same. The shape of the notches could be rectangular, semi-circular or u-shaped. These notches decrease cogging torque by increasing the number of interactions occurred between the stator slots and the permanent magnets. These notches create cogging torque with different displacement from the origin but with same behavior. Both cogging torque curves, the origin and the new created are added up and the resultant cogging torque is lower in magnitude with a greater frequency. In this approach it is important to choose the optimum number of notches with respect to the period number of the cogging torque as follows [18]

$$HCF\{(N_{notch}+1), N_{period}\} = 1 \tag{5}$$

where HCF is the Highest Common Factor, of the where HCF is the highest common factor, N_{notch} is the number of notches to use and N_{period} is the number of periods of cogging torque which is given in equation (4).

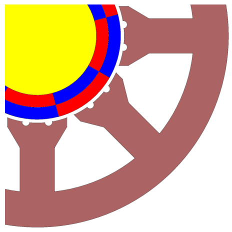
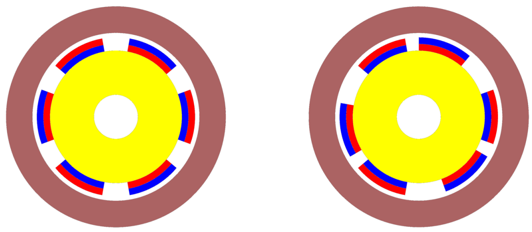


Fig. 3. Notching the stator teeth.

Having dummy slots might increase the cost slightly which can be counted as a drawback of this cogging torque reduction technique. Moreover, having dummy slots reduces the average torque of the machine and its efficiency [22].

2.4. Permanent Magnet Shifting

In [23], the effect of poles shifting on cogging torque magnitude was studied. It is explained that increasing the offset of pole pairs causes increasing of the magnetic leakage flux between them [23]. The magnetic leakage flux causes decreasing of rotor-stator coupling flux and thus cogging torque magnitude is reduced. The harmonic components of the cogging torque in permanent magnet shifting method for cogging torque reduction was discussed in [16],[24]. When the magnets are arranged uniformly on the circumference of the rotor, the cogging torque produced will be in phase with each other and thus the cogging torque will be largest. However, arranging the magnets non-uniformly on the circumference of the rotor with some shifting will cause the harmonic component of the cogging torque to be out of phase. The shifting of the magnet is schematically shown in Fig. 4.



(a) Magnets uniformly spaced **(b)** Magnets shifted

Fig. 4. Magnets placed uniformly and shifted.

The magnet shifting have a cancelling effect on the harmonics of the cogging torque thus reduce the cogging torque. For the highest harmonics cancellation, optimum shifting angle is given as [16]

$$\theta_o = \frac{2\pi}{N_s N_p} \tag{6}$$

where θ_o is the shifted relative angle for the arranged magnets. This equation is valid only for integer numbers of slots per pole.

2.5. Decreasing Radial Shoe Depth

In [23], it is stated that the magnetic flux flows from the rotor magnets through the stator (ferromagnetic material) in a perpendicular direction with the surface. At the side of the stator teeth, the tangential components of the attractive force (magnetic flux) are larger. When maximum flux passes to the stator teeth sides, it means that the cogging torque having a peak value at that position. Therefore, in [23] it is stated that the cogging torque magnitude varies with the radial shoe depth as illustrated in Fig. 5. This variation changes the tangential component distribution of the attractive force at the side of the shoe [23]. Having said this, however, the results presented in [23] did not show any significant reduction of cogging torque when the shoe depth is changed which states that the changing the radial shoe depth is not very efficient in reducing the cogging torque magnitude.

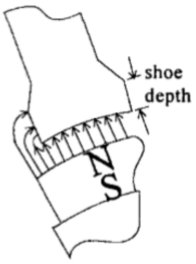


Fig. 5. Magnetic flux through the sides of the stator shoe.

3. Simulations and Results

3.1. Baseline Prototype PMSG Simulation

In order to study the effect of different cogging torque minimization techniques, a baseline prototype PMSG is considered with 12 slots 4 pole design. This considered baseline prototype PMSG design is available in JMAG application catalogue library [25]. The dimensions and configuration parameters of the chosen baseline prototype PMSG are given in Table 1 and Fig. 6.

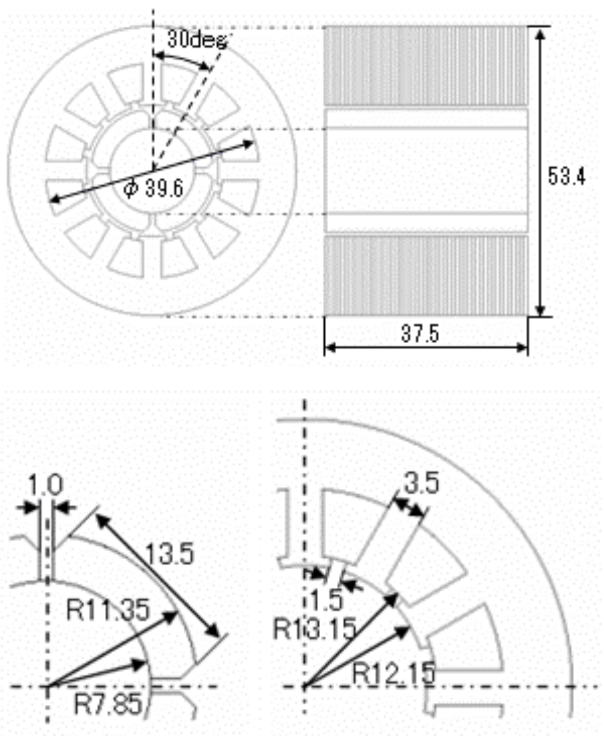


Fig. 6. Baseline prototype PMSG dimensions [mm].

Table 1. Baseline prototype PMSG configuration parameters.

Parameter	Value
Number of slots	12
Number of poles	4
Stator stack length	37.5 mm
Radius of rotor	11.35 mm
Outer stator radius	26.7 mm
Magnet thickness	3.5 mm
Air gap length	0.8 mm
Air gap slot width	1.5 mm
Tooth thickness	3.5 mm
Rated speed	1800 rpm

In simulating the PMSG, the materials of the permanent magnets, stator coil and shaft must be specified in JMAG simulation software. These materials are chosen according to the JMAG suggested design for cogging torque analysis. For the permanent magnets in the baseline prototype PMSG, Hitachi Metals (SSMC): NEOMAX-42 is chosen. They are magnetized in a radial pattern and circular direction. Moreover, the magnetization direction is inclined at 45 degrees from the reference axis. For the stator core material, NSSMC (50H600) steel sheet is chosen. It is laminated with 98 percent lamination factor. For the shaft material, NSSMC (15HX1000) steel sheet is chosen. Also, for the coil windings material copper is chosen in order to have electrical conduction within.

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In any finite element simulation, it is critical to have an appropriate mesh analysis in order to have accurate results. The mesh should be very fine at points where the parameters change rapidly or at points near sharp corners or edges in order to have high accuracy in finite element simulation results. For this reason, different element sizes are used in the present simulation mesh. At points close to the interaction area that cogging is created within, very fine mesh is used in order to resolve the physics better. For example, the edges that are close to the area between the magnet and the stator teeth and slots have finer mesh sizes than other parts. Moreover, since the flux circulates within the steel teeth, the element sizes at the internal teeth edges are also chosen to be very fine. The simulation is repeated many times with increasing the mesh size in each time until there is negligible difference in the results, in order to obtain the required mesh size for grid independent simulation results. The unstructured triangular mesh used in the present simulations has 128661 elements. Fig. 7 shows the mesh distribution for the baseline prototype PMSG used in this study.

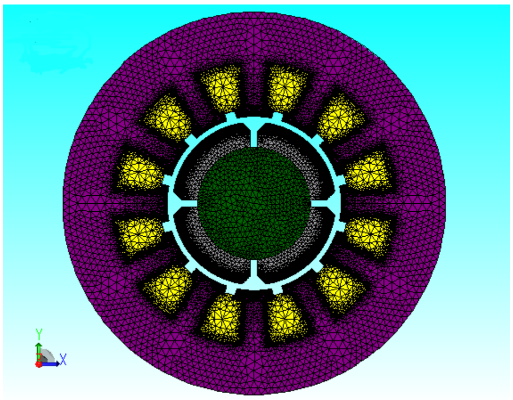


Fig. 7. Mesh used in baseline prototype PMSG.

Using JMAG software with the above given dimensions and specifications, the cogging torque for the chosen baseline prototype PMSG is simulated. Fig. 8 shows the simulation results for magnetic flux density distribution within the prototype PMSG.

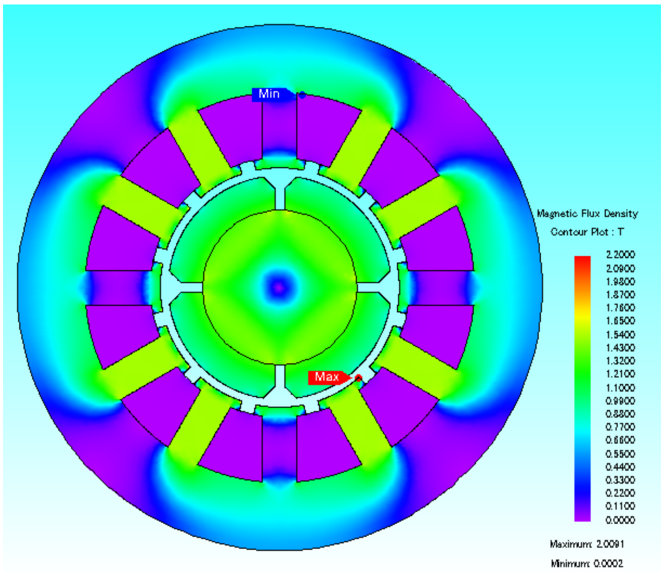


Fig. 8. Magnetic flux density in baseline prototype PMSG.

In Fig. 8 the intensity of the magnetic flux density distribution is shown by color contours where red color shows the highest magnetic flux intensity and violet shows the zero magnetic flux intensity as shown in the color bar on right of the same figure. As seen in Fig. 8, permanent magnets, shaft and the teeth have green to yellow colors as intensity. This means that the flux is circulating from the magnets towards the teeth and vice-versa depending on the magnetization direction of the PMs. However, in the same figure copper parts which belong to the windings show violet color which means that no magnetic flux is passing through. Inside the PMSG the flux distribution changes as the rotor rotates.

The calculated cogging torque for the baseline prototype PMSG is given in Fig. 9.

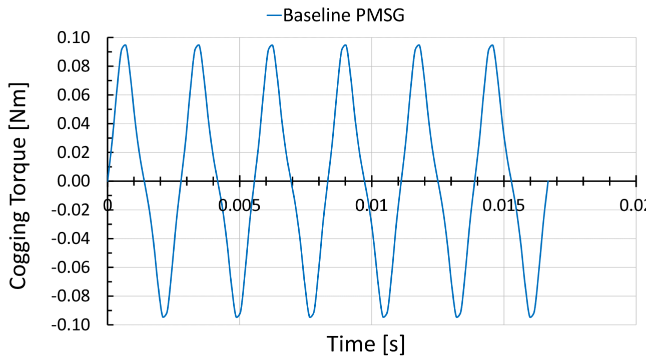


Fig. 9. Cogging torque in baseline prototype PMSG.

The different cogging torque reduction techniques considered in the present study is applied either to the stator or to the rotor of the baseline prototype PMSG respectively. After each cogging torque reduction technique is applied to the baseline prototype PMSG, the finite element simulation is done in order to calculate the new cogging torque. Then this obtained cogging torque is compared with that of the baseline prototype PMSG in order to see the effect of the cogging torque reduction technique. The continuous and step skewing and also magnet offset is applied by modifying the rotor side while the slot opening width, dummy slots and radial shoe length modifications are applied to the stator of the baseline prototype PMSG.

3.2. Simulations for Continuous Skewing

As mentioned in the literature review, continuous skewing cogging reduction technique could be applied to both rotor and stator. The skewing angle has an effect on the amount of cogging torque reduction. According to equations (3) and (4) the optimum skewing angle for 4 poles, 12 slots PMSG is calculated as follows

$$N_{period} = \frac{4}{HCF\{12,4\}} = 1 \quad , \quad \theta_{skew} = \frac{2\pi}{1 \times 12} = 30^{\circ} \qquad (7)$$

Fig. 10 shows the cogging torque variation for continuous skewing angles of 10°, 20°, 30° and 40° respectively.

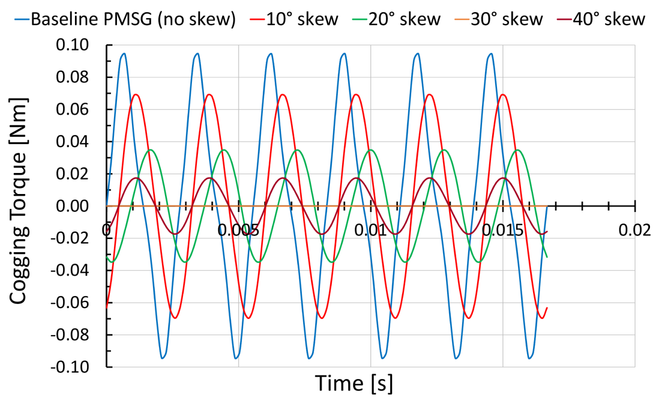


Fig. 10. Cogging torque at different continuous skew angles.

Fig. 11 shows the peak values of the cogging torque as a function of the skewing angle. The cogging torque magnitudes are decreasing until 30° where it is at minimum. Beyond the minimum cogging torque angle (30°), when the skewing angle increases again the cogging torque magnitude increases again. The simulation results agree with the calculated optimum angle such that the minimum cogging torque is obtained at 30° skewing angle.

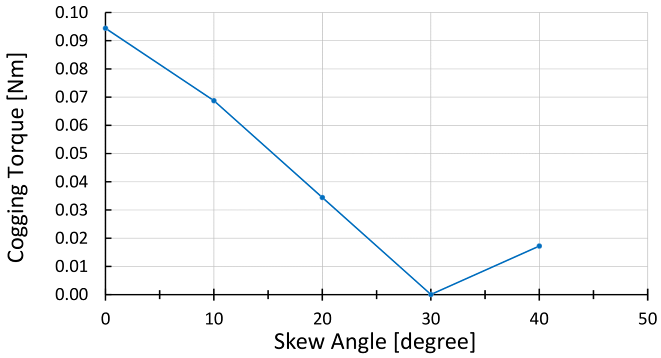


Fig. 11. Cogging torque w.r.t. skew angle.

3.3. Simulations for Step Skewing

In applying step skewing technique, different step numbers are simulated in order to see their effect on cogging torque magnitude. While keeping the skewing angle as optimum 30°, 3 and 5 step skewing are considered and simulated to observe the change in cogging torque peak.

Fig. 12 shows cogging torque for the baseline prototype PMSG together with 3 and 5 steps skewing and also Fig. 13 shows the variation of the maximum cogging torque with respect to the skewing step number. As seen in Fig. 13, the maximum cogging torque decreases as the skewing step number increases.

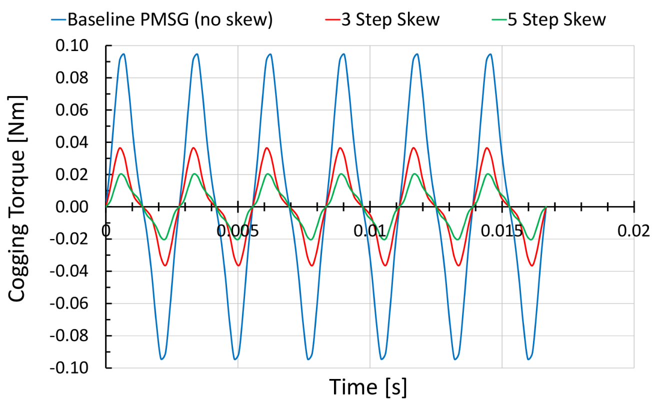


Fig. 12. Cogging torque at different step skew numbers.

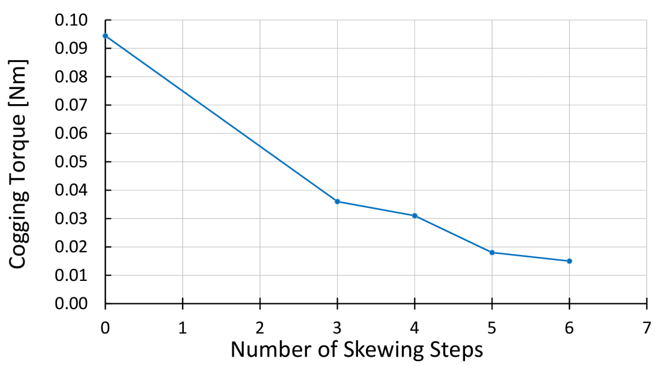
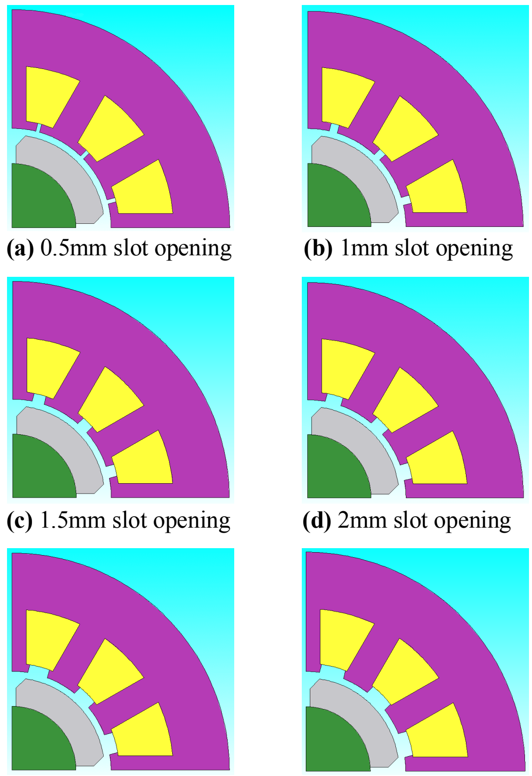


Fig. 13. Cogging torque w.r.t. skew step number.

3.4. Simulations for Decreasing Slot Opening Width

In order to obtain the effect of the slot opening width on the cogging torque in our simulations different slot width sizes varying between 0.5mm to 3mm with 0.5mm increments are considered. Fig. 14 shows the PMSGs with different slot opening widths.



(a) 0.5mm slot opening **(b)** 1mm slot opening
(c) 1.5mm slot opening **(d)** 2mm slot opening
(e) 2.5mm slot opening **(f)** 3mm slot opening

Fig. 14. PMSGs with varying slot widths.

The simulation results of cogging torque when different slot opening widths are considered are given in Fig. 15.

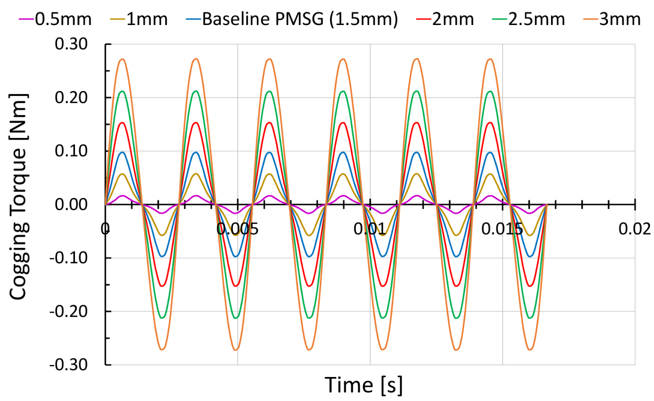


Fig. 15. Cogging torque at different slot opening widths.

Fig. 16 shows the maximum peak cogging torque as a function of the slot opening width. From this figure, it is clear that cogging torque peaks decrease when slot width size decreases. This implies that, to achieve less and less cogging torque magnitude a small slotted PM machine should be selected.

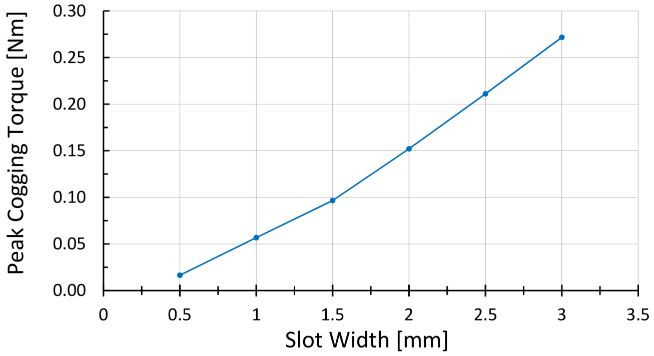


Fig. 16. Cogging torque w.r.t. slot width.

3.5. Simulations for Having Dummy Slots

In order to simulate the dummy slot cogging torque reduction technique, it is critical to choose the best number of notches to use. According to equation (5), for the considered baseline prototype PMSG the best number of notches is calculated as one notch per tooth. In this technique, it is also important to have the size of the notches match with the size of the slot opening width and also the notches should divide the stator tooth to equal parts. Fig. 17 shows the considered PMSG with one notch on each tooth.

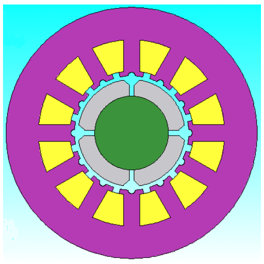


Fig. 17. PMSG with dummy slots.

Fig. 18 shows the magnetic flux emitting in the PMSG geometry. The figure also shows the high flux distributions created within the notches.

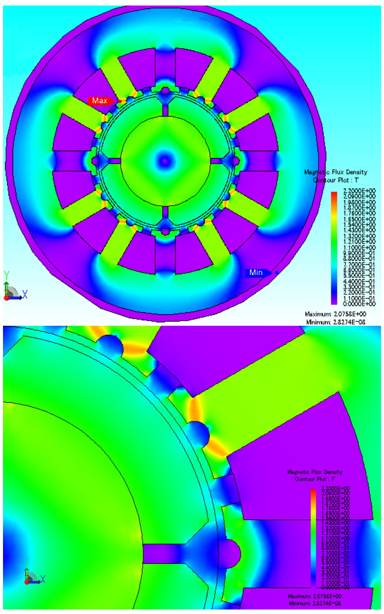


Fig. 18. Magnetic flux density in PMSG with dummy slots.

Fig. 19 shows the simulated cogging torque of the baseline prototype PMSG and the PMSG when dummy slots are used together. As the figure shows, when dummy slots are used such that the teeth of the stator are notched with equal size of the slot opening width, the frequency of the cogging torque increases compared to the baseline prototype PMSG. As also seen in the same figure, when dummy slots are used the magnitude of the maximum cogging torque decreases

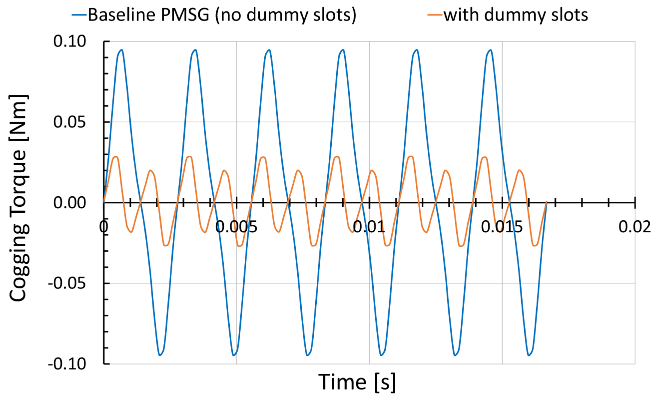
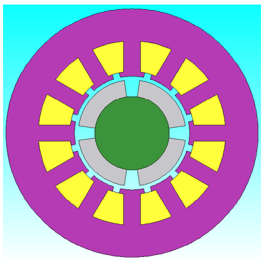


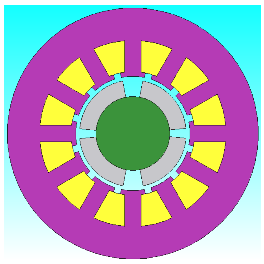
Fig. 19. Cogging torque with dummy slots.

3.6. Simulations for Permanent Magnet Shifting

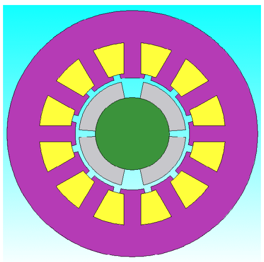
In applying the permanent magnet shifting technique, the magnets are shifted consecutively and the simulation is done after each shift. Fig. 20 shows the different permanent magnet shifting cases considered in this study.



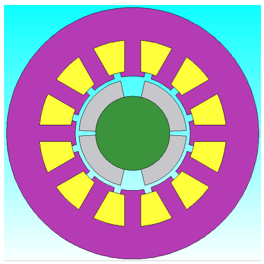
(a) no magnet shifting



(b) 5° magnet shifting



(c) 7.5° magnet shifting



(d) 10° magnet shifting

Fig. 20. Different permanent magnet shifting angles.

According to equation (6), the optimum shift angle (θ_o) is calculated as the following

$$\theta_o = \frac{2\pi}{12 \times 4} = 7.5° \qquad (8)$$

In [26] the same baseline prototype PMSG was also studied and it was concluded that the appropriate shifting angle is 7.5° based on the harmonics orders.

Fig. 21 shows the cogging torque obtained when different permanent magnet shifting is considered. Also Fig. 22 shows the change of the maximum cogging torque with respect to the permanent magnet shift angle. As seen in Fig. 21 and Fig. 22, when the permanent magnets are shifted the cogging torque reduces effectively. As calculated in equation (8), the optimum shifting angle is 7.5°. Even though at 10° magnet shift it looks like the cogging torque is decreased very small amount compared to 7.5°, we believe that this might be due to simulation numerical errors. In Fig. 17, until 7.5° angle the cogging torque decreases as the permanent magnet shift angle increases in agreement with the theoretical calculation in equation (8). Beyond 7.5° angle, the cogging torque shows almost a flat steady behavior.

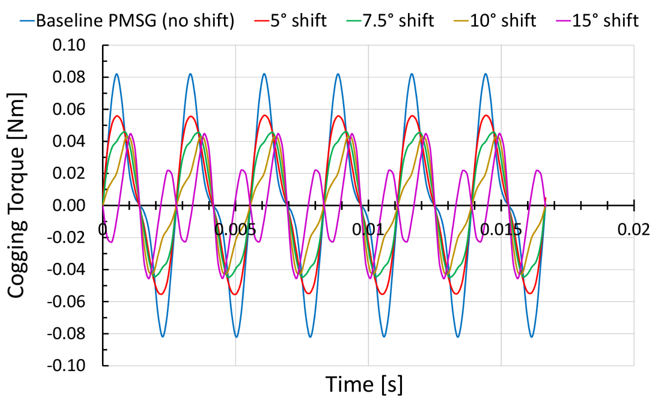


Fig. 21. Cogging torque at different PM shift angles.

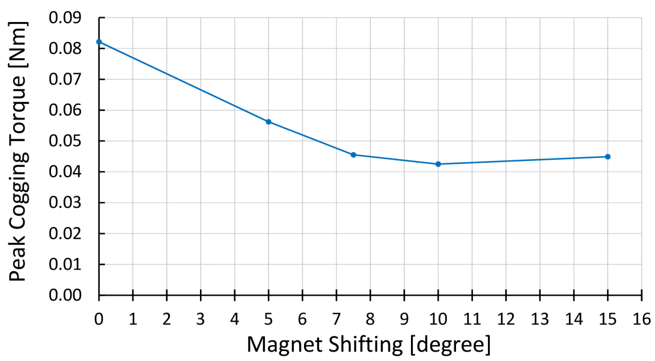
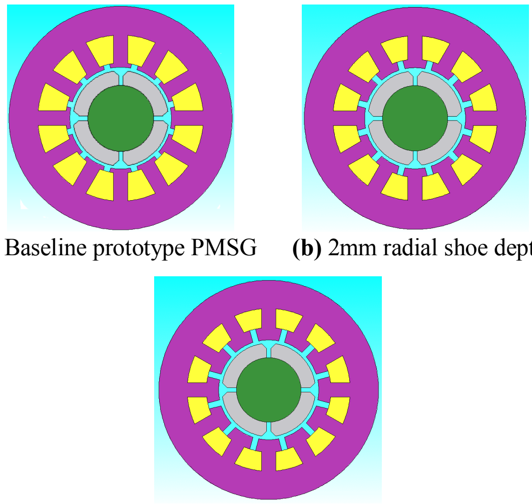


Fig. 22. Cogging torque w.r.t. magnet shift angle.

3.7. Simulations for Decreasing Radial Shoe Depth

In order to see the effect of the decreasing radial shoe depth cogging torque reduction technique, different radial shoe depths are considered. We note that, the baseline prototype PMSG has 1mm radial shoe depth. Two different cases with 2mm radial shoe depth and 3mm radial shoe depth are considered in the simulations. The considered different shoe depths are given in Fig. 23.

Fig. 24 shows the maximum cogging torque as a function of the shoe depth. As seen in Fig. 24, when the radial shoe depth is increased there is no clear cogging torque reduction, such that the maximum cogging torque almost remains the same when different shoe depths are used. This implies that radial shoe depth has almost no or negligible effect on cogging torque minimization.



(a) Baseline prototype PMSG **(b)** 2mm radial shoe depth

(c) 3mm radial shoe depth

Fig. 23. Different radial shoe depths.

Fig. 24 shows the maximum cogging torque as a function of the shoe depth. As seen in Fig. 24, when the radial shoe depth is increased there is no clear cogging torque reduction, such that the maximum cogging torque almost remains the same when different shoe depths are used. This implies that radial shoe depth has almost no or negligible effect on cogging torque minimization.

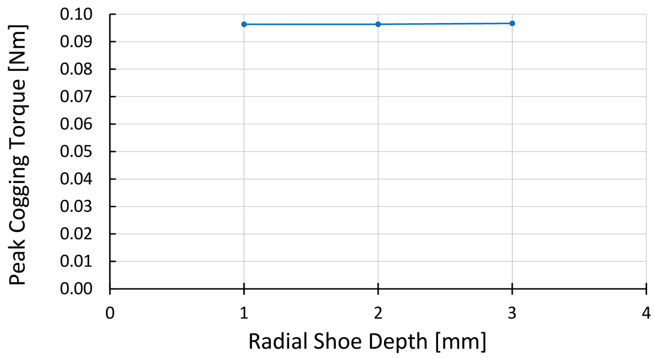


Fig. 24. Cogging torque w.r.t. radial shoe depth.

3.8. Comparison of Cogging Torque Reduction Techniques

For the six different cogging torque reduction technique considered in the present study, the percent reduction in maximum cogging torque from the baseline prototype PMSG is calculated, in order to compare them with each other. The results are given in Fig. 25. Present results show that, among the considered different approaches, when the optimum skew angle is used continuous skewing technique resulted the best cogging minimizing percentage with almost 99.9%. Following this, step skewing technique is also very effective such that the step skewing decreased the cogging torque magnitude by around 84.1% in present simulations. Decreasing the slot opening width almost show similar performance with the step skewing and present results indicate when this technique is used the cogging torque is decreased by 82.6%. Our simulations show that having dummy slots technique and permanent magnet shifting technique decrease the cogging torque with 70.4% and 48.3% respectively. Also present results indicate that decreasing the radial shoe depth have no meaningful effect in cogging torque magnitude which means that decreasing the radial shoe depth has 0% reduction in the cogging torque.

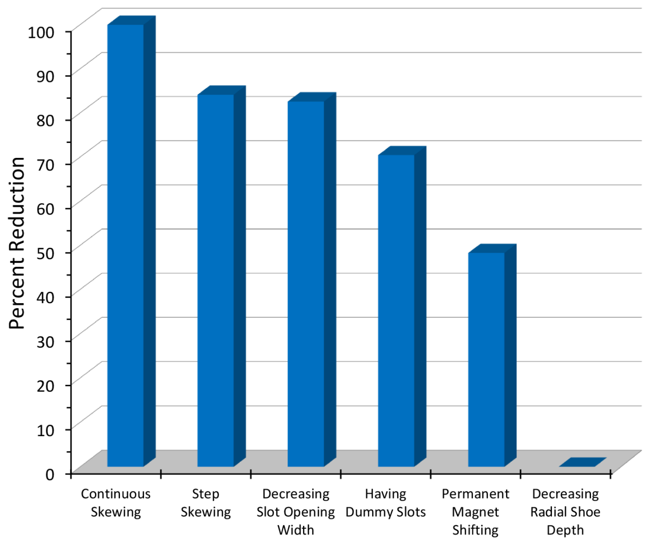


Fig. 25. Percent cogging torque reduction

4. Conclusions

Cogging torque is considered as a draw back problem for PMSGs which prevents the rotor from rotating smoothly and creates undesirable noises and vibrations. Many researches have attempted to minimize cogging torque magnitude as much as possible using different cogging reduction techniques. In this study 6 different cogging torque reduction techniques are applied on a 12 slots 4 poles baseline prototype PMSG respectively in order to compare their effectiveness with respect to each other. The cogging torque reduction techniques considered in the present study are continuous and step skewing, slot opening width variation, dummy slots, magnetic shifting and radial show depth variation. The present results show that:

- Among the 6 different cogging torque reduction technique considered in the present study, skewing is the best cogging minimizing technique when the optimum skewing angle is chosen such that skewing decreases the cogging torque more compared to the other considered techniques. Although skewing is very effective in reducing the cogging torque, it has some drawbacks also such that applying this technique can introduce some manufacturing difficulties during mass production of PMSGs. When the stator is skewed, it will be very difficult to do the slot filling automatically. When the rotor magnets are skewed, this would require special magnets to be manufactured which will increase complexity of the manufacturing and also the cost.
- In decreasing slot opening width technique, achieving the minimum cogging torque requires a small slot width size. However this can introduce complexity in slot filling during the manufacturing the PMSGs.
- In having dummy slots technique, although the dummy slots increase the frequency of the cogging torque, this technique decreases the cogging torque effectively when the appropriate number of notches are used. In terms of manufacturing, this technique introduces almost no complexity during production.
- Shifting the permanent magnets with the optimum angle leads to deleting some of the harmonics components and thus cogging torque is reduced. Permanent magnet shifting cogging reduction technique introduces very minor complexity in manufacturing.
- Although decreasing radial shoe depth helps in decreasing the high tangential components of attractive force area as mentioned in the literature, however present results indicate that this technique practically do not show any meaningful effect on the cogging torque magnitude.

Finally, while applying cogging torque minimization techniques on PMSGs may reduce the cogging torque, they may decrease the average torque of the PMSGs as well which affects the efficiency of the machine negatively. Moreover, applying those techniques on PMSGs is challenging in terms of the cost and manufacturing complexity.

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