OPTIMUM DESIGN OF A FIVE-PHASE SURFACE-MOUNTED PERMANENT MAGNET SYNCRONOUS MOTOR USING BEES ALGORITHM

Reza Ilka* **S. Asghar Gholamian*** **Jalil Addeh***

*Babol University of Technology, Iran, +98-111-3239214, Ilka@stu.nit.ac.ir

***Abstract**: Permanent magnet synchronous motors are very good alternatives which are increasingly used for lots of applications due to their superior features. Their merits can be considerably enhanced by design optimization, thus reduce production cost and improve performance of motors.*

This paper presents a new method for optimum design of a five-phase surface-mounted permanent magnet synchronous motor to achieve reduced total loss with high torque. A multi-objective optimization is performed in search for optimum dimensions of the motor using bees algorithm. The design optimization results in a motor with great improvement regarding the original motor.

Key words: *permanent magnet, design process, optimization, bees algorithm, finite element analysis.*

1. Introduction

Permanent magnet synchronous motors (PMSM) are one of the most proper and efficient motors in electricity industry which are good candidate for applications such as naval and space systems, electric vehicles and so on. Replacing excitation winding of rotor with permanent magnets (PM) makes these motors which have a reduced loss; hence they are used in applications with high efficiency. The most important advantages of such motors are: high efficiency and power density, low loss, low maintenance cost and etc. Besides, a five-phase motor has high reliability which is very important in some specific applications. After the invention of NdFeB (Neodymium-Iron-Boron) in 1983, an increasing trend of using PM motors has began. Utilizing this material as permanent magnet of motors helped to have high power density with low mass and volume. However, production cost of such motors is a challenging subject needing accurate and time-consuming analysis. In other words, motor has to be designed in a way its loss is minimum while it has nominal performance characteristics. Therefore, optimum design of PMSMs has gained great attention in recent years and researching about this subject is a necessity. For example, Jannot et al. [1] have presented a multiphysic modeling of a high speed PMSM which is carried out with genetic algorithm optimization. Objective functions of this paper are efficiency and weight of motor. A design optimization of PMSM for high torque capability and low magnet volume has been presented in [2]. In this paper, objective function is a combination of torque and magnet volume. Roshandel et al. [3] have proposed an optimization task for linear PMSM which is based on a reduction in thrust ripple. Design optimization of a linear permanent magnet synchronous motor for extra low force pulsations is presented in [4]. Besides, there are publications specified to design, analyze and study the PMSMs [5-9].

In this paper, a five-phase PMSM with surface-mounted (SM) permanent magnet is considered. Aim of this paper is to optimize a sample of such motor. For this purpose, bees algorithm (BA) is applied which is a new optimization algorithm and it has not been used for optimum design of such motors yet. Optimization is performed with an objective function which is a combination of total loss and torque of motor. The rest of paper is classified as follow:

Firstly, design process is presented in section 2. Then, a case study is presented for further investigation of the design methodology in section 3 which is validated by finite element analysis (FEA). After that, optimum design of PMSM is carried out in section 4. Finally, paper is concluded in section 5.

2. Design Methodology

Generally, designing electrical machines is a time-consuming task and to some extent empirical. Like all machine types, PMSMs are designed through some steps. First step is determining the application of the motor. Main rated values needed for a specific purpose should be mentioned. After that, some design initial parameters are defined through engineering insight and in some cases by experience. Finally, dimensions and other required parameters are calculated by design equations. These steps are categorized separately as follows:

2.1. Step 1: Defining motor's fundamental characteristics

In this step, motor's main rated values are specified. In other word, ratings for a special application are chosen. There are some parameters which should be defined in this step. Among all the parameters, some of them are more important like output power (*kW*), terminal voltage (*V*), rated speed (*r/min*) and frequency (*Hz*). Other parameters are phase number, rotation direction, duty cycle, cooling class and etc [10].

By defining these parameters, designer knows how to do with design. Determining the output power is concerned with the load and its type. Rated voltage is limited with insulation. Speed of motor is depended to the number of poles and supply frequency and the driven load.

2.2. Step 2: Selecting design initial parameters according to motor's characteristics

Designing electrical machines is highly concerned with machine's crucial parameters. Proper selection of these parameters leads to a good design. There are lists of initial parameters in publications. Some of the most important ones are listed in Table 1.

Generally speaking, these variables are selected based on motor's fundamental parameters introduced in Step 1.

Table. 1. Motor's initial parameters

Initial Parameter	Description
B_{av} (T)	Specific magnetic loading
ac (A/m)	Specific electric loading
B_{ys}, B_{yr} (T)	Stator and rotor yoke flux density
B_t (T)	Stator tooth flux density
L/τ_p	Axial length to pole pitch ratio
B_r (T)	Residual flux density
η (%)	Efficiency
PF	Power factor

Specific electric loading depends upon several variables such as power rating, speed, frequency, and voltage rating. For machines with a smaller number of poles, a small diameter, or a large pole pitch, a smaller value of ac should be used. Similarly, in high-voltage machines requiring larger slot insulation, ac must be smaller. For machines with a larger number of poles, low voltage, and low frequency, ac may be increased by up to *20%* [10]. Proper value of ac for PMSMs is in the range of *8000* to *30000 A/m*.

The specific magnetic loading is considered the same with average flux density (B_{gav}) which is limited primarily by saturation and core loss. For PMSMs, the proper value of B_{av} is between *0.45* to *0.8 T* [11, 12].

Other parameters such as flux density in stator and rotor yoke are between *1.3 to 1.8 T* and usually about *1.5 T* which are selected according to the material used as stator and rotor core. Flux density in tooth is a bit more than flux density in stator and rotor yoke. Residual flux density is determined by magnet type. Axial length to pole pitch ratio is a very important parameter which is concerned with the shape of the magnet. Its range is $0.6 < L/\tau_p < 0.7$ for non-salient pole and $1 < L/\tau_p < 3$ for salient pole machines.

2.3. Step 3: determining the dimensions and parameters of motor

Now, we have enough information about the design and we know how to deal with the design procedure. In this part, dimensions and necessary equation needed for design of a PMSM are provided. Some of these equations are gathered from valid books and papers [10-14], but some of them are devised. Motor's main dimensions are valid for any types of machines and it is applied to all of them. Actual motor design starts with the selection of the main dimensions of the motor i.e. *L* which is motor's axial length and *D* which is stator inside diameter or air gap diameter. These two parameters are the most crucial and prior dimensions in motor design which other dimensions and parameters are highly depended to them. Identity of motor is somehow specified by determining these two dimensions.

2.3.1. Motor's main dimensions

Output coefficient is calculated as follow

$$C_0 = 1.11 p^2 B_{av} ac K_W \times 10^{-3} \quad (1)$$

Apparent input power is

$$Q = \frac{P_{out}}{\eta PF} kVA \quad (2)$$

Besides, this power can be rewritten in terms of motor's main dimensions

$$Q = C_0 D^2 L n_s \ KVA \quad (3)$$

In electrical machine design, D^2L is an important parameter

$$D^2 L = \frac{Q}{C_0 n_s} m^3 \quad (4)$$

Where, *Q* is in *KVA* and n_s is *rev/s*.

By applying equation (5) and combining with (4), it is possible to obtain motor's main dimensions, i.e. *L* and *D*.

$$L = \alpha_\tau \frac{\pi D}{p} \quad (5)$$

where $\alpha_\tau = L/\tau_p$ and τ_p is in mm.

2.3.2. Air gap and permanent magnet

Air gap of synchronous motors is determined by (6)

$$g \geq \frac{1}{2} \alpha_{SM} \mu_0 \tau_p \frac{ac}{\hat{B}_\delta} = \gamma \tau_p \frac{ac}{\hat{B}_\delta} \quad (6)$$

Where $\gamma = 1/2 \alpha_{SM} \mu_0$ and it is considered $\gamma = 3.10^{-7}$ for non-salient pole and $\gamma = 4.10^{-7}$ for salient pole motor.

Magnet thickness is calculated as follow:

$$L_{PM} = (\mu_r B_g / (B_r - ((K_f / K_d) B_g))) K_c g \quad (7)$$

where $k_f = B_{gpk}/B_g$ and k_d is leakage flux factor. Then, air gap of permanent magnet synchronous motors is calculated as follow

$$g_{PM} = L_{PM} / \mu_{rPM} + k_c g \quad (8)$$

It is recommended for small PMSMs to have $0.3 < L_{PM} < 1$ *mm*.

2.3.3. Conductor turn

Because of lamination of stator, stator has an effective axial length which is described as below

$$L_i = L \times k_{st} \quad (9)$$

Where k_{st} is stator stacking factor and is usually around *0.9*. Flux under a pole is determined as follow

$$\phi = B_{av} . \tau_p . L_i \quad (10)$$

Stator phase voltage is $E_s = 0.97 \times V_L / \sqrt{3}$ and number of phase turn of stator is calculated by

$$T_s = \frac{E_s}{4.44 f \phi k_w} \quad (11)$$

Total number of conductors is

$$Z_T = 10 T_s \quad (12)$$

Number of conductors in each slot is

$$Z_{slot} = \frac{Z_T}{S} \quad (13)$$

where *S* is the number of slots.

2.3.4. Loss and Torque

Average stator winding length is [8]

$$l_{mts} = 2L + 2.3\tau_p \qquad (14)$$

Phase current is

$$I_s = \frac{Q}{mE_s} \qquad (15)$$

Stator phase resistance is

$$R_s = \frac{\rho T_s . l_{mts}}{a_S . 10^{-6}} \Omega \qquad (16)$$

where $a_s = I_s/J_s$ and $\rho = 1.8\times10^{-8}$

and J_s is selected according to I_s. For small PMSMs, it has a value of 3 to 7.

Total copper loss is

$$P_{cu} = 5R_s (I_s)^2 \qquad (17)$$

Core loss is

$$P_c = k_h f B_m^2 + k_e f^2 B_m^2 \qquad (18)$$

Mechanical loss (Windage and friction loss) is considered between *0.5* to *3* percent and stray loss is considered *0.5* to *1* percent of the output power.

Finally, output torque is calculated as follow

$$T = B_{av} k_w n_{spp} PL(D/2) I_s Z_{slot} \qquad (19)$$

where n_{spp} is the number of slot per pole per phase.

2.3.5. Slot dimensions

Determining slot dimensions is very important in design of electrical machines because it affects magnetic flux distribution and saturation. Hence, considerable efforts should be invested in this task.

Slot and PM configuration is shown in Figure 1. Parameters and dimensions are illustrated in this figure. In this section, all the necessary dimensions of motor's slot are provided one by one.

Slot pitch is the distance from the beginning of a slot to the beginning of the next one. It is formulated in (20) in mm.

$$\tau_s = \frac{\pi D}{S} \qquad (20)$$

Maximum tooth width is

$$\omega_t = \frac{B_g \pi D}{B_t S} \qquad (21)$$

Slot width is

$$\omega_s = \tau_s - \omega_t \qquad (22)$$

Stator yoke height is

$$h_{bis} = \frac{B_g \pi D}{2B_{ys} p} \qquad (23)$$

Similarly, rotor yoke height is

$$h_{bir} = \frac{B_g \pi D}{2B_{yr} p} \qquad (24)$$

Area in a slot can be found by below equation

$$A_{slot} = \frac{Z_{slot} I_s}{k_{fill} J_s} mm^2 \qquad (25)$$

where k_{fill} has a value of *0.4* to *0.6* [13].

Initial slot depth is

$$h_s^{(1)} = \frac{A_{slot}}{\omega_s} \qquad (26)$$

In this design, we first simply calculate h_s with (26) and after determining ω_{sb}, the corrected value of h_s (which is presented as $h_s^{(2)}$) is achieved.

Minimum tooth width is

$$\omega_{tb} = \frac{p\phi}{SB_t L_i} \qquad (27)$$

Slot bottom width, ω_{sb}, is calculated through following equation

$$\omega_{sb} + \omega_{tb} = \frac{\pi D_{sb}}{S} \qquad (28)$$

Knowing ω_{tb} from (27) gives the value of ω_{sb} from (28).

Therefore, corrected slot depth is

$$h_s^{(2)} = A_{slot} / (\frac{\omega_{sb} + \omega_s}{2}) \qquad (29)$$

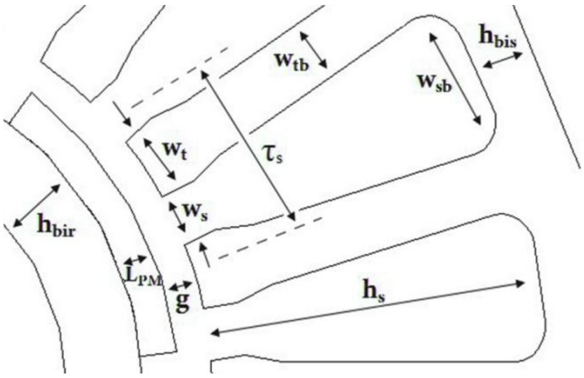

Fig. 1. Slot and PM dimensions and parameters.

3. Traditional design

3.1. Case study

In this section, a sample scheme is designed through three steps introduced in section 2. We've selected a common motor rating. Table 2 shows motor's initial parameters. It's a four-pole motor.

By explanations in section 2-2, we can chose variables according to parameters listed in Table 2. Variables are chosen and their values are illustrated in Table 3. Applying these two tables into design equations gives motor's dimensions and parameters which are shown in Table 4.

Besides, total loss and torque can be computed by equations introduced in section 2. Regarding the values of resistance and current of stator in Table 4, Copper loss (equation 17) becomes *55.17 W*. Core loss is *22.7 W* which is determined through hysteresis and eddy coefficients. Mechanical loss is considered one percent and stray loss 0.5 percent of the output power. Therefore, total loss becomes *92.87 W*. For determining torque, we use equation 20 which gives us the value of *2.64 N·m*.

Table. 2. Motor's initial parameters

Parameter	Value
Power (kW)	1
Rated voltage (V)	220
Rated speed (r/min)	1500
Frequency (Hz)	50

Table. 3. Motor's variables

Variable	Value
B_{av} (T)	0.5
ac (A/m)	22000
B_{ys}, B_{yr} (T)	1.5
B_t (T)	1.5
L/τ_p	1.25
B_r (T)	1.2
S	30
K_{fill}	0.5
J_s	4
η (%)	90
PF	0.8

Table. 4. Motor's obtained dimensions and parameters

Dimension/Parameter	Value
D (mm)	97
L (mm)	75
τ_p (mm)	50
L_{PM} (mm)	0.5
g_{PM} (mm)	0.8
ϕ (Wb)	0.0017
τ_s (mm)	10.1
ω_t (mm)	4.7
ω_s (mm)	5.4
ω_{tb} (mm)	3.3
ω_{sb} (mm)	9.2
h_s (mm)	17.5
h_{bis}, h_{bir} (mm)	12
I_s (A)	2.2
r_s (Ω)	2.28
E_s (V)	125.5
T_s (turns)	348
Z_{slot} (turns)	116

3.2. Finite Element Analysis Validation

Finite element analysis (FEA) is used here to validate the design process. Maxwell software which is based on FEA is one of the most important and efficient tools for this purpose.

Desirable output quantities can be extracted using this software by doing below steps:

- Drawing the PMSM motor according to optimized dimensions calculated by BA
- Assigning materials and boundary to the motor parts

- Performing mesh operation
- Setting up an analysis to solve
- Extracting output data and plots.

For this motor, stator and rotor core are composed of steel 1008. Surface-mounted permanent magnets are NdFeB with:

B_r: 1.23 T,

H_c: 890 kA/m.

We want to see weather our design is correct or not. It can be checked through results of the software. Figure 2 shows mesh generated by the software.

Flux density distribution and flux lines of motor are shown in Figure 3, simultaneously. It is obvious that flux density in stator and rotor yoke is around 1.5 T. This is the same we've chosen for analytical approach. Figure 4 shows phase voltage and phase current of motor. As shown in this figure, RMS value of phase voltage and phase current is close to the value obtained by traditional design.

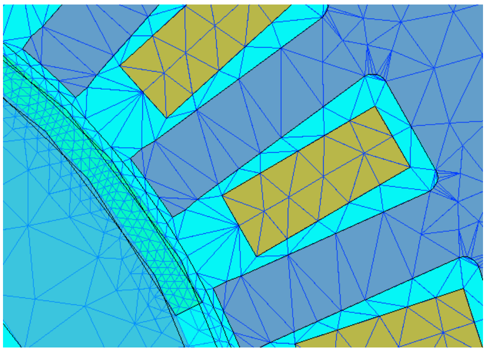

Fig. 2. Finite element mesh.

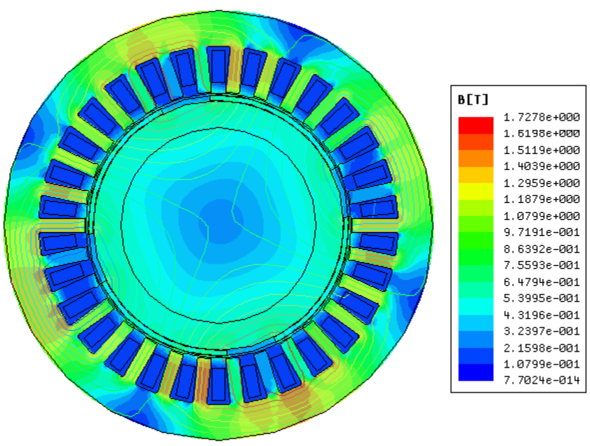

Fig. 3. Flux density distribution and flux lines.

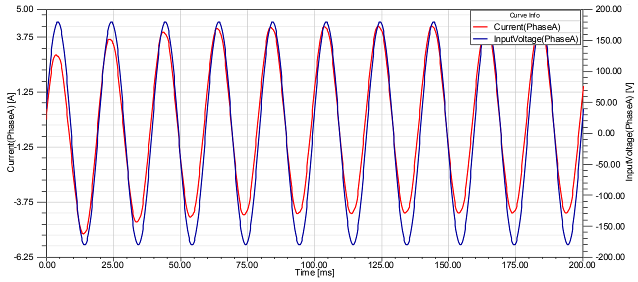

Fig. 4. Phase voltage and phase current of motor.

4. Optimum design using bees algorithm

Bees Algorithm is an optimization algorithm inspired by the natural foraging behavior of honey bees to find the optimal solution. Figure 5 shows the flowchart of the pseudo code for the algorithm in its simplest form. The algorithm requires a number of parameters to be set, namely: number of scout bees (n), number of sites selected out of n visited sites (m), number of best sites out of m selected sites (e), number of bees recruited for best e sites (nep), number of bees recruited for the other (m-e) selected sites (nsp), initial size of patches (ngh) which includes site and its neighborhood and stopping criterion. The algorithm starts with the n scout bees being placed randomly in the search space. The fitnesses of the sites visited by the scout bees are evaluated in step 2.

1. Initialise the solution population.
2. Evaluate the fitness of the population.
3. While (stopping criterion is not met)
//Forming new population.
4. Select sites for neighbourhood search.
5. Recruit bees for selected sites (more bees for the best e sites) and evaluate fitnesses.
6. Select the fittest bee from each site.
7. Assign remaining bees to search randomly and evaluate their fitnesses.
8. End While

Fig. 5. Flowchart of the Pseudo code for optimization.

In step 4, bees that have the highest fitnesses are chosen as "selected bees" and sites visited by them are chosen for neighborhood search. Then, in steps 5 and 6, the algorithm conducts searches in the neighborhood of the selected sites, assigning more bees to search near to the best e sites. The bees can be chosen directly according to the fitnesses associated with the sites they are visiting. Alternatively, the fitness values are used to determine the probability of the bees being selected. Searches in the neighborhood of the best e sites which represent more promising solutions are made more detailed by recruiting more bees to follow them than the other selected bees. Together with scouting, this differential recruitment is a key operation of the Bees Algorithm.

However, in step 6, for each patch only the bee with the highest fitness will be selected to form the next bee population. In nature, there is no such a restriction. This restriction is introduced here to reduce the number of points to be explored. In step 7, the remaining bees in the population are assigned randomly around the search space scouting for new potential solutions. These steps are repeated until a stopping criterion is met. At the end of each iteration, the colony will have two parts to its new population representatives from each selected patch and other scout bees assigned to conduct random searches [15].

It should be noted that in this survey, population size is considered 100, iteration 500 and elite number 40.

In this paper, objective function is a combination of total loss and torque of motor. Total loss contains copper loss, core loss (Hysteresis and Eddy loss), mechanical loss and stray loss. Objective function is defined as

$$F = \frac{P_{loss}(ac, B_{av}, L, D, \tau_p, \phi, J_s)}{T(B_{av}, L, D)} \qquad (30)$$

that should be minimized. This means minimizing total loss and maximizing torque simultaneously.

It should be noted that total loss could be minimized by choosing low values for main dimensions and loadings of motor, but this leads to a reduced torque which is not favorable. Therefore, an optimization must be performed to obtain the best values of variables. This multi-objective optimization selects the best values for main dimensions, loadings and other parameters in order to reduce total loss and increase torque of motor.

In this survey, design variables are: ac, B_{av}, L, D, τ_p, ϕ and J_s. variables limitations is introduced in section 2-2. Applying these limitations to the objective function which is based on these seven variables, optimum solution is achieved. Figure 6 shows objective function versus iteration. As shown in this figure, objective function reaches to its optimal value after about 200 iterations. In this optimization, total loss and torque will be *87.7 W* and *3.08 N·m*, respectively. It is clear that in comparison to traditional design, total loss has decreased and torque has increased. Besides, optimal dimensions of motor are presented in Table 5.

Comparing to the original motor, it is shown that specific magnetic loading and specific electric loading should be chosen more than the original motor in order to fulfill the optimized performance. Apparently, this leads to a motor with increased torque and total loss, but due to decrease in main dimensions of the motor, the optimized motor will have less total loss. Table 6 compares total loss and torque of the motor before and after optimization.

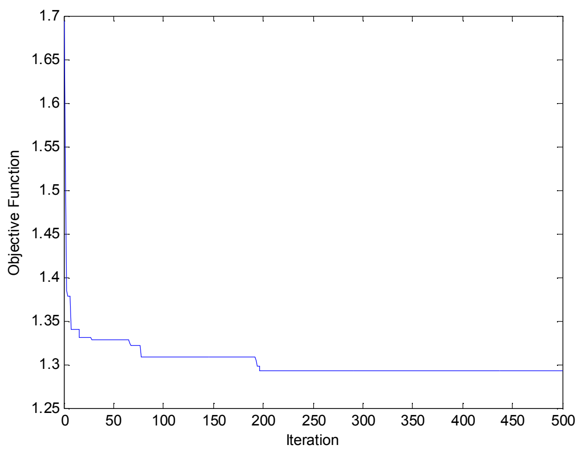

Fig. 6. Objective function versus iteration.

Table. 5. Optimal dimensions of motor

Dimension/Parameter	Value
B_{av} (T)	0.53
ac (A/m)	22351
D (mm)	90
L (mm)	71
τ_p (mm)	60
L_{PM} (mm)	0.5
g_{PM} (mm)	0.8
ϕ (Wb)	0.0019
τ_s (mm)	9.5
ω_t (mm)	4.4
ω_s (mm)	5.1
ω_{tb} (mm)	3
ω_{sb} (mm)	8.7
h_s (mm)	16.2
h_{bis}, h_{bir} (mm)	11.9

Table. 6. Comparison of total loss and torque before and after optimization

	Analytical	Optimized	%
Total loss (W)	92.87	87.7	-5.56
Torque (N·m)	2.64	3.08	16

5. Conclusion

This paper presented an optimum design for a five-phase surface-mounted permanent magnet synchronous motor. For this purpose, all the design procedure was discussed completely. Design procedure was examined with a case study. Then, finite element analysis confirmed the analytical design which proves the efficiency and accuracy of design methodology. After that, a design optimization is performed on a surface-mounted PMSM in search for proper dimensions to achieve a reduced total loss and a high torque. The design optimization leads to a motor with more than 5.56% reduction in total loss and 16% increase in the torque with respect to the original motor.

Future works may be devoted to the optimization of such motors with other optimizing algorithm or with other objective functions.

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