ISSN 1392 - 1207. MECHANIKA. 2013 Volume 19(6): 671-675

Research of vibrations in induction machines during transient processes using a Ferraris sensor

P. Hantel*, B. Spruogis, V. Turla***, A. Jakštas******
**Hantel Consulting, Hörnhang 13, Aachen, Germany, E-mail: peter.hantel@hantel-consulting.de*
*** Vilnius Gediminas Technical University, Plytines 27, 10105 Vilnius-16, Lithuania, E-mail: bsp@vgtu.lt*
**** Vilnius Gediminas Technical University, Basanaviciaus 28, 03224 Vilnius-6, Lithuania, E-mail: Vytautas.Turla@vgtu.lt*
***** Vilnius Gediminas Technical University, Basanaviciaus 28, 03224 Vilnius-6, Lithuania, E-mail: arunas.jakstas@vgtu.lt*

crossref http://dx.doi.org/10.5755/j01.mech.19.6.5985

1. Introduction

For root cause analysis it is necessary to measure the real input to a mechanical drive system. Induction machines are known for causing torsional vibration problems during start up, reversal or other transient phenomena [1]. As to the fact that the electrical torque of an induction machine is not able to be measured by the electrical units of current and voltage, the only possibility is to measure the shaft torque and the angular acceleration [2, 3].

According to Newton's second law of motion "the acceleration of an object is proportional to the forces applied", the equation for the flywheel mass Θ_1 (Fig. 1) is as follows:

$$\Theta_1 \ddot{\alpha}_1(t) = M_e(t) - M_s(t), \tag{1}$$

with $M_e(t)$ the electrical torque of the induction machine caused by the electromagnetic field in the air gap. $M_s(t)$ is the shaft torque, which is characterized by the spring– (c) and damping (k) factor of the shaft according to:

$$M_s = c\left(\alpha_2(t) - \alpha_1(t)\right) + k\frac{d}{dt}\left(\alpha_2(t) - \alpha_1(t)\right). \tag{2}$$

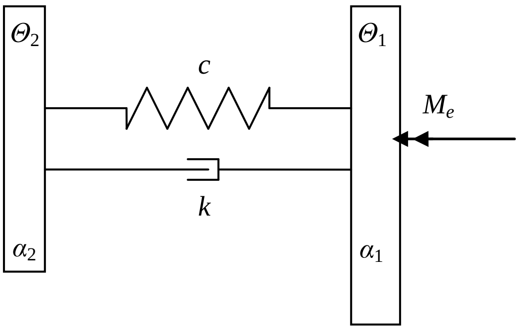

Fig. 1 Torsional vibration model

Under the precondition, that the damping is very low the damping torque:

$$M_d = k\frac{d}{dt}\left(\alpha_2(t) - \alpha_1(t)\right), \tag{3}$$

can be neglected and dynamic torque of the electrical machine can be measured by the difference of the angles of $\alpha_2(t) - \alpha_1(t)$ and the acceleration $\ddot{\alpha}_1(t)$ of Θ_1 [4, 5]:

$$M_e = c\left(\alpha_2(t) - \alpha_1(t)\right) + \Theta_1 \ddot{\alpha}_1(t). \tag{4}$$

2. Measurement principles for the angular acceleration

Acceleration sensors are well known for linear accelerations. The sensor market for angular acceleration sensors is very small. Two basic principles exist.

Fig. 2 shows the first principle of two linear acceleration sensors measuring the absolute angular acceleration.

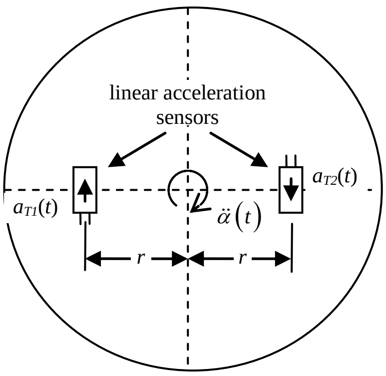

Fig. 2 Measuring angular acceleration $\ddot{\alpha}(t)$ with linear acceleration sensors

The angular acceleration is given by Eq. (5):

$$\ddot{\alpha}(t) = r\,a_{T1}(t) + r\,a_{T2}(t). \tag{5}$$

This configuration with two linear acceleration sensors causes different problems:

- at a constant speed the sensitivity of the sensor for lateral acceleration produces a constant signal caused by the centrifugal force at $\ddot{\alpha}(t) = 0$;
- the power supply for the sensors and the measurement signal is difficult to handle at higher speeds;
- the adjustment of the sensors on the radius r and the mechanical differences of two sensors cannot by 100% compensated.

The second principle is shown in Fig. 3.

A constant magnetic field induces an electric field strength in a conductible cylinder rotating at constant speed according to the law of electromagnetic induction:

$$\vec{E}_i = \vec{v}\,\vec{B} = \left(\vec{\omega}\vec{r}\right)\vec{B}. \quad (6)$$

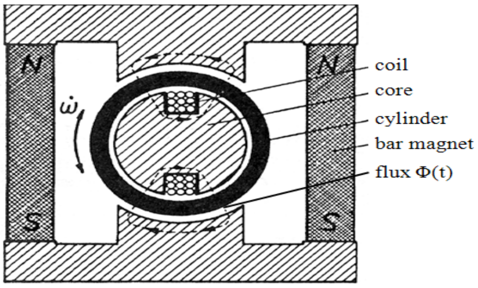

Fig. 3 Sensors measuring the relative angular acceleration [2]

This electric field causes a current I in the conductible cylinder with a constant magnetic flux Φ at constant speed ω. When the speed $\omega(t)$ changes, the flux $\Phi(t)$ changes accordingly and induces a voltage $U_i(t)$ in the induction coil according equation:

$$U_i(t) = \frac{d}{dt}\Phi(t). \quad (7)$$

As the flux $\Phi(t)$ is proportional to the current I and I is proportional to $\vec{E}_i$ which is proportional to $\omega(t)$ according Eq. 6, the induced voltage in the coil is proportional to the angular acceleration $\dot{\omega}(t)$:

$$U_i(t) = \frac{d}{dt}\Phi(t) \sim \frac{d}{dt}\omega(t) = \dot{\omega}(t). \quad (8)$$

This principle is named Ferraris principle according to the Italian Ingenieur Galileo Ferraris.

The cylinder is coupled to the end of the shaft and is the only rotating part of the sensor. So the signal for the angular acceleration can be picked up from the static coil. The sensitivity of the Ferraris sensor is typical 0.1 – 0.01 mV/rad/s².

To calibrate a Ferraris sensor a special test rig is necessary, see Fig. 4.

Fig. 4 Test rig to calibrate a Ferraris sensor

The aluminum cylinder of the Ferraris sensor is coupled to a highly dynamic DC motor with a disk-shaped rotor. The rotor is a disk which is a printed circuit board without any iron. So current of the motor is proportional to the torque without any distortion and can be used as angular acceleration reference.

With a frequency analyzer the frequency response (amplitude, phase) of the Ferraris sensor can be measured, see Fig. 5.

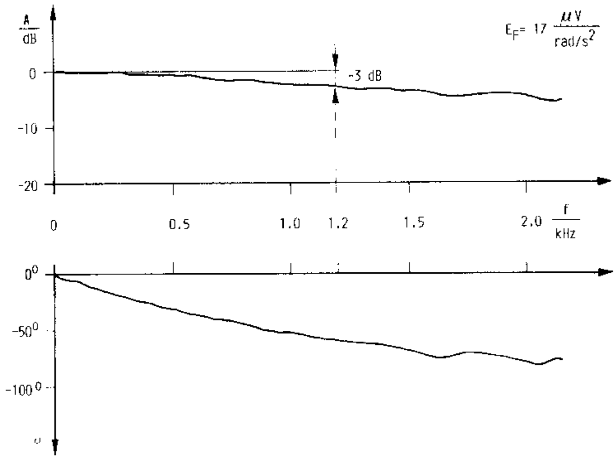

Fig. 5 Frequency response of a Ferraris sensor

The sensitivity is 0.017 mV/rad/s² (0 dB) and the resolution is 1 rad/s². The cut-off frequency is at 1.2 kHz (–3 dB). The phase in that frequency range is linear and the delay time:

$$t_d = \frac{d}{dt}\phi = 0.12\,\text{ms} = \text{const}, \quad (9)$$

is with 0.12 ms constant.

3. Torque measurement with resistance strain gauges

To determine the electrical torque according to Eq. (4) the displacement between the inertia of the rotor (Θ_1) and the flywheel (Θ_2) has to be determined. This has been done by four resistance strain gauges which have been glued under 45° on the shaft [6]. The four strain gauges are electricaly coupled to a wheatstone bridge (Fig. 6).

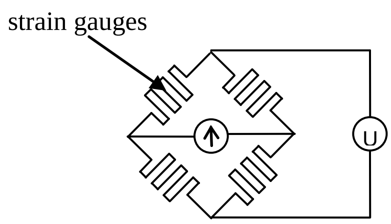

Fig. 6 Wheatstone bridge with resistance strain gauges

A carrier frequency amplifier was used to supply the wheatstone bridge. The sensitivity of the torque sensor is 0.482 V/Nm. The cut–off frequency of the carrier frequency amplifier is at 2 kHz (–3 dB) and the delay time is 0.3 ms.

4. Measuring the electrical torque M_e

To add signals in a measuring chain the delay time of each sensor has to be taken into account. As shown in Fig. 7 the lead time of a sinusidial signal is different, depending on the delay time of each measuring chain.

In the angular acceleration chain the phase shift after the DC amplifier is 46.8°. If the signals of the angular acceleration and the shaft torque would be added at that point, the result for the electrical torque would not be correct, because the shaft torque measurement via the elongation ε has a phase shift of 108°. Therefore an electrical all pass module is necessary to shift the phase of the angular acceleration signal from 46.8° up to 108°. The amplitude of the signal is not modified by an all pass module [7].

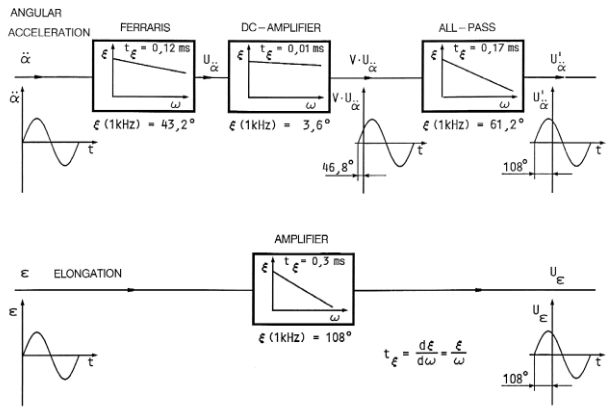

Fig. 7 Different delay times of measuring chains

After the calibration with the all pass module the two signals can be added by a normal operational amplifier.

The sensitivity for the electrical torque is 40 mV/Nm. The frequency range is determined by the Ferraris sensor with a cut–off frequency of 1.2 kHz. The delay time of 0.3 ms is determined by the carrier frequency amplifier.

5. Electrical torque measurements compensated by the angular acceleration

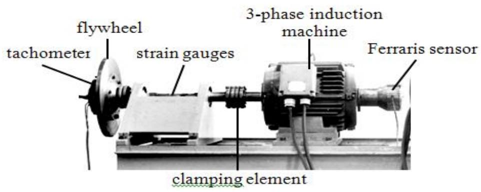

Fig. 8 Test rig

Fig. 8 shows a 3-phase 1.8 kW induction machine with a squirrel cage rotor that is coupled with a flywheel via a steel shaft.

This rig is very close to the representative model in Fig. 1. As there is no clutch with damping element the damping factor is with $D = 0.007$ very low and the precondition of Eq. 3 is fulfilled.

By variation of the diameter of the shaft and the flywheel mass it is possible to realize different resonance frequencies (fundamental mode of vibration), i.e. 33.5 Hz and 147 Hz. The flywheel mass of the clamping element is very small. It causes a resonance frequency of 1180 Hz (first harmonics) [8, 9].

To show the compensation an impact pulse is given to the system (Fig. 9).

The electrical torque M_e follows exactly the reference torque M_{Ref} while the shaft torque M_w and the angular acceleration signal are alternating with the resonance frequency of the mechanical system. The addition of both signals is zero what shows very clearly the compensation effect [10].

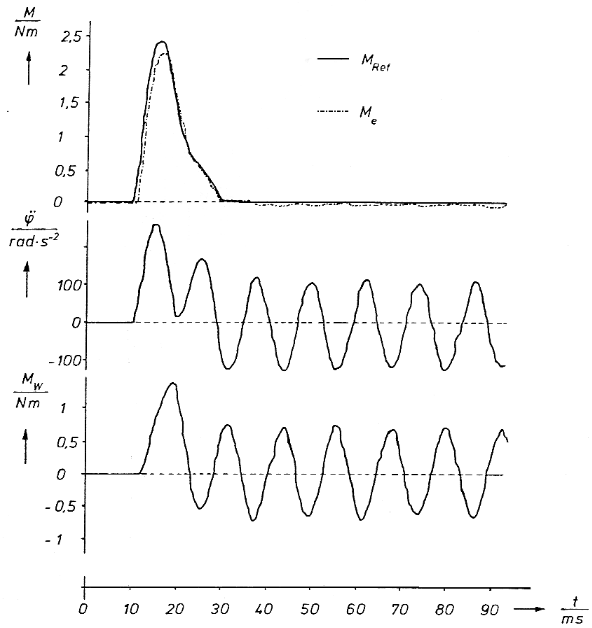

Fig. 9 Compensation of an impact pulse

Fig. 10 shows the electrical torque during run–up of the induction machine (Fig. 8) with the compensation method.

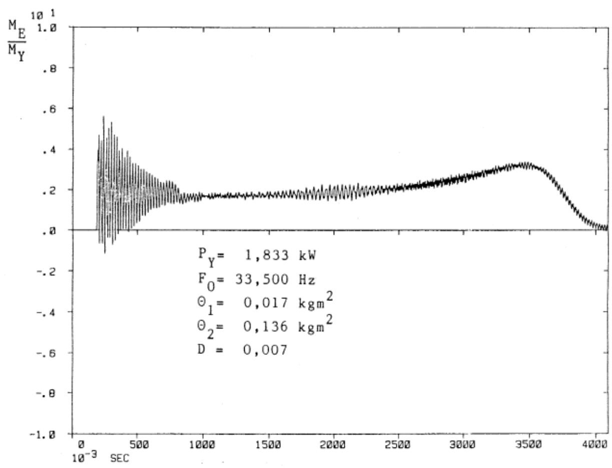

Fig. 10 Electrical torque (angular acceleration compensated) during run-up

After switch on the amplitudes of the electrical torque M_E are with 36 Nm up to 6 times higher than the nominal torque $M_Y = 6$ Nm of the induction machine. This forces the shaft torque to amplitudes up to 7 times of the nominal torque M_Y (Fig. 11).

After about 1.8 seconds the resonance frequency of the system is excited by the induction machine. This phenomenon is to be explained by parametric excitation of the induction machine [1].

The Fast Fourier Transformation (FFT) of electrical torque signal (Fig. 12) shows higher amplitudes in the range of 45 Hz to 50 Hz and also around 33 Hz. The amplitudes of the torsional oscillator become up to 42 Nm so that the loop back into the electrical torque, which can be seen in Fig. 10.

Another very interesting experiment, the reversing, reveals additional alternating torques in the electrical torque of the induction machine [11, 12].

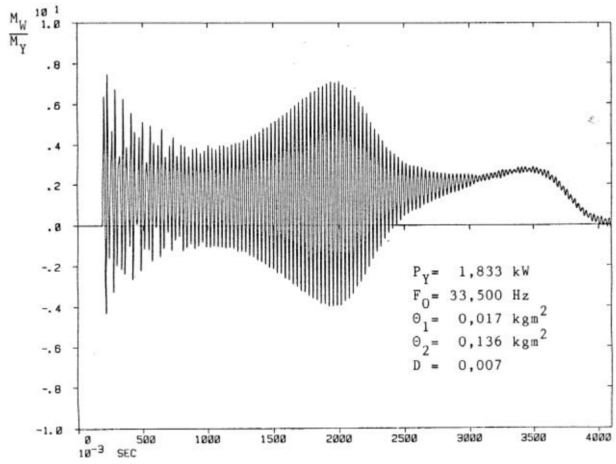

Fig. 11 Shaft torque during run-up

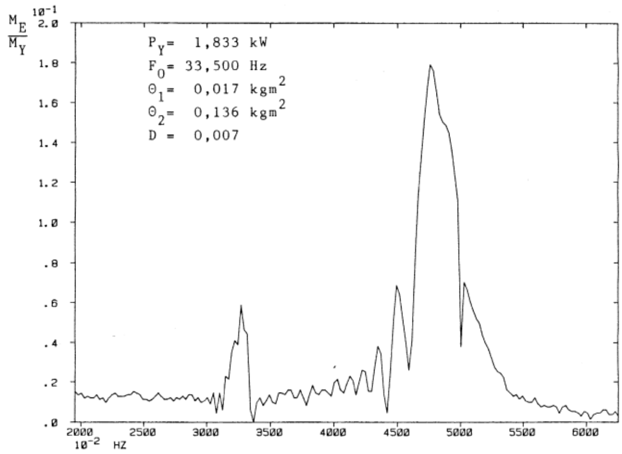

Fig. 12 FFT of the electrical torque of Fig. 10

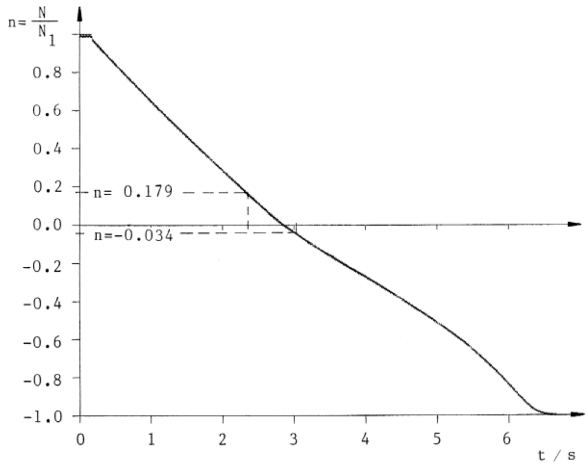

Fig. 13 Speed of the flywheel during reversingof the induction machine by swapping two phases

At the reversing two phase of the 3–phase power supply are swapped at full speed of 3000 rpm. When swapping two phases, the rotating electromagnetic field in the induction machine changes its direction and also does the electrical torque. This means, that the electrical torque works against the turning flywheel mass and brings it into the opposite direction with –3000 rpm (Fig. 13).

The electrical torque during reversing is shown in Fig. 14. The swapping of the electrical phases causes a peak in the electrical torque of about 25 times of the nominal torque (6 Nm). The time signal shows alternating torques with a changing frequency.

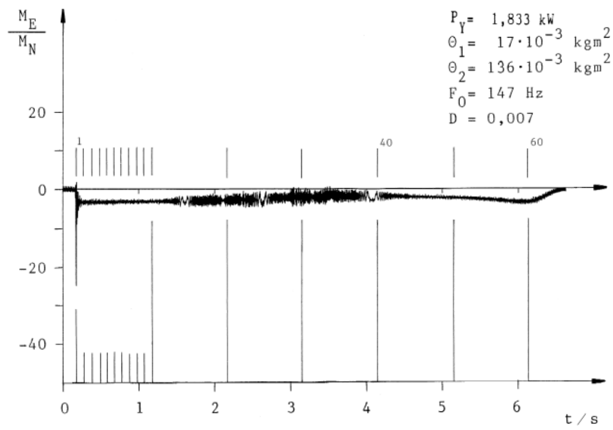

Fig. 14 Electrical torque during reversing

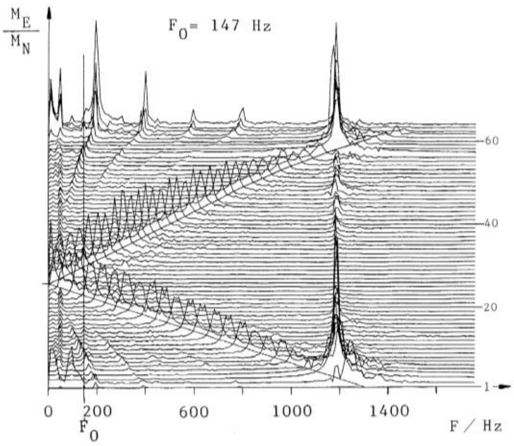

Fig. 15 FFT of the 64 time windows of Fig. 14

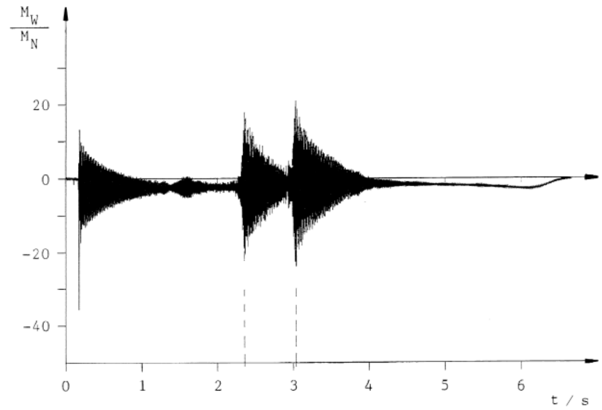

Fig. 16 Resonance excitation of the shaft torque by the sweep of the alternating electrical torque of Fig. 14

To analyze the electrical torque, the signal has been divided into 64 windows (Fig. 14). For each time window a FFT has been performed. All 64 spectra have been plotted as can be seen in Fig. 15.

The sweep of the alternating torque starts with about 1300 Hz, goes down to 0 Hz and increases up to about 1500 Hz.

This sweep passes two times the resonance frequency (F_0 = 147 Hz) of the torsional vibration system and excites it two times as it can be clearly seen in Fig. 16.

6. Conclusions

To measure the input torque of a torsional vibration system it is necessary to take the vibrations of the rotor mass Θ_1 into account. It is not sufficient only to measure the shaft torque. The shaft torque has to be compensated by the acceleration of the rotor mass. To get the exact electrical torque the delay time of the measuring chain has to be taken into account (Fig. 7).

The electrical torque shows several alternating vibrations in its torque signal, which causes high resonance excitations in low damped systems.

References

1. **Hantel, P.** 1986. Theoretische und experimentelle Untersuchungen von transienten Vorgängen bei Asynchronmaschinen in schwach gedämpften Antriebssystemen, Dissertation, RWTH Aachen.
2. **Juzėnas, E.; Jonušas, R.; Juzėnas, K.** 2008. Research of complex rotary systems vibrocondition based on analysis of dinamical processes and spectrum of vibrations, Mechanika 1(69): 42-45.
3. **Vosylius, M.; Didžiokas, R.; Mažeika, P.; Barzdaitis, V.** 2008. The rotating system vibration and diagnostics, Mechanika 4(72): 54-58.
4. **Jonušas, R.; Juzėnas, E.; Juzėnas, K.** 2010. Analysis of some extreme situations in exploitation of complex rotary systems, Mechanika 1(81): 53-57.
5. **Hantel, P.** Kompensierter Drehbeschleunigungs- messer für exzentrisch laufende Wellen. TM 54 (87) 10 S. 389-394.
6. **Bogdevičius, M.; Spruogis, B.; Turla, V.** 2004. A dynamic model of rotor system with flexible link in the presence of shafts missalignment, ISSN 0039–2480 Journal of Mechanical Engineering, Slovenia, 50: 598-612.
7. **Skrickij, V.; Bogdevičius, M.** 2010**.** Vehicle gearbox-dynamics: centre distance influence on mesh stifness and spur gear dynamics, Transport 25(3): 278-286. http://dx.doi.org/10.3846/transport.2010.34.
8. **Hantel, P.; Bogdevičius, M.; Spruogis, B.; Turla, V.; Jakštas, A.** 2008. Analysis of parametric excited vibrations of drive shafts caused by induction machines, Mechanika 4(72): 48-52.
9. **Spruogis, B.; Turla, V.** 2006. A damper of torsional vibrations and investigation on its efficiency, ISSN 0039–2480 Journal of Mechanical Engineering, Slovenia 52(4): 225-236.
10. **Jakštas, A.; Spruogis, B.; Turla, V.** 2007. Vibration dampers for transmission of mechatronic systems, Journal of Vibroengineering 9(4): 41-44.
11. **Hantel, P.; Bogdevičius, M.; Spruogis, B.; Turla, V.; Jakštas, A.** Research of parametric vibrations of drive shafts in induction machine. In: Proceedings of VI Triennial International Conference HEAVY MACHINERY HM 2008, June 24–29, 2008, Kraljevo, Republic of Serbia, ISBN 978–86–82631–45–3, E.29–E.34.
12. **Spruogis, B.; Turla, V.; Jakštas, A.; Bogdevičius, M.; Hantel, P.** 2009. Theory and Application of the Devices of Transmission and Stabilization of Rotary Motion: Monograph, Vilnius: Technika 479 p. (in Lithuanian).

P. Hantel, B. Spruogis, V. Turla, A. Jakštas

INDUKCINIŲ MAŠINŲ VIBRACIJŲ PEREINAMŲJŲ PROCESŲ METU TYRIMAS FERRARIO JUTIKLIU

R e z i u m ė

Indukcinių mašinų elektrinio sukimo momento negalima išmatuoti elektros srovės ir įtampos vienetais. Vienintelė galimybė – išmatuoti veleno sukimo momentą ir rotoriaus kampinį pagreitį. Veleno sukimo momentas nustatomas įtempių matuokliu, sujungtu su Wheatstone‘o tilteliu. Rotoriaus kampinis pagreitis matuojamas specialiai tam sukonstruotu Ferrario jutikliu. Nustačius vėlavimo laiką, abu signalai koreguojami elektros grandinėje. Straipsnyje aprašytas eksperimentinis stendas su abiem minėtais jutikliais ir pateikti jo parametrai. Indukcinės mašinos elektrinis sukimo momentas buvo matuojamas jai įsibėgėjant ir keičiant greičio kryptį. Keičiant veleno skersmenį ir smagračio masę, gauti įvairūs sistemos savieji dažniai. Matavimo rezultatai apdoroti sparčiųjų Fourier‘o transformacijų analizės metodu, parodant kintantį mechaninės sistemos sužadinimą veikiant elektriniam indukcinės mašinos sukimo momentui.

P. Hantel, B. Spruogis, V. Turla, A. Jakštas

RESEARCH OF VIBRATIONS IN INDUCTION MACHINES DURING TRANSIENT PROCESSES USING A FERRARIS SENSOR

S u m m a r y

The electrical torque of an induction machine cannot be measured by electrical units of current and voltage, the only possibility is to measure shaft torque and angular acceleration of the rotor mass. The shaft torque is measured with strain gauges, which are electricaly coupled in a Wheatstone bridge. The angular acceleration of the rotor mass is measured with a specially designed Ferraris sensor. For both signals the delay time has to be taken into account and adjusted by an electrical network. The test rig with the mentioned sensor and their parameters are presented in the paper. The electrical torque was measured during run-up and reversing of the speed of the induction machine. By variation of the diameter of the shaft and the flywheel mass different resonance frequencies of the system could be realized. The measured signals were processed by using the Fast Fourier Transformation (FFT) analysis method to show the sweep excitation of the mechanical system by the electrical torque of the induction machine.

Keywords: vibrations, induction machines, transient processes, Ferraris sensor.

Received December 06, 2011
Accepted October 10, 2013