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Research Article

Design Optimization of PM Synchronous Motor Using Gray Wolf Optimization Algorithm

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Abstract

In industrial fields, permanent magnet synchronous motors are preferred for several decades. This is because permanent magnet synchronous motors have a high torque/volume ratio, different design architectures and particularly high efficiency. The main factors to achieve these advantages are the use of the robust design algorithms and the selection of effective geometric parameters in design optimizations. This study proposes using the gray wolf algorithm to obtain a high efficiency surface mounted permanent magnet synchronous motor. The results of the gray wolf algorithm are compared with the results of the particle swarm optimization algorithm. The results obtained are very good in terms of motor efficiency. In this way, the effectiveness of the gray wolf algorithm in surface mounted permanent magnet synchronous motor design has also been represented.

Keywords: Gray wolf optimization algorithm, Particle swarm optimization algorithm, Permanent magnet synchronous motor

Gri Kurt Optimizasyon Algoritmasını Kullanarak PM Senkron Motorun Tasarım Optimizasyonu

Öz

Kalıcı mıknatıslı senkron motorlar, endüstriyel alanlarda birkaç on yıldır tercih edilmektedir. Bunun nedeni, kalıcı mıknatıslı senkron motorların yüksek bir tork / hacim oranına, farklı tasarım mimarilerine ve özellikle yüksek verimliliğe sahip olmasıdır. Bu avantajları elde etmenin ana faktörleri, sağlam tasarım algoritmalarının kullanılması ve tasarım optimizasyonlarında etkili geometrik parametrelerin seçilmesidir. Bu çalışma, yüksek verimli yüzeye monte sabit mıknatıslı senkron motor elde etmek için gri kurt algoritmasının kullanılmasını önermektedir. Gri kurt algoritmasının sonuçları, parçacık sürüsü optimizasyon algoritmasının sonuçlarıyla karşılaştırılmıştır. Elde edilen sonuçlar motor verimi açısından oldukça iyidir. Bu sayede, gri kurt algoritmasının yüzeye monte sabit mıknatıslı senkron motor tasarımındaki etkinliği de ortaya konmuştur.

Anahtar Kelimeler: Gri kurt optimizasyon algoritması, Parçacık sürüsü optimizasyon algoritması, Kalıcı mıknatıslı senkron motor

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1. Introduction

DC motors were highly preferred in the 20th century for ease of control. Electric motors, which later replaced dc motors and are more widely used, are induction motors in industrial fields. Compact motion system i.e. gearbox and induction motor are poor in performance, especially it has high cost, noise, and low efficiency. This is unacceptable in industrial applications requiring comfort, especially in elevator traction systems. Great efforts have been made for the optimum use of energy resources recently and therefore the use of energy efficient machinery is encouraged worldwide. In an industrial area, the overall system efficiency can be greatly increased in elevator traction systems by the use of higher efficiency permanent magnet synchronous motors (PMSMs) and especially by eliminating the gearbox and machine room [Hwang et al, 2012; Ficheux et al., 2001]. The situation has brought great benefits in terms of energy savings. For this reason, R&D studies continue for design optimization and drive systems of PMSMs with different architectures.

On the other hand, it is common to use artificial intelligence techniques (AITs) in the design optimizations of permanent magnet synchronous motors. Here, optimization studies of design focused on different aims such as reducing cogging torque and torque ripple, and increasing efficiency [Sim et al, 1997; Łukaniszyn et al., 2004; Cassimere and Sudhoff, 2009; Güemes et al, 2011; Sizov et al., 2011]. Obviously, PMSM's design optimization work is hard research. Because the PMSM's design parameters have a very large range, the design approach is not linear, and moreover, optimization studies have many limit values. Design parameters are chosen based on the design experience, knowledge and correlation between parameters and the purpose of optimization. As a result, these studies focus on comparing the performance of PMSMs or improving existing motor performance.

The design structures of PMSMs are variable according to the positions of permanent magnets in the rotor, slot/pole ratio, winding layouts used, stator and rotor tooth and yoke configurations. However, the main factors that determine motor types are industrial needs and environmental effects. Surface mounted PMSMs are often preferred as elevator traction systems at low speeds. Because surface mounted PMSMs have a simple structure compared to other magnet motors and their production costs are lower. Both distributed and concentrated windings are used in the inner and outer stators of these motors. Concentrated winding is superior to distributed winding in terms of copper loss. However, designers should be careful in choosing stator and rotor configurations, considering other factors.

This article proposes design optimization using the geometric parameters of the surface mounted PMSM. It is twelve-slot and ten-pole and has a concentrated double layer winding using gray wolf optimization (GWO) algorithm and particle swarm optimization (PSO) algorithm for low speed moving applications. The main purpose of the study is to obtain a better geometric model for a high-performance high-efficiency motor. The results obtained are finally acceptable and beneficial.

2. Optimization Algorithms

Any optimization process is an activity that seeks the most appropriate solution for an engineering problem. However, optimization results may not always be the best. This situation reveals the importance of determining the problem, choosing parameters and evaluating the results, and the continuity of the optimization process dimension. GWO and PSO algorithms are given below.

2.1. Particle Swarm Optimization Algorithm

PSO algorithm developed by Eberhart and Kennedy is a population-based artificial intelligence technique. The vital behaviors of flocks of birds and fish have been examined in the development of the algorithm. According to classical algorithms PSO algorithm has a few operators. Therefore, PSO algorithm provides superior performance for optimization problems have large solution space. Structure of PSO algorithm is similar the behavior of foraging flocks of birds and fish. Fitness values of individuals in the population are related with proximity of flock to food and each individual in population represents each bird or fish and “particle” is called.

PSO algorithm is composed of two main equations or operators; velocity vector and position vector. The velocity vector shows variation of fitness values of individuals is as follows:

$$V_j(i) = V_j(i-1) + c_1 r_1 \left[p_{best,j} - x_j(i-1)\right] + c_1 r_1 \left[g_{best} - x_j(i-1)\right] \quad (1)$$

where, "$V_j(i)$" is the velocity of the j.th individual in i.th iteration. "$p_{best,j}$" and "g_{best}" are the better local and the best global individuals. "c_1" and "c_2" are learning rates of individuals and the group respectively; "r_1" and "r_2" are distributed random numbers in the range of 0 and 1. The position vector is also as follows:

$$X_j(i) = X_j(i-1) + X_j(i) \quad (2)$$

where, "$X_j(i)$" is the position of the j.th individual in i.th iteration [Rao, 2009].

2.2. Gray Wolf Optimization Algorithm

Ali et al. [Mirjalili et al, 2014] states that for the swarm hierarchy-based GWO algorithm, since gray wolves have a very strict social dominance hierarchy, the parameters of the developed algorithm also indicate this collectivity when seeking solutions. Alpha wolf is the leader and dominant individual in the swarm. This shows that the alpha wolf is not the strongest member of the swarm, but the best member to lead the pack. The equivalent of the alpha wolf in the algorithm is that its position is the best solution for the hunt (objective). Other levels in the gray wolf hierarchy are beta, delta, and omega. The lowest ranked gray wolf in the hierarchy is omega.

The GWO algorithm exemplifies the hunting strategies of wolves. Here the individual in the center is alpha (α) worms, beta (β) and delta (δ) wolves are the second and third best individuals and lastly the remaining wolves are omega (ω). In the GWO algorithm, the search is driven by α, β and δ, ω does not participate in the search but follows the others. The hunting behavior of gray wolves can be modeled mathematically as follows:

$$\vec{D} = \left|\vec{C} \cdot \vec{X}_p(t) - \vec{X}_p(t)\right| \quad (3)$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \quad (4)$$

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \quad (5)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \tag{6}$$

where, t is the current iteration, $\vec{D}$ is the distance of wolves to the prey, $\vec{X}_p$ is the position of the prey, $\vec{X}$ is the position of each wolf, the vectors $\vec{r}_1$ and $\vec{r}_2$ take random values between 0 and 1 to determine the position changes of wolves relative to their prey. $\vec{A}$ and $\vec{C}$ are the coefficient vectors, the vector $\vec{C}$ provides the constant displacement of the prey (exit from the local solution in search), the vector $\vec{A}$ allows wolves to approach the prey (precision of the solution). $\vec{a}$ value decreases from 2 to 0 during the iteration. Detailed information about the algorithm is in reference [Mirjalili et al, 2014].

3. Analysis of the PM Synchronous Motor

Permanent magnet synchronous motors consist of five main parts: shaft, rotor, stator, permanent magnets, and windings. Their structures and placements may vary according to operating conditions. In low speeds, surface mounted PMSMs have been generally preferred because of low-cost. The motor structure affects the design parameters so that seven variables in Table 1 are used for the design optimization. The geometric parameters are shown in Figure 1. In addition, some parameters are invariable and the others are obtained optimization algorithms. Thermal and mechanical conditions regarding surface mounted PMSM design are considered ideal.

Some important design equations are as follows [Mutluer and Bilgin, 2016]:

$$D_{rc} = D - 2l_m - 2\delta \tag{7}$$

$$\tau_s = \pi D / Q_s \tag{8}$$

$$b_{ss1} = \pi \frac{D + 2h_{sw}}{Q_s} - b_{ts} \tag{9}$$

$$b_{ss2} = \pi \frac{D + 2h_{ss}}{Q_s} - b_{ts} \tag{10}$$

$$h_{sy} = (D_o - D - 2h_{ss})/2 \tag{11}$$

$$k_{open} = b_{so}/b_{ss1} \tag{12}$$

$$A_{sl} = \big((b_{ss1} + b_{ss2})(h_{ss} - h_{sw})\big)/2 \tag{13}$$

where, τ_s is slot pitch factor, Q_s is slot number, b_{ss1} is width of inner stator slot, b_{ss2} is width of outer stator slot, h_{sy} is stator yoke height, A_{sl} is slot area. In order to calculate the flux density of air-gap, the Equation 14 is used.

$$B_m = \frac{B_r}{1 + (\mu_r \delta k_c)/l_m} \tag{14}$$

where, k_c is carter factor, B_r is remanence flux density, μ_r is relative permeability and B_m is maximum flux density of air-gap. Other equations can be used to calculate the equivalent circuit parameter sizes of the motor:

$$E = \frac{1}{\sqrt{2}} \omega k_{\omega 1} q n_s \hat{B}_\delta L (D - \delta) \tag{15}$$

$$R = \rho_{Cu} \frac{(pL(D + h_{ss})\pi k_{coil}) n_s^2 q}{f_s A_{sl}} \tag{16}$$

$$L_q = \left(pq\lambda_1 + \frac{3}{\pi}(q k_{\omega 1})^2 \frac{(D - \delta)}{\delta k_c + l_m/\mu_r} \right) \mu_0 L n_s^2 \tag{17}$$

where, m is phase number, q shows number of slots per pole per phase, ρ_{Cu} is copper resistivity, k_{coil} is end winding coefficient, λ_1 is specific permeance coefficient for slot opening, n_s is conductor number per slot. The later equations are used to calculate losses and motor efficiency:

$$P_{Cu} = 3RI^2 \tag{18}$$

$$P_{Fe} = P_h + P_e = k_h B^{\beta_{st}} \omega_e + k_e B^2 \omega_e^2 \tag{19}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{Cu} + P_{Fe}} \tag{20}$$

where, β_{st} indicates Steinmetz constant, ω_e shows electrical angular velocity, k_h and k_e are iron losses coefficients as hysteresis and as eddy current, P_{out} is power of the motor, P_{Cu} is copper loss, P_{Fe} is iron loss, and η is motor efficiency. Other intermediate equations and parameters are given in [Mutluer and Bilgin, 2016; Hanselman, 1994; Pyrhonen et al, 2008].

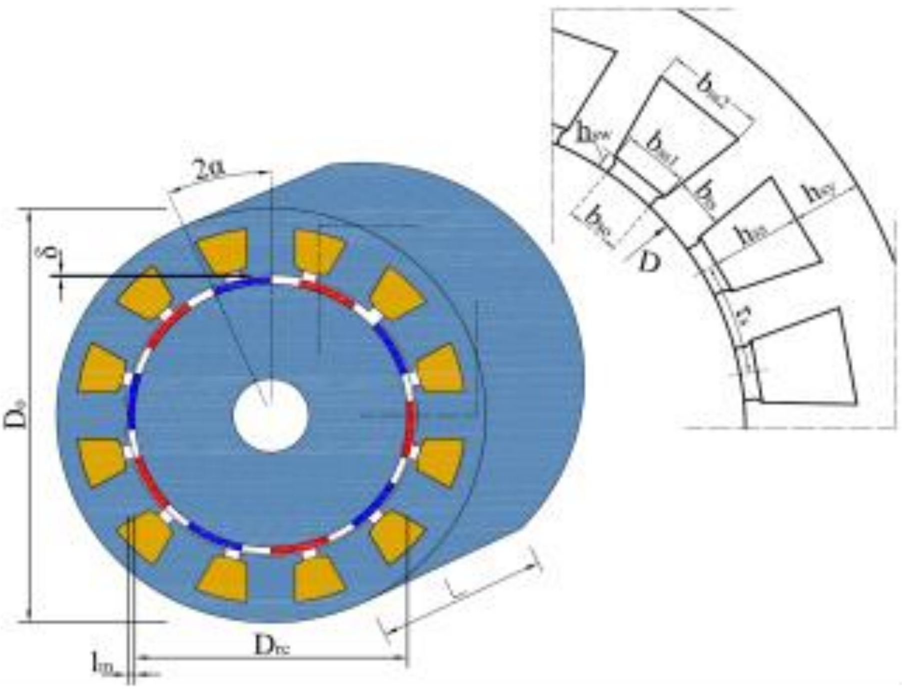

Figure 1. 2D and 3D views of the PMSM

Table 1. Design optimization variables and limits

Parameter	Symbol	Unit	Lower Limits	Upper Limit
Thickness of permanent magnet	h_m	mm	2	5
Length of air gap	δ	mm	0.5	1.2
Height of slot wedge	h_{sw}	mm	2	5
Width of stator tooth	b_{ts}	mm	30	40
Diameter of rotor outer	D_{rc}	mm	150	250
Height of stator slot	h_{ss}	mm	15	22
Ratio of the slot opening over the slot	k_{open}	-	0.25	0.40

3. Results and Discussion

Pre-analytical calculations of the surface mounted PMSM are achieved by means of an analytical design program. The efficiency is obtained as 92.05%. This study aims to perform PMSM design optimization using the GWO algorithm and then the obtained results are compared with the results using the PSO algorithm. The population and iteration numbers of the optimization algorithms are 30. For design optimization of the surface mounted PMSM, geometric variables and their limits are selected in Table 1.

Iteration graphs of the optimization algorithms are given in Figure 2. In design optimizations made with GWO and PSO algorithms, motor efficiency has been increased compared to the initial value. Motor efficiency, which was 92.05% at the beginning, increased to 94.20% with the GWO algorithm and 94.16% with the PSO algorithm. It is possible to say that better motor geometries are obtained according to these values.

According to the motor efficiency values, the GWO algorithm gave better results than the PSO algorithm. The geometric parameter values obtained and some dimensions of the design are given in Table 2 and Table 3, respectively. According to Table 2, the values at which both algorithms converge are close to each other. Especially the most important factor affecting the result is the ratio of the slot opening over the slot width. According to Table 3, motor design outputs close to each other are obtained. The total weight of the motor and the magnet weights are close to each other. There has not been a great deal of cost in between. Although the motor yoke fluxes are below the limit values, the stator tooth flux is partially higher.

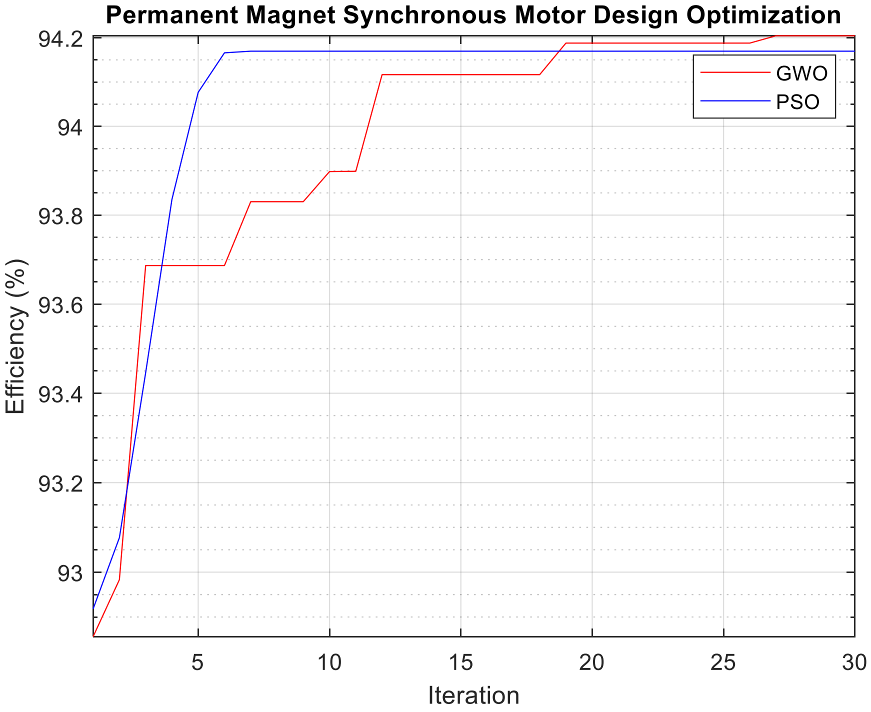

Figure 2. Iteration graphs of the GWO and the PSO algorithms

Table 2. Design optimization variables and limits

Algorithms	h_m **(mm)**	δ **(mm)**	h_{sw} **(mm)**	b_{ts} **(mm)**	D_{rc} **(mm)**	h_{ss} **(mm)**	k_{open}
GWO	5	0.5	2	30	196.21	22	0.26132
PSO	5	0.5	2	30	197.63	22	0.40

Table 3. Design optimization variables and limits

Algorithms	M_{PM} **(kg)**	M_T **(kg)**	**Cost ($)**	B_{ry} **(T)**	B_{sy} **(T)**	B_{st} **(T)**	B_{ry} **(T)**	**J (A/mm^2)**	n_s
GWO	1.99	62.83	248.59	0.35	0.95	1.90	0.35	3.37	97
PSO	2.01	62.93	250.29	0.35	0.98	1.89	0.35	3.33	97

4. Conclusions and Recommendations

In the optimization study of the surface mounted PMSM design performed here, the engine geometry with the highest efficiency was tried to be obtained by using GWO and PSO algorithms. Seven independent geometric design variables were chosen to provide simple optimization. The efficiency of the PMSM and the performance of the algorithms are investigated. According to the initial motor efficiency of 92.05%, the efficiency obtained with GWO is 94.20% with an increase of 2.33% and the efficiency obtained with PSO is 94.16% with an increase of 2.29%. This situation reveals that the GWO algorithm performs better than the PSO algorithm in the surface mounted PMSM design optimization.

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