Vibro-Acoustic Behavior vs. Conductive Interferences in PMSM drives

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***Abstract*—In this paper, a simplified high frequency model of the Permanent Magnet Synchronous Motor (PMSM) as well as the motor drive were developed and analyzed using Simulink. The currents in the normal and common mode paths were extracted and compared with the analytical results. A Finite Element Analysis (FEA) was performed on two PMSM with different topologies in order to obtain the radial forces on the stator teeth. The results were analyzed in order to try to establish a link between said forces and the high-frequency emissions that are present in the system.**

***Keywords*—permanent magnet synchronous motor (PMSM), electromagnetic interference (EMI), radial forces, common and normal mode currents, stray capacitance.**

I. INTRODUCTION

The automotive industry has a continuous high demand for electric drives. The field of actual automotive electric powered units spans a broad range including cooling fans, window and chair actuation, steering, braking, suspension, starter-alternator (integrated or belt driven), HVAC, propulsion for hybrid and full electric vehicles (HEV/EV). The further enhancement of high-performance automotive electric actuation requires energy-efficient, reliable, robust, low-cost electrical machines and highly integrated, energy-efficient power electronics and control modules. For achieving these requirements, the R&D activities should focus on the analysis and development of new topologies and concepts of electrical machines, taking into account the need for energy efficient drives, the harsh automotive environment (high temperature, vibrations, standards for the measurement of pass-by noise, etc.) and the availability of raw materials (in particular rare-earth materials for permanent magnets). Moreover, the integration of electric powered units in vehicles represents an important challenge due to strict and specific noise-vibration-harshness (NVH) and electromagnetic interferences (EMI) requirements.

PMSM is the most used electrical actuator used to drive small power automotive applications. Many control strategies were adopted over the course of time, with the objective of reducing the torque ripple and improve the dynamic performances of the PMSM drives [1]. The control strategies adopted, may have an effect on the voltage, with a multitude of harmonics appearing, which in turn can cause currents of high frequency to appear in the machine and the system. The high frequency current harmonics can have a negative effect on the system, by exciting the parasitic capacitances inside the electrical motor and generate capacitive and conductive disturbances within the system. Disturbing current components can thus flow in both common-mode and normal mode paths [2]. There have been a few studies done on this topic, regarding the high-frequency behavior of the PMSM drives, but they are mostly focused on the development and analysis of the high frequency circuit, and circuit parameters estimation and/or computation [3]. However, there haven't been any studies regarding the influence of the PMSM topology on the high-frequency response of the machine.

The coupled EMI and vibration analysis for EMDs is a very new field of study. There are very few research works and scientific articles on this subject. Several attempts of evaluating the influence of different design parameters, or different control strategies on EMI and vibration characteristics of the PMSM drives were already done. The work was focused on a basic study, mainly using experimental measurements without going further with the development of accurate theoretical approach to validate the experimental measurements and giving the possibility of predicting the coupled EMI-vibration behaviour or to identify the interdependencies between these two aspects.

This paper will propose a parallel analysis of the capacitive and conductive interferences vs. the radial forces that are present on the surface of the PMSM teeth, at the air-gap level, using different number of slots/number of poles combinations, utilizing the Space Vector Modulation (SVM), better known as Field Oriented Control (FOC). Section II presents the high-frequency equivalent circuit of the machine [4], and its parameters computation. The model will be further implanted and analyzed in Section III, using a speed-control of the PMSM. Finally, Section IV will show the radial forces in the stator teeth surface, as well as analyzing the harmonics spectrum of said forces.

II. PMSM EQUIVALENT HIGH-FREQUENCY CIRCUIT MODEL

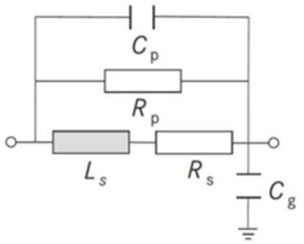

Fig. 1. Equivalent circuit for one phase.

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A simplified version for each phase of the PMSM is implemented, in order to easily observe and distinguish the parasitic currents that flow through the two normal and common mode paths (Fig. 1) [4].

The elements present in Fig. 1 represent:

- R_s – resistance of one phase;
- R_p – equivalent resistance depicting eddy losses:

$$R_p = \frac{p_{eddy} m_s}{I_{phN}} \quad (1)$$

where peddy stand for the eddy losses in the stator core, ms the stator mass, and IphN the current on one phase [2],

- L_s represents the inductance on one phase:

$$L_s = \frac{\phi_{ph}}{I_{phN}} \quad (2)$$

with Φ_{ph} is the phase linkage magnetic flux.

Overall, we can distinguish three kinds of parasitic capacitances which produce conductive disturbances in the system:

Capacitance between two turns which are present in one coil;

capacitance in between two phases present in the same stator slot, or which intersect at the coil ends;

Capacitance between the stator core and the ground.

The first step is to compute the turn to turn capacitance, by using the following equation:

$$C_{ss} = e_0 L_s \left[e_r \frac{D_a \theta}{2 s_{is}} + \cot\left(\frac{\theta}{2}\right) - 3.732 \right] \quad (3)$$

Where e_0 represents the vacuum permittivity, e_r the material (copper) permittivity, sis the width of the insulation used on the copper wires and Da the wire diameter. Θ is the angle at which the electric flux closes between two adjacent turns and can be computed as follows:

$$\theta = arccos\left(1 - \frac{2 s_{is}}{e_r D_a}\right) \quad (4)$$

The coil own stray capacitance can be found from the capacitance between turns, and can be computed as follows:

$$C_p = \frac{C_{ss}}{N_t - 1} \quad (5)$$

where Nt represents the number of turns present in one coil [6].

III. Implementation of the PMSM High-Frequency Model

As mentioned in Section I, three topologies of surface mounted Permanent Magnet Synchronous Machines were used to validate the proposed study. The stator lamination is the same for all three, the only differences being the coil pitch and the number of rotor poles, with each machine having 4, 6 and 8 poles respectively. The half cross-sections of said PMSMs which will undergo study are depicted in Fig. 2. A capacitance always appears between two differently charged surfaces (different voltages), which means, if we have 1 V supply in one coil and 0 V on another, situated in the same stator slot, we can find the capacitance between them. These values are used, in order to simplify the computation of said parameters. By using this FEA method we can obtain the phase to phase capacitance, as well as the stator to ground capacitance, in order to further validate the data obtained using the analytical approach. The extracted results from the two computation methods (analytical and numerical approach) can be seen in Table I.

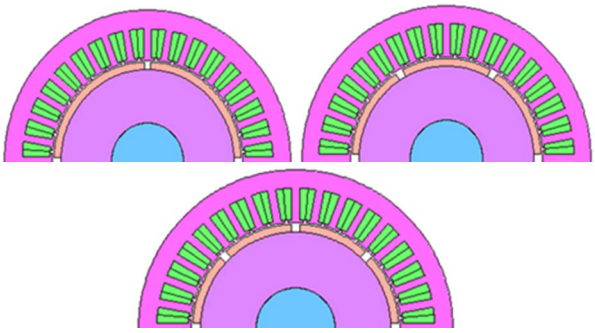


Fig. 2. PMSM topologies with different rotor pole number.s

TABLE I. Analytical vs. Numerical Computation of Parasitic Capacitance Between Two Phases

	Analytical approach	**Numerical Approach**	**Relative error**
4 poles	1.4294 pF	1.52 pF	5.1%
6 poles	0.6818 pF	0.67 pF	4.1%
8 poles	0.3806 pF	0.39 pF	3.5%

MATLAB-Simulink was used in order to implement tge PMSM high frequency parameters, which are depicted in Fig 3.

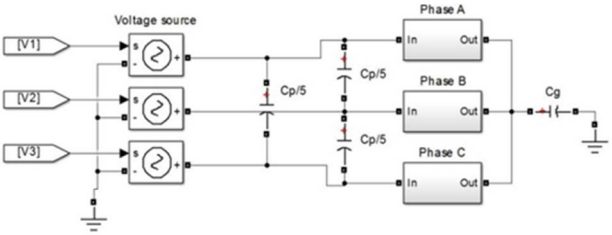


Fig. 3. PMSM high-frequency model.

The influence of the number stator slots, as well as the number of rotor poles combinations will be subjected to analysis, using a power converter that supplies the machines,

its gates being controlled with a Space Vector Modulation (SVM) control strategy type [5].

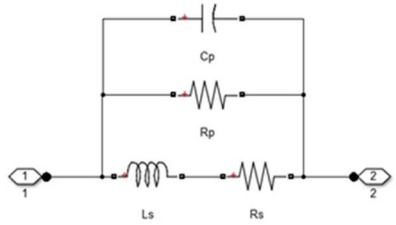
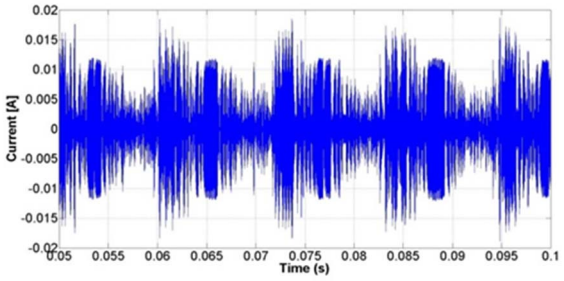
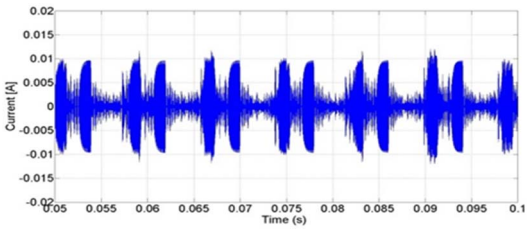


Fig. 4. Phase high-frequency equivalent circuit.

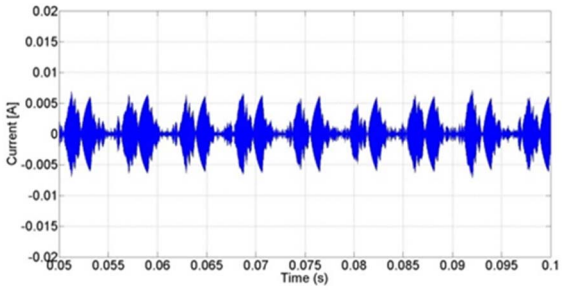
The main harmonic for both currents that flow through the normal and common paths can be distinguished at 500 kHz. The harmonic spectra is rich in identical side harmonics given by the switching frequency on the transistor gates, as a multiple of 20 kHz (depicted in Fig. 6 where we can observe the harmonics spectra for both the normal and common mode currents for all three topologies of PMSM).



a) 4 poles

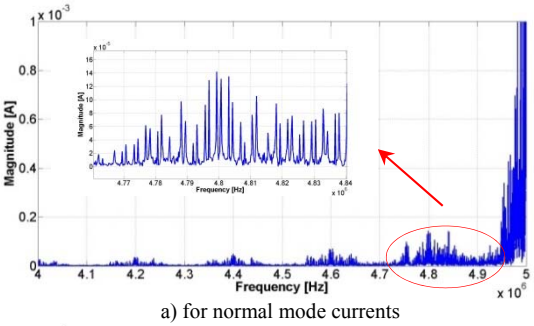


b) 6 poles

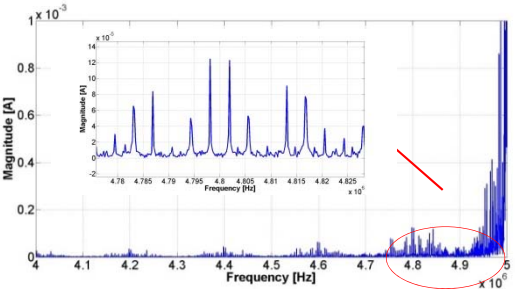


c) 8 poles

Fig. 5. Normal mode currents.

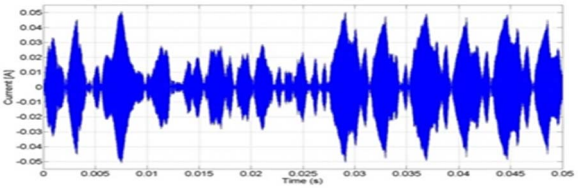


a) for normal mode currents

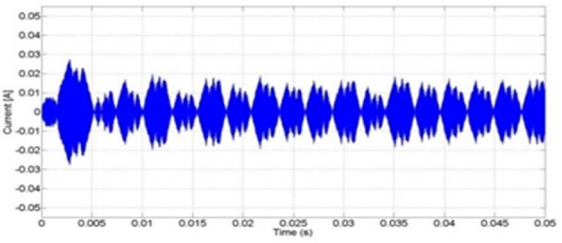


b) for common mode currents

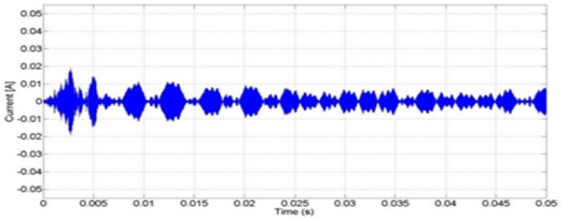
Fig. 6. Harmonics spectra.



a) 4 poles



b) 6 poles



c) 8 poles

Fig. 7. Common mode currents.

IV. VIBRO-ACOUSTIC BEHAVIOR

In this section the radial force distribution for each topology [6] will be discussed, using the Fourier Transform. Fig. 10 shows such an example of the radial forces. For the purpose of analyzing the nodal forces, only two motor topologies were chosen in order to validate the study: 27/4 and 36/8, taking into account the fact that simulation of the models is very time consuming.

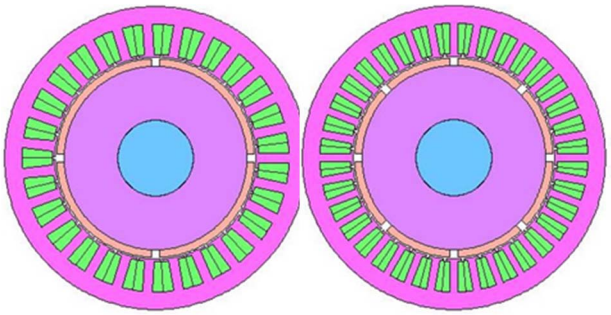


Fig. 8. Analyzed PMSM topologies.

Of course, in order to obtain more precise results, the chopped currents, depicted in Fig.8, were imported in JMAG-Designer and were used as the current source for the motor.

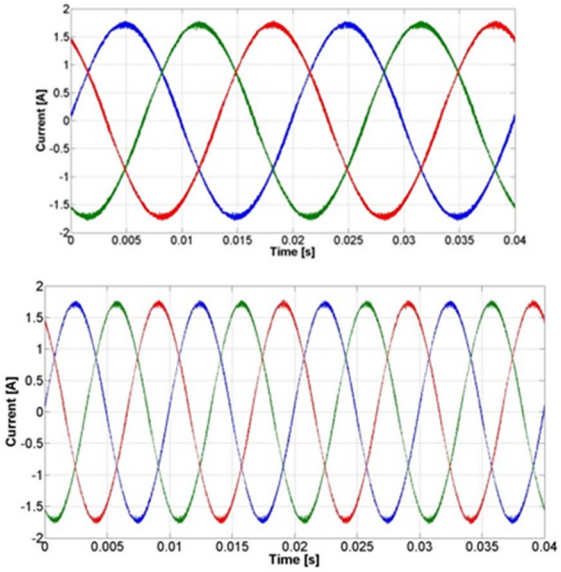


Fig. 9. Chopped current at 20kHz for a) 27/4 b) 36/8 PMSM topologies.

The current shape is a very important characteristic if we are to establish if there is any link between the radial forces and the normal and common mode currents in the stator windings. A PWM frequency of 20000Hz was used.

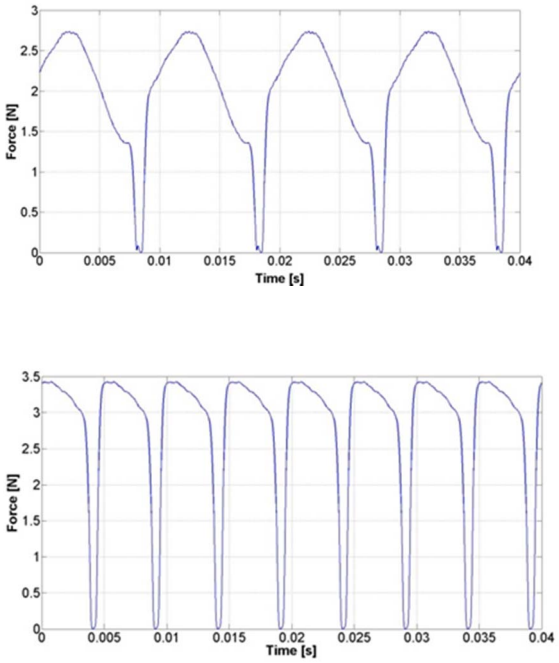


Fig. 10. Nodal force on stator tooth for a) 27/4 and b) 36/8 PMSM topologies

Fig. 10 represents the nodal force on the stator tooth vs. time for a complete rotation of the rotor. The number of rotor poles can be clearly seen here.

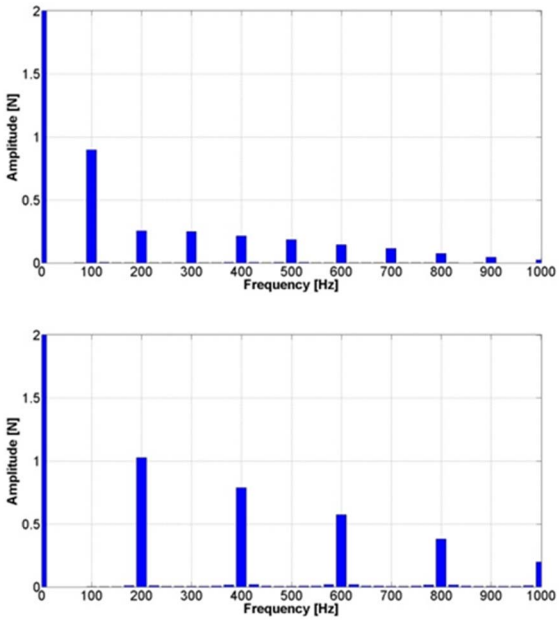


Fig. 11. Space harmonics for a) 36/8 b) 27/4 PMSM topologies.

The fundamental harmonic can be clearly distinguished and it is related to the supply frequency which is 50Hz and 100Hz for the 27/4 and the 36/8 PMSM topologies.

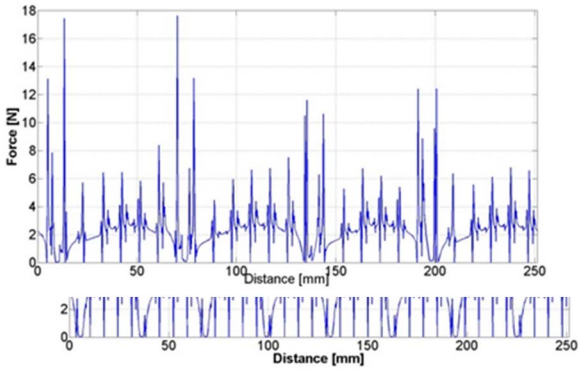


Fig. 12. Nodal force on stator for a) 36/8 b) 27/4 PMSM topologies

The harmonics spectrum of the nodal forces is tied to the number of poles on the rotor. The fundamental harmonic can be clearly seen in Fig. 13 and can be calculated with the following equation:

$$f = \frac{\tau}{2\pi D} \tag{6}$$

Where, τ is the stator coil pitch and D is the interior stator diameter. The values obtained are : 15.85 1/m and 31.7 1/m for the 27/4 and 36/8 PMSM topologies respectively.

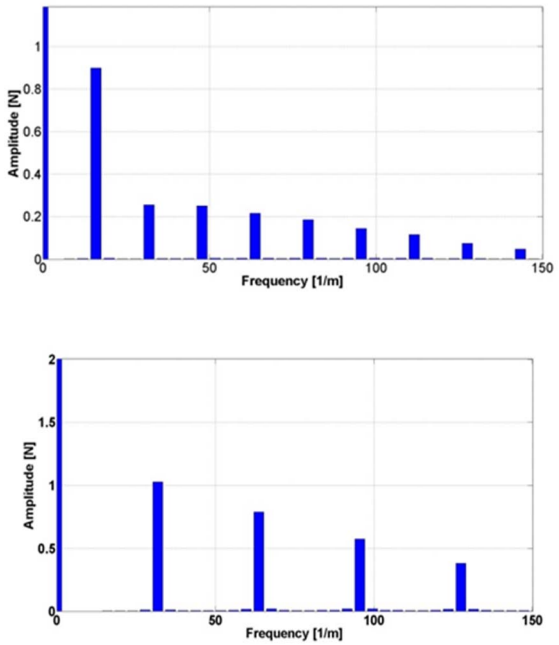


Fig. 13. Stator space harmonics for a) 27/4 and b) 36/8 PMSM topologies.

The final goal of this paper is to try to identify if there are any interdependencies between the nodal forces on the stator and the normal and common mode currents presented in Section III.

CONCLUSIONS AND FUTURE WORK

The main aim of this paper was to perform an analysis on the different PMSM topologies, and to determine main high-frequency parameters of the machine, in order to establish if there is any link between the normal and common mode parasitic disturbances and the radial forces on the stator tooth surface. A model concerning the high-frequency equivalent circuit is proposed, analyzed, and implemented using MATLAB-Simulink.

No interdependencies were established so far between the nodal forces on the stator and the EMI normal and common mode currents and more investigation is required.

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