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A 2D magnetic and 3D mechanical coupled finite element model for the study of the dynamic vibrations in the stator of induction motors

J. Martinez [a,*], A. Belahcen [a,**], J.G. Detoni [b,**]

[a] Department of Electrical Engineering, P.O. Box 13000, FI-00076 Aalto, Finland
[b] Department of Mechanical and Aerospace Engineering - Mechatronics Laboratory, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Turin, Italy

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ABSTRACT

This paper presents a coupled Finite Element Model in order to study the vibrations in induction motors under steady-state. The model utilizes a weak coupling strategy between both magnetic and elastodynamic fields on the structure. Firstly, the problem solves the magnetic vector potential in an axial cut and secondly the former solution is coupled to a three dimensional model of the stator. The coupling is performed using projection based algorithms between the computed magnetic solution and the three-dimensional mesh. The three-dimensional model of the stator includes both end-windings and end-shields in order to give a realistic picture of the motor. The present model is validated using two steps. Firstly, a modal analysis hammer test is used to validate the material characteristic of this complex structure and secondly an array of accelerometer sensors is used in order to study the rotating waves using multi-dimensional spectral techniques. The analysis of the radial vibrations presented in this paper firstly concludes that slot harmonic components are visible when the motor is loaded. Secondly, the multidimensional spectrum presents the most relevant mechanical waves on the stator such as the ones produced by the space harmonics or the saturation of the iron core. The direct retrieval of the wave-number in a multi-dimensional spectrum is able to show the internal current distribution in a non-intrusive way. Experimental results for healthy induction motors are showing mechanical imbalances in a multi-dimensional spectrum in a more straightforward form.

1. Introduction

Induction motors are one of the most popular electromechanical units employed in industry. This popularity is due to the simple and rugged construction, low cost, and reliability. In spite of their reliability, induction motors can undergo different types of failures. Most of the common types of failures affecting induction motors are caused by shaft misalignment and

* Principal author.
** Corresponding author.
E-mail addresses: javier.martinez.garcia.tenorio@aalto.fi (J. Martinez), anouar.belahcen@aalto.fi (A. Belahcen), joaquim.detoni@polito.it (J.G. Detoni).

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bearing problems, stator and armature related faults due to short circuits in the stator windings, and faults in the conductors of the rotor. These three types of faults account for the vast majority of failures in induction motors [1,2].

On-line fault detection is crucial for the diagnosis of problematic machines prior to complete failure. The most common fault detection technique used by researchers is the Motor Current Signature Analysis (MCSA) [3–6]. This technique employs the analysis of a single phase current or its space vector to detect faults. Many authors have been using MCSA for on-line detection of different faults in induction motors. However, a shortcoming of MCSA is the loss of information about the spatial distribution of currents inside the motor. This is explained by Faraday's law which states that the emf is the time derivative of the flux linked by different coils in the stator. The magnetic flux linkage is a time dependent variable for each motor coil. It is equal to the surface integration of the flux density crossing the coils. According to Ampere's law losing the spatial variation is seen as a loss of the spatial distribution of the currents inside the motor.

Ultimately, the loss of spatial distribution of currents can lead to ambiguities in the location of certain faults when MCSA is employed as it was described in [7].

An alternative method allowing us to eliminate these ambiguities was presented in [8]. In that work the authors used experimentally validated finite element (FE) models to describe the magnetic waves existing in the air-gap of induction motors having a broken cage by means of intensive computations. The multi-dimensional spectrum of radial and tangential flux density waves in the air gap were studied comparing the response for a healthy and a broken bar induction motor.

Following the ideas established in [8], the main difficulty to perform a multi-dimensional spectral analysis of the flux density is the difficulty in installing Hall effect sensors in the air gap because induction motors typically have very short air gaps. New generation Hall sensors could eventually solve this problem [9]. Nevertheless, this drawback can be overcome by analyzing the displacement fields on the surface of the stator. This derives from the fact that vibrations in the motor are excited by the flux density fields inside the air-gap. Owing to this, the present paper presents a 2D/3D FE magneto/mechanical model of an induction motor that is used to study the displacement field of the stator of a healthy machine. The analysis of the radial vibrations conducted in this paper shows that the magnitude of the mechanical waves produced by the stator current slot harmonics is clearly increased when the motor is loaded. Furthermore, the multidimensional spectrum analysis of both a FE and a grid of radial accelerometers is an indirect manner to show the main magnetic waves living inside of the stator. Mechanical wave parameters, such as wave-number and pulsating frequency, are related to their magnetic counterpart by a factor of two. Thus, the retrieval of the main characteristics of the radial mechanical waves opens the possibility to enhance the current MCSA technique since we can infer the inner current distribution inside of the motor. For instance, when the computed multi-dimensional spectrum is compared with its experimental counterpart, the latter shows small spectral peaks of waves whose pulsating frequency is an interaction between the supply frequency and the mechanical speed. The wave-number is having same value as the main mechanical wave of the motor, meaning that the internal current distribution is identical to the one produced by the main rotational wave. This is a different approach as the one presented in [10], where the authors developed a fault detection system based on the analysis of the vibration of a motor in a single point. The authors in [11] developed an inter-turn short circuit detection technique processing the information of a single accelerometer.

The classical scientific literature related to the vibrational analysis of induction motors presents the study of their resonance frequencies using analytical models [12,13] which were experimentally validated [14–16].

More recently, with the advent of the increased computational power, Wang and Lai [17] calculated the natural frequencies of the stator of an induction motor using FE models. These models were validated using modal tests of the different parts that compose the stator. However, copper windings in the slots and end windings were not modeled.

The previous scientific references are a good starting point for the analysis of vibrations of induction machines. Nevertheless, these works are lacking a description of the steady-state vibrations in a motor. The analysis of vibration in steady-state has been carried out using different approaches according to their computational complexity. For instance, Yang derived analytical expressions of the stress field for radial type machines [18].

In the last few years there have been several attempts to use FE models to study the vibrations of electric motors. With this computational technique there are two approaches for coupling electromagnetic and displacement fields. The first approach is to solve magnetic and displacement fields contemporaneously. This is used to accurately solve the magnetostriction effect in the iron core of electric motors, as in [19]. The second approach consists of firstly solving the magnetic field and later using the generated magnetic stress tensor as a boundary condition for the elastodynamic equations. This approach is known as weak coupling and it was used by different researchers.

Hilgert et al. solved the magnetostriction in one induction motor using a 2D FE model [20]. The displacement solution was computed using modal decomposition of the elastic equations for the two dimensional geometry of the motor. In [21], Lin and Arkkio utilized weak coupling to solve the vibrations of the end-windings of the motor. Since both the magnetic and mechanical models were three-dimensional, all the computations were time-harmonic. This type of simulation is not able to consider effects such as saturation, where the mesh needs to be moving.

Recently, Saito et al. developed a 2D-magnetic coupled with a 3D-mechanical model to perform a dynamic model of the vibrations of an interior permanent magnet motor [22]. In order to save computational time using FE, the authors used modal analysis techniques to the set of exciting forces in the air-gap together with a mechanical modal analysis of the stator. The main problem of the aforementioned model is that for the study of faulty motors a good description of spectrum is needed. Since the coupling is performed using a modal decomposition, the final result depends on how many spectral