Manufacturing tolerances influence on permanent magnet synchronous generator (PMSG) performance

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***Abstract—* Within SWIP project, a PMSG based wind turbine has been designed and manufactured to be installed in an educational area. During the design stage, several finite element studies has been performed to evaluate the PMSG behavior, including no-load voltage, generated power, or cogging torque analysis among others. During this stage no machine deformations are considered, that is, the rotor is perfectly cylindrical and the gap is uniform. When the real prototype is manufactured, these assumptions may not be valid, due to dimensional tolerances. Therefore, before PMSG manufacturing stage, a previous analysis must be done considering the influence of manufacturing tolerance.**

***Keywords—* Permanent magnet synchronous generator (PMSG); Manufacturing tolerances; Cogging torque; Torque ripple; Finite element analysis (FEA).**

I. INTRODUCTION

SWIP project [1] ('New innovative solutions, components and tools for the integration of wind energy in urban and peri-urban areas') aims to expand the market for Small Wind Turbines in Europe by developing, implementing and testing innovative solutions and components. Developments carried out through SWIP project will allow to improve performance, reduce maintenance costs, and encourage integration of turbines into urban and peri-urban areas by a holistic approach.

Within this project, permanent magnet synchronous generator (PMSG) and converter system have been designed and manufactured in order to reach a high efficiency system. Both components, generator and converter, are designed considering the different features of the pilot site:

- Noise level limits established for the local regulation (urban area, educational area...).
- Weight and size generator limits.
- Wind resource in the pilot site.
- Converter connection type: Connected to the grid or in island operation.

Furthermore, another technical aspects like Cp-λ curve of the blades or converter limits, such us maximum voltage or modulation level, are considered during the design stage.

Taking into the account all these aspects, a PMSG has been designed. This generator is selected due to advantages like high power density, high efficiency, simplification in the construction, low losses and free maintenance. One of the disadvantages of this technology is the permanent magnet price [2] and the deterioration of magnetic properties with the temperature.

During the design stage, no machine deformations are considered, that is, the rotor is perfectly cylindrical and the gap is uniform. When the real prototype is manufactured, these assumptions may not be valid, due to material dependent failure, geometrical or shape deviations and, as a consequence, the electrical machine behavior will differ from the expected. Therefore, before PMSG manufacturing stage, a previous analysis must be done considering the influence of rotor/stator deformation and eccentricity, which make a non-uniform gap, and the magnetic faults [3]-[6].

In order to evaluate manufacturing tolerances effects in designed PMSG behavior, several studies are performed. PMSG is modelled in FLUX 2D [7], a finite element software used for electromagnetic application. From these studies, electrical parameters such as no-load voltage, electric power and cogging torque will be evaluated and corrective actions may be taken into account before the manufacturing stage.

II. METHOD

This study allows to identify possible differences between PMSG behavior expected from simulation studies and measurements obtained in the test bench and later when the generator is installed in the wind turbine.

Fig. 1 establishes the flowchart applied before the PMSG prototype is manufactured. The flowchart is described in the following points:

A. Initially, all the input parameters and requirements are defined.
B. From these parameters, a new PMSG is designed through a software tool. Moreover, finite element analyses are performed in order to refine the obtained design.
C. If the study results fulfill all the requirements, the design process goes to the next step, otherwise the generator must be redesigned until an appropriate solution is reached.
D. Once the proposed PMSG design fulfills the input requirements, the effects of manufacturing tolerances are analyzed using finite element tool.
E. Finally, if the influences of the manufacturing tolerances are admissible, a prototype can be manufactured. Otherwise, the generator must be redesigned from the beginning of the process.

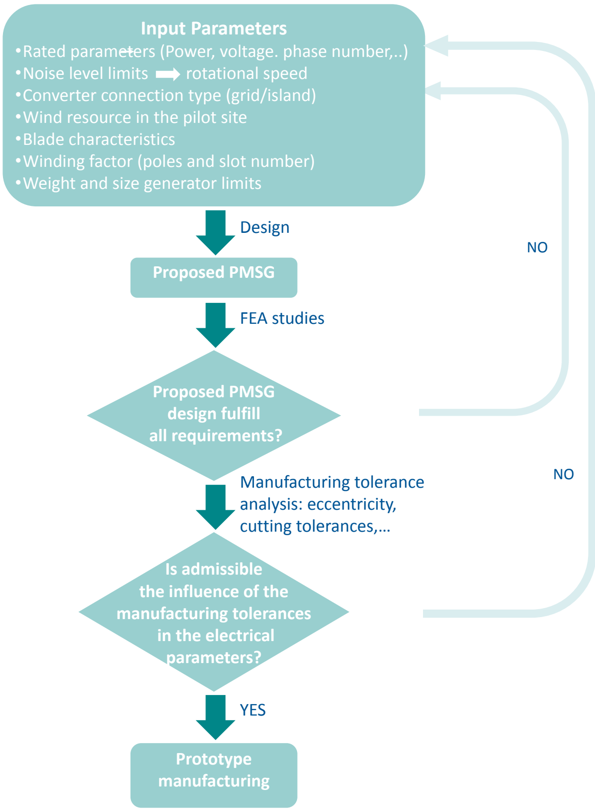

Fig. 1. Flowchart applied to the PMSG design.

Regarding point C, this paper considers manufacturing tolerances related to cutting process, to obtain the rotor/stator shape, and magnet manufacturing. Following, it is described the manufacturing tolerances considered in this study.

A. Cutting tolerance

The rotor/stator of an electrical machine is made of stacked metal sheets, so each sheet should be cut with the desired shape. To perform this process, different techniques are available on the market. In order to select the most suitable technique for each application, several aspects should be taken into account such as initial investment, geometrical tolerances, production volume and manufacturing times. TABLE I. shows the most used cutting techniques and their tolerances. Laser and waterjet cutting are used for prototypes or small productions. By contrast, single notching and punching are used for medium and large productions. In this project, the used technique for the prototype manufacturing is the laser cutting.

TABLE I. CUTTING PROCESS TOLERANCE VALUES OF ROTOR/STATOR [8].

Cutting process	Tolerances	Units
Laser cutting	±0.1	Mm
Waterjet cutting	±0.1	Mm
Single notching	±0.01	mm
Punching	±0.01	mm

B. Magnet tolerance

Magnets are manufactured through small particles of magnetic powder. Powder is compacted and sintered obtaining the desired shape [9]. During this process, magnet dimensions and magnet properties may differ from the theorical values. Therefore, PMSG behavior can be different from the expected. In order to evaluate the influence of these tolerances in the PMSG behavior, in this paper manufacturing tolerances of permanent magnet (PM) are considered. These tolerances, which are represented in Fig. 2, are gathered in TABLE II.

TABLE II. MANUFACTURING PROCESS TOLERANCE VALUES OF PM [10].

Magnet manufacturing process	Tolerances	Units
Magnetization angle (β)	±4	º
Remanence magnetization (Br)	±0.02	T
Dimensional tolerance	±0.2	mm

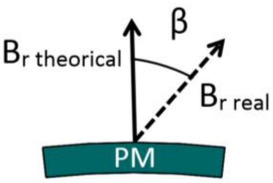

Fig. 2. Magnetic tolerances.

III. EXPERIMENTAL SETUP

The electrical machine under study is a radial flux permanent magnet synchronous generator, with permanent magnets located over the rotor surface, inner rotor and fractional slot winding. Fig. 3 shows a representation of the designed PMSG and the main parts which compound the generator.

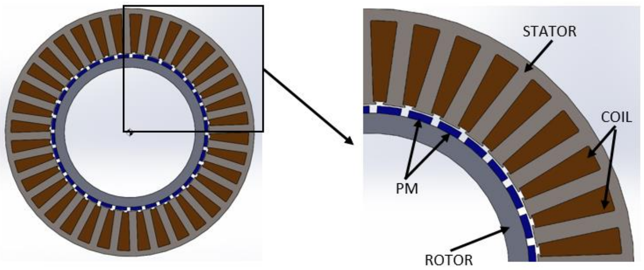

Fig. 3. PMSG design.

Initially, once the input parameters and requirements are defined, a PMSG is designed using a tailor made software tool based on analytical equations [11], [12]. This design is analyzed in finite element in order to refine the obtained PMSG. Fig. 4 shows the PMSG model developed in FLUX 2D. Furthermore, TABLE III. gathers the main generator characteristics.

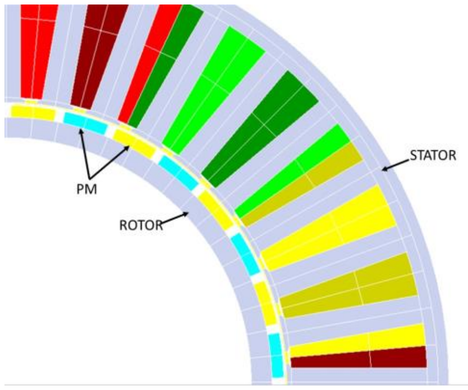

Fig. 4. 2D Finite element model PMSG.

TABLE III. PMSG CHARACTERISTICS.

Parameters	Values	Units
Rated power	2000	W
Rotational speed	120	r.p.m.
Phase number	3	
Slots number	36	
Pole number	32	

As it is explain in the flowchart described in section II, once the design fulfills all the input requirements, an analysis of the manufacturing tolerances influence in the proposed PMSG performance is carried out using FLUX 2D. Ripple output power and cogging torque are the parameters considered to evaluate this influence.

The manufacturing tolerances consider in this study are gathered in TABLE IV. and represented in Fig. 5. The tolerance influence of the selected cutting technique (in this case, laser cutting) is considered through the slot opening (*SO*), static and dynamic eccentricity [13]. The dimensional tolerances of the magnets are taken into account through magnet length (*LM*) and magnet angle (*θm*). Finally, the magnetization faults are assessed with magnetization angle (*β*) and remanence magnetization (*Br*).

TABLE IV. TOLERANCES ANALYZED DURING THE STUDY.

	Minimum value	***Rated value***	***Maximum value***	***Units***
Slot opening (SO)	SO-0.1	SO	SO+0.1	mm
Magnet length (LM)	LM-0.2	LM	LM+0.2	mm
Magnet angle (θ_m)	θ_m-0.3	θ_m	θm+0.3	º
Magnetization angle (β)	β-4	Β	β+4	º
Remanence magnetization (Br)	B_r-0.02	Br	B_r+0.02	T
Static eccentricity (e)	25% gap	0	50% gap	mm
Dynamic eccentricity		0	0.1	mm

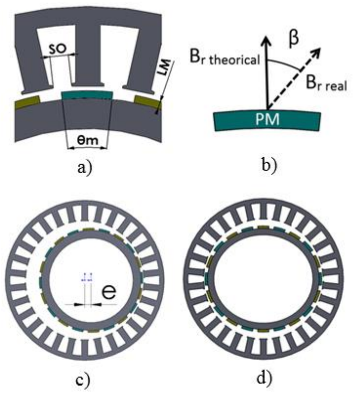

Fig. 5. Graphic representation of the tolerances under study. a) Dimensional tolerances; b) Magnetic tolerances; c) Static eccentricity; d) Dynamic eccentricity.

IV. Results

Following, the influence of the manufacturing tolerances in cogging torque and ripple power are analyzed.

A. Cogging torque

Cogging torque is an undesirable effect due to the interactions between the permanent magnets located over the rotor surface and the stator teeth [3], [6].

In order to evaluate the influence of manufacturing tolerances in cogging torque, a finite element simulation is performed. In the simulation the windings are removed and the rotor rotational speed is reduced up to 1/6 r.p.m.

Fig. 6 shows the study results considering cutting technique and magnet dimensional tolerances, and magnetization faults. From this figure, it can be observed that magnet length (LM) and magnet angle (θm) tolerances have the highest influence in cogging torque. By contrast, it is observed that slot opening (SO) and the remanence magnetization (Br) tolerances cause unimportant changes in the cogging torque. Finally, the magnetization angle (β), is barely affected to the cogging torque [3]-[6]. It is also concluded that the higher the LM and θm value, higher cogging torque value.

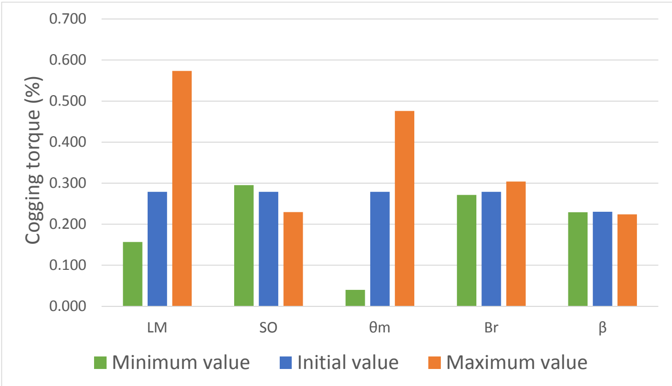

Fig. 6. Manufacturing tolerance influence in cogging torque (% Rated torque).

The influence of static and dynamic eccentricity in the cogging torque is represented in Fig. 7. From this figure, it is concluded that static eccentricity has higher influence than the dynamic eccentricity. Furthermore, it is seen that as higher static eccentricity, the higher cogging torque value.

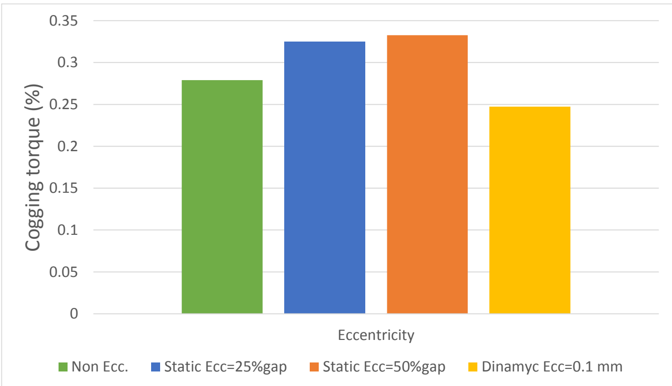

Fig. 7. Eccentricity influence in cogging torque (%).

B. Ripple output power

With the aim to analyze the influence of manufacturing tolerances in ripple power, a load test is carried out using finite element simulation. During this test, rated load is connected between the generator terminals and the rotor rotates at rated rotational speed.

The influence of cutting technique and magnet dimensional tolerances, and magnetization faults in ripple power is represented in Fig. 8. From Fig. 8, it is concluded that the length magnet (*LM*) and magnet angle (*θm*) tolerances have the highest influences in ripple power results. Furthermore, it is observed that slot opening variation (*SO*) produces small changes in response variation. Regarding the remanence magnetization (*Br*) and the magnetization angle (*β*), the influence in the ripple power is slight [3]-[6].

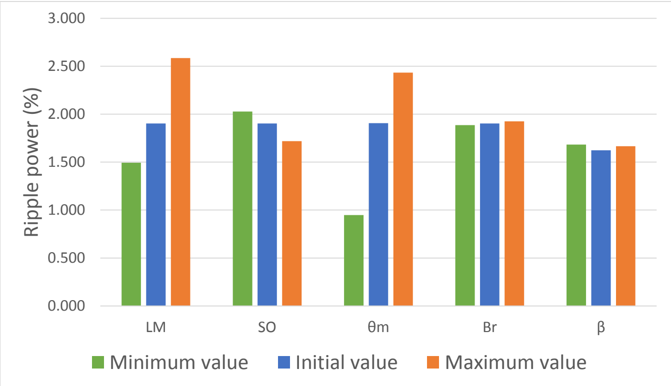

Fig. 8. Manufacturing tolerance influence in ripple power (%).

The influence of static and dynamic eccentricity in the ripple power is represented in Fig. 9. From this figure, it is concluded that static eccentricity has higher influence than the dynamic eccentricity. Furthermore, it is seen that as higher static eccentricity, the higher cogging torque value

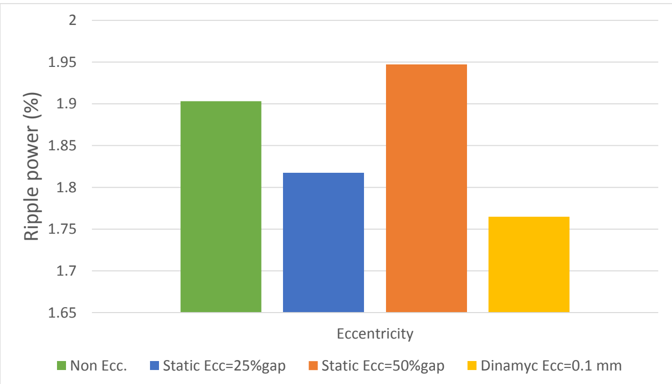

Fig. 9. Eccentricity influence in ripple power (%).

V. CONCLUSIONS

In this paper, it is shown the aspects that must be considered to design a high efficiency PMSG. The influence of manufacturing tolerances in PMSG behavior is evaluated before its manufacturing. In particular, the influence of eccentricity, rotor deformation and magnetic faults in electrical parameters such as ripple output power and cogging torque are evaluated by finite element simulations.

The evaluation of this influence allows to predict deviations of the real system from theoretical PMSG behavior, and make the necessary corrective actions on the design if is needed.

Geometrical magnet tolerances have been found as the ones that produce the highest influence in the ripple power and cogging torque. Furthermore, as higher tolerance value of these variables, higher ripple power and cogging torque value.

Static eccentricity is more than dynamic eccentricity, and its effects increase with the eccentricity value.

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