Modeling and Torque Ripple Control in Faulty SPMSM

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Abstract - **This paper presents a model of a Surface Permanent Magnet Synchronous Motor which can be used in a faulty case and a torque ripple control approach developed to be applied if the faulty case is detected. Two faulty cases are considered for study, the first consider an asymmetry between the stator phases of the motor created by unbalanced number of turns and the second a short circuit between the stator windings of the motor. Proposed torque ripple control use a phasor approach to provides the current reference for stator asymmetry and an injection of an inverse current for stator short circuit fault in order to decrease the motor torque ripple. The torque control has been implemented using a model of surface permanent magnet synchronous motor based on the dynamic equations. Simulation and experimental results highlight the link between the faulty and the torque ripple and show the possibility to decrease in this case the torque ripples by changing a balanced sinusoidal current reference by unbalanced one. In practical tests the impact of the unbalanced system of currents in the torque variation is studied using an analysis of vibratory harmonic measured at twice of the supply frequency.**

Keywords: *SPMSM, stator fault modeling, torque ripple control.*

I. INTRODUCTION

Surface **P**ermanent **M**agnet **S**ynchronous **M**otors (**SPMSM**) are widely used in various applications such as airplanes, industry, electric vehicles, etc ... These machines have multiple advantages like high performance, high torque density, robust construction and no use of brushes [1,2]. However, torque ripples generated by SPMSM and iron losses in the rotor are factors that hinder their use and reduce SPMSM efficiency [3-5].

The unbalanced of magnetic field in an electric motor, the demagnetization of the rotor, a short circuit between turns or rotor eccentricity, leads to increase the torque ripple and also the losses [6-8]. In these cases the global system reliability can decrease if the control of the currents is not adjusted for taking into account the motor fault [9, 10]. This is true for some specific applications such as those related to electric vehicles or aircraft systems.

Reducing torque ripple in a healthy synchronous motor has been the subject of several researches and different strategies have been proposed. The best known method is to control the stator currents to compensate the torque ripple. These currents are calculated by several methods, some of them uses the decomposition of the electromotive force in Fourier series to determine a limited number of current harmonics while others use the finite element method to estimate their parameters (amplitude, frequency) [11-13] or methods developed for determination of harmonic currents through an analytical modeling approach and an optimization criterion [14].

In the case of a faulty synchronous motor the torque ripple increases. As solution, some works develop methods based on dynamic modeling of the faulty machine that use mathematical development with voltages, flux and currents, separated in direct and inverse components [15].

Another method developed for multiphase motors use a phasor approach and the electromotive force to compute the optimal current references in order to maintain a smooth torque and minimal joule losses [16].

The aim of presented work is to compensate the torque ripple in a faulty case. The proposed method is based on control strategy of the stator currents obtained by a product of two phasors, the stator flux space phasor and current space phasor. A simplified analytical model of a SPMSM is used to elaborate the control strategy developed to decrease the effect of the fault. The considered fault is a stator's winding asymmetry and the proposed strategy control allows one to decrease the torque ripple and to maintain motor performance near the healthy case one. In this paper, the stator's winding asymmetry is generated by about 5.5 % lack of turns of the phase "A" of the motor.

This paper is organized as follows: in section II the model developed of the surface permanent magnet synchronous motors is presented. In section III the approach used to calculate the reference currents in order to reduce the torque ripple is given. Simulation results are presented in the last section of the paper to validate the proposed approach.

II. SPMSM ANALITICAL MODEL

The developed model to simulate the SPMSM operating is a three-phase dynamic model based on the equivalent electrical circuit. This model enables to consider the stator winding asymmetry fault easily. However it does not take into account the iron losses and saturation [10].

The electrical model considered is shown in Fig.1. With this model, it is possible to introduce the fault (unbalance number of turns between the three phases of the motor stator windings) by adapting the different machine parameters for each phase.

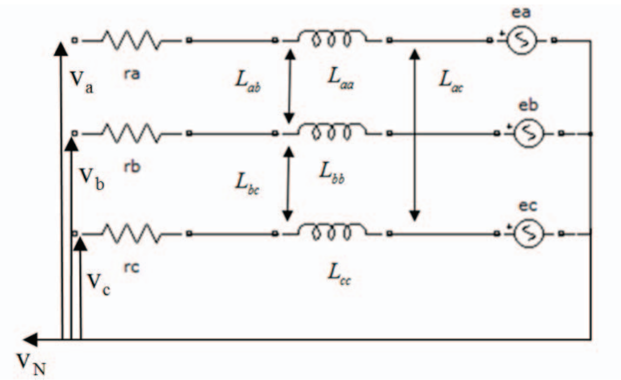


Fig. 1. Electrical model of the SPMSM used for simulation of the winding asymmetry fault.

In this model ra, rb, rc, Laa, Lbb, Lcc are the resistances and the main cyclic self inductances of each stator phase, ea, eb, ec are the electromotive forces and Lab, Lbc, Lac are the mutual inductances of stator windings.

A. Electrical Equations

In the proposed model the following electrical equations are considered:

$$V_{abc} = r_{abc} i_{abc} + \frac{d\psi_{abc}}{dt} \qquad (1)$$

$$\psi_{abc} = L_{abc} i_{abc} + \psi_{rabc} \qquad (2)$$

where i_{abc} are the stator currents, ψ_{abc} the stator flux and V_{abc} the phase-to-neutral voltage. These parameters can be expressed as:

$$V_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad e_{abc} = \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad i_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \psi_{abc} = \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix}$$

$$r_{abc} = \begin{bmatrix} r_a & 0 & 0 \\ 0 & r_b & 0 \\ 0 & 0 & r_c \end{bmatrix} \quad L_{abc} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \quad \psi_{rabc} = \begin{bmatrix} \psi_{ra} \\ \psi_{rb} \\ \psi_{rc} \end{bmatrix}$$

where L_{abc} is the inductance matrix, ψ_{rabc} the phasor of rotor flux and e_{abc} the electromotive force vector. In this model it is considered that the neutral point is not connected, therefore the sum of the stator currents is equal to zero:

$$i_a + i_b + i_c = 0 \qquad (3)$$

the stator fluxes are defined as:

$$\begin{aligned} \psi_a &= L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + \psi_{ra} \\ \psi_b &= L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + \psi_{rb} \\ \psi_c &= L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + \psi_{rc} \end{aligned} \qquad (4)$$

Considering the flux in each coil expressed with only i_a and i_b currents (4) can be expressed as:

$$\begin{aligned} \psi_a &= (L_{aa} - L_{ac}) i_a + (L_{ab} - L_{ac}) i_b + \psi_{ra} \\ \psi_b &= (L_{ba} - L_{bc}) i_a + (L_{bb} - L_{bc}) i_b + \psi_{rb} \\ \psi_c &= (L_{ca} - L_{cc}) i_a + (L_{cb} - L_{cc}) i_b + \psi_{rc} \end{aligned} \qquad (5)$$

In the developed SPMSM model for healthy and faulty case, (1-5) are used to determine the expression of flux and currents. In presence of the fault, the potential of the neutral point can vary. For modeling, equations independent of neutral point can be used:

$$\begin{aligned} \frac{d\psi_a}{dt} - \frac{d\psi_b}{dt} &= V_a - V_b - r_a i_a + r_b i_b \\ \frac{d\psi_a}{dt} - \frac{d\psi_c}{dt} &= V_a - V_c - (r_a + r_c) i_a - r_c i_b \end{aligned} \qquad (6)$$

The current expressions are obtained from (5) and (3):

$$\begin{aligned} i_a &= \frac{B(\psi_a - \psi_c) - D(\psi_a - \psi_b - \psi_{ra} + \psi_{rb})}{BC - AD} \\ i_b &= \frac{C(\psi_a - \psi_b - \psi_{ra} + \psi_{rb}) - A(\psi_a - \psi_c)}{BC - AD} \\ i_c &= -i_a - i_b \end{aligned} \qquad (7)$$

where $A = L_{aa} - L_{ac} - L_{ba} + L_{bc}$; $B = L_{ab} - L_{ac} - L_{bb} + L_{bc}$; $C = L_{aa} - L_{ac} - L_{ca} + L_{cc}$ and $D = L_{ab} - L_{ac} - L_{cb} + L_{cc}$

B. Electromagnetic Torque

In the considered model, the electromagnetic torque is obtained from vector product between the flux and the current space phasors. It can be expressed:

$$T_e = \frac{3p}{2} [\psi_s \wedge i_s] \qquad (8)$$

where p is the pole pair number. Ψ_s and i_s are the space vector of the flux and the stator current defined as:

$$\psi_s = \frac{2}{3} [\psi_a + a\psi_b + a^2 \psi_c] \qquad (9)$$

$$i_s = \frac{2}{3} [i_a + a i_b + a^2 i_c] \qquad (10)$$

with $a = \exp(i2\pi/3)$.

C. Mechanical Equation

The SPMSM rotor angular speed Ω is obtained from classical mechanical equation:

$$J \frac{d\Omega}{dt} = T_e - f_f \Omega - T_r \qquad (11)$$

where J is the moment of inertia, T_e the electromagnetic torque, T_r the load torque and f_f the friction parameter. The rotor angular speed is used to calculate the angular position:

$$\theta = \int \Omega dt \qquad (12)$$

D. SPMSM Simulation Model

1) Principle for healty case and faulty case

The bloc diagram presented in Fig 2 shows the principle of the simulation used in the considered model. The rotor flux values are stored in recording tables. Then they are read as a function of the angle θ of the rotor position.
In this model a sine signal is considered for simulation but in real case this parameter can be obtained from integration of electromotive forces which are previously identified using the SPMSM in alternator mode:

$$\psi_{rabc} = \int e_{abc} dt \qquad (13)$$

The rotor position angle is obtained from electromagnetic and load torque using (11) and (12). For torque calculation the phasor approach given by (8),(9) and (10) is used. At the end of the bloc diagram, the currents i_a, i_b, i_c supplying the SPMSM are obtained from electrical equations where the stator flux given by (4) at $t{=}t{-}\Delta t$ (Δt simulation step) is also used as input value.

2) SPMSM parameters

To simulate the faulty case, 1/18 lack of turns of the phase “A” winding is considered. Each phase is composed of 6 elementary coils with distribution presented in Fig. 3.

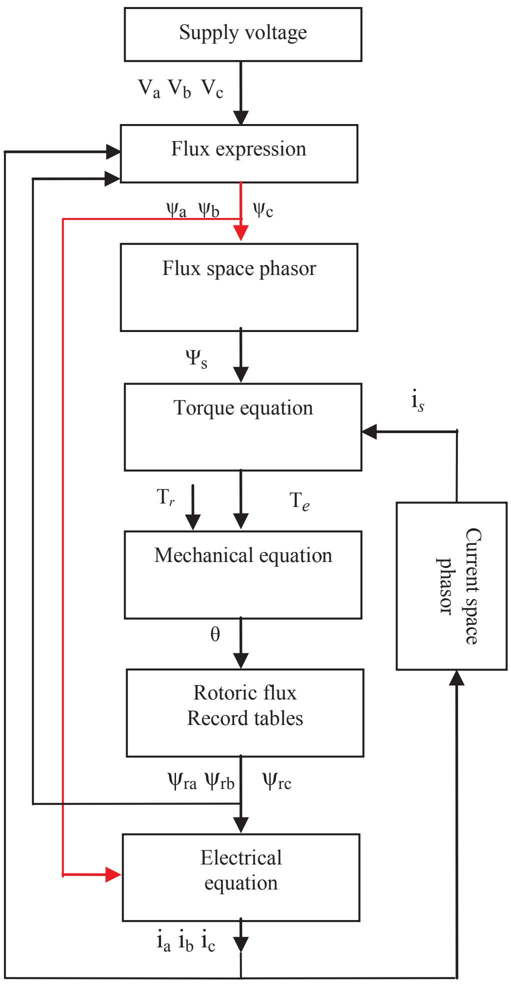


Fig. 2. Bloc diagram of the SPMSM model used in simulation for healthy and faulty case.

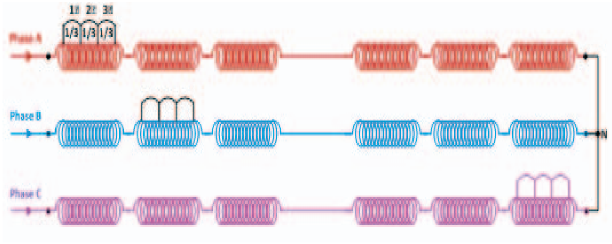


Fig.3. Turns distribution of the SPMSM used for simulation of the wining asymmetry fault. The first 1/3 turns of the first elementary coil of the phase “A” are not supplied by V_a voltage in the faulty case.

The fault corresponds to 1/3 of the first elementary coil of the phase “A”. This lack of turns introduces a change for each corresponding parameters taken in consideration by a step changing at *t=30s* from healthy to faulty parameters value during simulation.

The parameter values used in simulation for healthy and faulty case are presented in Table I where the subscript “f” means that the resistances and the inductances are related to the faulty case.

In practical case the determination of the SPMSM parameters in the healthy and faulty case is based on the method presented in [17] which use the magnetomotive force (mmf) generated by the stator winding in healthy and faulty case to calculate the inductance. The following relationship is used:

$$L_{xy} = \mu_0 RL \int_0^{2\pi} N_x(\alpha_s) N_y(\alpha_s) e^{-1}(\alpha_s) d\alpha_s \qquad (14)$$

where: L_{xy} is the self inductance (x=y), mutual inductance (x≠y) between windings *x* and *y*; μ_0 permeability of vacuum; R the radius of the stator; *L* the length of the slots; $N_x(\alpha_s)$, $N_y(\alpha_s)$ are magnetomotive force the of the windings ‘*x*’ respectively ‘*y*’ crossed by a unit current; e thickness of the air gap; α_s the angular abscissa of a point in the air gap in a stator reference. The numerical values applied in simulation are: V_A, V_B,V_C, =200 V, J=0.002 NM^2, F_F=0.0075.

III. Phasor Approach for Estimate the Reference Currents in Asymmerty Fault

The objective of the presented application is the reduction of torque ripple which increases in faulty case. According to the study of the torque equation, this one is derived from a vector product between the flux space vector and current space vector.

TABLE I.
PARAMETERS USED FOR SPMSM MODELISATION IN HEALTHY AND FAULTY CASE

r_a (Ω)	r_b (Ω)	r_c (Ω)	L_{aa} (mH)	L_{bb} (mH)	L_{cc} (mH)	L_{ab} (mH)	L_{ac} (mH)	L_{ba} (mH)
3.56	3.56	3.56	74.3	74.3	74.3	-37.2	-37.2	-37.2
L_{bc} (mH)	L_{ca} (H)	L_{cb} (H)	L_{aaf} (H)	L_{abf} (H)	L_{acf} (H)	L_{baf} (H)	L_{caf} (H)	r_{af} (Ω)
-37.2	-37.2	-37.2	70.2	-35.1	-35.1	-35.1	-35.1	3.362

Therefore, to produce a maximum torque, it is necessary that the current and the flux are in quadrature. In the basic control of the synchronous machine, the current is forced to move following the q axis (*$i_d=0$*). This procedure will not be verified in the case of a faulty machine where the rotor flux is no longer along the "d" axis [18]. So the control must respect following proprieties:

1) following a constant torque

$$T_e = \frac{3p}{2}(\psi_d i_q - \psi_q i_d) = cst \tag{15}$$

2) having a maximum torque (the flux is in quadrature whit the current

$$\psi_d i_d = -\psi_q i_q \tag{16}$$

where i_d and i_q are direct and quadrature components of the space phasor of the stator reference current. From (15) it can be written:

$$\begin{cases} i_d = -\dfrac{\psi_q i_q}{\psi_d} \\ i_q = -\dfrac{\psi_d i_d}{\psi_q} \end{cases} \tag{17}$$

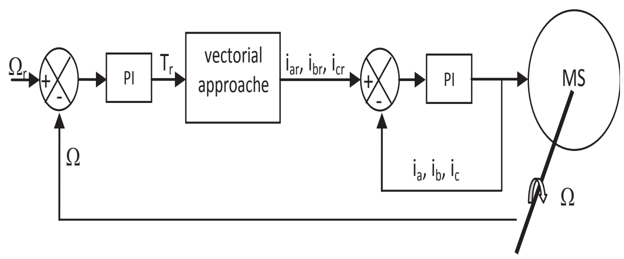
Replacing (17) in the torque equation, the current reference giving constant torque without variations is obtained:

$$\begin{cases} i_d = -\dfrac{2T_e}{3p}\dfrac{\psi_q}{\psi_q^2+\psi_d^2} \\ i_q = \dfrac{2T_e}{3p}\dfrac{\psi_d}{\psi_q^2+\psi_d^2} \end{cases} \tag{18}$$

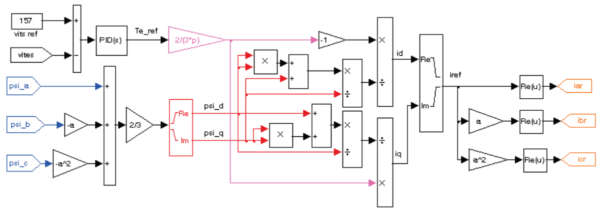
The direct and quadrature components of the flux space phasor ψ_d and ψ_q used in (18) are obtained from (9) and (5) considering the real and imaginary components of the space phasor flux:

$$\begin{cases} \psi_d = \mathrm{Re}(\psi_s) \\ \psi_q = \mathrm{Im}(\psi_s) \end{cases} \tag{19}$$

The global scheme of the phasor approach used to determine the current references for each phase of the motor is presented in Fig. 4a and a detailed implementation in matlab simulink of the phasor approach in Fig. 4.b.



a)



b)

Fig.4. Control loop applied to SPMSM a) scheme of global phasor control loop b) matlab implementation of phasor approach.

In matlab implementation the proportional integral constant values of the PI blocs used in the control loop for torque reference Tr are $K_{t\_P}= 2$, $K_{t\_I}= 1$ and for current references are $K_{c\_P}= 1000$, $K_{c\_I}= 500$.

IV. Approach for Estimate the Reference Currents in Inter-Turns Short Circuit Fault

If a stator inter-turns short circuit appear it induces torque ripple at twice of supply frequency and reduces the average torque [19, 20]. The torque harmonic component at twice of supply frequency mainly provides from the stator inverse sequence space harmonics of magnetomotive force (mmf) at h = -2 and by the fundamental rotor space harmonics flux density. In order to reduce this torque harmonic it is necessary to cancel the mmf at h=-2, for the considered machine with 2 pole pairs [21].

The SPMSM is assumed to be supplied with sine currents. The strategy for calculation of stator currents to decrease the space harmonic stator mmf at h = -2 in the case of a stator inter-turn short circuit in one phase winding is performed using the complex notation of the mmf components. So in order to decrease the negative sequence mmf of faulty SPMSM, an analytical method is developed which allow to determine the rms value $\mathrm{I_i}$ which must be injected in the global current references [21].

For study it is considered a stator elementary coil composed of two beams, one of them has a side inserted into the slot 3 and the other side inserted into the slot 10. In the case when the short-circuit fault occurs in this coil the relationship used between the direct current and the inverse current [22] used to compensate the harmonic of rank h=-2 is given by:

$$\overline{\mathrm{I_i}} = \frac{\mathrm{I_d}\sum\limits_{j=3,10} e^{j(-2\beta_j^s+\varphi_{dj})} - \mathrm{I_{cc}}\sum\limits_{j=3,10} e^{j(-2\beta_j^s+\varphi_{ccj})}}{\sum\limits_{j=1}^{N_t^s} e^{j(-2\beta_j^s+\varphi_{ij})}} \tag{20}$$

where I_{cc} is the rms value of the current in the coil where occurs the inter-turn short circuit and I_d the rms value of direct balanced currents system. The other parameters presented in (20) are:

β_j^s : angular position of the stator slot *j*.

φ_{dj} : phase angle of $\mathrm{I_d}$ current in the slot *j*.

φ_{ccj} : phase angle of $\mathrm{I_{cc}}$ in the slot *j*.

φ_{ij} : phase angle of inverse current I_i in the slot j.

N_t^s : total stator slot number.

Equation (20) leads to decrease the mmf space harmonic of rank h=-2, and then to reduce the torque ripple at twice the supply frequency. To simplify this equation, it is put in following form:

$$\overline{I_i} = \frac{I_d B - I_{cc} A}{C} \tag{21}$$

with A, B and C

$$A = \sum_{j=3,10} e^{j(-2\beta_j^s + \varphi_{ccj})} , B = \sum_{j=3,10} e^{j(-2\beta_j^s + \varphi_{dj})} ,$$

$$C = \sum_{j=1}^{N_t^s} e^{j(-2\beta_j^s + \varphi_{ij})}$$

In Fig.5 it is presented the diagram computation method of the temporal corrected current reference able to decrease the torque ripple. To validate this control strategy, first a direct balanced currents system of I_d rms value and f frequency is considered. The inverse current $\overline{I_i}$ is given by (20), and the reference current $\overline{I}_{ar}, \overline{I}_{br}, \overline{I}_{cr}$ to cancel torque ripple at 2f is calculated. Finally the time current references i_{ar}, i_{br}, i_{cr} are reconstructed. In following expressions "a" is a complex number: a= $e^{j2\pi/3}$.

V. Simulation Results

The simulation model of the SPMSM has been realized using MATLAB / Simulink. In order to test the torque regulation, a fault is simulated at t=30s.

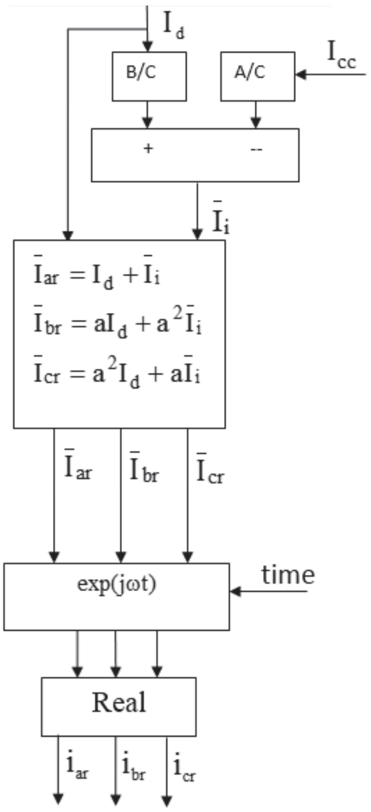


Fig. 5. Diagram computation of the temporal corrected currents reference

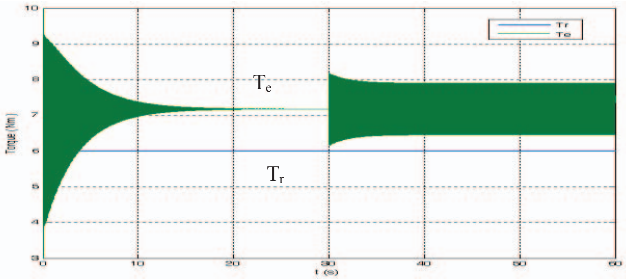


Fig.6. Electromagnetic torque Te and load torque Tr variation in healthy and faulty case for SPMSM supplied by balanced system of currents. Fault simulated at t=30s.

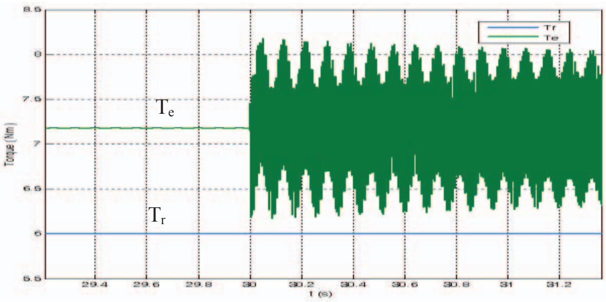


Fig.7. Zoom of electromagnetic and load torque (Te and Tr) around to faulty case for motor supplied by balanced system of currents.

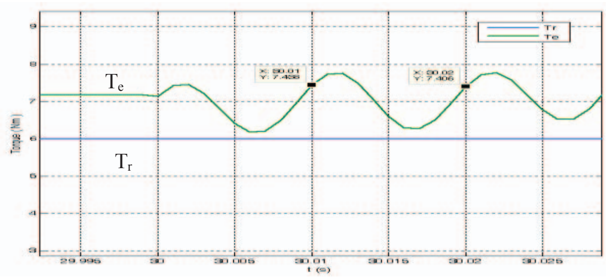


Fig.8. Zoom of electromagnetic and load torque (Te and Tr) at t= 30s to faulty case for motor supplied by balanced system of currents. Torque undulation at 100 Hz.

The fault is located in the first elementary section of the phase "A" by reducing its number of turns of two thirds of one elementary section. To analyze the impact of the current on the torque and speed variation, two cases are studied: the first one considers the motor supplied by a balanced system of currents, the second one considers the motor supplied by currents obtained with phasor approach presented in (18).

In this case the motor is integrated in a control loop in order to maintain the control law during the healthy and faulty cases.

The variation of electromagnetic and load torques (*Te, Tr*) for SPMSM supplied by balanced system of currents is shown in Fig. 6. In this case, the load torque remains constant at 6 Nm until the fault appear at *t=30s*.

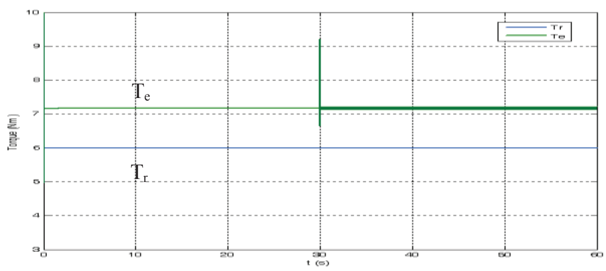


Fig.9. Electromagnetic *Te* and load torque *Tr* variation in healthy and faulty case for SPMSM supplied by unbalanced system of currents during the fault. Fault simulated at t=30s.

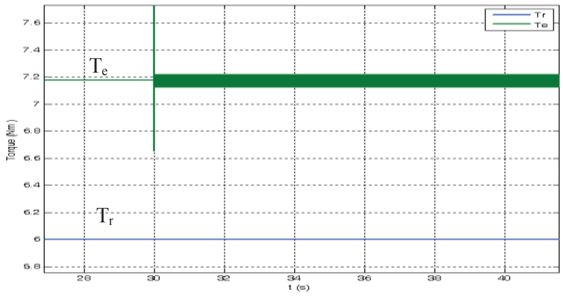


Fig.10. Zoom of electromagnetic and load torque (*Te* and *Tr*) around to faulty case for SPMSM supplied by unbalanced system of currents during the fault.

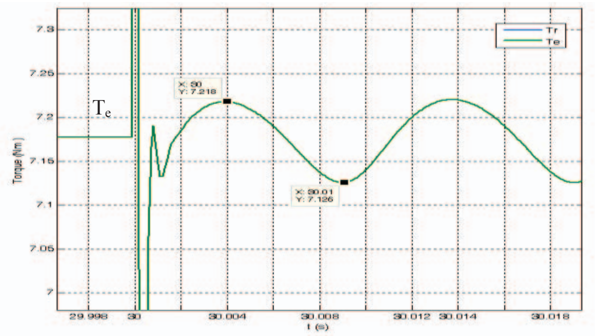
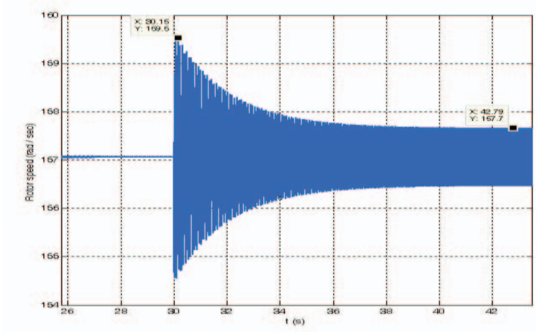


Fig.11. Zoom of electromagnetic torque (*Te*) at t= 30s to faulty case for SPMSM supplied by unbalanced system of currents. Torque undulation at 100 Hz.

The Fig. 7 shows a zoom around the time when the fault occurs. It can be remarked the torque variation between T_{min}= 6.2Nm and T_{max}= 8.2Nm. In Fig. 8 it is shown a zoom of the torque variation for the first two periods after the fault appearance. It can be noticed the electromagnetic torque variation at 100Hz frequency which corresponds to the double frequency of the supply currents (50Hz).

The torque variation can be demonstrated in practical tests by analyzing the spectrums of an accelerometer. The amplitude of vibration harmonic at 100Hz given by the accelerometer increases in faulty case.

The next simulation presented in Fig. 9 shows the variations of electromagnetic and load torques for SPMSM integrated in a control loop using a flux space vector control. Here the reference currents are calculated for each phase in order to decrease the torque variation so, during the faulty case the motor is supplied by unbalanced system of currents. Figure 10 shows a zoom of the Fig.9 around the time when the fault occurs and Fig. 11 a zoom of the torque variation for the first two periods after the fault appearance. It can be noticed that in presence of a flux control, one can obtain an important decrease of the torque variation (T_{min}= 7.12 Nm and T_{max}= 7.22 Nm) compared to the case without phasor flux control.



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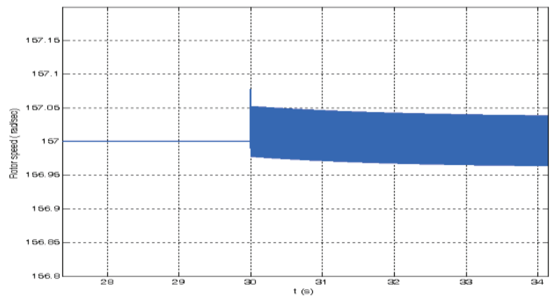
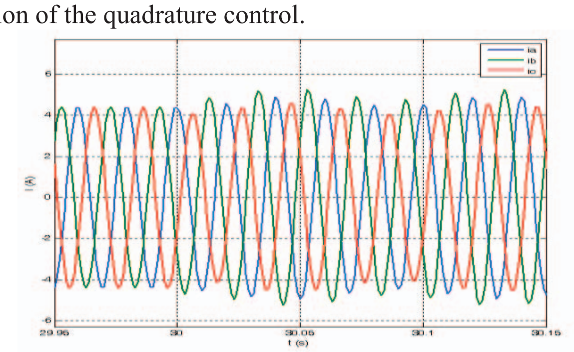


b)

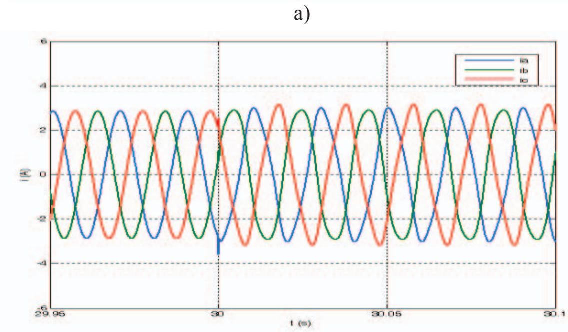
Fig.12. Speed variation during the faulty case for SPMSM supplied by: a) balanced system of currents, b) unbalanced system of currents.

The variation of the rotor speed around of *t=30s* is presented in Fig. 12. In the case of a faulty SPMSM supplied by balanced system of currents (Fig.12.a) the speed variation takes values between Ω_{min}= 156.5 rad/sec and Ω_{max}= 157.7 rad/sec. For a faulty SPMSM supplied by unbalanced system of currents (Fig. 12.b) like in the case of the torque, the speed variation is much decrease (between Ω_{min}= 156.98 rad/sec and Ω_{max}= 157.5 rad/sec) and the time of transient state is reduced.

Figure 13.a shows the currents variation for a motor supplied by balanced system of currents during the faulty case (starting at t=30s) and Fig. 13.b shows the currents waveform for SPMSM integrated in a control loop with unbalanced currents during faulty operation. In this case a control in quadrature between the stator flux and the currents is considered. It can be remarked a higher amplitude of the currents in Fig. 13.a and more variation during the faulty state in correlation with more important torque ripple as shown in Fig. 6, Fig. 7 and Fig.8. The decrease of the current amplitude in Fig.13.b for the same load and electromagnetic torque can be explained by the optimization of the quadrature control.



a)



b)

Fig.13. Current variation during the faulty case for SPMSM supplied by: a) system without currents control b) unbalanced system of currents.

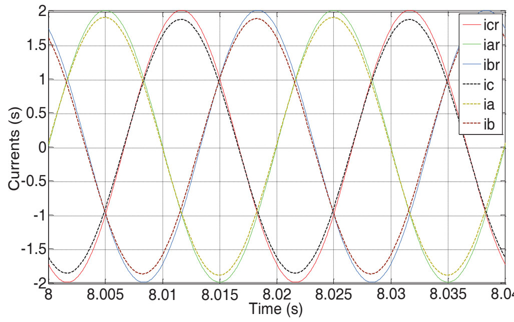


Fig. 14. Balanced stator currents supplying the faulty SPMSM: the reference and supply current.

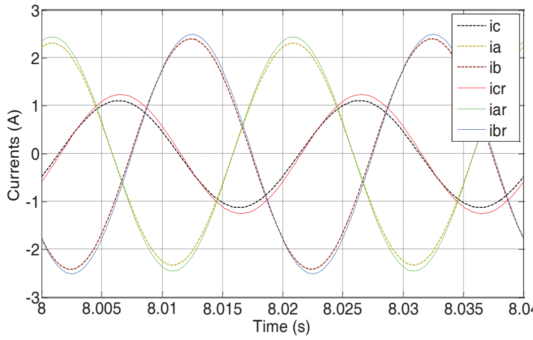


Fig. 15. Corrected stator currents for the faulty SPMSM: the reference and supply current.

The simulation case for a short-turn introduced into the first elementary section located in the winding phase A (Fig.3) is presented in the next simulations.

In Fig. 14 is simulated the currents variation for faulty SPMSM supplied by balanced currents and in Fig. 15 the currents variation faulty SPMSM supplied by corrected currents. In considered faulty case the short-turns current has a peak value of 14A with the same frequency as the supply currents and the inverse current is I_i =0.53A rms value. It can be remarked that the currents are still regulated and the references make an unbalanced system.

VI. Experimental Results

Simulations presented in paragraph V shows that it is possible to reduce the torque variation for asymmetry or short circuit in the stator windings of SPMSM by using adapted unbalanced current references. In experimental tests the influence of unbalanced currents in the decrease of torque variation if a faulty appears is bring to the fore by using an accelerometer sensor as shown in Fig. 16.

Vibration sensor

Fig. 16. Measurement of SPMSM vibrations in faulty case.

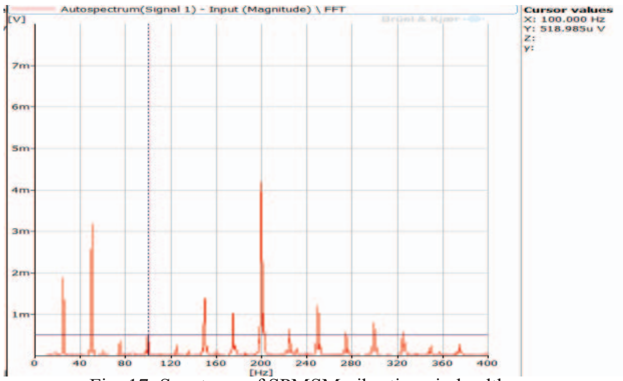


Fig. 17. Spectrum of SPMSM vibrations in healthy case.

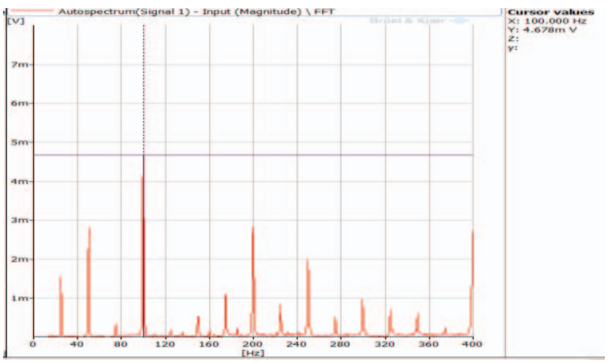


Fig. 18. Spectrum of SPMSM vibrations in faulty case.

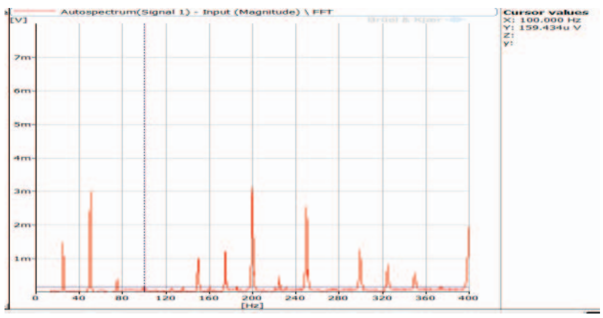


Fig. 19. Spectrum of SPMSM vibrations in faulty case after injection of inverse current.

The accelerometer sensor is connected to a frequency analyzer Brüel&Kjær 3560 which give the FFT spectrum of measured signal.

The spectrums for healthy machine, machine with short-turn faulty in the windings of the phase A and machine with correction by injection of an inverse current I_i are presented in Fig. 17, Fig. 18 and Fig. 19. Analyzing the accelerometer spectrum we can remarked in Fig. 17 the vibration harmonic measured at frequency 100Hz (rank h=-2) have 519μV amplitude; in Fig. 18 the same harmonic increase at 4670 μV and in Fig. 19 after correction with imbalanced currents the amplitude of harmonic at frequency 100Hz decrease at 159.43μV. This experimental test confirms the possibility to decrease the torque ripple by using specific non-balanced supply currents.

VII. Conclusion

This paper proposes a model for a Surface Permanent Magnets Synchronous Motor (SPMSM) which allows to study the motor torque ripple and an adapted current control in healthy and faulty case. The simulation result has shown the link between the presence of the fault in the motor and the increase of the torque ripple. As solution to reduce the torque ripples it is proposed, an adequate control of the currents using a phasor approach for asymmetry fault or injection of an inverse current for short-circuit fault. This approach is based on the use of unbalanced currents.

The simulation has been tested considering an asymmetry created by unbalanced number of turns in the motor stator windings and a short circuit in the stator windings of the SPMSM phase A. This solution does not affect the motor operation but we must mention here that the variation of absorbed power from supply has an important increase and this solution must be correlated in practical applications with the performances of the available supply used for the global system

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