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# Optimal Design of Three Phase Surface Mounted Permanent Magnet Synchronous Motor by Particle Swarm optimization and Bees Algorithm for Minimum Volume and Maximum Torque

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***Abstract***

*In this paper, the optimal design of a three phase surface mounted permanent magnet synchronous motor has been done by particle swarm optimization and bees algorithm. This machine has been designed for high speed applications, and an epoxy and glass fiber bandage is used for permanent magnet protection against centrifugal forces. The optimization has been done by new design equations to improve loss and torque in the machine. The results show the simultaneous improvement of loss and torque compared with the initial design of the motor*

***Keywords:*** *surface mounted permanent magnet, optimal design, particle swarm optimization algorithm, Bees algorithm.*

## 1. Introduction

Nowadays, permanent magnet synchronous machines, have found a special place in industry, because of their advantages and impressive capabilities. The excitation field of these motors is provided by permanent magnets mounted in rotor which has caused some limitations in terms of excitation control, high cost of permanent magnet materials and allowable operating temperature of machine, but the advantages of this kind of synchronous machine are much more, such as high torque density, efficiency and power density, low loss and volume, elimination of excitation windings and slip rings, and increase of reliability [1, 2].

Based on the modality of mounting permanent magnet on rotor, different structures is created for rotor such as Merrill's rotor, surface permanent magnet rotor, buried permanent magnet rotor, inset magnet rotor and interior magnet rotor [1]. In Ref. [3] Nilssen and his colleagues have designed a surface permanent magnet synchronous motor for the driving force of a ship. They combined a surface permanent magnet synchronous motor with an azimuth propulsion system which leads to improve the hydrodynamic characteristics, efficiency increase, tensile force increase and removing the vibrations in the system. Also in Ref. [4], design of an interior magnet synchronous motor for driving force of a ship has been discussed. The reason of using this topology is high reliability, good mechanical strength, good protection of magnets against demagnetization and corrosion and generating high torque. In Ref. [5], two kind of buried magnet scheme have been studied. One of them was V shape magnet, and the other was buried permanent magnet scheme which had been magnetized tangentially. The writer in the paper has been pointed to the problem of narrow iron poles saturation by increasing the number of poles in a diameter of the rotor.

The other kind of classification of permanent magnet synchronous machines is based on the different kinds of rotor and stator shape and the way of placing them next to each other, such as radial and axial, longitudinal and transverse fluxes machines, interior or exterior rotor and the slotted or slotless machines and stator core ones. In Ref. [6], common topologies in permanent magnet synchronous machines for direct drive applications have been studied. Also the application of each topology with respect to the surface mounted permanent magnet (SMPM), radial air gap and longitudinal stator core machine in terms of two indexes of cost to torque and torque to weight have been compared. In Ref. [7], the differences of longitudinal and transverse stator have been studied. In Ref. [8], a scheme about slotless machine has been presented. In Ref. [9] some of the advantages of constructing the exterior rotor machines such as magnets protection against centrifugal forces and better cooling of magnets have been discussed.

Another subject that has been under studied lately, is optimization of permanent magnet synchronous machine for achieving optimal characteristics by optimization algorithms or optimal design methods. In Ref. [10], the inverse problem method has been used to optimal design of permanent magnet synchronous motor. Using this method, the optimization target, which was torque increase, has been fulfilled. In Ref. [11], for torque increase and cost reduction of active materials, the design and optimization of permanent magnet synchronous machine, have been performed by genetic algorithm. In Refs [12] and [13], taguchi methods have been used for optimal design of a permanent magnet synchronous machine. In Ref. [14], design and optimization of a permanent magnet synchronous motor by bees algorithm, have been performed for industrial applications. In here, the optimization objective is torque density and efficiency increase. Design and optimization of an interior permanent magnet synchronous motor for an Automotive Active Steering System has been studied in Ref. [15]. In the paper, the genetic algorithm, network search and hooke - jeeves search have been used for optimization.

In this paper, a SMPM synchronous machine has been designed optimally, by particle swarm optimization and bees algorithm. The design has been performed by some of new design equations for this kind of machine topology. The design objective is improved the torque and efficiency with respect to initial machine design.



## 2. Generalities of under study machine

Based on the aforementioned classifications, a SMPM machine, with radial air gap, longitudinal stator core and slotted stator has been chosen to design. This kind of topology is called briefly SMPM machine. It is very common to use this machine in various applications, and also has simpler construction process compared with the other topologies. This machine has been designed for high speed applications. In these applications, a non-magnetic steel cylinder with carbon or glass fiber bandage is required for permanent magnet protection against centrifugal forces. The steel cylinder is very strong but the flux variations generate eddy currents which lead to more loss with respect to carbon bandage. Magnets with more height needs thicker bonds compared with thinner magnets. This leads to longer magnetic air gap, so the machine output power is directly affected by the limitation of fixing magnet. In this scheme, a bandage constructed by 60% glass fiber and 40% epoxy and thickness of 0.2 mm is used to protect the magnet against centrifugal forces. The iron sheets are made of M400-50A, which are classified into medium quality sheets, with the thickness of 0.5 mm. Also the NdFeB magnet is used in rotor construction.

## 3. Design Formulation of Permanent Magnet Synchronous Machine

In following, the equations for machine design are presented [16].

### *3.1 Loss Calculation in SMPM Machines*

Copper and iron losses are the main losses in a SMPM machine but there is also mechanical loss. The mechanical loss is small in relation to the eleectrical loss. But if the rotational speed is high, the bearing and the windag loss may become important.

#### *3.1.1 Copper Loss*

The copper loss are usually the biggest part of total loss of a SMPM machine. The copper loss are calculated as follows:

$$P_{cu} = 3R_{cu}I^2 \tag{1}$$

Where $R_{cu}$ the winding resistance of one is phase and $I$ is the rms-value of stator current. The winding resistance depends on the conductor length and area, i.e. the number of conductors in each slot $n_s$, and slot area $A_{sl}$. The one phase winding resistance is calculated as:

$$R_{cu} = \rho_{cu} \frac{(pL + (D + h_{ss})\pi k_{coil})n_s^2 q}{f_s A_{sl}} \tag{2}$$

Where $L$ effective length of machine, D is is the inner stator diameter, $h_{ss}$ is the slot height, $f_s$ is the filling factor of slot, $q$ and is the number of slots per pole and phase and $p$ is the number of poles. The End-windings are taken into account by introducing the term $\pi k_{coil} D$, where $k_{coil}$ is an empirical constant depending on the winding arrangement. $\rho_{cu}$ is the winding specific resistance at winding temperature which is calculated as follow:

$$\rho_{cu} = 2.10^{-8}(1 + 0,004(T - 25)) \tag{3}$$

#### *3.1.2 Iron Loss*

The Iron loss is due to the variation of the flux density in electromagnetic material. The flux variations create eddy currents and magnetic hysteresis in the iron laminations of motors. The hysteresis loss depends on peak value and frequency of flux density, and eddy current loss depends on time rate of flux density variation. Total iron loss density $p_{iron}$ is commonly expressed in the following form for a sinusoidal flux density of amplitude B with angular frequency $\omega_e$ :

$$P_{iron} = P_h + P_e = K_h \hat{B}^{\beta_{st}} \omega_e + K_e \hat{B}^2 \omega_e^2 \tag{4}$$

Where $P_h$ and $P_e$ are the hysteresis and the eddy current loss density, respectively, $K_h$ and $K_e$ are hysteresis and eddy current constants respectively, and $\beta_{st}$ is the Steinmetz constant. All constants depend on the iron lamination material. Typical values for grades of silicon iron laminations used in small and medium machines are in the ranges of:

$$\beta_{st} = 1.8 - 2.0$$

$$K_h = 40 - 55 \ [Ws / T^2 / m^3]$$

$$K_e = 0.04 - 0.07 \ [Ws^2 / T^2 / m^3]$$

The equation (4) is valid only for a sinusoidal flux density. If the flux density in the stator core is not sinusoidal, the iron loss density evaluates with a more complex model. In the analytical model, the stator core is divided into two parts: the stator teeth and the stator yoke. The power density in each area is sum of loss density of eddy current and hysteresis:

$$P_{teeth} = p_{h\_teeth} + p_{e\_teeth} \tag{5}$$

$$P_{yoke} = p_{h\_yoke} + p_{e\_yoke} \tag{6}$$

The hysteresis loss density can be calculated as follows:

$$P_{h-teeth} = K_h \hat{B}_{st}^{\beta_{st}} \omega_e \tag{7}$$

$$P_{h-yoke} = K_h \hat{B}_{sy}^{\beta_{st}} \omega_e \tag{8}$$

Where $B_{st}$ and $B_{sy}$ are maximum flux density in teeth and yoke of stator, respectively. A modified phrase for eddy current loss density in stator yoke is:

$$P_{e\_teeth} = \frac{12}{\pi^2} q k_q k_c k_e (\omega_e B_{st})^2 \tag{9}$$

Where $q$ is the number of slots per pole and phase. $k_c$ and $k_q$ are geometry dependent correction factors, which can be seen in Fig. 1 and Fig. 2.

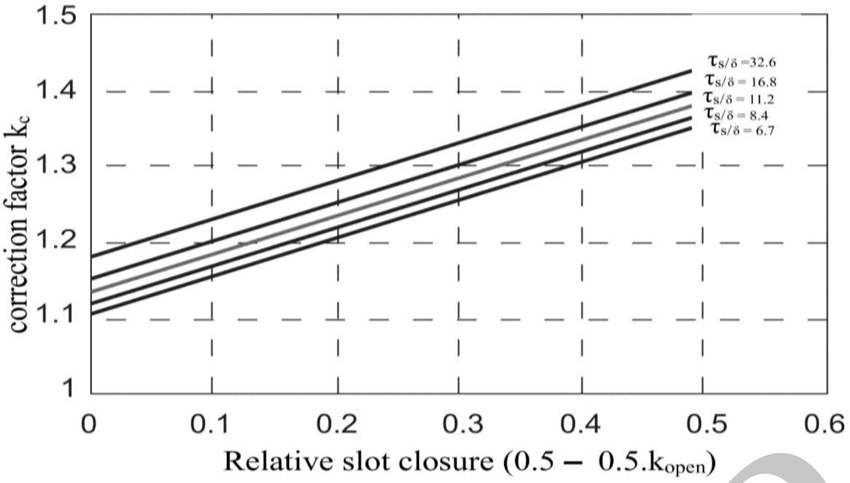


***Fig. 1: Determination of*** $k_c$

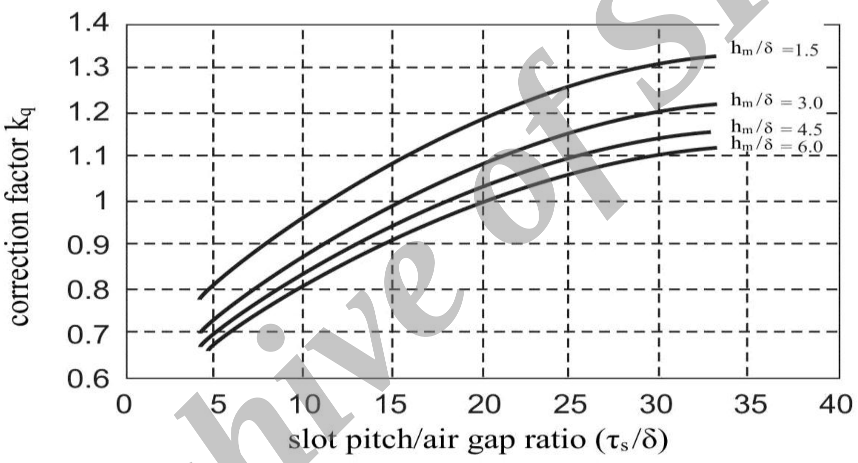


***Fig. 2. Determination of*** $k_q$

For stator yoke, the power loss density is calculated as:

$$p_{e\_yoke} = \frac{1}{\mathrm{cov}} \frac{8}{\pi^2} k_e \omega_e^2 \hat{B}_{sy}^2 \left( 1 + \frac{8 k_q h_{sy}^2}{27 \,\mathrm{cov}\, q \tau_{s2}^2} \right) \qquad (10)$$

Where *cov* is the magnet coverage in percentage of the rotor core pole pairs circumference:

$$\mathrm{cov} = \frac{2\alpha}{\pi} \qquad (11)$$

$\tau_{c2}$ is the projected slot pitch at the middle of the yoke, $2\alpha$ is the pole angle given in electrical rad. Now, using above equations, the modified loss model is obtained as:

$$P_{loss\_stator} = V_{teeth} P_{teeth} + V_{yoke} P_{yoke} \qquad (12)$$

Where $V_{teeth}$ and $V_{yoke}$ are the total volume of teeth and yoke, respectively.

***3.2. Calculation of Flux density in Different Parts of Machine***

It is assumed that the air gap flux density has a rectangular shape as wide as the magnets with a maximum value $B_m$.

$$B_m = \frac{B_r k_{leak}}{1 + \frac{\mu_r \delta k_c}{h_m}} \qquad (13)$$

Where $\delta$ is the air gap length, $\mu_r$ is the magnet relative permeability and $k_c$ is catrer factor. $k_{leak}$ is considered as magnetic leakage factor between magnets.

$$k_c = \frac{\tau_s}{\tau_s - \frac{(k_{open} b_{ss1})^2}{b_{ss1} k_{open} + 5\delta}} \qquad (14)$$

In above equation, $\tau_s$ is the slot pitch, $b_{ss1}$ is the width of stator slot opening and $k_{open}$ is the ratio of slot opening to slot width. Then, the magnitude of basic air gap flux density is calculated as follows:

$$\hat{B}_\delta = \frac{4}{\pi} B_m \sin(\alpha) \qquad (15)$$

Where $\alpha$ is the half of the pole angle. The peak value of the armature reaction flux density is calculated as:

$$\hat{B}_{\delta.arm} = \frac{3\mu_0}{\pi\left(\delta k_c + \frac{h_m}{\mu_r}\right)} q n_s k_{w1} \hat{I}_1 \qquad (16)$$

The relation of maximum flux density in the stator teeth is as follows:

$$\hat{B}_{st} = \frac{B_m 2\alpha(D - 2\delta)}{p b_{ts}\left(\frac{q_s}{p} - q\right) k_{Fe}} \qquad (17)$$

It should be noted that only the flux created by the magnets is taken into account and the the leakage flux flowing through the tooth shoe is neglected. In the equation (17), $q_s$ are the total stator slots, $k_{Fe}$ is the iron filling factor and $b_{ts}$ is the stator slot width. The maximum flux density in stator and rotor yoke is calculated as follow:

$$\hat{B}_{ry} = \frac{\alpha B_m (D - 2\delta)}{p k_{Fe} h_{ry}} \qquad (18)$$

$$\hat{B}_{sy} = \left( \frac{B_m 2\alpha(D-2\delta)L}{p} + \frac{6\mu_0 q n_s \hat{I}\, k_w \sin\left(\frac{\pi}{2}-\alpha\right) DL}{p\pi\left(\delta\, k_c + \frac{h_m}{\mu_r}\right)} \right) \times \frac{1}{2Lk_{Fe}h_{sy}} \quad (19)$$

Where $n_s$ is the number of conductors in each slot, $\hat{I}$ is the conductor current magnitude, $h_{ry}$ and $h_{sy}$ are the height of the stator and the rotor yoke, respectively.

### *3.3. The Calculation of Electrical Characteristics of Machine*

The required stator current loading is calculated from the rated torque $T_n$ as:

$$\hat{S}_1 = \frac{4T_n}{\pi\, L\hat{B}_\delta k_{w1}(D-\delta)^2 \sin(\beta)} \quad (20)$$

Where $\beta$ is the angle between armature and magnet basic flux density in the air gap. For non-salient pole machines, the maximum torque is obtained when $\beta = 90°$. The winding factor for first harmonic can be written as follows:

$$k_{w1} = \frac{\sin\left(\frac{\pi}{6}\right)}{\left(\frac{\pi}{6q}\right)} \quad (21)$$

The required peak value of the total stator current per slot is determined via the stator current loading as follows:

$$n_s \hat{I}_1 = \hat{s}_1 \tau_s \quad (22)$$

The stator slot area can be calculated by:

$$A_{sl} = \frac{b_{ss1} + b_{ss2}}{2}(h_{ss} - h_{sw}) \quad (23)$$

Where $b_{ss2}$ is the inner width of stator slot and $h_{sw}$ is the wedge height of stator slot. The copper area per slot is:

$$A_{cu} = f_s A_{sl} \quad (24)$$

Then the maximum current density is obtained by:

$$\hat{J} = \frac{n_s \hat{I}_1}{A_{cu}} \quad (25)$$

Based on Faraday´s law, magnet flux linkage $\Psi_m$ induces voltage $E$ in each phase winding. The phase voltage $E$, is calculated by:

$$E = \frac{d\Psi_m(t)}{dt} = N_s \frac{d\Phi_m(t)}{dt} \quad (26)$$

Where $N_s$ is the equivalent number of turns per phase and $\Phi_m$ is the fundamental magnet flux linked to one turn of the coil.

$$N_s = \frac{p}{2} q n_s k_{w1} \tag{27}$$

$$\Phi_m(t) = \frac{2\hat{B}_\delta L(D-\delta)}{p} \sin(\omega_e t) \tag{28}$$

The peak value of basic induced voltage *E* can be determined as follows:

$$\hat{E} = N_s \max\left(\frac{d\Phi_m(t)}{dt}\right) = \hat{B}_\delta L(D-\delta)\omega_e q n_s k_{w1} \tag{29}$$

The maximum stator current that is allowed, in order to avoid demagnetization of the magnets is given by:

$$I_{\max} \le \pi \frac{B_r h_m - B_d(h_m + \mu_r \delta k_c)}{3\mu_0 \mu_r q n_s k_{w1}} \tag{30}$$

## 4. Particle Swarm Optimization Algorithm

In PSO algorithm, a number of particles have scattered in search space [17]. Each particle calculates the value of objective function, in its space position, then combining the information of its current and the best pre-position, and also the information of one or some of the best particles, the particle choose a direction to move. After doing collective move, one algorithm stage comes to an end. This stage iterates as long as the desired solution is obtained. The *i*th particle in space has five property:

(1).Particle *i* position at *t* moment ($(x^i[t])$) (2).The objective function corresponding to that position (3).The velocity of particle *i* at moment *t* ($(V^i[t])$) (4).The best position experienced by particle *i* at moment *t* ($(x^{ibest}[t])$) (5).The objective function value corresponding to the best position

Accordingly, the velocity and position of *i* particle in each iteration, are updated by these equations:

$$\begin{aligned} V^i[t+1] &= wv^i[t] + c_1 r_1 (x^{ibest}[t] - x^i[t]) + c_2 r_2 (x^{gbest}[t] - x^i[t]) \\ x^i[t+1] &= x^i[t] + v^i[t+1] \end{aligned} \tag{31}$$

Where $x^{gbest}[t]$ is the best position experienced by the swarm until iteration t. $w$ is inertia coefficient and usually have the value between 0.4 to 0.9. $r_1$ and $r_2$ are uniformly distributed random numbers. $c_1$ and $c_2$ are personal learning coefficient and collective learning coefficient, respectively in the range between zero and 2.

Generally, the PSO algorithm stages are as follows:

1. Initialize the particle's position and evaluation them
2. Determination of the best personal and collective memories.
3. Updating velocity and position and evaluation new solutions
4. In the case of not satisfying conditions, the algorithm stops and gets back to the first stage.
5. end

Here for the better performance of PSO, the coefficients $c_1$ and $c_2$ and $w$ based on the constriction coefficients rule are considered as $w = 0.7298$ and $c_1 = c_2 = 1.4962$ [18]. The number of particles chosen for space searching is considered as 200 and the number of iterations is considered as 100.

## 5. Bees Algorithm

In computer science and applied researches, the bees algorithm is a search algorithm based on population, which has been developed firstly in 2005. This algorithm has been inspired from the group behavior of bees for searching food [19].

The food searching process in a colony starts with sending scout bees for searching promising food sites. The scout bees evaluate some places randomly. When these bees got back to the hive, if the quality of their food site was higher than a particular limit, the information's of that food site is transformed to other bees by a special dance called waggle dance. Based on the fitness of food, worker bees are sent to there from their position. Some of the food sites is chosen among the initial sites introduced by scout bees based on their fitness, and the remained scout bees is sent to discover other random food sites. Among the selected sites, the best sites are determined as elite sites. Most of worker bees are assigned to elite sites and less number of bees is sent to other selected sites. In the next stage, sent bees to each site, evaluate the food sites in addition to gathering food, and transfer information about the food sites to other hive bees by dancing. At the end of each searching, the best bee among the bees of each source and the best bee among the selected bees is determined. Then, the stages repeat until the food site with the desired quality is found.

The bees algorithm stages are as follows:

1. Generating initial sites and evaluation of these sites
2. Selecting the better sites and sending worker bees to there
3. Bees Returning to the hive and doing the special dance
4. Comparing all bees of a site and choosing the best one
5. Replacing the non selected sites with random sites
6. Saving the position of the best site
7. If the ending conditions do not meet, returning to stage 2
8. End [20]

In this paper, the number of scout bees is 30, the number of selected sites is 15, the number of elite sites is 12 and the number of bees assigned to the selected and elite sites is 15 and 30, respectively. The neighborhood radius for each variable is considered as 0.01 of the allowable limit for variable variation. After 500 iterations, the program will stop.

The advantages of bees algorithm are expressed below:

1. Bees algorithm has remarkable robustness, and it produces a very high success rate.
2. The algorithm converged to the maximum or minimum without becoming trapped at local optima.
3. The algorithm generally outperformed other techniques that were compared with it in terms of speed of optimization and accuracy of the results obtained.

The main advantageous of bees algorithm is high convergence speed and not stopping in local minimums.

## 6. Simulation and discussion

The cross sectional area of this motor has been shown in Fig. 3.

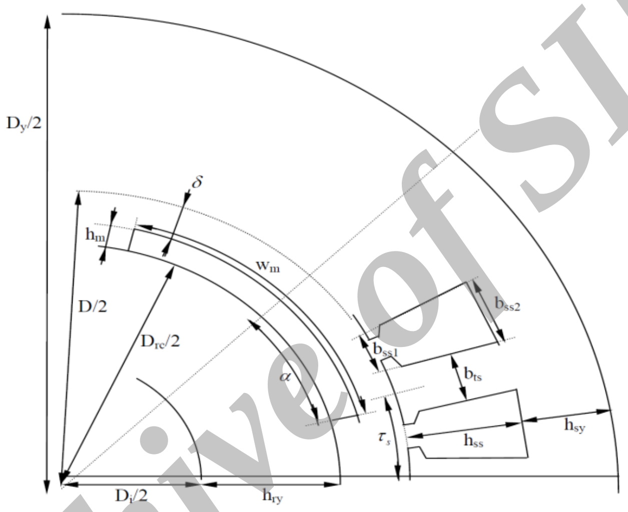


***Fig. 3: Cross section of selected motor***

In this figure $D_{rc}$ is the diameter of rotor core and $D_i$ is diameter of motor axis. The basic characteristics of machine have been shown in Table 1 and the dimensions and characteristics of initial motor have been shown in Table 2.

***Table 1. Motor basic characteristics***

| Parameter | Value |
|---|---|
| Pout (kw) | 5.75 |
| V(v) | 180 |
| Nn(rpm) | 10000 |
| f (Hz) | 333 |
| S | 12 |
| P | 4 |

Table.1 shows the working conditions of motor include power, voltage, rated speed, frequency and number of stator slots.

In Table.2, $M_{total}$ is motor weight, $C_{total}$ is motor cost, $C_{pm}$ is permanent magnet cost, $P_{cu}$ is copper loss, $P_c$ is iron loss, $P_{loss}$ is total loss, $eff$ is motor efficiency and $T$ is motor torque.

***Table. 2: Dimensions and characteristics of initial motor***

| Parameter | value |
|---|---|
| L(mm) | 55 |
| D(mm) | 40.5 |
| $J_s$ (A/mm2) | 11 |
| $b_{ts}$ (mm) | 5.5 |
| $D_i$ (mm) | 12 |
| $h_{ry}$ (mm) | 6.3 |
| g (mm) | 0.5 |
| $h_m$ (mm) | 2.7 |
| $\tau_p$(mm) | 25.9 |
| $\tau_s$ (mm) | 10.6 |
| $h_{ss}$ (mm) | 17.6 |
| $h_{sy}$ (mm) | 7.2 |
| $b_{ss1}$(mm) | 5.9 |
| $b_{ss2}$(mm) | 14.3 |
| $h_{sw}$(mm) | 1.3 |
| $K_{open}$(%) | 0.3 |
| $Z_{slot}$ | 54 |
| $R_{cu}$(Ω) | 0.56 |
| I(A) | 11.85 |
| $T_s$ | 108 |
| $B_{garm}$(T) | 0.348 |
| $Vol_{total}$ ($mm^2$) | 385060 |
| $M_{total}$ (Kg) | 2.904 |
| $C_{total}$(euro) | 21.5 |
| $C_{pm}$(euro) | 4.789 |
| $P_{cu}$(W) | 236.16 |
| $P_c$(W) | 89.28 |
| $P_{loss}$(W) | 470.02 |
| eff(%) | 92.48 |
| T(N.m) | 3.756 |

The design variables and their limit have been shown in Table .3. Also some of assumptions, used in machine design, have been shown in Table .4 .

***Table. 3: The design variables and their limit***

| Parameter | minimum | Maximum |
|---|---|---|
| $J_s$(A/mm$^2$) | 7 | 11 |
| L(mm) | 55 | 100 |
| $b_{ts}$(mm) | 55 | 60 |
| D(mm) | 40 | 60 |

***Table. 4: The assumptions used in machine design***

| Parameter | Value |
|---|---|
| $B_g$(T) | 0/9 |
| $B_{st}$(T) | 1/6 |
| $B_{ry}$ ,$B_{sy}$(T) | 1/4 |
| $B_r$(T) | 1/08 |
| $\mu_r$ | 1/03 |
| $K_h$ | 34/12 |
| $K_e$ | 0/028 |
| $K_{leak}$ | 0/9 |
| $K_{fe}$ | 0/95 |
| $B_{st}$ | 2 |
| B | π/2 |
| PF | 0/94 |
| eff(%) | 94/1 |



## 7. Objective Function Determination

Here the objective function is defined as sum of parameters. The parameters which needs maximization is considered inversely, because considering all needs and limitations of machine and by putting a coefficient behind each parameter, the effect of each parameter can be increased or decreased. Depending on type of the design equations, these coefficients can be low or high.

The objective function is written as a combination of loss and torque:

$$F = (\frac{1000}{T}) + P_{loss} \tag{32}$$

The 1000 is chosen experimentally and based on best results that have been obtained. Dimensions and characteristics of machine have been applied in table.5, after doing optimization using particle swarm optimization and bees algorithms.

In Table.6 the improvement rate of design objectives compared with initial motor have been shown.

In Table. 6, the positive sign shows parameters increase and negative sign shows parameters decrease compared with initial values. As it can be seen from the results, the optimization has considerably improved loss and torque compared with initial motor.

The optimization results using particle swarm optimization algorithm and bees algorithm have been shown in Fig. 4 and Fig. 5, respectively.

***Table 5. Dimensions and characteristics of machine after optimization***

| Parameter | Value | Value |
|---|---|---|
| Algorithm | ba | Pso |
| L(mm) | 85.4 | 85.4 |
| D(mm) | 50.8 | 50.8 |
| $J_s$ (A/mm2) | 7 | 7 |
| $b_{ts}$ (mm) | 5.5 | 5.5 |
| $D_i$ (mm) | 12 | 12 |
| $h_{ry}$ (mm) | 8 | 8 |
| g (mm) | 0.5 | 0.5 |
| $h_m$ (mm) | 2.7 | 2.7 |
| $\tau_p$(mm) | 29.3 | 29.3 |
| $\tau_s$ (mm) | 13.3 | 13.3 |
| $h_{ss}$ (mm) | 17.6 | 17.6 |
| $h_{sy}$ (mm) | 8 | 9.5 |
| $b_{ss1}$(mm) | 5.9 | 5.9 |
| $b_{ss2}$(mm) | 14.3 | 14.3 |
| $h_{sw}$(mm) | 1.3 | 1.3 |
| $K_{open}$(%) | 0.3 | 0.3 |
| $Z_{slot}$ | 54 | 54 |
| $R_{cu}$(Ω) | 0.735 | 0.735 |
| I(A) | 7.54 | 7.55 |
| $T_s$ | 108 | 108 |
| $B_{garm}$(T) | 0.2216 | 0.2219 |
| $Vol_{total}$ ($mm^2$) | 728240 | 727740 |
| $M_{total}$ (Kg) | 5.054 | 5.051 |
| $C_{total}$(euro) | 37.5 | 37.47 |
| $C_{pm}$(euro) | 8.44 | 8.435 |
| $P_{cu}$(W) | 125.4 9 | 125.68 |
| $P_c$(W) | 165.81 | 165.7 |
| $P_{loss}$(W) | 436.73 | 436.81 |
| eff(%) | 93.02 | 93.02 |
| T(N.m) | 4.68 | 4.69 |
| Function objective | 650.1669 | 650.2071 |

***Table.6 Improvement rate of design objectives compared with initial motor***

| Design objectives | Torque | Loss |
|---|---|---|
| Percentage change compared with initial motor | +19.5% | -7.08% |

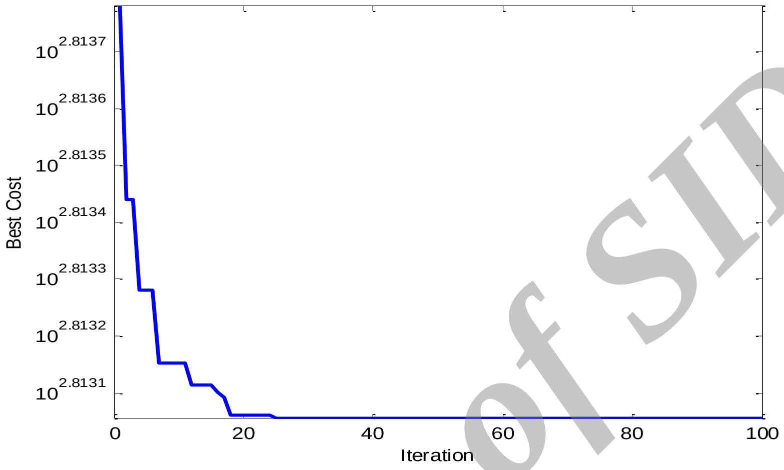


***Fig. 4: Optimization of objective functions of loss and torque using particle swarm algorithm***

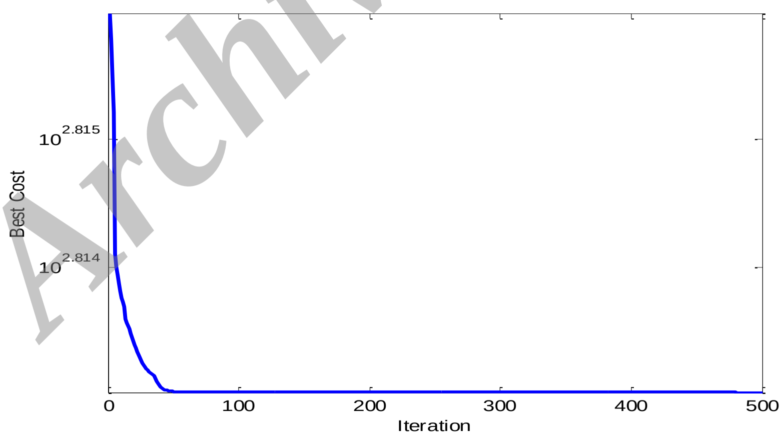


***Fig. 5: Optimization of objective functions of loss and torque using bees algorithm***

As it can be seen in figures 5 and 6, the particle swarm algorithm and bees algorithm have converged to final solutions after 25 and 40 iterations, respectively, which show the higher convergence speed of particle swarm algorithm compared with bees algorithm, but on the other hand, the bees algorithm has converged with more uniformity to the final solution.

## 8. Conclusion

In this paper, a surface mounted permanent magnet synchronous motor has been designed using particle swarm optimization and bees algorithm. The objective function is considered as a combination of loss and torque. To reach proper solutions, some torque coefficients have been considered, experimentally. The optimization caused 7.08% decrease for loss and 19.5% increase for torque, compared to motor initial values. After comparing two algorithms, it is concluded that the particle swarm algorithm is better in convergence speed and the bees algorithm is better in uniformity in objective function diagram. But the accuracy of algorithms cannot be compared by this information, because obtained values are so close to each other and the convergence accuracy may be changed in different conditions.

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