Atef S. AL-MASHAKBEH[1], Dmytro MAMCHUR[2], Andrii KALINOV[2], Mykhaylo ZAGIRNYAK[2]
[1]Tafila Technical University, [2]Kremenchuk Mykhailo Ostrohradskyi National University

doi:10.15199/48.2016.12.02

A diagnostic of induction motors supplied using frequency converter basing on current and power signal analysis

Abstract. *The paper describes a way for providing induction motor diagnostic in case of motor fed using frequency converter, when additional distortions caused by pulse-width modulation could affect the diagnostic result. It is proposed to use preliminary clarification of current and voltage signals, aimed to exclude from consideration harmonics caused by pulse-width modulation, with further re-computation of power spectra using discrete convolution algorithm.*

Streszczenie. *Artykuł opisuje metodę diagnostyki silnika indukcyjnego zasilanego przetwornikiem częstotliwości w przypadku występowania zakłóceń spowodowanych modulacją szerokości impulsu. Zaproponowano wstępne oczyszczanie sygnałów prądowych i napięciowych mające na celu wyłączenie z rozważań harmonicznych generowanych modulacją szerokością impulsu. Prowadzi to do ponownego obliczania spektrum mocy z wykorzystaniem dyskretnych algorytmów konwolucyjnych.* ***(Diagnostyka silników indukcyjnych zasilanych z przetworników częstotliwości opartych na analizie sygnałów prądu I mocy)***

Key words: *induction motors, fault diagnosis, instantaneous power, frequency domain analysis, frequency converters.*
Słowa kluczowe: silniki indukcyjne, diagnostyka uszkodzeń, moc chwilowa, analiza częstotliwościowa, przetworniki częstotliwości

Introduction

Nowadays reliable operation of induction motors (IM), as one of the biggest energy consumers that are used almost at all fields of industry, is very important task. To ensure their safety and reliability, it is essential to provide diagnostics of IM technical conditions. Traditional diagnostic techniques determine suspension of production, and partly disassembling of IM along with harmful testing operations. Thus, alternative diagnostic techniques become popular last years. These techniques allows one to provide diagnostic under operational conditions, they are not harmful for equipment, have well-grounded theoretical basis and provide reliable results. The most attractive among them are techniques based on electrical signals analysis, namely, motor current spectra analysis (MCSA) [1–5] and instantaneous power spectra analysis (IPSA) [6–9]. In previous works authors provided theoretical basis of IPSA [8, 9] and presented results of successful implementation of these methods in industrial applications [8]. The crack tip opening displacement test has been become a common method of measuring the real mechanical properties of used base materials [12].It should be mentioned, that all previous results were derived for IM fed by polyharmonic supply sources. However, modern electric drive systems often fed by frequency-controlled drives, with voltage signal formed by pulse-width modulated (PWM) source. Thus, influence of PWM voltage source on spectra composition of current and instantaneous power signals in tasks of MCSA and IPSA is not fully investigated, and this research is aim of current paper.

Problem statement

The development of approach for diagnostic IM supplied by FC basing on electrical signals spectra analysis.

Fundamentals of induction motors diagnostic methods based on electric signals analysis

In case of healthy symmetrical motor with symmetrical power supply, phase currents $i(t)$ and voltages $u(t)$ could be represented as purely harmonic signals:

(1) $$u(t) = \sqrt{2}U_1 \cos(\omega t),$$

(2) $$i(t) = \sqrt{2}I_1 \cos(\omega t - \varphi).$$

Thus, in case of healthy motor fed by “ideal” supply and running with constant velocity, instantaneous power could be described by following expression:

(3) $$p(t) = u(t)i(t),$$

or

(4) $$\begin{aligned} p(t) &= u(t)i(t) = 2U_1 I_1 \cos(\omega t)\cos(\omega t - \varphi) = \\ &= U_1 I_1 \cos(\varphi) + U_1 I_1 \cos(\varphi)\cos(2\omega t) + \\ &+ U_1 I_1 \sin(\varphi)\sin(2\omega t), \end{aligned}$$

where U_1, I_1 are RMS values of phase voltage and current, respectively; $\omega = 2\pi f_s$ is the angular frequency, where f_s is the supply frequency; φ is the motor load angle.

In case of IM faults or supply mains low-quality currents and voltages becomes polyharmonical. MCSA and IPSA are based on correspondence of certain fault types with certain harmonics in current or instantaneous power spectra. The frequencies of most typical damage types could be detected basing on the expressions, which were well-described and grounded in previous works [8, 9].

In case of frequency-controlled drives voltage signal will contain a number of non-informative harmonics, caused by PWM, which will influence on current and power signals, and lead to complication of harmonic analysis. These harmonics may cause multiplication of noise harmonics in resulting power spectra signal, or elimination from consideration of fault-related harmonics. Both cases lead to wrong diagnostic result using IPSA method.

In order to eliminate noisy harmonics from consideration, it is suitable to represent current and voltage signals as sum of Fourier series with cosine (U^a, I^a) and sine (U^b, I^b) components [10]:

(5) $$u(t) = \sum_{n=0}^{N_2} (U_n^a \cos n\omega t + U_n^b \sin n\omega t),$$

(6) $$i(t) = \sum_{m=0}^{N_1} (I_m^a \cos m\omega t + I_m^b \sin m\omega t).$$

In this case power signal is represented as product of sums of voltage and current Fourier series:

(7) $$\begin{aligned} p(t) = i(t)\cdot u(t) &= \sum_{m=0}^{N_1} (I_m^a \cos m\omega t + I_m^b \sin m\omega t) \times \\ &\times \sum_{n=0}^{N_2} (U_n^a \cos n\omega t + U_n^b \sin n\omega t) = \\ &= \sum_{k=0}^{N_1+N_2} (P_k^a \cos k\omega t + P_k^b \sin k\omega t). \end{aligned}$$

Such representation allows us estimate contribution of certain current and voltage harmonics into certain power harmonic. However, it is quite hard to use such representation for analyzing signals which contains big number of harmonics.

Implementation of discrete convolution algorithm [10] for multiplication of current and voltage Fourier series gives following equation for computation amplitude of each k-th cosine (P_k^a) and sine (P_k^b) power harmonic components basing on known current and voltage harmonics:

$$(8)\qquad P_k^a = \frac{1}{2}\cdot\left[\begin{array}{l} \sum\limits_{\substack{i=0\\ k-i\geq 0}}^{N-1} I_i^a\cdot U_{k-i}^a + \sum\limits_{\substack{i=0\\ k-i<0}}^{N-1} I_i^a\cdot U_{i-k}^a - \\ - \sum\limits_{\substack{k=0\\ k-i\geq 0}}^{N-1} I_i^b\cdot U_{k-i}^b - \sum\limits_{\substack{k=0\\ k-i<0}}^{N-1} -I_i^b\cdot U_{i-k}^b \end{array}\right]$$

$$(9)\qquad P_k^b = \frac{1}{2}\cdot\left[\begin{array}{l} \sum\limits_{\substack{i=0\\ k-i\geq 0}}^{N-1} I_i^b\cdot U_{k-i}^a + \sum\limits_{\substack{i=0\\ k-i<0}}^{N-1} I_i^b\cdot U_{i-k}^a + \\ + \sum\limits_{\substack{k=0\\ k-i\geq 0}}^{N-1} I_i^a\cdot U_{k-i}^b - \sum\limits_{\substack{k=0\\ k-i<0}}^{N-1} I_i^a\cdot U_{i-k}^b \end{array}\right]$$

Basing on equations (8) and (9) it is possible to detect contribution of each current and voltage harmonic with certain frequency in certain power harmonic component. Thus, it makes possible to analyse separately influence of noisy and/or fault-related current and voltage harmonics on the amplitude of certain power harmonic.

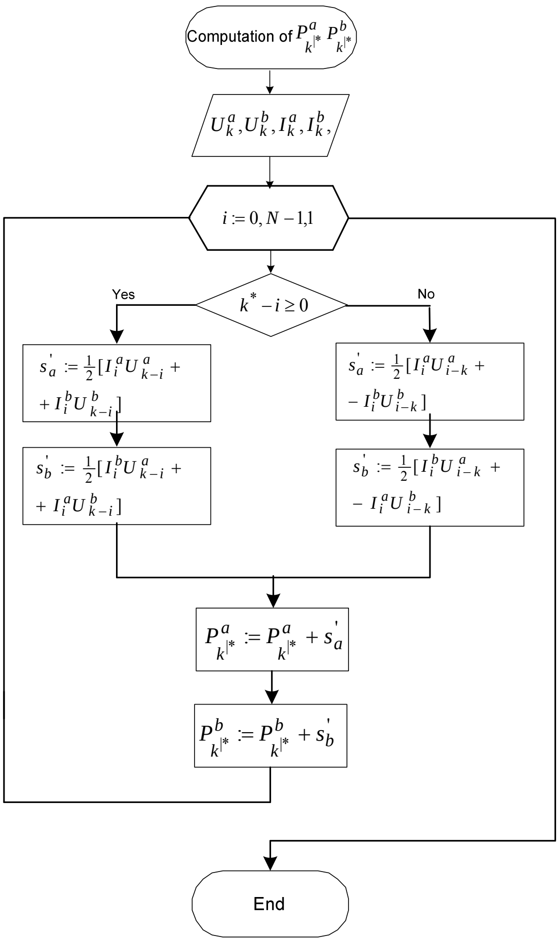


Fig. 1 An algorithm for computation power harmonics basing on discrete convolution of current and voltage harmonic series

An approach for diagnostic IM fed by FC basing on electrical signals analysis

To clarify current and power spectra from noisy harmonics it was proposed to eliminate non-informative harmonics, which certainly do not influence on final diagnostic result. Fulfilled analysis showed, that current harmonics with amplitudes less than 10% of main current harmonic amplitude, and voltage harmonics with amplitude values less than 5% of main voltage harmonic component amplitude could be excluded from consideration.

In this case we'll get clarified voltage and current spectra contained only main supply and valuable fault-related harmonics used for further analysis.

The idea of this method consists in preliminary exclusion of non-informative harmonics from current and voltage spectra with further computation instantaneous power signal values in time-domain using discrete convolution algorithm (8, 9). In result, it is possible to recalculate instantaneous values of power signal which is clarified from noisy harmonics caused by PWM.

Equations (8, 9) could be easily coded using any programming language and then implemented for automatic computations for IM diagnostic system based on electrical signals analysis. Thus, in order to automate computations for diagnostic system, it was developed related computation algorithm (fig. 1), which was implemented in developed software (fig. 2).

Experimental investigations

Basing on developed solutions and using previously developed diagnostic equipment [9] it was carried out experimental investigations of proposed approach on the basis of Ferrexpo mining company. It was investigated four mechanisms equipped with IM fed by FC: two flat-belt conveyors, circular refrigerant and movable lathing.

Analyzing derived power spectra on the example of IM of movable lathing mechanism it could be mentioned, that initial signal is too noisy, and fault-related harmonics are barely detectable in current signal (fig. 3, a) and almost equal to amplitudes of noisy harmonics in power spectra (fig. 4, a). After clarification, all informative harmonics, related to fault signatures and supply frequency harmonics, are clearly detectable, while all non-informative harmonics were eliminated from consideration (fig. 3b, 4b).

Thus, experimental verification of proposed solutions confirmed possibility of using electrical signals analysis for detection IM faults basing on their spectrum analysis with preliminary elimination of noise harmonics using power harmonics analysis basing on discrete convolution algorithm. This method, along with method for elimination of supply mains low-quality parameters on the results of induction motor diagnostics [11], will help to increase the reliability of IM operation, and, as sequence, could be used to forecast their lifetime.

Conclusions

It was developed an approach for analyzing current and instantaneous power spectra for purposes of MCSA and IPSA in case of IM fed by frequency converter. In order to eliminate influence of noise harmonics caused by PWM on diagnostic result, it was proposed to use discrete convolution algorithm for recalculation power harmonic components. For task of implementation of proposed solutions in automated diagnostic system it was developed related computational algorithm which was adopted as a base for creation related software.

Proposed approach and developed software were used for evaluation technical condition of IM at Ferrexpo mining company, and showed reliable results, which confirmed theoretical conclusions.

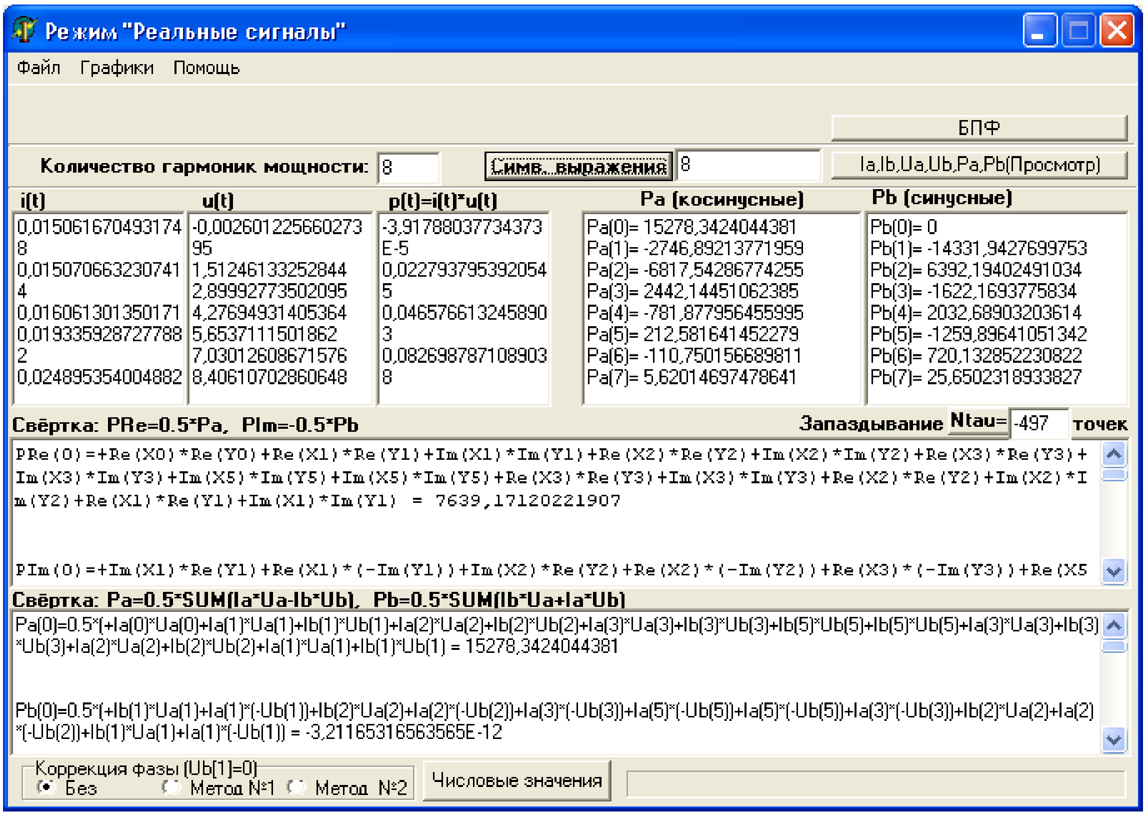
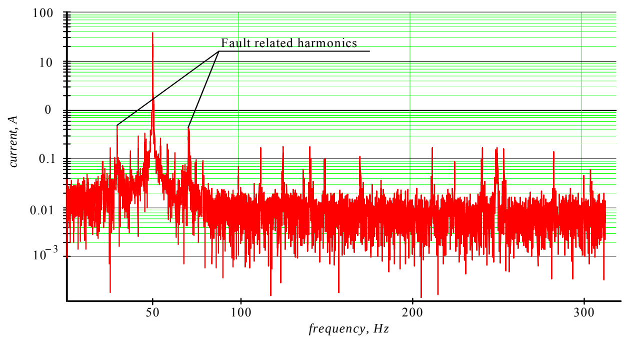
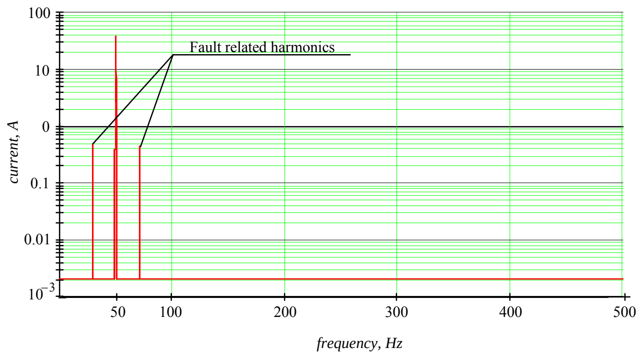


Fig. 2 Software interface for computation power harmonics basing on discrete convolution of current and voltage harmonics

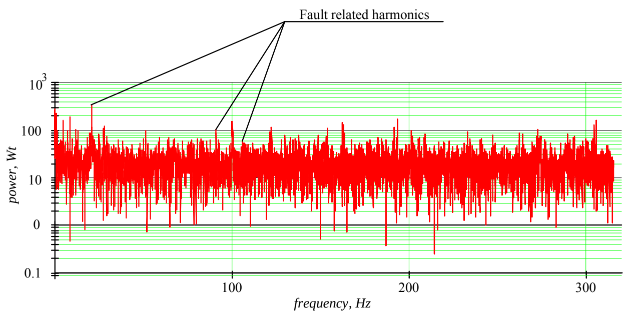


a) measured signal

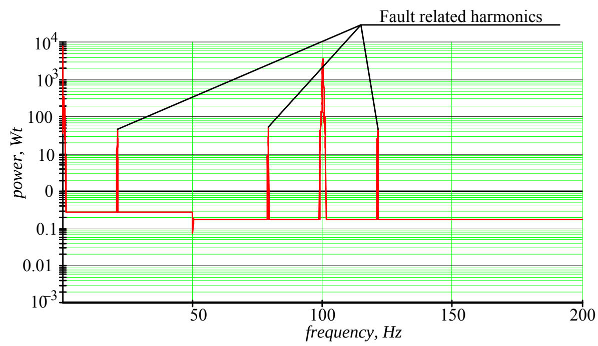


b) filtered signal

Fig. 3 Spectrum of current signal



a) measured signal



b) filtered signal

Fig. 4 Spectrum of power signal

***Authors**: Associate Professor of Electrical Engineering Department of Tafila Technical University Atef S. Al-Mashakbeh, Tafila, Jordan, E-mail: dr.atef_almashakbeh@yahoo.com; Associate Professor of Electric Drive and Control Systems Department of Kremenchuk Mykhailo Ostrohradskyi National University Dmytro Mamchur, Pervomayskaya str. 20, Kremenchuk, Ukraine, 39600, E-mail: dm@kdu.edu.ua; Associate Professor of Electric Drive and Control Systems Department of Kremenchuk Mykhaylo Ostrohradskyi National University Andrii Kalinov, Pervomayskaya str. 20, Kremenchuk, Ukraine, 39600, E-mail: scenter@kdu.edu.ua; Rector of Kremenchuk Mykhailo Ostrohradskyi National University and the Chairman and the Professor of Electric Machines Department Mykhaylo Zagirnyak, Pervomayskaya str. 20, Kremenchuk, Ukraine, 39600, E-mail: mzagirn@kdu.edu.ua*

REFERENCES

[1] Benbouzid M. E. H.and Kliman G. B., What stator current processing-based technique to use for induction motor rotor faults diagnosis?, *IEEE Transactions on Energy Conversion*, *vol. 18, no. 2, pp. 238–244, Jun. 2003.*

[2] Benbouzid M. E .H. A Review of Induction Motors Signature Analysis as a Medium for Faults Detection, *IEEE Transactions on Industrial Electronics, vol. 47, No. 5, pp. 984-993. Sep/Oct 2000*

[3] Onel I. Y., Dalci K. B. and Senol I., Detection of outer raceway bearing defects in small induction motors using stator current analysis, *Sadhana, vol. 30, no. 6, pp. 713–722, Dec. 2005.*

[4] Fišer R., Lavrič H., Ambrožič V., Bugeza M. Diagnostic system for on-line detection of rotor faults in induction motor drives Diagnostics for Electric Machines, Power Electronics & Drives (SDEMPED), 2011 IEEE International Symposium on, pp. 77-83

[5] Dorrell D. G., Thomson W. T., Roach S. Combined effects of static and dynamic eccentricity on air gap flux waves and the application of current monitoring to detect dynamic eccentricity in 3-phase induction motors Electrical Machines and Drives. Seventh International Conference on (Conf. Publ. No. 412), Durham, UK, pp. 151–155, 1995.

[6] Drif M., Benouzza N., Bendiabdellah A. and Dente J.A., The use of instantaneous power spectrum in the detection of rotor cage faults on 3-Phase induction motors. *"ELECO '99" International conference on electrical and electronics engineering, pp. 351-355.*

[7] A. M. Trzynadlowski and E. Ritchie, "Comparative investigation of diagnostic media for induction motors: a case of rotor cage faults," IEEE Transactions on Industrial Electronics, vol. 47, no. 5, pp. 1092–1099, Oct. 2000.

[8] M.V. Zagirnyak, D.G. Mamchur, A.P. Kalinov, "Comparison of induction motor diagnostic methods based on spectra analysis of current and instantaneous power signals," Przeglad Elektrotechniczny, Iss. 12b/2012, pp. 221–224.

[9] M. V. Zagirnyak, D. G. Mamchur, A. P. Kalinov, "Induction motor diagnostic system based on spectra analysis of current and instantaneous power signals," in Proc. IEEE SoutheastCon 2014, Lexington, KY, USA, March 13–16, 2014 © IEEE. doi: 10.1109/SECON.2014.6950721.

[10] M. Zagirnyak, A. Kalinov, M. Maliakova An algorithm for electric circuits calculation based on instantaneous power component balance // Przegląd elektrotechniczny (Electrical Review), R. 87 NR 12b/2011. – 2011. – pp. 212–215.

[11] Zagirnyak M.V., Mamchur D.G., Kalinov A.P., Elimination of the Influence of Supply Mains Low-Quality Parameters on the Results of Induction Motor Diagnostics, *in Proc. XIX International Conference on Electrical Machines - ICEM 2010, Rome. IEEE Catalog Number: CFP1090B-CDR. ISBN: 978-1-4244-4175-4. Library of Congress: 2009901651. RF-009474.*

[12] Z. Praunseis, M. Toyoda, T. Sundararajan, **"**Fracture behaviours of fracture toughness testing specimens with metallurgical heterogeneity along crack front. Steel research, Vol.71, No. 9, pp. 366-373, ISSN 0177-4832, September 2000