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A Shape Optimization of Universal Motor using FEM and Evolution Strategy

Pan-Seok Shin*

Abstract - This paper proposes an optimized universal motor for improving its performance using the finite element method (FEM) with the (1+1) Evolution Strategy (ES) algorithm. To do this, various design parameters are modified, such as air gap length, shape of motor slot, pole shoe, pole width, and rotor shaft diameter. Two parameters (arc length of stator pole and thickness of pole shoe) are chosen and optimized using the program, and the optimized model is built and tested with a performance measuring system. The measured values of the model are compared with those of the initial and the optimized model to prove the algorithm. As a result, the final model improves its performance compared with those of the initial model.

Keywords: evolution strategy, finite element method , shape optimization, universal motor

1. Introduction

The single-phase universal motor is very similar to a dc series motor. When the motor is connected to an ac source, the ac current flows through the armature and the series field. The field produces an ac flux that reacts with the current flowing in the armature to produce torque. Because the armature current and the flux reverse simultaneously, the torque always acts in the same direction.

The universal motor has the sharply drooping torque-speed characteristic of a dc series motor, so it is unsuitable for constant-speed applications. However, due to the advantages of its high speed, high starting-torque, and light weight, it is widely used for vacuum cleaners, drills, similar portable tools, and kitchen applications [1].

In this paper, the universal motor is designed to get the maximum torque and the minimum core volume profile. To do this, various design parameters are set, such as air gap length, stator yoke length, slot tip height, pole width, and so on. Initially, the basic dimension of the universal motor is determined by the experimental functions. The finite element method (FEM) is used to analyze the magnetic field and to calculate torque of the motor, and the initial parameters are partially modified to optimize the model. Then FEM simulation and the (1+1) evolution strategy are used to obtain the optimal dimension of the core of the motor [2,3]. After the optimized model is found by the program, the universal motor was built and tested with a performance measuring system. The measured values of the model are compared with those of the initial and the optimized model to prove the algorithm.

2. Algorithm Overview

2.1 Finite Element Method

Maxwell's equations to be solved in a general magnetostatic field are

$$\nabla \times \vec{H} = \vec{J}\,, \quad \vec{B} = \nabla \times \vec{A} \tag{1}$$

$$\nabla \cdot \vec{B} = 0\,, \quad \vec{B} = \mu \vec{H} \tag{2}$$

where, H is the field intensity, J is the current density, $\vec{B}$ is the flux density, μ is the permeability, and $\vec{A}$ is the vector potential. For an electromagnetic problem involving motion, the introduction of the velocity term leads to the following equation for a fixed reference:

$$\nabla \times \left[\frac{1}{\mu} \nabla \times \vec{A} \right] + \sigma \left[\frac{\partial \vec{A}}{\partial t} - v \times (\nabla \times \vec{A}) \right] = J_0 \tag{3}$$

where, v is the velocity, J_0 is the source current density, and σ is the electric conductivity. To eliminate eddy current and velocity term, Equation (3) has the following general Poisson's equation form in the magnetostatic field:

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* Electrical Engineering Department of Hongik University, Jochiwon, Chungnam, 339-701, KOREA (psshin@hongik. ac.kr)

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$$\nabla \times \left[\frac{1}{\mu} \nabla \times \vec{A} \right] = J_0 . \tag{4}$$

The method of weighted residual is applied to the field equation, Equation (4), in a discretized domain to yield the finite element matrix equations. After solving the equation, flux density, current, and torques of the modified model are calculated and analyzed.

2.2 Evolution Strategy Algorithm

The Evolution Strategy (ES) algorithm, one of the optimization techniques, is the non-deterministic method and shows a fast convergence characteristic [4]. The ES algorithm is combined with the genetic algorithm, which imitates the adaptive evolution procedures of the creature, and simulated annealing, which imitates the annealing in the refining process of the metal.

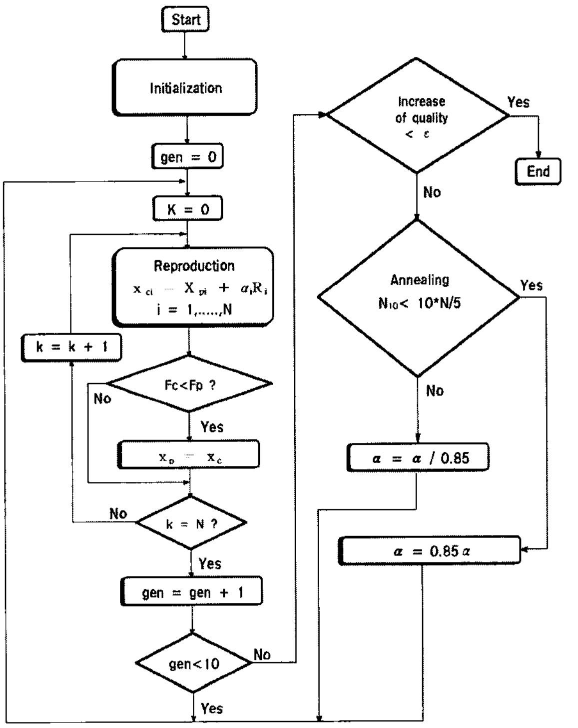


Fig. 1 Flow chart of (1+1) ES

In the simplest (1+1) ES scheme, there are 5 basic steps: initialization, reproduction, selection, annealing, and termination [5,6]. The (1+1) means that 1 parent and 1 offspring are compared iteratively over the total optimization procedures. Fig. 1 shows a flow chart of the (1+1) ES scheme and the procedure can be explained by the following 5 steps.

The (1+1) ES scheme starts the optimization with the first parent of feasible solution. This parent is created randomly within the domain of feasible space. Then, for the first selection of the variables to maximize the torque, the initial calculation of the objective function is carried out.

The second step is reproduction to produce off-springs from the parent. A design variable of offspring, X_o can be searched as described in the flow chart: $X_o = X_p + \alpha_i \cdot R_i$ where X_p is the design variable of parent, α is the mutation step length, and R_i is a random number between -1 and +1.

The third step implements the principle of fitness of nature and selects the one having superior fitness (objective value).

The fourth step is annealing to adjust the mutation step by the criteria of every 10 times. This process has the property of accelerating the convergence speed and guarantees optimality. Conventionally, the number 0.85 is in many research works. In the flow chart, N_{10} is the number advancing the objective function during 10 generations, N is the number of design variables, and α is the mutation step length.

If the termination values were satisfied, the procedure would be ended. Otherwise, the procedure goes back to the reproduction step. In this paper, the shape optimization of the stator pole is performed by the experimental functions and the (1+1) ES algorithm. Experimental functions are used for calculating torque and the total optimization procedures with the (1+1) ES algorithm. The FEM is used for magnetic field analysis to compute torque and to compare performance of the initial model with those of the optimized. Fig. 2 shows the simulation model of a 220 V, 700W, and 6000 rpm rated speed universal motor.

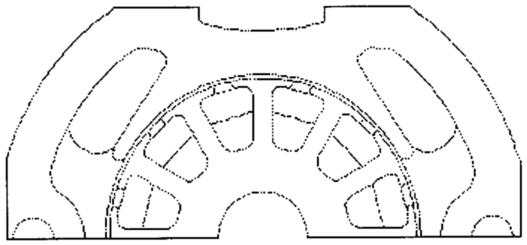


Fig. 2 Simulation model of the universal motor

3. Improvement of the Motor Parameters

To improve the performance of the motor, its parameters are modified and the current-torque characteristic is calculated. If the modification improves the performance, then it is chosen as an optimal point. The modified parameters are rotor inner diameter, air gap length, pole width, slot shape, and stator yoke length.

In the ES algorithm, the thickness and the arc length of stator pole shoe are chosen as the design parameters. Fig. 3

shows the model, which changes the value of the inner diameter of the rotor. To model a load condition, an external resistor is used as a load.

Fig. 4 shows the torque as function of the load current and rotor inner diameter. As the current increases, the torque of the ϕ 10 motor becomes gradually higher than that of the ϕ 12.

The shape of the rotor slot is modified from rectangular to round as shown in Fig. 5. As shown in Fig. 6, the torque of the round rotor is slightly higher than that of the rectangular one.

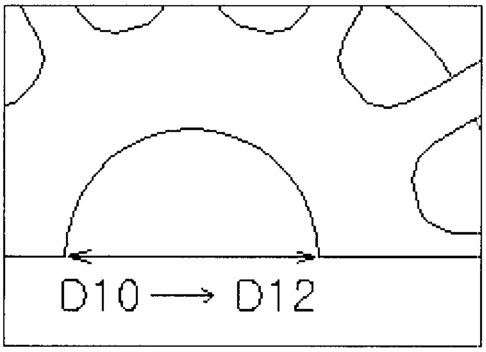


Fig. 3 Rotor inner diameter

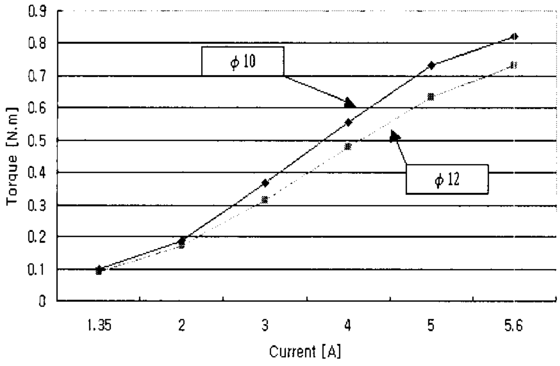


Fig. 4 Torque as function of load current

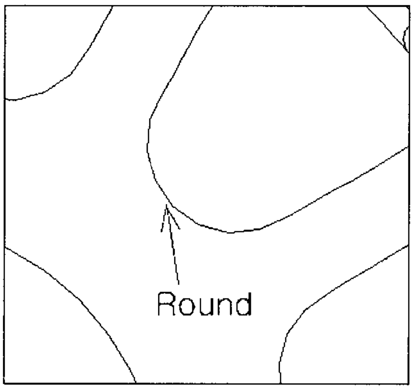


Fig. 5 The modified shape of rotor slot

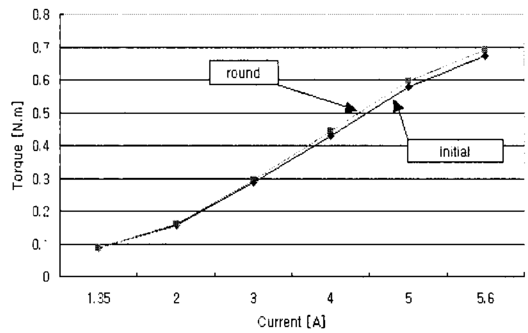


Fig. 6 Torque characteristic as function of load current with modified rotor slot

Fig. 7 describes the pole shoe of stator with chamfer, which has 2 different arc radii along the airgap line. As shown in Fig. 8, the torque of the motor with chamfer is evenly higher than the initial model without chamfer through the whole range of the load current.

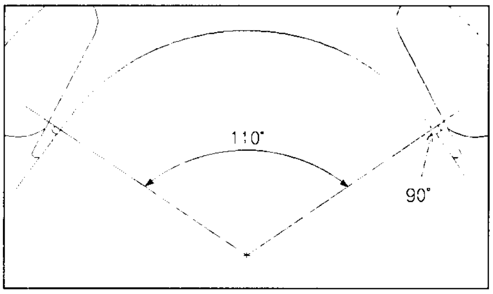


Fig. 7 The pole shoe of the stator with chamfer

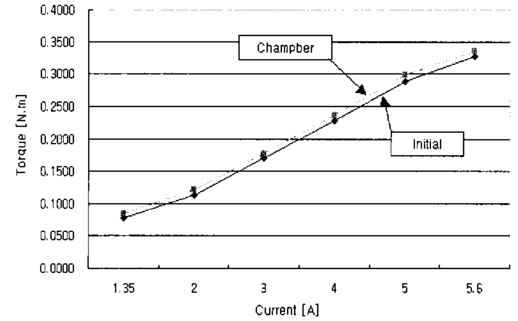
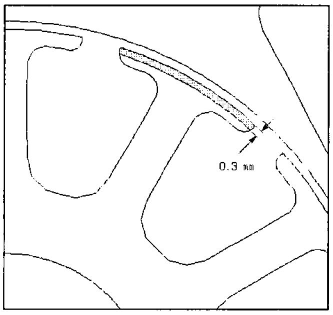
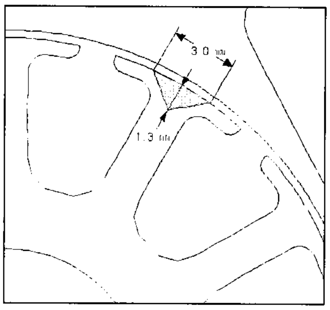


Fig. 8 Torque-current characteristic for the chamfer model



(a) Face cutting



(b) Polar cutting

Fig. 9 Cutting method to balance weight

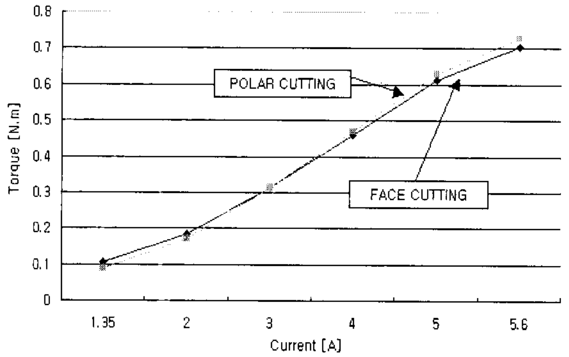


Fig. 10 Torque of motor with polar cutting and face cutting

Fig. 9 shows cutting methods to balance the rotor weight; the face cutting is to cut the pole face of the rotor tooth and the polar cutting is to remove the weight as shown in Fig. 9(b). Fig. 10 shows the torque-current characteristic of the two model. When the load is small, the face cutting method is good for the torque, and when the load is large, the polar cutting seems to be more effective.

In the similar method, the other parameters, like airgap length, rotor tooth width, rotor slot width, and shape of yoke, are chosen to improve the performance of the motor.

All these modifications result in a 2 % reduction in the cross-section area of the stator lamination and a reduction from 48x56 to 46x52 mm in the outer diameter of the stator. Thus, the production cost can be lowered.

4. Application of Evolution Strategy

First, constraint conditions are defined to apply the ES algorithm to the simulation motor. The fixed parameters are as follows: the rated current is 4 [A], the stator coil has 200 turns, the rotor has 20 turns, the stator pole angel is 130 degrees, and the other dimensions of the motor are fixed except for the design parameters. The geometry to be optimized is the arc length of stator pole, β, and the thickness of pole shoe at 40 degrees from center line, α, as described in Fig. 11.

After the (1+1) ES program with experimental function is performed, the final optimized parameters of the stator are obtained as described in Table 1.

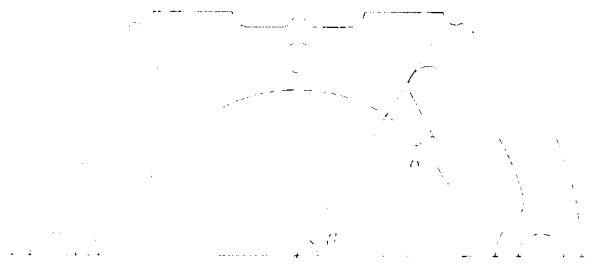


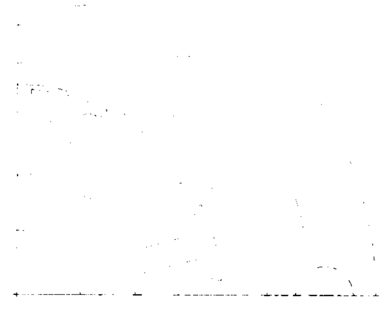
Fig. 11 Selected design variables

Table 1 The optimized design variables

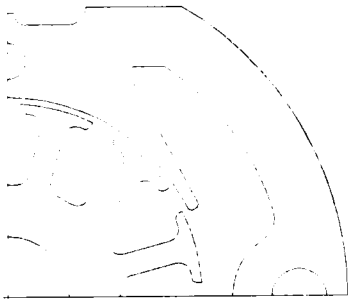
		Initial Value	Optimized Value	Range of Calculation
Design Variables	α	2.28[mm]	2.42[mm]	$1 < \alpha < 3.5$ [mm]
	β	57.8°	58.4°	$45° < \beta < 70°$

The arc length of stator pole is increased by 0.6° and the thickness of pole shoe is increased by 0.14mm. The airgap is increased by 0.05 mm from 0.35mm to 0.40mm. The larger airgap decreases power efficiency, but provides more mechanical space and more motor productivity.

Fig. 12 shows the cross-section of the initial and the optimized shape of the simulation model, respectively. As shown in Fig. 12(b), the window area of the stator coil is increased from 65 mm^2 to 70 mm^2; it can make the winding process quite easy. To analyze the performance of the two models, torque and flux density are calculated as a function of input current. Fig. 13 shows the equivalent flux lines of the two models. The final current-torque characteristic of the optimized model are described in Fig. 14. In spite of the increment of the airgap length, the torque characteristic is improved by about 7% on the whole range of the current.

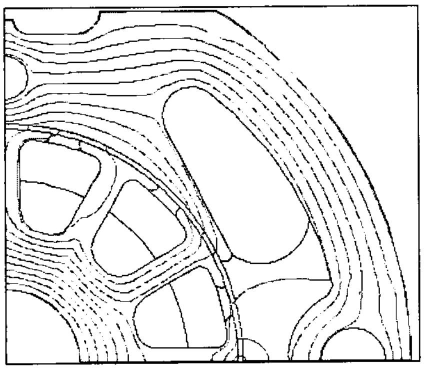


(a) The initial model

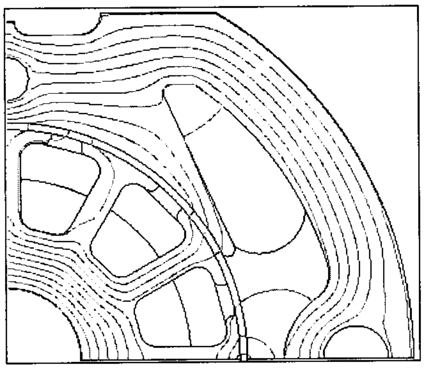


(b) The optimized model

Fig. 12 The cross-section of the simulation model



(a) Initial model



(b) Optimized model

Fig. 13 Equivalent Flux lines of the model

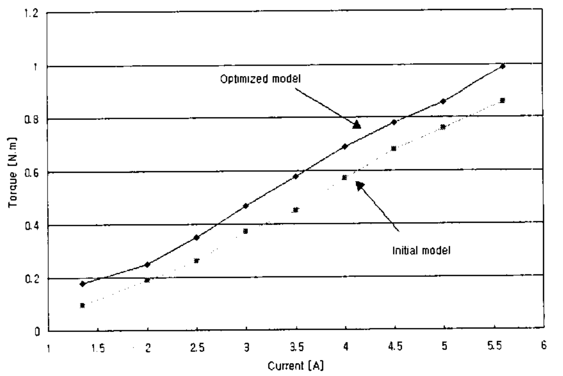


Fig. 14 The final current-torque characteristic of the optimized simulation model.

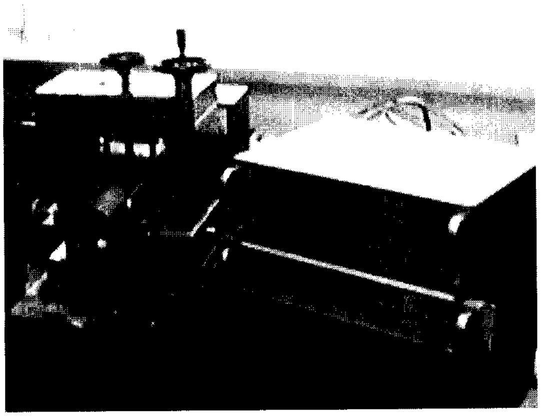


Fig. 15 Performance measuring system of the optimized model

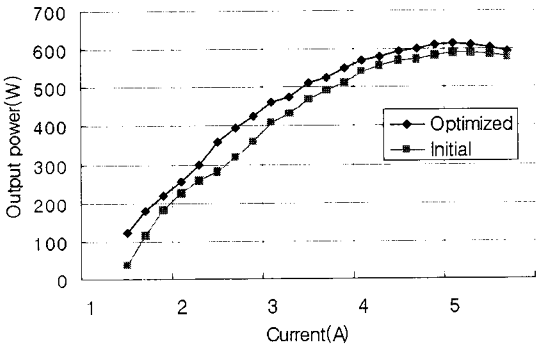


Fig. 16 Output power-current curves(measured) of the studied universal motor

The optimized motor was built and tested with the MAGTROL, DSP6000, Power analyzer 5100, Dynamometer-700, 2N experimental setup shown in Fig. 15. The measured values for current, voltage, torque, power, and efficiency of the optimized motor compared well with the computed values. Fig. 16 shows the test results of the studied model for output power as a function of the input current. The optimized model has a maximum power around the input current of 5A and slightly higher power than those of the initial model.

4. Conclusion

This paper proposes a parameter optimization method using the (1+1) ES algorithm and FEM to obtain the maximum torque and the minimum core volume profile of the universal motor.

The FEM is used to perform the field analysis and the (1+1) ES is used to find the optimal value of the model under given constraints, which results in a good improvement in motor performance.

As a result, the airgap length is increased by 14%, but torque is increased by 7% because the final model has all of the modified optimal parameters. The cross-section area of stator is reduced by 2%, reducing the outer size, which will cut down the material cost. The increased airgap length and the enlarged window area will improve the rotor manufacturing process of rotor as well as enhance mechanical safety. The optimized model is built and tested with the performance measuring system. The measured values of the model are compared with those of the initial and the optimized model to prove the algorithm. The final model considerably improves its performance compared with those of the initial model.

Acknowledgments

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Pan Seok Shin

He received the B.S. degree in Electrical Engineering from Seoul National University in 1977 and the M.S. and Ph.D. degrees in Electric Power Engineering from Rensselaer Polytechnic Institute in 1986 and 1989, respectively. From 1980-1993, he worked at the Korea Electrotechnology Research Institute as a researcher for projects involving magnetically levitated vehicles, various motors, and linear actuators. In 1993, he joined the Electrical Engineering Department of Hongik University as a professor. His teaching and research interests are analysis of electromagnetic fields, electric machinery, special actuators, and optimization techniques.