Engineering and Applied Sciences
2022; 7(2): 21-28
http://www.sciencepublishinggroup.com/j/eas
doi: 10.11648/j.eas.20220702.12
ISSN: 2575-2022 (Print); ISSN: 2575-1468 (Online)

Taguchi Method for Design and Optimization of a High-Speed Permanent Magnet Synchronous Generator Protected by Retention Sleeve

Hossein Parivar*, Ahmad Darabi

Department of Electrical Engineering, Shahrood University of Technology, Shahrood, Iran

Email address:
Hosseinparivar72@yahoo.com (H. Parivar)
*Corresponding author

To cite this article:
Hossein Parivar, Ahmad Darabi. Taguchi Method for Design and Optimization of a High-Speed Permanent Magnet Synchronous Generator Protected by Retention Sleeve. *Engineering and Applied Sciences*. Vol. 7, No. 2, 2022, pp. 21-28. doi: 10.11648/j.eas.20220702.12

Received: April 22, 2022; **Accepted**: May 23, 2022; **Published**: May 31, 2022

Abstract: High-speed permanent magnet synchronous generators (HS-PMSGs) suffer from mechanical stresses due to high speeds. With the predicted mechanical stresses that may occur in the rotor of the HS-PMSGs, the design of these machines should be very accurate. So, for the HS-PMSGs, a proper electromagnetic coupled with mechanical design is a critical issue. This paper presents a novel method for the electromagnetic and mechanical design of an HS-PMSG by finding an appropriate dimension of the retention sleeve and permanent magnets (PMs) based on the well-known Taguchi optimization method. A 40-kW, 60-krpm, 2-poles and 18-slots HS-PMSG is designed at the first step, and next, it has been optimized by the proposed optimization method, and finally modeled and analyzed through Finite-Element Method (FEM). Results obtained from the electromagnetic and mechanical simulations of the HS-PMSG show that in the optimized design of the HS-PMSG some parameters changed and the HS-PMSG has a better performance compared to the initial design. For example, The effective air gap has been reduced which leads to the better electromagnetic and mechanical performance of HS-PMSG compared to the initial design. By the reduction in the thicknesses of the retention sleeve and the PM, it can be concluded that the total size and dimensions of the HS-PMSG have been reduced. The weight of the PM and the retention sleeve are reduced by about 16.31% and 29.28% responsively, and as a result, the total weight of the HS-PMSG is reduced by approximately 1.94%, The Joule loss is reduced by about 9.80%, the HS-PMSG efficiency has been improved by 0.02%, and finally, the cogging torque is reduced by 27.87%, comparing with the initially designed. The FEM results ensure the electromagnetic and mechanical performance of the machine around the predicted speed of 60-krpm.

Keywords: High-Speed Permanent Magnet Synchronous Machine, Retention Sleeve, Taguchi Optimization Method, Finite-Element Method, Titanium

1. Introduction

Permanent magnet (PM) machines are extensively used largely in the past couple of decades. High-speed permanent magnet synchronous machines (HS-PMSMs) are utilized in commercial, industrial and, also home applications. One significant challenge is that they are faced with several mechanical limitations. At the initial design stage, physical parameters like centrifugal forces and generally, rotodynamic problems should be considered. These limitations are an issue that researchers are still exploring [1]. Most research focuses only on electrical limitations. Although, these include agents of electromagnetic, mechanical, and also thermal limitations. It should be noted that these limitations vary in the different structures of high-speed machines. PM machines, concerning their high efficiency and low volume, is the prime choice in high-speed application [2]. Various PM machines in both SPM (Surface-Mounted Permanent Magnet) and IPM (Interior Permanent Magnet) types are designed, tested and manufactured in high-speed applications. Comparisons explicate that in high-speed applications, SPMs are more widely used than IPMs with respect to different views. This view is rooted in the fact that in high-speed applications, the retention sleeve is easier to fit on the PMs in SPM types. The importance of the retention sleeve becomes visible when the rotor is faced by the radial and tangential stresses derived from the high speeds. Notwithstanding, choosing the optimal thickness for the retention sleeve and PM which covers both the proper mechanical and electromagnetic performance of the HS-PMSG, is an issue. Consequently, due to the predicted mechanical stresses that may occur, the design of the aforementioned machine, particularly the rotor, should be very accurate. So, along with mechanical consideration at high speeds, the selection of materials for HS-PMSG is limited. Hence, recent efforts have been made to produce new materials for use in HS-PMSGs. One of the most uncomplicated methods is to increase the silicon to materials similar JNEX10-Core, which has 6.5% silicon compared to traditional silicon steel sheets, which contain only 3.5% silicon. Though, excessive use of silicon reduces the strength of steel sheets and makes them brittle and undesirable for use at high speeds applications [3]. AMMs (amorphous magnetic materials) have much lower iron losses than silicon steels, and hence, their utilization in high-speed electric machines has been reported in various literature [4]. Neodymium (NdFeB) and samarium cobalt (SmCo), with respect to their high energy density, is preferred for use in HS-PMSGs. Some grades of neodymium alloyed with Dysprosium (Dy) can also be utilized at high temperatures upward to about 250°C. Of course, the use of this alloy, owing to its rare nature and consequently, their high cost is not economical [5]. Titanium alloys have very high tensile strength and reliable thermal conductivity. Along with the thermal limitations that exist through high speeds, this material is considered a proper material [6, 7].

The main focus of this paper is the design of a 60^{kw}, 2-poles, 18-slots and 60^{Krpm} HS-PMSG equipped with a titanium retention sleeve. The well-known Taguchi optimization method is utilized to define the proper and optimum PM and retention sleeve dimensions throughout the proposed optimizing approach.

The rest of this paper is arranged as: section II includes problem definition. The upcoming section is the proposed design approach. Section IV focused on results and discussion, and finally, section V is the conclusion.

2. Problem Definition

Figure 1, illustrates a PM machine designed without a retention sleeve. As it has been shown that, without sleeves, the structure of machines is destroyed. The PMs are displaced and sparked to the stator windings and led to burnt out. If the retention sleeve exists, that does not occur. As a result, it is important to use a retention sleeve to prevent the structure of the machine from collapsing. A proper and optimum design of an HS-PMSG still is a challenge that researchers and electrical machine designers and are faced. It consists of communication between electromagnetic coupled mechanical design properties of the HS-PMSG to select the most optimum points.

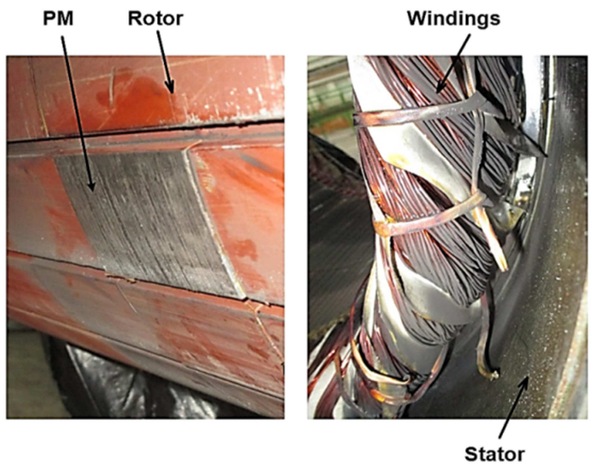


Figure 1. Designed HS-PMSG without retention sleeve.

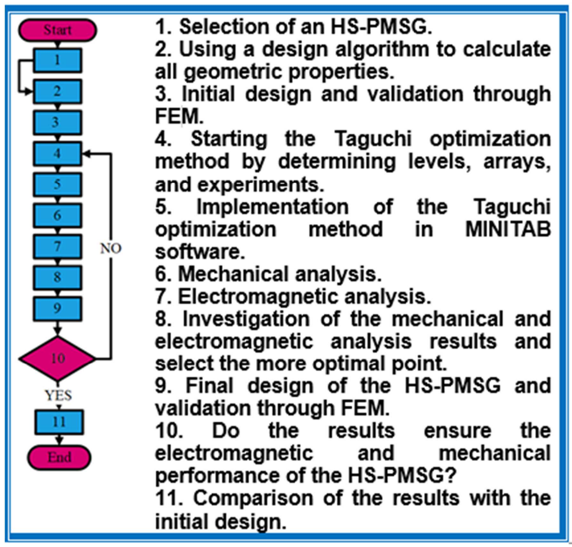


Figure 2. Proposed flowchart.

3. Design Process

With respect to Figure 2, at the first step, a 40^{kw}, 60^{krpm}, 2-pole and 18-slot HS-PMSG based on Table 1 and Table 2 which tabulated the materials and the initial design parameters of the HS-PMSG has been designed. In the second step, these initial design parameters are optimized through the Taguchi optimization method in the following sections. VACOFLUX-48, known as one of the iron-cobalt alloys, is one of the most becoming materials for use in high-speed machines. This material has a 30% higher saturation flux density. Although it has a high mass density, commonly, to use the most desirable kilowatt/kg, this material offers a better power density despite its high mass density. At a sheet thickness of 0.1^{mm}, the power density varies from $1^{watt/kg}$ to about $70^{watts/kg}$, depending on the flux density ranges from about 0.5^{T} to 2^{T} at a frequency of 1000^{Hz}. As the flux density increases, the core loss density for VACOFLUX-48 increases. High-strength materials, such as titanium and Inconel, are utilized at high speed to maintain the mechanical integrity of the rotor as a retention sleeve [8, 10]. Moreover, carbon fiber has also often been offered as a proper retention sleeve [11-13]. In [14] also presented a high-speed rotor design with metallic and CFRP material. Based on results obtained from rotor dynamics analysis, it has been concluded that the CFRP retention sleeve has a better performance compared with metallic ones. In the proposed method, to determine the fittest thickness of the retention sleeve and PM, firstly, the geometry of the rotor of the HS-PMSG is designed in ABAQUS CAE. In this method, utilizing the orthogonal arrays (OA) that be described in the subsequent sections, the parameters affecting each process can be recognized and accommodated for optimization. An OA consists of a matrix that rows are the levels (β) of each factor (η) in each experiment (Λ), and its columns depict the number of factors. This parameter is also represented as $L_n(X^Y)$, where *n* represents the number of experiments or the number of factors (η), *X* represents the number of levels (β), and *Y* represents the maximum number of arrays. For example, Table 3 represent the OA by $L_9(3^4)$, which is number of 9 experiments (Λ), and with this OA, a maximum of 4 factors (η) can be chosen and the total number of possible combinations between the factors is $\Pi=3^4=81$ combinations.

Table 1. *HS-PMSG Materials.*

Parts	Materials
Stator and Rotor Core	VACOFLUX-48
PM	NEOREC 50H (TDK)
Windings	Copper
Sleeve	Titanium

Table 2. *Initial HS-PMSG Design Parameters.*

Parameters	Initially Value
Stator Diameter in airgap side	77mm
Efficient inner stator radius	38.54mm
Stator core thickness	12.5mm
The opening slot at the top side	2mm
Wedge height to stator slot bottom	13.36mm
Rotor inner diameter	44mm
Rotor radius in airgap side	37.5mm
Physical airgap	1mm
PM thickness	3mm
Frame Thickness	1.47mm
Sleeve Thickness	3.85mm
wire area	6.5mm^2
Active Length	80mm
Stator core thickness	12.5mm
Stator teeth width	3.11mm
The opening slot at the wedge side	11.02mm
Stator wire diameter	1.43mm
Stator outer diameter	133.26mm
Rotor core outer radius	34.5mm
Efficiency air gap	3.85mm
Slot area	165mm^2
Stator core weight	30.8kg
Stator tooth weight	5.68kg
PM weight	3.47kg
Frame weight	5.25kg
Rotor core weight	14.41kg
Winding weight	2.64kg
Sleeve weight	2.39kg
Total weight	64.64kg
Copper loss	103.83w
Iron loss	528.96w
Windage and fracture loss	400w
Efficiency	97.48%
Stator winding resistance	0.05Ω
Armature reaction inductance	1.54mH
Stator slot leakage inductance	0.033mH
End winding leakage inductance	0.703mH

Table 3. *L_9 (3^4) OA.*

	η				
		Array 1	Array 2	Array 3	Array 4
Λ	A	1	1	1	1
	B	1	2	2	2
	C	1	3	3	3
	D	2	1	2	3
	E	2	2	3	1
	F	2	3	1	2
	G	3	1	3	2
	H	3	2	1	3
	I	3	3	2	1

Table 4. *Thickness of Retention Sleeve and PM at L_9 (3^4) OA.*

Λ	Sleeve Thickness (mm)	PM Thickness (mm)
A	1	2
B	1.5	2
C	2	2
D	1	2.5
E	1.5	2.5
F	2	2.5
G	1	3
H	1.5	3
I	2	3

The start of the Taguchi optimization method is according to the following steps.

1) Selection the OA based on the numbers of η and β;
2) Consideration the βs to selected array columns;
3) Determining the composition of the η of each Λ.

Given that in the mechanical analysis of the HS-PMSG, three parameters of centrifugal force, Von Mises stresses and Von Mises strains are vital; therefore, it is necessary a 3-level (β) OA (L_9 (3^4) containing 9 experiments (Λ) like as Table 4, and two OA as described;

1) The retention sleeve thickness;
2) The PM thickness, and
3) three β as described;
4) The centrifugal force of the retention sleeve and PM;
5) The Von Mises stress of the retention sleeve and PM;
6) The Von Mises strain of the retention sleeve and PM.

Table 5 presents the results of the Taguchi optimization method. Supplementary parameters are named Delta and Rank which represents the difference between maximum and minimum obtained value in the optimization process and level of each Delta, responsively. In a way, the Rank of the highest Delta is 1. Owing to Table 5, the following results are obtained: The thickness of the retention sleeve has a direct effect on its centrifugal force, while the thickness of the PM has no effect. The thickness of the PM has a direct effect on its centrifugal force, while the thickness of the retention sleeve has no effect. The thickness of the retention sleeve has a direct effect on the maximum Von Mises stress of retention sleeve greater than the thickness of the PM. The thickness of the retention sleeve on the maximum Von Mises stress of PM is more important than the thickness of the PM. For maximum Von Mises strain of the retention sleeve, both the thickness of the retention sleeve and the PM have a direct effect, but the effect of the thickness of the retention sleeve is greater. The effect of the thickness of the retention sleeve from the thickness of the PM on the maximum Von Mises strain of PM is more than the thickness of the PM. The thickness of the PM only affects its centrifugal force more than the thickness of the retention sleeve. According to the results of Taguchi analysis, the thickness of the retention sleeve on;

1) The maximum Von Mises stress of the sleeve is 5.56%,
2) The maximum Von Mises stress of the PM is 41.37%,
3) The maximum Von Mises strain of the sleeve is 3.48%,
4) The maximum Von Mises strain of the PM is 60.86%,

more effective than the thickness of the PM.

Table 5. *Taguchi Optimization Results.*

	η	
Sleeve Centrifugal Force (N)		
β	Sleeve Thickness	PM Thickness
1	19.86	29.11
2	29.11	29.11
3	39.20	29.11
Delta	19.34	0.00
Rank	1	2
Sleeve Centrifugal Force (N)		
β	Sleeve Thickness	PM Thickness
1	139.84	111.84
2	139.84	139.84
3	139.84	167.81
Delta	0.00	55.97
Rank	2	1
Sleeve Maximum Von Mises Stress (MPa)		
β	Sleeve Thickness	PM Thickness
1	2804	2799
2	2838	2871
3	2880	2861
Delta	76	62
Rank	1	2
PM Maximum Von Mises Stress (MPa)		
β	Sleeve Thickness	PM Thickness
1	3491	3504
2	3523	3512
3	3532	3533
Delta	41	29
Rank	1	2
Sleeve Maximum Von Mises Strain (MPa)		
β	Sleeve Thickness	PM Thickness
1	0.01604	0.01604
2	0.01633	0.01617
3	0.01643	0.01650
Delta	0.00039	0.00046
Rank	1	2
PM Maximum Von Mises Strain (MPa)		
β	Sleeve Thickness	PM Thickness
1	0.01619	0.01608
2	0.01582	0.01582
3	0.01613	0.01604
Delta	0.00037	0.00026
Rank	1	2

Table 6. *Results of 5 States (v=cogging torque (N.m), w=maximum flux density is a slot (T), x=maximum flux density in the stator (T), y=Joule loss (W) and z=voltage (V)).*

Λ									
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
v	0.39	0.39	0.39	0.39	0.68	0.66	1.10	1.15	1.23
w	0.45	0.44	0.44	0.44	0.57	0.52	0.72	0.64	0.80
x	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
y	86.32	86.35	86.35	86.35	92.74	93.65	114.09	116.14	116.14
z	156.11	156.11	156.23	192.03	193.36	221.71	227.14	227.15	227.19

Forasmuch as the mechanical performance of HS-PMSG depends on its accurate electromagnetic performance, and in a way, these two design parameters are related to each other, so in addition to the mechanical analysis performed in the earlier section based on the Taguchi optimization method, it should do an electromagnetic analysis based on experiments (Λ) extracted from the Taguchi method, to ensure the proper and optimum thickness which can assure the electromagnetic and mechanical performance of the HS-PMSG in each critical states and rotational speeds. Therefore, 5-states which is named v=cogging torque ($N.m$), w=maximum flux density is a slot (T), x=maximum flux density in the stator (T), y=Joule loss (W) and z=voltage (V), based on said 9-experiments is done and results are summarized in Table 6. Since the maximum Von Mises stress of PM is a proper criterion for mechanical analysis of HS-PMSG, according to Table 5 and Table 6, this parameter has its minimum value in the A and the F experiments. In the A experiment, the thickness of the PM is 2^{mm} and the thickness of the retention sleeve is only 1^{mm}. The results obtained from the Taguchi method as well as electromagnetic analysis of the HS-PMSG shows that at these thicknesses, the electromagnetic performance of the machine is not satisfying and of course, the mechanical strength is not provided for the rotor. In the F experiment, the maximum Von Mises stress of PM is less than the other states and also, the maximum Von Mises strain of PM is in the appropriate range compared to others. Therefore, according to the results obtained from Taguchi analysis as well as electromagnetic analysis of the HS-PMSG, it can be found that the optimal value for the two OA of the thickness of the retentions sleeve and the thickness of the PM are 2^{mm} and 2.5^{mm}, respectively. In the coming section, the electromagnetic and mechanical design of the machine is performed based on the optimum parameters obtained from the previous sections and the results are validated using the FEM.

4. Results and Discussion

In the Taguchi optimization method, all the parameters affecting the mechanical and electromagnetic behaviour of the HS-PMSG are determined and it is possible to focus on the significant parameters and optimize them, so the aforementioned method, as opposed to other methods like trial and error, is preferred. It may be possible to determine these parameters using trial and error methods after numerous steps, but the Taguchi optimization method responds to the process faster than others [15-17].

In this part, the final electromagnetic modelling of the HS-PMSG is explained. The aforementioned HS-PMSG is made of an internal rotor consisting of three cylindrical layers which are designated as shaft, PMs and retention sleeve, respectively. Furthermore, the stator consists of two layers, which include the stator body and the number of slots inside which the three-phase winding is distributed. Electromagnetic modelling of the machine is performed based on the following assumptions: The magnetic flux density is defined only by radial component. The MMF drop on the iron path above the stator and rotor is neglected. The retention sleeve acts as an extra air gap. No magnetic saturation occurs. And, there are three-phase distributed windings with a symmetrical distribution of 60° below each pole. Figure 3 illustrates FEM analysis of the final design of the HS-PMSG and Figure 4 shows the final mechanical design of HS-PMSG. According to Table 7, which presents the yield stress of the materials used in the rotor of the HS-PMSG, at the speed of 60^{krpm} the HS-PMSG has a proper electromagnetic coupled mechanical operation and the mechanical integrity of the HS-PMSG is fixed.

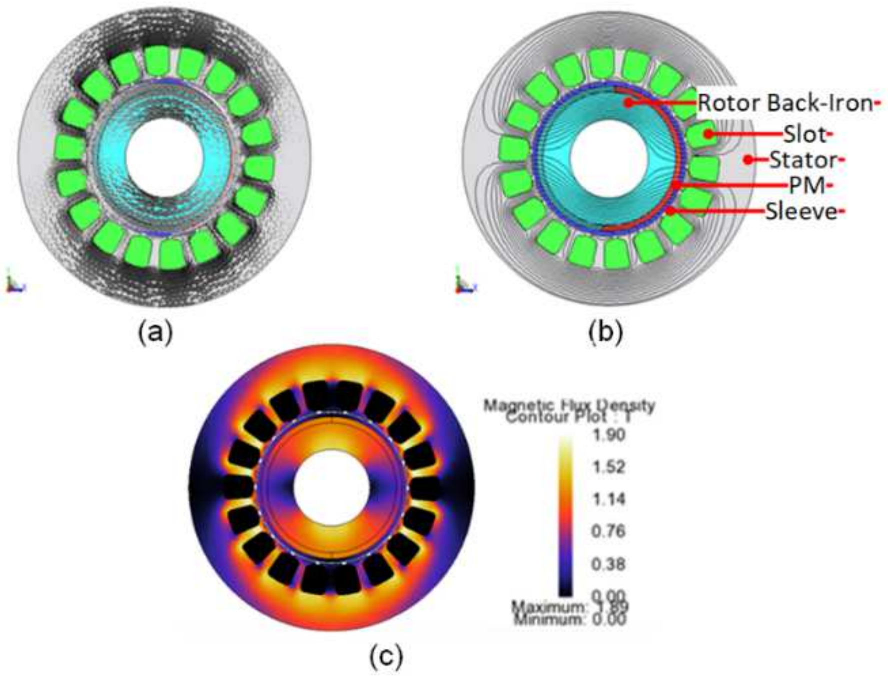
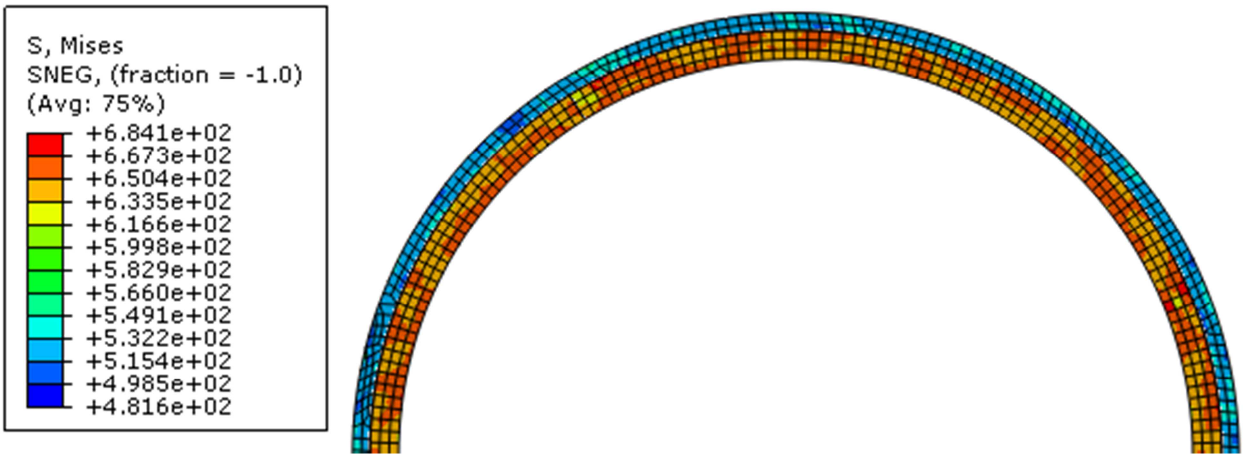
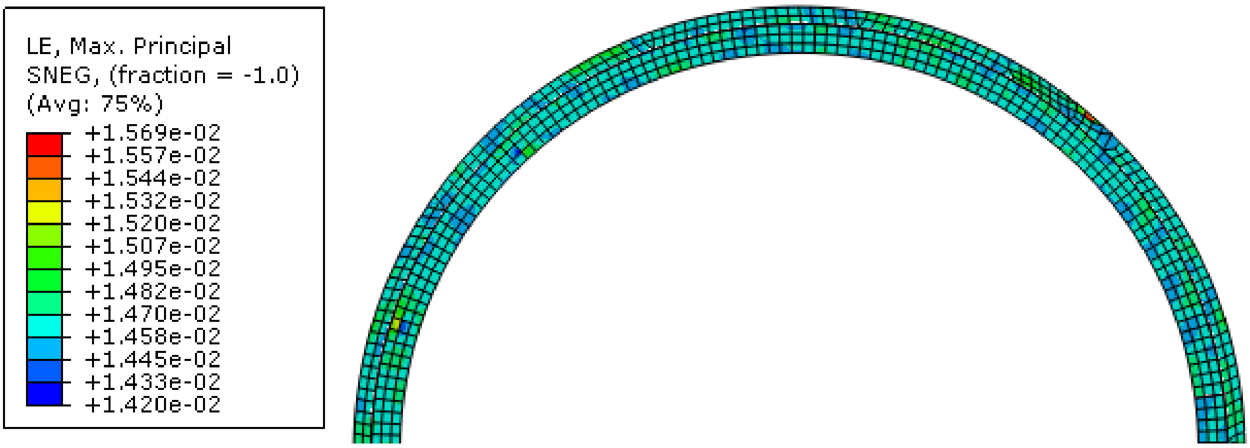


Figure 3. *FEM analysis of the final design of HS-PMSG, flux line orientations (a), flux line distributions (b) and magnetic flux density (c).*



(a)



(b)

Figure 4. *FEM analysis of the final design of HS-PMSG, Von Mises stress (MPa) (a) and Von Mises strain (MPa) in the PM and the retention sleeve (b).*

Consequently, at the critical speeds, the HS-PMSG does not collapse and results that the electromagnetic and mechanical design of the HS-PMSG is well done. Owing to the optimization strategy introduced in this paper, some of the initial design parameters of the machine has been modified. Figure 5 and Figure 6 compares the variations in the weight of the retention sleeve, PM and the total, based on changes in parameters involved with the initial design and the final design of HS-PMSG. As been revealed, the weight of PM is reduced by 16.31% and also, the retention sleeve and the total weight of HS-PMSG are reduced by nearly 29.28% and 1.94%, responsively. The proposed scheme led to enhance HS-PMSG performance, therefore, with respect to Figure 7, the efficiency of the HS-PMSG is improved. Figure 8 demonstrates the Joule loss and the total loss in both the initial and final design. It has been shown that the total loss has been reduced. As the final parameter, with regard to Figure 9, the cogging torque, also reduced by about 27.87% compared to the initial design. Owing to Figure 10, in the worst-case, at a point with the greatest value, the Von Mises stress does not enter the yield area, so the failure does not occur. Lastly, for more comparison, Figure 11, shows the maximum Von Mises strain at a point with the highest value.

Table 7. *Yield Stress of Rotor's Materials.*

Material	Yield Stress (MPa)
VACOFLUX-48	190-200 MPa
Titanium	729-844
NEOREC 50H (TDK)	220-280

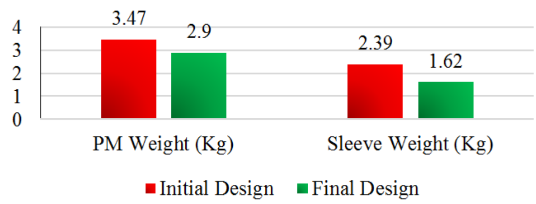


Figure 5. *Comparison between the retention sleeve and the PM weights in the initial and the final design of HS-PMSG.*

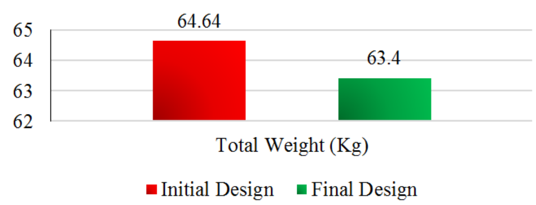


Figure 6. *Comparison between the total weight in the initial and the final design of HS-PMSG.*

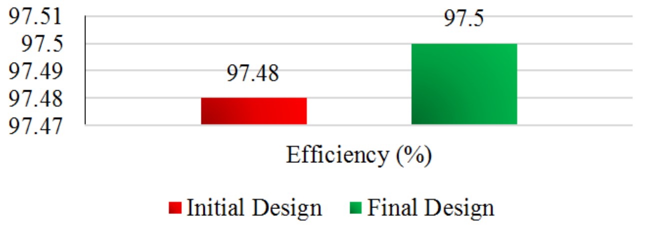


Figure 7. *Comparison between efficiency in the initial and the final design of HS-PMSG.*

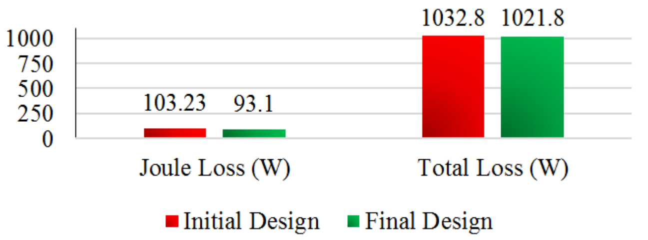


Figure 8. *Comparison between Joule loss and total loss in the initial and the final design of HS-PMSG.*

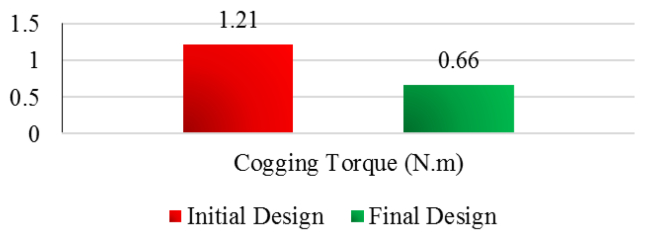


Figure 9. *Comparison between cogging torque in the initial and the final design of HS-PMSG.*

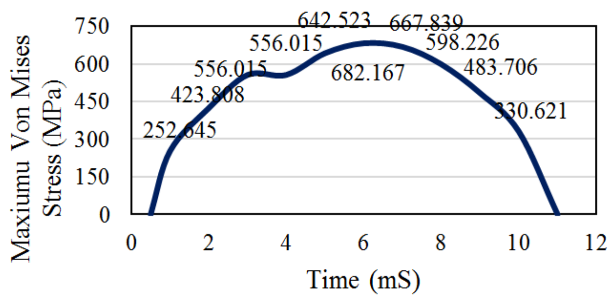


Figure 10. *Maximum Von Mises stress in the rotor.*

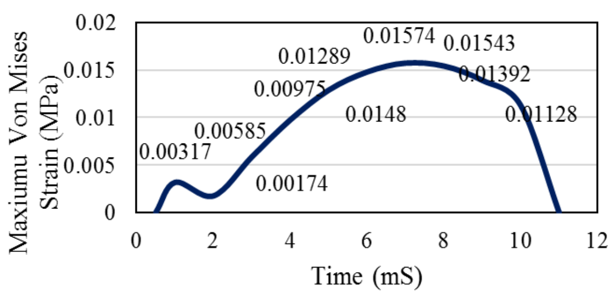


Figure 11. *Maximum Von Mises strain in the rotor.*

5. Conclusion

In the high-speed permanent magnet synchronous generators (HS-PMSGs) rotordynamic problems are an important issue when the rotor faces by centrifugal forces and mechanical stresses. So, the rotor's permanent magnet (PM) is not protected against mechanical stresses resulting from the high rotational speeds. Hence, recently a protected scheme based on non-magnetic allays retention sleeves are proposed. But the proper electromagnetic and mechanical design of HS-PMSGs is also challenging. A novel approach based on the well-known Taguchi optimization method to design an HS-PMSG with a retention sleeve is presented in this paper. FEM results obtained from the electromagnetic coupled mechanical simulations of the HS-PMSG show that in the optimized and finally design of the HS-PMSG some parameters changed and optimized. For example,

1. The weight of PM and the retention sleeve are reduced by about 16.31% and 29.28% respectively, and also, the total weight of HS-PMSG is reduced by 1.94%,
2. The Joule loss is reduced by nearly 9.80%,
3. And lastly, the cogging torque is reduced by approximately 27.87%, comparing with the initially designed HS-PMSG. The corresponding FEM results are validated the electromagnetic and mechanical performance of the finally designed HS-PMSG at the predicted operation speed of around 60-krpm and all operating conditions. The proposed scheme presented in this paper can help the researchers and electrical machine designers that are faced with the challenges of the design of the high-speed machine.

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