Cogging Torque Comparison of Interior Permanent Magnet Synchronous Generators with different Stator Windings

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***Abstract*— This paper presents the comparison between the cogging torques produced by four IPMSGs (Interior Permanent Magnet Synchronous Generators) with different stator winding configurations. More in detail, an IPMSG model, which is derived from a commercial geometry, is analyzed through means of a FEM (Finite Element Method) approach. Then, three more structures are determined and analyzed by adequately changing the number of stator slots of the basic IPMSG stator structure and by maintaining the same rotor configuration. From the obtained simulation results, the cogging torque components for each structure are determined and compared. From this comparison, it can be stated that the use of dissymmetric windings does not affect significantly the generated cogging torque.**

Keywords — Cogging torque, FEM analysis, permanent magnets, IPMSG

I. INTRODUCTION

Over the last decades the adequate use of renewable energy resources towards a sustainable development has been one of the most important issues faced by the scientific community [1-16]. In this context, Permanent Magnet Synchronous Machines have acquired great significance in the field of electrical drives and renewable energies, especially because of their great advantages in comparison with machines of the traditional type [17]. In order to improve their performances, the scientific research has been directed towards the optimization of torque/weight and torque/moment of inertia ratios [18], efficiency [19] and through the minimization of the generated cogging torque [20-22]. The latter is a very critical phenomenon that could affect the generator performances for certain applications.

Most of the design procedures used for electrical machines are focused on the achievement of a flux density distribution in the air-gap with the lowest possible harmonic content [23]. In this context, particular care should be dedicated to the adequate choice of the winding type and on the calculation of the differential leakage factor, for both cases of symmetrical and dissymmetrical winding configurations. As a matter of fact, the latter configuration is required when it is needed to use the same stator iron laminates for more slot-pole combinations. Non-symmetrical windings can be also used in machines with Pole Amplitude Modulation (PAM), or for the three-phase pole-changing induction machines.

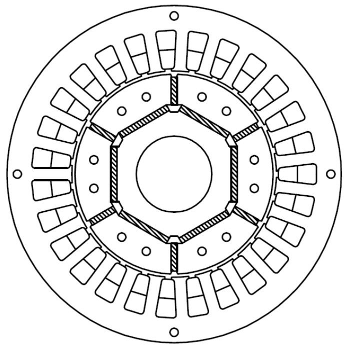

Fig. 1. IPMSM-A geometry.

Therefore, a study in terms of cogging torque produced by IPMSGs with fractional slot single and double layer windings can be an important aid in order also to design non-symmetrical windings with low torque ripple.

This paper presents the comparison between the cogging torques produced by four IPMSMs (Interior Permanent Magnet Synchronous Machines) with different stator winding configurations. More in particular, an IPMSM model, which is derived from a commercial geometry, is analyzed through means of a FEM approach. Then, three other geometries, determined by adequately changing the stator winding without modifying the original rotor configuration, are proposed and analyzed. It will be demonstrated that the use of unsymmetrical windings does not affect the generated cogging torque in a significant manner. In addition, the authors believe that the proposed analysis can be a very useful tool during the design process of electrical machines.

The paper is organized as follows:

- The proposed IPMSM models, differing in their stator slot numbers and without affecting the rotor geometry, are descrive in Section II
- Section III outlines the Finite-Element-Method analysis of the proposed structures, highlighting also the differences between the models in terms of harmonic content
- Section IV shows the most important results carried out by the simulations and the related conclusions are drawn.

II. IPMSM Structures

The cross section of the IPMSM model considered in this work as reference structure, namely IPMSM-A, is depicted in Fig. 1. It is a six-poles machine with 27 stator slots and a three-phase, star, double layer and shortened pitch stator winding (number of slots per pole per phase equal to 1.5).

The PMs are of the NdFeB type, adequately located so that the magnetic flux is generated both in the radial and tangential directions. The stator and rotor cores are realized with iron laminates, whose magnetic permeability in the linear region and electrical conductivity are equal to μ_r = 14800 and σ = 10.44 MS/m, respectively. The winding scheme of the machine is depicted in Fig. 2.

The IPMSM-A geometry has been then modified by changing the number of stator slots of the proposed model and by maintaining the same rotor structure. More in detail, three IPMSM models have been obtained: the IPMSM-B model, composed by 18 slots and shown in Fig. 3, the IPMSM-C model (Fig. 4), composed by 24 slots and the IPMSM-D model, composed by 33 slots and whose cross section is depicted in Fig. 5.

The winding schemes of IPMSM-B, IPMSM-C and IPMSM-D, which have been all obtained from [23], are depicted in Figs. 6,7 and 8, respectively.

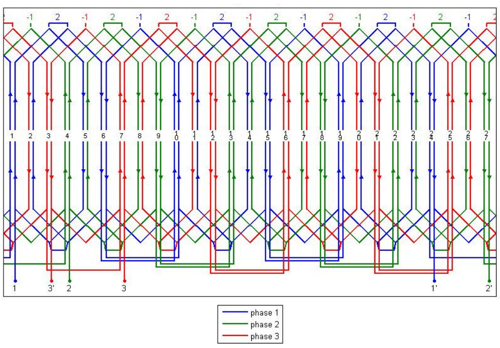

Fig. 2. Winding scheme of the IPMSM-A, n=27.

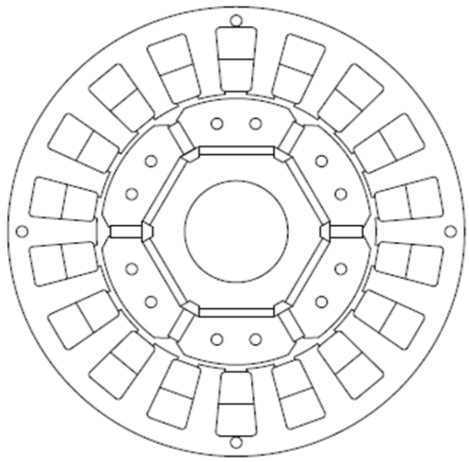

Fig. 3. IPMSM-B geometry.

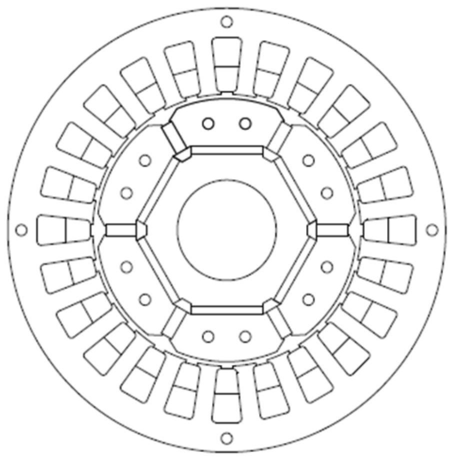

Fig. 4. IPMSM-C geometry.

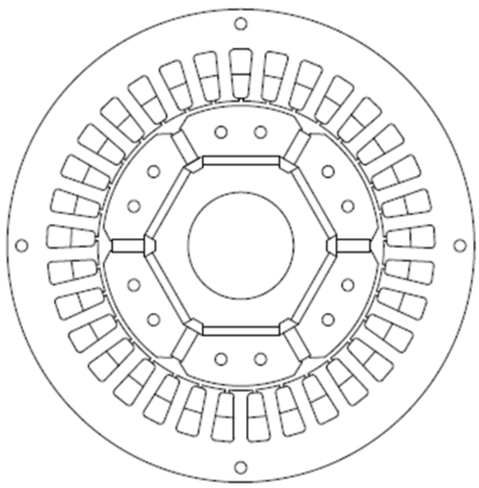

Fig. 5. IPMSM-D geometry.

III. FEM ANALYSIS OF THE PROPOSED IPMSMS

The four proposed geometries are analyzed by adopting a finite element approach through means of the FEMM4.2 open-source software. This analysis has lead to the determination of the following quantities:

- the flux density plot;
- the spatial distribution of the average flux density, B_{avg}, as function of the coordinate y, which corresponds to the distance measured along the mean air-gap circumference;
- the average value of the pole flux;
- the generated torque as a function of the angular position of the rotor;
- the values and the trends of the cogging torque as function of the rotor position;
- the cogging torque harmonic spectra for each of the proposed models.

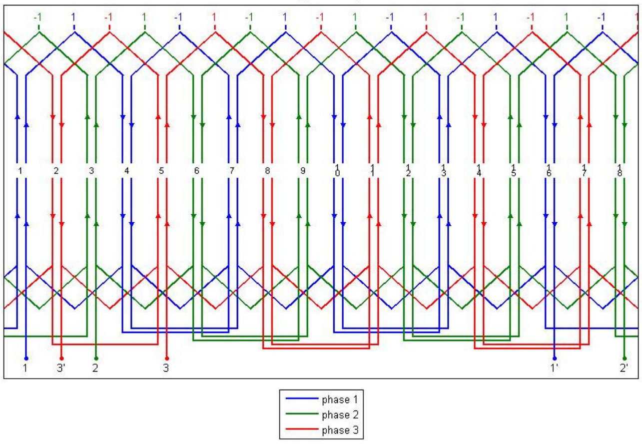

Fig. 6. Winding scheme of the IPMSM-B, N=18.

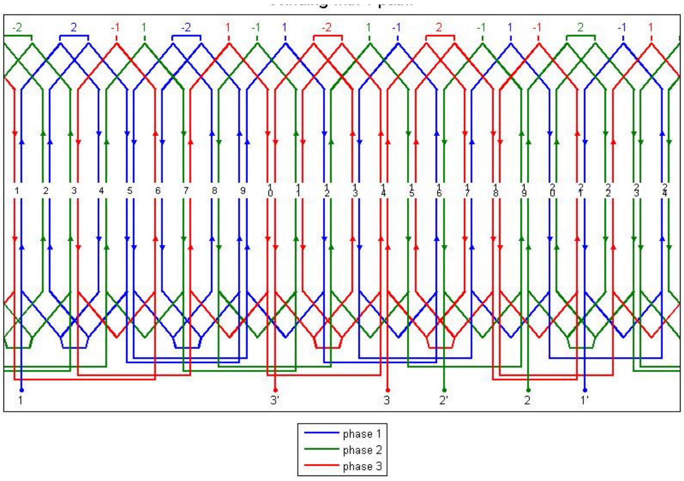

Fig. 7. Winding scheme of the IPMSM-C, N=24.

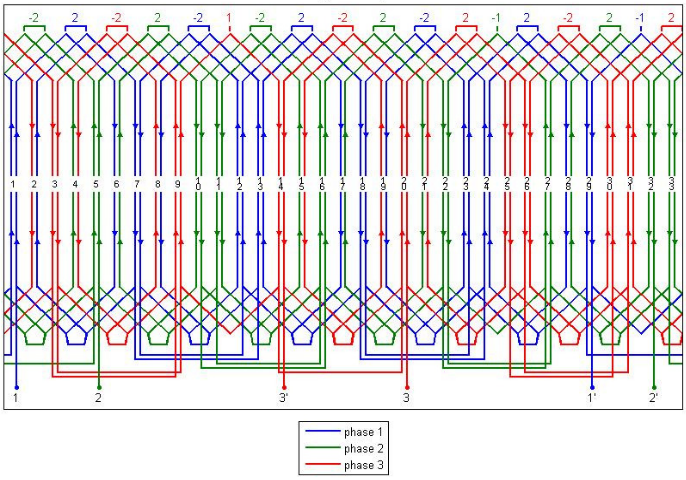

Fig. 8. Winding scheme of the IPMSM-D, n=33.

As examples, the density plot of the IPMSM-A model is shown in Fig. 9, while the harmonic spectra for all the proposed models are plotted in Figs. 10, 11, 12 and 13.

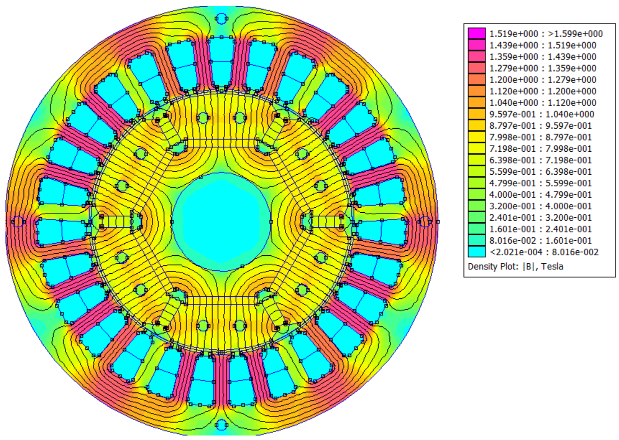

Fig. 9. Flux density plot for the IPMSM-A structure.

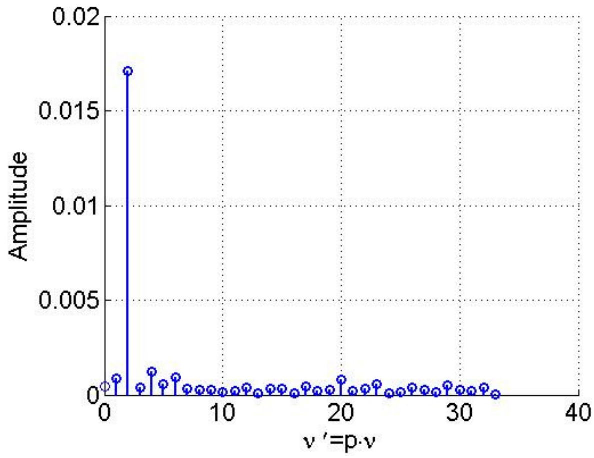

Fig. 10. Harmonic spectrum for the IPMSM-A structure, N=27.

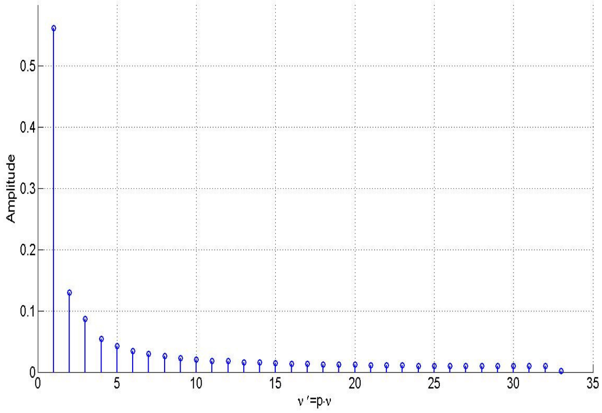

Fig. 11. Harmonic spectrum for the IPMSM-B structure, n=18.

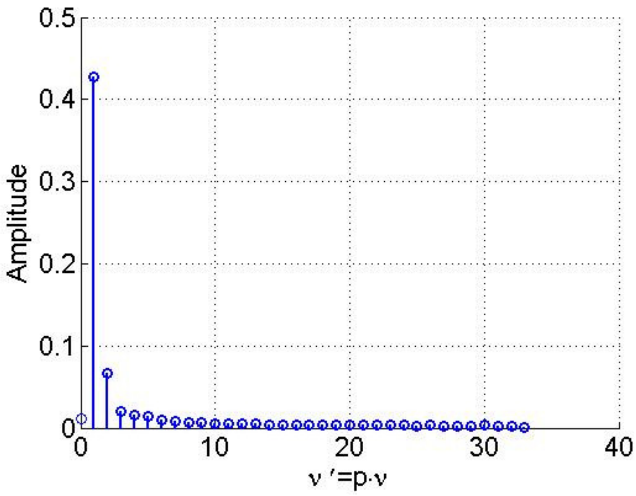

Fig. 12. Harmonic spectrum for the IPMSM-C structure, n=24.

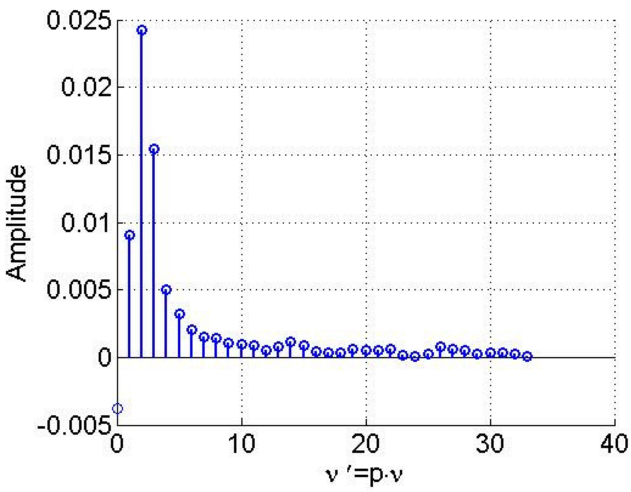

Fig. 13. Harmonic spectrum for the IPMSM-D structure, n=33.

IV. Results and Discussions

Fig.5 shows the cogging torque/load angle characteristics for each of the proposed models. As expected, the frequency of the cogging torque is strictly dependent on the number of slots. In addition, it can be noticed that the cogging torque amplitude significantly decreases when the number of stator slots is increased. Furthermore, it can be noticed that the use of dissymmetric winding configurations do not considerably influence the cogging torque amplitude. In fact, the amplitude of the cogging torque corresponding to the stator slot configuration of N=33 is relatively low.

Table I summarizes the modules and phases of the e.m.f.s generated by the IPMSM-D for each winding phase section, it can be noticed that the degree of unbalance (DU%= $k_i/k_d \cdot 100$) is relatively low. Therefore, in this case the use of unsymmetrical windings does not even affect significantly the harmonic content.

In conclusion, it can be stated that the use of unsymmetrical windings can be a choice that does not affect neither in terms of produced cogging torque or degree of unbalance, increasing also the possibility to use also non-traditional slots/poles configurations. Therefore, it is possible to optimize the IPMSM structure in both its rotor and stator geometries so that the cogging torque components are minimized.

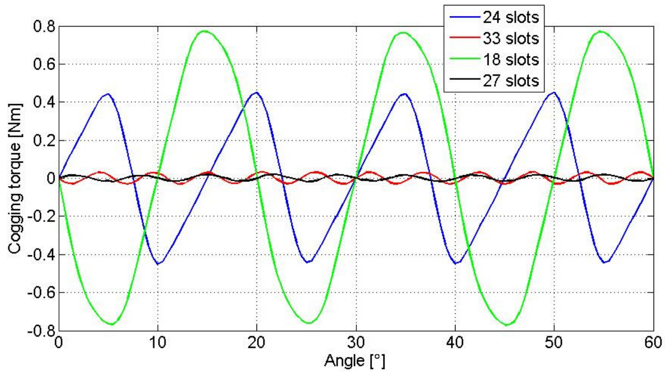

Fig. 14. Cogging torque Comparison of the trends of the cogging torques produced by the four IPMSM geometries.

TABLE I. Module and phase of the Winding Factors for each Phase Section of the IPMSM-D Winding

k_d (direct sequence)	0.9427
k_i (inverse sequence)	0.0027
k_o (homopolar sequence)	0.0060
D.U. [%]	0.28
Phase A [°]	0°
Phase B [°]	240.9°
Phase C [°]	120.5°

V. CONCLUSIONS

This work has presented the cogging torque comparison between four IPMSMs with different stator structures without changing the rotor geometry and taking also into account fractional winding configurations. The FEM approach has allowed the analysis and the cogging torque comparison of the proposed structures. The obtained simulation results have confirmed that the use of dissymmetric windings does not affect the generated cogging torque.

ACKNOWLEDGEMENTS

This work was financially supported by SDESLab (Sustainable Development and Energy Saving Laboratory) of the University of Palermo.

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