

EVS29 Symposium

Montréal, Québec, Canada, June 19-22, 2016

Multi-Objective Optimal Designing of IPMSM for Electric Vehicle Application

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Abstract

In this paper, a method of multi-objective optimal designing on interior permanent magnet synchronous machines (IPMSM) for electric vehicle application to get higher the torque produced by per unit mass PM, lower torque ripple and lower iron loss is presented. The relevant structure parameters of the IPMSM, such as PM size, location of barriers in rotor and air gap length are optimized. The effects and its relative importance of each optimization variable on the torque produced by per unit mass PM, the torque ripple and the iron loss of the machine are analyzed to get the best optimization scheme. The iron loss and torque ripple are effectively reduced by adopting the method, and the torque produced by per unit mass PM of the machine is greatly increased as well.

Keywords: finite element (FE) calculation, motor design, optimization, permanent magnet motor, synchronous motor

1 Introduction

Compared with other motors, IPMSM has the advantages of wide speed range, high efficiency, high torque-current ratio, high torque density, compact structure and quick reaction capability, which are widely used in electric vehicle, high-precision servo drive system and aerospace[1]. In recent years, with the flux-weakening control technology maturing gradually, IPMSM which has good flux-weakening capability get larger development space. Therefore, it's particularly

important for the optimal designing of IPMSM.

The usual way for optimal designing of IPMSM structure include following four steps: first, taken one structure parameter of machine as single variable and maintain other parameters constant; and then, FE simulation is taken for some discrete values of selected parameter, simulation result is analyzed to get the parameter value which meet requirements; after that, the same simulation are taken for other structure parameters; last, the

optimal motor structure is got that all parameters obtained appropriate values. This method not only complicated and time consuming but also difficult to find the real optimal motor structure. If the optimization algorithm are applied in the optimal process of machines, the designing quality will improved and could save many designing time. Intelligent simulated annealing(SA) algorithm, improved particle swarm optimization(PSO) and genetic algorithm(GA) has used to optimized the structure of motor in literature [2-4] respectively. This kind of algorithm is global optimization algorithm which could included all uncertain factor in optimization objective, but it's very complicated for built specific objective function and can consuming lot of time for computation. And local optimization algorithm such as hill climbing method, simplex method and complex method has good astringency, but it just applied to single objective optimization and not for multi-objective optimal designing.

Taguchi method is a local optimization algorithm which based on orthogonal experiment and signal to noise ratio(SNR) technology and founded by Dr Genichi Taguchi of Japanese. Be different with other local optimization method, Taguchi method could realized multi-objective optimal designing. It could analyzed the best combination of each structure parameters with minimum times of experiments by built orthogonal experiment table as multi-objective optimization for motor is conducted. At present, literature [5-10] has researched the application of Taguchi method in optimal designing of motors. But most of optimized object is the PMSM of simple rotor structure like surface mounted and interior line-styled. In this paper, Taguchi method is used in the optimal designing of U-type IPMSM. And the level number of each optimization variable is 5, which has higher optimal precision compared with the 3 or 4 levels of previous research.

The relative parameters such as PM size, location

of barriers in rotor and air gap length have major impact on performance of IPMSM. Therefore, these parameters has been optimized by Taguchi method which based on orthogonal experiment in this paper. And largest the torque produced by per unit mass PM, lowest torque ripple and lowest iron loss as target to optimized the design of IPMSM.

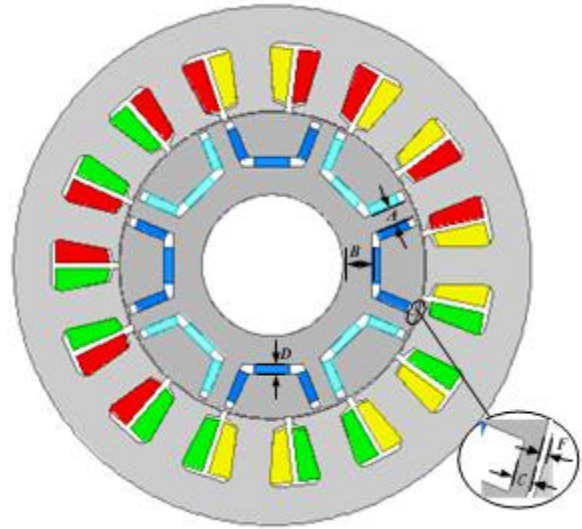


Figure 1: The sketch map of FE model and part of optimization variables for IPMSM

Table 1: The main parameters of IPMSM

Parameter	Value
Rated speed n_N/rpm	1000
Pole pair number p	4
Slot number Q	15
Outer diameter of stator D_o/mm	165
Inner diameter of stator D_i/mm	98
Air gap length F/mm	0.4
Inner diameter of rotor d_i/mm	97.2
PM type	N38SH

2 The Structure Model and Major Parameters of IPMSM

The 15-slot and 8-pole IPMSM with U-shaped PM rotor geometry and fractional-slot concentrated windings (FSCW) shown in Fig.1 is used to illustrate the multi-objective optimal design method. The main parameters of machine is shown

in Tab.1.

3 Multi-objective Optimal Design

Taguchi method is local optimization method which combined with orthogonal table to selected experiment conditions and arranged experiments. It could obtained the optimal combination of each design parameters by used this method at least number of times of experiments and come ture the optimization of machine.

The implementation process of multi-objective optimal design mainly includes the following three steps:

- 1) Identify the optimization variables, the value levels of optimization variables and optimization objectives;
- 2) Built the experimenting orthogonal table according to the number of optimization variables and its levels, perform finite element analysis for each experiments of the orthogonal table;
- 3) The analysis of mean values and variances for the experimental result to evaluates the effects and its relative importance of the selected optimization variables to the performance index, identify the optimal combination of parameters and verify it by finite element analysis.

The reference value of optimization variables is generally selected 3 to 5 value. Each value of each variable is named as level 1, level 2, level 3 and so on, according to the order from small to large of it. In view of the relative parameters such as air-gap length, PM size and location of PM in rotor have major impact on performance of IPMSM. Hence, in this paper, width of magnetic bridge between two adjacent poles, depth of rotor yoke, magnetic bridge length, thick of magnet, total width of 3 magnets on one pole and air gap length which represented as A , B , C , D , E and F respectively is selected as optimization variables. Each variable take 5 factor levels. Part of optimization variables of IPMSM shown in Fig.1. Levels and

corresponding value taken by each optimization variable of IPMSM shown in Tab.2. Value of these optimization variables at each level is selected based on practical process of the allowable range.

These optimization variable has impact on iron loss P_{Fe} , coefficient of torque ripple K_{mb} , the torque produced by per unit mass PM T_d and so on. For the first two, smaller value is better; for the last, the larger the better. K_{mb} and T_d is calculated by equation (1) and (2).

$$K_{mb} = \frac{T_{max} - T_{min}}{2T_{avg}} \times 100\% \quad (1)$$

$$T_d = \frac{T_{avg}}{m_{PM}} \quad (2)$$

m_{PM} is the mass of magnet of the machine.

Table 2: Levels and corresponding value taken by each optimization variable of IPMSM

Variable	A/mm	B/mm	C/mm	D/mm	E/mm	F/mm
Level 1	4.8	8	0.8	2.5	28	0.35
Level 2	5.1	8.5	0.9	3	29.5	0.4
Level 3	5.4	9	1	3.5	31	0.45
Level 4	5.7	9.5	1.1	4	32.5	0.5
Level 5	6	10	1.2	4.5	34	0.55

3.1 Experiment matrix and FE result

The orthogonal table is established according to the number of optimization variables and the number of levels for each variables. The code of orthogonal table represented as $L_n(q^t)$, of which, L is orthogonal table, n is experiment number that is row number of orthogonal table, q is level number corresponded to value of each variable and t is the number of optimization variables which also the column number of orthogonal table. For standard same levels orthogonal table which have same number of level for each variable, row number generally is the square of level number which is q^2 , and this kind of orthogonal table could make different level for each variable appear in the column of table an equal number of times. Numbers of transverse combination for any two columns of table is balanced. The orthogonal table

which same code is not unique but equivalent. Number of optimization variables is 6 and number of levels is 5 in this paper, therefore, the code of orthogonal matrix is $L_{25}(5^6)$. For traditional design method, that is FE calculation is taken for every value of optimization variables and need conducted $5^6=15625$ times of FE calculation. But it just need $5^2=25$ times of FE calculation for Taguchi method by built orthogonal matrix which could greatly shorten the design period of motor. The orthogonal matrix shown in Tab.3 and the level number of it respectively correspond to the value of each optimization variable in Tab.2.

Table 3: Orthogonal matrix and experimental results

Experiment number	Orthogonal matrix						T_d (N.m/kg)	$K_{mb}(\%)$	P_{Fe} (W)
	A	B	C	D	E	F			
1	1	1	1	1	1	1	63.34	2.257	40.76
2	1	2	2	2	2	2	51.87	2.121	38.59
3	1	3	3	3	3	3	43.15	1.343	39.07
4	1	4	4	4	4	4	36.55	1.167	40.51
5	1	5	5	5	5	5	31.86	1.351	42.97
6	2	1	2	3	4	5	40.39	1.735	37.8
7	2	2	3	4	5	1	37.49	2.177	49.64
8	2	3	4	5	1	2	36.88	2.979	39.5
9	2	4	5	1	2	3	57.55	1.741	34.95
10	2	5	1	2	3	4	49.19	1.942	34.94
11	3	1	3	5	2	4	34.73	2.876	38.82
12	3	2	4	1	3	5	53.57	1.546	32.23
13	3	3	5	2	4	1	49.81	1.954	43.61
14	3	4	1	3	5	2	42.29	1.895	47.22
15	3	5	2	4	1	3	40.46	1.789	38.25
16	4	1	4	2	5	3	46.83	1.609	41.16
17	4	2	5	3	1	4	43.33	1.913	33.69
18	4	3	1	4	2	5	38.44	1.709	37.22
19	4	4	2	5	3	1	36.24	2.5	49.14
20	4	5	3	1	4	2	58.21	1.407	40.48
21	5	1	5	4	3	2	38.83	2.716	43.06
22	5	2	1	5	4	3	34.39	3.086	48.05
23	5	3	2	1	5	4	54.43	1.322	37.91
24	5	4	3	2	1	5	48.92	2.338	31.82
25	5	5	4	3	2	1	46.06	2.812	43.42

FE simulation is conducted according to the value of each level taken by each optimization variables for each experiment in Tab.3 and get result of the torque produced by per unit mass PM T_d , coefficient of torque ripple K_{mb} and iron loss P_{Fe} . The experimental results shown in Tab.3.

3.2 Analysis of Mean

In order to analyzed the effects and its relative importance of each optimization variable on the torque produced by per unit mass PM T_d , coefficient of torque ripple K_{mb} and iron loss P_{Fe} , mathematical statistical methods has applied to conducts the FE simulation results in Tab.3. First, analysis of mean; and then, analysis the corresponding variance; last, get the optimal result. The average values for each performance index of each experiment results is calculated in accordance with equation (3) and the results shown in Tab.4.

$$m = \frac{1}{n} \sum_{i=1}^n m_i \quad (3)$$

Where m is the overall average of the experimental results for certain performance index in Tab.3; n is the number of experiment; m_i is value of one performance index for the i th experiment.

Table 4: The overall average of experimental results

	m_{T_d} (N.m/kg)	$m_{K_{mb}}$ (%)	$m_{P_{Fe}}$ (W)
m	44.5924	2.0114	40.1924

And then, the average of each performance index for each optimization variable at each level is calculated. For example, the average value of iron loss for width of magnetic bridge between two adjacent poles A at level 1 is calculated by equation (4). And the similar calculations could conducted for other 5 variables. The results shown in Tab.5.

$$m_{P_{Fe}}(A_1) = \frac{1}{5} (P_{Fe1} + P_{Fe2} + P_{Fe3} + P_{Fe4} + P_{Fe5}) \quad (4)$$

Where $P_{Fe1} \sim P_{Fe5}$ is iron loss of 1-5 th experiment for width of magnetic bridge between two adjacent

poles A at level 1.

Table 5: Average of each performance index for each optimization variable at each level

Variable	Level	m_{T_d} (N.m/kg)	$m_{K_{mb}}$ (%)	$m_{P_{Fe}}$ (W)
A	1	45.35	1.648	40.38
	2	44.30	2.115	39.37
	3	44.17	2.012	40.03
	4	44.61	1.827	40.34
	5	44.52	2.455	40.85
B	1	44.82	2.239	40.32
	2	44.13	2.169	40.44
	3	44.54	1.862	39.46
	4	44.31	1.928	40.73
	5	45.16	1.86	40.01
C	1	45.53	2.178	41.64
	2	44.68	1.89	40.34
	3	44.50	2.028	39.97
	4	43.98	2.023	39.36
	5	44.28	1.935	39.66
D	1	57.42	1.655	37.27
	2	49.32	1.993	38.03
	3	43.05	1.939	40.24
	4	38.35	1.912	41.74
	5	34.82	2.558	43.70
E	1	46.59	2.255	36.80
	2	45.73	2.252	38.60
	3	44.20	2.009	39.69
	4	43.87	1.870	42.09
	5	42.58	1.671	43.78
F	1	46.59	2.34	45.31
	2	45.61	2.224	41.77
	3	44.48	1.914	40.30
	4	43.65	1.844	37.17
	5	42.64	1.736	36.41

It can be observed from Tab.5 that the smaller the variables of D , E or F , the smaller the iron loss P_{Fe} and the larger the torque produced by per unit mass PM T_d will be. And the larger the variables of E and F , the smaller the coefficient of torque ripple K_{mb} will be. Moreover, the combination of the level taken by each variable with optimum each

performance index can be achieved from Tab.5. In detail, the combination of the level taken by each variable makes the torque produced by per unit mass PM T_d largest, the coefficient of torque ripple K_{mb} smallest and the iron loss P_{Fe} smallest respectively is $A(1)B(5)C(1)D(1)E(1)F(1)$, $A(1)B(5)C(2)D(1)E(5)F(5)$ and $A(2)B(3)C(4)D(1)E(1)F(5)$. Obviously, the combination of each variable level that makes each performance index optimal respectively are different. Therefore, variance analysis needs conducted to dissected the proportion that the influence of the change of each variable on each performance index, thus, to get optimal result.

3.3 Analysis of Variance

Variance is a statistic which evaluated the degree of deviation between one date and mean value. The proportion that the influence of the change of each variable on each performance index could obtained by analyzed the variance between the mean of one performance index for each variables at each levels and the overall average of experimental results for that performance index. The calculation formula of variance is shown as

$$S_P = \frac{1}{Q} \sum_{i=1}^Q (m_{P(i)} - m)^2 \quad (5)$$

Where P is the optimization variables such as A , B , C , D , E and F ; S_P is the variance of one performance index under variables P ; Q is the level number of each variable and $Q=5$; $m_{P(i)}$ is the mean of one performance index for variables P at level 1 in Tab.5; m is the overall average of one performance index in Tab.4.

Take, for example, calculation for the variance of the iron loss under variable A of 5 levels, to explain equation (5). The expression shown as

$$S_{P_{Fe} A} = \frac{1}{5} \sum_{i=1}^5 (m_{P_{Fe} A(i)} - m_{P_{Fe}})^2 = 0.24 \quad (6)$$

Similarly, the variance of each performance index

under other variables of 5 level could calculated by equation (5) as well. And the result shown in Tab.6.

Table 6: Variance and ratio of performance index under each optimization variable of 5 levels

	S_{T_d}		$S_{K_{mb}}$		$S_{P_{Fe}}$	
	Value	Ratio (%)	Value	Ratio (%)	Value	Ratio (%)
<i>A</i>	0.169	0.24	0.0747	24.7	0.24	1.03
<i>B</i>	0.134	0.19	0.0257	8.50	0.187	0.81
<i>C</i>	0.275	0.40	0.00958	3.17	0.627	2.70
<i>D</i>	64.742	93.46	0.0884	29.23	5.585	24.05
<i>E</i>	1.999	2.89	0.0507	16.77	6.152	26.50
<i>F</i>	1.954	2.82	0.0533	17.63	10.429	44.91
Total	69.273	100	0.30238	100	23.22	100

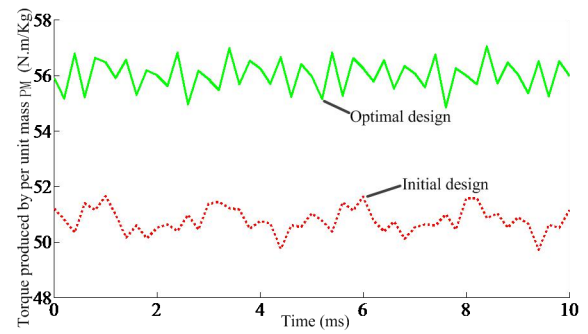
4 The Optimal Result

From Tab.6, the values of variance has determined the proportion that the influence of the change of each optimization variable on each performance index. Obviously, the change of variables *A*, *B* and *C* has greatest influence on coefficient of torque ripple K_{mb} . Similarly, the change of variable *D* has greatest impact on the torque produced by per unit mass PM T_d and the change of variables *E* and *F* has greatest impact on iron loss P_{Fe} . From the analysis of section 3.2, the combination of the level taken by each variable makes the torque produced by per unit mass PM T_d largest, the coefficient of torque ripple K_{mb} smallest and the iron loss P_{Fe} smallest respectively is $A(1)B(5)C(1)D(1)E(1)F(1)$, $A(1)B(5)C(2)D(1)E(5)F(5)$ and $A(2)B(3)C(4)D(1)E(1)F(5)$. According to above analysis, take the minimum coefficient of torque ripple K_{mb} as the standard for the value selected of variables *A*, *B* and *C*, the maximum the torque produced by per unit mass PM T_d as standard for the value selected of variable *D* and the minimum iron loss P_{Fe} as standard for the value selected of variables *E* and *F*. Therefore, the optimal combination of the level taken by each

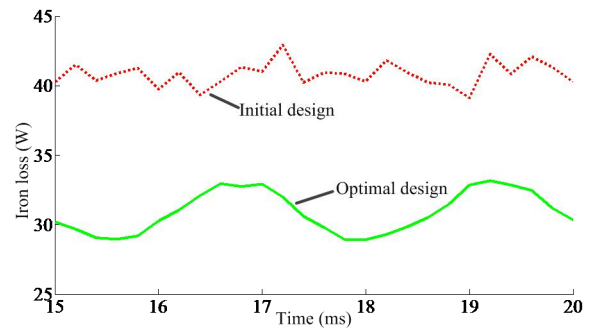
variable is $A(1)B(5)C(2)D(1)E(1)F(5)$ and the value taken by each variable for final optimization scheme is shown in Tab.7.

Table 7: Level combination and corresponding value taken by each optimization variable for final optimization scheme

Level combination	$A(1)B(5)C(2)D(1)E(1)F(5)$					
Variable	<i>A/mm</i>	<i>B/mm</i>	<i>C/mm</i>	<i>D/mm</i>	<i>E/mm</i>	<i>F/mm</i>
Value	4.8	10	0.9	2.5	28	0.55



(a) Torque produced by per unit mass PM



(b) Iron loss during stable operation for motor

Figure 2: FE result for initial design and optimal design

Table 8: Performance comparison between the initial and optimal design

	$T_d(N.m/kg)$	$K_{mb}(\%)$	$P_{Fe}(W)$
Initial design	50.79	1.873	40.84
Optimal design	56.21	1.760	30.87

According to the value taken by each variable for the optimal scheme shown in Tab.7, built FE model and taken simulation. The finite element results of the initial design and the optimal design is shown in Fig.2. And the specific performance comparison after analysis of Fig.2 is listed in Tab.8.

It's indicate that iron loss and torque ripple of optimal design are reduced by 24.41% and 6.03% respectively compared with the initial design, and the torque produced by per unit mass PM is increased by 10.67% as well.

5 Conclusion

In this paper, multi-objective optimal designing method was combined with FE software. Take the torque produced by per unit mass PM T_d largest, coefficient of torque ripple K_{mb} minimum and iron loss P_{Fe} minimum as optimization objective and 6 structure parameters of IPMSM are optimized. That is width of magnetic bridge between two adjacent poles A , depth of rotor yoke B , magnetic bridge length C , thick of magnet D , total width of 3 magnets on one pole E and air gap length F . The performance index of optimal motor has been greatly improved which verified the validity of the method. The results of this paper provide some guidance to practical application.

Acknowledgment

This study was supported by State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources of china (Grant No. LAPS16021)

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