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An Algorithm for Induction Motor Monitoring System Based on Electrical Signals Analysis

Abstract. *In the paper it was developed indexes for evaluation induction motor (IM) current operational conditions basing on electrical signals analysis. Basing on these indexes it were derived logical rules for evaluation IM operational conditions, which were laid down in the basic of algorithm for IM monitoring system. It were developed related software for monitoring system, and it was conducted experimental verification, which confirmed possibility of use derived indexes and logical rules for evaluation current IM operational conditions.*

Streszczenie. *W artykule opracowano wskaźniki do ewaluacji bieżących warunków działania silnika indukcyjnego bazujące na analizie sygnałów elektrycznych. Bazując na tych wskaźnikach wyprowadzone zostały logiczne zasady ewaluacji warunków działania silnika indukcyjnego, stanowiące podwaliny do budowy algorytmu monitorowania sinika indukcyjnego. Opracowany został program monitorujący oraz przeprowadzono weryfikację eksperymentalna, która potwierdziła możliwość użycia wyprowadzonych wskaźników i logicznych zasad ewaluacji bieżących warunków działania silnika indukcyjnego.* ***(Algorytm systemu monitorującego silnik indukcyjny opartego na analizie sygnałów elektrycznych)***

Key words: electrical signals analysis, monitoring, diagnostics, software.
Słowa kluczowe: analiza sygnałów elektrycznych, monitorowanie, diagnostyka, oprogramowanie

Introduction

Modern technologies allow one ensure comprehensive control of production operation, which increase its reliability and efficiency. However, sudden failures of operational equipment could lead to production breaks, which, in turn, lead to financial losses. As induction motors (IM) are used to drive predominant number of actuating mechanisms, theirs failures cause most significant financial losses and could lead to failure of other industrial equipment. In order to avoid significant financial losses due to production stoppage because of sudden IM failure it is reasonable to use monitoring systems at important parts of production process. Such systems should use data for analysis which could be easily measured and don't need expensive additional equipment. The best choice, in this case, is collection data from electrical signals for further analysis. As it was stated in [1], induction motor diagnostics and monitoring, as well as its life forecast and necessity of maintenance, could be done basing on analysis of electrical energy transformation process. One of the features describing energy processes in IM is its power consumption. This signal is quite suitable to be chosen as a basis for IM diagnostic and monitoring system, as it doesn't require suspension of production, and needs only motor's measured currents and voltages, while all the rest necessary features could be computed indirectly. Moreover, power spectra signal analysis is more reliable than current spectra analysis and contain additional information which could be used for evaluation current motor technical conditions [2]. In [3] it were derived mathematical expressions for determination power spectra frequencies related to most frequently caused IM damages. However, low-quality of supply mains, electrical disturbances and simultaneous presence of several damage types could cause difficulties in diagnostics basing on these frequencies. Thus, there is necessity to develop some addition diagnostic features to improve reliability of IM monitoring and diagnostics basing on power signal analysis.

Problem statement

Development of indexes and algorithm for monitoring IM technical conditions aiming to avoid sudden failures and predict its remaining lifetime.

Indexes for induction motor monitoring system based on power signal analysis

The supply mains quality influence significantly on the waveform and features of instantaneous power signal, and could be estimated basing on normalized quality factors [4]. Thus, it is necessary to fulfill a complex analysis of IM damages and supply mains low quality influence on power consumption waveform. To meet this goal it is reasonable to develop diagnostic factors based on the analysis of change the features and waveform of three phases power consumption signal. These factors should vary in well-defined ranges and should contain information about reason of power signal waveform change and level of overall motor's condition deterioration. Also these factors should take into account current load or rated value of controlled feature.

It is reasonable to fulfill initial analysis basing on power consumption spectra, total three phases signal, as well as separately for each phase. Total three phases power consumption for healthy motor fed by ideal supply represented on a time-chart as straight line. Significant variable component usually indicates whether motor or load malfunction, thus addition analysis, aimed to detect its source, should be done. Experimental data analysis showed, that IM operation under total variable components value more than 10% of rated power indicated motor unsatisfactory operation condition. To take this into account, it was proposed to use higher power harmonics index:

$$K_{Phh} = \sqrt{\sum_{\nu=1}^{N-1} P_{\nu}^{2}} \Bigg/ P_{н}\,, \qquad (1)$$

where P_r – rated power; P_{ν} – amplitude value of ν-th power harmonic.

For healthy motor fed by ideal power source this index is equal to zero. It takes into account value of variable component relating to rated signal value, which allows one to estimate appropriateness of further motor operation under current operational conditions.

In addition, it could be used following indexes.

Power index of polyharmonic current and voltage signals:

$$K_{\varphi} = P_0 \Bigg/ \sqrt{P_0^2 + \sum_{k=1}^{K-1} Q_k^2}\,, \qquad (2)$$

where P_0 – power signal constant component; $Q_k = \sum_{k=0}^{K-1} \left(Ia_m Ub_n - Ib_m Ua_n \right)$ – reactive power of k-th harmonic, calculated for power harmonics of order $k = m \pm n$, where m, n – are numbers of current and voltage harmonics, accordingly.

In case of unsinusoidal current and voltage signals, due to low-quality supply or IM damages, K_{φ} would vary due to appearance of additional components in signals. Thus, basing on this index value, it is possible to evaluate total deterioration of power consumption quality and IM operability.

Development of semantic expressions for evaluation IM technical conditions.

IM electrical parameters, derived using approach proposed in [5, 6] are input parameters for computation grounded diagnostic indexes. To use these indexes in IM technical conditions monitoring system it is necessary to develop certain rules, which would be used for automatic detection of current IM technical condition and detect a type of present damage, if it exists. Such rules were developed basing on correspondence of proposed indexes with values of vibration velocity for related operational modes according to national standard GOST ISO 10816-1-97:

- «excellent» – equipment operates under ideal conditions under symmetrical sinusoidal supply source, with healthy IM and transforms energy with rated power losses;
- «good» – equipment operates under permissible exploitation parameters values, overall conditions of power supply and IM damages do not influence significantly on system operation and equipment deterioration. Motor considered acceptable for long-term exploitation;
- «satisfactory» – equipment is capable for performing technological operations under enough reliability, however, exploitation parameters deteriorate due to additional losses caused by IM damages or supply mains low-quality, which leads to accelerated IM ageing. Motor allowed to operate under such condition until convenient occasion for its maintenance or replacement;
- «emergency» – equipment is capable to perform technological operations but without ensuring reliability and quality. Deviation of exploitation features is significant, significant part of energy spend for losses. Monitoring system should advice to repair such equipment immediately and provide detailed diagnostics.

Preliminary IM evaluation is conducted via comparison of experimental indexes values with their boundary values, which relates to one of the described operational modes. Boundary values derived basing on analysis results of mathematical models for IM with different damage types taking into account current load. Basing on the analysis results, it were chosen following indexes for evaluation: K_{φ} used for analysis the change of power consumption due to change of higher harmonics in current and voltage signals; K_{Phh} used for analysis particle of variable component comparing to rated total power consumption value, comparing to related vibration velocity value could be used for analysis of possibility of motor further operation; efficiency η for analyzing of effectiveness of power consumption; instant value of heating losses $\Delta P_{heat} = \Delta P_{m1} + \Delta P_{il}$, where ΔP_{m1} are mechanical losses, and ΔP_{il} are iron losses, allows one to analyze heating in windings and possibility of IM breakdown due to overheating.

As result, it were developed the following rules for evaluation of IM current operational mode.

If the following rule is truth:

$$\begin{aligned}(3)\qquad &\left(K_{\varphi} = K_{\varphi\ excel}\right) \wedge \left(K_{Phh} = 0\right) \wedge \\ &\wedge \left(\eta = \eta_{rat}\right) \wedge \left(\Delta P_{heat} = \Delta P_{heat\ excel}\right) = 1,\end{aligned}$$

where $K_{\varphi\ excel}$, $\Delta P_{heat\ excel}$ – are values of power factor and heating losses for healthy motor fed by sinusoidal symmetrical supply, respectively, and, a η_{rat} is rated efficiency; than operational condition of the tested motor could be classified as “excellent”.

Operational condition could be classified as “good”, it the following rule is truth:

$$\begin{aligned}&\left(K_{\varphi\ good} \le K_{\varphi} < K_{\varphi\ excel}\right) \wedge \left(0 < K_{Phh} \le K_{Phh\ good}\right) \wedge \\ (4)\quad &\wedge \left(\eta_{good} \le \eta < \eta_{rat}\right) \wedge \\ &\wedge \left(\Delta P_{heat\ good} \le \Delta P_{heat} < \Delta P_{heat\ excel}\right) = 1,\end{aligned}$$

where $K_{\varphi\ good}$, $K_{Phh\ good}$, η_{good}, $\Delta P_{heat\ good}$ – are permissible values of related indexes, matching “good” operational condition.

Accordingly, motor operates in “satisfactory” mode if the following rule is truth:

$$(5)\quad \begin{aligned}&\forall\begin{pmatrix}\left(K_{\varphi} > K_{\varphi\ sat}\right) \wedge \left(K_{Phh} > K_{Phh\,sat}\right) \wedge \\ \wedge \left(\eta > \eta_{sat}\right) \wedge \left(\Delta P_{heat} > \Delta P_{heat\ sat}\right)\end{pmatrix}\exists \\ &\exists\begin{pmatrix}(K_{\varphi} < K_{\varphi\ good}) \vee (\ K_{Phh} < K_{Phh\,good}) \vee \\ \vee (\eta < \eta_{good}) \vee (\Delta P_{heat} < \Delta P_{heat\ good})\end{pmatrix} = 1,\end{aligned}$$

where $K_{\varphi\ sat}$, $K_{Phh\ sat}$, η_{sat}, $\Delta P_{heat\ sat}$ – are permissible values of related indexes, matching “satisfactory” operational condition.

Truth of the following rule:

$$(6)\quad \begin{aligned}&\forall\begin{pmatrix}\left(K_{\varphi} > K_{\varphi\ emerg}\right) \wedge \left(K_{Mhh} > K_{Mhh\,emerg}\right) \wedge \\ \wedge \left(\eta > \eta_{\ emerg}\right) \wedge \left(\Delta P_{heat} > \Delta P_{heat\,emerg}\right)\end{pmatrix}\exists \\ &\exists\begin{pmatrix}\left(K_{\varphi} < K_{\varphi\ sat}\right) \vee \left(K_{Phh} < K_{Phh\,sat}\right) \vee \\ \vee \left(\eta < \eta_{\text{зад}}\right) \vee \left(\Delta P_{heat} < \Delta P_{\text{гр}\ sat}\right)\end{pmatrix} = 1,\end{aligned}$$

where $K_{\varphi\ emerg}$, $K_{Phh\ emerg}$, η_{emerg}, $\Delta P_{heat\ emerg}$ – are permissible values of related indexes matching “emergency” operational conditions, identifies “emergency” operational mode of the equipment.

Permissible values for each operational mode are calculated taking into account requirements of national standard GOST 183-74 for related motor type.

Thus, basing on developed rules it is possible to monitor current IM operational mode and generate emergency signals or breakdown operational process, if necessary. Derived values of heating losses ΔP_{heat} and higher power harmonics index K_{Phh} could be additionally used for forecasting motor lifetime. Basing on developed rules it was developed an algorithm (Fig. 1) for monitoring current IM technical conditions.

This algorithm was laid down into the basis of developed software for IM monitoring system (Fig. 2). This software allows one to collect currents and voltages signals for each of three phases, compute current, voltage and power spectra, provide preliminary IM diagnostics basing both on motor current spectra analysis and instantaneous power spectra analysis [3], and, basing on developed logical rules (3)–(6) implementing developed algorithm presented in Fig.1, provide evaluation of current IM operational condition with suggestion to maintenance it, if necessary.

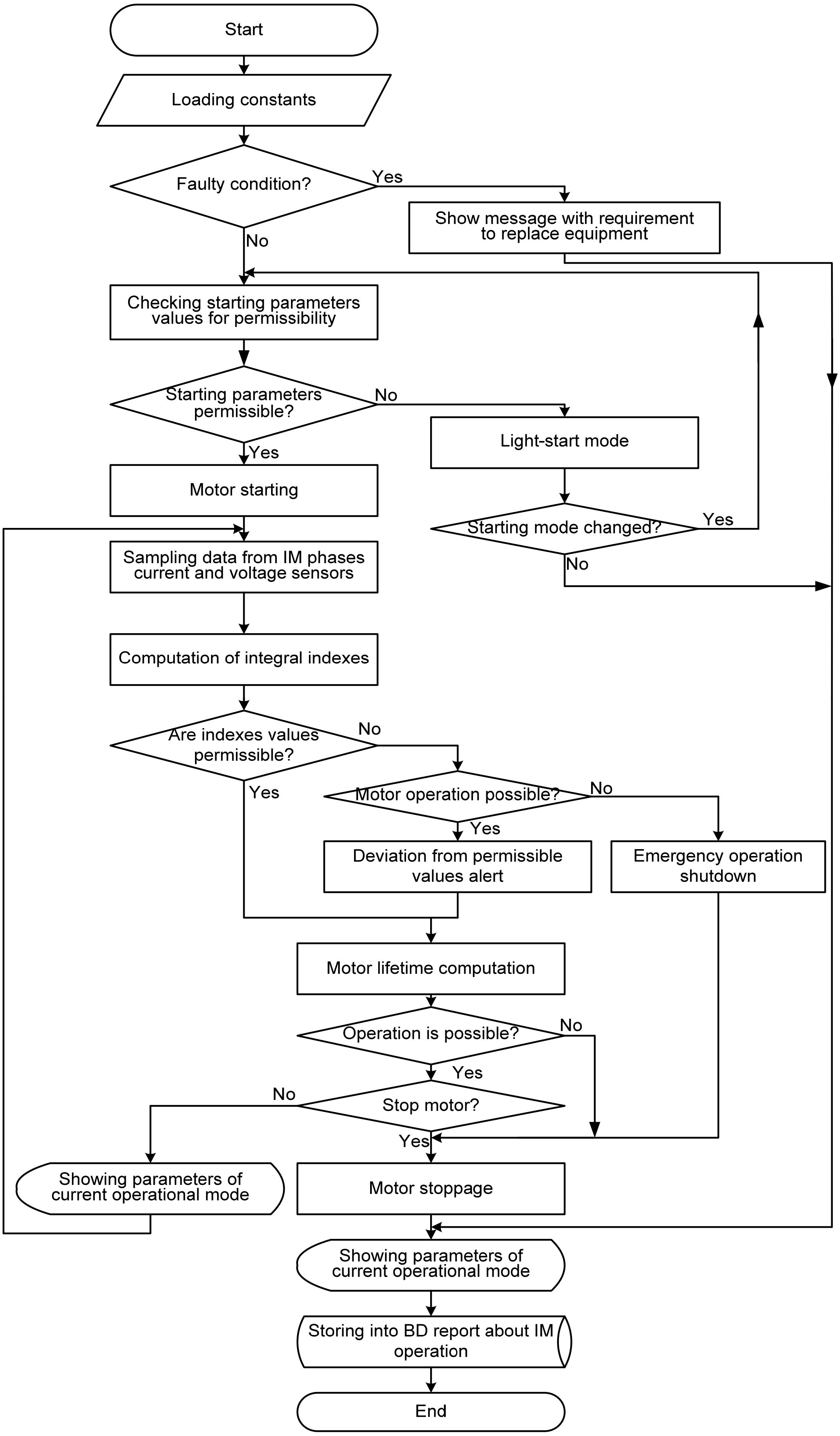
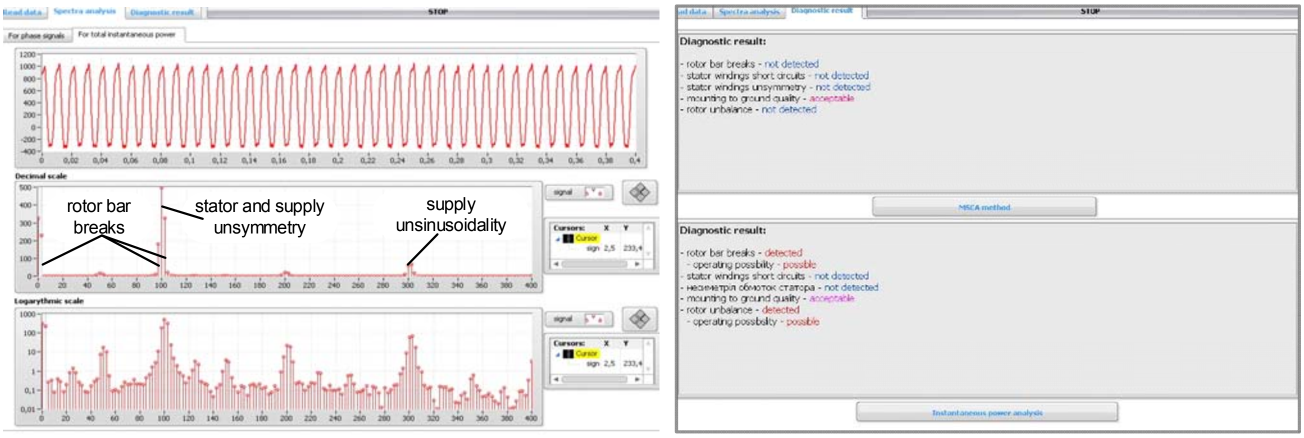


Fig. 1. An algorithm for IM current technical condition monitoring



Diagnostic result:

- rotor bar breaks - not detected
- stator windings short circuits - not detected
- stator windings unsymmetry - not detected
- mounting to ground quality - acceptable
- rotor unbalance - not detected

Diagnostic result:

- rotor bar breaks - detected
  - operating possibility - possible
- stator windings short circuits - not detected
- несиметрія обмоток статора - not detected
- mounting to ground quality - acceptable
- rotor unbalance - detected
  - operating possibility - possible

Fig. 2. Software for induction motor operational condition monitoring system

To verify theoretical results and developed hardware and software solutions, it was provided tests with three identical IM of type AIR80V4U2, 1.5 kW. These motors were artificially damaged with different number of broken rotor bars and short-turns number in stator windings. In Fig. 2, left, it is showed window with IM diagnostic result for motor with healthy stator and inception of rotor bar breaks basing on instantaneous power spectra analysis. Besides rotor bar breaks diagnostics and monitoring system, basing on power signal anaysis, detected motor and supply unsymmetry as well as supply unsinusoidality. Basing on these input data it were computed results for motor diagnostics and evaluation of its overall operational conditions. In Fig. 2, right, it is showed motor diagnostic and evaluation results basing both on motor current and motor power consumption signals analysis. It is clearly visible, that motor current signal analysis failed to detect inception of rotor bar breaks, in difference to power spectra analysis method. Moreover, power analysis allow one to evaluate current operation mode as “possible”, which is result of logical “truth” according to equation (4). Experimental results showed that developed software could accurately detect IM damage type basing on instantaneous power spectra analysis and also could identify current IM operational mode and propose decision about possibility of further motor operation.

Conclusions

It was developed indexes for evaluation current IM operational conditions basing on electrical signals analysis, which could be used in IM monitoring system.

Basing on developed indexes in were derived logical rules for decision making about current IM operational conditions.

It was developed algorithm and related software for IM monitoring system basing on electrical signals analysis. Experimental verification confirmed possibility of use derived indexes and logical rules for evaluation current IM operational conditions.

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