Impact of Geometrical Abnormalities in the Modeling and Diagnosis of Short Circuit Faults in Permanent Magnet Synchronous Machines

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***Abstract* -- This paper presents a dynamic model for multiphase short circuit in a permanent magnet synchronous machine (PMSM) and how geometrical abnormalities in the motor can lead to false information for a fault detection algorithm. Different types of short circuit faults were simulated on a permanent magnet synchronous machine, purchased directly from the market. The tests revealed that a third harmonic was present in the stator currents even in healthy mode. A finite element study (FEM) was also carried out by taking exact dimensions of the machine. The FEM analysis showed that the origin of third harmonic in current was due to a stator teeth having double width. It is therefore necessary that a fault detection algorithm should be based on the real data of machine to avoid misleading results. Thus some adjustments appear to be necessary to perform on the proposed fault sensitive model.**

I. INTRODUCTION

IN THIS era where applications force to design new sophisticated machines almost every day, it is equally important to develop algorithms for their protection. Permanent magnet machines in their various structural configurations have now proved to be real competitors for the non-magnet type counterparts. Their key advantages reside on high torque density, less weight and compactness and with the advent of new hard magnetic materials; their cost has also appreciably decreased. These features make them a preferred choice in novel tasks [1]. Fault detection and diagnosis schemes are important as they reduce machine's downtime and maintenance costs. Moreover earlier detection schemes help to avoid a complete destruction. These detection algorithms can only be effective if information data is sufficient and precise. More clearly the detection algorithm should be able differentiate between a real fault and a false signal. Earlier research on fault detection has been focused on the induction type machines [1], [2] compared to permanent magnet ones. Dai *et al.* [3] investigate some stator winding faults for permanent magnet brushless DC motors by finite element (FEM) simulations. Gerada *et al* [4] use reluctance network to simulate winding faults for permanent magnet machines, Mohammed *et al* [5] discuss an inter turn fault for brushless AC motors.

The aim of this paper is firstly, to give a dynamic model tacking into account the short circuit fault in the stator winding of a PMSM, even that the short circuit is partial (inter-turns), full (all the turns of the coil), localized at one phase or concerning two or even the three phases. Thus, an experimental test bench dedicated to short-circuit a PMSM is presented with a study on one geometrical abnormality through the analysis of some experimental measurements and finite element simulations. Finally, the impact of this kind of abnormalities on the proposed model is highlighted.

II. MULTIPHASE SHORT CIRCUIT MODELING

In the reference [6], the authors presented a dynamic model of a PMSM having a short-circuit fault in one of its three phases. The inter-turn short-circuit fault of the winding has been modeled through two parameters: "σ" the ratio of the short-circuited turns with respect to total number of turns of the winding and "R_f" the short circuit resister through which the faulty current flows. In the present work, the previous model is generalized to a three phase short-circuit fault. In order to include a multiphase short-circuits six parameters are necessary: σ_a, σ_b, σ_c, R_{fa}, R_{fb} and R_{fc} reflecting respectively the short-circuited winding part and shorted resistors in the phases a, b and c. Thus the obtained model is as follows:

$$v^s_{abc} = R_{abc} i^s_{abc} + L_s \frac{di^s_{abc}}{dt} + \frac{d\Psi_{mabc}}{dt} \qquad (1),$$

where,

$$\Psi_{mabc} = \Psi_m \begin{bmatrix} (1-\sigma_a)\sin(\theta_r) \\ \sigma_a \sin(\theta_r) \\ (1-\sigma_b)\sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \sigma_b \sin\left(\theta_r - \frac{2\pi}{3}\right) \\ (1-\sigma_c)\sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \sigma_c \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix},$$

is the permanent magnet flux getting through the windings of the three phases a, b and c (ψ_m is it's maximum value according to one period of the angular rotor position θ_r);

$$v^s_{abc} = \begin{bmatrix} v^s_{a1} & v^s_{a2} & v^s_{b1} & v^s_{b2} & v^s_{c1} & v^s_{c2} \end{bmatrix}^T,$$

are the voltages of the phases a, b and c of the machine. The indexes 1 and 2 express respectively the healthy and the short-circuited parts in each winding.

$$i^s_{abc} = \begin{bmatrix} i^s_a & (i^s_a - i_{fa}) & i^s_b & (i^s_b - i_{fb}) & i^s_c & (i^s_c - i_{fc}) \end{bmatrix}^T,$$

are the three phase currents with i_{fa}, i_{fb} and i_{fc} are the short-circuit currents in the phases a, b and c respectively; R_{abc} and L_s are two 6×6 matrices of respectively, the stator winding resistors and inductors including healthy and short-circuited parts.

III. EXPERIMENTAL SETUP

In order to check the validity of the proposed model an experimental test has been build. The stator of the PMSM has been modified to simulate different type of short circuit faults. On the basis on the data sheet of the manufacturer and some classical measurements, the studied PMSM has been identified by assuming that the machine is perfectly symmetric; see the characteristics of Table 1.

TABLE I
CHARACTERISTICS OF THE STUDIED MACHINE

S. No	Parameter	Value
1	Nominal Torque	3.2 Nm
2	Nominal Current	6.2 A
3	Poles pairs	3
4	Induced EMF	33 V/1000 rpm
5	Rated Speed	3000 rpm
6	Inertia	1.8 kgcm^2
7	Stator resistance R_a	0.8 Ω
8	Cyclic stator inductance	3.2 mH

After the control program was implemented the stator currents were measured. The harmonic analysis of these currents, presented on Fig. 1(a), shows a presence of a third harmonic in the amplitude of the three currents. This phenomenon may be due to some dissymmetry in the machine. After analyzing the stator currents in healthy mode, a single phase inter-turn short circuit faults was simulated. The obtained results show clearly a raising of the third harmonic component regarding to the healthy mode, see Fig. 1(b).

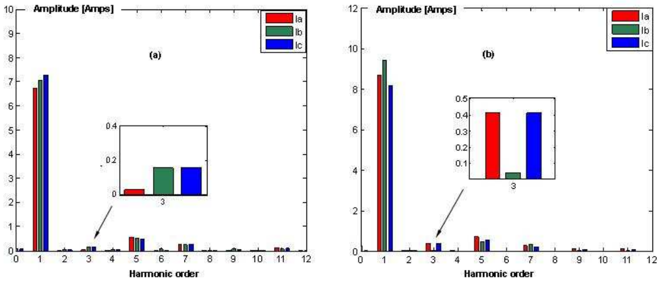

Fig. 1. Harmonic analysis of experimental stator current: (a) healthy mode, (b) faulty mode (single phase inter-turn short circuit of 15%, in phase “a”)

As a first conclusion, one must take into account the possible abnormalities of the PMSM to correctly diagnose the inter-turn short circuit. Thus, it is necessary to find the origin of the 3rd orders in the current harmonic spectra when the machine is in its healthy operating mode. Firstly, the finite element software Flux2D has been used to simulate the real geometry of the studied machine. Thus, the obtained results are used for the dynamic model adjustments.

IV. FINITE ELEMENT ANALYSIS

In order to investigate the presence of third harmonic component in the stator currents even in healthy mode, the machine was opened and its dimensions were taken to simulate its structure in Finite Element software, Flux2D. A unique feature observed in the structure of studied machine was that one of the teeth has double width compared to others (Fig. 2a). This dissymmetry may be the cause of third harmonic in the stator currents even in healthy mode.

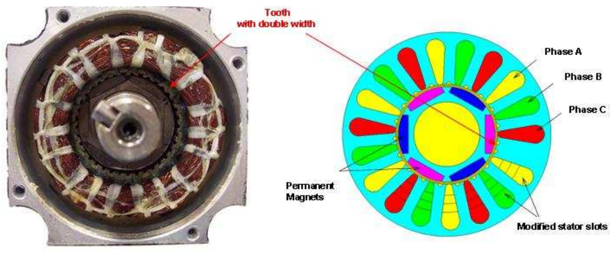

Fig. 2. Cross section of the studied machine with one teeth having double width: (a) real picture, (b) Geometry drawn in Flux2D

Figure 2b shows the structure of machine simulated in Flux2D. The stator slots were modified to simulate short circuit fault through the coupling of a Matlab control program with Flux2D model. The machine was first simulated without fault. Fig. 3a shows the harmonic analysis of stator currents, clearly there exists a third harmonic component which may be due to the double width tooth. This magnitude increases in the inter-turn fault case.

Once validated that a short circuit fault generates a third harmonic component in the stator currents, it was interesting to find the origin of third harmonic component in the stator currents even in the healthy mode. The geometry of the machine was modified with all teeth having equal width. Simulations of machine were carried out in normal mode. Fig. 3(b) shows harmonic analysis of stator currents, clearly the third harmonic component vanishes. This confirms that its origin was due to the dissymmetry in the stator core.

On the basis of these results, it can be concluded that the origin of the presence of a third harmonic in the current spectra, even the machine operates in healthy mode, is due to the presence of a tooth with a double width regarding to the other stator teeth. This geometrical abnormality allows reducing considerably the cogging torque of the machine. However, it should be taken into account in the modeling process of the machine especially when the searched models are dedicated to a diagnosis purposes.

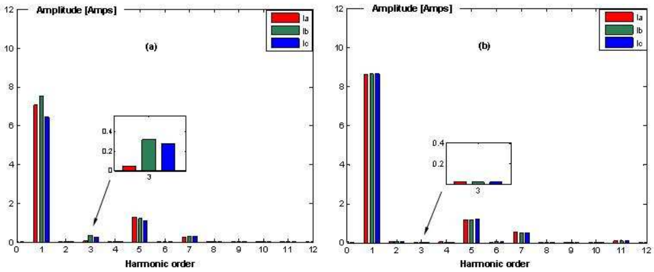

Fig. 3. Harmonic analysis of stator currents in healthy mode, with FEM: (a) case of one double width tooth, (b) case of all teeth with the same width

V. CONCLUSION

In this paper we have presented the symptoms originating in case of short circuit fault in permanent magnet synchronous machines. It has been proved that the third harmonic component in the stator currents can be used as a clear indication of short circuit fault. Furthermore it has been shown that machine’s data in the normal mode is important so that if there exist, some dissymmetry in the machine’s structure, the diagnostic algorithm as well as the used model can be adjusted accordingly. In the full paper more details will be given about the dynamic model adjustments and new results will be included.

VI. REFERENCES

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