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Identification of harmful time harmonic interactions in a high power squirrel-cage traction machine

Vladimír Kindl [a,*], Michal Hajžman [b]

[a] Faculty of Electrical Engineering, University of West Bohemia, Univerzitní 26, 306 14 Plzeň, Czech Republic
[b] European Centre of Excellence, NTIS – New Technologies for Information Society, Faculty of Applied Sciences, University of West Bohemia, Univerzitní 22, 306 14 Plzeň, Czech Republic

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ABSTRACT

The paper offers a methodology for the identification the time harmonic interactions with a strong negative impact on the rotor of a high power induction machine. These potentially dangerous pulsating torques may be effectively reduced by carefully setting the machine's drive control. A novel approach based on a complex finite element model and further post-processing is used. Results obtained from electromagnetic calculations in the form of pulsating torques are used as mechanical loading of a structural dynamic model. This complex model intended for rotor vibration analysis is described in brief in the mechanical part of the paper. The proposed methodology is applied to the machine used as a propulsion unit for multisystem locomotives of 1600 kW power.

1. Introduction

This paper stems from the solution of the well-known problem of breaking rotor bars of high power induction machines. An explanation of the physical background of such faults is given e.g. in [1], where many types of machine's failures are listed. It is clear that an efficient and suitable modeling methodology should be developed for the analysis of such problems.

In case of this paper, the motor can be classed as a machine with a fabricated copper squirrel cage. The rotor cage is designed as a packet of laminated metal sheets with embedded bars interconnected by an end ring outside the rotor stack. Because of manufacturing technology and mechanical properties the link between both parts must be made at a small distance (approximately 30 mm) from the packet edge. This arrangement makes the end ring free to vibrate which causes enormous dynamic stresses in the bars. As it was noted in [2], undesirable mechanical loads may occur for many reasons (see Fig. 1).

The main propulsion torque contains higher space harmonics defined by geometry due to the slotting of machine's lamination. The forces act on stator/rotor teeth tangentially and radially across the full speed range [3,4]. In our case they have negligible amplitudes because of the small slot opening. The next component is the centrifugal force stressing all connections between the end ring and the rotor bars (it is reduced by a shrink ring). Additional stress can also be caused by linear expansion and contraction of rotor bars in their slots due to thermal heating, when the copper is heated more rapidly then the rotor steel. This phenomenon is reduced by loose fitting of rotor bars which are locked (calked) in the middle of their

* Corresponding author.
E-mail addresses: vkindl@kev.zcu.cz (V. Kindl), mhajzman@kme.zcu.cz (M. Hajžman).

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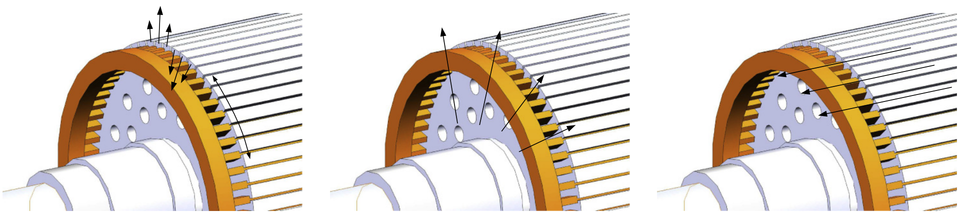

(a) slotting forces (b) centrifugal forces (c) thermal dilatation forces

Fig. 1. Forces acting on the machines' rotor.

length. Such an arrangement makes the bar free to move equally in both directions. The last of the most significant sources of parasitic torques are the power electronics of the machine's supply.

It is obvious, that the enormous stress may cause the rotor cage failure. This usually makes the rotor bar disconnected out of the end ring at the location of their brazed joint. Such a faulty state can be easily detected using monitoring online diagnostics [5–7] but not predicted. Hence, in the last few years a growing interest has been devoted to the research on the problem of breaking rotor bars [8–14]. From the work of related references it can be concluded that the problem is potentially connected with the parasitic torques [15–20] acting on the machine's rotor. The very interesting approach to this issue has been proposed for example in [21,22].

The parasitic torque can excite harmful vibrations affecting the structural strength and fatigue of machine's mechanical parts. They may even cause a mechanical resonance occurring when the frequency of parasitic torque is closed to the natural frequency of rotating rotor mass. In this paper, the possibility to reduce the inauspicious causes related to drive control of the machine is explored. The methodology therefore focuses mainly on time torque harmonics and their interactions in order to find the amplitudes and frequencies with strong negative impact on the rotor. These potentially dangerous harmonic components may be preventively excluded from the spectrum of supplying voltage [23]. General methods of mechanical system dynamics are suitable for the mathematical modeling of the vibrations of the rotating part of a squirrel-cage machine [24]. However, very simple models (e.g. [25,26]) are usually used for the dynamic analysis of this type of machine. A more advanced and usable dynamic model is used in this paper. The model was introduced in [27] and is characterized by the end rings and shrink rings considered as rigid bodies. It is suitable for dynamic mechanical analysis with low-frequency excitation and motion. The dynamic structural model is composed of a flexible shaft modeled by means of 1D shaft finite elements, a rotor stack is modeled as a set of five rigid bodies connected with translational and torsional springs, the end parts of the rotor bars are modeled as massless discrete springs connecting the rotor stack rigid bodies with the end rings (considered together with shrink rings) rigid bodies.

The paper is organized as follows. The theoretical brief discussion of time parasitic torques appearing in induction machines is given in the second section after the Introduction. The third section deals with the calculation of electromagnetic forces and torques for a particular machine (see Table 1 for parameter details). The fourth section is devoted to the description of the structural mechanical model and the fifth section deals with the vibration results for the chosen machine. The machine is produced by a leading Czech producer and is used as a propulsion unit for multisystem locomotives. The machine's drive control is as described in [23].

2. Parasitic torques

In [3] the authors present a very detailed theory of parasitic torques [15–20] endangering the rotor of an induction machine. The mathematical derivation considers the magnetic field in the air gap containing space harmonics due to the uneven air gap (slotted packet) and time harmonics due to inharmonic supply. Each harmonic component may act on the rotor and cause additional parasitic torques. The general formula for electromagnetic torque calculation with consideration

Table 1
Table of details of analyzed motor.

Rated power	1600 kW
Rated torque	8370 Nm
Rated voltage	1130 V
Rated current	2 × 518 A
Rated speed	1825 RPM
Maximal speed	3700 RPM
Winding connection	Double star
Power supply	Traction inverter
Pole number	6
Insulation class	200