Investigation Effects of Narrowing Rotor Pole Embrace to Efficiency and Cogging Torque at PM BLDC Motor

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Abstract: **Engineers think that pole embrace size of a PM BLDC motor affects directly the efficiency and the torque. Dealing with theexperimental research, in the studywe have investigated the effects of narrowing rotor pole embrace step by step by changing sizes parametrically. By doing so, high efficiency and low cogging torque would have been obtained for a 20 W PM BLDC motor. In order to do this,pole arc to pole pitch ratio of magnets at the rotor poles has been changed parametrically (0.5 to 1) by genetic algorithm methodfirst. Then the electromagnetic field dispersions, output parameters of the motor, new rotor constructions have been obtained; and new pole embrace has been derived from the variation of pole arc to pole pitch ratio. We have also calculatedthe magnetic flux distribution, output power, torque, cogging torque and efficiency values analytically and the effects of new pole embrace to motor efficiency and torque have been simulated. The developed 18 slots, 6 poles, surface mounted inner runner configuration rotor machine is proposed as to be used insmall dentistry apparatus.**

Keywords: **PM BLDC Motor, Pole Embrace, Genetic Algorithm, Dentistry apparatus.**

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1. Introduction

Due to the excellent performances such as high torque and high efficiency,the brushless DC motors are widely used for various applications. Because of the high power density and high efficiency of BLDC motors, there has been a trend of using them in especially industrial applications[1],[2]. In this research,the effects of magnet types in rotor to power density of a spherical motor have been showed [3].

With the developments in materials science today, it is possible to produce magnets with high power density. Thereby, it has been facilitating to realize special designs for more compact PM motors. In the cases which are not meeting the requirements, the motor design should be revised [4].

In this study, the pole arc to pole pitch ratio (embrace) of the magnets that form the poles of the BLDC motors is being defined as a variable. The analyses have been done by using analytical and finite element methods via ANSYS Maxwell and RMxprt software for each defined parameter. The obtained results have been compared and the effects of the pole arc to pole pitch ratio have been examined by taking into account the flux distributions and output parameters of the motor used in the study.

2. Designing principles for brushless dc motor

The design of the electrical machines generally starts with dimensioning equation;

$$S = 11.K_{w1}.\bar{B}.ac.\left(\frac{D}{1000}\right)^2.\frac{L}{1000}.n \qquad (1)$$

where S is the motor power in terms of volt.amp, B is the specific magnetic loading, ac is the specific electrical loading, D is the stator diameter, L is the stack length of the motor, K_{w1} is the winding factor and n is the rated speed of the motor [5], [6], [7].

In the case that voltage equation of the phase A is written by using 3-phase equivalent circuit of BLDC;

$$V_a = i_a R_a + L_a \frac{di_a(t)}{dt} + e_a \tag{2}$$

The voltage equations for each phase is expressed in matrices form as seen in (2) by using (1);

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_{aa} & L_{ab} & L_{ca} \\ L_{ab} & L_{bb} & L_{bc} \\ L_{ca} & L_{ba} & L_{cc} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{3}$$

And the synchronous inductances can be calculated as;

$$\begin{aligned} L_a &= L_{aa} - M \\ L_b &= L_{bb} - M \\ L_c &= L_{cc} - M \end{aligned} \tag{4}$$

where L_a is the synchronous inductance value of phase A, L_{aa} is the self-inductance value of phase A and M is the mutual inductance value. By using (3) and (4), voltage equation can be updated as;

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

The value of the back-EMF varies related to number of turns, magnetic field intensity and rotor speed/position. If back-EMF constant is λ, then the back-EMF values for the phased can be calculated as;

$$\begin{aligned} e_a &= \omega\lambda(\theta) \\ e_b &= \omega\lambda\left(\theta - \frac{2\pi}{3}\right) \\ e_c &= \omega\lambda\left(\theta + \frac{2\pi}{3}\right) \end{aligned} \tag{6}$$

The instantaneous power produced by BLDC motor is equal to the multiplication of back-EMF and phase current. According to these assumptions, input power of BLDC motor can be calculated as (7) [8], [9];

$$P_i = i_a e_a + i_b e_b + i_c e_c \tag{7}$$

By taking into account all losses in BLDC motors, the output power of the machine can be written as;

$$P_o = P_i - \left(P_{fw} + P_{Cua} + P_t + P_{Fe}\right) \tag{8}$$

where P_i is input power, P_{fw}, P_{Cua}, P_t, P_{Fe} are frictional and windage losses, copper loss, the transistor/diode loss and iron loss, respectively. Efficiency expression which is obtained by taking into consideration output power, input power and all losses is expressed as in (9) [7];

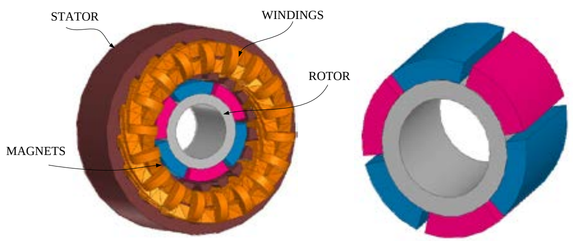
$$\eta = \frac{P_o}{P_o + \left(P_{fw} + P_{Cua} + P_t + P_{Fe}\right)} \tag{9}$$

Electromagnetic torque is obtained by (10)[9]:

$$T_e = (e_A i_A + e_B i_B + e_C i_C)/\omega \tag{10}$$

where ω is the mechanical speed in rad/s of the motor.

In this study, a 3–phase, 24V, 20W, 3000 rpm, inner-runner BLDC motor will be designed.Fig 1.shows such motor's simulated view.This motor will consist of 6 magnets which are surface mounted.



(a) (b)

Figure 1.Proposed BLDC motor; a) entire structure, b)rotor with magnets.

Regarding the proposed motor as shown in Fig.1.,the initial design parameters of the motor are calculated by using analytical method as given in Table 1.

Table 1. Initial design parameters

Permanent Magnet	N35UH
Efficiency	88.65%
Rated Power	20W
Rated Voltage	24V
Pole Number	6
Embrace	0.85
Stator Material	M270-35A
Rotor Material	ST37
Stator Outer Diameter	38.3mm
Stack Length (mm)	18mm
Number of Slots	18

FromTable 1.,in order to achieve higher motor efficiency, it can be seen that the low loss stator material and high temperature grade magnet have been chosen byconsidering thermal demagnetization of the magnet.

While θ_1 is the angle of the magnetic pole arc and θ_2 is the mechanical angle of 1 pole, pole embrace value is defined as θ_1/θ_2 [10]. If embrace value is “1”, there will not be any space between two poles as shown in Fig.2.

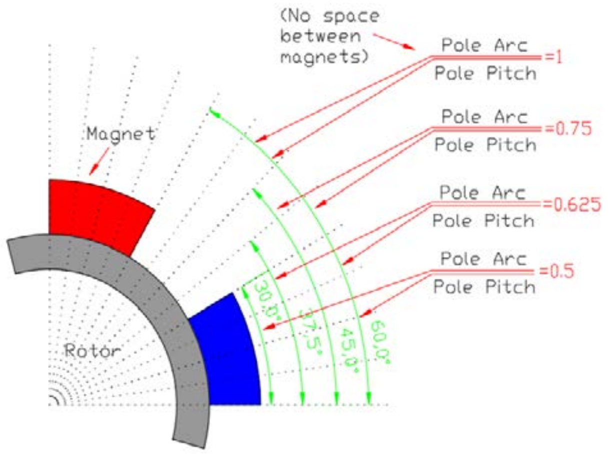


Figure 2. Variation of pole geometry versus embrace

Fig. 2.shows how the geometry of pole varies with the embrace value. Embrace value has a vital place in designing a motor or generator due to itseffects on cogging torque, efficiency, air gap flux density and so on. Defining an embrace value according to the design requirements is a complex problem that requiresa series of comparative simulations to find an optimal value.

In the study,the parametric approach, genetic algorithm and sequential non-linear programming methods are usedto define the optimal pole embrace of a 6-pole surface magnet brushless DC motor with the aid of ANSYS Maxwell package. During the achieved analyses efficiency and cogging torque parameters have been obtained related to variation of pole embrace. Thus, the pole embrace values meeting minimum cogging torque and maximum efficiency have been found for each discrete solution method.

3. Pole embrace optimization by parametrically, genetic algorithm and SNLP

Parametric solution methods used in size optimization of electrical machines are widely used due to the fact that they are practical, results-oriented and fast. For tangentially magnetized brushless DC motor, pole embrace was optimized to decrease torque ripples [10]. In the parametric solution method, a geometrical structure or electrical parameter is basically chosen and a variable parameter is defined instead of a constant value. The solution steps are determined with the lower and the upper limits and the analysis is performed at desired sensitivity. The solution range and the amount of resolution step affect the solution sensitivity directly. At this point; as the sensitivity increases, the steps of the solution will be increased, hence the computation time will be longer [11].

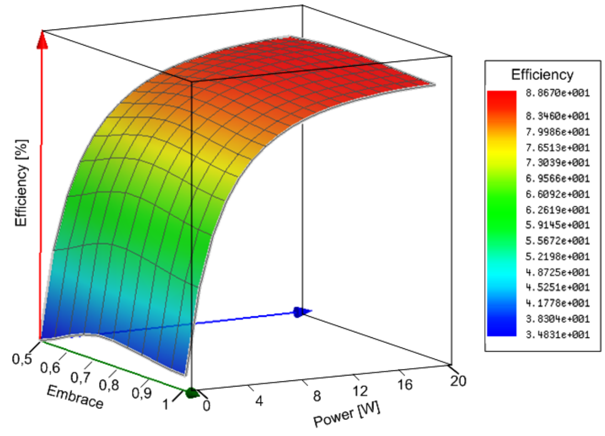


Figure 3. Efficiency related to the variation pole embrace and output power

In Fig.3., the variation of efficiency and output power of the motor related to pole embrace is given. While the motor is producing 20 W output power at 0.73 pole embrace, the highest value for the efficiency is recorded as 88.6518%. Because the motor is designed at 20W, it is away from the desired efficiency ranges at lower power rates.

The variation of all losses related to output power and pole embrace point is given in Fig. 4. As expected, the maximum loss value is reached at the highest power rate. Power loss values generated by the yield curves in Fig. 3.support each other.

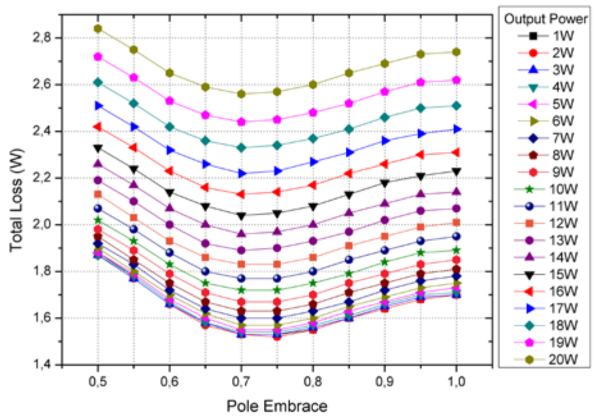


Figure 4.Total loss related to the variation pole embrace and output power

The variation of cogging torque with respect to output power and pole embrace is given in Fig.5. As seen in figure5., the cogging torque is independent of the output power.

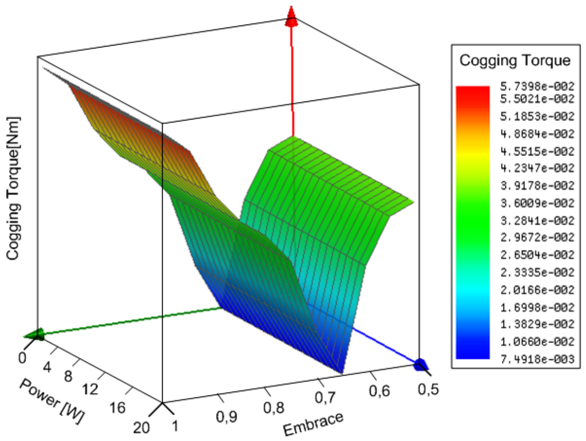


Figure 5.Cogging torque related to pole embrace and output power

From Fig. 5., when the embrace is "1", the cogging torque is obtained as 64.3159mNm maximum value; on the other hand it is seen that the cogging torque is 7.5575mNm (minimum) while the embrace is taken as 0.65.

The variation of air gap flux density obtained via analytical calculations related to output power and pole embrace is given in as shown in Fig.6.

The value of cogging torque is the minimum where the offset is the lowest. The torque value increased until a certain point (45 mm) and then decreased slightly.Because the cogging torque is an undesirable value, it would be right to choose the point where the cogging torque is the lowest.

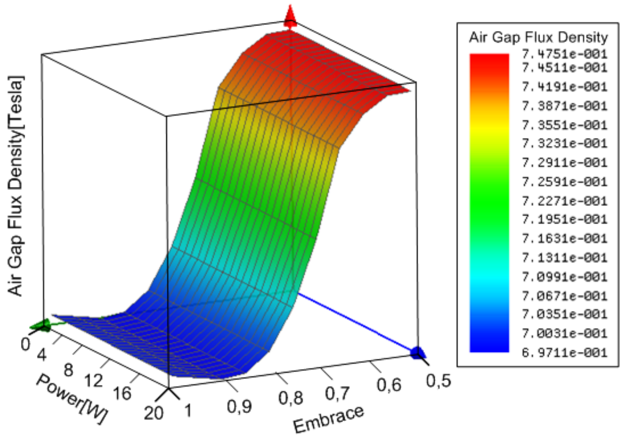


Figure 6. Variation of air gap flux density with pole embrace and output power

However, the best value will be chosen by observing other output parameters with the variation of offset value.

Genetic Algorithm (GA) optimizers are part of a class of optimization techniques called stochastic optimizers. They do not use data out of the experiment or the cost function to determine where to further explore the design space. Instead, they use a type of random selection and apply it in a structured manner. The random selection of evaluations to proceed to the next generation has the advantage of allowing the optimizer to jump out of a local minimum distance at the expense of many random solutions which do not provide improvement toward the optimization goal [12].

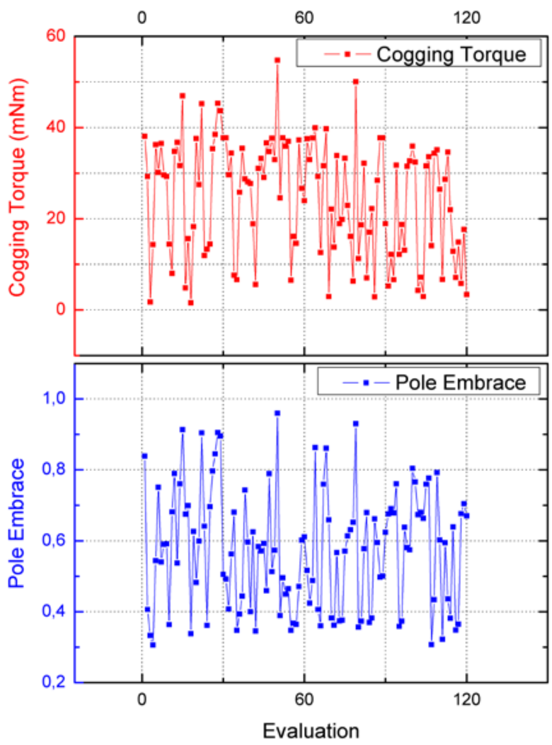


Figure 7.Calculated cogging torque values corresponding to genetic algorithm evaluations

One of the optimization methods used in software package in order to determine optimal pole embrace value is the genetic algorithm. The goal of using such a method is to find the optimal pole embrace value meeting maximum efficiency and minimum cogging torque parameters. In Fig. 7.are given the calculated cogging torque values corresponding to genetic algorithm evaluations.

In Fig.8., the efficiency values corresponding to genetic algorithm evaluations are presented in order to find optimal pole embrace. The highest efficiency value is obtained at evaluation 84 and the lowest cogging torque is obtained at evaluation 18.

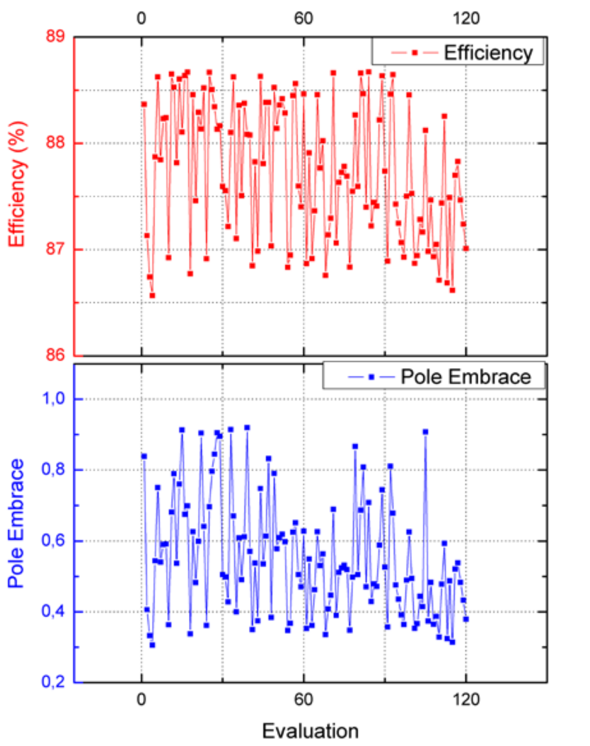


Figure 8.Calculated efficiency values corresponding to genetic algorithm evaluations

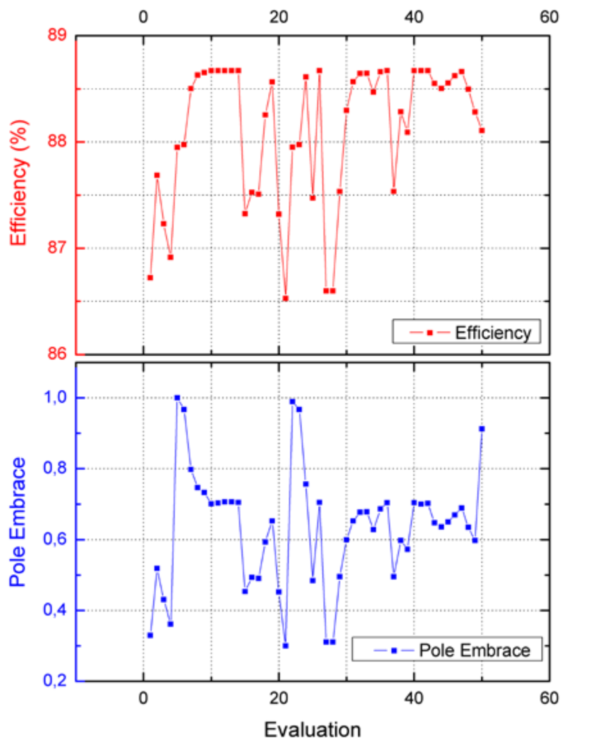


Figure 9.Efficiency and embraces as a result of SNLP optimization

The highest efficiency and corresponding pole embrace values derived from genetic algorithm evaluations are given in Fig.8. The highest efficiency is reached at evaluation 84 and 0.70869 pole embrace value.

The other optimization method found in the package is Sequential Non-linear Programming (SNLP).

The main advantage of SNLP over Quasi Newton is that it handles the optimization problem in detail. This optimizer assumes that the optimization variables span a continuous space. As a result, there is no minimum step size specified in this optimizer and the variables may take any value within the allowable constraints and within the numerical precision limits of the simulator [12]. Like Quasi Newton, the SNLP optimizer assumes that the noise is not significant. It does reduce the effect of the noise, but the noise filtering is not strong;

In the study, this method is also preferred to optimize pole embrace value and compare the results. The variation of efficiency and cogging torque as a result of SNLP optimization are also given for a comparative study.

As a result of SNLP optimization, calculated pole embrace values and number of evaluations for minimum cogging torque are given in Fig.9.

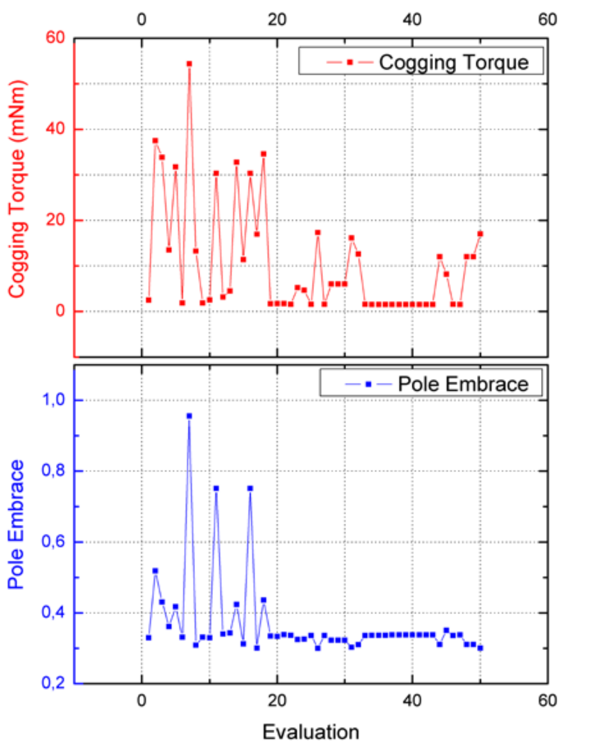


Figure 10.Cogging torque and embraces as a result of SNLP optimization

Calculated pole embrace values and the number of evaluations for maximum efficiency are given in Fig.10.

4. Results

In parametric approach; efficiency, cogging torque, air gap flux density and total power loss parameters have been obtained at rated state by varying pole embrace between 0.5 and 1. At 20W rated power; while the pole embrace is 0.73, maximum 88.65% efficiency value is recorded. During the analysis performed via GA, the embrace value is obtained as 0.709. Although the pole embrace is 0.33 where minimum cogging torque is reached, the optimal value 0.709 is chosen because of the fact that the efficiency is so low at this rate. As for the SNLP method, the maximum efficiency is obtained as 88.67% at iteration 14 and 0.704 pole embrace value. Achieved cogging torque, efficiency and optimal embrace values are summarized in Table 2.For obtaining the lowest cogging torque and the highest efficiency, optimisation results have been compared to initial design results.

Table 2. Comparison of the results

Parameter	Initial	Parametric	GA	SNLP
Efficiency (%)	88,32	88,65	88,67	88,67
Cogging Torque (Nm)	0,039	0,027	0,019	0,017
Pole Embrace	0,85	0,73	0,709	0,704

In parametric solution method, the analysis is performed step by step in order to find optimal embrace value. The analysis step is specifying both solution process and solution sensitivity. In the study, the sensitivity is chosen as 0.01. The embrace is primarily analysed at 0.5 and then jumped to 0.51. Other intervals such as 0.515 or 0.518 could not be processed. Because of that, the GA and the SNLP analyses are applied for better detailed solutions. As shown in Table 2.,the GA optimization result for best pole embrace is 0.709 and it is 0.704 for the SNLP optimization.

The comparison of cogging torque waveforms which were obtained by initial design, parametric, the GA and the SNLP optimisations are given in Fig.11. Another comparison obtained by the same methods based on efficiency-speed curve is given as shown in Fig. 12. As seen from Fig.11., a considerable decrease in cogging torque has been obtained between initial design and after optimisations. TheSNLP method gives the lowest cogging torque values by 0,704 pole embrace although there is almost no considerable change in efficiency as seen in Fig.12.

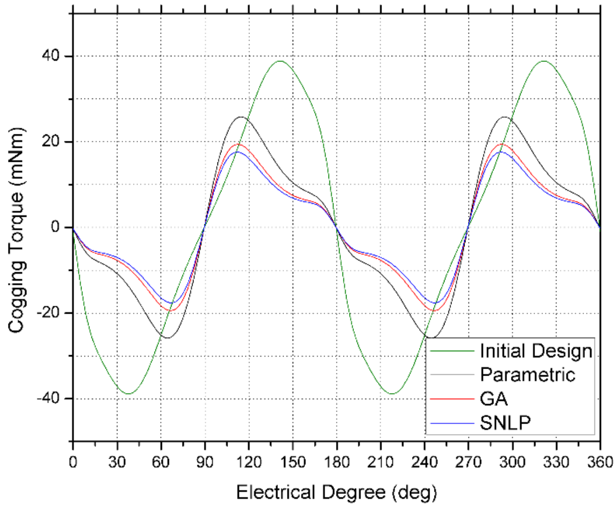


Figure 11.Comparison of cogging torque waveforms between two teeth

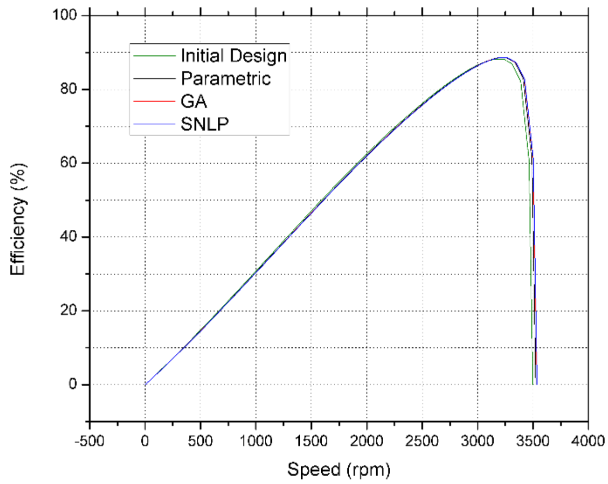


Figure 12.Comparison of efficiency-speed curves

Efficiency-speed curves obtained by proposed methods with different embrace values are almost identical and prove that it's possible to optimize the cogging torque profile without any decrease or critical change in efficiency.

5. Conclusion

In this research, the value of pole embrace for a 20W PM BLDC motor was optimized and the effect of this parameter on motor performance was investigated. Based on the research, the analysis and the calculations have brought the following conclusions:

Pole embrace parameter has a significant effect on motor efficiency and motor cogging torque for PM BLDC motors.

Pole embrace parameter derived from analytical calculations can be easily optimized by using different optimization techniques.

The methods applied in the work and the results obtained in the paper are intended to provide a very useful output for motor designers.

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