A Multi-step Optimization Method for Optimization of Interior Permanent Magnet Motor for EV

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Abstract

The IPM motors built with magnets placed inside the rotor body are attracting great attention in several variable-speed applications, such as electric vehicles and industrial and domestic appliances, where the most challenging requirement are high efficiency, high torque density, good overload capability, and extended speed range. This paper will develop A novel hybrid multi objective optimization method which combines the Taguchi method with different rotor pole topologies for optimization of interior permanent magnet synchronous machines (IPMSMs). This method is capable to pre-optimize rotor pole topology and given multi objective optimization problem compared with the conventional IPM. The method is applied to maximize the power density and the efficiency of an IPMSM under constraints. In the optimization process, the power density of the IPMSM is significantly improved and the volume of the IPMSM is minimized. However this method can improve the efficiency while increasing the power density. Finally, a rotor lamination prototype is manufactured to verify the feasibility of this method.

Keywords:

Interior permanent magnet synchronous machines (IPMSMs), Finite Element Analysis-FEA. Taguchi, Power density, hybrid rotor shape design

Introduction

Interior permanent magnet synchronous machines (IPMSMs) have been extensively adopted in electric and hybrid electric vehicles due to high torque density and desirable high efficiency. The performance of IPM machines is significantly affected by the magnet rotor topologies in Chen Peng 2021, Wenliang Zhao 2015. Thus, several Interior Permanent Magnet Synchronous Motor Design Trend are developing different topology rotor designs such as V-shaped from manufacturer Tesla; double V magnet shape from manufacturer China, delta shape from manufacturer AVL, hybrid delta shape based on the V shape from both manufacturer Tesla and manufacturer Nissan; hybrid double V shape from both manufacturer T and manufacturer V. Those design of rotor shape have aimed to maximize efficiency, torque density, overload load capability Chen Peng 2021, Wenliang Zhao 2015, Yang, Y 2017. However, this study will focus on comparing power, torque and efficiency maps of IPM 150kW. This study will improve average torque current characteristic by hybrid rotor shape design and step skewing magnet segment. The Torque and power vs current of the IPM step-skew magnet rotor are simulated to verify by FEA method. Many researches have been done for the optimization method for IPM EV applications, Kriging model is a one of popular method for optimization owing to its advantage which can predict surface of objective function through exploiting the spatial correlation of data which only based on limited information .

However, the Kriging model with higher precision requires more interpolation points that increase the number of finite element analysis (FEA) calculations, thus the computation time is overload. Therefore, it becomes a focus problem to reduce the computation cost. In Taguchi method was developed the pre-optimization to reduce the optimization variables, then Kriging model is created based on the FEA, and this method can sharply reduce the FEA calculations due to the number of variables decreases. In the Kriging method is used to approximate the extracted variables to reduce FEA calculations. Other methods have improved efficiency of optimization process by reducing iteration . All these literatures have tried to reduce the computation time. Especially, the dimension of parameters is large, and the number is larger than 8, the computation load is still large. Therefore, in the process of a multi-objective optimization with large parameter dimension, After the above analysis, a novel hybrid multi - objective optimization method combining Taguchi method with multi - level Kriging model is proposed in this paper. The proposed multi - objective optimization method is adopted to optimize an IPMSM used in electric vehicles.

Table 1. Power density requirement

Parameter	**Value**
Peak power kW	150
Winding Type	Hairpin
Stator assy weight	23.6
Stator LAM weight	17.98
Copper weight	5.388
kW/ Stator Assembly	>=6.36
kW/kg Copper	>=27.40
kW/ kg Stator Iron	=>8.30
Cooling system	Liquid cooling
Voltage/Current	394VDC/400A

The study subject optimized by the method proposed in this paper is a 150 kW, 16000 rpm IPMSM and its cross-sectional structure of 1/8 geometry is shown in Figure 1. The IPMSM adopts a structure of 8 poles and 48 slots with three phase distributed winding. In order to ensure that the temperature rise of this motor is within an allowable range, water cooling structure is adopted in the stator shell. The initial design parameters of the IPMSM are shown in Table 2.

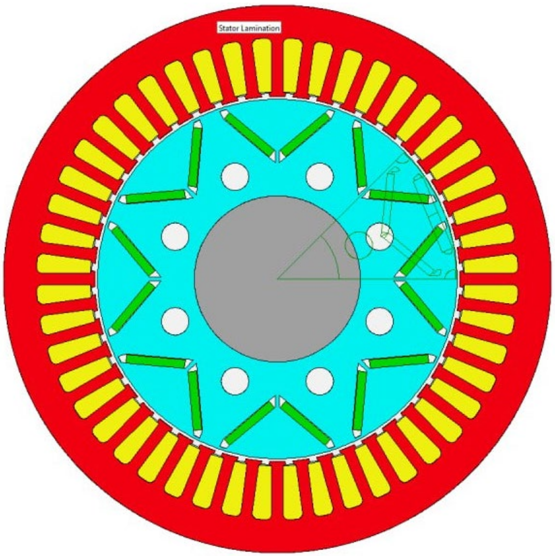


Figure 1. V shape topologies

Table 2. Optimization decision variables

Variable	**Range**	**Range**
Rotor radius	20–40	mm
Stator outer ring width	1–20	mm
Magnet width	1–15	mm
Magnet length	5–20	mm
Teeth width	1–10	mm
Teeth length	7–20	mm
Airgap	0.7–1.5	mm
Current density	12-20	A/mm2

Constraints are listed in Table 2. These include constraints derived from application-specific requirements, such as maximum dimensions and weight, but also thermal limitations of windings and permanent magnets, and maximum magnetic flux density. The latter is set as 1.6T for FeSi and 2.2T for VaCoFe. Objective functions and constraints are evaluated with the presented electromagnetic and thermal models for each element of each generation

Table 3. Optimization constraints by type and respective **ranges**

Type	Constraint	Range
Geometrical	Weight	<35kg
	Stator outer radius	<150mm
	Motor stack length	110mm
Thermal	PM's temperature	<120ºC
	Windings' temperature	<180ºC
Magnetic	Magnetic flux density	FeSi: <1.6T
		VaCoFe: <2.2T

The main geometry parameters of the improvement IPM is shown in Table 3.

Table 4. Dimensions of PMA-SynRM

Parameters	**Values**	**Unit**
Slot Number	72	
Stator Lam Dia	230	mm
Stator Bore	112	mm
Tooth Width	4.15	mm
Slot Depth	21.1	mm
Motor Length	150	mm
Stator Lam Length	150	mm
Magnet Length	150	mm
Rotor Lam Length	150	mm
Pole Number	8	
Airgap	0.75	mm

The numbers of slot and poles, stack length, the diameter of stator and rotor, the air-gap length listed in table 2 is designed for the power inverter of 450VDC/500 A, the continuous rated power of IPM machine is 150 kW, and the maximum speed of the machines is 18000 rpm. The main part of the process is to design the rotor configuration which is an embedded permanent magnet.

2 The Proposed Method For Optimization

In this paper, a multi step multi objective optimization method is optimal rotor pole topology with 6,8,12 poles in step 1 and combining Taguchi method with multilevel Kriging model to optimize geometry parameters with maximum power density. The proposal IPM with 8 poles, 72 slots have PM in the delta arrangement. The main specifications of the original SynRM (without PMs) is shown in Table 1.

2.1 Rotor pole topology optimization

The design characteristics of the IPM with 6-8-12 poles are evaluated using finite element analysis (FEA). The flux density is given in Figure 4. The total torque of the IPM motor 72s/12p is designed to be equivalent at the same current density by using full coil pitch windings on the double-layer IPMSM and short-pitch windings for the 8 poles and 12 poles one. A method for flux density calculation of an interior permanent magnet (IPM) motor at base operating point using 2-D finite element method is presented in fig 4. The IPM with 72 slot and 12 rotor poles has higest value of airgap flux density. Electromagnetic torque has been calculated based on the stator, rotor diameter, and power inverter voltage and currents. The electromagnetic parameters can inertial calculated as:

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

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.

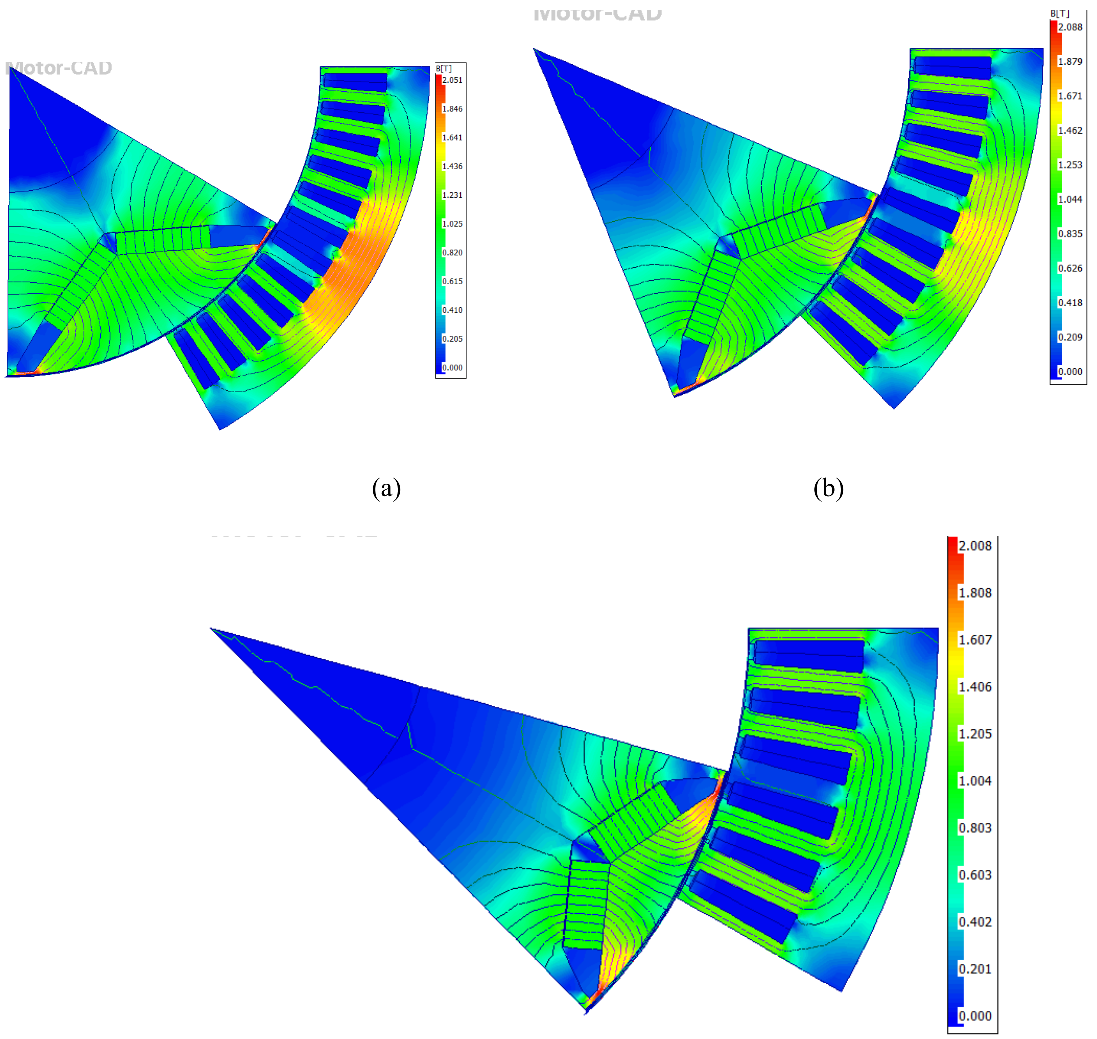
Torque prediction is carried out for any stator-rotor relative position and the finite element grid is automatically adjusted when the rotor is rotated. The influence of mesh has been investigated to get satisfactory accuracy avoiding inaccuracies due to the element distortion. Only one pole is simulated,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

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

$$\begin{aligned} v_d &= Ri_d - \omega L_q i_q \\ v_q &= Ri_q + \omega L_d i_d + \omega L_q i_q \end{aligned} \tag{2}$$

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.

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



(a) (b)

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Figure 2. Flux density distribution of IPM 6P(a), 8P (b) and 12P (c)

2.2 Rotor Geometry Parameters Optimization

In this paper, a novel multi objective optimization method combining Taguchi method with multi - level Kriging model is used to process the selected parameters, the results of sensitivity analysis can significantly reduce the dimension of parameters that need to be accurately optimized with Kriging model, so the computational burden can be sharply reduced. In the optimization process, Taguchi method and the proposed multi - level Kriging model method are used to obtain the optimal solutions and the main optimization process can be summarized as follows.

The maximum of Dp and the maximum of η are expected to obtain in the optimization process. Similarly, the optimal points of Dp and η are also at different points in the range of parameters. The absolute difference ε is larger than the maximum tolerance error ε0. Therefore, it is necessary to build new Kriging models to obtain the acceptable ε. However, if sampling points are added in the whole domain to improve the accuracy of the new models, the computational burden will be greatly increased. In order to reduce the computational burden, new method is taken in the process of optimization. Different design requirements have different weight coefficients for the objectives. In this paper, the weight coefficients of the two objectives Dp and η are represented as w1 and w2 respectively. Before determining the weight coefficients, the two objectives are normalized, the process can be expressed as follows:

Step 1: Select parameters related to the objectives and divide the selected parameters into two groups which according to the results of sensitivity analysis. The parameters in group 1 have significant influence on the objectives, and parameters in the other group have less effect on these two objectives:

Step 2: Compare the predicted values given by the Taguchi and kriging model with the objective values of the designated points and record the maximum ratio of absolute difference to value of the designated point as ε. Then compare ε with the maximum tolerance error ε0 which is set as 0.001, if ε is less than ε0, the process ends and outputs the results, otherwise proceed to the next step:

$$\varepsilon = \max\left(\frac{y - \hat{y}}{y}\right)$$

Step 3: Obtain the aimed areas on the Pareto front according to weight coefficients of two objectives in design requirements.

Step 4: Add new sampling points in the aimed area and build new Kriging models, then proceed to step 4.

Different design requirements have different weight coefficients for the objectives. In this paper, the weight coefficients of the two objectives Dp and η are represented as w1 and w2 respectively. Before determining the weight coefficients, the two objectives are normalized, the process can be expressed as follows:

$$f^* = \frac{f - f_{\min}}{f_{\max} - f_{\min}}$$

where fmax and fmin are the maximum and minimum values of an objective, respectively

Table 5. The optimal results of parameters in the interior permanent magnet synchronous machines

Parameters	**Min**	**Max**	**OP1**	**OP2**	**OP3**	**OP4**	**OP5**
L1 Magnet Thickness	3.9	3.93	3.9222338	3.902235	3.9284483	3.9103663	3.902266
L1 Pole V Angle	124.7	125.1	124.95677	125.08936	124.73919	124.93995	125.03282

Slot Depth	2.15	21.3	12.337185	13.086829	13.563223	14.452595	14.631666
L2 Pole V Angle	63.8	64.2	64.080752	63.835132	63.850558	64.12446	63.91454
L2 Magnet V Width	21.9	22.2	22.040527	22.030915	21.966844	22.140347	22.064663
Slot Opening	2	2.2	2.0836328	2.0032451	2.0780503	2.1032775	2.140492
Torque Weighted Error:			0.0031179	0.0031275	0.0031344	0.0031487	0.0031524

After the proposed method is applied to the optimization process of the selected parameters, the optimal values of these parameters are obtained as shown in Table 5. In order to verify the reliability and practicability of the proposed method, a prototype is manufactured according to the optimal values.

Table 6. Optimized comparison results

Parameter	72S12P	72S8P	72S6P	Unit
Maximum torque possible (DQ)	285.76	275.98	226.72	Nm
Average torque (virtual work)	284.15	265.65	210.68	Nm
Average torque (loop torque)	283.66	263.91	210.47	Nm
Torque Ripple (MsVw)	71.944	54.069	21.807	Nm
Torque Ripple (MsVw) [%]	5.358	20.392	10.362	%
Cogging Torque Ripple (Ce)	65.026	64.076	53.859	Nm
Cogging Torque Ripple (Vw)	9.2589	12.318	1.9835	Nm
Total weight	34.42	34.42	34.42	kg
Input Power	1.51E+05	1.42E+05	1.14E+05	Watts
Total Losses (on load)	4278.6	4408.8	4500.5	Watts
Output Power	1.47E+05	1.38E+05	1.09E+05	Watts
System Efficiency	97.165	96.894	96.041	%
Shaft Torque	280.04	262.68	208.54	Nm

After the prototype is manufactured, the prototype is measured at 34.52 kg in weight. The maximum output power is 155 kW, so the power density Dp of the prototype is 4.5 kW/kg. The prototype rotor lamination and the test platform are shown in Figure 3&4. The six-segmented magnets prototype was manufactured in figure 3. Each segment with a thickness of 20mm is skewed 1.5 mechanical degrees. In order to insert six segment simply, every segment block was designed one guide pin to fix correct position when all segment assembled together.

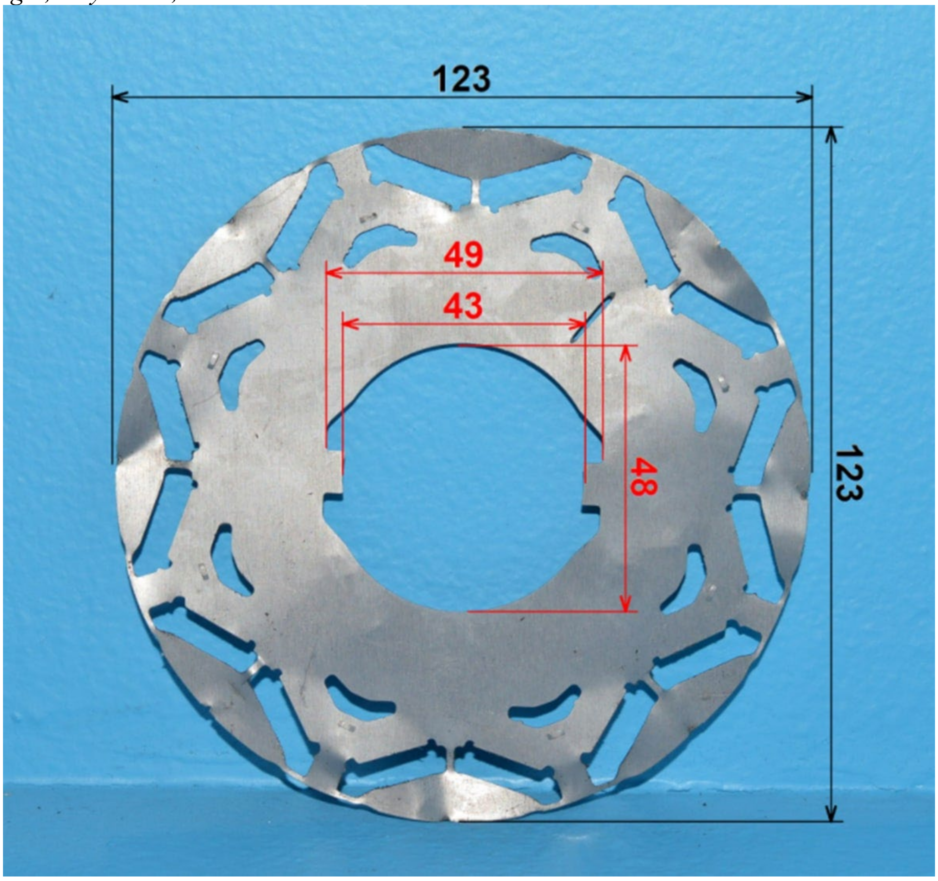

Figure 3. Rotor Lamination

The whole hardware of IPM motor was built together as fig 4. The torque transducer with high accuracy was used to measure torque and speed values under different load

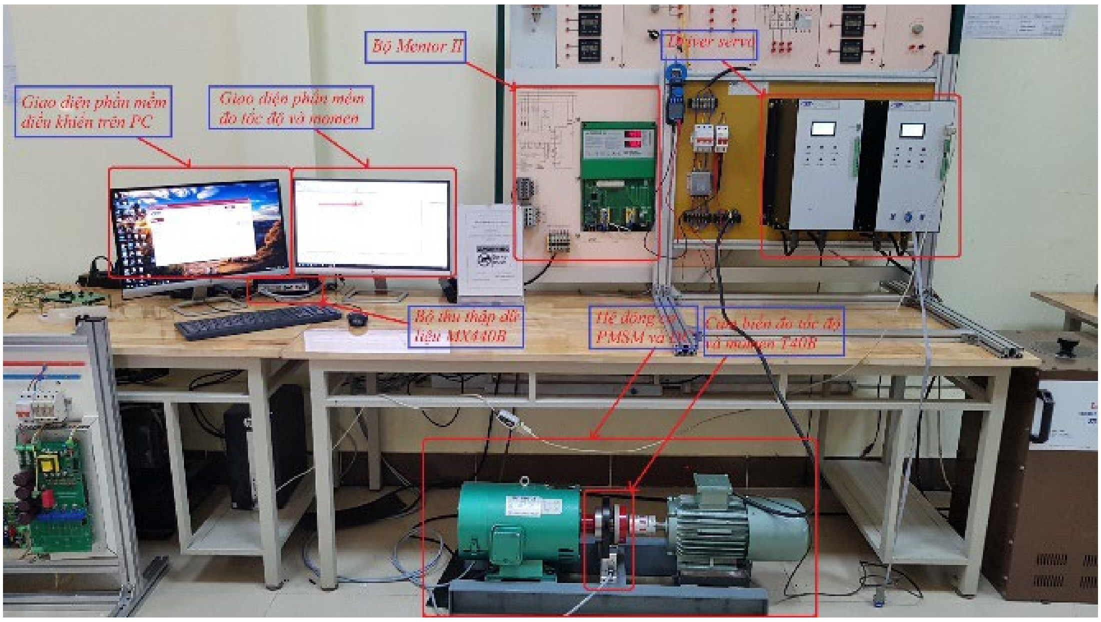

Figure 4. Hardware of IPM motor system

The measured no-load phase electromotive force (EMF) at 1500 rpm of IPM is shown in Fig. 4. In order to verify the electromagnetic performances, a 48/8p proposed PM machine is built and the distributed windings are adopted. It should be noted that the PM machine is a present prototype. The no-load Back-EMFs is carried out using voltage sensor.

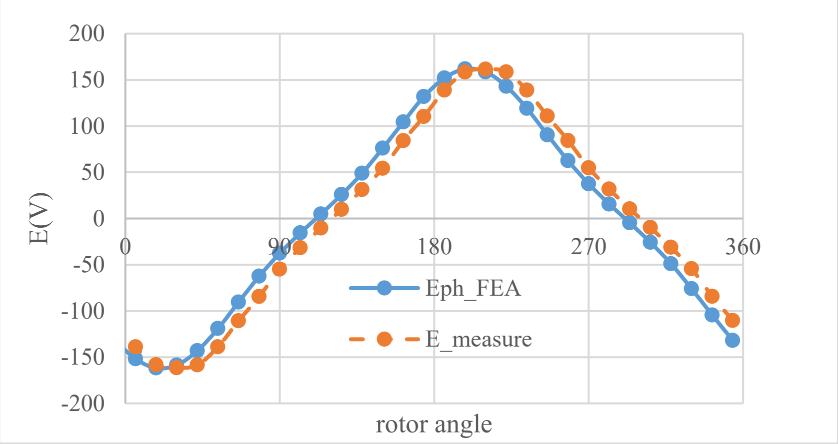

Figure 5. Back EMF comparison of IPM motor system

Back EMF waveforms of simulations and measured results are shown in Figure 9. One circle of back EMF was measured by Oscilloscope and recorded in data files for plotting those curves.

4. Conclusions

This paper presents the shape optimization of a IPM using a Multistep optimization method. To maximize the performance of the IPM, the average torque, torque ripple, DC link voltage and Radial forces were set as the multi-objective function, and efficiency and torque ripple were set as constraints. FEA was used to improve the accuracy of the design results. As a result of the parametric study, the lower bar, and rib thickness magnet angle parameters were determined to be design variables. 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 technique of SSR is an efficient way to improve the performance of the motor as a technique of skewing slot. A hybrid genetic algorithm (HGA), which combined a genetic algorithm (GA) with the Taguchi method, is proposed to optimize the rotor structure of an IPMSM for an electric vehicle application, to maximize the torque and efficiency, and minimize the torque ripple and iron losses.

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