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Intelligent diagnosis of the electrical equipment technical condition
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Abstract

An intelligent method of diagnosing the technical condition of electrical equipment and mechanical devices connected with it is described. The method is based on the combined use of fuzzy logic and neural networks. Fuzzy submodel determines the degree of development of each fault. The neural network determines the state of the object as a whole. The experimental study of the method for the diagnosis of a brushless DC motor and associated equipment at different speeds is presented. It was found that this method allows troubleshooting at any speed. The most informative rate equals half of the maximum. The fault detected in the experiment was confirmed during the inspection of electrical equipment.

Keywords: electrical equipment, diagnostics, fuzzy logic, neural networks, neuro-fuzzy based diagnosis model, supply current

1. Introduction

Electrical equipment is very important link in the country's energy supply and demand, which places special demands on reliability and performance. Operation in poor technical condition of generators, motors, transformers and cable lines leads both to direct financial losses related to unpredictable failure of equipment and a consequent violation of the technological process, and significant indirect unproductive expenses of electricity, due to increased power consumption at the same useful power. Therefore, the actual problem is to ensure reliable and efficient operation of high-voltage electrical equipment. One way to solve this is to control the current condition of the application of methods and means of diagnosis. The main problem of the development of such methods is the large amount of non-

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formalized qualitative information that can’t be used with conventional modeling methods. To solve this problem allows the use of artificial intelligence methods.

2. Intelligent method for diagnosis of electrical equipment

Long operation activity of the electrical equipment at the large reversed loads can produce faults. Therefore it is necessary to supervise periodically the high-voltage electrical equipment inspection done by means of a systematic diagnosing.

One of the most simple and accessible methods of diagnosing is the method of the spectral analysis of stator current signals, as it does not require additional material and time expenses and can be made directly on the working equipment.

The spectral analysis of the stator current signals allows to carry out diagnostics of the electric motor and the mechanical devices connected with it at which during the set time interval the steady-state currents consumed by the motor are recorded as exemplarily shown in Fig 1,a

![Fig. 1. (a) Steady state time series of the current consumed by electrical equipment; (b) frequency spectrum of the electrical equipment](image)

The received data are converted into the frequency domain using the Fourier transformation (refer with: Fig 1,b).

3. The neuro-fuzzy based diagnosis model

Characteristic frequency peaks contain the electrical equipment faults and can be extracted from spectral analysis of the stator current. For the analysis the current signal of a new serviceable motor, which is accepted to be the basic reference standard, is measured once before the long-time exploitation. When faults advance there is a change in the common level and single amplitudes on the characteristic frequencies. The search of faults is carried out by comparison of a currently spectrum with the basic reference spectrum done by means of computational intelligence. Midrange current signal (refer with: Eq. 1), which can be considered as a bias arising from process noise is obtained from all amplitudes of a current spectrum without characteristic frequencies/

where: $a_i$ - current signal amplitude; $i, j$ - frequency indices; $g$ - frequencies of a spectrum interval; $h$ - characteristic frequencies of diagnosing.

The spectrum analysts is restricted to the normalized characteristic frequencies under consideration (refer with: Eq. 2).

$$k_i = \frac{A_i - A_i^0 + \Delta a_{mid}}{a_{mid 0} + A_i^0}$$

where $A_i$ - amplitude of the analyzed spectrum on the $i$-th characteristic frequency; $A_i^0$ - amplitude of a reference spectrum on the $i$-th characteristic frequency; $a_{mid 0}$ - midrange current signal of the reference spectrum;
Δa_{mid} = a_{mid t} - a_{mid 0} - absolute deviation of the midrange current signal; a_{mid t} - midrange current signal of the analyzed spectrum.

If the analyzed spectrum is equal with the reference one then the normalized factor k_i = 0. If a fault occurred then the change of the midrange current signal and amplitude on characteristic frequencies lead to a change of normalized factor [1].

If all normalizing factors are «nearby 0» the object is serviceable. If all normalizing factors are «nearby 1» that the object is corrupt. These data is written down in the form of predicate rules:

\[ IF \ k_i \ is \ B_1 \ and \ \cdot \cdot \cdot \cdot \cdot \cdot \cdot \ k_m \ is \ B_1, \ then \ \chi_i = f_1 \]
\[ IF \ k_i \ is \ B_2 \ and \ \cdot \cdot \cdot \cdot \cdot \cdot \cdot \ k_m \ is \ B_2, \ then \ \chi_i = f_2 \]

where \( k_i \), ..., \( k_m \) – current amplitude on characteristic frequencies; \( B_1, B_2 \) – S and Z shaped functions of sigmoid type (Fig. 2,a); \( \chi_i \) – predicted output fault; \( f_1 \) – conclusion «object is supposed to operation»; \( f_2 \) – conclusion «object is not supposed to operation».

The output is defined by means of an algorithm of the fuzzy logic Takagi-Sugeno [2].

- It is supposed, that the input variables offer some determined values \( k^0_1 \) ... \( k^0_m \) and there are \( \alpha \) - levels of precondition for each of the rules:

\[ \alpha_1 = \min [B_1(k^0_1) ... B_1(k^0_m)] \]
\[ \alpha_2 = \max [B_2(k^0_1) ... B_2(k^0_m)] \]

- For each individual rule the outputs are computed \( x^*_1 = f_1 \) and \( x^*_2 = f_2 \).

- The output of the fuzzy logic system is determined by

\[ x^* = \frac{\alpha_1 \cdot x^*_1 + \alpha_2 \cdot x^*_2}{\alpha_1 + \alpha_2} \]

The simulated results of an exemplarily two-dimensional output surface are referred with: Fig. 2.b.

Similar sub models are involved for making each fault decision, having received a set of current factors of faults progress \( X = \{ x'_i \}, i \in [1, n] \). As a progress of any faults leads to the object refusal an approximating minimum function is chosen. The approximation is carried out by a radial basic network with Gauss functions of activation [3], with displayed target layer linear neuron (refer with: Fig. 3).
Output of the radial neuron (refer with: Eq. 3):

\[ F(x^*_i) = \sum_{i=1}^{N} \rho(\|x^*_i - c_i\|) \]

where \( N \) - the number of neurons in the hidden layer; \( c_i \) - the center vector for neuron \( i \); \( \rho \) - Gaussian; \( \|x^*_i - c_i\| \) - the Euclidean distance.

Outputs of the radial neuron are multiplied by weights vectors of the linear neuron. Weights vectors of the linear neuron are set on an interval \([-1, 1]\) such that maximum \( F(x^*_i) \) corresponded the minimum weight. As training function is the minimum then the output of the linear neuron:

\[ F(x^*) = \min(a_i \cdot F(x^*_i)) \]

where \( a_i \) - are the weights of the linear output neuron.

The received output value allows to estimate a current condition of the object, having carried it to one of the following classes: \( F(x^*) = 1 \) - serviceable; \( 0 < F(x^*) < 1 \) - operative; \( -1 \ll F(x^*) \ll 0 \) - corrupt.

4. Experimental results

The proposed method of diagnosing has been evaluated on the BLDC actuator having the principal structure as depicted in Fig. 4.

Rotary motion of the BLDC motor is transferred through the coupling of the reducing gear connected to an actuation mechanism. Current measurement is carried out within a low level BLDC control, therefore using a spectrum current it is possible to determine only the technical condition for BLDC with the full load which is directly connected with it. Reducing gear is a constant passive load and there is no variable influence on a frequency spectrum of the current consumed by the motor. In Fig. 5, the basic typical faults of the BLDC motor and their characteristic frequencies are summarized.
Time series of the consumed current of the motor are recorded at frequencies of rotation 1, 10, 15, 20, 25 and 30 Hz. Two types of equivalent measurement were performed, once with a priorly faultless coupling, and once with a damaged coupling that exhibits a side crack. The collected data is converted by fast Fourier transformation to the frequency domain and scanned by the aforementioned method. Results of diagnosing at various frequencies of rotation of the BLDC motor are referred with Table 1.

**Table 1. Value of diagnosing function at various frequencies of rotation of the motor**

<table>
<thead>
<tr>
<th>Fault type</th>
<th>1</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commutation faults</td>
<td>0.5</td>
<td>0.6324</td>
<td>0.9398</td>
<td>0.5</td>
<td>0.5</td>
<td>0.9470</td>
</tr>
<tr>
<td>Rotor faults</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Voltage ripples</td>
<td>0.0011</td>
<td>0.7964</td>
<td>1</td>
<td>0.5</td>
<td>0.4984</td>
<td>0.5154</td>
</tr>
<tr>
<td>Coupling faults</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-0.1354</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Stator faults</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.9753</td>
<td>0.7871</td>
</tr>
</tbody>
</table>

Results of the diagnosing testifies the coupling fault. From the Tab. 4 it is visible, that to the same faults on various frequencies of rotation there are corresponding various values of diagnosis function. For an establishment of the reasons of these divergences it is necessary to carry out the analysis of amplitudes on characteristic frequencies of diagnosing. The characteristic frequencies given allows to make the following classification (Figure 7). From the listed classification follows, that all characteristic frequencies are the natural either of the rotation frequency or of the power line frequency. The commutation and coupling faults have identical characteristic frequencies. Therefore the values of dividing functions for commutation fault are decreased.

The reason for decrease of the dividing functions at 1 Hz frequency is a noise by the switching of the windings of the motor [1].

Voltage ripples are shown on 1., 2., and 3. harmonics of a power line (50, 100, 150 Hz). Low stator faults variations detect are shown on the second harmonic of the frequency of a power line (100 Hz). Characteristic frequencies of diagnosing of other faults are harmonics of the frequency motor rotation. Commutation faults are

\[
\text{Characteristic frequencies of diagnosing}
\]

- **Harmonics of frequency of rotation**
  - Commutation faults: \(2 \cdot k \cdot p \cdot f_r\), \(k \cdot f_r\)
  - Rotor faults: \(2 \cdot p \cdot f_r\), \(k \cdot f_r \pm 2 \cdot p \cdot f_r\)

- **Harmonics of frequency of a power line**
  - Voltage ripples: \(k \cdot f_s\)
  - Stator faults: \(2 \cdot f_s\)

where \(f_s\) - frequency of power supply for the rectifier, Hz;

\(f_r\) - rotation frequency of the motor, Hz;

\(k = 1, 2, 3\) - current harmonic number;

\(p\) - number of poles.

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Fig 5. Classification of characteristic frequencies of diagnosing
shown on 1 - 4, 8 and 12, rotor defect - on 4, 5, 6 and 7, coupling defects - on 1, 2 and 3 harmonics of frequency of rotation (refer with: table 2).

<table>
<thead>
<tr>
<th>Number of a harmonic of frequency of rotation</th>
<th>Frequency of rotation of the motor, Hz / frequency of a power line, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 10 15 20 25 30</td>
</tr>
<tr>
<td>2</td>
<td>2 20 30 40 50 60</td>
</tr>
<tr>
<td>3</td>
<td>3 40 60 80 100/100 120</td>
</tr>
<tr>
<td>4</td>
<td>4 50/50 75 100/100 125 150/150</td>
</tr>
<tr>
<td>5</td>
<td>5 105 140 175 210</td>
</tr>
<tr>
<td>6</td>
<td>6 60 90 120 150/150 180</td>
</tr>
<tr>
<td>7</td>
<td>7 70 105 140 175 210</td>
</tr>
<tr>
<td>8</td>
<td>8 80 120 160 200 240</td>
</tr>
<tr>
<td>12</td>
<td>12 120 180 240 300 360</td>
</tr>
</tbody>
</table>

From the Tab. 2 it is visible, that at the fifth harmonics of frequencies of rotation 10, 20 and 30 Hz are equivalents with the first, second or third harmonics of frequency of the power line. It is a reason by decrease in value of dividing function for voltage ripples and rotor faults on the frequency 20 Hz.

The fact, that the values of dividing function for «coupling fault » are larger than -1 can be explained by the oscillation damping of the second and third harmonics rotation, which be balanced out by increase on the 4 and 6 harmonics of rotation.

The imposing of three harmonics of a power line on 2, 4 and 6 harmonics of rotation on the frequency 25 Hz are decreased of the second and sixth and increase of the fourth and eighth harmonics of frequency of rotation. Decrease in the values of dividing function «stator faults» at 30 Hz is characterized by increase on the second harmonic of the power line which compensates at the fifth harmonic of rotation and at the second harmonic of the power line.

5. Conclusions

The neuro-fuzzy method of diagnosing BLDC motor on a current spectrum is described.

The analysis of initial data has shown, that the spectrum of the current which has been removed on low frequencies of rotation (1 Hz), has a large noise contribution which hinder to analyses properly the characteristical fault frequencies. In the current spectrum which has been obtained on frequencies 10, 20, 25 and 30 Hz there is an impose of harmonics of a power line and rotation that can give an uncertain information about a currently technical condition of the motor. The most informative spectrum is obtained on the frequency of rotation of 15 Hz at which there are marginal imposing harmonics.

The described neuro-fuzzy method of diagnosing allows to determine the technical drive condition, using the current spectrum of the steady-state drive, from which the normalized characteristical values are determined. The latest ones constitute an adequate input for the applied neuro-fuzzy method.

References