The diagnostic classifier of the squirrel-cage induction motors with a minimal number of diagnostic premises

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Abstract. The problems of control and identification of failures of units that have a different degree of technological advancement are still important tasks to be addressed. A description of the dependence of complex production systems, regarding to the prediction of their faults and their consequences is also an important issue. The definition of state classifiers and the algorithm used for the graph searching are presented. A modified algorithm used in its principle to the needs of a solution of the stated problem leads to obtaining a path with the most probable states, defined on the basis of ordered series of relations (structural, reliability and failures forms). Assumed form of functional relationships of constituent components of distributed mechatronic systems allows for simplifying also the prediction process. The described advantages result from usage of computer algorithms (allowing for a mapping of the path identifying consequences of successive failures) and possibilities of representation of machines on different complexity levels (systems, subsystems, components etc.).

1. Introduction
Monitoring and technical diagnostics [2,9] constitute inseparable elements of different maintenance strategies of machinery and production processes. However these concepts should not be treated as mutually replacing themselves techniques of the Operations and Maintenance (O&M) [11]. The maintenance programmes may be divided into three main groups depending on the adopted supervision method [10]:

- unsupervised [3,9] - device (or process) is not repaired until the breakdown (such proceeding extends a total time of overhauls about the periods of spare parts delivery, generates additional costs related with a storage of spare parts or requires good distribution networks),
- with the diagnostic supervision - monitoring should be adopted to the values of significant symptoms according to a specified schedule [12]; based on the current value the decision is made (a tuning, repairs or a replacement of components) [14,16,17],
- an integrated supervision and prediction [5,6,7] - recording the values of selected symptoms, forecasting times to failures, and the simultaneous validation of an impact of current states at the development of quantitative and qualitative defects or wear.

Assumptions regarding diagnosis and forecasting of technical systems (based on the minimum set of diagnostic premises) presented in this article require the analysis of main failures of mechatronic drives.
2. Identification of main failures of AC electric drives

Mechatronic drives belong to devices with a high reliability of operation [16]. Despite these features, there are many failures arising from interference with driven equipment. Failures of electric drives may result from many root causes [17], which can include improper installation and exploitation, mechanical or electrical damages, hardware errors or improper configuration parameters of control subsystems (figure 1).

The main faults appearing in the assembly phase are inaccuracies of shaft alignment between a motor and a driven unit, unbalance of driven machines, incorrect foundation, loose fasteners (inducing for example a soft foot effect, bending of feet or their breakage), damages due to use of inappropriate tools or installation techniques.

Operational errors may be summarized in the following groups excessive load of the drive, dynamic overload (e.g. too short times of acceleration and deceleration, high or too low working...
speed), bending of shafts manifested by excessive wear of bearings, excessive service life of the bearings. Among the electrical faults dominate short circuits (leading to failures or destruction of components of electric motors), lowering the power voltage or voltage sags [17]. The main causes of short circuits are insulation faults (caused by mechanical damage, effects of electrical stresses or temperature increase) [15]. Due to presented assumptions, a classifier with three numerical parameters has been identified:
- characteristic frequency values (identification of defect source),
- amplitude values (determining the threshold of classification into the group of full proper or improper functioning),
- temperature value (an additional significant symptom of condition deterioration).

3. The overall form of the operational state classifier
The applied classifier include strict criteria used for identification of states of mechatronic drives. The overall form of a classifier can be presented as:

\[ C_{OS} = \langle O, A, V_s, f_C \rangle \]  \hspace{1cm} (1)

where: 
- \( O \) - a finite set of objects,
- \( A \) - a finite set of attributes, \( V_s = \bigcup_{a \in A} V_a \) - set of attribute values, \( V_a \) - domain of the “V” attribute, \( f_C \) - the decision function, defined within the following rules:

\[ f: O \times A \rightarrow \delta(V_s), \text{ where: } V_{o \in O} f(o, a) \in V_a \]  \hspace{1cm} (2)

Monitoring of the temperature and vibrations leads to obtaining the diagnostic symptoms on the basis of which it is possible to identify even electric malfunctions of motors (even in the early stages of development). As an example the bearing classifier has been presented. Characteristic frequencies of piece parts of rolling bearings can be identified on the basis of the characteristic frequencies of fundamental train frequency (FTF), ball pass frequency of the outer race (BPFO), ball pass frequency of the inner race (BPFI) and ball spin frequency (BSF) [14]. Determination of the characteristic parameters (FTF, BPFO, BPFI, BSF) combined with the range of acceptable amplitude values (\( V_{FTF}, V_{BPFO}, V_{BPFI}, V_{BSF} \)) and RMS value (Root Mean Square) allows for specifying conditions of the decision function. Therefore, the adopted classifier (based on the FFT spectrum) can be obtained as the following formula:

\[ C_{OS} = \langle E_M, \langle V_{FTF, Val}, V_{BPFO, Val}, V_{BPFI, Val}, V_{BSF, Val}, T_{M, Val} \rangle, ... \rangle \]  \hspace{1cm} (3)

where: 
- \( E_M \) - tested electric drive, \( V_{FTF, Val}, V_{BPFO, Val}, V_{BPFI, Val}, V_{BSF, Val} \) - data registers of fundamental train frequency, ball pass frequency of the outer race, ball pass frequency of the inner race, ball spin frequency, respectively, [m/s], \( V_{FTF}, V_{BPFO}, V_{BPFI}, V_{BSF} \) - peak values of speed in case of fundamental train frequency, ball pass frequency of the outer race, ball pass frequency of the inner race, ball spin frequency, respectively, [m/s], \( T_M \) - temperature value [°C].
The decision function $f_C$ may be presented as:

$$
\begin{align*}
V_{\text{Peak}_\text{FTF}} &< V_{\text{Peak,Max}_\text{FTF}}, \\
V_{\text{Peak}_\text{BFPO}} &< V_{\text{Peak,Max}_\text{BFPO}}, \\
V_{\text{Peak}_\text{BFPI}} &< V_{\text{Peak,Max}_\text{BFPI}}, \\
V_{\text{Peak}_\text{BSF}} &< V_{\text{Peak,Max}_\text{BSF}}, \\
V_{T_{\text{Min}}} &< T_{M} < V_{T_{\text{Max}}}, \\
\end{align*}
$$

where: $V_{\text{Peak,Max}_\text{FTF}}$, $V_{\text{Peak,Max}_\text{BFPO}}$, $V_{\text{Peak,Max}_\text{BFPI}}$, $V_{\text{Peak,Max}_\text{BSF}}$ - constant numerical value of maximum threshold of allowable vibration amplitudes regarding to bearing components, respectively, $V_{T_{\text{Min}}}$, $V_{T_{\text{Max}}}$ - maximum and minimum values of temperature measured on the housing, respectively.

In the similar way, other damages or detuning of the drive system are classified (including misalignment, imbalance, mechanical and electrical damage of rotors and stators). After determination of the current state and transformation of initial values to the operational state, the modified algorithm reconstruct the set of possible future states.

4. The notation of cause-and-effects relations using a directed graph and the principle of operation of the algorithm used to identify the operational and future states

The causes-and-effects graph is defined as a collection of failures related to their consequences dependent on an individual structure defined by the user of the mechatronic drive system. It should be noted that in the scope of the same technical agent (taking into account the context of diversified applications) defined structure of the causes and effects graph may not take diverse forms (despite influence of improper mounting, environmental conditions and other factors). The figure 2 presents the section of the overall graph of causes and effects, containing significant symptoms and faults of squirrel-cage induction motors, with conditions corresponding to damages of the drive bearings.

![Figure 2](image_url)
Each of the vertexes of the graph is uniquely defined by the state classifier and values measured from the drive system. The defined graph is universal (in the squirrel cage induction motors domain), but weights may vary depending on the application of specific drives (even within the different branches of one plant). A simplified graph of causes and effects was developed in accordance with the following assumptions: identification of the vertex (diagnosis - the current operational state) is performed on the basis of the classifiers (set of dependences between identified rules) and expertise (classification rules), graph belongs to the group of simple graphs [4], simplifying the structure was made within assumption of using the minimum set of symptoms that identify critical failures or detuning of the electric motor (the requirement related to the necessity of disturbance prevention of the control unit which performs also a function of diagnostic data processing system). For the purpose of the conditions prediction based on the current state the Single-Source Shortest Path method has been chosen. For matching of the Dijkstra’s algorithm to requirements the author has made assumptions in the following form [1,8,13]:

- changes of edge weights in the directed graph, within the equation:
  \[
  S_{\text{EMP}(i,j)} = 1 - \frac{p(i,j)}{w}
  \]
  where: \( S_{\text{EMP}(i,j)} \) - the weight of the edge coming from vertexes i to j, \( p(i,j) \) - value defines the number of damage or failure (i.e. state transitions from the i and to the j), \( w \) - total number of failures or damages assigned to all edges out coming from the analysed vertex.

- checking of the sum of weights probabilities of incoming and outgoing edges of the considered vertex, according to the relationship (where n is a number of outgoing edges from the considered vertex):
  \[
  \sum_{n=1}^{n} \text{EMP}(i,j) = 1
  \]

- reduction of the search depth up to the level of nearest neighbours, then setting a new source vertex,

- an implementation of the function connected with an estimation of a transition probabilities (from source to sink vertexes), with the usage of a product function of the edge weights connecting considered vertexes.

Periodic verification of the states classifier within the range of the devices for monitoring the physical layer containing electric motors allows to specify changes in the operation of the considered system. An identification of the next stage of a damage can be reduced to the designation of a neighbourhood list of vertexes, assuming the analysis takes into account the weights of the edges. Result of the graph searching (in the form of a sink vertex) is unknown but its finding is the main task of the algorithm. In addition, the method is a response to the need of the use of the prediction-oriented expertise, without fitting statistical hypotheses to specific aspects of course of work of mechatronic devices. Presented modification of the Dijkstra algorithm assumes a resignation from a phase of determination of the path characterized by the minimum sum of the weights between source and sink vertexes, in favour of the probability analysis (reliability or unreliability functions) of adjacent vertexes up to further determination of the failures path.

In case of the presented example, a depth of the search was limited to two iterations. The realization of functioning of the modified algorithm leads to the designation of a state (represented by the graph vertexes) responsible for the further development of errors, failures or detuning of the analysed system. Enumerated qualities do not constitute restrictions of the presented method, but rather advantages (the matching ability the nature of the work to suit individual conditions and disturbances affecting a system during tasks execution).
5. Conclusions
The proposed diagnostic and prediction system (based on digraphs methods) allows description of different types of systems due to the universal form related to defined structural components (functional description), subsystems, and the overall system definition. Difficulties in selection of statistical hypothesis to the concrete machine or process, data handling, and results interpretation lead to the conclusion that the statistical methods are rather difficult for the practical implementation or in many cases practically unfeasible. But in many cases sufficient amount of information can be derived as a result of utilization of the expert knowledge. A description and a searching of the following states is based on the grounds of simple relationships between the signals (for example, definition of the threshold temperature above which the system identify an abnormality or the total system failure). Periodic verification of the vector states within the range of the devices for monitoring the physical layer containing electric motors allows to specify changes in the operation of the considered system. The author's aim is to implement described method with usage of PLC controllers [18], what will allow for implementing the method to the operation and control of distributed systems (electric drive motors controlled with the aid of inverters).

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