Advancing Pole Arc Offset Points in Designing an Optimal PM Generator

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Abstract – **In this study, the offset points which locate at the pole arc of the designed 1 kW direct-drive permanent magnet synchronous generator (PMSG) have been changed based on parametric approach, and a performance rise for the designed generator has been observed by changing offset parameters. In order to obtain efficient physical sizes and electrical values of the designed generator, the pole arc offset points have been taken forward gradually by using finite element methods. The effects of different offset points on the generators performance have been simulated and interpreted graphically. It has been shown that changing pole arc offset sizes has decreased harmonics distortion and magnet weight in designing 1 kW PM generator. As a result, the 1 kW PM generator has been obtained with high efficiency, less harmonic distortions at sinusoidal wave and less PM weight at whole generator weight.**

Keywords – **permanent magnet, pole arc offset, sinusoidal wave, harmonic distortion, weight.**

1. Introduction

Nowadays the use of direct driven multi-pole permanent magnet synchronous generators (PMSG) has been increasing gradually in producing electricity because of the relatively decreased costs with novel magnet technology, easiness in power control and developments in power electronics [1]. Comparing them to conventional wind turbine generators with gear box, direct driven PMSGs have many advantages like high efficiency, high power/weight ratio, brushless structure, no need to excitation current and winding, low maintenance and setup costs and linear speed-voltage relations [2]. In literature, there are many studies on pole optimization of PMSGs with numerical and finite element analysis. These studies generally focus on optimizing the magnet geometries; by doing so, it is expected that the cogging torque(s) are reduced to lower values. Dosiek et al. have suggested magnet shifting and optimization of pole arc point methods to decrease the cogging torque in PM machines [3]. There are some other studies in literature on investigation of the effects of magnet shape and size on different machine parameters as well [4-9]. Dai and etal. have investigated rotor shape optimizing in terms of the offset arc method in permanent synchronous electric machine [12]. Zheng and etalhave determined the correctness of the magnetic field calculation in brushless DC motors [13].

Even though there are less studies on optimization of pole arc offset point and its effects on machine output parameters, however, the pole arc offset point, whether the machine is constructed with permanent magnet or field coils, is important seriously on designing synchronous generators in regard to outputs (sinusoidal voltages) and total harmonic distortion (THD). In this paper, the generator performance was analyzed by changing the value of PMSG's pole arc offset point, from 0 *to 52 mm* with *5 mm* intervals and theseexperimental values were drawn as shown in the figures. The experimental designing works have been made by changing pole arc offset' sizes. The flux lines and the stator core's flux density are investigated by finite element analysis. In addition to these analyses, the cogging torque, efficiency, output power, induced torque and voltage values are obtained and interpreted.

2. Designing parameters of PM generator

A permanent magnet synchronous machine can be constructed in different ways. In order to design the construction of PM synchronous machine, it's necessary to refer to magnetic flux in machine and rotor construction type with magnets. It is known that

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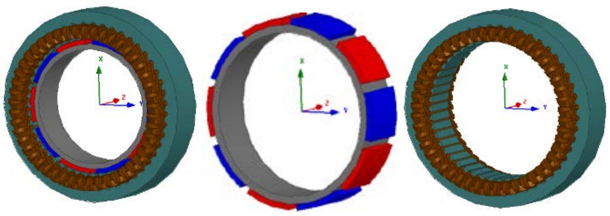
the active part of an electric machine is associated with $D^2.L$ and proportional to the rated output power [10]. This equation defines net volume of the machine regarding to its diameter and length.

The main machine dimensions and performance characteristics for this design are calculated analytically by optimizing via AnsysRmxprt and Maxwell softwares. Considering all of them, the optimum design parameters without taking into account effects of the pole arc offset point (taken as zero) are obtained as given in Table 1.

Table 1. Design parameters for 1 kW direct-drive PMSG

Stator slots	48	Coil pitch	4
Number of poles	10	Shaft Speed	600 *rpm*
Stator outer diameter	240 *mm*	Generator efficiency	93.13%
Stator length	45 *mm*	Induced voltage	60 *V*
Stator / Rotor materials	M530-50A / ST37	Pole Embrace	0.833
Magnet material	N38H	Output torque	17,76*Nm*
Air gap	1 *mm*	Output power	1 *kW*

From Table 1., it is shown that the designed generator has 48 slots, and 10 poles; it is figured out as inner rotor configuration and surface mounted magnets. Frictional, windage and stray losses are not taken into account while calculating the generator efficiency for better comparisons.



a) b) c)

Figure 1.3D models of the generator: (a) Complete view of the generator, (b) Rotor with magnets, (c) Stator with coils.

The 3D structure of the generator is created via Ansys Maxwell 3D. The entire models of the designed generator without shaft are given in Fig. 1.(a, b, c), respectively as shown in Fig. 1., magnetic direction of the air gap is radial; this type of machines iscalled radial flux machine. The magnets of the proposed generator are radially magnetized.

3. Adaptation parametric approach to generator design

Among optimization methods of electric machine designing, parametric solution method differ from others since they are practical, result-oriented and fast applicable. Parametric analytical models are built from a set of mathematical equations. In this method, pole arc offset is defined as a variable. At the beginning, an initial pole arc offset value must be assigned. Then, solution range and solution steps are identified for the variables. Solution range and solution steps are directly proportional with sensitivity and accuracy of solution.

The 1 *kW* synchronous generator's performance analysis is realized by changing the value of pole arc offset point from "0 *mm*" to "52 *mm*" with 5 *mm* intervals (0 *mm*< a < 52 *mm*) for this study. The change in the size of the magnet offset points variation can be seen in Fig. 2.

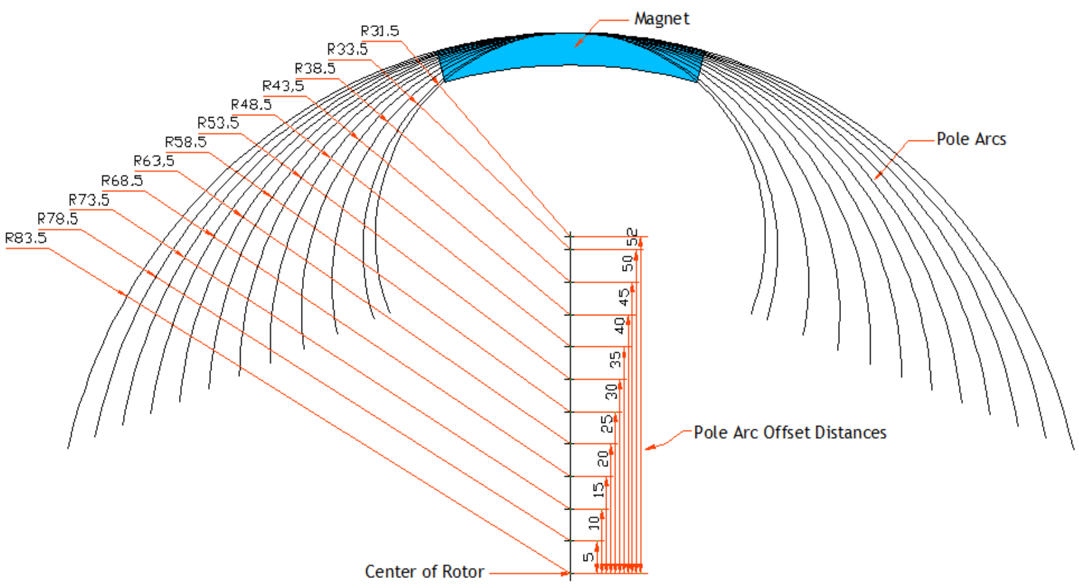


Figure 2.Variation of the parameters of pole arc offset

As the offset point value increases, the eccentricity of the tips of magnet is increased as well, and this leads to a drop in the volume of the magnet. As can be seen in Fig. 2., the maximum value of pole arc centre is “52 mm”. “52 mm” is the limit value and no more offset can be assigned for the defined pole number and outer diameter.

Fig. 2.demonstrates change of the magnet shape with variation of 0 to 52 *mm* offset distances. If the offset value would be taken “zero”, air gap distances between stator teeth and magnets keeps constant. If the offset values increases, this case will make air gap distances to become higher. The more the offset values from the centre of outer surface of magnets to magnet edges increase, the more air gap distances increase. These distances for each offset values are shown in Fig. 2.

The parametric solutions resulted by finite element analysis which points out flux lines and flux density of the stator core. In the study, these are investigated by changing the magnet offset values of the designed generator. The analysis also covers how to vary cogging torque values, efficiency, output power, induced torque and load voltage. These electrical parameters are obtained by calculating pole arc offsets for several values. The view of flux lines per different offsets, variation of flux lines and phase current, and core losses in PMSG are presented graphically as shown in figures 3 – 6.

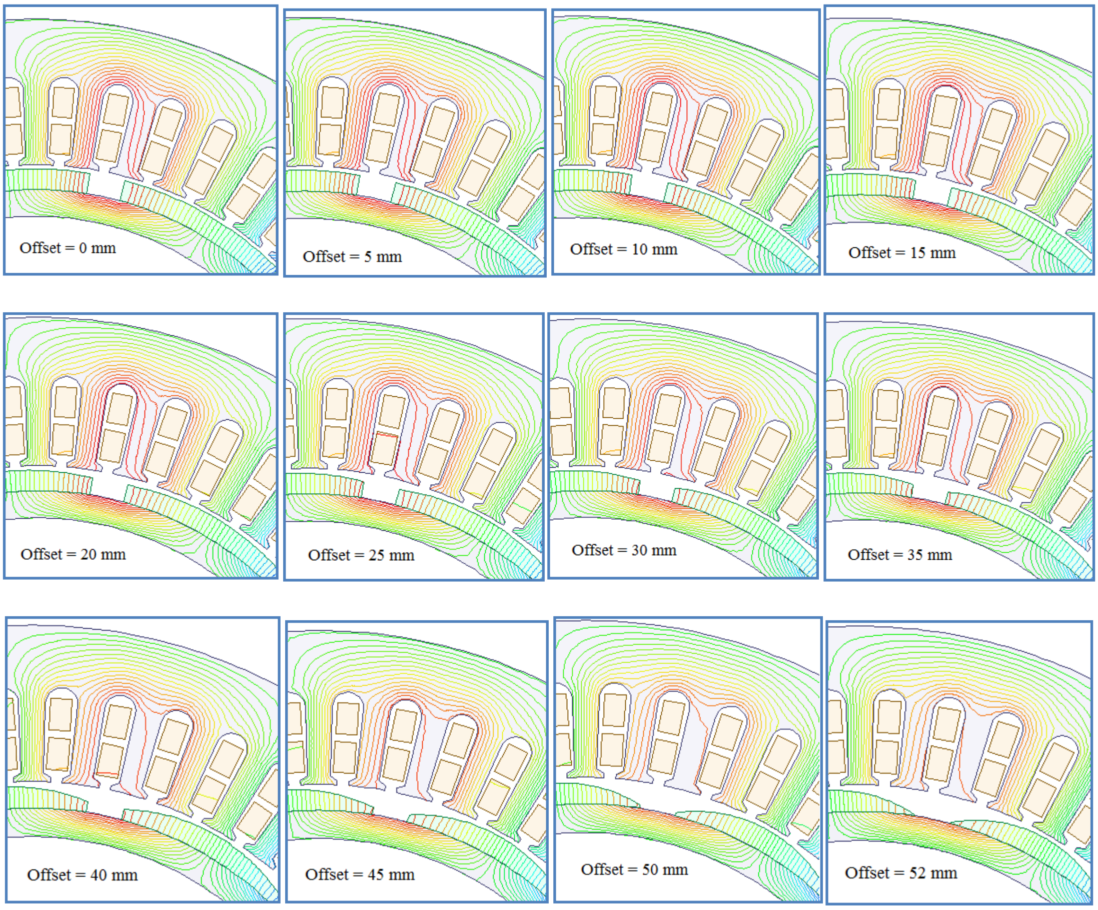


Figure 3.The view of flux lines per offset values and air gaps for 1 kW PMSG

After the pole arc offsets are assigned, the flux lines are created parametrically. The view of flux lines, and air gap dimensions’ changes are shown in Fig.3. As shown inFig. 3., the offset values are taken from 0 to 52 *mm*, and the scale for these values ischosen the same. If the offset value is taken high, the magnetic flux value in both rotor core and stator teeth shall be low; so, this satisfies the design procedure. If the offset values decrease, then the density of flux lines increases and this causes the core to be saturated, which is undesirable. Fig. 4. shows variation of the induced flux lines versus time.

It is seen from Fig. 4., as the offset varies, the induced flux lines for phase A also varies. If the offset is taken 0 *mm*, the flux shall be 0.2486 *Wb*. Alike to this situation, when the offset value is taken 52 *mm*, the flux shall be 0.2087 *Wb*. The more the pole arc offset values are increased, the more the core fluxes are decreased. Fig. 5.shows variation of the phase current versus time.

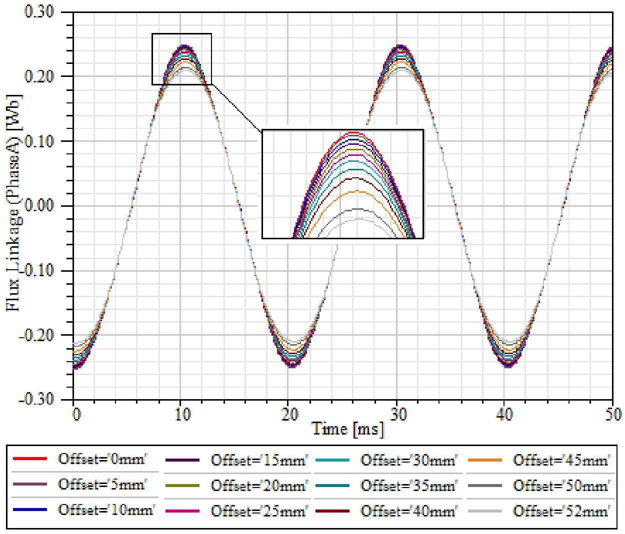


Figure 4.Variation of flux lines versus time

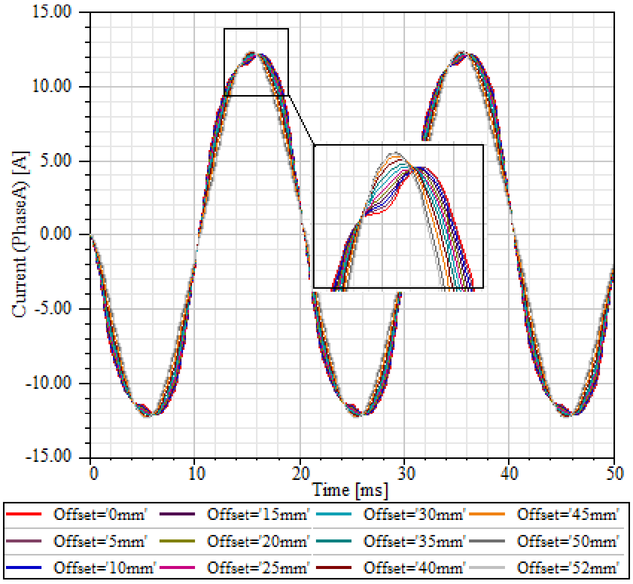


Figure 5.Variation of current in phase A versus time

It is seen from Fig. 5., as the offset varies, the current also varies. An increase in offset value causes the current to decrease. Nevertheless, there are current sags in the cases where current waveform is at the peak point. Besides, a harmonic effect for offset value can also be observed over the waveform. During design process of electrical machines, the core loss is another important parameter which has to be considered. Fig. 6.shows the parametric analysis results. It is shown from Fig. 6.that the core loss depending upon offset value is maximum while there is not any offset on magnet (offset value is "0") and it is minimum with the maximum offset. The more the offset value gets to increase, the more the generator's losses decrease.

As a result, the pole arc offset of the designed generator is assigned as a variable and the parametric solution is derived for 12 different values between "0 *mm*" and "52 *mm*".

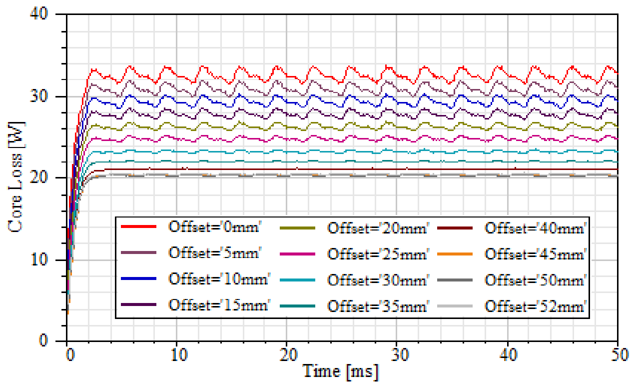


Figure 6.Variation of core loss versus time

The generator's cogging torque, efficiency, air gap flux density, THD of back EMF variables are shown graphically in Fig. 7. The change in cogging torque, in efficiency, in air-gap flux density and in THD of back EMF (%) related to pole arc offset can also be seen in this figure.

The value of cogging torque can be calculated by using (1).

$$T_{cog} = \frac{1}{2} \varnothing_g^2 \frac{dR}{d\theta} \qquad (1)$$

where Φg is air gap flux value, R is the reluctance of the air gap and θ is the position of the rotor.

This occurred by the magnetic interaction between the magnets on the rotor surface and stator teeth (source of changing air-gap reluctance) in the PM machine. This effect is undesirable, because it causes noise and vibration in the generator. The periodic variation of air-gap reluctance causes the cogging torque to change periodically. Because of this periodic variation, the value of the cogging torque can be calculated by using the Fourier series;

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

where m is the least common multiple of the number of stator and the number of poles, k is an integer and T_{mk} is the Fourier coefficient [11].

The value of cogging torque is the minimum where the offset is assigned as the lowest. The torque values increase until a certain point (45 *mm*) and then decrease slightly. Because the cogging torque is an undesirable value, it would be right to choose the point where the cogging torque is the lowest. However, the best value will be chosen by observing other output parameters with the variation of offset value.

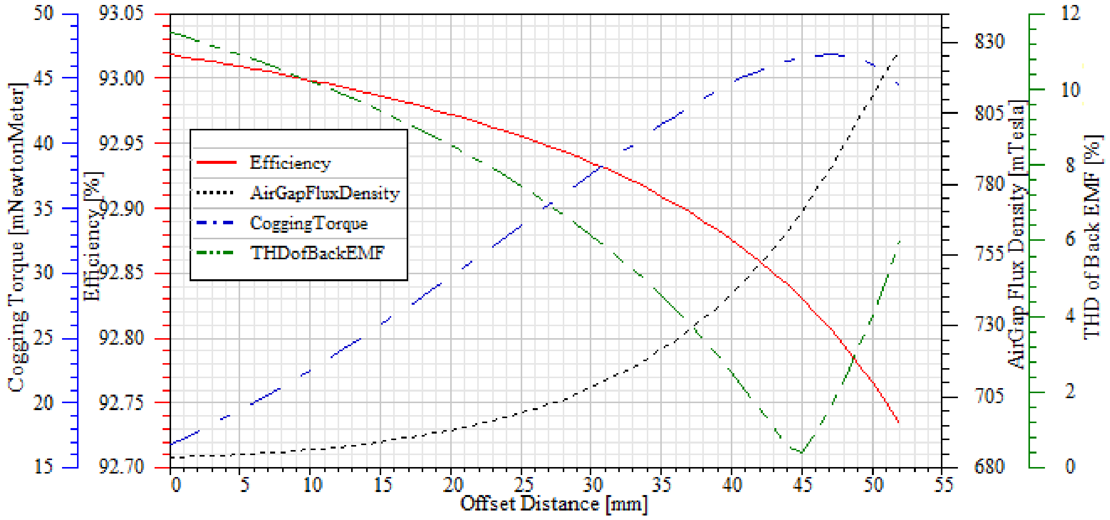


Figure 7.Effect of pole arc offset to efficiency, cogging torque, air gap flux density and THD of back EMF

Generators' efficiency can be derived by using (3);

$$\eta = \frac{P_{input} - W_{iron-per} L - W_{copper}}{P_{input}} \times 100 \quad (\%) \quad (3)$$

whereP_{input} is input power, $W_{(iron\text{-}per)}$ is iron loss per unit stack length (*W*), W_{copper} is copper loss (*W*) and *L* is the stack length of generator and is calculated by using (4);

$$L = \frac{P_{input}}{\omega_m T_{per} + W_{iron-per}} \ (mm) \quad (4)$$

whereT_{per} is average torque per unit stack length (*Nm*) and ω_m is mechanical rotational speed (*rad/s).*

As it is seen in Fig. 7., with the increasing offset value, the generator's efficiency decreases slightly. A change of 52 *mm* in offset value causes to decrease efficiency totally to 0.2532%.

Net flux density in the air gap is calculated by (5);

$$B(\theta,t) = \frac{m}{2} B_m \cos(\theta \pm \omega t) \quad (5)$$

whereB_m is the peak flux density value (T) for each phase, θ is the electrical angle (*rad*), ω is the electrical angular velocity of the current (*rad/sec*) and *m* is number of phases.

As seen from Fig. 7., if the offset value is increased, the generator's THD of back EMF (%) is decreased until a certain point (45 *mm*). When the offset value is kept as zero, THD of back EMF takes its maximum value. By taking the useful amount of offset value helps the waveform of back EMF toclose to better sinusoidal form. The change in the rated torque related to pole arc offset is shown in Fig. 8.

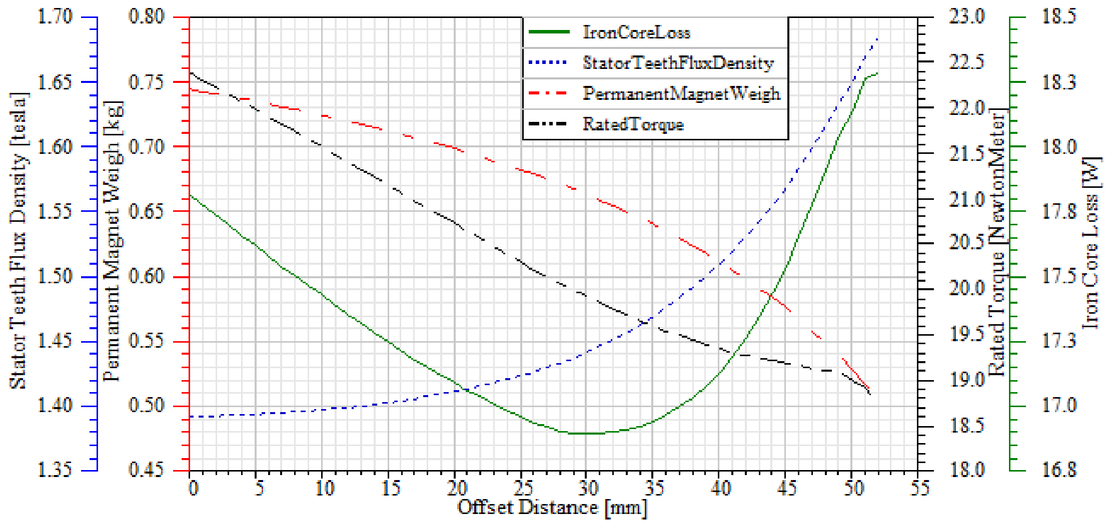


Figure 8.Effect of pole arc offset to rated torque, permanent magnet weight, iron core lossesand stator teeth flux density

As seen from Fig. 8., the torque is obtained as maximum where the offset is minimum. The magnitude of the offset value is inversely proportional with the torquecan also be shown from this figure.The difference in torque between offset's minimum and maximum values is approximately 4 *Nm*.

Fig. 8.shows an increase in the pole arc offset of the permanent magnet causes a drop in the core losses of the designed PM generator until a certain point, which is approximately 30 *mm*. Then it starts to increase due to increasing stator teeth flux density. Another important parameter that changes with the variation of the pole arc offset is total permanent magnet weight. The total permanent magnet weight is reduced from 0.745 *kg* to 0.515 *kg* since the pole arc offset is taken 52 *mm* bigger than the initial value. With the increasing offset value, the generator's total magnet weight and a result of this volume of the entire machine will decrease. The decrement at the volume shall be less about 30% of the total for an offset value ranging from 0 mm to 52 *mm* for the 5 *mm* magnet thickness.

As shown from both figures 7–8, optimal pole arc offset distance can be chosen for different design scenarios and improvements. On the one hand, it is known that magnet weight and THD of back EMF are important design parameters for PM generators and pole arc offset has a great impact on decreasing them. On the other hand, changing pole arc offsets results in evident changes in generator parameters such as efficiency, cogging torque and flux densities. In order to obtain an optimal design without compensating these parameters, each design parameters should be monitored carefully. At the end, effects of design variations such as slot skewing, pole embrace and magnet thickness should be taken into account.

It is aimed that total permanent magnet weights and THD of back EMF (*%*) of the 1 *kW*generator might decrease in the study. Table 2.gives a comparison of two separate designs in which the pole arc offset distances are 0 *mm* and 34 *mm*.

Table 2. Design comparison

Parameter	*Offset:0mm*	*Offset:34mm*
Generator efficiency	93.13%	92.92%
Output power	1039 *W*	1012 *W*
Line voltage	61.67 *V*	57.85 *V*
THD	11.5%	4.9%
Cogging Torque	0.017 *Nm*	0.04 *Nm*
PM Weight	0.74 *Kg*	0.64 *Kg*

As seen from Table 2., there is an allowable decrease in values of the efficiency, output power and line voltage while the offset distance is 34 *mm*. Increase in cogging torque can be easily reduced by giving a slot/magnet skewing or changing pole embrace. Despite that, there isa significant decrease in PM weight (as 0.1 *kg*). It is said that the total weight of the designed generator is lighter than the design where the offset size is equal to 0 *mm*. In addition to this, the THD of back EMF in line voltage waveform has been decreased from 11.5% to 4.9% totally 6.6 %. It is said that the waveform of the line voltage has been closer to sinusoidal shape as it is seen in Fig. 9.

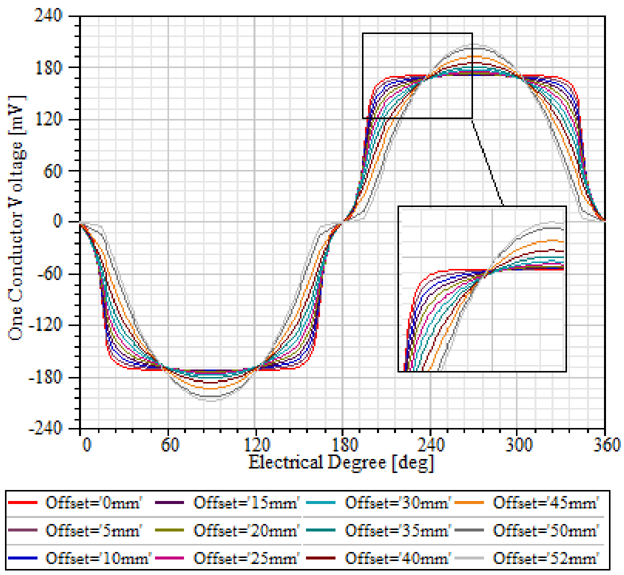


Figure 9.Variation of one conductor voltages and waveforms

4. Conclusion

In this study, the effects of the change in the pole arc offset pointto 1 kW PMSG's generator performance have been investigated. As discussed in the study, the pole arc offset point is one of the popular parameters as a design parameter which effects machine overall performance.

It has been clearly stated in the study that defining optimal pole arc offset point principally can result with better values in efficiency, output power, induced torque, cogging torque, flux distribution, core loss, induced voltage waveform, THD of back EMF and total magnet weight. It is seen from the resultsthat the cogging torque for this generator has increased totally 0.023 Nm with increasing pole arc offset. This amount in the cogging torque is negligible.

It can be concluded from the results that using parametric approach method and finite element analysis satisfies defining optimal offset point. The method proposed and the results obtained in the study can be proposed as a guideline for electric machine designers.

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