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Optimization Approach for the Design of IPM Synchronous Motor for Express MotorCycle

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Abstract

The paper proposes an optimization procedure for the design of a three-phase Interior Permanent Magnet synchronous motor. The multi-objective function maximizes the average torque, and the constraints are the efficiency and torque ripple. Various metamodels were generated for each of the multi-objective functions and constraints, and the metamodels with the best prediction performance were selected. By applying a multi-objective genetic algorithm, several optimal solutions were compared to those of the initial model. The proposed multi-objective optimization method can guide the design of IPMs for electric vehicles with high reliability and strong demagnetization characteristics.. This program allows estimating the back emf, flux density, electromagnetic torque, and ripple torque by analytical MATLAB program coupling to finite element magnetic method (FEMM) and GA optimization. Finally, rotor lamination was stamped and assembled in the motor for the back EMF test and no load-test. The design optimization is based on a new algorithm belonging to the class of Controlled Random Search algorithms. This optimization technique has been able to find a very efficient design pointing out its effectiveness besides its versatility and robustness

Keywords: Brushless DC motor, electric bike (E-bike), external rotor, Special Power Electric Engineering (SPEED), Finite element method (FEM).

1. INTRODUCTION

This paper will describe the design optimization of a three-phase interior PM synchronous motor. The aim is to investigate the possibilities to maintain constant power in the field-weakening region minimizing the active volume and maximizing the power output. The design optimization of the IPM motor is based on a new algorithm belonging to the class of Controlled Random Search (CRS) algorithms that derive from the algorithm proposed in Hong, G 2018, Shuangshuang 2020. Multi-objective optimization of maximum average torque and outpower is employed to design a 5 kW- IPM synchronous motor. Several parameters of stator diameter, slot depth, air gap, and magnet angle are variables. Mid-drive motors are known for higher performance and torque when compared to a similarly powered traditional hub motor in Edhah, S.O. 2018 because they have higher torque and power density. This design proposal will be applied for the middle drive motor for a sports scooter developed by Selex company in Vietnam. The Express delivery motorcycle for Viettel post drivers has some special requirements such as high load capacity and long distance for one charge.

Figure 1. Industrial design of Viettelpost Express Delivery Motorcycle

In order to design an Ebike for Viettelpost driver, a motor has a high load capacity and the maximum power is 5000W for overload case and high slope road up to 35 degrees.

Table 1. Technical Requirement

Frame size	1840*660*1130mm
Wheel size	24'*1.95
Net weight	35kgs
Load	78kgs
Max speed	90km/h
Slope angle	3-35 degree
Mileage	70km
Battery	lithium battery
Battery Capacity	100A
Motor	IPM
Motor power	3050W
Max power	5000W
Motor rpm	3000-5000rpm
Voltage	60V/72V
Peak Torque	100N.m

2. DESIGN VARIABLES AND CONSTRAINTS

Electromagnetic torque has been calculated based on stator, rotor diameter and power inverter voltage and currents. The electromagnetic parameters can inertial calculated as:

$$T = \frac{\pi}{2} D^2 L_{stk} \sigma, \qquad (1)$$

where T is the electromagnetic torque, D is the rotor diameter, L_{stk} is the stack length and $\sigma = \frac{L}{D}$ is defined from 0.8 to 1.25 for the inner rotor.

Torque prediction is carried out for any stator-rotor relative position and the finite element grid is automatically adjusted when the rotor is rotated. The influence of mesh has been investigated in order to get satisfactory accuracy avoiding the inaccuracies due to the element distortion. Only one pole is simulated, due to the motor symmetry.

The steady-state stator voltage equations written in the d-q rotating reference frame are:

$$v_d = R\, i_d - \omega L_q\, i_q$$

$$v_q = R i_q + \omega L_d\, i_d + \omega \Phi_M \qquad (2)$$

where: i_d , i_q , v_d and v_q are the d and q axis components of the armature current and terminal voltage respectively, R is the winding resistance per phase, L_d and L_q are the axis inductances and Φ is the magnets flux linked with the armature winding. The electromagnetic torque is calculated using the well-known equation.

$$T = \frac{3}{2} p \left[\Phi_M i_q + \left(L_d - L_q \right) i_d i_q \right] \tag{3}$$

The study concerns the design for a three-phase 5 kW, 8 poles, 24 slots, IPM synchronous motor. The cross-section of the stator and rotor core is shown in Fig. 1. The rotor presents one barrier per pole and the magnet material is inserted into this cavity. The stator and rotor consist of a stack of laminated high permeability non-oriented grain silicon steel. Three-phase double-layer distributed windings are inserted in the 24 stator slots. The set of parameters x used in the optimization procedure are listed in Table I. The motor has 8 variables (magnet length, outer stator diameter, airgap, slot depth and magnet angles) that vary in a discrete way. For good electromagnetic performance, it should be necessary to minimize irreversible demagnetization. The centrifugal force on steel bridges should be considered with maximum mechanical stress in high-speed operation. From a preliminary analysis a minimum value of 2 mm is imposed. This value is consistent with the maximum speed and mechanical stress.

Table I MINIMUM AND MAXIMUM RANGES OF DESIGN VARIABLES

Parameters	**Discrete variables**	**min**	**max**	**step**
L1 Magnet Thickness (mm)	x1	2	4	0.2
L1 Magnet Bar Width (mm)	x2	8	12	1
L1 Pole V Angle (deg)	x3	120	150	1
Airgap (mm)	x4	0.5	1.5	0.1
Stator Lam Dia (mm)	x5	130	150	1
Stator Bore (mm)	x6	70	90	1
Tooth Width (mm)	x7	4	6	0.2
Slot Depth (mm)	x8	16	20	0.4

The design optimization needs to satisfy several constraints to guarantee the reliability and feasibility of the final design (Table II). The main design constraint is the value of the back EMF at maximum speed which has not been allowed to exceed the rated terminal voltage and maximum current density.

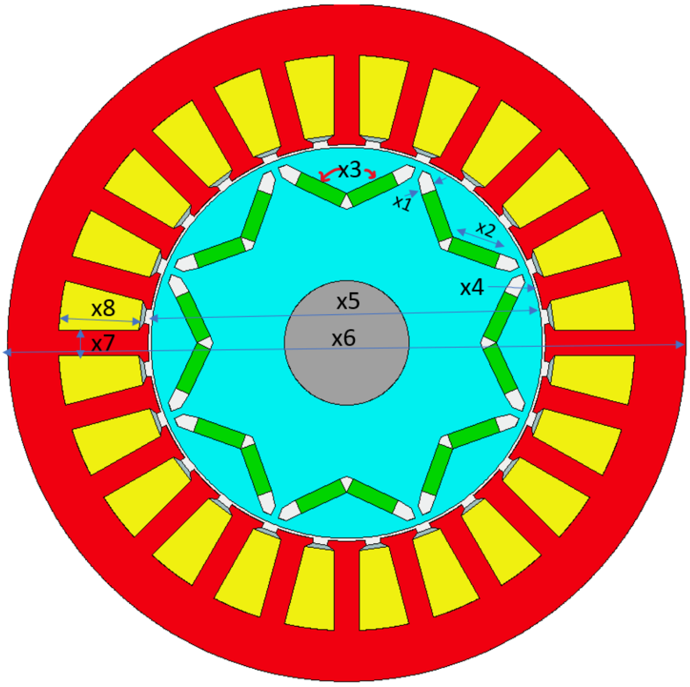
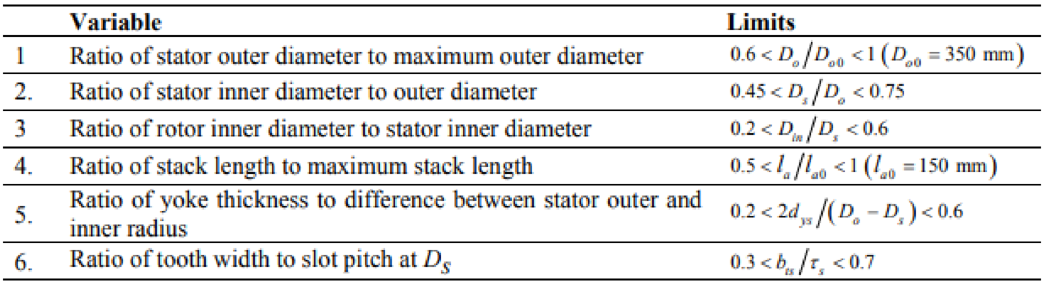


Figure 2. Design variables

Main constraints are ratios of inner, outer stator/rotor, stator tooth and stator yoke and stack length

TABLE II CONSTRAINTS



	Variable	**Limits**
1	Ratio of stator outer diameter to maximum outer diameter	$0.6 < D_o / D_{o0} < 1 \ (D_{o0} = 350 \text{ mm})$
2.	Ratio of stator inner diameter to outer diameter	$0.45 < D_s / D_o < 0.75$
3	Ratio of rotor inner diameter to stator inner diameter	$0.2 < D_{in} / D_s < 0.6$
4.	Ratio of stack length to maximum stack length	$0.5 < l_a / l_{a0} < 1 \ (l_{a0} = 150 \text{ mm})$
5.	Ratio of yoke thickness to difference between stator outer and inner radius	$0.2 < 2d_{ys} / (D_o - D_s) < 0.6$
6.	Ratio of tooth width to slot pitch at D_S	$0.3 < b_{ts} / \tau_s < 0.7$

The Finite Element analysis is used to evaluate the motor performance and the design requirements (at base speed and maximum speed), namely, to compute the objective function values and constraints of the minimization problem which represents mathematically the optimal design problem, and which considers the parameters of the motor as independent variables. The optimization procedure uses the information obtained by the FE program to iteratively update the set of motor parameters and try to identify an "optimal" motor by making a trade-off between the different parameters of the machine.

3. THE OPTIMIZATION ALGORITHM

An initial modeling and parametric analysis setting for the automatic change of design variables was performed using the FEA software SPEED. By creating Matlab files and batch files, electromagnetic analysis was automatically performed in SPEED. SPEED's analysis results were transferred to Matlab, and the responses of multi-objective functions and constraints were automatically calculated. In addition, when the computational analysis for one experimental point was finished, the shape design parameters were automatically changed in SPEED with the aid of CAD tools by receiving MATLAB command. As described before, the optimal design of an IPM synchronous motor can be formulated as a particular multi-objective mixed-integer nonlinear programming problem. As regards the multi-objective aspect of the optimization problem, our numerical experience showed that, for this particular optimal design problem, a good compromise among different objectives can be obtained just by minimizing the sum of the weight of the motor and the opposites of the two torques. The general multi objective optimization problem can be defined as find the vector of parameters $x=[x_1, x_2,\dots,x_n]$ and constraint functions $g_j(x)<0$ subject to m and D boundary constraints $x_{i\_min}<x<x_{i\_max}$, vector function $f(x)=[f_1(x), f_2(x),\dots.f_k(x)]$

$$\begin{gathered} min\ f(x) \\ g(x) \leq 0 \\ min \leq x \leq max \end{gathered}$$

The result of the optimization is a population of solutions which belong to a Pareto optimal set. In other words, the vectors of the Pareto set are not dominated by any other vector in the set. Since none of the vectors dominate, they are all equally good solutions which provide invaluable insight to the decision maker on how to choose the best design to satisfy the performance criteria. The plot of the objective functions whose nondominant vectors are in the Pareto optimal set is called the Pareto front.

Parameters	**min**	**max**	**Result 1**	**Result 2**	**Result 3**	**Result 4**	**Result 5**
L1 Magnet Thickness	2	4	3.4272793	2.5130562	2.1064572	2.2644588	2.5225527
L1 Magnet Bar Width	8	12	8.1163493	11.888318	11.746571	9.4149265	8.5429805
L1 Pole V Angle	120	150	134.69761	138.9336	126.55029	149.82566	142.12168
Airgap	0.5	1.5	0.6404491	0.7522818	0.6831523	1.2167976	1.0402752
Stator Lam Dia	130	150	144.76056	142.5347	144.05618	130.56861	134.97574
Stator Bore	70	90	76.629091	80.863833	74.495305	82.988289	83.311474
Tooth Width	4	6	5.7777594	5.6619628	4.3202164	5.351977	5.1164671
Slot Depth	16	20	16.779366	19.544437	17.123348	18.363938	18.102328
Total Weighted Error:			0.0328837	0.0328837	0.0328837	0.0328837	0.0328837

The 5 kW prototype IPM motor has been designed using the multi-objective optimization algorithm previously described. The outer diameter of the stator core has been fixed in order to fit inside the standard aluminum cast frame of the motor manufacturer. The same has been done with the inner diameter of the rotor core to fit the standard shaft size.

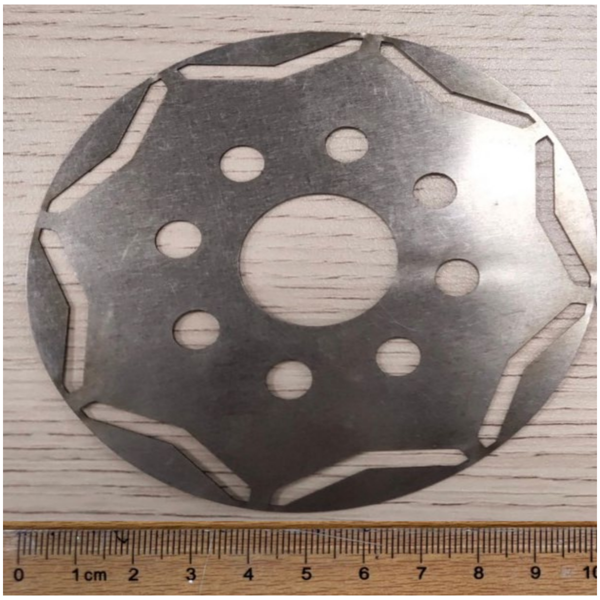


Figure 3. Rotor Lamination

The purpose of rotor designing and building the prototype has been to investigate if the physical properties of the motor predicted in the design stage can be actually achieved in practice regardless of any design limitations dictated by the available magnet materials or the requirements for having specific motor dimensions.

5. CONCLUSION

An effective analytical model is developed and verified with a prototype. To optimize the design process of the motor in a very short period of time and also without any need of FEM an intelligent optimization algorithm is fully implemented and described. The result of optimization shows the efficiency of the entire approach. The analytical model and the optimization program are both implemented using MATLAB which makes it easier to use. To validate if the suggested motor truly meets the requirements and boundaries, results are verified using FEM which is also controlled via MATLAB and will be initiated automatically after optimization. The entire package is a very powerful tool for the optimized design of a permanent magnet synchronous motor.

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