Enhanced Simulink Induction Motor Model for Education and Maintenance Training

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ABSTRACT

The training of technicians in maintenance requires the use of signals produced by faulty machines in different operating conditions, which are difficult to obtain either from the industry or through destructive testing. Some tasks in electricity and control courses can also be complemented by an interactive induction machine model having a wider internal parameter configuration. This paper presents a new analytical model of induction machine under fault, which is able to simulate induction machines with rotor asymmetries and eccentricity in different load conditions, both stationary and transient states and yielding magnitudes such as currents, speed and torque. This model is faster computationally than the traditional method of simulating induction machine faults based on the Finite Element Method and also than other analytical models due to the rapid calculation of the inductances. The model is presented in Simulink by Matlab for the comprehension and interactivity with the students or lecturers and also to allow the easy combination of the effect of the fault with external influences, studying their consequences on a determined load or control system. An associated diagnosis tool is also presented.

Keywords: Simulation, training, induction motor, Matlab/Simulink, interactive tools, maintenance, e- training.

1. INTRODUCTION

This paper presents an induction machine model developed in Simulink environment able to simulate the currents, speed and torque of a faulty induction motor for its application in education and training of maintenance techniques in predictive maintenance and fault diagnosis, and its associated analysis tool. On the contrary to the basic model included in the Simulink tool, the proposed model provides a wider machine internal parameters configuration which allows the simulation of the current feeding an induction machine suffering a rotor asymmetry and/or eccentricity, as well as its effect in torque and speed, both in stationary and transient state. In addition, its implementation in Simulink permits the easy combination of the effect of the fault with external influences, or conversely, studying its effect on a determined load or control system.

Maintenance of induction motors is an issue of special concern in the industrial environment. Eccentricity under its various kinds is a common fault, and broken rotor bars and, more generally, rotor asymmetries, amount for around 10% of the failures in such equipment [1]. Although this fault does not cause an immediate collapse of the machine, its importance cannot be understated, since it propagates progressively towards the adjacent bars, leading to an irreversible failure. Moreover, large motors –being difficult to replace and involving the highest repair costs– started under high inertias are especially prone to suffer this type of fault, thus the need for having well trained maintenance personnel able to diagnose it in advance.

In the industrial environment, the most widely spread technique for the detection of rotor bar breakages and eccentricities is known as Motor Current Signature Analysis [2]-[4] and involves the identification of specific fault components in the spectrum of machine stator current waveform during stationary operation. This has some drawbacks, such as the difficulty of being applied to machines under unloaded condition or under unbalanced supply voltages, varying load or load torque oscillations [5]-[7]. Thus, recent methods have been developed to overcome these drawbacks, such as the demodulation using the Hilbert transform [8] or the study the transient processes of the machine and specifically, the startup transient. Due to the time-varying frequency spectrum of the startup current signal during the transient, modern time-frequency decomposition tools have been applied, such as wavelet transforms [9]-[12], Hilbert-Huang transform [13] and other Time Frequency Distributions (TFD), such as Wigner-Ville [14]-[16].

Furthermore, previous works have stated the Simulink induction motor model suitability for being successfully applied to undergraduate electric machinery courses, in order to introduce induction motor tests and to evaluate its steady state characteristics [17]. Nevertheless, others have indicated its shortages when it has been tried in more advanced tasks, which arise as the field of application of induction machines widens, such as machines with an arbitrary number of phases [18].

In addition, some authors have identified key features that tailored Simulink models should accomplish in order to be successfully applied in education and training of electrical equipment, such as simplicity [18] and interactivity [19], features that cannot be obtained from Finite Element Methods, the most accurate approach to asynchronous machine fault simulation.

Therefore, the authors propose a computationally fast and interactive induction motor model, based on Simulink, capable of simulating under variable load conditions, the instantaneous values of the current waveforms, torque and speed in stationary and transient state of a machine having rotor asymmetry and/or eccentricity for its application in education, training and e-training in conventional and new fault diagnosis tecniques.

For these purpose, this paper will be structured as follows: section 2 establishes the theoretical background of the proposed model; section 3 introduces some of the fault frequency components which should be correctly simulated and section 4 shows examples of its application in maintenance training. Finally, section 5 renders the conclusions.

2. THE UPV MODEL

The new analytical model of induction machine developed to be able of simulating a machine suffering a rotor asymmetry is based on the following equations:

System equations

In the general case (that is, even under fault conditions like inter-turn short circuits or broken bars), the following equation system can be written for an induction machine with *m* stator and *n* rotor phases:

$$[U_S] = [R_S][I_S] + \frac{d[\Psi_S]}{dt} \tag{1}$$

$$[0] = [R_r][I_r] + \frac{d[\Psi_r]}{dt} \tag{2}$$

$$[\Psi_s] = [L_{ss}][I_s] + [L_{sr}][I_r] \tag{3}$$

$$[\Psi_r] = [L_{sr}]^T [I_s] + [L_{rr}][I_r] \tag{4}$$

$$[U_S] = [u_{s1} \ u_{s2} \ \dots \ u_{sm}]^T \tag{5}$$

$$[I_S] = [i_{s1} \ i_{s2} \ \dots \ i_{sm}]^T \tag{6}$$

$$[I_r] = [i_{r1} \ i_{r2} \ \dots \ i_{rn}]^T \tag{7}$$

where $[U]$ is the voltage matrix, $[I]$ is the current matrix, $[R]$ is the resistance matrix, $[\Psi]$ is the flux linkage matrix and $[L]$ is the matrix of inductances. Subscripts s and r are assigned to the stator and rotor. The mechanical equations are:

$$T_e = [I_S]^T \frac{\partial [L_{sr}]}{\partial \theta} [I_r] \tag{8}$$

$$T_e - T_L = J \frac{d\Omega}{dt} = J \frac{d^2\theta}{dt^2} \tag{9}$$

where T_e is the electromechanical torque of the machine, T_L is the load torque, J is the rotor inertia, Ω is the mechanical speed and θ is the mechanical angle.

In order to solve (3), (4) and (8), self and mutual phase inductance matrices must be obtained. Due to the presence of the derivatives in (1) and (2), this computation should be very accurate (especially, if different fault conditions are to be detected and diagnosed in a sure way). Consequently, the model presented in this paper takes into account the actual position and current of every conductor in the airgap of the machine during the inductances calculation process. End turn and slot leakage inductances need to be pre-calculated, and are treated as constants in (3) and (4), as usual in the technical literature and also done, for instance in [20]-[21].

Proposed method for computing the mutual inductance between two phases via the discrete circular convolutions and FFT

The inductance between two phases, A and B, is calculated in this paper trough the following process:

The flux linkage of an arbitrary phase can be expressed very easily as the sum of the yoke flux at all the yoke sections corresponding to the angular positions of its conductors.

1) The air gap MMF, $F_A(\varphi)$, of phase A, fed with a unit current, is obtained, starting from the conductor MMF.

2) The yoke flux (Fig. 1) produced by $F_A(\varphi)$ is calculated as in [22]

3) Flux linkage of phase B due to the yoke flux of phase A is determined, which corresponds to the mutual inductance between the phases. (The phase magnetizing self inductance is obtained when B=A).

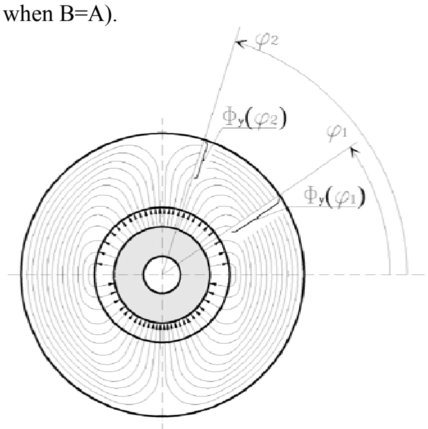

Fig. 1. Yoke flux generated by a sinusoidal distribution of air gap MMF, and its value at two different angular coordinates.

The use of the yoke flux has two key advantages. The first one is that it has a clear physical meaning and matches very well the use of the conductor as the basic winding unit. The great advantages of using the conductor instead of the coil, especially for irregular windings (e. g., fault conditions), were already strongly emphasized by [23]. And secondly, the yoke flux produced by a phase can be obtained very quickly by means of a circular convolution solved via FFT.

It must be underlined that not only step 2 (yoke flux), but all the three process steps listed above, despite being very different from a physical point of view, can be treated with the same mathematical tool: a circular convolution, computed via the FFT. In summary, the mutual inductance of two phases, with arbitrary winding layout, can be obtained for each relative angular position between them in an extremely fast way with a single computation, which involves the FFTs of three discrete sequences: the conductor distributions for phases A and B, and the yoke flux generated by a single conductor, as presented in [24].

3. HARMONICS SHOWING FAULTS

The most used method for diagnosing rotor asymmetries is the current signature analysis (MCSA); this approach is based in the detection of harmonics with characteristic frequencies into the spectrum of the stator current in steady state regime.

The two main frequency components often traced for the diagnosis of rotor asymmetries appear during stationary operation as sidebands of the main current harmonic and are known as *lower sideband harmonic* (LSH) and *upper sideband harmonic* (USH). Their frequencies f_{sb} can be calculated using (10) (s=slip and f=supply frequency) [2].

$$f_{sb} = (1 \pm 2 \cdot s) \cdot f \qquad (10)$$

The frequencies of these components are a particular case of the general expressions of the components amplified by the fault, given by (11) and (12) [25-26].

$$f_b = \left(\frac{k}{p}(1-s) \pm s\right) \cdot f \qquad \frac{k}{p} = 1,3,5.... \qquad (11)$$

$$f_b = (1 \pm 2 \cdot k \cdot s) \cdot f \qquad k = 1,2,3.... \qquad (12)$$

Furthermore, expressions for the calculation of the characteristic frequencies of the components introduced by static or dynamic eccentricities have been proposed by several authors [27]. Usually both kinds of eccentricity coexist, yielding low frequency components that appear near the fundamental [28]. Those frequencies can be computed by (13), where f_r is the frequency of rotation of the rotor.

$$f_{ecc} = \left[\left(1 + m\left(\frac{1\text{-}s}{p}\right)\right)\right].f \qquad m = \pm 1, \pm 2, \pm 3... \qquad (13)$$

The characteristic fault-related frequencies given by these expressions are constant during stationary operation. However, during the start up transient they evolve in a particular way, as the slip s varies from a value equal to 1, when the machine is connected, to a value near to 0 (steady-state). This evolution creates characteristic pattern whose detection is the base of new diagnosis methods recently developed; These methods use time-frequency signal analysis techniques for revealing the characteristic patterns produced by the fault components under transient conditions [10]-[16].

Since the electrical and mechanical magnitudes computed by the proposed model contains all the fault components, it can be used either for training purpose with conventional permanent based diagnostic techniques as well as for teaching and training with the new transient based diagnostic approaches.

Table 1 characterizes the evolution of the main frequency components amplified by the rotor asymmetry for a one pole pair motor from the connection instant ($s=1$) to the steady state, assuming ideal unloaded condition (s=0), according to (11). Using the "+" sign; these components have positive initial frequencies at startup. In these cases, their frequencies increase from the fundamental frequency value up to their final steady-state value (direct evolution).

TABLE 1
HIGH FREQUENCY COMPONENTS AMPLIFIED BY THE ASYMMETRY ACCORDING TO (11) (DIRECT EVOLUTION).

	k/p	$f \cdot \left(\frac{k}{p} \cdot (1-s) + s\right)$	$f_b(s=1)Hz$	$f_b(s=0)Hz$
LSH+S 150	3	f·(3-2·s)	50	150
LSH+S 250	5	f·(5-4·s)	50	250
LSH+S 350	7	f·(7-6·s)	50	350

Table 2 presents the lower sideband harmonics whose absolute frequency value decreases at first, falling progressively to zero and increases again until reaching its steady state frequency.

TABLE 2
HIGH FREQUENCY COMPONENTS AMPLIFIED BY THE ASYMMETRY ACCORDING TO (11) (INDIRECT EVOLUTION).

	k/p	$f \cdot \left(\frac{k}{p} \cdot (1-s) - s\right)$	$f_b(s=1)Hz$	$f_b(s=0)Hz$
LSH 50	1	f·(1-2·s)	-50	50
LSH-S 150	3	f·(3-4·s)	-50	150
LSH-S 250	5	f·(5-6·s)	-50	250

Table 3 shows the evolution during startup of the main components introduced by a mixed eccentricity fault for a two pole pair machine, according to (13):

TABLE 3
MAIN ECCENTRICITY COMPONENTS ACCORDING TO (13) IN HZ

Component	**m**	Initial frequency value (connection, s=1)	Final frequency value (steady-state, s=0)
EC 25	-1	50	25
EC 75	1	50	75
EC 100	2	50	100

4. CLASSROOM EXAMPLES

This section shows the ability of the developed model for including in the computated signals the fault components theorically predicted, and therefore, enabling for the experimentation of different diagnostic approaches.

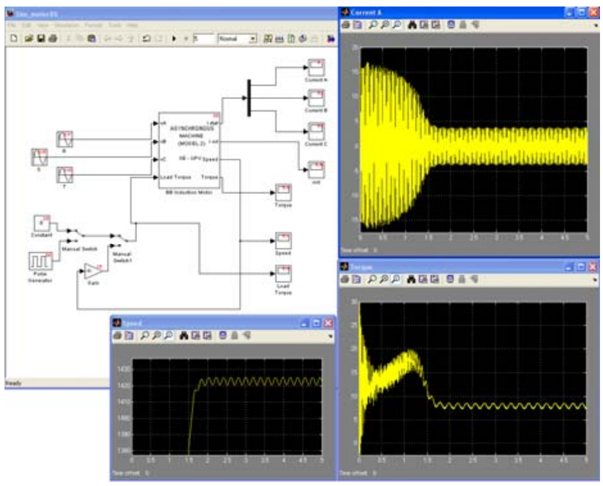

Fig. 2. Simulation of a 1.1 kW, four pole Siemens motor having two broken bars, during a start-up and stationary operation. From top to bottom and left to right: current in one phase, speed and output torque.

Along the model, a diagnosis module in Simulink has been programmed, in order to accomplish the desired interactivity with the students. This module calls the needed MATLAB functions and offers a user-friendly interface to input the parameters required to adjust some of the analysis tools.

In order to show some of the capabilities of the combination of both tools, their applications in two particular cases in maintenance practices on induction motors follow:

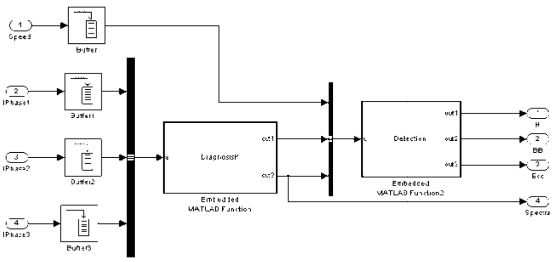

Fig. 3. Diagnosis and fault detection module.

Machine with two broken bars

Traditional MCSA utilizes the FFT to diagnose rotor asymmetries in induction motors. Current from the mains of the machine is captured in steady state, and then the components related to the fault, usually the sidebands around the main harmonic, are measured from its spectrum. Their value relative to the main harmonic has been the traditional method of assessing the degree of progression of this failure. In Fig. 4 such sidebands (a1, a2), separated from the main component (50 Hz) a value of 5.3 Hz, as predicted by (10) for a rotating speed of 1420 rpm, are clearly seen. Furthermore, higher order harmonics (a3) associated to the fault, predicted by (11) and (12) are also correctly simulated.

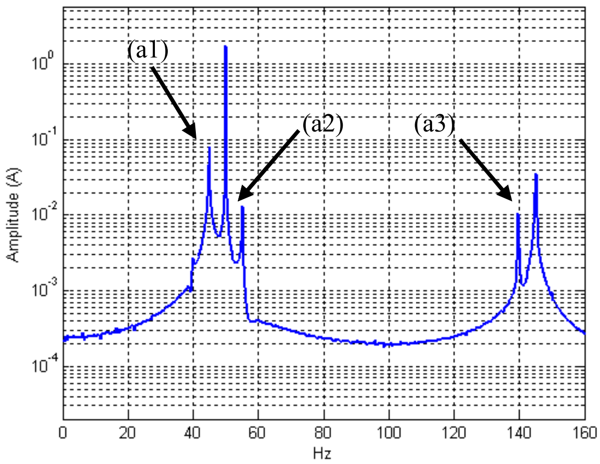

Fig. 4. FFT spectrum from a simulated current of a 1.1 kW, four pole Siemens motor having two broken bars.

Pulsating torque load

However, this traditional approach of diagnosing the rotor asymmetry cannot be applied on a machine coupled to a pulsating torque load, since the irregularities in the rotor's movement introduce a modulation that may blur or disguise the sidebands caused by the asymmetry around the main current harmonic, as shown in Fig. 5 for a healthy machine.

Several methods have been developed to overcome this problem. One approach consists in studying higher order harmonics (a3), usually less affected by the oscillations produced by the pulsating torque due to the machine inertia. Others involve the capture of a current during a transient and its analysis through time-frequency tools, as in Fig. 6, which utilizes the method presented in [16] for a machine having one broken bar and operating under pulsating torque load.

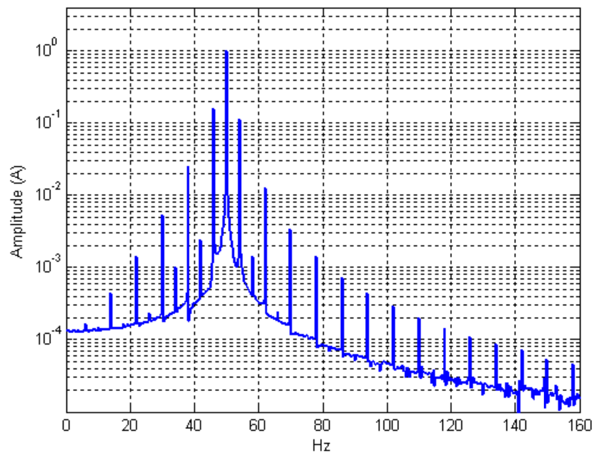

Fig. 5. FFT spectrum from a simulated current of a 1.1 kW, healthy four pole Siemens motor coupled to a pulsating torque load.

In this case, the pattern of several harmonics related to the fault is clearly discernible. The LSH 50 (b1) increases their frequency in the last part of the startup, from 0 to 50 Hz, according to (11). High order components LSH+S 150 (b3) and LSH-S 150 (b2) are also identified. The sidebands having the greatest amplitude related to the pulsating torque remain around the fundamental current component at 50 Hz.

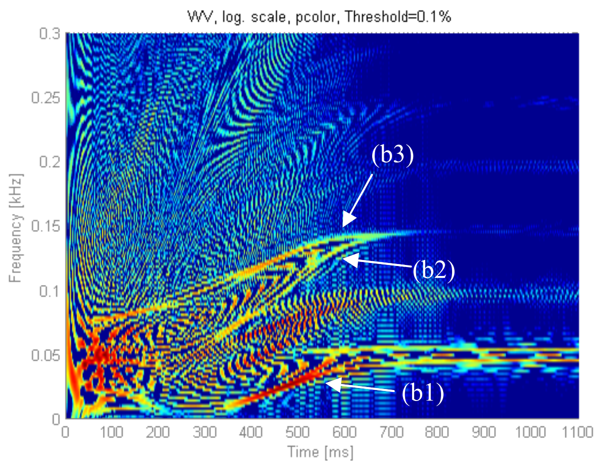

Fig. 6. Wigner-Ville distribution from the simulated startup current of a 1.1 kW four pole Siemens motor coupled to a pulsating torque load and having a broken bar.

The same fault features can be seen in Fig. 7, where the time-frequency plot of the startup current taken from the mains of a real machine is presented

Eccentricity

Eccentricity is handled by the model computing a matrix of inductances prior to the simulation, which takes into account the variations of permeance that the non-uniform air gap causes.

In a healthy machine, the inductances depend only on the relative position between conductors, yielding a vector that is processed accordingly. For static eccentricity the value of the inductances also change relative to the position of center of the rotor, being distributed their values in a matrix. Finally, for mixed eccentricity, a 3D matrix is needed to also handle their variation with respect to the position of the rotor.

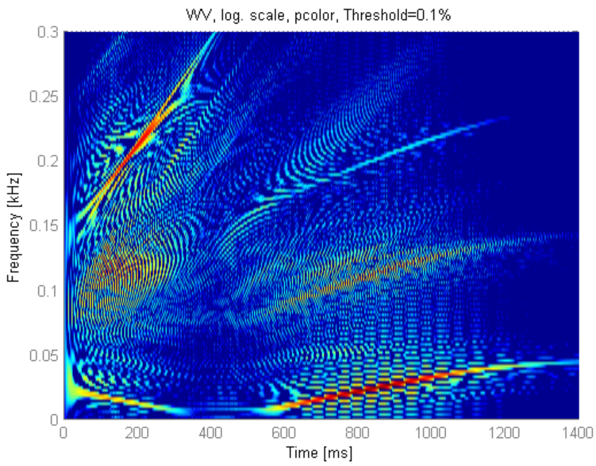

Fig. 7. Wigner-Ville distribution from the real startup current of a 1.1 kW four pole Siemens motor having a broken bar, coupled to a speed-dependant load.

The matrix is calculated once prior to the simulation of the machine in each state, stored and its values selected as they are needed to solve equations (3), (4) and (8). This allows performing several simulations on a specific machine and state under different power supply and load conditions with no need of recalculating it, which shortens the computation time, a critical aspect considering its application in education and training.

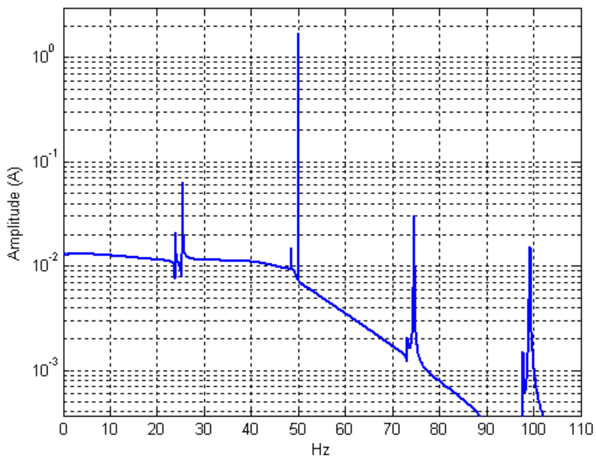

Fig. 8. FFT spectrum of the current from a simulated 1.1 kW Siemens induction motor suffering 20% static and 50% dynamic eccentricity

Fig. 8 shows the results of applying the proposed model to simulate a mixed eccentricity in a four pole motor during stationary operation. All low frequency components presented in Table 3 can be detected: EC 25 (c1), EC 75 (c2) and EC 100 (c3).

5. CONCLUSIONS

This paper presents a new induction motor model able to simulate an induction machine having a rotor asymmetry or eccentricities faults, both in stationary and transient operation and under variable load conditions. Due to a method of discrete circular convolution carried out through the FFT, the computation is fast enough (1 minute per second simulated at 5 kS/s) to assure the suitable interactivity for its application in education, training and e-training.

The model has been programmed in Simulink in order to be used with different loads and control systems. An analysis tool coupled to its output facilitates the presentation of several new techniques of diagnosis in maintenance training courses.

The presented model has been introduced in the lecturing of electronic engineers with encouraging results.

6. ACKNOWLEDGEMENT

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