



Analytical estimation on divergence and flutter vibrations of symmetrical three-phase induction stator via field-synchronous coordinates



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ABSTRACT

The electromagnetically induced parametric vibration of the symmetrical three-phase induction stator is examined. While it can be analyzed by an approximate analytical or numerical method, more accurate and simple analytical method is desirable. This work proposes a new method based on the field-synchronous coordinates. A mechanical-electromagnetic coupling model is developed under this frame such that a time-invariant governing equation with gyroscopic term can be developed. With the general vibration theory, the eigenvalue is formulated; the transition curves between the stable and unstable regions, and response are all determined as closed-form expressions of basic mechanical-electromagnetic parameters. The dependence of these parameters on the instability behaviors is demonstrated. The results imply that the divergence and flutter instabilities can occur even for symmetrical motors with balanced, constant amplitude and sinusoidal voltage. To verify the analytical predictions, this work also builds up a time-variant model of the same system under the conventional inertial frame. The Floquet theory is employed to predict the parametric instability and the numerical integration is used to obtain the parametric response. The parametric instability and response are both well compared against those under the field-synchronous coordinates. The proposed field-synchronous coordinates allows a quick estimation on the electromagnetically induced vibration. The convenience offered by the body-fixed coordinates is discussed across various fields.

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1. Introduction

Periodically time-variant systems appear naturally in many branches of the engineering applications, such as the permanent magnet motors, planetary gears and other structures subjected to traveling load. The rotating magnetic load in the three-phase induction motor increases when the mechanical deflection increases, which in turn increases the magnetic load more, and thus a mechanical-electromagnetic coupling is aroused. This coupling can lead to a governing equation of motion with periodically time-variant coefficients, and thus create an unstable parametric vibration with an ever-increasing amplitude. As an important dynamic behavior, the vibration instability becomes a basic concern in particular for those heavy-load applications. This instability affects the performance or even leads to rotor-stator rubbing causing permanent damage, but it is complicated to analyze due to the multi-field coupling effect. Because of the interdependence between the excitation and displacement, a difficulty in the analytical

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Nomenclature			
t	time	$b(\varphi)$	air-gap flux density in radial direction in field-synchronous coordinates
θ	position angle in inertial coordinates	Λ	air-gap permeance
φ	position angle in field-synchronous coordinates	F_{mmf}	magnetomotive force
u_θ	tangential displacements in inertial coordinates	F_{max}	maximum magnetomotive force
v_r	radial displacement in inertial coordinates	k_{N1}	fundamental winding factor
u_φ	tangential displacement in field-synchronous coordinates	N	number of conductors per pole per phase
v_ρ	radial displacements in field-synchronous coordinates	I_m	RMS (Root mean square) current
k_u	support stiffness in the tangential direction	p	number of pole pairs
k_v	support stiffness in the radial direction	k_{q1}	fundamental distribution coefficient
ω	angular frequency	k_{y1}	fundamental pitch coefficient
Ω	rotation speed of magnetic load	q	slots per pole per phase
c	axial height	α	groove angle
h	radial thickness	m	number of phases
d	density	z	number of slots
E	Young's modulus	y_1	tooth pitch
R	neutral circle radius	τ	polar distance
A	cross-sectional area	δ	air-gap length
T	kinetic energy	g	average of the air-gap length
U_0	potential energy of the stator	U_q	potential energy induced by the electromagnetic force
I	cross-sectional moment of inertia of the stator	U	total potential energy
U_s	potential energy of the support	s	bending flexibility
$P(\varphi)$	electromagnetic force per unit area in field-synchronous coordinates	$\eta_{\varphi n}$	the n th response in field-synchronous coordinates
$P(\theta, t)$	electromagnetic force per unit area in inertial coordinates	n	wavenumber
μ_0	permeability of the free space	β	time phase
		λ	eigenvalue
		$\eta_{\theta n}$	the n th response in the inertial coordinates

estimation on the instability behaviors may be encountered. This work deals with the accurate and quick analytical estimation of the symmetrical three-phase induction motors with a balanced, constant amplitude and sinusoidal voltage.

Singh et al. [1] examined the parametric instability of a multi-phase induction motor without any mechanical or electric error. They determined the stability through the placement of the eigenvalues. Most often, the unstable parametric vibration is aroused by the manufacture and installation errors. This instability was captured based on the rigid-body assumption by Belmans et al. [2], but the parametric source was omitted during analysis. Iwatsubo et al. [3] studied the parametric vibration induced by the electromagnetic force. Yang et al. [4] derived an ordinary differential equation with periodically time-variant coefficient of a large induction motor, and they investigated the instability and imbalanced response. Karlsson et al. [5] dealt with the rotor dynamic behaviors of an eccentric hydropower generator. The above studies treat the motor as rigid-body by removing the elasticity of the stator and rotor such that the parametric source results from the time-variant air-gap length. For an ideally symmetrical motor when the force wavenumber is greater than the value of two, rigid-body assumption makes the net electromagnetic force become zero because all forces in the radial and tangential directions are naturally neutralized. Thus, this assumption can omit certain instabilities especially for those motors with thin components.

Apart from the rigid vibration caused by eccentricity, the elastic deflection of an ideally balanced motor can generate a time-variant air-gap length such that the motor can experience an elastic instability, but no previous work can be found in this respect. In fact, whatever the parametric sources and assumptions are, the unstable vibration can be induced if the load is related to the displacement in a time-variant fashion. This leads to time-variant stiffness coefficient in the governing equation of motion. While the research in this regard is scarce, related studies can be found in other systems, such as the ring gear subjected to rotating mesh stiffness [6,7], the stator subjected to rotating magnetic stiffness [8], general ring-shaped component subjected to rotating support stiffness [6,9] and even cylindrical shell subjected to periodic axial load [10]. All these systems have time-variant stiffness coefficients. One can predict that this can exist in the induction motor because of the similarities in the structure and excitation, where the excitation becomes the rotating magnetic stiffness. This vibration is independent of the rigid displacement, fabrication error, and installation error, and it can be aroused even in ideally symmetrical motor.

As a primary difficulty, the analytical solution of the parametric system is normally difficult to achieve except for some special class of periodic system. For the induction motor, the vibration instability can be analyzed in a preferred coordinates frame. The most commonly used include the stationary [2,11], rotor [5,12], synchronous [1,13] and quasi-rotating [14] coordinates, where the first is the conventional inertial frame, but the other three are the so-called “body-fixed” ones. Under the stationary frame, the

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