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***Abstract*—This paper presents an optimal design approach for a single-sided axial flux permanent magnet(AFPM) machine. A multi-objective differential evolution based optimization algorithm is implemented, which is to maximize the output torque density (Nm/kg) and efficiency. Design constraints including geometrical and operating limits are considered. Total of seven independent variables are employed in the design. Optimization results are compared with a prototype design.**

I. INTRODUCTION

Axial flux permanent magnet (AFPM) machines have gained much attention because of their disc shaped structure, which is suitable for traction systems such as in hybrid vehicles [1].

Numerous work has been done about machine design optimizations. In [2], [3], it proposes an analytical procedure for the design of a surface mounted PM machine with binary genetic algorithm in order to optimize a single objective function of material cost. In [4], [5], a multi-objective optimization of a 48 slot/4 pole IPM motor with three barriers per pole is presented. The objective is optimizing the torque and saliency to obtain a good performance in sensorless control. The optimization is carried out by FEA model and binary genetic algorithm. It uses weighted sum method,thus the multi-objective function reduces to a single objective problem. In [6], the optimization design of IPM motor is presented by means of a FEA-based multi-objective genetic algorithm (MOGA). In [7], the author includes rotor losses in the optimization process with an additional cost function. In [8], first global search MOGS is implemented. After that one solution machine is selected manually from the Pareto front on the basic of its performance.

The implementation of differential evolution in electrical machine design optimization has been studied recently. In [9]–[15]. In [9], a multi-objective optimization for the design of IPM motor based on the differential evolution and finite element model is presented. The objective is to minimize active volume and while maximizing the power output in the flux weakening area. In [10], an optimal design practice of IPM machine with modular stator structure based on finite element analysis (FEA) and different evolution is discussed. Single and multi-objective of maximum torque and minimum THD of back EMF is implemented. In [11], an automated machine design process with differential evolution techniques is proposed to maximum the torque and efficiency. In [12], [13], a bi-objective optimization of PM machine with 11 parameter variables using computationally efficient-FEA and differential evolution are employed to minimize torque ripple and maximize the torque production per unit volume. Four different machine topologies are evaluated through comparing Pareto-optimal design set. In [14], a multi-objective optimization of a surface PM motor with 5 variables comprises the minimization of total weight and maximizing a goodness function, which is defined as torque per root square of losses at rated load is studied. The results using by differential evolution(DE) is compared with response surface(RS) method. It shows DE has better capability dealing with large candidate designs. In [15], a optimal design of surface PM of with 8 variables with the objective of relative cost of active materials per cost is presented by differential evolution. Stopping criteria for DE algorithm is discussed based on solution space and design space.

This paper is focused on the optimization by means of a multi-objective differential evolution algorithm of a single-sided non-overlapped windings AFPM machine. Design objects are to maximize the output torque density (Nm/kg) and efficiency. Design constraints including geometrical and operating limits are considered. Total of seven independent variables are employed in the design. Optimization results are compared with a prototype design.

II. FEA MODEL OF AN AXIAL FLUX PM MACHINE

The target machine is used as an integrated starter-alternator for hybrid vehicles. The rated torque is 22.8 Nm, rated speed is 2800 rpm . A prototype machine was previously designed but not optimized.

Ideally the FEA model should be in 3-D to better evaluate the performances as in Fig. 1, however, due to the computation time, 2-D model is used in the optimal design with transient solution.

The approach to model the AFPM in 2-D is to view the machine from the side. The geometry is a cylindrical cross-section taken at the average radius as shown in Fig. 1. And rotational motion is assigned to model it as a very small portion of a radial flux machine with a very large radius (e.g. the radius is 100 m). Depending on the number of slots and poles, only a fraction of the machine is modelled. For the 24 slot/22 pole machine, the 2-D model contains 12 slots and 11 poles. The symmetric multiplier is 2 with the master and slave

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boundary conditions are applied. The modelling is shown in Fig. 1.

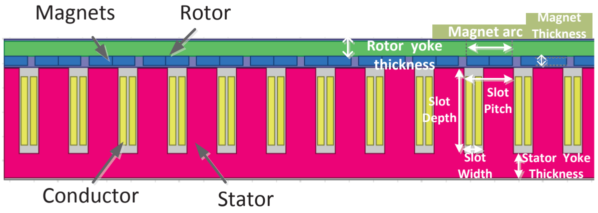


Fig. 1. 2D-FEA Model of a 24 slots/22 poles double layer winding AFPM

A. Design Variables

2D-FEA model of the machine is shown in Fig. 1. These seven variables are slot depth, slot width, stator yoke thickness, magnet thickness, magnet span to pole pitch ratio, rotor yoke thickness and split ratio, which is defined as the ratio of stator inner diameter and stator outer diameter.

TABLE I
DESIGN VARIABLES AND RANGES

	Variables	Range	*Unit*
x1	Slot Depth	[25, 40]	*mm*
x2	Slot Width to Slot Pitch Ratio	[0.3, 0.8]	
x3	Stator Yoke Thickness	[8, 20]	*mm*
x4	Magnet Thickness	[3, 5]	*mm*
x5	Magnet Span to Pole Pitch Ratio	[0.5, 0.9]	
x6	Rotor Yoke Thickness	[5, 10]	*mm*
x7	Split Ratio	[0.5, 0.7]	

B. Design Constrains

There are geometry constrains and operating limits as shown in Table II.

The stator outer diameter is fixed at 196 mm which is usually the case due to space limitations in reality. The air gap length is fixed at 1 mm since a slightly adjustment of air gap will result in significant difference in machine performance, which makes it difficult to evaluate the impact of other parameters.

Current density is fixed at 4.1 A/mm^2 due to cooling requirements, which is also same as the reference machine. The maximum stator tooth and back iron flux is 1.5 T. The material properties can be changeable and included in the optimal design. However, here the materials types are fixed as the electrical steel type is M19-29G. The permanent magnet material is NdFeB 40H with the residual induction Br=1.26T.

TABLE II
DESIGN CONSTRAINS

Variables	Value	*Unit*
Number of slots	24	-
Number of poles	22	-
Stator outer diameter	196	*mm*
Air gap length	1	*mm*
Slot fill factor	0.4	-
Current density	4.1	A/mm^2
Maximum stator tooth flux	1.5	*T*
Maximum stator back iron flux	1.5	*T*

C. Design Objectives

The purpose of the optimal design is to design a machine with high torque density and high efficiency with a minimum torque requirement of 22.8 Nm to guarantee the 6700 W output power.

A multi-objective optimization algorithm is implemented. The objectives are to maximize the output torque density (Nm/kg) and efficiency:

$$\begin{aligned} \text{maximize } : f1 &= \frac{T_{em}}{W_C + W_S + W_M} \\ \text{maximize } : f2 &= \frac{P_o}{P_o + P_s + P_r + P_c} \end{aligned} \tag{1}$$

in which, W_C, W_S, W_M are the weight of used copper, steel and magnets. P_o is the output power,P_s is the stator core loss, P_r is the eddy current loss in rotor back iron and magnets, P_c is the copper loss.

Once the Pareto front is obtained, the designer can select the best design one with reasonable comprise between different objectives.

III. OPTIMIZATION PROCESS

A. Flowchart of the Design Optimization

The flowchart of the optimal design is shown as in Fig. 2.

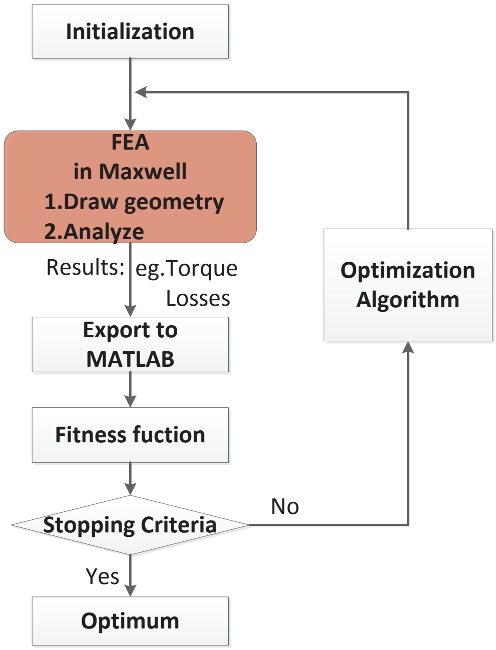


Fig. 2. Flowchart of optimization with MATLAB/Maxwell

Fig. 2 show the flowchart of the optimal design. The FEA model is in Maxwell. MATLAB is interfaced with Maxwell to change the input parameters and postpocessing the simulation data. Differential evolution algorithm is selected as the optimal algorithm. First an initial input parameter is generated in MATLAB, it passed the value into Maxwell FEA parametric model. The machine geometry is redraw automatically. After the simulation in Maxwell is completed, the output parameters such torque, losses will be exported to MATLAB. Fitness function will be calculated. If the machine performance does not meet the requirement, the differential evolution algorithm will generate the next design parameters. The process will be repeated.

IV. OPTIMIZATION RESULTS

A. *Optimization Results*

The population size for the differential evolution is 40, generation size is 20, which leads to total 800 design. Cr is 0.9426, Fr is 0.6607. The simulation time is 25 hours in a single computer.

Fig. 3. shows the optimization results and the plotted Pareto front. One optimized M1 is selected for the design as the blue dot. The purple dot is the reference prototype machine. it could be seen that both the torque density and efficiency are improved.

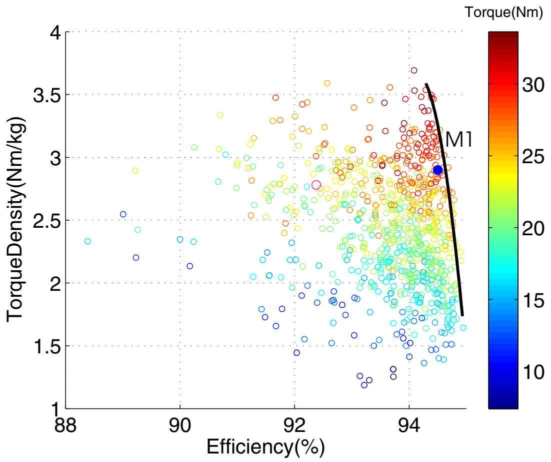


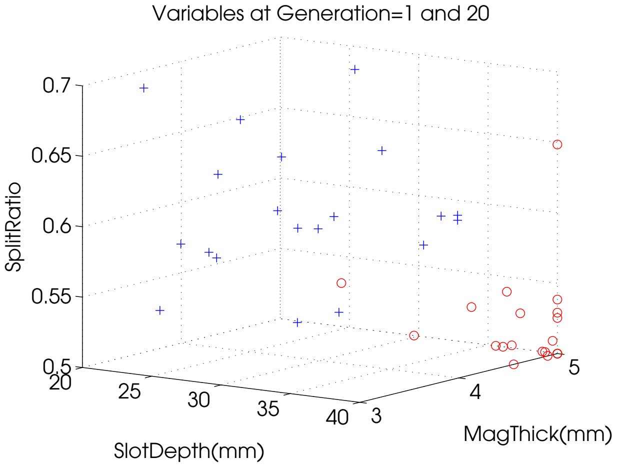
Fig. 3. Optimization results

TABLE III
OPTIMIZATION RESULTS

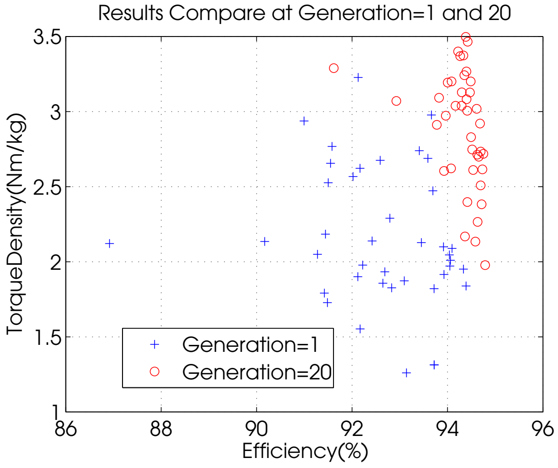
	Variables Compare	**Initial Design**	**Optimized-M1**	Unit
x1	Slot Depth	35	40	n
x2	Slot Width to Slot Pitch Ratio	0.3918	0.5149	-
	Slot Width	8	10	n
x3	Stator Yoke Thickness	10	14.81	n
x4	Magnet Thickness	4	5.0	n
x5	Magnet Arc	14	9	d
x6	Rotor Yoke Thickness	6	5.49	n
x7	Split Ratio	0.5918	0.5257	-
	Stator Inner Diameter	116	103	n
	Performance Compare	**Initial Design**	**Optimized-M1**	U
	Torque Density	2.78	2.9	N
	Efficiency	92.38 %	94.50 %	-
	Max Tooth Flux	1.33	1.34	T
	Max Back Iron Flux	1.07	0.7172	T
	Output Torque	23	29	N

B. *Parameter Profile*

Fig. 4. shows the input and output results as Generation 1 and 20. It could be seen that as the generation number increase, the results will be more close to the Pareto front.



(a)



(b)

Fig. 4. Optimization results

Fig. 5 and Fig. 6 show the relationship between the each input parameter and the output parameter.

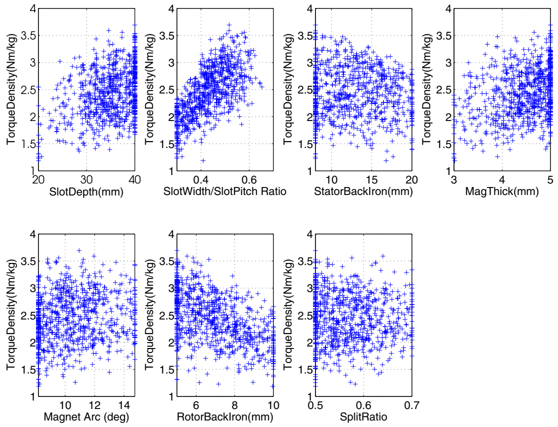


Fig. 5. Variables vs TorqueDensity

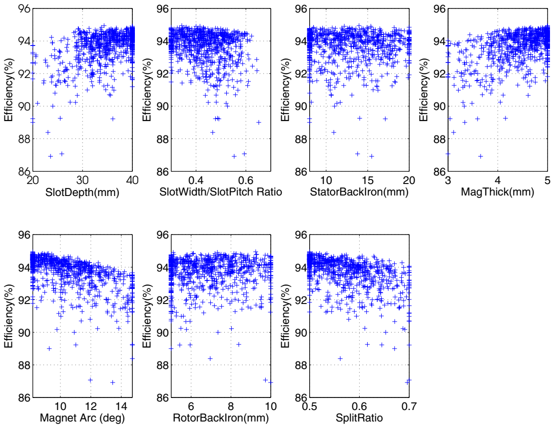


Fig. 6. Variables vs Efficiency

V. CONCLUSION

In this paper, an automatic optimal machine design approach is presented. An optimized design of a 24 slots/22 poles single-side axial flux machine is illustrated with 2-D transient FEA model in Maxwell and in MATLAB as an example.

Further improvements may be applied. For the optimization,it is ideal case that we might run more generations get more optimal solution sets. Considering the time constraints, this runs only implements 800 design, using 25 hours on a single lab computer. Also the input parameters relationship with the output parameters may be analyzed by some statistic tools. It should be noted that this optimization focuses on only one type of axial flux machine. It has not compared with other types, like the Torus type AFPM or different machine types like radial flux and etc.

The machine optimized is with fixed slot/pole numbers. The broad concept of an 'optimized machine' should include different slot/pole combinations. However, the difficult in including the slot number and pole number as variables is that, the machine winding, excitation and boundary conditions setting would be different in the FEA model, which is not easy to define them automatically. But it would be possible, as the developed software 'KOIL' used to design the winding of rotating electric machinery automatically.

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