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Optimal Design of an Axial Flux PMSM for Hybrid Vehicle Use

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Abstract

Increase of energy consumption and air pollution are big crises in recent two decades. Due to these crises and also increase of energy costs, utilization of hybrid electric vehicles becomes conventional and vehicle companies are increasing their investment in these kinds of vehicles. The main issue for these vehicles, besides energy storage system, is efficiency of electric motor and its weight and cost. Axial Flux Permanent Magnet Synchronous Motors (AFPMSM) have become popular for hybrid vehicles as they have better efficiency and less weight. In this paper an AFPMSM, which would be used in hybrid electric vehicles, is designed to get less weight and cost and more efficiency. PSO and GA algorithms have been applied in this design. Inner and outer diameter of axial flux permanent magnet motor and air gap flux density are taken as variables in the mentioned design.

Keywords: Hybrid vehicle, PSO, GA, AFPMSM, Optimization.

1. INTRODUCTION

Increasing of world temperature and air pollutions beside energy crisis forced industries to find ways for reducing pollutions, energy consumption and costs. In vehicle industries development of electric and hybrid types are given high priorities. Today as there are technical problems in electrical energy saving technology like battery; hybrid vehicles are more interested than pure electric ones.

Electrification of vehicles has grown significantly over the past decade. Many EVs and HEVs are developed with different electric propulsion systems. In order to be applied as electric drives, electric machines must match several conditions such as high torque/power density, wide flux weakening operation range, high efficiency over a wide speed range and reasonable cost [1].

In [2] it is confirmed that for hybrid electric vehicles PMSMs are the best choice. Among PMSMs, axial flux machine are preferable choice for traction application. Due to higher aspect ratio (outer diameter to overall axial length), power density of axial flux machines is higher than that of radial flux ones [3]. PM machines efficiency is also higher than induction machines due to lack of rotor windings.

The purpose of this paper is optimal design of an AFPMSM for hybrid electric vehicles by Genetic Algorithm and Particle Swarm Optimization. The design is implemented to reach optimum torque density and efficiency. MATLAB software is applied to perform optimization and Maxwell software is used for electromagnetic analysis.

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2. SIZING EQUATIONS AND OBJECTIVE FUNCTION

The sizing equation has the following form in axial flux machines [4]:

$$P_r = \frac{1}{1+K_\varphi}\frac{m}{m_1}\frac{\pi}{2}K_e K_i K_p \eta B_g A \frac{f}{p}\lambda_o^2 D_o^2 L_e \quad (1)$$

In other words and as shown in [5]:

$$P_r = \frac{1}{1+K_\varphi}\frac{m}{m_1}\frac{\pi}{2}K_e K_i K_p \eta B_g A \frac{f}{p}(1-\lambda^2)\frac{1+\lambda}{2}D_o^3 \quad (2)$$

Efficiency equation could be obtained from the above equations as below:

$$P_r = \frac{1}{1+K_\varphi}\frac{m}{m_1}\frac{\pi}{2}K_e K_i K_p \eta B_g . A\frac{f}{p}\left(1-\lambda^2\right)\frac{1+\lambda}{2}D_o^3 \quad (3)$$

This equation is one of objective functions of this paper. Second objective function is torque density of the machine. The general equation of the torque is as equation (4) and thus torque density could be written as equation (5):

$$\mathrm{T_{em}} = \frac{\pi}{4}\mathrm{B_{ave}A_{in}K_d}\lambda(1-\lambda^2)\mathrm{D_o^3} \quad (4)$$

$$\mathrm{T_{den}} = \frac{\frac{\pi}{4}\mathrm{B_{ave}A_{in}K_d D_i}\left(\mathrm{D_o}^2-\mathrm{D_i}^2\right)}{\frac{\pi}{4}\mathrm{D_t}^2\mathrm{L_e}} \quad (5)$$

Thus far, two objective functions of the paper have been specified. It is intended to maximize efficiency and torque density. In these functions, B_g is air gap flux density, L_e, D_i and D_o are axial length, inner diameter and outer diameter of machine respectively, *Ke* is emf factor, *Ki* is current waveform factor, *Kp* is electrical power waveform factor, *f* stands for frequency, η is efficiency of motor, λ is ratio of inner and outer diameters of machine and *A* is total electrical loading including both stator and rotor electrical loadings. The last two factors are set to be 1 as waveforms are considered rectangular, as shown in [6]. Other parameters are mentioned in Table 2.

3. OPTIMIZATION ALGORITHMS

Optimization methods are divided in two categories. The first category is classic methods and the second one is heuristic methods. Due to development of computers capabilities, use of heuristic optimization is increasingly growing. Although classic methods give global solution instead of local solutions obtained by heuristic methods, but heuristic methods have acceptable performance; especially when the optimization problem has lots of variables. In optimization of electrical machines different types of heuristic optimizations have been used. Literature reports show that Genetic Algorithm and Particle Swarm Optimization can achieve acceptable results, even in multi objective optimization problems.

In this paper optimization of an axial flux PMSM is a multi objective problem. There are two methods to solve these problems. The first one is use of non domination sorting and Pareto line and second one is combination of objective functions.

Since multi objective problems have non unique solution and there are a set of optimal solutions, a question arises that how to choose one solution among those in the set of solutions [7]. As an answer to this question and in first method mentioned above, the designer defines preferences for various objectives and accordingly obtains a single Pareto optimal point [8].

One of the intuitive ways used to obtain a unique solution for multi objective optimization is to constitute weighted sum of functions. In this approach, the multi objective optimization problem is converted into a scalar weighted function using a linear weighted sum [7].

In this paper, the method of weighted sum of objective functions is applied. In this method six combinations of objective functions is considered to obtain best answer, as shown in Table 1. It should be noted that optimization algorithms are usually standardized for minimization. To be in accordance with

Table 1. ***Variable limitations.***

Objective function number	Objective functions combination

1	$\frac{1}{Tden}+\frac{1}{\eta}$
2	$\frac{1}{Tden}\times\frac{1}{\eta}$
3	$\frac{1}{\sqrt{Tden^2+\eta^2}}$
4	$-(Tden+\eta)$
5	$-(Tden\times\eta)$
6	$-(\sqrt{Tden^2+\eta^2})$

Do	Di	Bg	Result

Fig. 1. Chromosome structure used in this paper.

this standardization, objective function of maximization problem could be multiplied by -1.

3.1 Genetic Algorithm (GA)

The first algorithm which is used to solve the considered optimization problem is genetic algorithm. Genetic algorithm is one of the most popular methods for optimization problems. In this paper, initial population has 20 chromosomes. After chromosomes involvement in objective function, chromosomes are sorted by results. Eighty percent of the initial population is chosen for mutation. Seventy percent of first population is chosen for cross over. These chromosomes are replaced in objective function and are sorted by results again. Bad chromosomes are excluded from process and only top 20 chromosomes are chosen for next iteration. One hundred iterations have been performed in this paper. The chromosome of genetic algorithm of this paper is as shown in Fig. 1.

3.2 Optimization (PSO)

The other optimization method which is used in this paper is particle swarm optimization. This method is also named “fish school” and “birds flock” method. This method is developed in 1995 by Dr. Eberhart and Dr. Kennedy on the basis of fish school or birds flock behaviors. In this method, first population is created as particles and after involving in objective function, particle with the best result is selected as the best one and other particles move towards it by a velocity which is determined by the algorithm constants. Different iterations may produce different best particles so other particles move in different ways in the search space. The best answer after last iteration is selected as final result. PSO algorithm is generally faster than GA algorithm. In this paper first population of PSO is consists of 20 particles as GA first chromosomes have 20 members, too. Weight and acceleration coefficients are set to be 0.0005 and 0.0006, respectively. Selecting proper value for these constants significantly affects performance of PSO algorithm.

Table 2. ***Parameters of the machine.***

Parameter	Quantity	Value
Pr	rated power	50000 W
p	number of pole pairs	3
f	nominal frequency	60 Hz
A	electric loading	60000 A/m
Lg	air gap length	0.005 m
Kcu	copper filling factor	0.8
J	current density	6000000 A/m^2
Br	residual flux density	1.5 T
Kf	waveform factor	1.11
Bcr	rotor flux density	1.7 T
Mu r	permanent magnet permeability	1
Kφ	electric loading ratio of stator to rotor	zero for PM machines
m	number of machine phases	3
m1	number of stator phases	3

4. PARAMETERS AND VARIABLES OF THE OPTIMIZATION PROBLEM

Power and frequency of the machine have been assigned by considering Toyota Prius Hybrid 2009 model which needs an electric vehicle with 50 KW power in 60 Hz frequency. Dimensional constraints are based on YASA axial flux motor which is introduced in [9]. For the considered parameters of motor, Tables 1 and Table 2 show related upper and lower margins.

Table 3. ***Results for GA method***

Objective Function	Di (m)	Do (m)	Bg (T)	Tem (NM)	Efficien-cy
1	0.19063	0.31033	0.81975	193.07	0.97
2	0.14526	0.30025	0.80039	193.06	0.96
3	0.14424	0.30014	0.80035	192.92	0.96
4	0.14379	0.30002	0.80072	192.91	0.96
5	0.14425	0.30019	0.80015	192.86	0.96
6	0.1441	0.30016	0.80012	192.87	0.96

VA = volt ampere, Hz = Hertz, T = tesla, m = meter, A = ampere

Table 4. ***Results for PSO method.***

Objective Function	Di (m)	Do (m)	Bg (T)	Tem (NM)	Effi-ciency
1	0.15745	0.3	0.82535	193.07	0.97
2	0.14956	0.3011	0.8	193.06	0.96
3	0.17105	0.30549	0.80689	192.96	0.96
4	0.16149	0.3	0.84169	191.45	0.96
5	0.20536	0.31737	0.80476	192.99	0.97
6	0.13572	0.3	0.8	190.51	0.95

VA = volt ampere, Hz = Hertz, T = tesla, m = meter, A = ampere

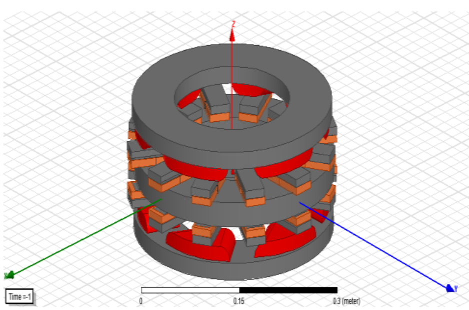

Fig. 2. Torus model of AFPMSM.

Selected variables for optimization are inner diameter of the machine, outer diameter of the machine and air gap flux density. Axial flux machine for optimization is considered as Torus, which is consists of two stators and a permanent magnet rotor. Its 3D simulation in Maxwell software is shown in Fig. 2.

5. OPTIMIZATION RESULTS

In this paper multi objective optimization for torque and efficiency functions has been conducted by introducing a new function which is combination of the two objective functions. In order to obtain preferable combination of the two functions, different model are simulated as shown in Table 3 for GA method and Table 4 for PSO method, and best answer is selected.

Table 5. ***Optimized machine dimensions.***

Name	Wcuo	Wcui	Lss	Lpm	Lcr
Dimension	cm	cm	cm	cm	cm
Value	1	1.5	1.5	3	3.5

Table 6. ***Optimum results.***

Method	Function Number	Di (m)	Do (m)	Bg (T)	Tem (NM)	Efficiency %	cost	weight	volume
GA	1	0.1906	0.31033	0.81978	193.07	97	**	**	*
PSO	1	0.1574	0.3	0.82535	193.07	97	***	***	*
PSO	5	0.2053	0.31737	0.80476	192.99	97	*	*	***

As it is observed in Tables 3 and 4, best answers are the first model in GA and the first and fifth models of PSO. Putting these solutions in objective functions, results of Table 5 are obtained.

It should be noted that more difference between inner diameter and outer diameter means more material and so it will cause more cost and also more weight. Also, in hybrid vehicles weight and efficiency are of direct concerns, because of their direct impact on fuel consumption. By considering these limitations the best answer is the first model solved by GA. Table 6 shows machines dimensions according to the best solution.

Iteration trend of GA and electromagnetic analysis corresponding to the best result are shown by figures 3 and 4, respectively. For permanent magnets, NdFe35 is used while coils are steel and windings are made of copper.

Electromagnetic analysis indicates that optimization algorithm results in dimensions which are acceptable. As shown in Fig. 4 and 5, there is no saturation in back iron, but is in surface of pole teeth which can be tolerated as volume of the machine and cost of material is reduced. In

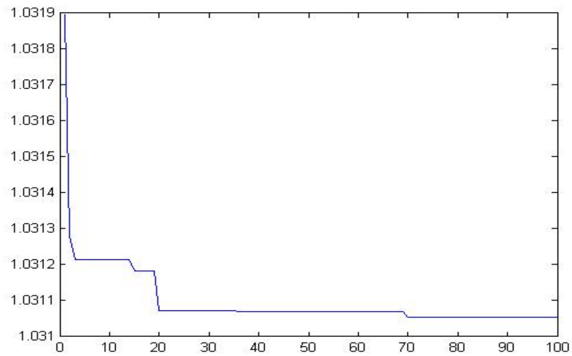

Fig. 3. GA result graph of best asnwer.

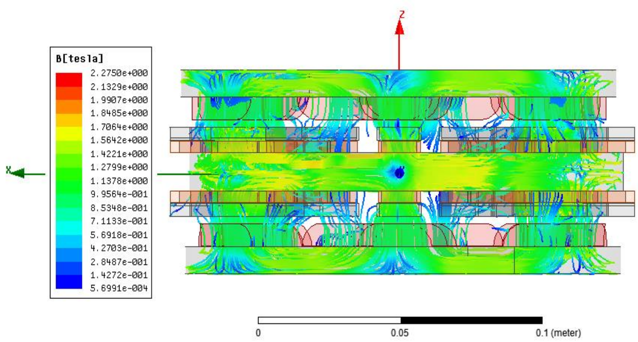

Fig.4. Electromagnetic analysis of optimized AFPMSM.

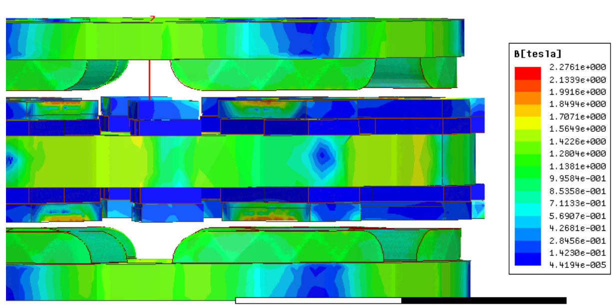

Fig.5. Another veiew of electromagnetic analysis for optimized AFPMSM.

this simulation windings are simulated as solid (not stranded), but the result difference is ignorable.

6. CONCLUSION

In this paper an axial flux permanent magnet synchronous motor is optimally designed by GA and PSO algorithms for application in a hybrid vehicle. Objective functions of the optimization are torque density and efficiency. For obtaining best solution a function composed of the two objectives is considered. With material and cost constraints, it is shown that GA method gives the best result. Optimization algorithms have been executed in MATLAB software. Also, electromagnetic analysis of designed machine has been performed in Maxwell Software.

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