Electrical Modeling for Faults Detection Based on Motor Current Signal Analysis and Angular Approach

Aroua Fourati, Nabih Feki, Adeline Bourdon, Didier Rémond, Fakher Chaari and Mohamed Haddar

Abstract Recently, Motor Current Signal Analysis (MCSA) appears as an effective tool for fault diagnosis in rotating machinery and proved to be sufficient for detecting localized mechanical faults in electromechanical systems operating in stationary conditions. In the case of non-stationary conditions, speed variations must be distinguished from angular velocity perturbation caused by the presence of a defect. In the framework of diagnosis of rotating machinery, angular approaches are well suited to make monitoring resistive to speed disturbances. This paper proposes a reformulation of the MCSA associated with angular approach in modeling multiphysic behavior. The resulting model described in this paper can be used to investigate of the influence of the Instantaneous Angular Speed (IAS) variations on the electrical responses of the whole rotating system.

Keywords Motor current signal analysis condition monitoring · Non-stationary conditions · Rotating machines · Angular approach

A. Fourati (✉) · A. Bourdon · D. Rémond
LaMCoS UMR5259, CNRS, INSA-Lyon, University of Lyon, Lyon, France
e-mail: aroua.fourati@insa-lyon.fr; arwafourati@gmail.com

A. Bourdon
e-mail: adeline.bourdon@insa-lyon.fr

D. Rémond
e-mail: didier.remond@insa-lyon.fr

A. Fourati · N. Feki · F. Chaari · M. Haddar
La2MP, National School of Engineers of Sfax, Sfax BP 1173-3038, Tunisia
e-mail: fekinabih@gmail.com

F. Chaari
e-mail: fakher.chaari@gmail.com

M. Haddar
e-mail: mohamed.haddar@enis.rnu.tn

F. Chaari et al. (eds.), *Advances in Condition Monitoring of Machinery in Non-Stationary Operations*, Applied Condition Monitoring 4,
DOI 10.1007/978-3-319-20463-5_2

Contents

1 Introduction

Induction motors connected to mechanical systems are widely used in industrial applications due to their robustness, their compactness, low cost and high degree of reliability. Condition monitoring and diagnosis of these systems by detecting small variations of their dynamic behavior are among challenges to improve their availability. The use of stator current signals constitutes a non-intrusive method to acquire information necessary to diagnosing electromechanical systems and thus to ensure effective monitoring. Many researches focused on this framework and proved the capacity of this method to explicit mechanical defect localized on the electromechanical system related to the motor [1, 2]. In a previous work, [3] an analytical model of an asynchronous motor has been proposed and proved the possibility to detect pitting in a geared system operating under stationary conditions. The classical theory of these motors is based on the assumption that the current produced by their stator winding is sinusoidally distributed in time. This assumption is limited to systems operating under stationary conditions. However, in real cases, current components related to faults are confused to those resulting from dynamic variations, and thus, are very difficult to extract without a dedicated signal processing. Moreover, some recent results in rotating machine monitoring have proven that the shaft rotation speed contains dynamic responses of faulted components in now well-known Instantaneous Angular Speed (IAS) signal [4].

To overcome these difficulties of non-stationary operating conditions, for example, velocity variations that can hide the appearance of defects on the current signal, angular approaches seems to be well suited. In [5], a new way of writing differential equations in rotating machines by translation into the angular domain was proposed and proved the interest of angular sampling in rotating machines [6]. When addressing the case of rotating machines operating under non-stationary conditions, every time their rotating element passes through a disturbance, a perturbation takes place. These perturbations are managed by the rotation periodicity of the machine whatever the overall rotational speed. This leads to the new assumption that the stator current is periodically distributed in reference with the angular position of the shaft of rotating machines.

In this paper, the authors' purpose is to develop a new approach to investigate the MCSA method on electromechanical systems operating under non-stationary conditions in order to analyze in a more efficient way the information given by stator currents for the detection of defects. Firstly, stator's current and torque responses of a healthy motor are presented under this new formalism. In a second step, the proposed study is extended to present the responses under two different excitations mechanisms which are varying IAS due to the presence of bearing faults.

2 Asynchronous Motor Model Formulation

For the framework of detecting faults in electromechanical systems, the common assumption is based on the fact that a magnetic disturbance is created in the air gap of the induction machine whenever the system passes through a mechanical fault (like bearing spall for example). For this purpose, a permeance network model is used Fig. 1. The interest in this model is motivated by its capacity to detect very small magnetic disturbances and to offer a detailed representation of the machine magnetic state which is sensitive to faults.

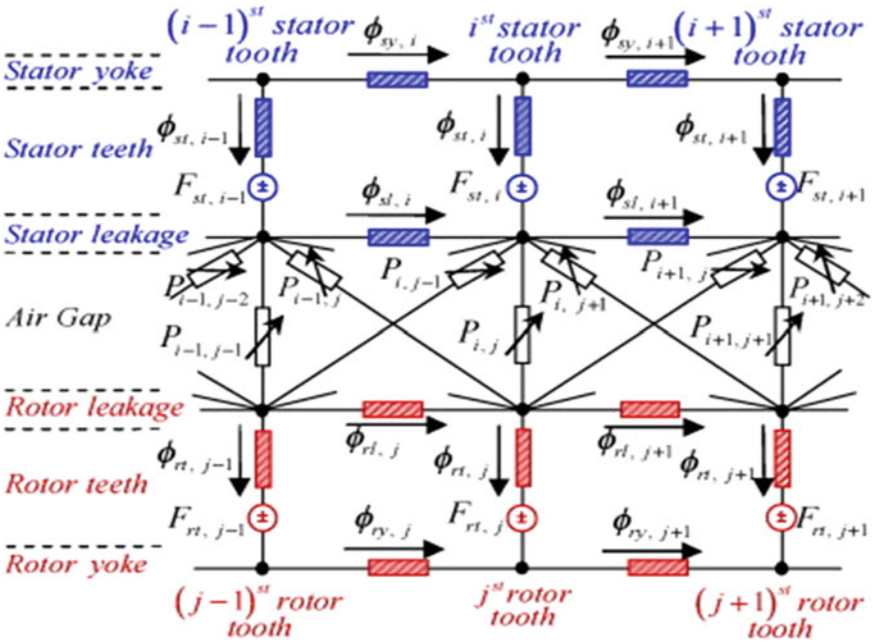

Fig. 1 A part of the permeance network model [7]

In order to simulate its magnetical behavior, the induction machine is discretized on a finite number of nodes. In The overall network, N_n nodes are uniformly distributed. Between each two node there is a branch representing flux circulation. Each flux tube is characterized by its permeance. Permeances in the stator and the rotor are supposed to be constants whereas permeances of the air-gap are varying. In the complete permeance network model, there are N_{b} branches and N_{bent} branches in the gap, these numbers are relative to the stator teeth and the rotor numbers n_{s} and n_{r}, where $N_{\mathrm{bent}} = n_{\mathrm{s}} \cdot n_{\mathrm{r}}$ and $N_{\mathrm{b}} = 3n_{\mathrm{s}} + 3n_{\mathrm{r}} + N_{\mathrm{bent}}$.

Where $\phi_{sy,i}$, $\phi_{\mathrm{st},i}$, $\phi_{sl,i}$, $\phi_{\mathrm{ry},j}$, $\phi_{\mathrm{rt},j}$ and $\phi_{\mathrm{rl},j}$ are stator yoke, stator teeth, stator leakage, rotor leakage, rotor teeth and rotor yoke flux. $F_{\mathrm{st},i}$ and $F_{\mathrm{rt},j}$ are stator teeth and rotor teeth magnetomotive forces. $P_{i,j}$ is the air-gap permeance which connect the ith stator tooth and the jth rotor tooth.

In the temporal domain, an induction machine is modeled using a unique differential equation combining its electrical and magnetical behavior as following [7]:

$$\left[[L_t]_{(n_{\mathrm{ph}}+n_{\mathrm{r}},n_{\mathrm{ph}}+n_{\mathrm{r}})} + [G(t)]_{(n_{\mathrm{ph}}+n_{\mathrm{r}},n_{\mathrm{ph}}+n_{\mathrm{r}})}\right] \frac{\mathrm{d}\{I(t)\}_{(n_{\mathrm{ph}}+n_{\mathrm{r}},1)}}{\mathrm{d}t} + \left[[R_t]_{(n_{\mathrm{ph}}+n_{\mathrm{r}},n_{\mathrm{ph}}+n_{\mathrm{r}})} + \frac{\mathrm{d}[G(t)]_{(n_{\mathrm{ph}}+n_{\mathrm{r}},n_{\mathrm{ph}}+n_{\mathrm{r}})}}{\mathrm{d}t}\right]\{I(t)\}_{(n_{\mathrm{ph}}+n_{\mathrm{r}},1)} = \{V(t)\}_{(n_{\mathrm{ph}}+n_{\mathrm{r}},1)} \quad (1)$$

where $\{I(t)\}$ is the generalized stator and rotor current vector, $\{V(t)\}$ is the stator and rotor voltage supply vector, $[L_t]$ and $[R_t]$ are respectively matrix of inductances and resistances of the rotor and the stator, n_{ph} and n_{r} are respectively the number of stator phases and the number of rotor teeth and $[G(t)]$ is the matrix describing the electro-magnetical behavior of the induction machine.

These parameters will be involved to calculate the $[G(t)]$ matrix. In this model we consider stator and rotor permeances as constant whereas permeances on the air-gap depend dynamically from the angular displacement between the stator and the rotor as shown in Fig. 2. This consideration induces the angular-depending character of the induction machine.

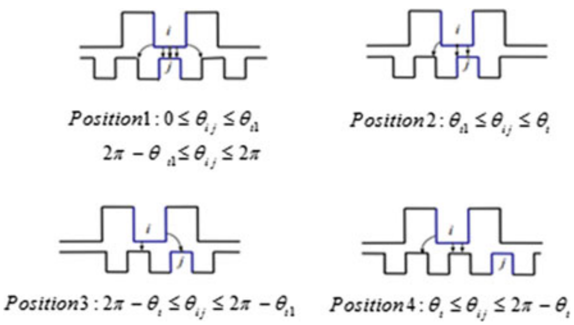

Fig. 2 Evolution of the angular position between a couple of stator and rotor teeth

For each couple of teeth; *i*th stator tooth and *j*th rotor tooth, the value of the permeance is updated for every rotor position relatively to the following expression [8]:

$$P(\theta_{ij}) = \begin{cases} P_{\max} & \text{if } 0 \le \theta_{ij} \le \theta_{t1} \text{ and } 2\pi - \theta_{t1} \le \theta_{ij} \le 2\pi \\ P_{\max} \frac{1+\cos \pi \frac{\theta-\theta_{t1}}{\theta_t-\theta_{t1}}}{2} & \text{if } \theta_{t1} \le \theta_{ij} \le \theta_t \\ P_{\max} \frac{1+\cos \pi \frac{\theta-2\pi+\theta_{t1}}{\theta_t-\theta_{t1}}}{2} & \text{if } 2\pi - \theta_t \le \theta_{ij} \le 2\pi - \theta_{t1} \\ 0 & \text{if } \theta_t \le \theta_{ij} \le 2\pi - \theta_t \end{cases} \tag{2}$$

where θ is the rotor angular displacement relatively to the stator, θ_{ij} the *j*th rotor tooth rotational displacement referring to *i*th stator tooth, θ_t and θ_{t1} are limit angles representing the angular variation of the permeance and $P_{\max}$ is the maximal value of the permeance of any couple of teeth.

The expression of $P_{\max}$ depends on geometrical characteristics of the motor. It is defined as:

$$P_{\max} = \frac{\mu_0 L_m L_{dr}}{e} \tag{3}$$

where μ_0 is the air-gap permeability, L_{m} is the machine length, L_{dr} is the rotor tooth width and e is the air-gap thickness.

The starting point of the classical temporal approach for modeling the motor is based on the fact that the temporal variable is linearly coupled to the angular variable through a constant rotating speed as provided by Eq. (4), and then modeling will be limited to a stationary operating conditions system.

$$\theta = \omega t \tag{4}$$

To overcome these limitations, we proceeded by an angular sampling. This approach was well defined in [4]. Let θ be the angular position of the rotor. For non-stationary rotating machines, the relation which links temporal to angular variables is provided by means of the IAS function $\tilde{\omega}$ as following:

$$\frac{\mathrm{d}t}{\mathrm{d}\theta} = \frac{1}{\tilde{\omega}(\theta)} \tag{5}$$

Then, a reformulation of the permeance network model used to calculate variations of current signals in the case of an asynchronous motor in an angular domain is proposed as following:

$$\begin{cases} \left[[L_\theta]_{(n_{ph}+n_r,n_{ph}+n_r)}+[G(\theta)]_{(n_{ph}+n_r,n_{ph}+n_r)}\right]\dfrac{d\{I(\theta)\}_{(n_{ph}+n_r,1)}}{d\theta}\tilde{\omega}(\theta) \\ \left[+[R_\theta]_{(n_{ph}+n_r,n_{ph}+n_r)}+\dfrac{d[G(\theta)]_{(n_{ph}+n_r,n_{ph}+n_r)}}{d\theta}\tilde{\omega}(\theta)\right]\{I(\theta)\}_{(n_{ph}+n_r,1)}=\{V(t)\}_{(n_{ph}+n_r,1)} \\ \dfrac{dt}{d\theta}=\dfrac{1}{\tilde{\omega}(\theta)} \end{cases} \tag{6}$$

In order to minimize the number of equations and the dependence on the angular variable, a basis change is defined. If we consider a relative frame whose axes are rotating in accordance with the rotor angular displacement, resulting projected currents are obtained according to the relation:

$$\begin{Bmatrix} I_d(\theta) \\ I_q(\theta) \end{Bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\omega_s t) & \cos\left(\omega_s t-\frac{2\pi}{3}\right) & \cos\left(\omega_s t+\frac{2\pi}{3}\right) \\ -\sin(\omega_s t) & -\sin\left(\omega_s t-\frac{2\pi}{3}\right) & -\sin\left(\omega_s t+\frac{2\pi}{3}\right) \end{bmatrix}\cdot\begin{Bmatrix} I_1(\theta) \\ I_2(\theta) \\ I_3(\theta) \end{Bmatrix} \tag{7}$$

Coupling the electrical model of the induction machine to a mechanical model of a defective system, the magnetic torque is expressed as:

$$C_{em}(\theta)=\frac{1}{2}\sum_{i}^{n_s}\sum_{j}^{n_r}\frac{dP_{ij}}{d\theta}\varepsilon_{ij}^2 \tag{8}$$

where n_s and n_r are respectively stator and rotor tooth number, P_{ij} and ε_{ij} are respectively the permeance and the magnetic potential difference in the air-gap which connects the ith stator tooth and the jth rotor tooth; Then it must be noticed that differential equations expressed in the angular domain are nonlinear but with parameters which can be explicitly calculated, therefore decreasing calculation time.

3 Introducing Instantaneous Angular Speed Disturbances

Comparing to temporal domain, in the differential Eq. (6) the rotational speed appears explicitly written in the angular domain. This allows integrating a disturbance of the IAS in the model, this dynamic behavior being proven to be induced by typical bearing faults. The form of the disturbance is inspired from the model developed in [9] as a function of the angular position of the shaft. The expression proposed to characterize the disturbance is defined as a periodic function; each occurrence is divided into 3 areas as shown in Fig. 3:

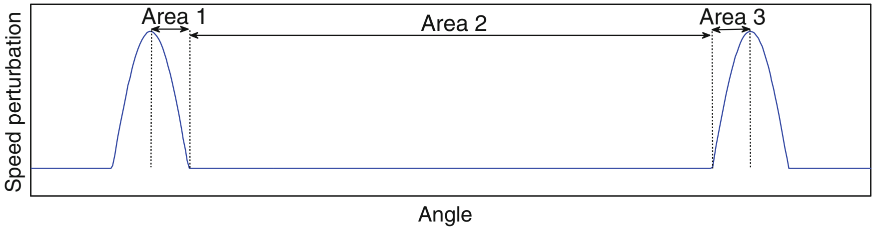

Fig. 3 Angular variation of the disturbance function

$$\begin{aligned} &\text{Area1: } \Delta\omega(\theta) = \omega_{\mathrm{p}} \sin\left(\frac{\pi}{L_{\mathrm{p}}}\left(\theta - \theta_1 + \frac{L}{2}\right)\right) \\ &\text{Area2: } \Delta\omega(\theta) = 0 \\ &\text{Area3: } \Delta\omega(\theta) = \omega_{\mathrm{p}} \sin\left(\frac{\pi}{L_{\mathrm{p}}}(\theta - \theta_3)\right) \end{aligned} \tag{9}$$

where ω_{p} and L_{p} are respectively the amplitude and angular length of the perturbation.

4 Results and Discussions

In order to show results of the motor current signal analysis (MCSA) method coupled to the angular approach, current signal of a machine has been simulated without and with IAS perturbations. The considered model is a 50 kW, 50 Hz, 400 V, 2 poles, 24 stator slots, 30 rotor slots, star connected, standard squirrel cage induction motor rotating at a stationary speed $\omega = 300$ rad/s.

Figure 4 shows a sinusoidal stationary variation of the stator first phase current. When projected onto d-axis, the combination of the three phase currents oscillates stationary Fig. 5. Theses oscillations appear due to discontinuities of the magnetic flux passing through the stator and rotor slots. Although the motor is currently working in stationary conditions, we can, also notice some perturbations in the torque curve Fig. 6. These perturbations are about 8 % of the torque value and depend of geometrical parameters of the motor.

After adding the perturbation function to the constant rotational speed as recalled in Fig. 7, the stator first phase current variations Fig. 8, the projection of stator currents Fig. 9 and the torque Fig. 10 versus angular position of the rotor are presented.

Through these figures, it was shown that a perturbation may not appear in either the stator per phase current or the torque curve. On the contrary, it appears clearly as a periodic perturbation in the d-axis projected signal. This perturbation appears each time a speed perturbation takes a place. It was proven through this graph that a

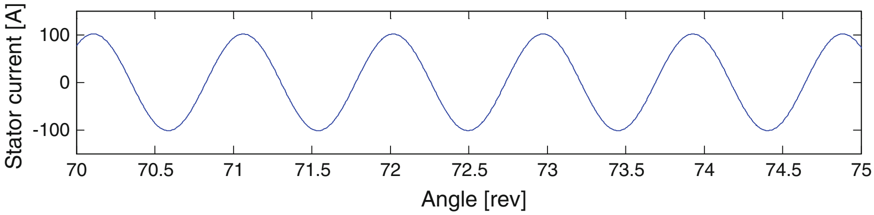

Fig. 4 Stator current versus angle of rotation for a constant rotational speed $\omega = 300$ rad/s

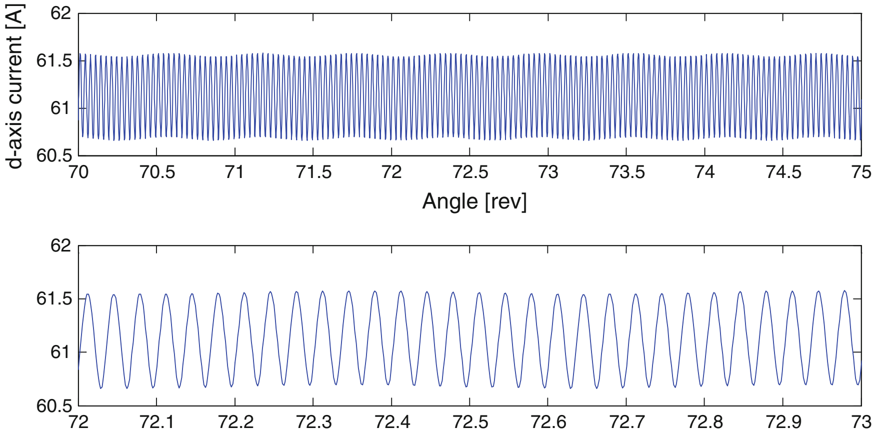

Fig. 5 *d*-axis current and zoom of the *d*-axis current for a constant rotational speed $\omega = 300$ rad/s

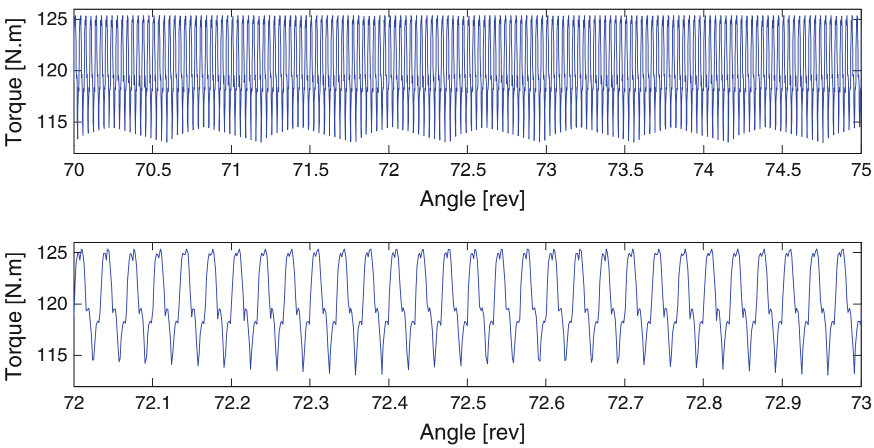

Fig. 6 Torque and zoom of the torque for a constant rotational speed $\omega = 300$ rad/s

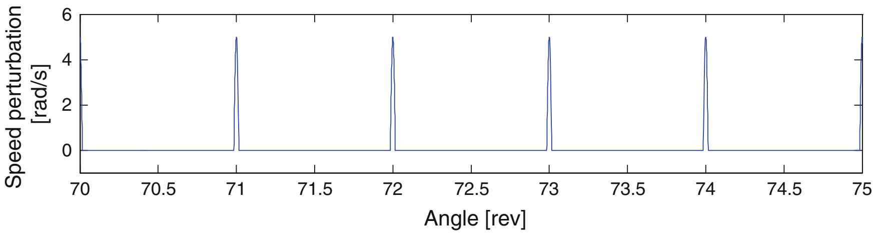

Fig. 7 Stator current versus angle of rotation for a disturbed rotational speed

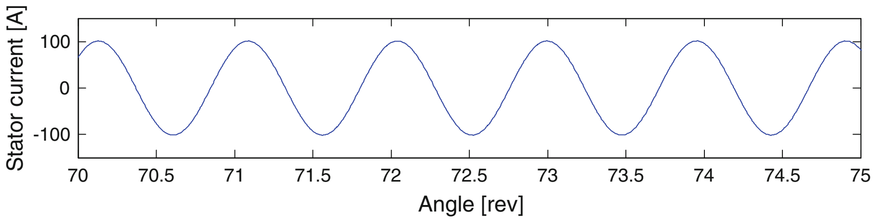

Fig. 8 Stator current versus angle of rotation for a disturbed rotational speed

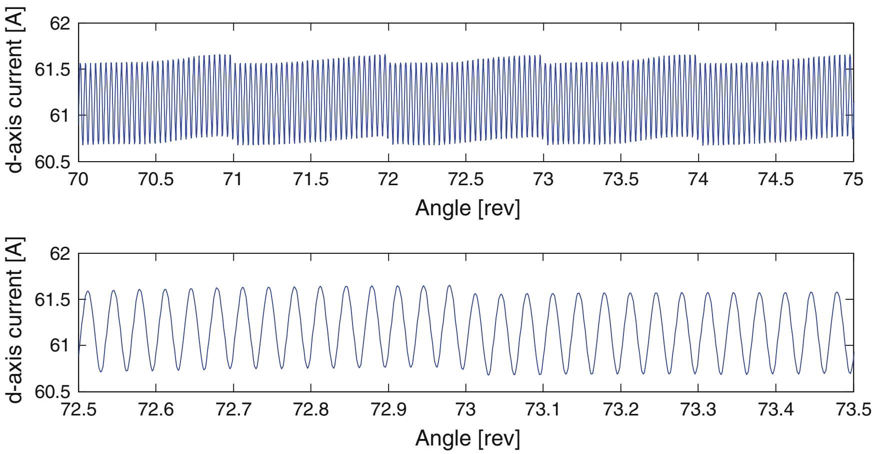

Fig. 9 *d*-axis current and zoom of the *d*-axis current for a disturbed rotational speed

very small perturbation in the rotation speed can be distinguished in the projected signal, proving the capacity of this method to small faults detection. It remains to address the sensitivity of the method to the perturbation amplitude.

The simulation demonstrates also the importance of considering angular domain for modeling the motor in term of computation time. A comparison between model

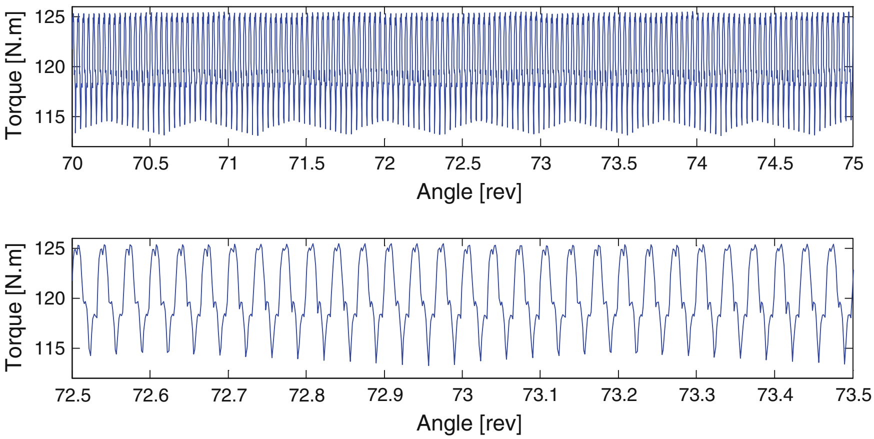

Fig. 10 Torque and zoom of the torque for a disturbed rotational speed

runs in time and angular domains was performed for 1 s of a stationary motor rotation. Through this comparison is noticed that using angular domain reduce 70 % of the simulating time. This is justified by the fact that a large part of the numerical calculation was performed analytically. In fact, angular modeling allows determining the instantaneous angular variation of each coefficient of the $[G(\theta)]$ matrix and its derivate with respect to angle. Regarding these coefficients, it is noticed that they are depending on angularly periodic functions independently of the rotation speed. This ascertainment strengthens our angular approach to modeling.

5 Conclusion and Perspectives

The work presented in this paper is an extension of a previous one aimed to formulate an analytical modeling of the MCSA for systems operating under stationary conditions. By introducing angular approach in classical models, an original reformulation of the method is presented to make it available for rotating systems operating under non-stationary conditions. The validation of this new methodology improves the use of MCSA. It also emphasizes the potential of the angular approach to solve non-stationary problems and extend its application on electrical machines. Results for constant and disturbed angular speed of the motor shows the importance of dealing with non-stationary conditions to get effective monitoring.

From a modeling viewpoint, coupling the electrical model with a mechanical one seems to be a natural extension of the present work in order to simulate perturbations induced by the presence of a fault on stator current signals.

Acknowledgements Authors gratefully acknowledge Rhone-Alpes Council support via mobility grant "Acceuil Doc" 13722.

References

1. Blodt M, Granjon P, Raison B, Rostaing G (2008) Models for bearing damage detection in induction motors using stator current monitoring. IEEE Trans Ind Electron 5(4)
2. Rajagopalan S, Habetler TG, Harley RG, Sebastian T, Lequesne B (2006) Current/voltage-based detection of faults in gears coupled to electric motors. IEEE Trans Ind Appl 42(6)
3. Feki N, Clerc G, Velex Ph (2013) Gear and motor fault modeling and detection based on motor current signal analysis. Electr Power Syst Res 95:28–37
4. Renaudin L, Bonnardot F, Musy O, Doray JB, Rémond D (2010) Natural roller bearing fault detection by angular measurement of true instantaneous angular speed. Mech Syst Signal Process 24(7):1998–2011
5. Bourdon A, André H, Rémond D (2010) A new way of writing motion equations in rotating machines by translation into the angular domain. In: Proceedings of the 8th IFToMM international conference on rotor dynamics, KIST, Seoul, Korea, 12–15 September 2010
6. Rémond D, Antoni J, Randall RB (2014) Editorial for the issue on instantaneous angular speed (IAS) processing and angular applications. Mech Syst Signal Process 44:1–4
7. Feki N (2012) Modélisation électro-mécanique de transmissions par engrenages- Applications à la détection et au suivi des avaries, N° 2012 ISAL 0041 INSA of Lyon
8. Ostovic V (1989) Dynamics of saturated electric machines. Springer, New York
9. Bourdon A, André H, Rémond D (2014) Introducing angularly periodic disturbances in dynamic models of rotating systems under non-stationary conditions. Mech Syst Signal Process 44:60–71

http://www.springer.com/978-3-319-20462-8

Advances in Condition Monitoring of Machinery in
Non-Stationary Operations
Proceedings of the Fourth International Conference on
Condition Monitoring of Machinery in Non-Stationary
Operations, CMMNO'2014, Lyon, France December
15-17
Chaari, F.; Zimroz, R.; Bartelmus, W.; Haddar, M. (Eds.)
2016, XI, 494 p. 295 illus., 248 illus. in color., Hardcover
ISBN: 978-3-319-20462-8