

Optimal Design of Six-phase Outer-rotor Permanent Magnet Synchronous Motor Via the Particle Swarm Technique

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Permanent Magnet Synchronous Motors (PMSMs) are no longer unfamiliar to industrial applications due to their high torque and power density, high efficiency, reliability and excellent dynamic performance. Six-phase PMSMs represent an important step forward in enhancing overload capability and fault tolerance of these motors. With outer rotor (OR), PMSMs increase the ability to produce more torque, making them especially suitable for traction applications i.e. ship propulsion, lifting, mining, oil exploitation, etc. This study proposes an optimal design strategy for six-phase OR SPMSM using particle swarm optimization (PSO). Firstly, an analytical method is introduced to calculate the main dimensions of a 155kW six-phase OR PMSM with 10-pole/30-slot combination. Next, an optimal method using PSO is developed by MATLAB programming with objective functions focusing on minimizing total losses of iron and copper as well as material cost. The finite element method is then employed to calculate electromagnetic parameters of motors to validate the accuracy of the proposed analytical method and optimal design. The results of the motors are analyzed and compared, showing that after optimization process, the efficiency of the motor increases by 0.2% along with a reduction of 54\$ in material cost. Moreover, other electromagnetic parameters such as back EMF THD, torque ripple are improved in comparison to the initial motor design.

Index Terms—PMSM, optimization method, particle swarm optimization, analytical method, finite element method

I. INTRODUCTION

Recently, many studies have conducted research on design optimization of six-phase motors. In Ref. [1], an optimization approach for a 36-slot/34-pole six-phase PMSM using supervised machine learning with the objective functions of maximize torque density and minimize torque ripple was proposed. The results on average torque, torque ripple, efficiency and cost of the initial model and the optimal model were performed. In Ref. [2], an analytical magnetic equivalent circuit modelling for a six-phase SPMSM with FSCW configuration for integrated onboard chargers was first introduced. Next, the optimal design using multi-objective genetic algorithm was presented with the objective functions of torque ripple, core losses under both monitoring and charging modes, electromagnetic forces and demagnetization capabilities under charging, and overall cost. The simulation results showed that the selection of the pole/slot combination highly affect the performance of the motor under both operational modes. A higher slot/pole combination results in a decrease in permanent magnet (PM) volume. As a result, PM losses are significantly reduced in both operational modes, while still achieving the same average torque in propulsion mode. The analytical model for six-phase PMSMs play a crucial role not only for optimal designs but for other studies later such as equivalent reluctance network. In Ref. [3], authors have also successfully proposed the analytical calculations for six-phase SPMSM with outer rotor (OR) configuration and verified by the FEM. It is shown that the IPM has better performance with the same drive system condition in comparison to the SPM. However, the SPM is still used in many applications due to their simple control system and magnetic circuit structure [4]. The OR PMSMs have larger torque density than the IR PMSMs, which means the ORs can produce more torque, making them suitable for traction applications [5]. Moreover, in low-speed direct drive systems, the PMSMs become the best choice for

applications in the fields of ship propulsion, lifting, mining, oil exploitation [6]. The fractional-slot concentrated winding (FSCW) is highly suited to such low-speed applications as the offer more poles and large torque density [7]. This type of winding has the advantages of short end winding and less copper loss at low frequency, but it also has some drawbacks such as lower winding factor, high amplitude of harmonic components of magnetomotive force distribution in comparison to the integral-slot winding [8], [9], [10], [11], [12]. Therefore, designers must consider carefully the pole/slot combinations to reduce the disadvantages of the FSCW.

Six-phase systems can be divided into three types based on the angle between each phase, which are dual three-phase systems (0°), asymmetrical six-phase systems (30°), and symmetrical six-phase systems (60°). The asymmetrical six-phase systems find better performance when compared to the two other systems due to its low torque ripple when operating with six-phase inverter. However, symmetrical six-phase and dual three-phase systems can be considered as two promising options as they can provide similar performance as asymmetrical six-phase systems [13]. The six-phase motors have some crucial advantages over the three-phase motors, including higher overload capability and higher fault tolerance. In six-phase motors, not only the phase current are shared into more phases, but also providing robust control strategies during faults by enabling three-phase system, four-phase system, and five-phase system to continue operation when one or more phases meet faults within the motor [14], [15]. Additionally, six-phase motors exhibit higher efficiency along with the reduction of torque ripple due to lower amplitude of harmonic components of flux linkage in comparison to three-phase motors [16], [17], [18].

Some studies have conducted research on design optimization of six-phase motors. In Ref. [19], a six-phase permanent-magnet-assisted synchronous reluctance motor (PMa-SynRM) was designed using the lumped-parameter method (LPN) and genetic algorithm. The effectiveness of the optimal design was

verified by comparing the results from FEM, LPN, and experimental test. The results after optimization by LPN showed the increase of the efficiency from 94.2% to 95.1% and the reduction of the torque ripple from 12.1% to 4.9% at the speed of 4500 rpm. The FEM results showed the small differences when compared to the results from LPN. The torque characteristics results in relation to current from FEM were also compared to test results which showed the differences lower than 7% except for 14.3% error at 2A and 6° of load angle. Ref.[20] proposed an optimization approach for a 36-slot/34-pole six-phase PMSM using supervised machine learning with the objective functions of maximize torque density and minimize torque ripple. The results on average torque, torque ripple, efficiency and cost of the initial model and the optimal model were performed. In Ref.[21], a design optimization method using Kriging model was proposed for a 12-pole/10-slot six-phase Switched Reluctance Motor (SRM) with the purposes of reducing the current asymmetric and consequent torque ripple. Moreover, the optimization problem was performed not only based on structural design optimization, but also asymmetric control, and the best solution from optimization process was chosen for the drive system. The results from FEM showed that the acceptable errors within 10% when compared to the optimization results. The proposed asymmetric control method also slightly reduced the torque ripple in comparison to the traditional symmetric control method. The results from FEM were then compared to experimental test results, which also showed that proposed asymmetric control method can enhance the symmetric control method of phase currents and decreased the torque ripple. In Ref.[22], an analytical magnetic equivalent circuit (MEC) modelling for a six-phase SPMSM with FSCW configuration for integrated onboard chargers was introduced with the BMW i3 design specification. Next, the optimal design using multi-objective genetic algorithm was presented with the objective functions of torque ripple, core losses under both monitoring and charging modes, electromagnetic forces and demagnetization capabilities under charging, and overall cost. The FEM was applied to verify the results obtained from analytical MEC model. The optimization results showed that the purposes cannot be achieved simultaneously. Therefore, six motors with best compromise have been highlighted. The simulation results showed that the selection of the pole/slot combination highly affect the performance of the motor under both operational modes. A higher slot/pole combination results in a decrease in PM volume. As a result, PM losses are significantly reduced in both operational modes, while still achieving the same average torque in propulsion mode. With higher slot/pole combinations, torque ripple is reduced in both operational modes, along with lower core losses during charging.

The analytical model for six-phase PMSMs play a crucial role not only for optimal designs but for other studies later such as equivalent reluctance network. In the previous studies, we have successfully proposed the analytical calculations for six-phase OR SPMSM and verified by FEM in [23], [24]. Moreover, we have introduced the analytical calculations and the optimal model using genetic algorithms (GA) for three-phase IR SPMSMs in [25], [26], [27]. In this paper, with the proposed analytical model of six-phase OR SPMSM, an optimal model is

introduced using particle swarm optimization (PSO) which is programmed by MATLAB to minimize total losses of iron and copper as well as material cost of a six-phase OR SPMSM with the power level of 155kW for traction applications. The FEM is then employed to verify and compare the objective functions and electromagnetic parameters of the model before and after optimization.

II. ANALYTICAL DESIGN OF A SIX-PHASE OR SPMSM

In this section, a six-phase OR SPMSM with power level of 155kW is considered. The design requirements of the motor are given in Table 1.

TABLE 1. DESIGN REQUIREMENTS OF THE SIX-PHASE OR SPMSM.

Parameter	Value	Unit
Output power	155	kW
DC Bus voltage	600	V
Number of phases	6	Phase
Number of slots	30	Slot
Number of pole pairs	5	Pole pair
Output torque	970	Nm

For the PMs, three types of magnet are commonly used for PMSM which are Neodymium Iron Boron (NdFeB), Samarium Cobalt (SmCo), and Ferrit. Due to highest magnetic properties of all rare-earth magnet materials, NdFeB is usually the best choice for PMSMs due to their high efficiency and power density [28]. Therefore, in this study, NdFeB N38SH is employed with the demagnetization curve is presented in Figure 1.

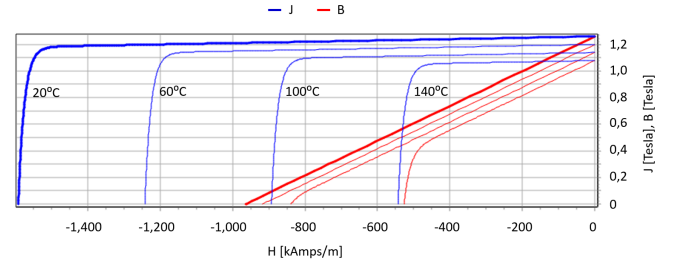


Fig. 1. Demagnetization curves for N38SH

As can be seen in Fig.1, the remanence of NdFeB N38SH reaches 1.26T with the coercive force of nearly 1000kAmps/m. Working point of PMs of 0.9T is chosen in calculating other parameters. The airgap flux density is important in determining the dimensions of PMs. With SPM type, the airgap flux density is calculated as:

$$B_g = \frac{4}{\pi} \sin(\alpha) B_m \quad (1)$$

where α is the coverage angle of PM and B_m is the working point of flux density of the PM. The main dimensions of the magnetic core is shown in Fig.2, where D_{ir} is the inner rotor diameter; g is the airgap length, h_{sy} is the height of stator yoke; h_{ry} is the rotor yoke, L is the length of the stator and rotor L ; b_{so} is the slot opening; h_{so} the height of tooth; w_t is the width of tooth; b_{s1} is the above width of slot; b_{s2} is the bottom width of slot; h_s is the height of slot.

The thickness of the PM is computed as

$$d_m = \frac{\mu_m g_{eff}}{\frac{B_r 4 \sin(\alpha)}{B_g \pi} - 1} \quad (2)$$

Variables	Upper boundaries	Lower boundaries
x_1	1	1.55
x_2	290	310
x_3	20	25
x_4	20	25
x_5	10	15
x_6	9.5	10.5
x_7	160	170

Combined with the upper and lower boundaries, constraint functions help limit the search space for the algorithm. Therefore, the constraint functions are an unignorable part of the algorithm. In this study, four constraints are chosen, which are flux density on stator yoke, rotor yoke, and stator tooth as well as the slit fill factor with the ranges as below:

- Constraint 1:

$$1 \leq \frac{\pi B_m V_m (B_r - B_m)}{8 k_j V_s \mu_m k_c B_m} \cdot \frac{x_2^2}{x_1 x_3} \leq 1.5$$

- Constraint 2:

$$1 \leq \frac{\pi B_m V_m (B_r - B_m)}{8 k_j V_s \mu_m k_c B_m} \cdot \frac{x_2^2}{x_1 x_4} \leq 1.5$$

- Constraint 3:

$$1.5 \leq \frac{\pi p B_m V_m (B_r - B_m)}{2 Q k_j V_s \mu_m k_c B_m} \cdot \frac{x_2^2}{x_1 x_5} \leq 2$$

- Constraint 4:

$$0.45 \leq \frac{x_2 - 2A_1 x_1 - 2A_2 - 2x_3 - x_7}{2} \cdot \left[\frac{\pi(x_2 - 2A_1 x_1 - 2A_2 + x_7 + x_3)}{Q} - 2x_5 \right] \leq 0.55, \text{ where: } A_1 = \frac{\mu_m k_c B_m}{B_r - B_m} + 1; A_2 = h_{so} + h_w$$

The objective functions are the final part and the target of an optimization problem. Choosing and constructing the objective functions are crucial as they decide how optimal the motor can be. Therefore these functions must be considered carefully. In this paper, two parameters are defined and constructed as objective functions which are the total losses of iron and copper, and material cost. These objective functions are written in detail as below:

-Objective function 1: Total losses of iron and copper

$$f_1(x_1, x_2, x_3, x_4, x_5, x_6, x_7) = M_s p_{ts} + M_r p_{tr} + M_t p_{tt} + Q I^2 R, \quad (12)$$

where M_s, M_r, M_t stand for the iron mass of stator yoke, rotor yoke, and stator tooth; p_{ts}, p_{tr}, p_{tt} represent the core loss factors on stator yoke, rotor yoke, and stator tooth; I and R are the phase current and the resistance of each coil.

$$M_s = 4V_s \gamma_{Fe} k_j \frac{x_3 x_7 + x_3^2}{x_2^2}, M_r = 4V_s \gamma_{Fe} k_j \frac{x_2 x_4 + x_3^2}{x_2^2},$$

$$M_t = L \gamma_{Fe} \left\{ \frac{\pi}{4} [(x_2 - 2x_1)^2 - (x_7 + 2x_4)^2] - Q \left[\frac{h_s}{2} (b_{s1} + b_{s2}) + h_{so} b_{so} + \frac{h_w}{2} (b_{so} + b_{s1}) \right] \right\},$$

$$p_{ts} = k_h f \left[\frac{\pi B_m V_m}{2V_s k_j (A_1 - 1)} \right]^{1.7} \left[\frac{(x_2 - 2x_1)^2}{x_1 x_3} \right]^{1.7} + k_e f^2 \left[\frac{\pi B_m V_m}{2V_s k_j (A_1 - 1)} \right]^2 \left[\frac{(x_2 - 2x_1)^2}{x_1 x_3} \right]^2,$$

$$p_{tr} = k_h f \left[\frac{\pi B_m V_m}{2V_s k_j (A_1 - 1)} \right]^{1.7} \left[\frac{(x_2 - 2x_1)^2}{x_1 x_4} \right]^{1.7} + k_e f^2 \left[\frac{\pi B_m V_m}{2V_s k_j (A_1 - 1)} \right]^2 \left[\frac{(x_2 - 2x_1)^2}{x_1 x_4} \right]^2,$$

$$p_{tt} = k_h f \left[\frac{\pi p B_m V_m}{2V_s k_j Q (A_1 - 1)} \right]^{1.7} \left[\frac{(x_2 - 2x_1)^2}{x_1 x_5} \right]^{1.7} + k_e f^2 \left[\frac{\pi p B_m V_m}{2V_s k_j Q (A_1 - 1)} \right]^2 \left[\frac{(x_2 - 2x_1)^2}{x_1 x_5} \right]^2,$$

$$R = \frac{\rho_{Cu} L_{dq}}{I} x_6,$$

Where γ_{Fe}, ρ_{Cu} stand for electrical steel density and copper resistivity; V_s, V_m represent the volume of stator and magnet; L_{dq} is the length of the winding each coil.

$$L_{dq} = 2 \left[\text{floor} \left(\frac{\sqrt{h_s^2 + (b_{s1} - b_{s2})^2}}{d_{co}} \right) \right] \cdot \left\{ 4d_{co} \cdot \left[\text{ceil} \left(\frac{2n_1 N}{\text{floor} \left(\frac{\sqrt{h_s^2 + (b_{s1} - b_{s2})^2}}{d_{co}} \right)} \right) - 1 \right] + \frac{8V_s}{\pi(x_2 - 2x_1)^2} + 2x_5 \right\} + 2 \left\{ 2n_1 N - 3 \left[\text{floor} \left(\frac{\sqrt{h_s^2 + (b_{s1} - b_{s2})^2}}{d_{co}} \right) \right] \cdot \left\{ 2d_{co} \cdot \left[\text{ceil} \left(\frac{2n_1 N}{\text{floor} \left(\frac{\sqrt{h_s^2 + (b_{s1} - b_{s2})^2}}{d_{co}} \right)} \right) - 1 \right] + \frac{8V_s}{\pi(x_2 - 2x_1)^2} + 2x_5 \right\} \right\}, \text{ where:}$$

$$h_s = \frac{x_2 - 2A_1 x_1 - 2A_2 - 2x_3 - x_7}{2},$$

$$b_{s1} = \frac{\pi(x_2 - 2A_1 x_1 - 2A_2)}{Q} - x_5,$$

$$b_{s2} = \frac{\pi(x_7 + 2x_3)}{Q} - x_5.$$

-Objective function 2: Material cost

$$f_2(x_1, x_2, x_3, x_4, x_5, x_6, x_7) = c_{Fe} M_{Fe} + c_{Cu} M_{Cu} + c_m M_m \quad (13)$$

Parameters c_{Fe}, c_{Cu}, c_m are the cost per kilogram of electrical steel, copper, and magnet; M_{Fe}, M_{Cu}, M_m are the total mass of steel, copper, and magnet, respectively.

$$M_{Fe} = M_s + M_r + M_t, M_{Cu} = \frac{\gamma_{Cu} L_{dq} I}{n_1} \cdot \frac{1}{x_6}$$

$$M_m = 2p \gamma_m V_m$$

After the optimization process, the dimensions the model before and after optimization are applied into FEM to calculate the electromagnetic parameters and compared to each other in the

next part.

IV. OPTIMIZATION AND NUMERICAL RESULTS

In this section, a six-phase SPMSM with the OR configuration is consider with required parameters: Output power of 155kW, DC bus voltage of 600V, phase number of 6 (phase), slot number of 30, number of pole pairs of 5 (slots) and output torque of 970 N.m.

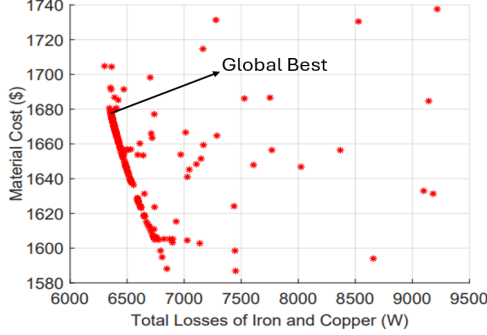


Fig. 1. Relation between objective functions through iterations and global best position.

As presented, the PSO returns only a single global best value. However, it is easier to see the position where the global best locates by showing the personal best through the iterations in Fig. 1. The global best value corresponds to the values of optimal variables as: $x_1 = 1.55$ mm; $x_2 = 301.55$ mm; $x_3 = 20$ mm; $x_4 = 22$ mm; $x_5 = 12.83$ mm; $x_6 = 9.5$ (A/mm²); $x_7 = 170$ mm. With the values of optimal variables as shown above, the dimensions of the optimal model are recalculated. The dimensions of model before and after optimization are given in Table 3 as below:

TABLE 3. MAIN DIMENSIONS OF THE INITIAL MODEL AND THE OPTIMAL MODEL OF 155KW SIX-PHASE OR SPMSM

Parameter	Before Optimization	After Optimization
Outer rotor diameter (mm)	419.3	421
Back iron thickness (mm)	22.7	22
Magnet thickness (mm)	4.1	4.3
Magnet Arc (EDeg)	140	134.75
Air gap length (mm)	1.5	1.55
Outer stator diameter (mm)	288.8	289.9
Slot opening height (mm)	2	2
Slot opening width (mm)	5	5
Wedge height (mm)	2	2
Tooth width (mm)	12.6	12.82
Slot height (mm)	33	34
Inner stator diameter (mm)	169.5	170
Number of turns per coil (turns)	4	4
Number of strands in hand (conductors)	15	15
Wire diameter (mm)	1.25	1.28

Both the initial model and optimal model are employed step rotor skewing technique with 5 magnet segments. The skew angle of each segment is shown in Table 4 as:

TABLE 4. SKEW ANGLES OF MAGNET SEGMENTS.

Slice	Proportional length	Angle (MDeg)
1	1	-6

2	1	-3
3	1	0
4	1	3
5	1	6

The maps of flux density distribution of the model before and after optimization are shown in Fig.2.

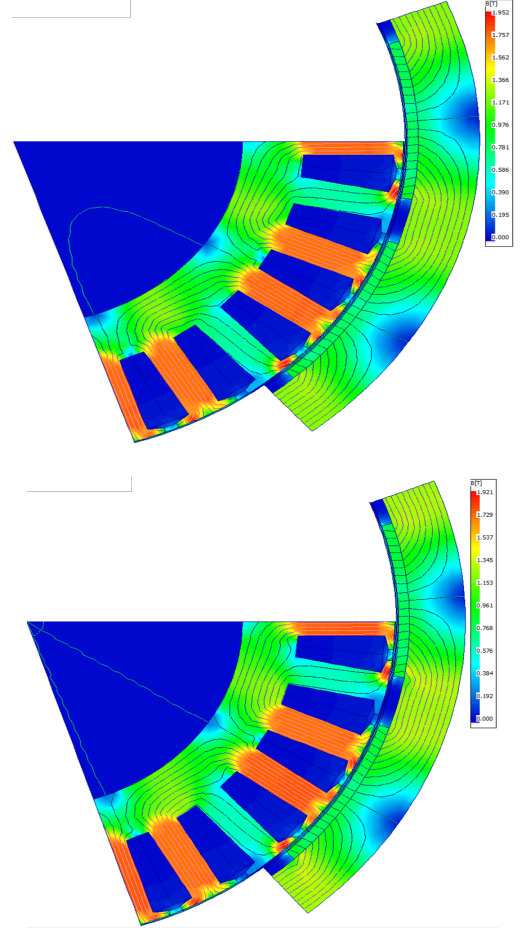


Fig. 2. Maps of flux density distribution before (left) and after (right) optimization

The maximum values of flux density on the magnetic circuit before and after optimization are 1.952T and 1.921T respectively. These two values still lay on the linear part of the magnetization curve of the steel sheet so they do not make any problems in the normal operation of the motor. The airgap flux density is an important parameter as it decides the THD of the back EMF. The radial air gap flux density of SPMSM must be sinusoidal as much as possible in the load condition of the motor to ensure the low amplitude of high harmonic components of the back EMF. The waveform of radial airgap flux density in load condition before and after optimization are presented in Figure 3 as below.

As can be seen, the waveform is mostly sinusoidal with the value of THD only 0.9%. The amplitude of harmonic components of back EMF before and after optimization in Figure 5 show the decrease in the amplitude of the 5th harmonic order of the optimal model in comparison to the initial model, leading to the reduction of back EMF THD, which is the desirable result.

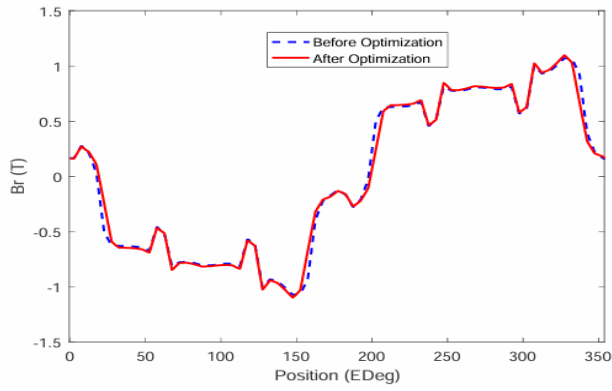


Fig. 3. Radial air gap flux density waveform in load condition before and after optimization

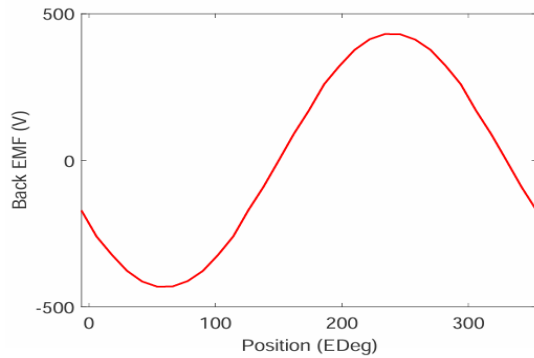


Fig. 4. Back EMF waveform after optimization.

The back EMF waveform after optimization is presented in Figure 5.

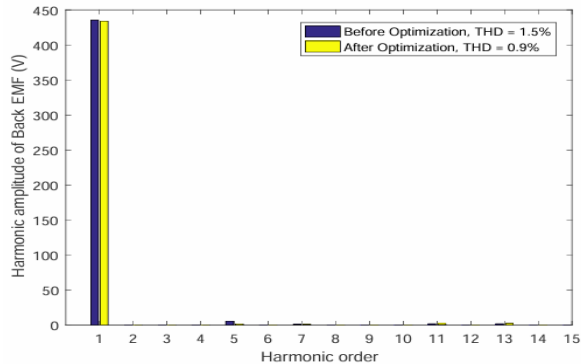


Fig.5. Amplitude of harmonic components of back EMF before and after optimization.

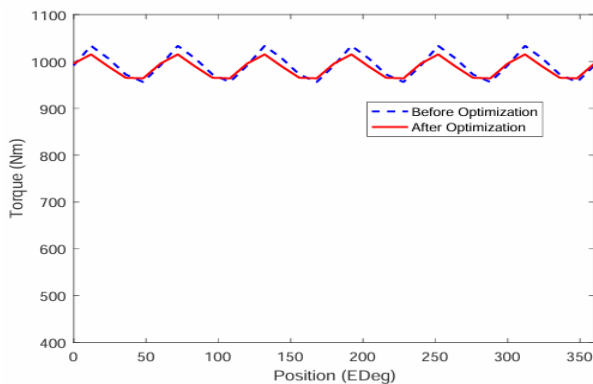


Fig. 6. Output torque waveform before and after optimization.

Figure 6 and Figure 7 show the results of output torque waveform and torque ripple of the two models. It is clear that after optimization, the torque ripple is reduced, from 8.6% of the initial model to 6.1% of the optimal model, which means the torque characteristic is also enhanced. With the values of optimal variables as shown above, the dimensions of the optimal model are recalculated. The output results the the models are given in Table 5.

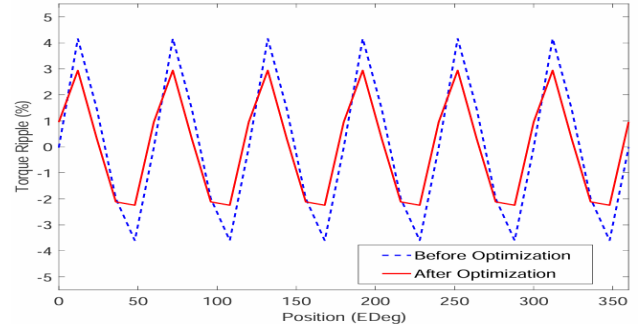


Fig.7. Torque ripple waveform before and after optimization

TABLE 5
ELECTROMAGNETIC PARAMETERS BEFORE AND AFTER OPTIMIZATION

Parameters	Before optimization	After optimization
Output power (kW)	155	155.06
Output torque (Nm)	970	970.3
Torque ripple (%)	8.6	6.1
Efficiency (%)	95.18	95.354
DC Loss (W)	4868	4554
Magnet loss (W)	497.2	479.5
Stator iron loss (W)	2450	2490
Rotor iron loss (W)	31.53	30.21
Total loss (W)	7847	7554
THD back EMF (%)	1.5	0.9
Material cost (\$)	1727	1673

It can be seen that after the optimization process, the efficiency increase nearly 0.2% and the material cost decrease 54\$. This means the two objective functions, i.e total loss of iron and copper, and material cost reach the targets. Moreover, the electromagnetic parameters and output parameters also have the enhancement with the reduction of 0.6% back EMF THD and 2.5% torque ripple. These are all the desirable results after the optimization process.

V.CONCLUSION

The PSO is successfully constructed by MATLAB programming for optimal design of the practical problem. The obtained results have shown that the optimal model has the advantages over the initial model. The total losses decrease, leading to the growth of the efficiency. Moreover, the material cost decreases 54\$ from 1727\$ down to 1673\$. The other electromagnetic parameters also have the improvement. The back EMF THD reduce 0.6% from 1.5% to 0.9%. The torque ripple declines 2.5% from 8.6% to 6.1%, in other words, the torque characteristic is enhanced. A comparison between the optimization design of PMSM using genetic algorithm (GA) and PSO will be considered in the future work.

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