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SIMULATION OF THE PERMANENT MAGNETS SYNCHRONOUS MACHINE DRIVE IN FAULT CONDITIONS

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Abstract **– By a proper choice of the motor, of its control strategy and of the architecture of the power electronics feeding the motor, the reliability of electromechanical actuation systems, as those used in aerospace applications, may be improved. This paper presents a Simulink library for the simulation of the motor and of its control electronics, both in normal operation conditions and certain faults. The motors models allow choosing between three types of motor and between two types of vector control. The simulation of different fault conditions was requested in order to identify the weak and strong points of different architectures. The research reported in this paper was performed within the European Union FP6 project DRESS (Distributed and Redundant Electromechanical nose gear Steering System) for more electrical aircraft (http://www.dress-project.eu).**

Keywords: *PMSM, vector control, fault operation, Simulink library.*

1. INTRODUCTION

The permanent magnets synchronous machine is a well known compact motor, suited for high power density applications. In most of electrical drives using this type of machine, the motor is Y connected, fed by a three phase inverter and equipped with a classic vector control allowing the regulation of the torque. A way to improve the reliability of such type of drives consists of choosing a power electronic architecture allowing a two phase remedial operation [1, 2, 3]. The paper will present a Simulink library which allows the study of several architectures, both under normal and fault operation. Basically, the investigated architectures are the classic PM synchronous machine fed by a three phase inverter and equipped with a classic vector control and two variants of a more special type of motor, the HDD servomotor® [4]. This last type offers, in addition to a higher torque to mass ratio, the very interesting feature of having magnetically and mechanically decoupled phases and the possibility to split each phase into two half phases, also mechanically and magnetically decoupled. Furthermore in addition to the classic vector control, a phase by phase pseudo vector control is also considered. This type of control is suited for HDD servomotors both for normal and fault operation, but for the classic PM synchronous machine only for normal operation.

The paper will present the approach for building the different models, their inter-connection and some results of the simulation of the different systems.

As the work described in this paper presents only a part of the models developed within the DRESS project, in the very first stages of the work, a model assembly philosophy was stated. In accordance with this, the models of the motors must have as inputs the phase voltages delivered by the inverter, the mechanical speed and position of the rotor. The outputs must be the phase currents and the electromagnetic torque. The mechanical parameters (rotor inertia, friction) are included in the model of the mechanical load (not presented in the paper) which is then driven by the electromagnetic torque. The controllers which deliver the reference phase voltages must have as input the electromagnetic torque reference, delivered by an upper level controller.

Finally, it should be noted that the PWM inverters are considered to act as pure gains blocks in the proposed library.

2. MOTORS MODELS

The requirements in building the models were that they must be able to deal with several types of fault:

- a broken phase (i.e a phase in open circuit);
- a phase totally or partially short circuited;
- the loss of a current sensor.

For this reason, the machines were modelled in terms of instantaneous phase variables.

2.1 Three phase classic PMSM with separated phases

The first architecture considered corresponds to the classic PM synchronous motor with separated feeding of the phases, each phase being fed by an H bridge (Fig. 1).

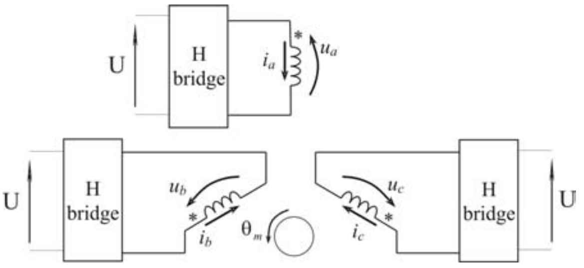


Fig. 1 - Three phase machine with separated phases

In this case the electrical equations are (all the notations are specified in the Appendix):

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + $$
$$+ K_T \dot{\theta}_m \begin{bmatrix} -\sin P\theta_m \\ -\sin\left(P\theta_m - \frac{2\pi}{3}\right) \\ -\sin\left(P\theta_m - \frac{4\pi}{3}\right) \end{bmatrix} \tag{1}$$

The electromagnetic torque is given by the expression:

$$T_{em} = -K_T \left(i_a \sin P\theta_m + i_b \sin\left(P\theta_m - \frac{2\pi}{3}\right) + \right.$$
$$\left. + i_c \sin\left(P\theta_m - \frac{4\pi}{3}\right) \right) \tag{2}$$

In these equations, rotor zero position is considered to correspond to the maximum coupling between phase “a” and the rotor, so that the flux induced in the phase “a” by the magnets is maximum for $\theta_m = 0$. Consequently, assuming a sinusoidal coupling, the back emf induced by the magnets in phase “a” will be:

$$e_a = -P\Phi_M \dot{\theta}_m \sin P\theta_m = -K_T \dot{\theta}_m \sin P\theta_m , \tag{3}$$

with $K_T = P\Phi_M$.

With this model, the following faults can be simulated:

- one phase in open circuit is simulated by imposing simultaneously its current and *di*/*dt* to zero;
- one phase in short circuit is simulated by imposing to zero the corresponding feeding voltage;
- fault of a current sensor is simulated by imposing to zero the feedback value of the current on one phase (phase “a”).

2.2 Classic PMSM with star connected windings and insulated neutral

If the machine phases are star connected with insulated neutral, it must be fed by a three phase inverter (Fig. 2).

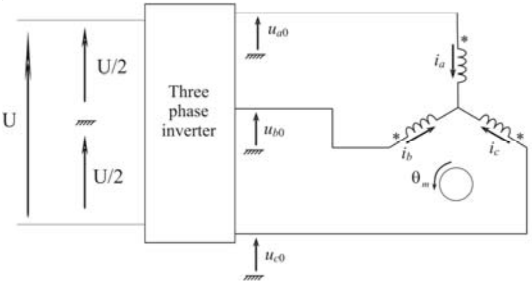


Fig. 2 - Three phase machine star connected

Since in this case $i_a + i_b + i_c = 0$ and the input variables controlled by the inverter are the line voltages u_a-u_b, u_b-u_c and u_c-u_a, their sum being equal to zero, only two of them are independent, so the motor equations can be written in terms of line voltages [5].

With $i_c = -i_a - i_b$, the electromagnetic torque is obtained with the same expression as the previous model.

With this model, the fault that can be simulated is the current sensor failure as for the previous model.

2.3 HDD servomotor with separated six half phases

The HDD servomotors (Fig. 3) has six physically and magnetically separated half phases which can be fed by six H bridges.

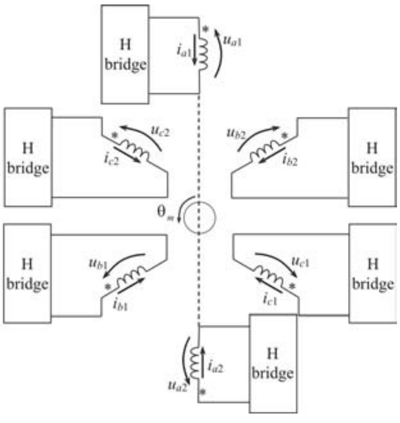


Fig. 3 - HDD Servomotor

The model consists in the concatenation of two three phase machines with no mutual inductances between the phases, shifted between them by 180°.

In addition to the faults that can be simulated for the three phase classic PMSM with separated phases (Fig. 1), considering the case of partial short circuit of several turns of one winding was of interest for the research. In this case, the equivalent circuit is the one depicted in Fig. 4.

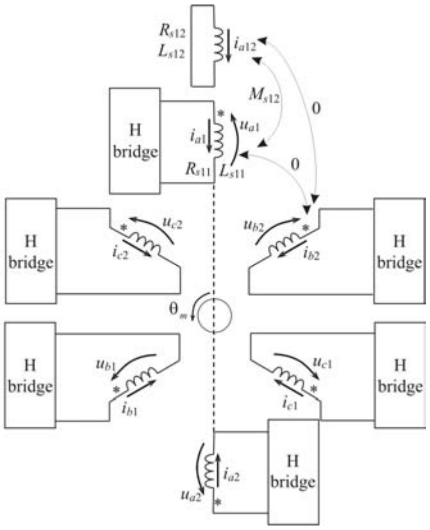


Fig. 4 - HDD servomotor with partial short circuit

It is important to note that in this case a seventh circuit appears corresponding to the section in short circuit. The corresponding equations are

$$\begin{bmatrix}u_{a1}\\ u_{c2}\\ u_{b1}\\ u_{a2}\\ u_{c1}\\ u_{b2}\\ 0\end{bmatrix}=\left[R\right]\begin{bmatrix}i_{a1}\\ i_{c2}\\ i_{b1}\\ i_{a2}\\ i_{c1}\\ i_{b2}\\ i_{a12}\end{bmatrix}+\left[L\right]\frac{d}{dt}\begin{bmatrix}i_{a1}\\ i_{c2}\\ i_{b1}\\ i_{a2}\\ i_{c1}\\ i_{b2}\\ i_{a12}\end{bmatrix}+$$

$$+K_T\dot{\theta}_m\begin{bmatrix}0\\ -\sin\left(P\theta_m-\frac{\pi}{3}\right)\\ -\sin\left(P\theta_m-\frac{2\pi}{3}\right)\\ -\sin\left(P\theta_m-\pi\right)\\ -\sin\left(P\theta_m-\frac{4\pi}{3}\right)\\ -\sin\left(P\theta_m-\frac{5\pi}{3}\right)\\ 0\end{bmatrix}+\dot{\theta}_m\begin{bmatrix}K_{T11}\left(-\sin P\theta_m\right)\\ 0\\ 0\\ 0\\ 0\\ 0\\ K_{T12}\left(-\sin P\theta_m\right)\end{bmatrix}, \quad (4)$$

with

$$\left[R\right]=\begin{bmatrix}R_{s11}&0&0&0&0&0&0\\ 0&R_s&0&0&0&0&0\\ 0&0&R_s&0&0&0&0\\ 0&0&0&R_s&0&0&0\\ 0&0&0&0&R_s&0&0\\ 0&0&0&0&0&R_s&0\\ 0&0&0&0&0&0&R_{s12}\end{bmatrix}, \quad (5)$$

$$\left[L\right]=\begin{bmatrix}L_{s11}&0&0&0&0&0&M_{s12}\\ 0&L_s&0&0&0&0&0\\ 0&0&L_s&0&0&0&0\\ 0&0&0&L_s&0&0&0\\ 0&0&0&0&L_s&0&0\\ 0&0&0&0&0&L_s&0\\ M_{s12}&0&0&0&0&0&L_{s12}\end{bmatrix}. \quad (6)$$

The electromagnetic torque is in this case given by

$$\begin{aligned}T_{em}&=-K_T\left(i_{c2}\sin\left(P\theta_m-\frac{\pi}{3}\right)+i_{b1}\sin\left(P\theta_m-\frac{2\pi}{3}\right)+\right.\\ &\left.+i_{a2}\sin\left(P\theta_m-\pi\right)+i_{c1}\sin\left(P\theta_m-\frac{4\pi}{3}\right)+i_{b2}\sin\left(P\theta_m-\frac{5\pi}{3}\right)\right)+ \quad (6)\\ &+K_{T11}\left(-i_{a1}\sin P\theta_m\right)+K_{T12}\left(-i_{a12}\sin P\theta_m\right)\end{aligned}$$

The parameters of the two sections of the partial short circuited phase are automatically computed within the block mask in accordance with the number of turns in short circuit, also specified in the dialog box of the Simulink model.

It must be noted that before a partial short circuit of an half phase occurs (i.e. during normal operation) the model has only 6 state equations instead of 7 after the occurrence of the fault. As Simulink does not allow such a change during simulation, a special technique was used by the author for bypassing the problem.

3. CONTROLLERS MODELS

Two types of controllers were considered for the vector control of the drive.

The first one is the classic vector control in the Park reference frame [5, 6].

This type of controller can be used with all types of the motors described above provided that the machine emf's are purely sinusoidal. In fact, this is generally not the case, as the phase emf's contain generally a significant amount of third harmonic which are homopolar components. For a motor fed by a three phase inverter, these third hamonics are not seen from the terminals due to the Y connection so that the presence or not of the third harmonics in the emf's is without any importance and emf's can be considered as purely sinusoidal as far as the control is concerned. For a motor which phases are fed separately, it is necessary to add to the voltages generated by the controller a third harmonic component equal to that present in the emf's in order to avoid the appearance of homopolar currents. As the third harmonics in the feeding voltages and in the emf's cancel each other, both have been discarded in building the models.

The second type of vector control is a phase-by-phase control with a simulated β phase.

Indeed, with a phase-by-phase current control it is possible to use a pseudo dq control in order to control currents which are constant at constant torque. For that purpose, the scheme in Fig. 5 could be used, following denoted dq-αβ control.

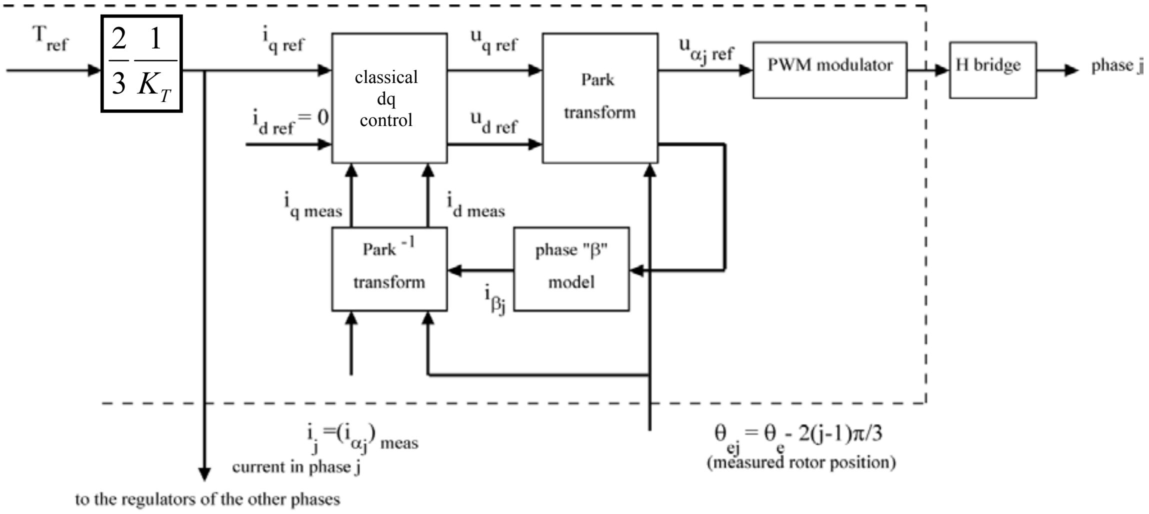


Fig. 5 - The dq-αβ vector control of the PMSM

This control consists in building for each phase of the machine (a,b,c), assimilated to be the α phase of a fictitious αβ machine, the model of the corresponding β phase, since the rotor position $\theta_{el}=P\cdot\theta_m$ is known.

For instance, if we assume that phase j is phase α_j we get for this phase

$$u_{\alpha j}=R_s i_{\alpha j}+L_0\frac{di_{\alpha j}}{dt}-K_T\dot{\theta}_m\sin\left[P\theta_m-2(j-1)\frac{\pi}{3}\right], \quad (7)$$

the associated fictitious phase β_j being ruled by the equation

$$u_{\beta j}=R_s i_{\beta j}+L_0\frac{di_{\beta j}}{dt}+K_T\dot{\theta}_m\cos\left[P\theta_m-2(j-1)\frac{\pi}{3}\right]. \quad (8)$$

For the HDD servomotors, as the phases are magnetically separated, the mutual inductances between the phases are almost equal to zero and the above model is valid for normal or fault conditions.

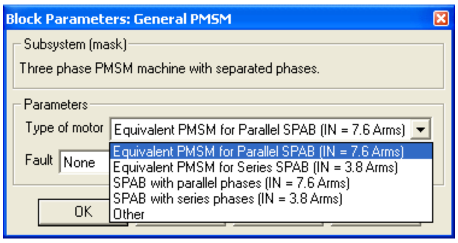
For a classical three phase machine, the above model ceases to be valid if one phase is in fault (in open or short circuit) since, in this case, the sum of the three phase currents is no more equal to zero, so that we may no more discard the coupling between the phases by taking in the model the cyclical inductance.

4. SIMULINK LIBRARY

The models described above were implemented in Simulink and a new library regrouped them.

Basically, it contains five types of blocks, three corresponding to the three variants of PMSM and two for the controllers.

Concerning the motors blocks, all were developed in a quite compact manner, the heart being an S-function block corresponding to each variant of PMSM. As the models are quite general, the parameters of some predefined types of motors were included in the masks of the blocks being associated to the type of motor chose in the dialog box (Fig. 6).


Block Parameters: General PMSM

Subsystem (mask)

Three phase PMSM machine with separated phases.

Parameters

Type of motor: Equivalent PMSM for Parallel SPAB (IN = 7.6 Arms)

Fault: None

- Equivalent PMSM for Parallel SPAB (IN = 7.6 Arms)
- Equivalent PMSM for Series SPAB (IN = 3.8 Arms)
- SPAB with parallel phases (IN = 7.6 Arms)
- SPAB with series phases (IN = 3.8 Arms)
- Other

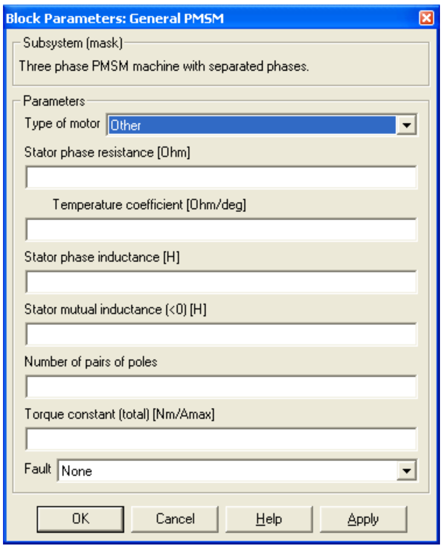
Fig. 6 - The choice of the type of motor

The masks allow to use the model for different, by the pre-defined ones, types of motors, by choosing the "Other" type of motor. In this case, the dialog box expands with the necessaries parameters to be specified (Fig. 7).

The dialog box of the motors' models allows the choice, during simulation, of one type of fault, as can be seen in Fig. 8.

The dialog box adapts itself to the chosen type of fault, being possible to specify further information, as the location of the short circuit in the case of the entire phase short circuit (Fig. 9), or the number of turns in short circuit in the case of partial short circuit of one phase (Fig. 10).

The two blocks for the vector control can be used for any type of motor and use a special mechanism for automatic identification of the type of motor used in a certain model, necessary for using the proper parameters. Knowing that Simulink does not allow the transfer of the parameters from one dialog box to another, this special mechanism was developed by the author within the masks of controllers blocks.



Block Parameters: General PMSM

Subsystem (mask)

Three phase PMSM machine with separated phases.

Parameters

Type of motor: Other

Stator phase resistance [Ohm]

Temperature coefficient [Ohm/deg]

Stator phase inductance [H]

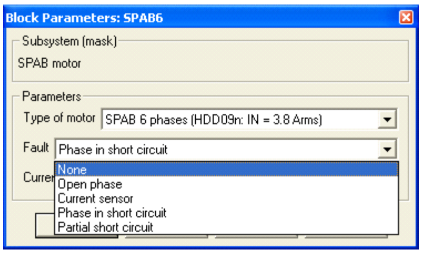
Stator mutual inductance (<0) [H]

Number of pairs of poles

Torque constant (total) [Nm/Amax]

Fault: None

Fig. 7 - The dialog box for “Other” type of motor



Block Parameters: SPAB6

Subsystem (mask)

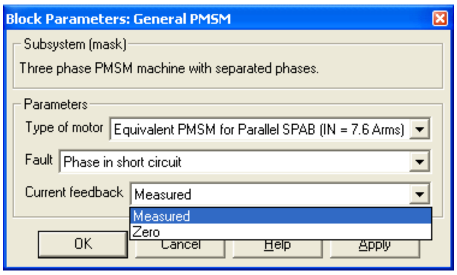
SPAB motor

Parameters

Type of motor: SPAB 6 phases (HDD09n: IN = 3.8 Arms)

Fault: Phase in short circuit

Fig. 8 - The choice of the type of fault



Block Parameters: General PMSM

Subsystem (mask)

Three phase PMSM machine with separated phases.

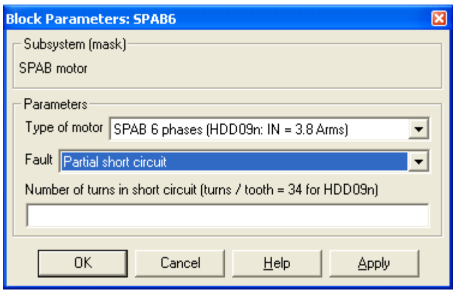
Parameters

Type of motor: Equivalent PMSM for Parallel SPAB (IN = 7.6 Arms)

Fault: Phase in short circuit

Current feedback: Measured

Fig. 9 - The location of the entire phase short circuit



Block Parameters: SPAB6

Subsystem (mask)

SPAB motor

Parameters

Type of motor: SPAB 6 phases (HDD09n: IN = 3.8 Arms)

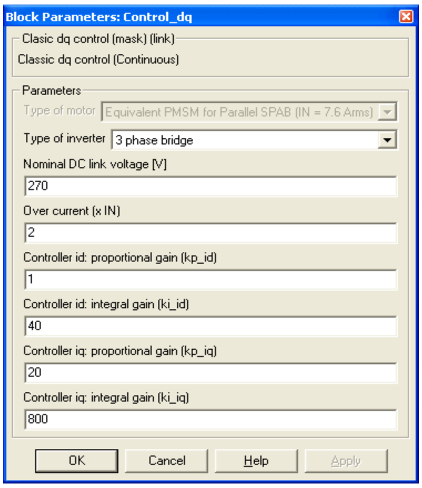
Fault: Partial short circuit

Number of turns in short circuit (turns / tooth = 34 for HDD09n)

Fig. 10 - The number of turns in short circuit

The mechanism is based on identification of the parameter specified in the “Type of motor” field of the motors dialog boxes and automatically updated in its proper field with the same name which is not active (Fig. 11). Internally, the controller block gets the right parameters, corresponding to the identified type of motor.

If “Other” type of motor is chosen within the dialog box of the motor used in the model, the dialog box of the controller automatically expands to specify the additional necessary parameters.



Block Parameters: Control_dq

Clasic dq control (mask) (link)

Classic dq control (Continuous)

Parameters

Type of motor: Equivalent PMSM for Parallel SPAB (IN = 7.6 Arms)

Type of inverter: 3 phase bridge

Nominal DC link voltage [V]: 270

Over current (x IN): 2

Controller id: proportional gain (kp_id): 1

Controller id: integral gain (ki_id): 40

Controller iq: proportional gain (kp_iq): 20

Controller iq: integral gain (ki_iq): 800

Fig. 11 - Automatic update of the type of motor in the controller dialog box

5. SIMULATION RESULTS

As indicated in the introduction, the developed Simulink models are quite versatile. It results a large number of possible combinations motor-controller. For each of the combinations it is possible to simulate different faults which could occur at different operating conditions.

Hereafter will be given only an example obtained with the HDD servomotor and dq-αβ control when one phase is suddenly broken (open circuit). In Fig. 12 is plotted a detail of the phase currents and the electromagnetic torque after this fault occurs. As it can be expected, the torque oscillations are quite important, being of the order of the rated torque (imposed earlier in the simulation).

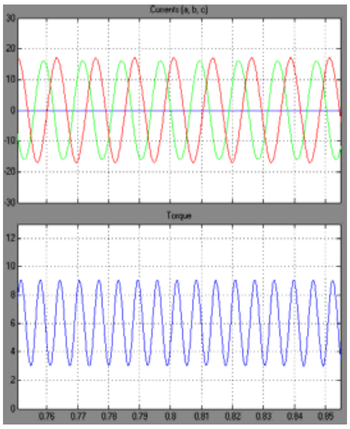


Fig. 12 - Details of the phase currents and electromagnetic torque when one phase is in open circuit

With this type of control, the special HDD motors can continue to operate if a proper remedial is applied. The remedial consists in supplying the two remaining phases with currents having adequate amplitude and phase shift with respect to the corresponding emf' [2]. Fig. 13 allows following the phase currents before the fault, when the fault occurs (about 0.3 sec) and after a remedial is applied (about 1 sec).

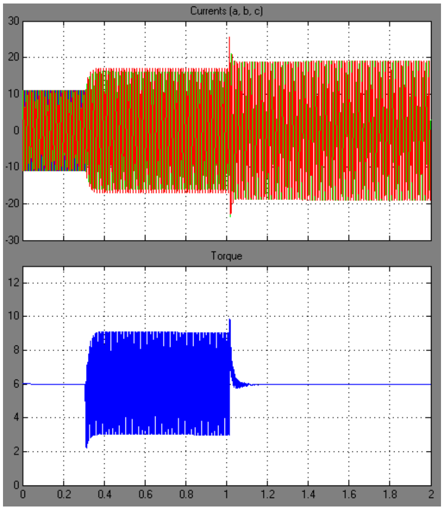


Fig. 13 - Fault occurrence and its remedial

It is important to note that, the torque oscillations totally disappear provided that, as assumed in the models, the machine emf's are purely sinusoidal, but at the price of higher currents in the remaining phases. This is not quite dangerous, as only two phases contribute now to the heating of the motor. If the phase emf's contain a certain amount of third harmonic, with the implemented control strategies, a given amount of torque ripple remains which is directly proportional to the amplitude of the third harmonic. Fig. 14 depicts a detail of the currents and the electromagnetic torque, after the application of the remedial to a motor for which the third harmonic of the emf's is considered.

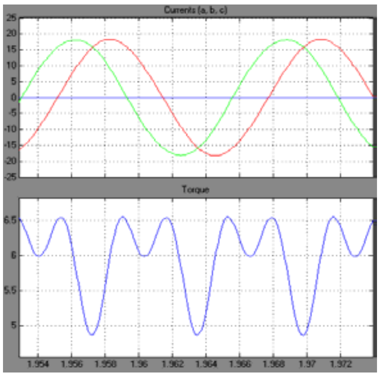


Fig. 14 - Detail of the currents and torque when the third harmonic of the emf's is considered

6. CONCLUSIONS

The paper describes a Simulink library for the simulation of different structures of PMSM and vector control, in normal operation, as well as when different faults occur.

The developed blocks are quite versatile, allowing the simulation of a large number of possible types and sizes of motors. The vector control blocks use a special mechanism developed by the author to identify the type of motor used in model and to adjust its own parameters consequently.

The results of the simulations are very useful when the decision on the most suited system would have to be done.

ACKNOWLEDGMENTS

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