Modeling of PM Synchronous Machines Under Inter-turn Fault

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Abstract — This paper presents a theoretical approach as far as faulty Permanent Magnet Synchronous Machines (PMSM) are concerned. PMSM's behavior under inter-turn fault is very useful in order to check drives performances under fault conditions. Control, stability and fault detection often requires faulty models. The aim is to have the dynamical model of a PMSM under fault consideration without using simulation models coupled with finite element analysis (FEA). The method exposed in this paper only needs some preliminary FE computations before a dynamical simulation. It can be also adapted for different winding distributions.

I. INTRODUCTION

One way to study PMSM's behavior under inter-turn fault is to build a faulty model. Many authors have developed PMSM models under inter-turn faults [1]. Such models often require strong hypotheses. Core saturation, leakage inductances are often neglected and winding arrangements are simplified [2]-[4]. This leads to a lack of accuracy on results. The results can be strongly improved by using time-stepping finite element method (TSFEM). However, this approach need to perform a new simulation for every fault configuration and requires too much CPU time. In addition, TSFEM cannot be easily coupled with a faulty controlled model implemented under MATLAB/SIMULINK® environment.

The authors present a weak coupled model using FEA to determine elementary inductances of the different coils. An appropriate method gives the right self and mutual inductances of the equivalent external circuit of the faulty machine. Then, thanks to a precise identification of the various parameters (inductances, no-load EMF), the study of the behavior of the faulty machine can be easily performed whatever the fault configuration is.

II. MODEL OF PM MOTOR UNDER FAULT CONDITION

Consider a 3-phases PM motor with inter-turn short circuit. The main idea consists in considering an additional circuit in the model as shown in Fig. 1. The electric equation of such model can be written of the form:

$$v_{abcf} = R_{abcf}.i_{abcf} + L_{abcf}.\frac{di_{abcf}}{dt} + e_{abcf} \quad (1)$$

$$R_{abcf} = \begin{bmatrix} R_s & 0 & 0 & -R_{a2} \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ -R_{a2} & 0 & 0 & -(R_{a2}+R_f) \end{bmatrix} \quad (2)$$

where, R_{abcf} and L_{abcf} can be expressed as follows:

$$L_{abcf} = \begin{bmatrix} L_c & 0 & 0 & -(L_{a2}+M_{a1a2}) \\ 0 & L_c & 0 & -M_{a2b} \\ 0 & 0 & L_c & -M_{a2c} \\ -(L_{a2}+M_{a1a2}) & -M_{a2b} & -M_{a2c} & L_{a2} \end{bmatrix} \quad (3)$$

$$\begin{cases} i_{abcf} = [i_a \quad i_b \quad i_c \quad i_f]^T \\ v_{abcf} = [v_a \quad v_b \quad v_c \quad v_f]^T \\ e_{abcf} = [e_a \quad e_b \quad e_c \quad e_f]^T \end{cases} \quad (4)$$

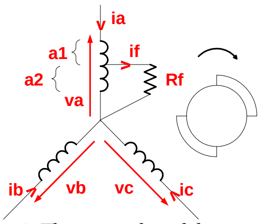

Fig. 1. The external model

R_s and L_c are respectively the phase resistance and the self inductance of the healthy machine. R_{a2} and L_{a2} are the resistance and the self inductance of the faulty winding $a2$ and e_f is its no-load EMF. M_{a1a2}, M_{a2b} and M_{a2c} are respectively the mutual inductances between the winding $a2$ and the windings $a1$, b and c. i_f and R_f are the fault current and the fault resistance (Fig. 1.). It has been shown that the parameters of the different parts affected by the short-circuit are directly linked to the ratio $\mu = N_{cc}/N_s$ between the number of shorted turns and the number of total turns of one phase. This assumption is exact in the case of windings with one slot per pole and per phase. In fact, the previous equations (3), (4) depend on the winding arrangement. In the case of non conventional winding or windings with more than one slot per pole and per phase, a more rigorous approach need to be adopted. The aim of this paper is to develop a general method based on FEA and winding arrangement modeling which leads to determine the parameters of the faulty model for various fault configurations.

III. INDUCTANCE MATRIX CALCULATION

We assume that saturation of iron materials is mainly due to the magnet flux. The main idea presented in this paper concerns the use of a minimum number of FEA simulations in order to obtain the inductance matrix of the equivalent scheme of a PM motor under fault condition.

A $2p$-pole, N_e-slots PM non-salient machine is considered with N_t turns per coil with a concentric winding arrangement (Fig. 2.). Field calculation is performed with nonlinear FEM. If only one coil k is supplied by the current i_k, the fluxes φ_i in the different coils can be determined by:

$$\varphi_i = \frac{L_z}{S_c}\left[\iint_{S_+} A ds - \iint_{S_-} A ds\right] \quad i = 1, \ldots N_e \quad (5)$$

where L_z is the axial length of the machine, S_c is the cross section area of the coil. S_+ and S_- denote the go and return

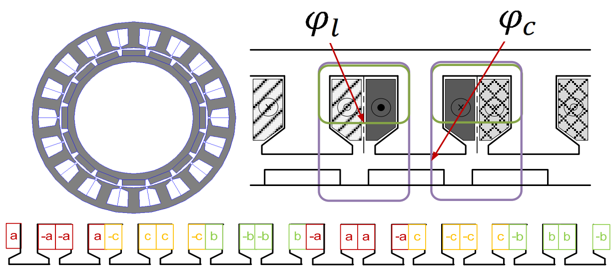

Fig. 2. Example of PM motor and concentric winding arrangement

areas of the coil. The fluxes of the different coils allow us to determine the self inductance L_k of the coil k and the different mutual inductances $M_{k,i}$. Self and mutual inductances can be divided in two parts: $L_k, M_{k,i}$ and L_σ, M_σ matching respectively with common flux φ_c and leakage flux φ_l as shown on Fig.2. Even if φ_l does not cross the air-gap, it contributes to the mutual inductance between the two coil. This is specific to concentric windings with two coils per slots. In the case of concentric windings and considering the symmetry of the machine, the previous calculation is performed once and permutation technique leads to obtain the inductance matrix of the healthy N_e coils:

$$L = \begin{bmatrix} L_1 + L_\sigma & M_{1,2} + M_\sigma & M_{1,3} & & M_{1,17} & M_{1,18} + M_\sigma \\ M_{1,18} + M_\sigma & L_1 + L_\sigma & M_{1,2} + M_\sigma & \cdots & M_{1,16} & M_{1,17} \\ M_{1,17} & M_{1,18} + M_\sigma & L_1 + L_\sigma & \cdots & M_{1,15} & M_{1,16} \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ M_{1,3} & M_{1,4} & M_{1,5} & \cdots & L_1 + L_\sigma & M_{1,2} + M_\sigma \\ M_{1,2} + M_\sigma & M_{1,3} & M_{1,4} & & M_{1,18} + M_\sigma & L_1 + L_\sigma \end{bmatrix}$$

A similar approach can be applied to distributed windings with single or double layer configurations.

IV. IDENTIFICATION WITH THE EXTERNAL MODEL

We consider that N_{cc} turns of coil 1 are short-circuited. The ratio μ becomes $\mu' = N_{cc}/N_t$. Additional row and column are inserted in the inductance matrix in order to represent the faulty coil. Unlike previous presented models, the self and mutual inductances $L_1, M_{1,i}$ $(i = 2, \ldots N_e)$ are affected by μ':

$$L_1{}' = (1 - \mu')^2 . L_1 \;\; ; \;\; M_{1,i}{}' = (1 - \mu') . M_{1,i} \qquad (6)$$

The self and mutual inductances of the additional circuit can be given by:

$$L_{N_e+1} = \mu'^2 . L_1 \;\; ; \;\; M_{N_e+1,i} = \mu' . M_{1i}$$
$$M_{1,N_e+1} = \mu' . (1 - \mu') . M_{1i} \qquad (7)$$

In addition to the self and mutual inductances corresponding to the common flux φ_c, the self and mutual inductances corresponding to the leakage flux have to be properly identified. The leakage inductances $L_{\sigma 1}$ and $L_{\sigma N_e+1}$ are added in the diagonal terms of the new matrix whereas the mutual leakage inductances $M_{\sigma 1,N_e+1}$, $M_{\sigma 1,2}$ and $M_{\sigma N_e+1,2}$ are added in the non-diagonal terms. These terms are calculated using magnetic field energy W in a slot considering a coil supplied by a current i :

$$L_\sigma,\, M_\sigma = 2 . W / i^2 \qquad (8)$$

The final matrix for the faulty machine is defined as:

$$L = \begin{bmatrix} (1-\mu)^2 . L_1 + L_{\sigma 1} & (1-\mu) . M_{1,2} + M_{\sigma 1,2} & & (1-\mu) . M_{1,18} + M_{\sigma 1,2} & \mu . (1-\mu) . L_1 + M_{\sigma 1,N_e+1} \\ (1-\mu) . M_{1,18} + M_{\sigma 1,2} & L_1 & & M_{1,17} & \mu . M_{1,18} + M_{\sigma N_e+1,2} \\ (1-\mu) . M_{1,17} & M_{1,18} & \cdots & M_{1,16} & \mu . M_{1,17} \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ (1-\mu) . M_{1,3} & M_{1,4} & \cdots & M_{1,2} & \mu . M_{1,3} \\ (1-\mu) . M_{1,2} + M_{\sigma 1,2} & M_{1,3} & & L_1 & \mu . M_{1,2} + M_{\sigma N_e+1,2} \\ \mu . (1-\mu) . L_1 + M_{\sigma 1,N_e+1} & \mu . M_{1,2} + M_{\sigma N_e+1,2} & & \mu . M_{1,18} + M_{\sigma N_e+1,2} & \mu^2 . L_1 + L_{\sigma N_e+1} \end{bmatrix}$$

By using the winding matrix connection, we can easily identify the fault parameters (3) and the no load EMF e_f.

V. VALIDATION OF THE METHOD USING FULL FEA

Self and mutual fault inductances are calculated using FEA and using the proposed method. Fig.4 shows the comparison between the results obtained by the two approaches for different values of μ'. A good agreement is observed between the two models. The slight difference is due to the assumption that saturation is only caused by the magnets. In fact, stator currents modify the local saturation level. Further comparisons using TSFEM will be presented in the extended version.

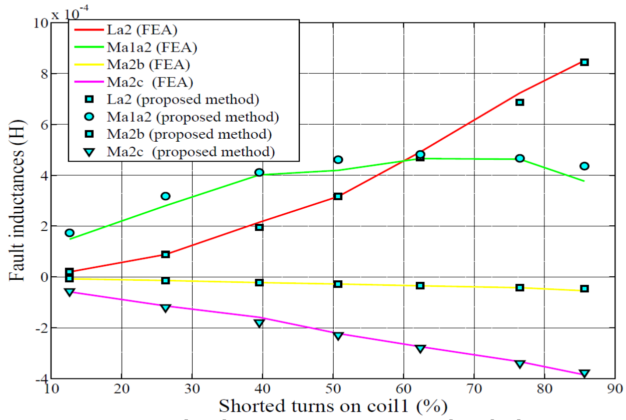

Fig. 4. Fault inductances: FEA vs proposed method

VI. CONCLUSION

The method proposed in this paper provides a new way to simulate PMSM under inter-turn faults. It can cover any type of windings and various fault configurations. Compared to TSFEM, it does not require a large CPU time and the accuracy of the results is not affected. Moreover, thanks to the theoretical expressions, parametric studies can be easily performed.

VII. REFERENCES

[1] T. Boileau, B. Nahid-Mobarakeh, F. Meibody-Tabar, “Back-EMF based detection of stator winding inter-turn fault for PM Synchronous Motor Drives”, *VPPC’2007* [CD-ROM], Arlington, Texas, U.S.A, Sept. 2007.

[2] P.P. Reichmeider, C.A. Gross, D. Querrey, D. Novosel, S. Salon, “Internal Fault in Synchronous Machines: Part I: The Machine Model”, *IEEE Trans. on Energy Conversion.*, vol.15, no.4, pp. 376-379, 2000.

[3] A.B. Dehkordi, A.M. Gole, T.L. Maguire, “Real Time Simulation of Internal Faults in Synchronous Machines”, *IPST’2007* [CD-ROM], Lyon, France, Jun. 2007.

[4] B. Vaseghi, B. Nahid-Mobarakeh, N.Takorabet, F. Meibody-Tabar, “Inductance Identification and Study of PM Motor with Winding Turn Short Circuit Fault”, *IEEE Trans. on Magn.*, [in press].