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Angular-based modeling of induction motors for monitoring

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ABSTRACT

Understanding the occurrence of bearing defects in electrical current signals using Motor Current Signal Analysis (MCSA) requires the implementation of numerical models. In this paper, an electro-magnetic-mechanical model is proposed to describe the dynamic behavior of a squirrel cage induction motor coupled to a rotating shaft supported by elastic foundations. The aim of this research work is to gain understanding of the interaction between multiphysics subsystems, mainly in faulty cases, to decipher the transfer path from the defect to its manifestation in stator currents. A new method of writing dynamic equations for simplified simulations of an induction motor is developed using an angular approach. In addition to its capacity to extend the modeling to non-stationary operating conditions, the model proposed highlights the angular periodicity of the rotating motor's geometry. The electromagnetic field of the motor is redistributed periodically when a geometric defect occurs on a rotating part of the global system. In this case, the electromagnetic torque of the induction motor may present angularly-periodic variations. After having presented the electromagnetic-mechanical coupling methodology, the influence of torque variations is investigated and the importance of the angle-time function is highlighted.

1. Introduction

Many industrial activities are faced with the challenge of ensuring effective monitoring to reduce machine downtime and improve operation under optimal conditions. In the case of rotating machinery, especially induction motors, the presence of a defect on a mobile part of the system generates disturbances associated with its characteristic frequencies (e.g. bearings). These disturbances may be caused by electric, magnetic or mechanical faults and are detectable on measured signals (acoustic signals, accelerations, rotation speed, electrical signals, etc.) [1]. Investigating these signals generally provides information about the defect. Thus numerous research works have focused on monitoring induction motors using techniques based on signal processing tools to identify the presence of a defect by detecting characteristic fault frequencies [2–5]. In spite of many available techniques for monitoring motors, industrial sectors are still faced with unexpected faults in

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Nomenclature

P	permeance
ϕ	magnetic flux
F_m	magnetomotive force
F	electromotive force
ε	Magnetomotive potential
n_{ph}	number of phases
n_s	number of stator teeth
n_r	number of rotor teeth
θ	rotor angular displacement relative to the stator
θ_{ij}	jth rotor tooth angular displacement referring to the ith stator tooth
$\mathbf{I_d}$	identity matrix
f_s	stator current fundamental frequency
f_{sh}	slot harmonic frequency
f_d	defect characteristic frequency

Subscripts

$()_s$	stator
$()_r$	rotor
$()_t$	tooth
$()_{sy}$	stator yoke
$()_{st}$	stator tooth
$()_{sl}$	stator leakage
$()_{rl}$	rotor leakage
$()_{rt}$	rotor tooth
$()_{ry}$	rotor yoke
$()_{br}$	branches
$()_n$	nodal quantity
$()_a$	active branch
$()_i$	stator node where $i = 1$ to ns
$()_j$	stator node where $j = 1$ to nr

electric motors and the resulting decrease in their predicted lifetime. Indeed, although these techniques provide useful information, they do not allow deciphering the occurrence of phenomena in the signals monitored. Several of these investigations proposed the use of the stator current spectrum to detect mechanical defects [6–8]. More intrusive models of motors are required to obtain a precise description of the electromagnetic behavior of the machine and decipher the transfer path from the mechanical defect to its manifestation in electrical signals. Several methods have been proposed in the literature to build models of motors. A simplified model based on a d–q representation of an asynchronous motor was proposed [9]. However, the d–q model is clearly inadequate when attempting to account for the effects of machine geometry, and more refined and realistic modeling appears necessary. Thus sophisticated models based on finite element modeling can be found [10]. Although these methods offer good precision on the motor dynamics, they require excessive computation time, especially when analyzing the couplings between realistic bearing failures at the early stage of development (bearing pitting) and induction motors. Relatively simplified models of induction motors can be found in the literature in which the machine is discretized as a finite number of nodes, such as in the multiple coupled circuit approach [11] and the Permeance Network Model (PNM) [12]. The PNM requires a limited number of nodes while offering sufficient precision for describing electromagnetic phenomena occurring during operation. An analytical model of a squirrel cage induction motor based on permeance network modeling was proposed in [13]. The model developed was coupled to a geared mechanical system and proved its efficiency for detecting gear defects using MCSA. This model also provided a satisfactory description of the motor's electromagnetic behavior. Indeed, it was accurate enough to account for the effects of machine slotting and periodicities, rotor eccentricity, and air-gap variations which can be disturbed by the presence of mechanical faults. The model was well formulated but its performance was limited to stationary operating conditions and had to be extended to less energetic faults like bearing faults.

With the ultimate goal of identifying the transfer path from bearing defects to electrical signals, it was demonstrated in [6,14] that a localized bearing defect induces torque variations. In fact, torque oscillations exist naturally in a healthy motor due to the angular variations of the air-gap field. However, bearing defects induce additional torque perturbations which are present at particular frequencies related to the geometry of the global rotating system and the rotational speed of the motor. Therefore mechanical-speed oscillations due to load-torque variations occur [15]. These variations are very weak and must be distinguished from macroscopic velocity variations representative of non-stationary operating conditions.

Generally, rotating machinery presents periodic geometries in the angular domain. These geometries define characteristic frequencies and govern the kinematic relationships between rotation speeds of the machine's technological elements. These frequencies are homogenous with respect to the number of events per revolution of the reference element, generally the shaft of the machine. Taking this into account, it therefore appears natural to express the model equations of the rotating machine in terms of the angular displacement of the shaft. In this context, the angular approach has been used increasingly for rotating machines, incorporating technological elements with discrete geometry such as bearings, gears, synchronous belts, etc. This approach involves two main features simultaneously: firstly, angular sampling, and, secondly, Instantaneous Angular Speed (IAS) measurement. The latter has recently emerged as a sensitive source of information for monitoring the mechanical parts of rotating machines [16]. Its sensitivity for detecting mechanical defects, such as bearing faults, was proven theoretically and with experimental measurements in [17,18]. Nevertheless, few papers have dealt with the application of angular approaches when writing classical equations of motion in the angular domain, to take into account two advantages: the angular periodicity of a rotating system, even under non-stationary conditions, and the cyclic characteristic fault frequencies of the rotating elements which are independent from the IAS [17]. In addition to the ability to represent