

Design of external rotor permanent magnet synchronous motor based on genetic algorithm and differential evolution algorithm

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Abstract: Permanent magnet synchronous motors have been preferred in industrial fields for a few decades. It is reason for that the permanent magnet synchronous motors have high torque/volume ratio, large flux weakening region, and especially highly efficient. The main factor to obtain these advantages is the selection of suitable geometric parameters in their design optimizations. As a design optimization this study investigates external rotor permanent magnet synchronous motor with fractional slot windings. Pre-analytical designs and subsequently design optimizations by genetic algorithm and differential evolution algorithm have been studied. The better results obtained were tested by the finite element method. Thus, so much more compact and efficient motor model was to be achieved based on the design geometries. The results are very reasonable and useful.

Keywords: Design optimization, differential evolution algorithm, genetic algorithm, external rotor permanent magnet synchronous motor.

1. Introduction

The more commonly used electric motors are induction motors in industrial fields. The compact motion system, namely induction motor and gearbox have noise, high cost, and low efficiency in particular. This situation is not acceptable in industrial applications, e.g. electric vehicles and elevator traction systems. In recent years, great efforts have been made on the optimum use of energy resources and thus the using of energy-efficient machines around the world is encouraged. In an industrial field the total efficiency of the system can greatly increased by use of permanent magnet synchronous motors (PMSMs) because of elimination of the gearbox [1-2]. The situation has provided great benefits in terms of energy saving. Therefore R&D activities on the design optimization of PMSMs are underway.

Artificial intelligence techniques (AITs) have been used for design optimization of permanent magnet synchronous motors as well as for other electric motors. Herein the optimization studies have focused on different topics such as decreasing of cogging torque, torque ripple, and increasing of motor efficiency [3-7]. Obviously the studies on the design optimization of PMSM are more challenging investigations. Because input design parameters of PMSM are very large, the optimization problem is nonlinear, and moreover the optimization studies have a lot boundary values. The design parameters are selected according to design knowledge, experience and correlation between the parameters and the aim of the optimization. As a result, these optimization studies concentrate on comparison of performances of PMSMs which have different design architectures or on improving the current motor performance.

The design architectures of PMSMs are variable according to placements of magnets on rotor, pole/slot number, winding layouts, and rotor/stator configuration. The main factors that determine the variety are industrial requirements and environmental impacts. For low speed applications, surface-

mounted inner rotors PMSMs have often been preferred. Because the surface-mounted motors have simple structure and the cost of their production is lower than others. But the centrifugal force which increases with the rotational speed may cause detachment of magnets from rotor. Instead, external rotor motors provide higher power density with more magnet space and make use of the centrifugal force effect [8]. Distributed and concentrated windings have been used in inner and outer stators of these motors. Concentrated winding is superior to distributed winding according to copper loss. Therefore the designers must be careful in choosing rotor/stator configuration.

This paper proposes design optimization of surface-mounted external rotor PMSM have 12 slots 10 poles and concentrated double-layer winding for low speed applications. The main objective of the study is to achieve the better geometries for high efficient motor. Depending on the results the performances of the AITs were also compared. Then the better results were tested with the finite element method. The inferences are finally acceptable and useful.

2. The Artificial Intelligence Techniques

Optimization process is an activity that searches the optimal solution for a problem. However, the results may not be the best. This situation reveals the continuity of the optimization process aspect of the identification of the problem, selection of the parameters, and evaluation of the results. Genetic algorithm and differential evolution algorithm used in this study are given below. These techniques will be explained briefly [9-13].

2.1. Genetic Algorithm

The basic principle of GA developed by John Holland of the University of Michigan is the struggles of individuals to survive. GA does not produce only one solution to solve the optimization problem. Instead, GA tries to make the optimal solution in a population-based solution space of the problem. Populations are composed of individuals independently of each other; individuals are composed of genes containing the solution of the problem. GA

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does not require the initial solution and also does not guarantee to find the optimal solution to the global optimization problems. However, it converge a local solution. GA has three operators; reproduction, crossover and mutation [9-11]. Crossover and mutation operators and the flowchart of the genetic algorithm were shown in Figures 1-3.

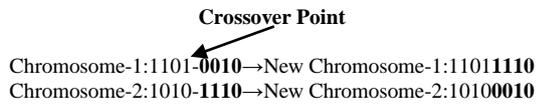


Figure 1. The use of crossover operator

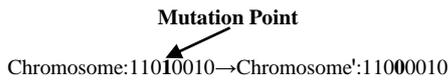


Figure 2. The use of mutation operator

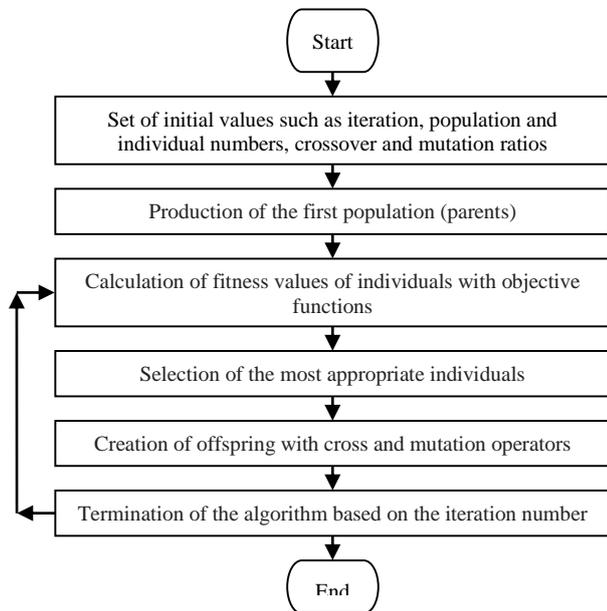


Figure 3. Flowchart of the genetic algorithm

2.2. Differential Evolution Algorithm

Differential evolution algorithm, for the first time in 1995 for use in global optimization problems, is proposed by Price and Storm. DEA is basically similar to GA. But the most striking aspect of DEA is the used differential operator. Differential action shall be taken to increase fitness values on the parents' genes by the differential operator. In this way, the quality of the population is tried to be increased. Easy application on an optimization problem is an important criterion in the history of artificial intelligence techniques. DEA exhibits superior performance because it has a very small number of parameters to be set and has the understandable actual code sequence. The creation of the initial population for the differential evolution algorithm and the use of differential operator are respectively as follows:

$$x_{j,i,g} = x_{j,i,g} + rand_j[0,1] \times (x_j^h - x_j^l) \quad (1)$$

$$x_{j,i3,g} + F \times (x_{j,i1,g} - x_{j,i2,g}) \quad (2)$$

where, "j" is iteration number, "i" are individual, x_j^h and x_j^l upper

and lower values of individuals and "g" shows the gen, "F" is weighted difference vector, " $i_{1,2,3}$ " are individuals, and "g" shows the gen [12-13]. The flowchart of the differential evolution algorithm was given in Figure 4.

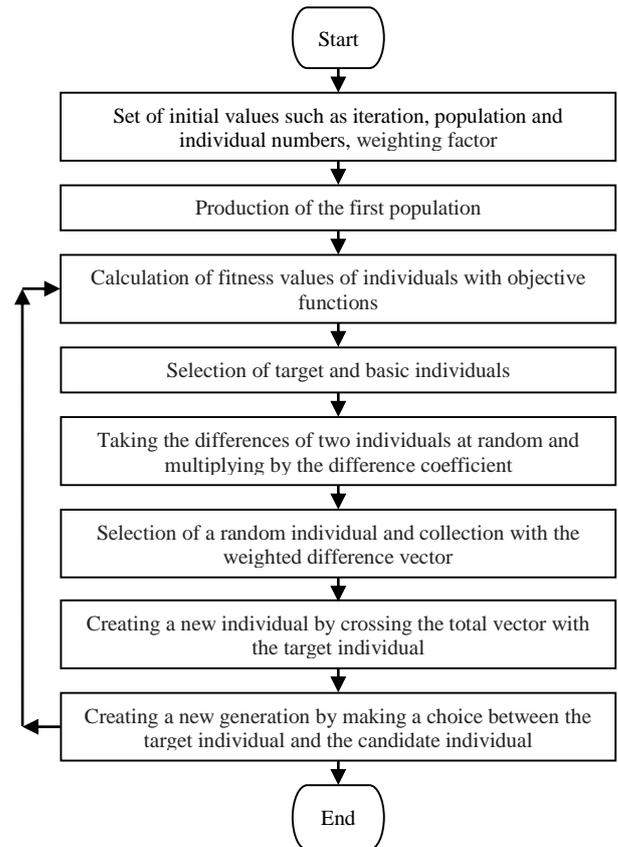


Figure 4. Flowchart of the differential evolution algorithm

3. The Structures of The Permanent Magnet Synchronous Motors

Permanent magnet synchronous motors consist of five main parts: shaft, rotor, permanent magnets, stator, and windings. Their structures and placements may vary according to operating conditions. Surface mounted PMSMs have been generally preferred because of low-cost. The main features of the selected PMSM which affect the power density were given in Table 1.

The motor structure affects the design parameters which are more important, so that seven independent variables in Table 2 were used for the design optimization.

Table 1. Basic characteristics of the PMSM

Features and Units	PMSM
supply (V)	340
power (W)	2400
speed (rpm)	250
pole number – p	10
slot number – Q_s	12
winding type	Concentrated (double-layer)
stack length – L (mm)	120
outside stator diameter – D_o (mm)	340
pole angle – 2α (°)	126
type of PMS	NdFeB

Table 2. The design optimization parameters

Parameter and Units	Symbol
magnet thickness (mm)	l_m
air gap length (mm)	δ
slot wedge height (mm)	h_{sw}
stator tooth width (mm)	b_{ts}
inside rotor diameter (mm)	D_{rc}
stator slot height (mm)	h_{ss}
ratio of the slot opening over the slot width	k_{open}

In addition some parameters are invariables and the others were determined by both algorithm and then copper losses, iron loss, and efficiency were calculated.

The geometric equations are as follows [8, 14-15]:

$$D = D_{rc} - 2l_m - 2\delta \quad (3)$$

$$\tau_s = \pi D / Q_s \quad (4)$$

$$b_{ss1} = \pi \frac{D - 2h_{sw}}{Q_s} - b_{ts} \quad (5)$$

$$b_{ss2} = \pi \frac{D - 2h_{ss}}{Q_s} - b_{ts} \quad (6)$$

$$h_{sy} = (D - D_{shaft} - 2h_{ss}) / 2 \quad (7)$$

$$k_{open} = b_{so} / b_{ss1} \quad (8)$$

$$A_{sl} = ((b_{ss1} + b_{ss2})(h_{ss} - h_{sw})) / 2 \quad (9)$$

where, D is outside stator diameter, D_{shaft} is shaft diameter, τ_s is slot pitch factor, b_{ss1} is inner stator slot width, b_{ss2} is outer stator slot width, b_{so} is stator slot opening and A_{sl} is slot area. For calculating the air-gap flux density, the following equations are used.

$$k_c = \frac{\tau_s}{\tau_s - b_{so}^2 / (b_{so} + 5\delta)} \quad (10)$$

$$k_{leak} = \frac{100 - (7p/60 - 3)}{100} \quad (11)$$

$$B_m = \frac{B_r k_{leak}}{1 + (\mu_r \delta k_c) / l_m} \quad (12)$$

$$\hat{B}_\delta = (4/\pi) B_m \sin \alpha \quad (13)$$

where, k_c is carter factor, k_{leak} is correction factor for the air-gap flux density calculation, B_r is remanence flux density, and its value is 1.2T, μ_r is relative permeability and its value is 1.03, B_m is maximum air-gap flux density, \hat{B}_δ is amplitude of fundamental air-gap flux density.

Each motor has different current loading ranges.

$$\hat{S}_1 = \frac{4T}{\pi D^2 L \hat{B}_\delta k_{\omega 1} k_{cor} \sin \beta} \quad (14)$$

where, k_{cor} is correction factor for the current loading calculation, β is angle between the d-axis and current vector and its value is $\pi/2$ radian for non-salient motors, T is rated torque, $k_{\omega 1}$ is fundamental winding factor and its value is 0.933 for used double layer concentrated winding.

$$n_s \hat{I} = \hat{S}_1 \tau_s \quad (15)$$

$$E = \frac{d\psi_m}{dt} = \frac{1}{\sqrt{2}} \omega k_{\omega 1} q n_s \hat{B}_\delta L (D - \delta) \quad (16)$$

$$R = \rho_{Cu} \frac{(pL(D - h_{ss})\pi k_{coil}) n_s^2 q}{f_s A_{sl}} \quad (17)$$

$$L_q = \left(pq\lambda_1 + \frac{3}{\pi} (qk_{\omega 1})^2 \frac{(D - \delta)}{\delta k_c + l_m / \mu_r} \right) \mu_0 L n_s^2 \quad (18)$$

$$n_s = \frac{\hat{v}}{\sqrt{(E' + R' n_s I)^2 + (L'_q \omega n_s I)^2}} \quad (19)$$

where, ψ_m is magnet flux linkage, m is phase number, $q = Q_s / pm$ is number of slots per pole per phase and its value is 0.4, ρ_{Cu} is copper resistivity, k_{coil} is end winding coefficient and its value is 0.93, λ_1 is specific permeance coefficient of slot opening, n_s is conductor number per slot, $L_q = n_s^2 L'_q$ is q-axis inductance, $E = n_s^2 E'$ is fundamental of induced voltage, $R = n_s^2 R'$ is one phase resistance of stator winding. Equation 19 is based on the vector diagram in Figure 5.

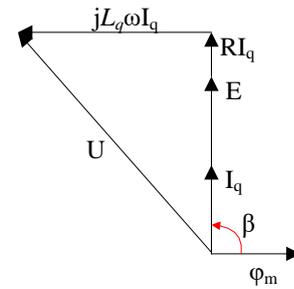


Figure 5. Phasor diagram for a non-salient PMSM

After that, copper and iron losses are calculated and the efficiency equation is acquired as follows:

$$P_{Cu} = 3I^2 R \quad (20)$$

$$P_{Fe} = P_h + P_e = k_h B^{\beta_{st}} \omega_e + k_e B^2 \omega_e^2 \quad (21)$$

$$\eta = \frac{P_{out}}{P_{out} + P_{Cu} + P_{Fe}} \quad (22)$$

where, β_{st} Steinmetz constant, ω_e is electrical angular velocity, k_h is hysteresis loss coefficient, k_e is eddy current loss coefficient, P_{out} is output power, P_{Cu} is copper loss, P_{Fe} is iron loss, and η is efficiency. Other pre-equations and intermediate design parameters can be examined in [8, 14-15].

Stator winding is important in design of an electric motor because of efficiency, cost, and torque ripple etc. Herein the different winding layouts with periodicity are shown in Figure 6 [8, 14].

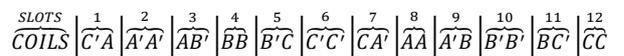


Figure 6. 12/10 slots/poles concentrated (double-layer) winding layout

4. Application of The Design Optimization of The PMSMs

Firstly motor windings have been run in series and in parallel. So pre-analytical design and optimizations of the PMSM were achieved and then the better results were tested with the finite element method. In addition the optimal geometric parameters, convergence times, and convergence graphics were given and finally were comprehensively evaluated. Some geometric, electrical, and magnetic constraint functions have been used in the optimization study to obtain accurate results.

Both population and iteration numbers are 200 and crossover and mutation ratios are 0.85 and 0.01 respectively for each optimization algorithms. This value is quite sufficient to get results. GA is binary coded and DEA is real coded. Boundary values of the geometric variables were chosen as in Table 3. The efficiency results were given Table 4.

Table 3. The boundary values of the geometric variables

Design Variables	l_m (mm)	δ (mm)	h_{sw} (mm)	b_{ts} (mm)	D_{rc} (mm)	h_{ss} (mm)	k_{open}
Upper Value	4.75	1.5	5	43	280	45	0.5
Lower Value	3.25	1	1	20	220	25	0.1

Table 4. The PMSM efficiency results

Method	Winding Form	η (%)
Analytical	Series	93.326
	Parallel	97.052
GA	Series	94.546
	Parallel	97.196
DEA	Series	95.247
	Parallel	97.615

According to Table 4, in general the parallel wound has higher efficiency than the series wound. Optimization in series and parallel wound motor designs has been a positive effect. Both optimization algorithms have investigated the motor geometries with highly efficient. The maximum efficiency increase in the series winding motors is 2.06% while the maximum efficiency increase in the parallel winding motors is 0.58%. The maximum achieved efficiency is 97.615% obtained with the differential evolution algorithm. Finite element analysis was also done for this maximum efficient motor geometry.

The durations of both algorithms and the convergence graphs are given in Figures 7-9. According to these graphs, the convergence speed and the sensitivity of the differential evolution algorithm are higher than the genetic algorithm.

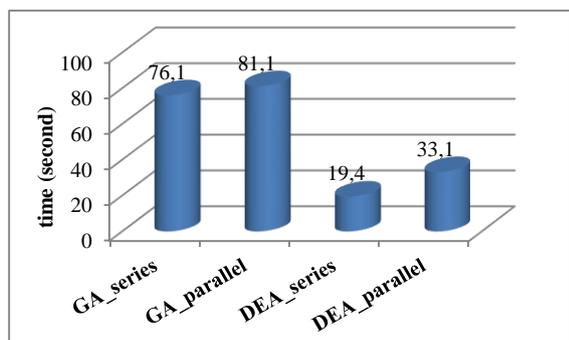


Figure 7. The convergence times of both algorithms

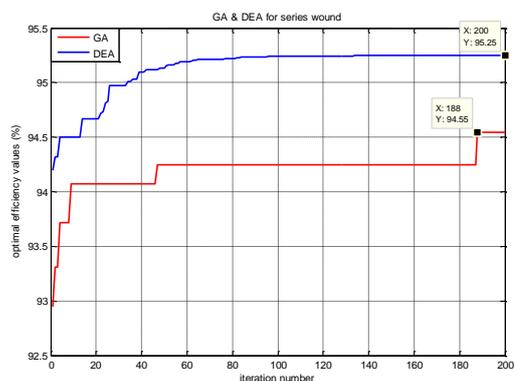


Figure 8. The convergence graphics of GA&DEA for series wound

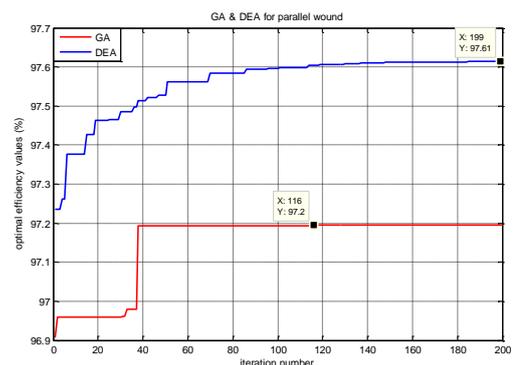


Figure 9. The convergence graphics of GA&DEA for parallel wound

The minimum convergence time is 19.4 seconds, which belongs to the differential evolution algorithm. When looking at the convergence graphs, it can be observed that the genetic algorithm falls into the local regions.

Other motor dimensions were obtained by using the optimal geometric parameters in Table 5.

Table 5. The geometric parameters for the better efficiency

l_m (mm)	δ (mm)	h_{sw} (mm)	b_{ts} (mm)	D_{rc} (mm)	h_{ss} (mm)	k_{open}
3.25	1.5	4.83	31.02	265.41	27.43	0.49984

The values obtained for the parallel wound motor with the differential evolution algorithm were tested by the finite element method. According to this test, the output power is 2406.1 watts, the input power is 2621.2 watts and the efficiency is calculated as 91.8%. The efficiency error value between the finite element and the optimization is 6.33%. The equations that better express the motor design geometry and the constraint functions in the optimization algorithms can be used more effectively to reduce this difference.

5. Conclusion

In this study design optimization of surface mounted external rotor permanent magnet synchronous motor were investigated by using genetic algorithm and differential evolution algorithm. A sufficient amount of design parameters were selected to provide a simple design optimization. The efficiencies of the PMSM and the performances of the algorithms were evaluated. According to the

efficiency results, the external rotor PMSM is structurally high power density and high efficiency, and the parallel connected motor structure is more efficient. The differential evolution algorithm also has more robust research capabilities than the genetic algorithm. But the design equations and the constraint functions used in the optimization study are very influential on the results.

Finally, permanent magnet synchronous motor designs are multivariable engineering problems that are not linear. Therefore, the use of effective algorithms in such studies is reflected in the results. In addition, multi objective design studies on topics such as efficiency, cost, weight, cogging torque and torque ripple will contribute to the motor design in terms of stability of the results. When these studies are carried out, attention should be paid to geometric, electrical, magnetic, thermal and mechanical boundary values. Because there are many different permanent magnet synchronous motor structures and the boundary values are specific to each motor design.

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