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ROTOR DESIGN OF A LINE START PERMANENT MAGNET SYNCHRONOUS MACHINE USING THE TAGUCHI METHOD

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Abstract: This paper investigates the use of the Taguchi method for the design and optimization of a line-start (LS) permanent magnet synchronous machine (PMSM). The method is implemented separately for the steady-state and transient performance optimization. The optimized machine shows good transient performance as well as the steady-state performance that complies with IE4 efficiency standards. The main advantage of the Taguchi method is the large reduction in computational efforts when compared with traditional optimization methods.

Key words: Taguchi method, line-start motor, design optimization, transient performance.

1. INTRODUCTION

Induction motor (IM) drives have been widely used in a broad industrial drive application, of which a high percentage of the IM drive systems are line-start motors. These motors are of relatively poor efficiency, power factor and power density. The LS PMSM has been regarded as a promising alternative to traditional line-start IM. However, the design of an LS PMSM is rather complicated as it involves the design for both asynchronous and synchronous operation modes. This paper presents the design optimization of an LS PMSM by implementing the Taguchi method for robust design. The performance optimization considers both steady state and transient performance.

1.1 Taguchi Method Design Approach

Taguchi method is a modified and standardized form of design of experiments (DOE), which was proposed by Dr. Genechi Taguchi in 1957. This method is based on the DOE method developed by Sir R.A Fisher [1, 2] and was initially intended to increase quality control during the design phase for products and processes [3]. The main difference between the Taguchi method and DOE is the standardized application approach and methodology, which is done through the use of unique orthogonal arrays. The orthogonal arrays pre-define the conditions of each parameter in the array for each experiment or trail. Taguchi also introduced the use of the signal-to-noise (S/N) ratios to analyze the experiment results. Fig. 1 is a illustration of how the Taguchi method is used.

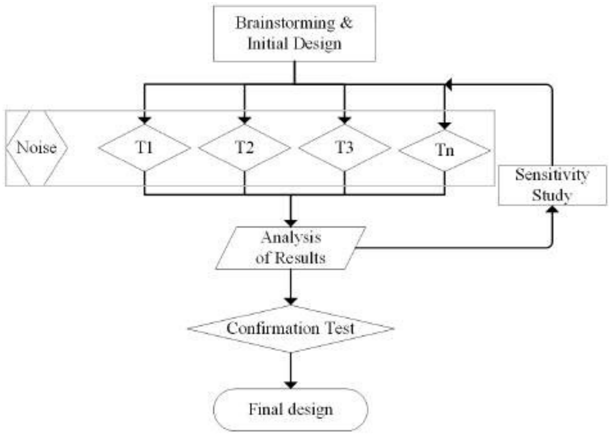

Figure 1: Flowchart of the Taguchi method design approach

The orthogonal arrays trial results can be used to view the quality characteristics (QC) of the project, product or design depending on the desired result and the outcome of the QC. The three evaluations are *Bigger is Better* (QC = B), *Smaller is Better* (QC = S) and *Nominal is Better* (QC = N). In order to measure variation in a set of sample data the Mean-Squared Deviation (MSD) is calculated, which represents the deviation from the target. To calculate the MSD and then the S/N of a trial, each trial must be exposed to noise factors. By doing this, the robustness of the design is investigated. The noise factors are uncontrollable but known factors.

Once all the trials are performed, only then can the results be analyzed. The trial results are used to construct the S/N ratio plots of each factor used. From these plots the optimum conditions are determined. A conformation trial test is then done to ensure that the criteria is met. The optimum design as determined by the Taguchi method is not always the best performing design but rather the best performing consistent design within the noise exposure.

The Taguchi method has been used in some electrical machine designs in recent years. It has been used to reduce cogging torque and torque ripple in permanent magnet and synchronous reluctance machines. In one instance, the method was used to optimize a RSM. This was done by varying the parameters defining the flux barriers in the rotor to gain the highest possible saliency ration [4]. This design approach not only produces a design with an improved performance but also gives an insight on which topology factor influences the optimum conditions the most.

2. ROTOR DESIGN

For this study, an existing commercial 2.2 kW 4-pole induction motor stator is used as part of the design. The Taguchi method will only be applied to the rotor design of the machine. Table 1 gives the rated specifications of the proposed machine.

A comparative study [6] reveals that the LS PMSM rotor with an interior asymmetrical magnet array (shown in Fig. 2) demonstrates the best overall transient and steady state performance among different rotor topologies. This paper focuses on the further design analysis of this specific rotor topology. The objective is to search for an optimum design that is of high efficiency and power factor at steady-state and also a good starting performance. Considering the inherent conflict between magnetic and cage torques in an LS PMSM during asynchronous operation, a fine balance between the cage and PM array designs should be attained where the following favourable conditions are met: (i) under transient starting operation, the cage torque can sufficiently overcome the magnet's braking torque and accelerate the load to synchronous speed; (ii) under synchronous operation, the LS PMSM exhibits a good steady-state performance that a typical PM synchronous motor offers. Clearly, the design of an LS PMSM entails both steady-state and transient designs.

Table 1: Design specifications of the machine

Parameters	Value
Rated output power, kW	2.2
Rated voltage (line-to-line), V	525
Rated speed, rpm	1500
Rated torque, Nm	14

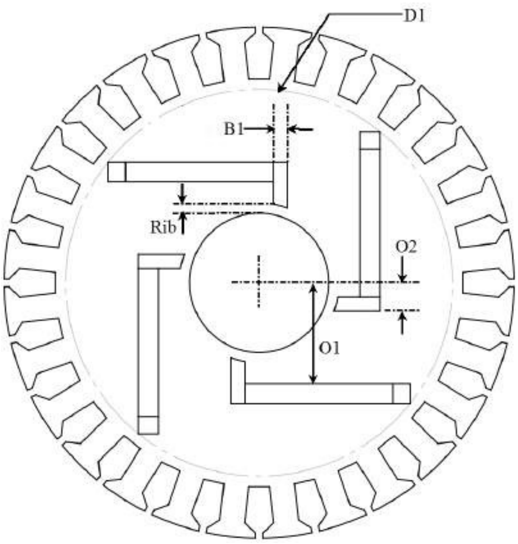

Figure 2: Interior asymmetrical PM array rotor topology

2.1 Steady State Design

The steady state design is of importance as it is the primary operation condition of the machine. Information from the steady state performance is also required for the rotor cage design as the cage produced torque needs to overcome the magnet braking torque and load inertia during transient operation. For this design, the PM dimensions, material and grade are fixed as an extra set of magnets was ordered for a previous project.

During steady state operation, the machine operates as a PMSM thus, the torque produced by the machine is the sum of the reluctance and PM torque. Fig. 2 illustrates the dimensions that are identified as design parameters for the steady state performance optimization. For all five design parameters an L16 inner array is required, which allows for the five parameters to be varied with four different states. Initially D1, Rib, O1, O2, B1 as in Fig. 2 is chosen for the inner array. As stated in Section 2, the use of an outer noise array is needed. To include this in the design, uncontrollable but known factors can be used. The PM property variation, PM thickness and shaft material are chosen as the outer array noise parameters. These parameters are chosen in order to account for manufacturing tolerances and the effect of material. For the outer noise array a L4 array is selected, which allows for three noise factors with two states. The final steady state array is indicated by Table 4 in the Appendix. The simulation process is given by Fig. 3, where *Tx* represent the main array, *x* is the 16 main designs that is individually exposed to the noise array *Ny*, *y* represents the four noise conditions. In total 64 simulations are required before the results can be analyzed and the five main array factors can be adjusted.

The area allocated for the PM slot is carefully selected so that all possible designs as per the L16 array is possible. From this the upper and lower limits for the initial design are defined and summarized in Table 2. The magnet slots

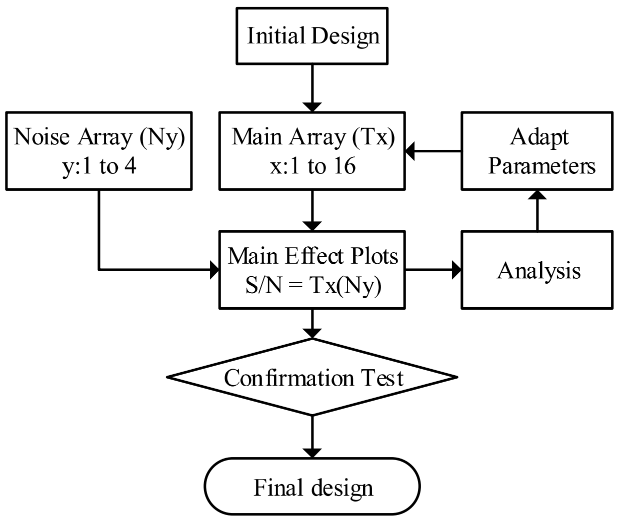

Figure 3: Taguchi steady state array simulations

have to be constrained to fit in the space available on the lamination while accounting for the rotor cage slots.

The four levels for each factor (D1, Rib, O1, O2, B1) in the main array are determined by dividing the lower and upper limits with equal increments. These states are then used to produce the first orthogonal array and design the first iteration of experiments. In theory the Taguchi method should provide the optimum result after one iteration. Since only four definite levels are selected for each factor the results may be non-liner between the different levels. To overcome this more than one iteration is done and after each iteration the worst performing level of each factor is reduced or eliminated with the aid of the main effects plot. As the maximum efficiency is desired a Bigger-is-better MSD is used to calculate the S/N results for the main effect plots. Fig. 4 contains the S/N plots of the first iteration and the final iteration of factor B1 and Rib. If focus is placed on the initial design it is clear that there is a big variance in performance as a result of factor change. By reducing the range of the levels after each iteration the final design resulted in a near horizontal plot, this is an indication that both B1 and Rib have reached its optimum level.

During the investigation it is found that by minimizing the two areas (A and B) as indicated in Fig 5 the steady state performance improves. Obviously, to minimize undesired leakage flux these areas need to be magnetically saturated. With the knowledge of this, the two parameters characterizing these two areas, D1 and Rib, can be suitably chosen and fixed, which frees two factors in the L16 array. This opens the opportunity to incorporate two of the rotor slot factors as in Fig. 6. Since Bs2 and Hs2 influence the cross-sectional area the most, they are selected to replace D1 and Rib in the array. It can be observed that adjusting Hs2 leads to an change in distance between the rotor cage and the PM duct. Thus the following relation must be implemented to ensure that the distance is constant.

$$D1 = 2[(OD/2) - (Hs0 + Hs1 + Hs2 + 0.7)] \quad (1)$$

During steady state optimization it is found that minimizing Hs2 would result in optimal steady state performance. However, the excessive minimization of Hs2 would drastically decrease the transient performance of the machine. This shows a drawback of the Taguchi method as it can only consider a solitary output parameter during design and optimization. It is possible to use multiple criteria optimization, but this would require the knowledge of the interactions between the different performance criteria [1–3]. Having realized this, a reconsideration of the previous steps in the optimization process is necessary. A trade-off is needed between steady state and transient performances. An increasing of Hs2 results in a drop in efficiency. This efficiency decrease is attributed to the decrease in D1, which in turn reduces the size of the flux barriers and changes the pole arch coefficient. A change in pole arch coefficient affects the air-gap flux density [7, 8].

The larger the flux barrier is, the less the leakage flux becomes. The machine's efficiency also improves with larger flux barrier. However, there exists an optimum point where any further barrier size increase leads to negligible

Table 2: Upper and lower limits for magnet slots

Variables	Lower limit	Upper limit
D1	76	83
Rib	0.7	1.4
O1	15.2	23.2
O2	4	10
B1	4	7

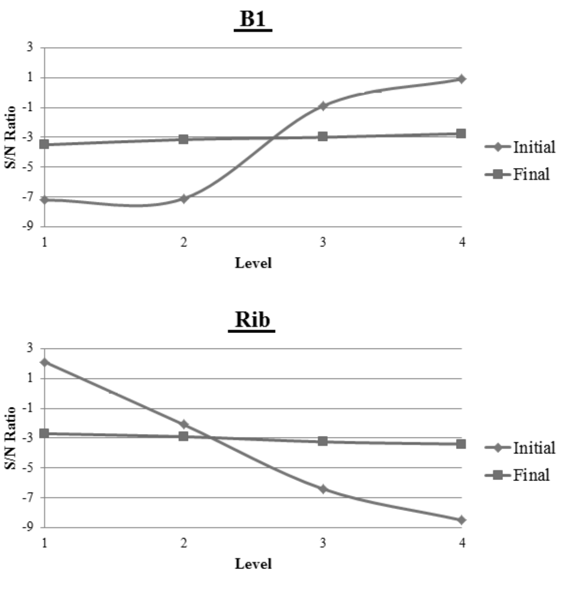

Figure 4: S/N ratio plots of two factors

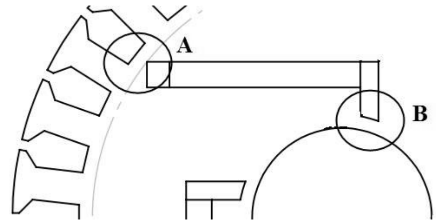

Figure 5: Saturation zones formed by D1 and Rib

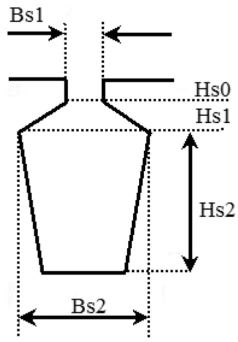

Figure 6: Rotor cage bar dimensions

efficiency benefits. This optimum point has been identified through several iterations of the L16 array and D1 is so constrained that the maximum allowable height of the rotor bar slots is subjected to (2)

$$Hs01 + Hs1 + Hs2 < D_{\text{rotor}} - D1_{\text{optimum}} \quad (2)$$

2.2 Transient Design

The rotor slot shape for the cage design is shown in Fig. 6. The slot has five parameters and a L16 array can be used for the simulations. Since FEM time-step simulations are computationally expensive, it is decided to fix one of the factors so an L9 array can be used. This will reduce the number of simulations by half. The L9 array allows for four, three-level factors, thus Bs1, Bs2, Hs1 and Hs2 are selected with Hs0 fixed at 0.3 mm. For the transient optimization no noise array is used. This again reduces the required number of simulations, but it also removes the option to use the S/N ratio main effects plot. To overcome this, three normalized performance objective is selected to quantify the transient performance. These objectives are the synchronization time, (τ_{synch}), settling time ($\tau_{settling}$) and speed overshoot as illustrated in Fig. 7. By normalizing the three objectives the MSD can be calculated. The final transit array is indicated by Table 5 in the Appendix.

3. SIMULATION RESULTS

This section contains the simulation results for both the steady state and transient operation as determined by ANSYS' Maxwell. The steady state performance of the machine is evaluated using ANSYS Maxwell RMXprt. Efficiency is the primary performance factor considered with some focus on the starting torque and back-EMF. In first iteration of the steady-state design experiments, the efficiency varies between 82% and 90% and for the final iteration the steady-state efficiency varies between 92% and 92.5%. Table 3 contains the steady-state performance of the final machine.

The transient simulations was done using ANSYS

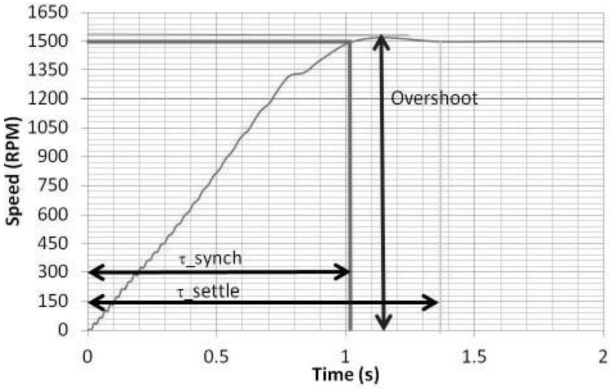

Figure 7: Illustration of transient parameters of interest

Table 3: LS-PMSM final design: steady-state performance

Parameter	Value
Efficiency	92.98 %
Power factor	0.954
Starting torque, Nm	43.55
Rated torque, Nm	14

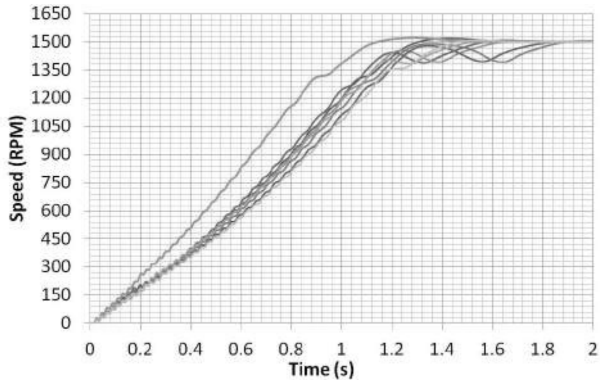

Figure 8: Initial transient performance

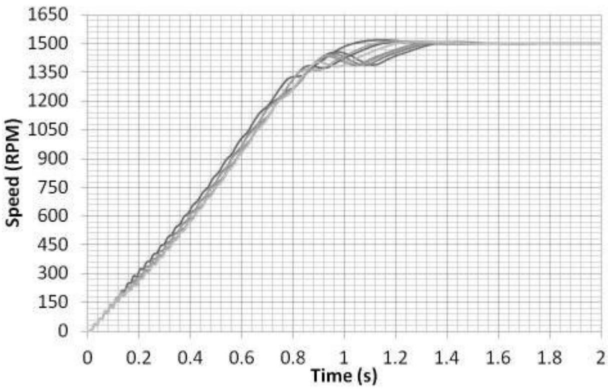

Figure 9: Final transient performance

Maxwell 2D FEM as time-step simulations is required. It is also possible to incorporate a load equation as part of a mechanical transient. The load characteristics of a custom designed fan is used in the simulations. Several iterations are carried out for the transient design. The results of the initial and final transient experiments can be seen in Figs. 8 and 9 respectively. The machine that delivers the shortest settling and acceleration time is used.

Figs. 10 to 12 indicates the transient performance of the designed machine when driving a fan load. The machine achieves synchronization within 0.9 seconds with negligible overshoot. Figs. 11 and 12 indicates the torque developed during this time.

4. CONCLUSION

This paper presented the design and optimization of an LS PMSM using the Taguchi method. For the optimization both steady-state and transient performance

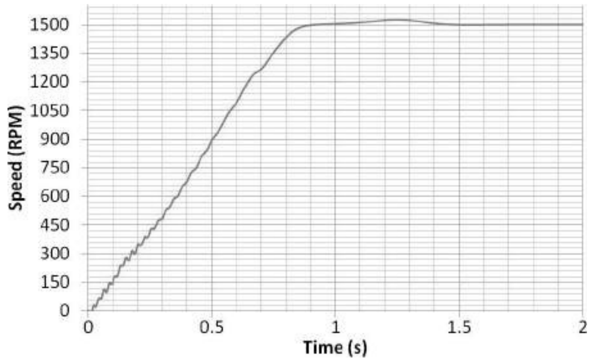

Figure 10: Final design: speed versus time plot

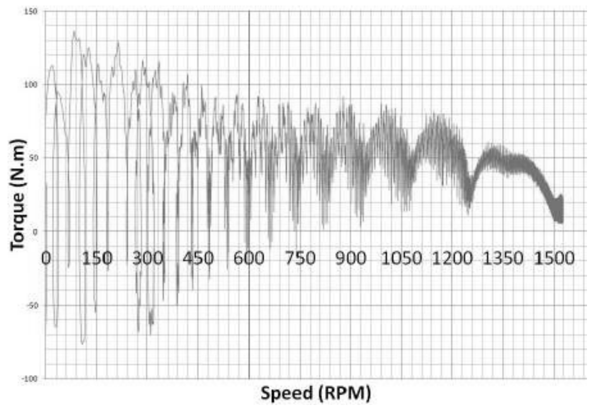

Figure 11: Final design: torque versus speed plot

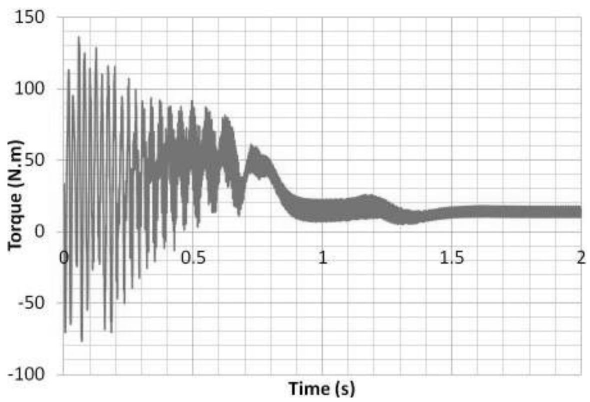

Figure 12: Final design: torque versus time plot

are individually considered. However, it is necessary to incorporate design constraints concerning the PM duct and rotor cage. This is to maintain a balance between the cage and PM array designs, which is important to realize acceptable transient and steady-state performances. The implementation of the Taguchi method to optimize the steady state performance has been a success. The use of the parameter interactions and how it can be used in the optimization of machine performance requires further investigation as some of the factors in the array moved to the optimum point within an iteration or two. With regards to transient optimization the Taguchi method proves to be time efficient, which is one of the main advantages of the Taguchi method. The use of noise array also needs further study.

ACKNOWLEDGMENT

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REFERENCES

[1] R.K. Roy, A Primer on the Taguchi Method, 2nd Edition. Michigan, USA: Society of Manufacturing Engineers, 2010.

[2] G. Taguchi, S. Chowdhury, Y. Wu, Taguchi's Quality Engineering Handbook, 1st Edition. New Jersey, USA: John Wiley and Sons Inc, 2005.

[3] R.K. Roy: Design of Experiments Using the Taguchi Approach, Wiley-Interscience, 2001, New York, USA.

[4] H. Azizi, A. Vahedi: "Rotor geometry parameter optimization of synchronous reluctance motor using Taguchi Method", Przeglad Electrotechnical, no. 1, pp.197-201, 2013.

[5] M. Chowdhury, M. Islam, A. Gebregergis and T. Sebastian: "Robust design optimization of permanent magnet synchronous machine utilizing genetic and Taguchi's algorithm," Energy Conversion Congress and Exposition, vol., no., pp.5006,5012,15-19 Sept. 2013

[6] J.P. Els, A.J. Sorgdrager and R-J Wang, "A Study of Rotor Topologies of Line-Start PM Motors for Cooling Fan Applications" in Proceedings of the 22nd South African Universities Power Engineering Conference, pp.284-289, Feb 2014.

[7] C. Zhao, S. Li and Y. Yan, "Influence factor analysis of PMSM air gap flux density," Electrical Machines and Systems, 2005. ICEMS 2005. Proceedings of the Eighth International Conference on, vol.1, pp.334-339, 27-29 Sept. 2005

[8] A.J. Sorgdrager and A.J. Grobler, "Influence of magnet size and rotor topology on the air-gap flux density of a radial flux PMSM," Industrial Technology (ICIT), 2013 IEEE International Conference on, pp.337-343, 25-28 Feb. 2013

APPENDIX

Table 4: Steady state design array

L9	*O1*	*O2*	*B1*	Rib	*D1*	R1	R2	R3	R4	Mean	MSD	S/N
T1	1	1	1	1	1							
T2	1	2	2	2	2							
T3	1	3	3	3	3							
T4	1	4	4	4	4							
T5	2	1	2	3	4							
T6	2	2	1	4	3							
T7	2	3	4	1	2							
T8	2	4	3	2	1							
T9	3	1	3	4	2							
T10	3	2	4	3	1							
T11	3	3	1	2	4							
T12	3	4	2	1	3							
T13	4	1	4	2	3							
T14	4	2	3	1	4							
T15	4	3	2	4	1							
T16	4	4	1	3	2							
					PM	T	T	M	M			
					PM t	5	4.9	5	4.9			
					Shaft	M	nM	nM	M			

Table 5: Transient design array

L9	*Bs1*	*Bs2*	Hs1	*Hs2*	$\tau sync$	τset	Overshoot	Mean	MSD	S/N
T1	L1	L1	L1	L1						
T2	L1	L2	L2	L2						
T3	L1	L3	L3	L3						
T4	L2	L1	L2	L3						
T5	L2	L2	L3	L1						
T6	L2	L3	L1	L2						
T7	L3	L1	L3	L2						
T8	L3	L2	L1	L3						
T9	L3	L3	L2	L1						

T Typical PM Magnetic Properties
M Minimum PM Magnetic Properties
M Magnetic Shaft
nM non-Magnetic Shaft
PMt PM thickness