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Condition Monitoring System for Induction Motor

***Abstract**. The aim of this research is to implement induction motor lifetime estimation methods into a Python-based monitoring system. According to the collected statistics and investigated researches it was defined most common induction motors breaking types and units that require the most careful attention. Windings' insulation condition in this case has significant influence on the overall induction motor reliability. Its rated exploitation time depends on mechanical, chemical, and temperature operational conditions. Bearings are also might be damaged because of inappropriate exploitation. The development of a monitoring and diagnostics system which takes into account current technical condition of the most responsible induction motor units to forecast its remaining expected lifetime is based on methods that allow defining all required induction motor parameters based on its voltage and current signals. Online monitoring and storing received data to the remote databases at the same time makes it possible to separate the actual production process from IM diagnostic and data analysis.*

***Streszczenie.** Celem badań jest wdrożenie metod szacowania czasu życia silników indukcyjnych do systemu monitoringu opartego na programie Python. Na podstawie zebranych statystyk i przeprowadzonych badań określono najczęściej spotykane typy i zespoły wyłączające silniki indukcyjne, które wymagają jak największej uwagi. Stan izolacji uzwojeń ma w tym przypadku istotny wpływ na ogólną niezawodność silnika indukcyjnego. Jego znamionowy czas eksploatacji zależy od mechanicznych, chemicznych i temperaturowych warunków pracy. Łożyska również mogą ulec uszkodzeniu w wyniku niewłaściwej eksploatacji. Opracowanie systemu monitoringu i diagnostyki uwzględniającego aktualny stan techniczny najbardziej odpowiedzialnych zespołów indukcyjnych silników do prognozowania pozostałej przewidywanej żywotności, oparte jest na metodach pozwalających na określenie wszystkich wymaganych parametrów silnika indukcyjnego na podstawie jego sygnałów napięciowych i prądowych. Monitorowanie on-line i jednoczesne przechowywanie otrzymanych danych w zdalnych bazach danych umożliwia oddzielenie rzeczywistego procesu produkcyjnego od diagnostyki IM i analizy danych. (**System monitorowania silnika indukcyjnego**).*

Keywords: induction motor, field-oriented control, artificial neural network.
Słowa kluczowe: silmik indukcyjny, sterowanie polowe, sztuczna sieć neuronowa

Introduction

Induction motors are the most popular and widespread in electric drive systems comparing to other motor types. This is justified by their robust and reliable construction which simplifies the maintenance process. The power range of induction motors (IM) covers most of the production requirements and branches where they can be used.

Although IM are so popular, their predictable exploitation and expected lifetime are strongly related to the operational conditions. Low power supply quality, lack of proper maintenance, or deviations in operational mode comparing to the rated one significantly reduce their lifetime.

According to the researches and statistics [1-4] most breakings are related to the stator or rotor windings and bearings breaks. These failures influence not just the productivity, but also distort current and voltage signals, thus, could be detected based on electrical signals analysis [5-7].

On the other hand, all motor damages or electrical system low-qualities lead to a decrease in a motor expected lifetime. There are a number of methods for recalculating expected lifetime of IM units described in classical literature. However, most of them had not been implemented practically because of lack of proper equipment previously.

In this work, it is proposed to develop IM monitoring and expected lifetime forecasting system which collects current and voltage electrical signals from motor connection points, provides IM online diagnostics, and recalculates its expected remaining lifetime basing on current exploitation parameters.

This approach allows us to decrease IM operational expenses due to providing maintenance based on real necessity and economic reasons.

Theoretical theses

The equation for the expected remained IM lifetime includes the rated value for this model and calculated changes according to actual operational conditions.

$$R_{rem} = R_{base} - R_0 - \Delta R_{Temp} - \Delta R_{Vibr} - \Delta R_{Nat} - \Delta R_E \tag{1}$$

where R_{rem} – calculated remained expected lifetime; R_{base} – rated IM lifetime with nominal parameters; R_0– IM lifetime reduction that caused by exploitation with rated parameters; ΔR_{Temp} – lifetime reduction caused by windings overheating; ΔR_{Vibr} – lifetime reduction caused by vibration; ΔR_{Nat} – lifetime reduction caused by environmental conditions; ΔR_E – lifetime reduction caused by electric field exposure.

When IM is operated under rated parameters in the proper environment, this equation will be reduced to include just its actual resource change:

$$R_{rem} = R_{base} - R_0 \tag{2}$$

According to current conditions and deviations in IM exploitation parameters it can be calculated its expected remaining lifetime.

The time needed to reach the limit of insulation resource could be calculated as follows:

$$R_{base1} = e^{\frac{E_a}{R \cdot Q} - G} \tag{3}$$

where E_a – activation energy; R – universal gas constant; Q – absolute temperature, K.

If the insulation resource is known (before the limit is reached) R_{base1} with rated temperature Q_1, than resource with different temperature Q_2 can be calculated using the following equation:

$$R_{temp} = R_{base1} \times e^{\frac{E_a}{R}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right)} \tag{4}$$

where values E_a, G, $B = -{E_a}/{R}$ for different insulation types are determined experimentally.

Time required to cause insulation damage by mechanical and thermo-mechanical processes R_{base2} can be calculated as:

(5) $$\boldsymbol{R_{base2}} = \frac{\boldsymbol{F_1}}{\boldsymbol{\psi \cdot k_f^n}}$$

where $\boldsymbol{\psi}$ – insulation material coefficient; $\boldsymbol{n}$ – parameter that depends on temperature, $\boldsymbol{F_1}$ – function for $\boldsymbol{n}$, $\boldsymbol{k_f}$ – force in the wires contact area.

Resource for $\boldsymbol{R_{vibr}}$ is calculating by the following equation:

(6) $$\boldsymbol{R_{vibr}} = \boldsymbol{R_{base2}} \cdot \frac{(k_f^n)_1}{(k_f^n)_2}$$

The time needed to reach the insulation resource limit caused by electric field:

(7) $$\boldsymbol{R_{base3}} = \frac{\boldsymbol{A_e}}{\boldsymbol{E^m}}$$

where $\boldsymbol{E}$ – electric field density; $\boldsymbol{A_e}$,$\boldsymbol{m}$ – coefficients, that depend on insulation material.

In this case, insulation resource is calculated as follows:

(8) $$\boldsymbol{R_e} = \boldsymbol{R_{base3}} \frac{\boldsymbol{E_2^m}}{\boldsymbol{E_1^m}}$$

The overall influence of exploitation parameters and environment on the insulation lifetime could be determined as follows:

(9) $$\boldsymbol{R_{base4}} = \boldsymbol{A} \cdot \boldsymbol{e}^{\frac{B}{Q} \cdot C^{-m} \eta^{-n}}$$

where $\boldsymbol{C}$ – aggressive agent concentration, $\boldsymbol{\eta}$ – relative humidity, $\boldsymbol{m}$,$\boldsymbol{n}$ – coefficients, $\boldsymbol{Q}$ – absolute temperature value.

In this case resource $\boldsymbol{R_{nat1}}$ with temperature $\boldsymbol{Q_2}$:

(10) $$\boldsymbol{R_{nat1}} = \boldsymbol{R_{base4}} \cdot \boldsymbol{e}^{B \cdot C^{-m} \eta^{-n} \left(\frac{1}{Q_2} - \frac{1}{Q_1}\right)}$$

And resource $\boldsymbol{R_{nat2}}$ calculated for humidity $\boldsymbol{\eta_2}$:

(11) $$\boldsymbol{R_{nat2}} = \boldsymbol{R_{base4}} \cdot \boldsymbol{e}^{\frac{B}{Q} \cdot \left(C^{-m} \eta_1^{-n} - C^{-m} \eta_2^{-n}\right)}$$

Another aspect of diagnosis is to detect deviations in IM units that can lead to breakings or serious damage without proper and timely maintenance. Based on the current signal were investigated methods for diagnostics the most common breaking types that include broken rotor bars, stator windings short-turns and bearing damage.

Motor Current Signature Analysis (MCSA) is based on Fast Fourier Transform (FFT) of IM current signal [8]. Harmonics at some specific frequencies are pointing to the deviations or breakings in different IM units [9].

Broken rotor bars can be detected by the following equation:

(12) $$\boldsymbol{f}_{\mathrm{bb}} = \boldsymbol{f_s}[\boldsymbol{1} \pm \boldsymbol{2s}]$$

where $\boldsymbol{f_s}$ – the supply fundamental frequency, $\boldsymbol{s}$ – the motor slip.

The equation for stator windings short-turns detection is following:

(13) $$f_{st} = f_s\left[\frac{n}{p}(1-s) \pm k\right]$$

where f_s – the supply main frequency; n – positive integer number (1, 2, 3…); k can be equal to 1, 3, 5 or 7.

Frequencies that correspond to damaged bearings:

(14) $$f_{\mathrm{brg}} = \left[f_s \pm m f_{i,o}\right]$$

where $m = 1,2,3\ldots$, and $f_{\mathrm{I,o}}$ – one of the characteristic vibration frequencies, which are based upon the bearing dimensions:

(15) $$f_{\mathrm{i,o}} = \frac{n}{2} f_v \left[1 \pm \frac{bd}{pd} \cos\beta\right]$$

where n – the number of bearing balls; f_v is the mechanical rotor velocity in hertz; bd is the ball diameter; pd is the bearing pitch diameter.

Based on these frequencies were determined equations to detect presence of described damages in motor current and motor power consumption signals [10], which were used as a basis for mathematical apparatus used in IM monitoring and remaining lifetime estimation system.

Developing Python-based Diagnostic system

As a media for the creation IM monitoring and diagnostics system it was chosen the Python programming language because of its popularity and capabilities in data analysis and machine learning which can be used to estimate IM current condition and predict its remaining lifetime. It also provides easy and readable source code that can be improved and appended with new diagnostic methods. This programing language is object-oriented which also simplifies the developing process by creating and using standard controls and separating program into different blocks. Proposed system could use data derived from the Mathlab simulation model or real IM data either previously stored in a database or collected online using a measurement system. The range of tools allows processing received data based on formulas that were investigated in the previous block and provide an informative and intuitive interface.

Based on all requirements that were mentioned and revised, the user interface was developed to provide all required tools. It can be easily set up and it could use different types of incoming data.

Main window contains three tabs that include data preparation, controls and analyzed data areas (fig. 1).

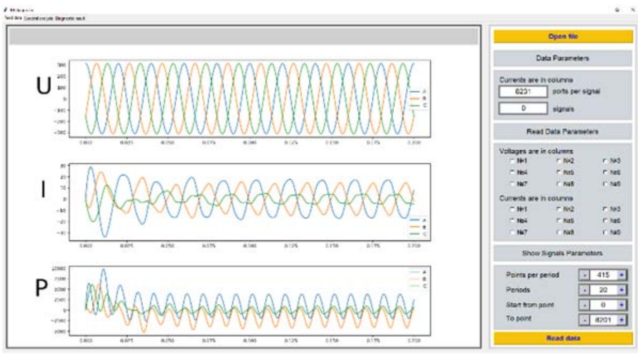


Fig. 1 Read data tab in the user interface

Python provides instruments that allow to process signals and use Fast Fourier Transform which was described previously. On the second page, it was provided spectral analysis results for the current signal that helps to detect broken rotor bars, stator windings short-turns, and damaged bearings (fig. 2).

The third tab contains a block for conclusions that provide a short and informative result of data analysis. According to the aspects that are supervised for each diagnostic, it was created a list of possible issues and recommendations concerning further IM exploitation (fig 3).

Developed user interface and used approaches for breakings diagnosis required testing. For these purposes, it was used an IM simulation model was created in the Matlab environment. The first block simulated and provided needed data files with signals for the motor with rated parameters and nominal mode. Another block provides data for the motor with breakings that were mentioned and were expected to detect. For local tests, it was received arrays of current signals for further processing.

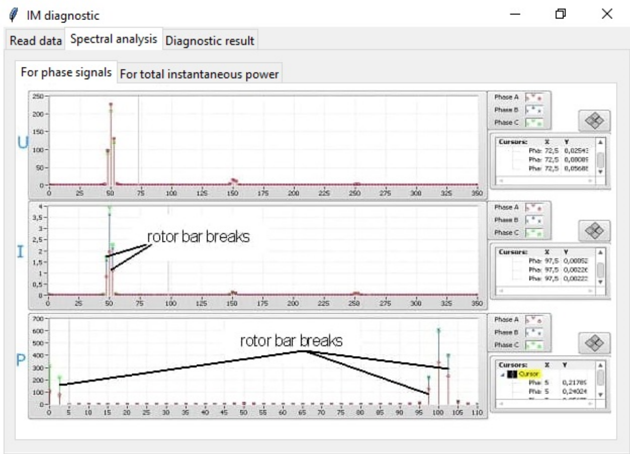


Fig. 2 Spectral analysis tab

Fig. 3 Diagnosis conclusion tab

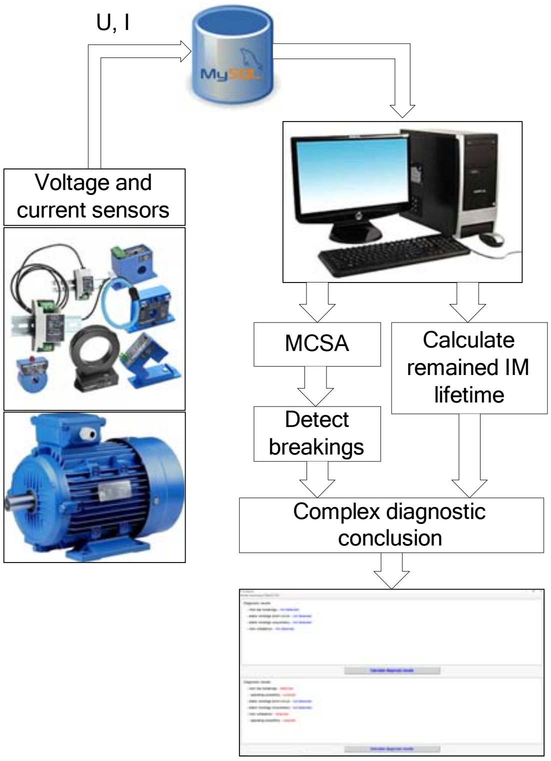
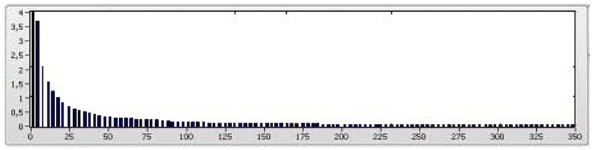


Fig. 4 Diagnosis system schema

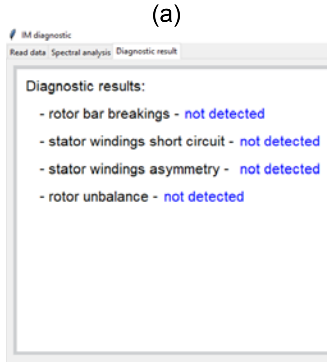
In terms of the production environment for non-intrusive diagnosis required signals should be collected and stored in the database. Remote data processing in this case simplifies the process and demands properly configured sensors (fig. 4). Such system can be effectively used and operated in any production that can provide proper data collection.

Experimental diagnostic

Diagnosis system configuring and setting up is an important step before its actual usage on production. Created for these purposes Matlab model was used to generate the amount of data for different cases of operational modes which included nominal operation mode with rated parameters, deviations in power supply, and breakings that are supposed to be defined by the developed system. Results were received for an induction motor that works with rated parameters and has high-quality power supply. Chart for spectral analysis of one of the phases (fig. 5a) and conclusion on the "Diagnostic result" tab (fig. 5b) are presented.



(a)



(b)

Fig. 5 Diagnostic for IM without breakings

In order to receive data for analysis, we used experimental equipment, which consists of Microchip dsPICDEM MCHV-3 testing board, representing Frequency Converter to feed the motor. This board allows us to implement different motor control algorithm, as well as modify them when needed to enhance IM operability similar to approach described in [11].

To verify developed system with real data it was used laboratory equipment which consists of two identical IM, one of which was used to make loading, and another one, tested motor, was artificially damaged with stator windings asymmetry and rotor bar breaks. Tested motor additionally equipped with current and voltage sensors, torque and speed sensors to control accuracy of provided indirect computations. Appearance of tested equipment is shown in fig. 6.

Conclusion about fault presence is done basing on calculated frequencies related to specific fault types. Comparing harmonics values allows one to define if any deviations are presented.

Spectral analysis chart for the IM with rotor bar break showed peaks at the frequencies where it was expected (fig. 7a). Any time when the breaking was detected, additional message in "Diagnostic result" tab of the user interface will show up to display if repair is required immediately. According to the harmonic value it was evaluated the possibility of IM further exploitation (fig. 7b). For the tested motor where it was artificially simulated breakage of 1 rotor bar the systems show, that damage is not critical for further exploitation. These diagnostics data also feed motor expected lifetime evaluation sub-module which, basing on IM real operational parameters, re-calculates its expected remaining lifetime basing on previously described formulas, and provides recalculated IM maintenance schedule (fig. 8).

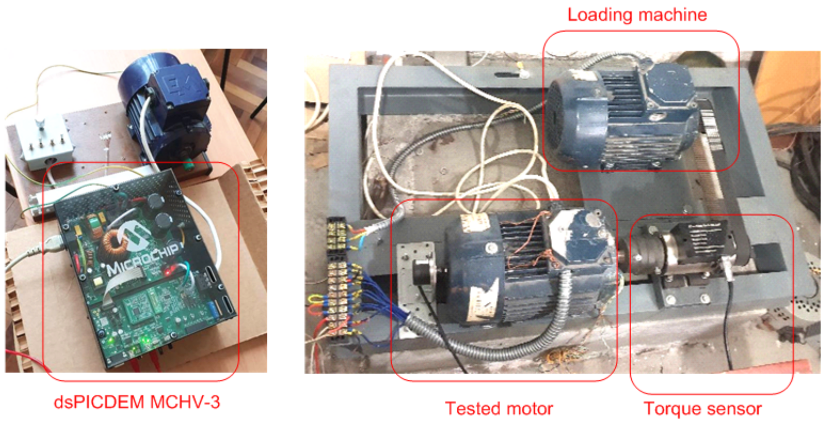
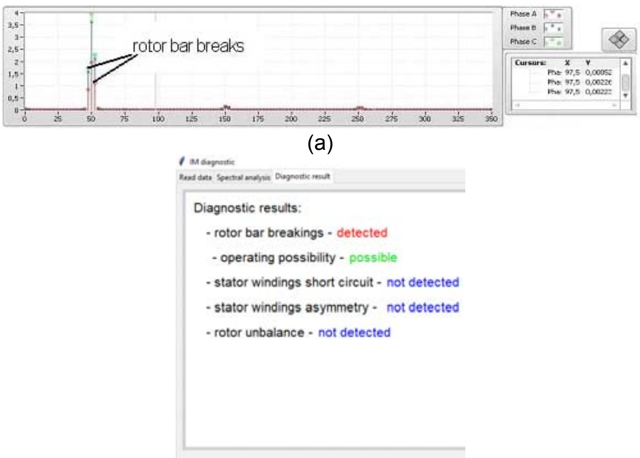


Fig. 6 Laboratory equipment appearance



(a)

(b)

Fig. 7 Diagnostic for IM with the broken rotor bar

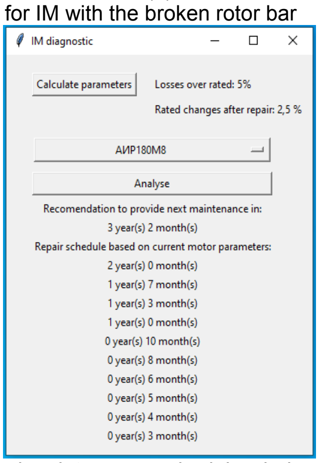


Fig. 8 Recalculated maintenance schedule window

Derived data allows one to consider that diagnostics results are valid and reliable. Conclusions made by algorithm corresponds to breakings that were investigated.

Conclusions

In this work it was the IM monitoring and lifetime estimation system which is based on motor electrical signals analysis was proposed.

The proposed system allows one, basing on the analysis of motor current, voltage, and power consumption signals, provide IM diagnostics, reviling motor real condition, faults presence, degree of fault development.

Basing on reviled fault influence on IM electrical losses increase it was proposed IM remaining lifetime recalculation depending on its real exploitation parameters.

Proposed methods were approbated basing on simulation models and experiments for IM with different degrees of stator faults development and showed the possibility of their implementation to improve motor maintenance.

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