Frequency modulations in a multiphysic model of an induction motor applied to the diagnosis of bearings using MCSA

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Abstract

In this paper, we investigate stator current signals generated by a numerical model of an induction machine coupled to a rotating shaft supported by two rolling bearings. An intrusive model of the induction motor that takes into account its angular geometry allows the introduction of angular periodicities. Contrary to several diagnosis techniques based essentially on signal processing tools, the major interest of presenting this model lies in the description of the transfer path from a small localized bearing defect until its manifestation on electrical signals. By taking into account the Time-Angle relation in the modeling, the introduction of the concept of time-dependent and angular-dependent frequencies is permitted. In fact, bearing defects induces torque oscillations at particular frequencies that modulate the magnetic fields in the motor and then it appears in the signature of current signals on the stator of the induction machine. Moreover the proposed way of dealing with the topic removes limitations of diagnosis of rotating machinery under non-stationary conditions. Results found intend to be a contribution to a better exploitation of the Motor Current Signal Analysis (MCSA) method for condition monitoring and a better comprehension of the impact of a mechanical defect on the whole electro-magnetic-mechanical system.

1 Introduction

In an induction machine, the diagnosis of bearing defects using frequency analysis of electrical current signals requires the knowledge of the dynamic behavior of the entire system. In fact, in addition to external sources of excitation, the dynamic behavior of the motor is governed by a set of frequencies modulated as a result of multiphysic subsystem interactions.

In addition to the multiphysic behavior of the dynamic system, the geometry of the rotating machinery influence its performance. The rotating machinery presents cyclic morphology in the angular domain. When a defect appears on a mobile part of the rotating system, the characteristic frequency of the defect will be combined with characteristic frequencies of the motor. The comprehension of these interactions is realized via setting numerical models that represent phenomena manifestations and multiphysic interactions. We present in this paper, the model that integrates geometrical characteristics of the machine. The objective is to evaluate their degree of influence of an angularly cyclic defect such as the bearing outer race defect on the diagnosis and the transfer path of the defect signature through multiphysic sub-systems. Contrary to several signal processing tools used for diagnosis that propose analytical expression of the quantity to diagnose, frequency modulations in the system that we propose will be generated naturally through the interaction of dynamic quantities. Depending on the geometry and the location of the defect, the fault signature changes allowing efficient fault interpretations.

Recent research work have proven that a bearing defect induces in the induction machine, in addition to excentricity, a contribution on the IAS (Instantaneous Angular Speed). It is then important to set a dynamic model that is able to consider those rotation speed variations. In the modeling, the IAS is considered as the quantity that ensures the transmission of information about the presence of the defect from the mechanical parts to

the electrical quantities. Investigating rotation speed signal is also an important alternative to be tracked. In numerical models, access to IAS in modelling is allowed by an original approach "Angular approch" which recently proposed to describe dynamic behavior of rotating machinery. This approach was firstly applied to simple rotating systems of limited Dof in [1]. Through the possibility to represent non-stationary conditions and highlighting angular frequencies in the rotating machine, the importance of the application of the method is proven.
In other hand, rotation speed variations are present in industrial applications du to non-constant operating regimes and varying loading. Operating conditions influence considerably the signature of the defect on the quantity to diagnose. Non-stationary conditions are at the origin of lack of relevance in diagnosis of rotating machinery and the effect of those operating conditions on the dynamic behavior of the machine lacks of comprehension.

In this paper, we propose to study modulations on a three-phase induction machine while considering geometrical effect, multiphysic behavior, non-stationary conditions and geometrically-defined outer-race bearing defect. The ultimate objective is a better diagnosis using MCSA and IAS analysis.

2 Presentation of the multiphysic system considered for diagnosis

2.1 General description of the system operating

The objective of this section is to present the proposed multiphysic system considered for the diagnosis. Since the diagnosis focuses on the bearings inside the motor, the proposed system consists in a squirrel cage induction machine that supply a mechanical sub-system of a simple shaft supported by two simple raw rolling bearings in its endings. The Figure shows a 3D presentation of the global system.

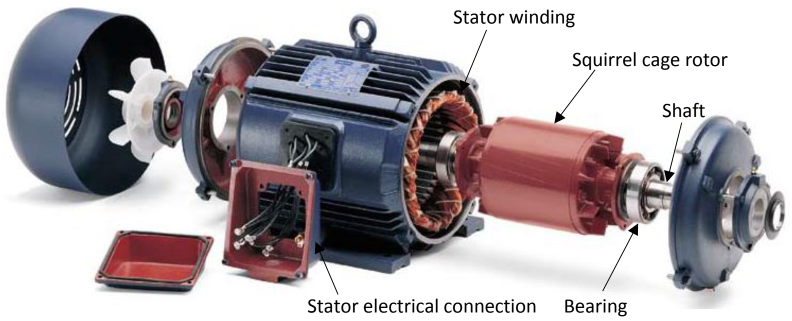


Figure 1: 3D presentation of the multiphysic system

The geometry of the induction machine is composed of a stator and a rotor separated by a thin air-gap. The stator and the rotor structures are composed by slots and teeth uniformly distributed as shown in Figure 2. Through the stator slots, passes a copper winding alimented by the power supply. Through the rotor slots, passes the rotor bars of the squirrel cage. The bars are uniformly distributed and short-circuited by two rings at there extremities.

The induction machine is fed by a three-phase power supply. The alternative power supply in the stator of the induction machine is on the origin of the generation of a magnetic field in the air-gap. The rotating magnetic field in the air gap generates an electromagnetic torque which is quite enough to drive the rotation of the rotor. The shaft being adherent on the one hand to the rotor of the machine and on the other hand to the inner races of the bearings, transmits the rotational movement between the electromagnetic rotating subsystem and the mechanical rotating subsystem.
Since the geometry of the rolling bearings have cyclic periodicities in the radial plane, we can generate this characteristic to the global electro-magnetic-mechanical system. The interest of this research work is to investigate the effect of the cyclic geometry of the rotating system. The angular periodicity of the system is on the

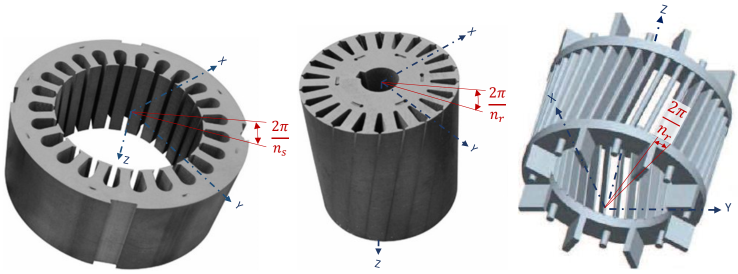


Figure 2: Morphology of the stator, the rotor and the squirrel cage

origin of angular frequencies in the coupled multiphysic system since phenomena depend necessarily on the geometry of the rotating machine.

2.2 Time and Angular frequency modulations

In the induction machine, in addition to external excitations that may be on the origin of additional frequencies, internal component of the machine are frequency sources. In fact, relatively to its rotating characteristic, phenomena relative to the machine physical behavior are manifesting in a cyclic way. In fact, in the induction machine considered in this work, phenomena which appear clearly as a frequency origins are:

- 3 phases sinusoidal power supply at the time frequency $50Hz$ (Figure 3),
- Angularly cyclic geometry of the stator and the rotor structure at respectively n_s event/revolution and n_r event/revolution,
- Rotor excentricity which characteristic frequency depend on the type of excentricity (static, dynamic, mixed),
- Defect characteristic frequency. The frequency of the defect depend on its location. For a bearing defect an outer race defect on bearings, the frequency of the defect correspond to the BPFO (Ball Pass Frequency on the Outer race).

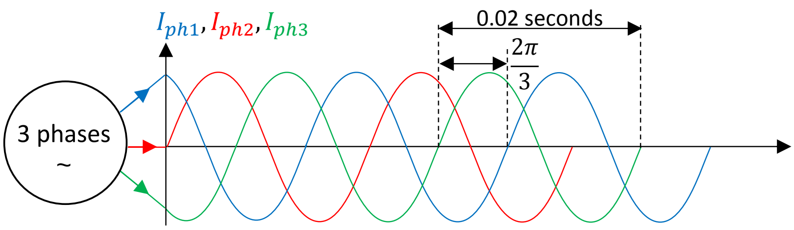


Figure 3: 3-phase equilibred stator current of an induction machine operating in ideal stationary conditions

Particularly, frequencies relatives to stator and rotor slots intervene to the definition of the magnetic field on the induction machine. In fact, magnetic permeances which are characteristic of the flux circulation in the air-gap of the machine depend on the geometry of the machine slotting. During the rotor moving, values of the permeances of each couple of stator and rotor teeth change. They depend on the angular displacement of the rotor since the geometry of fictive flux tubes in the air-gap changes instantaneously with the dynamic movement of the rotor (Figures 4 and 5).

Frequencies described previously do influence the dynamic behavior of the induction machine. Depending on the physical quantity to diagnose (electrical current, magnetic flux, instantaneous angular speed or vibration signals), the manifestation of the defect changes. Frequency modulations are generated naturally during the machine operating and differently in each physical quantity. In fact, contribution of each quantity including frequency characteristics change. Depending on the external excitations, further modulations can be associated with the other frequency sources. The machine behavior is naturally adapted the input data. Actually,

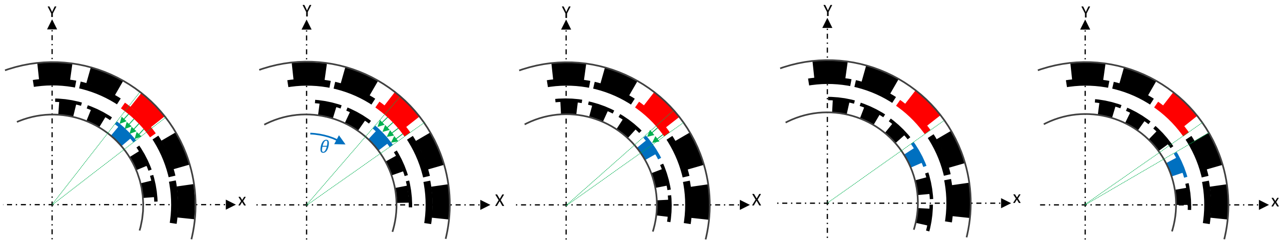
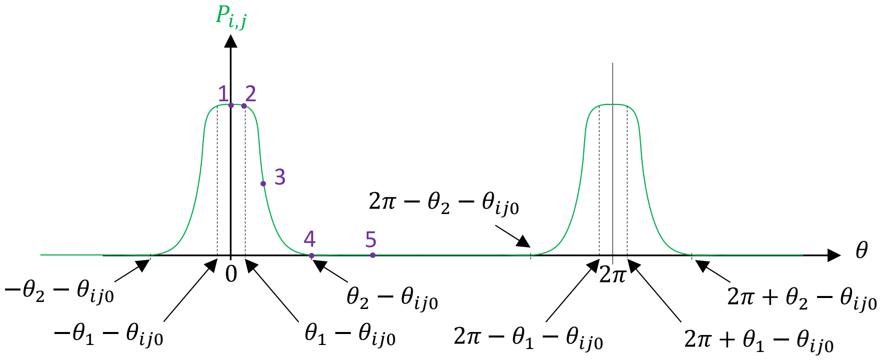
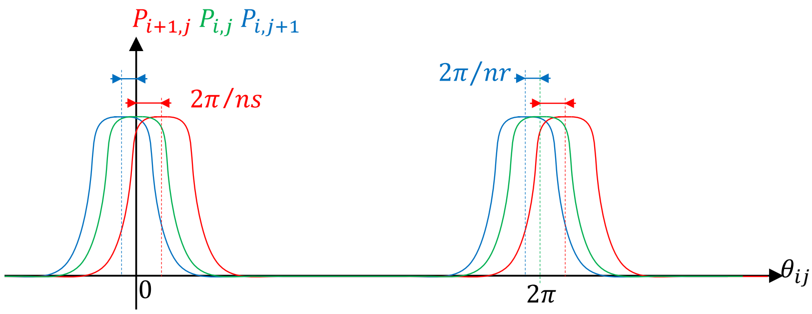


Figure 4: Flux transfert between a stator and a rotor teeth for 5 cases during the rotor moving



(a) Corrolation with the 5 cases defined in Figure 4



(b) Air-gap permenaces of adjacent couples of teeth relatively to the relative angle between couple of teeth (i, j)

Figure 5: Air-gap permeance of the couple of teeth relatively to angular rotation of the rotor θ

the machine behavior is responsive and very sensitive to additional time/angular frequencies. In this paper, the target quantities for bearing defect diagnosis in the induction machine are the stator phase current and the IAS. Relatively to the dynamic behavior of the multiphysic system, the defect will follow a transfer path much longer and by integrating more components representing additional time and angular characteristic frequencies to reach the electrical quantity. The comprehension of the defect manifestation is more difficult in this case because reciprocal interactions are taken into account along the entire transfer path.
Since the induction machine represents simultaneously time and angular frequencies, non-stationary conditions influence highly the diagnosis results. In Figure 6, we represent the variation of an arbitrary chosen signal x which represent a cyclic frequency f in the angular domain. The signal is then represented relatively to the time variable t for three operating regimes. Only one of the regimes is non-stationary. Through this figure, we can show clearly that even this signal conserve its angularly periodic characteristic in the time domain in stationary conditions, this characteristic is hidden by non-stationary conditions. In the opposite case, let us suppose a signal y with temporal periodicity, this frequency characteristic will be hidden in a representation in the angular domain for a non-stationary regim.

In conclusion, frequency modulations between angular and temporal frequencies are sources of inaccu-

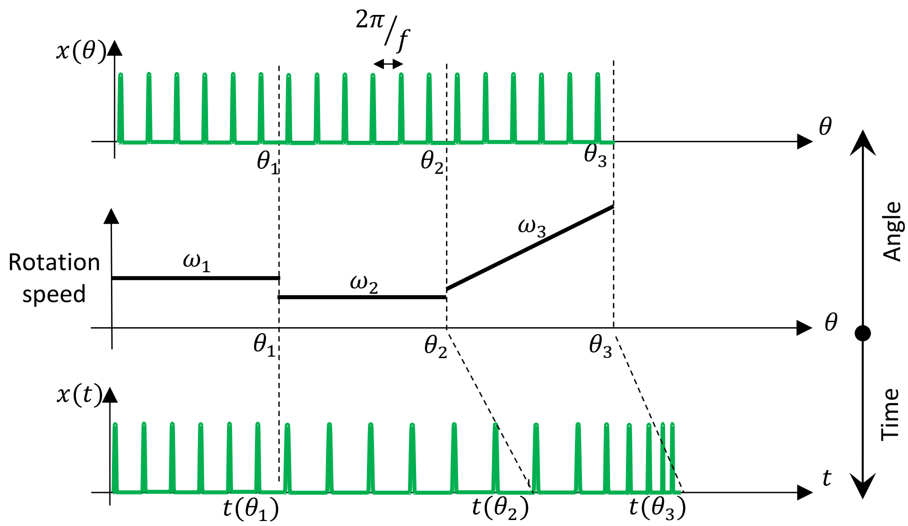


Figure 6: Representation in the temporal and angular domains of an arbitrary choosen signal x with cyclic frequency

racy of diagnosis in non-stationary operating cases. In this paper, we will propose a solution for an effective diagnosis including all the machine characteristic and in realistic highly non-stationary conditions.

2.3 Electro-magnetic-mechanical model

The corresponding model proposed to represent the dynamic behavior of the multiphysic system is composed by a two subsystems (the induction machine subsystem and the shaft-bearings subsystem) and three fields (electrical, magnetic and mechanical).
The induction machine is presented by a permeance network model. The use of this model is motivated by its capacity to provide a quite representative description of the geometry of the machine. Particularly, it takes into account the effects of slotting, air-gap length variations and winding distribution. The rotor of the induction machine is presented by a 3D electrical circuit of resistances and inductances. By discretizing the magnetic model to a finite number of nodes, in which each node represent a magnetic potential, a 2D magnetic network composed of permeances and magnetomotive network is set. The modelling of the induction machine is presented in [4]. The electrical and the magnetic parameters of the model are constant. The coupling of the motor model to the rotational dynamic movement of the rotor is ensured by the air-gap permeances value which consider the effect of the instantaneous rotation of the rotor. One of the originalities of this model is its capacity to consider small fluctuations of the rotation speed eventually produced by small defects, and large variations in rotational speed which can be induced by realistic non-stationary operating conditions.
The shaft is modeled by a 3D Finite Element model composed of a limited number of nodes. In each node, six degrees of freedom are considered. The nodes of the shaft are not taken arbitrarily. Each node represents a specific node on the shaft of the induction machine. Particularly, the electromagnetic torque and radial forces induced by the induction machine are applied on the central nodes of the shaft. In industrial applications, the induction machine is coupled to a receiver that resists to the movement of the shaft. Accordingly, a constant resistant torque is applied on the node on the extremity of the shaft. Axial forces are applied on the nodes localizing bearing inner races.
The rolling bearing model proposed in this work is presented in [2]. The model is chosen to its capacity to represent non-stationary operations and rotation speed fluctuations. This ability is ensured by considering tangential forces in each bearing element while respecting the static equilibrium of the bearing. The bearing model generates rolling bearing radial efforts that will be introduced in the mechanical system of the shaft as external forces (as shown in Figure 7).

In order to proceed to the coupling of the different subsystems, a comprehension of the operating of the machine and multiphysic interactions are needed. The induction machine is fed by the voltage power supply.

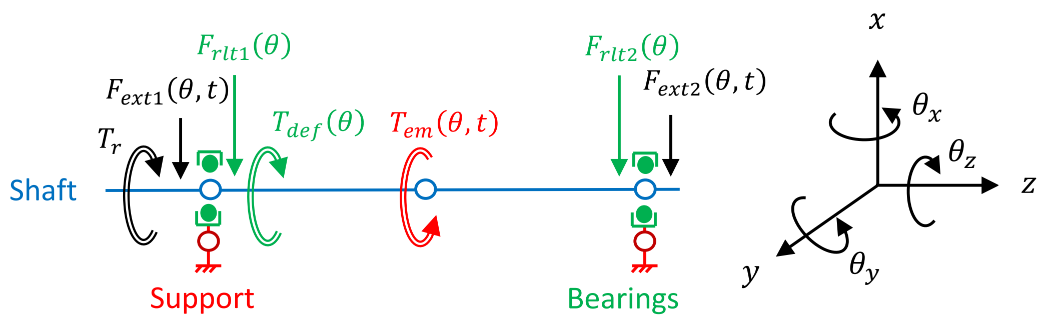


Figure 7: Schematic representation of the electro-magneto-mechanical model

Electrical current will be produced in the copper coils on the stator of the machine as a consequence. As a product of the variable electrical current in the stator, a rotating magnetic field in the air-gap is produced. The magnetic field is manifested by an electromagnetic torque that ensure the rotation of the rotor (idem. of the shaft). In the same time, the movement of the shaft that depends directly on the forces produced by the bearing manages the values of rotor instantaneous radial eccentricities, rotational axial velocity, and instantaneous angular position. In each angular position, the forces induced by the bearing dynamics are re-calculated. This physical description was detailed in the schematic coupling methodology representation in Figure 8.

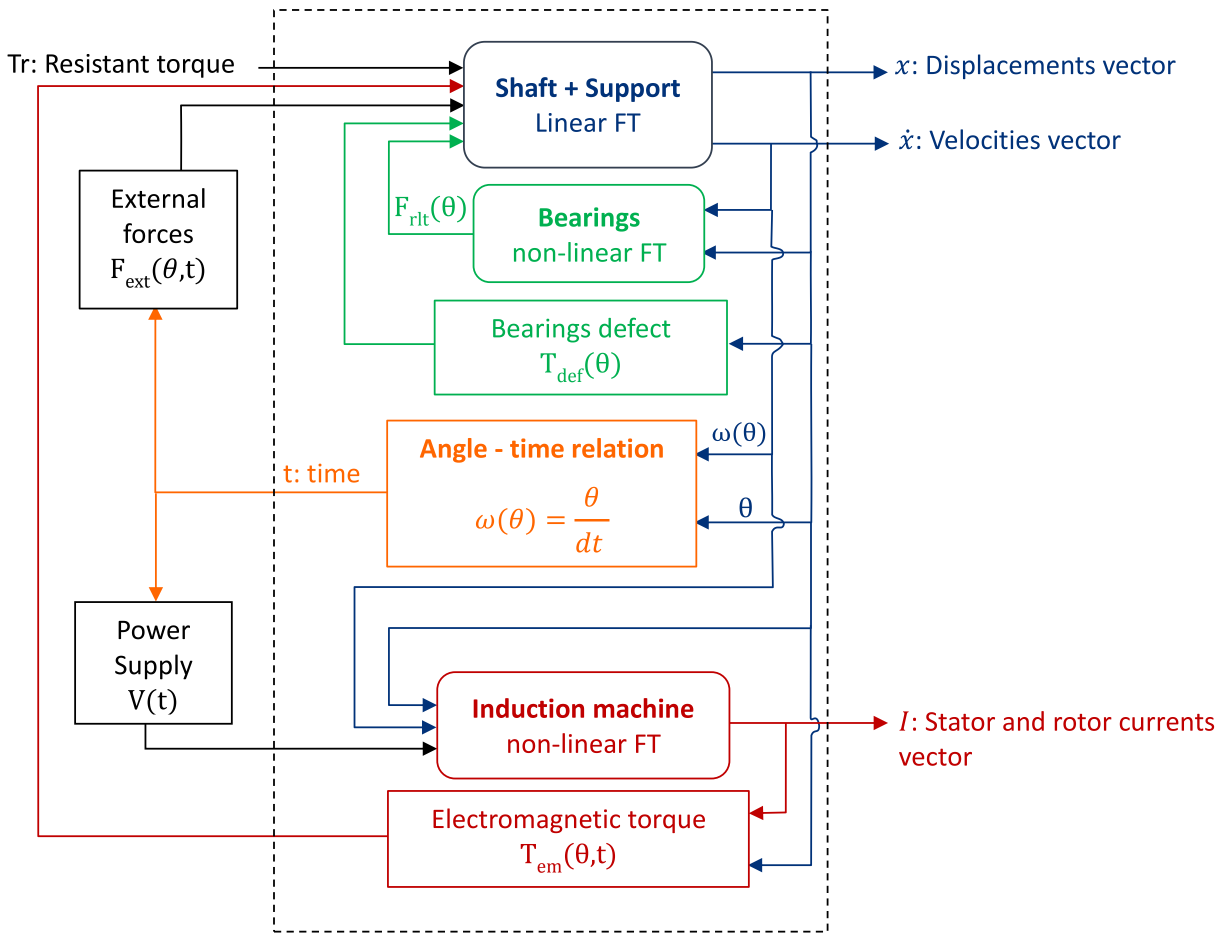


Figure 8: Coupling methodology of the multiphysic subsystems while considering "Angle-Time" relation

As mentioned in the previous section, the angular geometry of the rotating system is highlighted. In order to realize this objective, the whole modeling of the different subsystems was realized using an original approach called the "Angular Approach" [3]. The angular approach reinforce the comprehension of the angular periodicity of the multiphysic characteristics of the rotating system by discretizing the model in the angular domain rather than the temporal domain. The resolution of the dynamic system can be done in the time domain or in the angular domain, since the "Angle-Time" relation is taken into account in the modelling. The relation allows to define a bridge to switch from the time resolution to angular resolution and reciprocally. The relation that is conditioned by a nonzero rotation speed is defined as follows

$$\omega(t) = \frac{d\varphi(t)}{dt} = \frac{d\theta}{dt} = \frac{d\theta}{d\psi(\theta)} = \hat{\omega}(\theta) \tag{1}$$

while, φ and ψ are bijective functions strictly monotnic.
By definition, the expression of the rotation speed is written as follows

$$\omega(t) = \frac{d\varphi(t)}{dt} = \frac{d\theta}{dt} = \frac{d\theta}{d\psi(\theta)} = \hat{\omega}(\theta) \tag{2}$$

This definition, allows to generalize a relation between the derivation of quantities in the time and the angular domains by the following relations

$$\frac{d\bullet}{dt} = \frac{d\bullet}{d\theta} \cdot \omega(t) = \frac{d\bullet}{d\theta} \cdot \hat{\omega}(\theta) \tag{3}$$

Those relations are in the origin of the enlargement of the field of the study of the dynamic behavior of the multiphysic model to non-stationary conditions. In fact, the relations explicate the capacity to integrate variable expression of the rotation speed. This variation can be defined relatively to time or/and angle variable. The resolution is also permitted in the time or angular domain.
The differential system in the state format can either be defined relatively in the time or the angular domain as follows.
In the angular domain:

$$\begin{Bmatrix} \frac{d\{\hat{I}(\theta)\}}{d\theta} \\ \frac{d\{\hat{Q}(\theta)\}}{d\theta} \\ \frac{dt}{d\theta} \end{Bmatrix} = \frac{1}{\hat{\omega}(\theta)} \cdot [A(\theta)] \cdot \begin{Bmatrix} \{\hat{I}(\theta)\} \\ \{\hat{Q}(\theta)\} \\ t \end{Bmatrix} + \frac{1}{\hat{\omega}(\theta)} \cdot [B(\theta)] \cdot \{U(\theta,t)\} \tag{4}$$

where, θ is the rotational dof on the axial direction z of the central node. t is the time variable. $\hat{\omega}(\theta)$ is the rotation speed expressed relatively to the angular variable.
$\{\hat{I}(\theta)\}$ is the electrical part of the state vector composed of stator phases and rotor bars currents. A part of the state variable is gathered in the state vector as $\{\hat{Q}(\theta)\} = \begin{Bmatrix} \{\hat{X}(\theta)\} \\ \left\{\frac{d\hat{X}(\theta)}{d\theta}\right\} \end{Bmatrix}$
$\{\hat{X}(\theta)\}$ is the generalized displacements vector written relatively to the angular variable. As the shaft is represented by discret representation, $\{\hat{X}(\theta)\}$ is the displacement of the Dof of the different nodes relatively to the angular variable. The corresponding vector written relatively to the time variable is $\{X(t)\}$.
The state matrices are defined as follows

$$[A(\theta)] = \begin{bmatrix} [A_1(\theta)] & [0] & \{0\} \\ [0] & [A_2(\theta)] & \{0\} \\ \{0\} & \{0\} & 0 \end{bmatrix} \tag{5}$$

with,

$$[A_1(\theta)] = \left[-\left([L] + [J(\theta)]\right)^{-1} \cdot \left([R] + \hat{\omega}(\theta) \cdot [dJ(\theta)]\right) \right] \tag{6}$$

$$[A_2(\theta)] = \begin{bmatrix} [0] & [I_d] \\ -[M]^{-1} \cdot [K] & -[M]^{-1} \cdot [C] \end{bmatrix} \tag{7}$$

and,

$$[B(\theta)] = \begin{bmatrix} \left[\left([L] + [J(\theta)]\right)^{-1}\right] & [0] & \{0\} \\ [0] & \begin{bmatrix} [0] \\ [M]^{-1} \end{bmatrix} & \{0\} \\ \{0\} & \{0\} & 1 \end{bmatrix} \tag{8}$$

where, $[M]$, $[K]$ and $[C]$ are respectively mass, stifness and damping constant matrices.$[L]$ and $[R]$ are respectively constant matrices of resistances and inductances of the stator and the rotor of the induction machine. $[J(\theta)]$ and $[dJ(\theta)]$ are respectively angularly varying matrices of electric-magnetic interaction and its derivate relatively to the angular variable.
The external forces vector is composed from electrical and mechanical sources of excitation as follows

$$\{U(\theta,t)\} = \left\{ \begin{array}{c} \{V(t)\} \\ \{T_{em}(\theta,t)\} + \{T_r\} + \{F_{ext}(\theta,t)\} + \{F_{rlt}(\theta)\} + \left\{T_{def}(\theta)\right\} \\ 1 \end{array} \right\} \tag{9}$$

$\{T_{em}(\theta,t)\}$, $\{T_r\}$, $\{F_{ext}(\theta,t)\}$, $\{F_{rlt}(\theta)\}$ et $\left\{T_{def}(\theta)\right\}$ are respectively vectors of electromagnetic torque produit, resistant torque, external efforts eventually applied to the mechanical system, bearing forces and defect induced torque.
<u>In the time domain:</u>

$$\left\{ \begin{array}{c} \frac{d\{I(t)\}}{dt} \\ \frac{d\{Q(t)\}}{dt} \\ \frac{dt}{d\theta} \end{array} \right\} = [A(\theta)] \cdot \left\{ \begin{array}{c} \{I(t)\} \\ \{Q(t)\} \\ t \end{array} \right\} + \frac{1}{\omega(t)} \cdot [B(\theta)] \cdot \{U(\theta,t)\} \tag{10}$$

avec,$\{I(t)\}$ is the vector of stator phases and rotor bars currents described relatively to the time variable and $\left\{\hat{Q}(\theta)\right\}$ is the vector of displacment and velocity relatively to the time variable.

3 Diagnosis of defective bearing using MCSA and IAS analysis

In order to prove the capacity of the proposed model on the diagnosis of localized bearing outer race defect, the geometry of the defect was introduced to the bearing model. In fact, the defect on the outer race is defined in the radial plane of the bearing by its postion, depth and angular width. In Figure 9, we show a schematisation of the geometrical characteristic of the defect on the fixed outer race. The defect considered in the simulation is of $50\mu m$ of depth and 4° of angular width. The defect on the outer race characteristic frequency is relative to the bearing geometry. It is equal to $4.1045 event/revolution$.

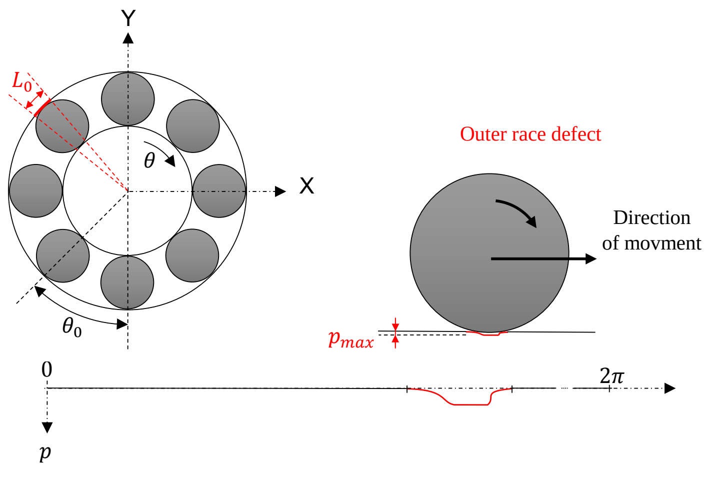
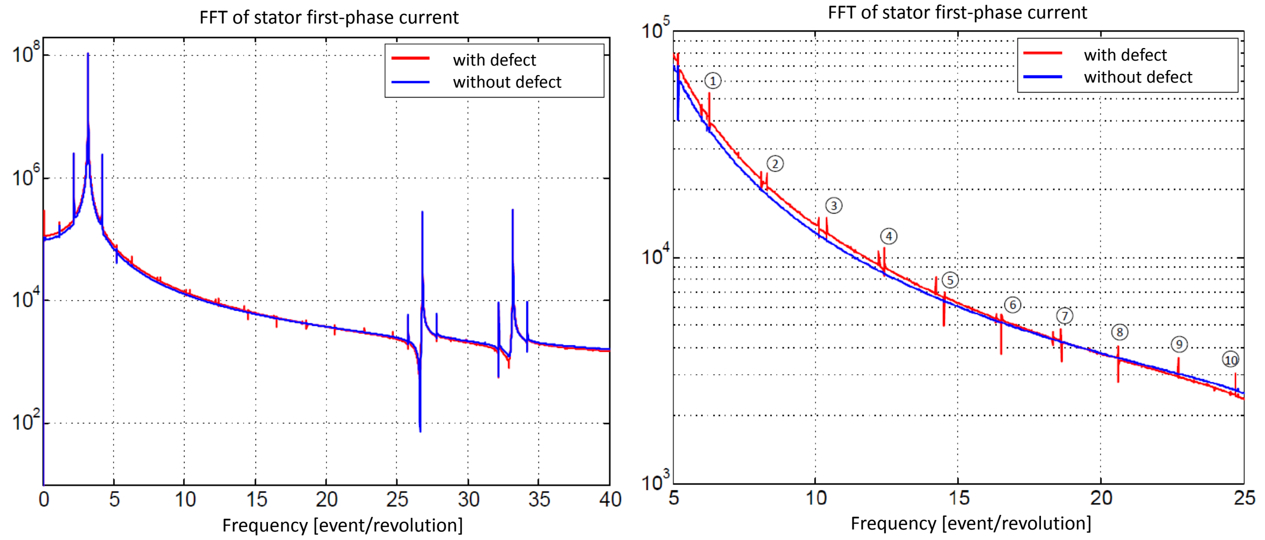


Figure 9: Geometry of the defect in the case of localized outer race fault

The shaft considered in the modelling is $80mm$ of diameter and $240mm$ length. The rotation of the shaft is ensured by a 3-phase, 2 poles, squirrel cage induction machine alimented by a supply of 220V and $50Hz$ of frequency. The machine geometry contains 24 stator slots and 30 rotor bars uniformly distributed on the angular circumference of the rotating machine. External radial forces are applied on the shaft. Specifically, $1kN$ is applied on each node representing the localization of the bearing inner race. A $5N.m$ resistant torque is applied on the node on the extremity of the shaft.

3.1 Case of defective bearing in stationary operation



(a) Angular FFT of the first-phase stator current

(b) Angular FFT of the first-phase stator current. idem 5 ev/tr - 25 ev/tr

Figure 10: Angular FFT of the first-phase stator current for a healthy motor and with presence of outer race defect in stationnary conditions

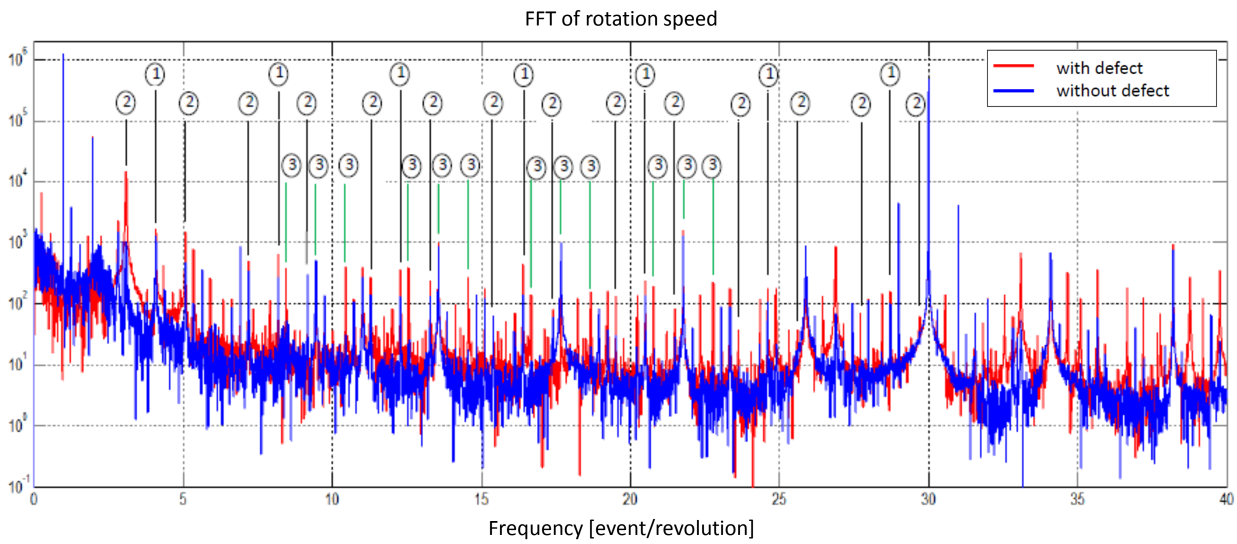


Figure 11: Angular FFT of the IAS for a healthy motor and with presence of outer race defect in stationnary conditions

While stationary conditions previousely defined are maintained, simulations were performed for a healthy system and a defective bearing one. Simulations were performed for $150 revolutions$ of the rotor. Long simulations are justified by the willness to highlight the contribution of phenomena of small energie such as those induced by bearing defects and abled by the angular description of the model which allows to reduce 72% of the simulation time relatively to time description. We show in the following figures frequency analysis of stator current and IAS. The spectral analysis are performed without windowing and in the logarithmic scale to explicit clearly contribution of the defect frequency.

The angular FFT of the stator current shows in Figure 10(a) characteristic freuqencies of the rotating machinery. Particularly, f_s the current frequency $50Hz$ defined in the angular domain ($3.21 event/revolution$). We can explicit also the modulation of this frequency with f_r the rotation frequency $1 event/revolution$ as $f_s \pm k \cdot f_r$

$(1.21, 2.21, 3.21, 4.21$ and $5.21 event/revolution)$. Modulations are manifested between f_{sh} slots harmonics freuqency $30 event/revolution$, current freuquency and rotation frequency $(25.79, 26.79, 27.79, 32.21, 33.21$ and $34.21 event/revolution)$.

The zoomed view in Figure 10(b) explicits frequency modulations relative to the outer race defect. Frequencies numbered from 1 to 10 in the figure are corresponding to modulations between the defect frequency on the outer race f_d with the rotation frequency and the current frequency. Analytically, the expression can be written as $f_s + k \cdot f_d \pm f_r$. For example (6.3, 8.3, 10.41, 12.41, 14.52, 16.52, etc.)

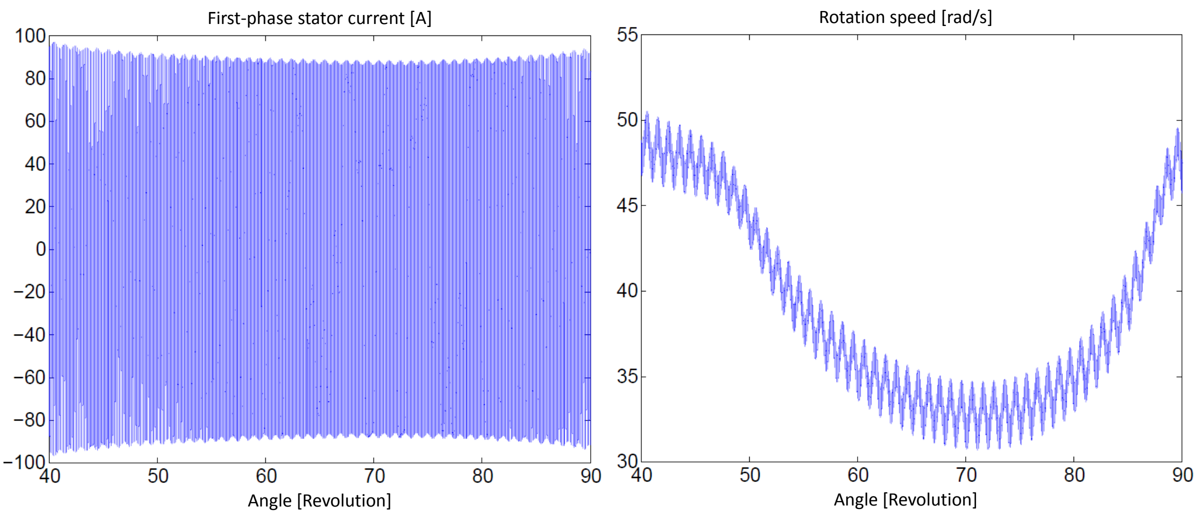
In the Figure 3.1, the IAS angular spectrum shows in addition to frequencies relative to the dynamic of the machine as $k \cdot f_r$ and $f_{sh} \pm f_r$, harmonics of the defect frequency $k \cdot f_d$ and modulations of this frequency. Three levels of modulation are highlighted:

$$\begin{cases} f_{sh} - k \cdot f_d \\ k \cdot f_d - f_r \\ f_{sh} - k_1 \cdot f_d - k_2 \cdot f_r \end{cases} \quad \text{where, } k, k_1 \text{ and } k_2 \text{ are integers.}$$

As a conclusion, the model has permitted to explicit the modulations auto-produced by the machine dynamics. Especially, the defect signature appears clearly in the IAS and current spectrum in a machine operating under stationary conditions.

3.2 Investigation on diagnosis in non-stationary operating regims

In industrial applications, operating conditions are never ideally constant. This reality induces that practical investigations on the diagnostic of rotating machinery must consider all the time realistic operating conditions. Similarly, investigations on numerical diagnosis of rotating machinery defects must consider thoses variations of operating conditions on the simulations. As the model proposed in this paper consider in the same time small fluctuations induced by bearing defects and high perturbations of operating conditions, we will investigate in this section the influence of a localised bearing defect while considering varying operating conditions. The variation of the operating conditions are generated in the model by introducing a non-constant power supply frequency. This configuration is in total agreement with industrial applications where the moteur is alimented by power supply caming from a frequency converter. For the simulation, we consider a continueous variations of the frequency between $50 Hz$ and $60 Hz$.



(a) Spectre angulaire du signal de courant de phase 1

(b) Spectre angulaire du signal de courant de phase 1. idem 5 ev/tr - 25 ev/tr

Figure 12: Angular signal of the first-phase stator current and the IAS with presence of outer race defect in non-stationairy conditions

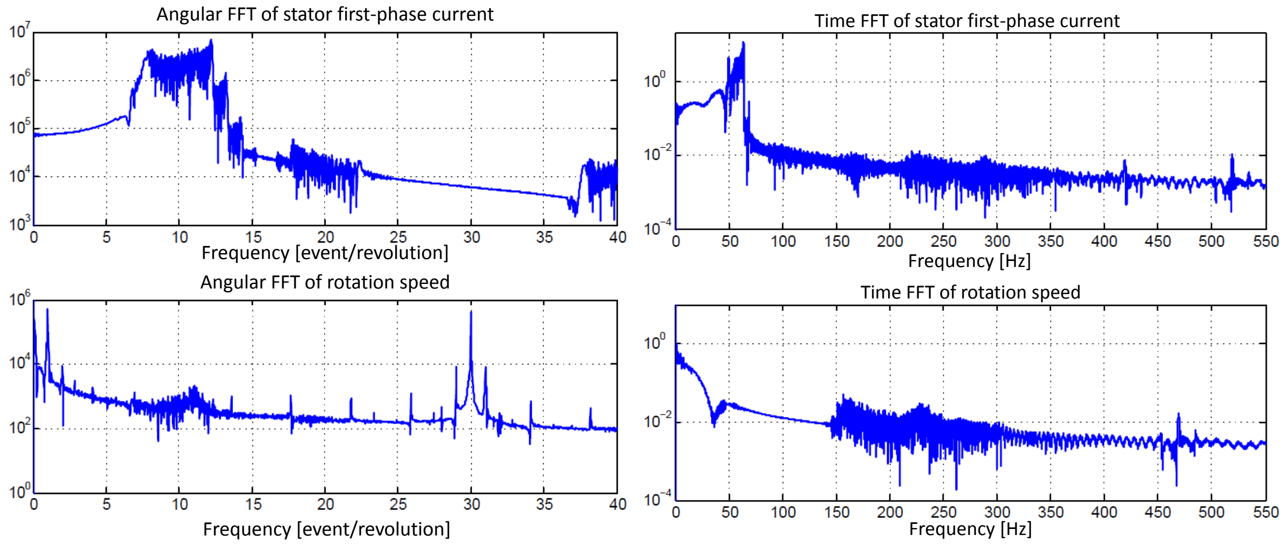


Figure 13: Time and Angular FFT of the first-phase stator current and the IAS with presence of outer race defect in non-stationnary conditions

In Figure 12, we show the output signal of the stator first-phase current and the IAS versus the angular rotation of the rotor. Due to frequency variations, the rotation speed of the machine vary between $31 rad/s$ and $50 rad/s$. We note also variations of the stator current amplitude and frequency.

Since time and angle are outputs of the dynamic system, spectral analysis are possible in time or angular domains. In the Figure 3.2, the current and the IAS are shown versus time and angular frequencies domains. As the angular speed of the machine is variable, angular frequencies of the stator current and the IAS are variables in the time representation. Temporal spectrum can't contain useful informations. The current characteristic frequency is also variable in the angular spectrum. This reality induces that current spectrum is non useful even in the angular domain. However, IAS spectrum in the angular domain is independant from the current frquency f_s. That's why the diagnosis of defect remain possible using this spectrum.

As a conclusion, we prove through the example of a bearing defect in an induction machine that diagnosis of rotating machinery is possible even in non-stationary operating conditions using analysis of angular FFT of the IAS.

4 Conclusion

In this paper, an electro-magnetic-mechanical model of an induction machine coupled to rolling bearing. Being modelled relatively to angular approach and by considering Angle Time relation, the model is adapted to non-stationary operating conditions. The coupling methodology was presented. The model highlights the angular periodicity of the geometry of the rotating system. Particularly, time and angular frequencies induced by the geometry, internal characteristic of the machine and the operating conditions are investigated. It was clarified that modulations of time and angular frequencies especially in non-stationary operations are sources of ambiguity for diagnosis of rotating machinery in realistic operating conditions. The defect is defined in the model through the definition of its geometry: location, depth, angular width. Through the investigation of the modulations produced in the machinery it was demonstrated that stator current and IAS are able to give effective information about the presence of the defect in stationary conditions. Otherwise, in non-stationary operations, it was shown that the frequency investigation of the IAS in the angular frequency domain remains able to give effective information about the defect. However, current analysis is unable to give those informations since the current frequency is no more constant either in time or in angular presentations.

Acknowledgements

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