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A general electromagnetic excitation model for electrical machines considering the magnetic saturation and rub impact

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ABSTRACT

The electromagnetic vibration of electrical machines with an eccentric rotor has been extensively investigated. However, magnetic saturation was often neglected. Moreover, the rub impact between the rotor and stator is inevitable when the amplitude of the rotor vibration exceeds the air-gap. This paper aims to propose a general electromagnetic excitation model for electrical machines. First, a general model which takes the magnetic saturation and rub impact into consideration is proposed and validated by the finite element method and reference. The dynamic equations of a Jeffcott rotor system with electromagnetic excitation and mass imbalance are presented. Then, the effects of pole-pair number and rubbing parameters on vibration amplitude are studied and approaches restraining the amplitude are put forward. Finally, the influences of mass eccentricity, resultant magnetomotive force (MMF), stiffness coefficient, damping coefficient, contact stiffness and friction coefficient on the stability of the rotor system are investigated through the Floquet theory, respectively. The amplitude jumping phenomenon is observed in a synchronous generator for different pole-pair numbers. The changes of design parameters can alter the stability states of the rotor system and the range of parameter values forms the zone of stability, which lays helpful suggestions for the design and application of the electrical machines.

1. Introduction

The vibration level of three phase synchronous motors has become a very important issue in the design process [1]. Air-gap eccentricity which implies the axes of the stator and the rotor are not coincident is very common in a rotating electrical machine [2-4]. The whirling motion of an eccentric rotor makes the air-gap field distorted and a net unbalanced electromagnetic force emerges on the rotor as a consequence. This force is referred to as the unbalanced magnetic pull (UMP) [5,6]. UMP results in motion of the rotor moving towards stator along the direction of the minimal air-gap, which conversely increases the eccentricity further. The interaction effect between the electromagnetic field and mechanical structure may create undesirable vibrations [7], lead to stability problems [8], influence the wear of bearings [9] and even cause a rub

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between the rotor and the stator. The potential hazards are prodigious. Therefore, the investigation of this interaction mechanism is significant and necessary.

The calculation of UMP in electrical rotating machinery is indispensable for the study of vibrations and the optimal design. The analytical method and the finite element method (FEM) are two widespread approaches. Although the FEM has been extensively applied to investigate the UMP [10-12], the analytical method still attracts much attention because an observation into the origins and pivotal factors in the production of UMP is provided by this method. Earlier publications such as reference [13] concentrated principally on the theoretical formulation of UMP and the linear equations were primarily applied. A dynamic model for an induction motor with eccentric rotor was established by taking a radial electromagnetic stiffness into consideration [14]. The linear expression is convincing only for cases that the eccentricity is small enough. Therefore linear approach is far from industrial applications. The nonlinear relationship between the UMP and eccentricity was pointed out in Ref. [15]. After that, many researchers have introduced nonlinear approaches to determine UMP in the last two decades. For instance, winding function analysis [16], conformal mapping method [17], energy conservation law [18], magnetic equivalent circuit method [19] and exact subdomain model [20] were applied to investigate the magnetic field distribution and UMP for electrical machines with non-uniform air-gap. The most commonly adopted analytical method is the air-gap permeance approach [21,22]. An analytical expression of UMP for different pole-pairs was obtained by expressing the air-gap permeance as a Fourier series in Ref. [21]. A calculation model for UMP was presented in Ref. [22] based on the actual position of the rotor inside the stator.

A literature review indicates that magnetic saturation was neglected in most of existing studies. However, the saturation phenomenon is inevitable because of two major factors. One is due to the saturation effects of magnetization characteristic of the ferromagnetic materials. And the other is the existence of magnetic flux leakage caused by the distortion in the narrow air-gap space. There exists much evidence supporting the idea of magnetic saturation. For example, as reported in Ref. [23], the air-gap inhomogeneity imposes that the saturation level must vary along the machine periphery with regard to the flux density value. Therefore higher saturation occurs at the narrow air-gap than at the wide one. This implies that the reluctance increases considerably at the smaller air-gap.

Although magnetic saturation phenomenon is easy to be understood and some investigations were conducted [24-26], saturation effects were seldom considered when studying the influence of electromagnetic force in rotor dynamics. The radial vibration of large hydro-turbine generators under the influence of UMP was investigated by taking the saturation effects of the ferromagnetic materials into consideration [24]. Whereas the magnetic circuit problem should be solved first as the pre-work. The saturation effects on the UMP in a hydroelectric generator with eccentricity were studied [25]. Nevertheless the flux leakage was neglected and the magnetic flux was assumed to be constant around the magnetic circuit. The saturation effects were characterized as a saturation coefficient [26]. However, the coefficient is complicated and inconvenient to be adopted. Consequently, an appropriate calculation model of electromagnetic force which takes the magnetic saturation into consideration is of great significant.

On the other hand, the electromagnetic force is always in the direction of the minimum air-gap, which will increase the vibration of the rotor system and reduce the air-gap length further. The rub-impact between the rotor and the stator will occur as a consequence. Therefore, the rub-impact besides the magnetic saturation should be considered in a general electromagnetic excitation model. In the past few decades, the nonlinear phenomena of rotor system with rub-impact have attracted great concerns and many results were obtained. For instance, authors in Ref. [27] performed the experimental investigation of a rub-impact rotor system and observed the nonlinear vibrations. Recently, through the numerical and experimental studies, various nonlinear phenomena such as periodic, quasi-periodic and chaotic motions were studied with the change of parameters [28]. Although the dynamics of rotor system with rub-impact has been extensively investigated and the theory is mature, the rub-impact coupled with electromagnetic force is rarely involved.

In this paper, the general electromagnetic excitation model which can deal with large eccentricity is derived and verified by the FEM method and reference. The electromagnetic force and the rubbing force are considered in the proposed model simultaneously. And then the dynamic equations of a Jeffcott rotor system are pretested in section 3. The effects of pole-pair number and rubbing parameters on vibration amplitude are investigated in section 4. Moreover, the Floquet theory is applied to study the stability of the rotor system. The influences of mass eccentricity, resultant MMF, stiffness coefficient, damping coefficient, contact stiffness and friction coefficient on the rotor stability are investigated in section 5, respectively. Finally, some conclusions are presented.

2. General electromagnetic model

As Fig. 1 displays, the orthogonal coordinate system Oxy is established for an eccentric rotor. The O and O_r are the geometrical centers of the stator and the rotor, respectively. r represents the eccentricity which indicates the geometric center distance between the rotor and stator. θ is the angle of rotor position with reference to x-axis. α is the air-gap angle with respect to x-axis.

The air-gap length which is a function of the air-gap angle and time can be approximately expressed by the equation as follows:

$$\delta(\alpha,t) = \delta_0 - r\cos(\alpha-\theta) \tag{1}$$

where δ_0 is the average air-gap length without eccentricity.