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Multi-objective optimization to seek optimal structure factors to improve the DDPMS motor performance

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Abstract

Efficient design of direct-drive permanent magnet synchronous (DDPMS) motors will have sufficient power factor and torque density. They are being used in aerospace, automated robot systems and electric vehicles. The desirable motor performance factors in design are torque, efficiency, torque ripple and back-electromotive force distortion rate. Basic design considers 4 motor structure factors (viz., magnet height, magnet width, air-gap width, and opening slot width). Design through analysis of such systems will be complex due to many structure factors. More factors and levels demand more number of trial runs. To overcome such time-consuming computational tasks, a simple statistical approach, the so-called Taguchi method is more appropriate. It considers an orthogonal array and suggests few tests for obtaining the complete data relevant to all combinations of the design factors with levels. This paper applies the modified Taguchi approach and utilizes a simple and reliable multi-objective optimization procedure for optimal structure factors to improve the performance of permanent magnet motors and demonstrates its potentiality through comparison of the performance indicator estimates.

Keywords: Air gap width; Back-electromotive force distortion rate; Efficiency; Magnet height; Magnet width; Opening slot width; Torque; Torque ripple.

1. Introduction

Efficient permanent magnet motors with sufficient power factor and torque density, are well suited for direct-drive applications in aerospace, automated robot systems (for manufacturing) and electric vehicles [1, 2]. There is a demand for the multi-objective optimization of motors with complex design factors. The desirable motor performance factors in the optimization process are torque (T_{em}), efficiency (η), torque ripple (T_{rip}) and back-electromotive force distortion rate (THD_{emf}). Guo et al. [2] have incorporated IFBTM (an improved fuzzy-based Taguchi method) with FEA (finite-element analysis) while optimizing the direct-drive permanent magnet synchronous (DDPMS) motors. They have adopted Taguchi's $L_{16}\,OA$ (Orthogonal array) for the four structure factors viz., magnet height (h), magnet width (τ), air-gap width (δ), and opening slot width (β) with 4 levels. Figure-1 shows the factors and the motor performance indicators for realizing the optimal structural configuration. They have made a comparative study on the optimal solutions of the structure factors from the Taguchi method, FBTM (Fuzzy-based Taguchi Method) and IFDTM. Finally, they have recommended the IFBTM for the selection of optimal set of structure parameters to seek better performance of the motor.

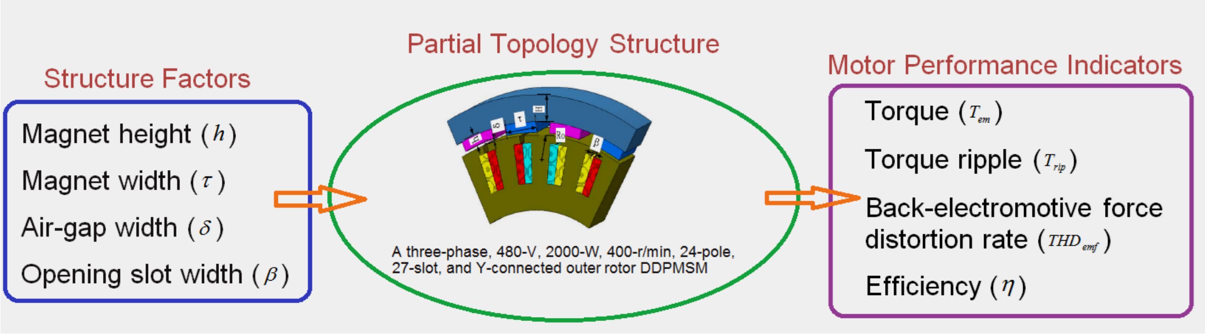

Figure-1: Structure factors to design for optimal motor performance [2]

In fact, Taguchi method is a simple statistical approach, which considers OA and suggests few test runs to obtain the information for all combinations of the selected factors with assigned levels [3]. This method minimizes the cost and time of testing. Many researchers have utilized the technique in finding the optimal parameters to confirm the results through tests. This paper applies the modified Taguchi approach [4] and utilizes a simple and reliable multi-objective optimization procedure on FEA results to improve the performance of direct-drive permanent magnet motors [2] and demonstrates its potentiality through comparison of the performance indicator estimates.

2. Analysis

Guo et al. [2] have proposed an improved fuzzy-based Taguchi method (IFBTM) to select optimal motor structure factors performing FEA. Numerical simulations are carried out for the specified sets of structural factors as per the Taguchi's $L_{16}\,OA$ (Orthogonal array) for 4 structure factors viz., magnet height (h), magnet width (τ), air-gap width (δ), and opening slot width (β) with 4 levels. They have presented the motor performance indicators: torque (T_{em}), efficiency (η), torque ripple (T_{rip}) and back-electromotive force distortion rate (THD_{emf}). Optimal set of structure factors is arrived by maximizing T_{em} and η, and minimizing T_{rip} and THD_{emf}. Table-1 gives the levels of structure factors and the performance indicators ($T_{em}, T_{rip}, THD_{emf}$ and η) for the assigned structure factors (h, τ, δ and β) as per $L_{16}\,OA$. Table-2 presents ANOVA (analysis of variance) results. Air gap width (δ) indicates high %Contribution on the grand mean of the performance indicators. Denoting ψ as a performance indicator, whose estimate (ψ_e) for the specific levels of the process variables $(h_i, \tau_j, \delta_k, \beta_l)$ can be found using the additive law [1]

$$\begin{aligned}\psi_e &= \psi(h_i,\, \tau_j,\, \delta_k,\, \beta_l) = \psi_g + \Delta\overline{\psi}_{hi} + \Delta\overline{\psi}_{\tau j} + \Delta\overline{\psi}_{\delta k} + \Delta\overline{\psi}_{\beta l} \\ &= \psi_g + (\overline{\psi}_{hi} - \psi_g) + (\overline{\psi}_{\tau j} - \psi_g) + (\overline{\psi}_{\delta k} - \psi_g) + (\overline{\psi}_{\beta l} - \psi_g) \\ &= \overline{\psi}_{hi} + \overline{\psi}_{\tau j} + \overline{\psi}_{\delta k} + \overline{\psi}_{\beta l} - 3\psi_g \qquad (1)\end{aligned}$$

Here ψ_g is the gross mean (that is the mean value of the total test runs); $(\overline{\psi}_{hi}, \overline{\psi}_{\tau j}, \overline{\psi}_{\delta k}, \overline{\psi}_{\beta l})$ are the mean values of ψ corresponding to the specific levels of the process variables $(h_i, \tau_j, \delta_k, \beta_l)$ in which subscripts $(i, j, k, l = 1\,to\,4)$ are the levels. With inclusion of fictitious (ε), estimate of the performance indicator (ψ_e^*) is from

$$\psi_e^* = \psi_e + \Delta\overline{\psi}_{\varepsilon m} = \psi_e + (\overline{\psi}_{\varepsilon m} - \psi_g) \qquad (\forall\ m = 1\ to\ 4) \qquad (2)$$

The difference in estimates $\left(\psi_e \text{ and } \psi_e^*\right)$ is $\Delta\overline{\psi}_{\varepsilon m} = \left(\overline{\psi}_{\varepsilon m} - \psi_g\right)$. It is due to exclusion and inclusion of the fictitious factor (ε), which can be referred as correction to ψ_e. Considering only the levels of minimum and maximum mean values $\overline{\psi}_\varepsilon$ for ε, corrections to estimates is arrived.

Table-1: Levels of structure factors and performance indicators of DDPMS motors.

Structure factors	Designation	Level-1	Level-2	Level-3	Level-4
Magnet height (mm)	h	3	3.5	4	4.5
Magnet width (mm)	τ	14	15	16	17
Air-gap width (mm)	δ	0.5	1	1.5	2
Opening slot width (mm)	β	2	3	4	5
Fictitious	ε	ε_1	ε_2	ε_3	ε_4

Test run	Levels of structure factors					Performance Indicators			
	h	τ	δ	β	ε	$T_{em}(Nm)$	$T_{rip}(\%)$	$THD_{emf}(\%)$	$\eta(\%)$
1	1	1	1	1	1	116.96	4.2	4.62	94.6
2	1	2	2	2	2	120.17	5.7	5.2	93.4
3	1	3	3	3	3	120.63	4.04	5.87	90.7
4	1	4	4	4	4	119.9	3.31	5.82	81.6
5	2	1	2	3	4	133.65	6.95	4.78	92.7
6	2	2	1	4	3	152.65	9.82	4.89	92.1
7	2	3	4	1	2	103.18	2.52	6.54	91.6
8	2	4	3	2	1	124.03	6.79	6.4	91.9
9	3	1	3	4	2	138.33	4.7	4.79	90.4
10	3	2	4	3	1	126.25	2.24	5.28	89.8
11	3	3	1	2	4	148.11	13.7	4.68	92.5

12	3	4	2	1	3	130.08	11.72	5.47	94.1
13	4	1	4	2	3	120.01	2.32	4.81	91
14	4	2	3	1	4	121.51	6.54	5.11	93.9
15	4	3	2	4	1	161.02	7.76	5.05	92.1
16	4	4	1	3	2	166.03	8.45	4.74	90.9

Table-2: Analysis of variance (ANOVA) on the performance indicators of DDPMS motors.

Structure factors	Performance Indicator				Sum of Squares (SOS)	%Contribution
	1-Mean	2-Mean	3-Mean	4-Mean		
Torque, $T_{em}(Nm)$ - Grand mean=131.41 Nm						
h	119.42	128.38	135.69	142.14	1146.4	25.2
τ	127.24	130.15	133.24	135.01	141.20	3.1
δ	145.94	136.23	126.13	117.34	1841.3	40.5
β	117.93	128.08	136.64	142.98	1415.3	31.1
ε	132.07	131.93	130.84	130.79	5.60	0.1
Torque ripple, $T_{rip}(\%)$ - Grand mean=6.2975%						
h	4.3125	6.52	8.09	6.2675	28.814	16.7
τ	4.5425	6.075	7.005	7.5675	20.972	12.2
δ	9.0425	8.0325	5.5175	2.5975	99.375	57.8
β	6.245	7.1275	5.42	6.3975	5.8866	3.4
ε	5.2475	5.3425	6.975	7.625	16.943	9.9
Back electromotive force distortion rate, $THD_{emf}(\%)$ - Grand mean=5.2531%						
h	5.3775	5.6525	5.055	4.9275	1.2810	23.1
τ	4.75	5.12	5.535	5.6075	1.9036	34.3
δ	4.7325	5.125	5.5425	5.6125	2.0014	36.1
β	5.435	5.2725	5.1675	5.1375	0.2166	3.9
ε	5.3375	5.3175	5.26	5.0975	0.1421	2.6
Efficiency, $\eta(\%)$ - Grand mean=91.456%						

h	90.075	92.075	91.7	91.975	10.477	7.9
τ	92.175	92.3	91.725	89.625	18.617	14.0
δ	92.525	93.075	91.725	88.5	50.297	38.0
β	93.55	92.2	91.025	89.05	43.652	33.0
ε	92.1	91.575	91.975	90.175	9.357	7.1

Corrections to the estimates of the performance indicators ($T_{em}, T_{rip}, THD_{emf}$ and η) from the additive law (1) give the lower and upper bound estimates. Corrections to T_{em} estimates at the specified levels of the structure factors $(h_i, \tau_j, \delta_k, \beta_l)$ are -0.61437 and 0.658125 Nm. Corrections to T_{rip} estimates are -1.05 and 1.3275%. Corrections to THD_{emf} estimates are -0.15563 and 0.084375%. Corrections to η estimates are -1.28125 and 0.64375.

Using the additive law, the performance indicators are evaluated for selective test runs in Table-3 and compared the results with simulations [2]. Inclusion of fictitious parameters, the estimates are matching well with simulation results [2]. Discrepancy in the estimates is noticed with exclusion of the fictitious parameter. All the simulation results in Table-1 are found to be within/close-to the expected range of the performance indicators.

Table-3: Comparison of estimates of performance indicators with simulations (Estimates from Equation (2) and Equation (3) represent exclusion and inclusion of fictitious parameter).

Test Run	Method	Performance Indicators			
		$T_{em}(Nm)$	$T_{rip}(\%)$	$THD_{emf}(\%)$	$\eta(\%)$
1	Simulation [2]	116.96	4.2	4.62	94.6
	Equation (1)	116.30	5.25	4.54	94.0
	Relative Error (%)	0.6	-25.0	1.8	0.7
	Equation (2)	116.96	4.2	4.62	94.6
	Expected Range	115.69 – 116.96	4.20 – 6.58	4.38 – 4.62	92.68 – 94.60
	Simulation [2]	126.25	2.24	5.28	89.8

10	Equation (1)	125.59	3.29	5.20	89.2
	Relative Error (%)	0.5	-46.9	1.6	0.7
	Equation (2)	126.25	2.24	5.28	89.8
	Expected Range	124.98 – 126.25	2.24 – 4.62	5.04 – 5.28	87.88 – 89.80
16	Simulation [2]	166.03	8.45	4.74	90.9
	Equation (1)	165.51	9.41	4.68	90.8
	Relative Error (%)	0.3	-11.3	1.4	0.1
	Equation (2)	166.03	8.45	4.74	90.9
	Expected Range	164.90 – 166.17	8.36 – 10.73	4.52 – 4.76	89.50 – 91.43

PMSM drives find wide applications having smooth torque requirements. The machine should be free of torque ripples, which leads to mechanical vibration and acoustic noise [5]. From the mean values of the performance indicators in ANOVA Table-2, the set of optimal structure factors to achieve maximum torque $T_{em}(Nm)$ is ($h_4\ \tau_4\ \delta_1\ \beta_4$). Subscripts denote the levels of the factors. For minimum torque ripple $T_{rip}(\%)$, the set of optimal factors is ($h_1\ \tau_1\ \delta_4\ \beta_3$). For minimum back electromotive force distortion rate $THD_{emf}(\%)$, the set of optimal structure factors is ($h_4\ \tau_1\ \delta_1\ \beta_4$). For maximum efficiency $\eta(\%)$, ($h_2\ \tau_2\ \delta_2\ \beta_1$) is the set of optimal structure factors. These are in good agreement with the main factor effects on motor performance in Figure-2 of Guo et al. [2]. Reverse in trend is claimed by Guo et al. [2] for the above factor-level combinations. It should be noted that simulation results for these 4 sets of optimal structure factors are not in the test runs of $L_{16}\ OA$ of Table-1. Table-4 presents the estimates of performance indicators utilizing the additive law (2).

Table-4: Estimates of the performance indicators for the 4 sets of optimal structure factors

Set of optimal structure factors	Performance Indicators			
	$T_{em}(Nm)$	$T_{rip}(\%)$	$THD_{emf}(\%)$	$\eta(\%)$
($h_4\ \tau_4\ \delta_1\ \beta_4$) for max. T_{em}	**171.8**	10.38	4.65	88.81

($h_1\ \tau_1\ \delta_4\ \beta_3$) for min. T_{rip}	106.4	**-2.02**	5.15	87.41
($h_4\ \tau_1\ \delta_1\ \beta_4$) for min. THD_{emf}	164.1	7.36	**3.79**	91.36
($h_2\ \tau_2\ \delta_2\ \beta_1$) for max. η	118.5	7.98	5.54	**96.63**

The bold numerical values in Table-4 represent the optimal performance indicators, which confirm the maximum/minimum to the results of test runs in $L_{16}\ OA$ of Table-1. For free of torque ripples, it is necessary to find a set of structure factors which yield a positive value close to the identified ($h_1\ \tau_1\ \delta_4\ \beta_3$) for min. T_{rip}. The results in ANOVA Table-2 indicate the high %Contribution of structure factor as Air-gap width (δ). Hence, the positive value of T_{rip} close to the identified ($h_1\ \tau_1\ \delta_4\ \beta_3$) for min. T_{rip} is found to be 0.99 for the set of structure factors ($h_1\ \tau_1\ \delta_3\ \beta_3$). Free of torque ripples can be expected in between δ_3 and δ_4.

Since the above 4 sets of optimal structure factors are different, this problem has to be solved by selecting an appropriate multi-objective optimization concept. A simple multi-objective optimization technique [6] is adopted to specify a set of optimal structure factors (viz., h, τ, δ *and* β) for obtaining maximum T_{em}, minimum T_{rip} and THD_{emf}, and maximum η.

In this technique, a single objective function (ζ) is constructed as a function of $\zeta_1\left(=1-\dfrac{T_{em}}{T^*_{em}}\right)$, $\zeta_2\left(=\dfrac{T_{rip}}{T^*_{rip}}\right)$, $\zeta_3\left(=\dfrac{THD_{emf}}{THD^*_{emf}}\right)$ and $\zeta_4\left(=1-\dfrac{\eta}{\eta^*}\right)$. Superscript * denotes maximum value of the respective performance indicator. In the present study, $T^*_{em}=171.84\,Nm$ for ($h_4\ \tau_4\ \delta_1\ \beta_4$); $T^*_{rip}=12.935\%$ for ($h_3\ \tau_4\ \delta_1\ \beta_2$); $THD^*_{emf}=6.5481\%$ for ($h_2\ \tau_4\ \delta_4\ \beta_1$); and $\eta^*=96.63\%$ for ($h_2\ \tau_2\ \delta_2\ \beta_1$). Introducing the positive weighing factors $\omega_i\ (i=1\ to\ 4)$ which satisfy $\sum_{i=1}^{4}\omega_i=1$, the single objective function (ζ) is constructed in the form

$$\zeta=\sum_{i=1}^{4}\omega_i\,\zeta_i \tag{3}$$

Minimization of ζ provides the maximum T_{em}, minimum T_{rip} and THD_{emf}, and maximum η for a set of structural factors. The non-dimensional performance indicators $\zeta_i\ (i=1\ to\ 4)$ in equation (3) are determined from the test runs data in $L_{16}\ OA$ of Table-1. For common optimum process conditions, $\omega_1 = \omega_2 = \omega_3 = \omega_4 = \frac{1}{4}$ (equal weighing), $L_{16}\ OA$ data for the multi-objective function (ζ) are generated and presented the mean value results (similar to those of ANOVA Table-2) in Table-5.

Table-5: Mean values of the single objective optimization function (ζ)

Structure Factors	1-Mean	2-Mean	3-Mean	4-Mean
h	0.3737	0.4047	0.4000	**0.3532**
τ	**0.3374**	0.3736	0.4026	0.4180
δ	0.3876	0.3973	0.3871	**0.3596**
β	0.4030	0.4011	**0.3578**	0.3697

Bold numbers of Table-5 corresponds to the minimum mean values of ζ for identifying the levels of structure factors. The set of optimal structure factors ($h_4\ \tau_1\ \delta_4\ \beta_3$) obtained for the minimum ζ from Table-5. The motor performance factors: torque (T_{em}), torque ripple (T_{rip}), back-electromotive force distortion rate (THD_{emf}) and efficiency (η) obtained from the additive law (1) for the identified set of optimal structure factors ($h_4\ \tau_1\ \delta_4\ \beta_3$) are 129.1 Nm, -0.06%, 4.7% and 89.31% respectively. Since, air-gap width (δ) is the highest %Contributing structure factor, the positive value of T_{rip} close to the identified set of structure factors ($h_4\ \tau_1\ \delta_4\ \beta_3$) is ($h_4\ \tau_1\ \delta_3\ \beta_3$) for which the motor performance indicators are: T_{em}=137.9 Nm; T_{rip}=2.86%; THD_{emf}=4.63%; and η=92.53%. Free of torque ripples can be expected in between ($h_4\ \tau_1\ \delta_3\ \beta_3$) and ($h_4\ \tau_1\ \delta_4\ \beta_3$).

It should be noted that free torque ripples can be expected for the air-gap width, δ=1.8mm. Hence, optimal structure factors are: h_4 = 4.5mm; τ_1 = 14mm; δ=1.8mm and β_3 = 4mm for which the expected range of performance indicators (viz., T_{em}, T_{rip}, THD_{emf} *and* η) are 131.9 – 133.2 Nm, 0.10 – 2.48%, 4.26 – 4.50%, and 89.8 – 91.7%.

Improved fuzzy-based Taguchi method (IFBTM) of Guo et al. [2] considers the simulation results and applies S/N ratio transformation, which are stratified and standardized to arrive the best combination of structure factors ($h_4\, \tau_1\, \delta_3\, \beta_3$) for which the estimates of motor performance indicators (viz., T_{em}, T_{rip}, THD_{emf} and η) are 137.3 – 138.6Nm, 1.81 – 4.18%, 4.47 – 4.71% and 90.6 – 92.5%. Though, T_{em} and η are slightly higher than those proposed in this study, the presence of torque ripples is unavoidable. The method of approach followed in this study is quite simple and easy to compute on Microsoft Excel.

3. Concluding remarks

Permanent magnet synchronous (PMS) motors drives having smooth torque requirements find wide applications. The machine should be free of torque ripples. Efficient permanent magnet motors are suitable for direct-drive applications in aerospace, automated robot systems (for manufacturing) and electric vehicles. Modified Taguchi approach suggests a few tests and provides the results for all combinations of the factors with levels. This paper applies the modified Taguchi approach on the existing FEA results and demonstrates its potentiality through comparison of the performance indicator estimates. A simple and reliable multi-objective optimization procedure is followed for specifying the optimal structure factors to minimize the torque ripples and maximize the efficiency.

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