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Including slot harmonics to mechanical model of two-pole induction machine with a force actuator

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ABSTRACT

A simple mechanical model is identified for a two-pole induction machine that has a four-pole extra winding as a force actuator. The actuator can be used to suppress rotor vibrations. Forces affecting the rotor of the induction machine are separated into actuator force, purely mechanical force due to mass unbalance, and force caused by unbalanced magnetic pull from higher harmonics and unipolar flux. The force due to higher harmonics is embedded to the mechanical model. Parameters of the modified mechanical model are identified from measurements and the modifications are shown to be necessary. The force produced by the actuator is calculated using the mechanical model, direct flux measurements, and voltage and current of the force actuator. All three methods are shown to give matching results proving that the mechanical model can be used in vibration control. The test machine is shown to have time periodic behavior and discrete Fourier analysis is used to obtain time-invariant model parameters.

1. Introduction

Induction machines are still extremely popular type of electrical machines in industry. Like other rotating machines, induction machines can develop faults that lead to vibration problems. Different methods have been researched to detect different faults in induction machines [1–3]. One common fault type is rotor eccentricity [4]. In induction machines, rotor eccentricity leads to unbalanced magnetic pull (UMP) that can cause much worse vibration problems and even instability [5–7]. These magnetic forces have to be considered during machine design.

One way to mitigate the eccentricity related problems is to design the machine with parallel paths in the stator winding [8–10]. This provides passive damping effect but might not be enough in all cases. Rotor vibrations can also be damped with active magnetic bearings (AMB) [11–13] but controlling the rotor position only from the ends sets a limitation for the rotor length.

Based on the ideas in [14], it is possible to embed the AMB into an induction machine. Basically it only requires a stator that can produce a magnetic field with two consecutive pole-pair numbers to the air-gap as opposed to regular machines having only one dominating harmonic field in ideal case. The easiest ones to use are the two- and four-pole fields.

The two controllable harmonic fields can be implemented with two separate windings [15,16] or a four-pole winding with a bridge connection like in [17]. In this paper, the separate winding solution is used with the main torque producing winding having two poles and a four-pole winding acting as a radial force actuator. In [15], the goal was magnetic

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suspension; whereas, in this paper and in [18,16], the research is aiming at vibration suppression of a long flexible rotor in large induction machines.

The active vibration control concept has been shown to work in [16,19] where model based control was used. Problem there is the generality of the results. Control was based on a non-parametric model identified for one operation point of the machine. The dynamics of the actuator depend on the supply frequency and the rotation speed of the machine as well as on the two-pole flux density in the air-gap. These dependencies should be in the model thus a parametric model is needed. The model should be simple enough to be used efficiently in control design.

Obtaining the total parametric model has proven to be complicated; therefore, the model is here divided into two parts; electrical circuit of the actuator winding and mechanics of the rotor. In addition to the magnetic force from the two- and four-pole fields, significant force is produced by the higher flux harmonics at least when the torque producing winding has two-poles [20]. It is known that UMP acts like a negative spring constant in rotor mechanics [7] thus the force from the higher harmonics can be included in the mechanical part of the model. Possible electromechanical interaction [5] for the higher harmonics is neglected.

This paper will show that the modified mechanical model is useful and how the parameters for the model can be identified from measurement data. The model is used to calculate the actuator force from the rotor displacement measurements and shown to match the force calculated from the electrical measurements.

2. Theory

$$m\frac{\mathrm{d}^2}{\mathrm{d}t^2}\underline{z}+d\frac{\mathrm{d}}{\mathrm{d}t}\underline{z}+k\underline{z}=\underline{F}_{\mathrm{tot}} \tag{1}$$

The mechanical model used here is a one dimensional second order differential equation (1), the same as in [5]. The model describes the relationship between the displacement of the center point of the rotor with respect to center of the stator, $\underline{z}$, and the total of external forces on rotor, $\underline{F}_{\mathrm{tot}}$, with modal mass m, damping coefficient d and spring constant k. The mechanical model is meant to capture the lowest flexural bending mode of the rotor core and the rotor shaft. More complicated mechanics could also be used like in [21].

The rotor displacement and the force are modeled as two dimensional but are presented as complex variables instead of vectors, i.e. horizontal displacement and force being real and vertical being imaginary, respectively, Fig. 1. Complex valued representation is natural to electrical variables; three-phase voltage and current can be presented as space vectors. The space vector of voltage is defined as a function of the phase voltages:

$$\hat{\underline{u}}_{\mathrm{n}}(t)=\tfrac{2}{3}(u_{\mathrm{n}1}(t)+u_{\mathrm{n}2}(t)e^{\mathrm{j}2\pi/3}+u_{\mathrm{n}3}(t)e^{\mathrm{j}4\pi/3}) \tag{2}$$

Complex representation can also be used for the air-gap flux density spatial-harmonics. Using notations (3) and (4)

$$\hat{\underline{B}}_{\nu}=\hat{\underline{B}}_{\nu}(t)=\hat{B}_{\nu}(t)e^{\mathrm{j}\varphi_{\nu}(t)} \tag{3}$$

$$\underline{B}_{\nu}(\varphi,t)=\hat{B}_{\nu}(t)\cos(\nu\varphi-\varphi_{\nu}(t))e^{\mathrm{j}\varphi} \tag{4}$$

where φ is the polar coordinate in the air-gap (Fig. 1), the radial magnetic force on rotor will be

$$\underline{F}_{\mathrm{e}}=\frac{\pi D_{\delta}l_{\mathrm{r}}}{4\mu_0}\left(\hat{\underline{B}}_0\hat{\underline{B}}_1+\hat{\underline{B}}_0^{*}\hat{\underline{B}}_1+\sum_{\nu=1}^{\infty}\hat{\underline{B}}_{\nu}^{*}\hat{\underline{B}}_{\nu+1}\right) \tag{5}$$

as derived in [20]. Constants D_{δ} and l_{r} are the diameter of the air-gap of the machine and the effective air-gap length, respectively, and μ_0 is the permeability of free space.

There are basically two forces acting as the external force for the mechanical equation. One of them is the magnetic force and the other purely mechanical. The purely mechanical force can be caused by mass unbalance in the rotor core or a bowed rotor [4]. Whichever the cause, the mechanical force excitation is tied to the rotation angle of the rotor.

The magnetic force is a sum over spatial harmonic pairs of the air-gap flux density, with consecutive pole-pair numbers (5). Since it is a two-pole machine, the two-pole flux, $\nu=1$, can be assumed to dominate. The most significant force would

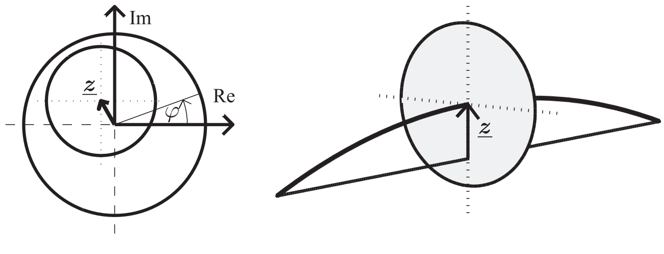

Fig. 1. Rotor displacement in complex coordinates.