Open-Circuit Fault Diagnosis Problem In Two-Level Voltage Inverter-Fed AC Drives

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Abstract

In this paper a transistor open-circuit fault diagnosis problem in two-level voltage inverter-fed AC drives was discussed. Taking into consideration requirements of the contemporary monitoring drive systems two original transistor fault diagnostic techniques were proposed and compared with each other. Presented results were obtained by designed in MATLAB/Simulink software simulation model of the direct field oriented controlled induction motor drive.

1. Introduction

For many years vector controlled AC motor drives, due to their high performance have been commonly used in industrial applications. Despite the fact that these systems, especially based on squirrel cage induction machines, are consider as high reliable, they still suffer several faults, among others, transistor open- and short-circuit faults in the inverter [1]. Subsequent to these faults the drive performance could be significantly decreased, possibly the motor operation could be interrupted [2]. For this reason, for several years switch fault detection techniques as well as fault-tolerant control strategies have been expanded thereby an appropriate maintenance of the drive system can be achieved under the failure condition as well.

The classification method for open-switch fault diagnosis is based on the analysis of easily accessible signals, namely current or voltage [3]. In papers [2]-[7] the voltage-based approaches were presented. Some of them require additional measurements systems for diagnostic procedure, which strongly increase the implementation cost of the drive, therefore theirs real application are rather limited. For instance, in the paper [4] four diagnostic methods based on a comparison between measured inverter voltages and their expected references were suggested. This publication was the basis for few further works considering „death time” influence on effectiveness of the diagnostic procedure, e.g. [3, 5, 6]. In the paper [3] the switch failure detection procedure is based on errors between the phase reference voltages and the estimated ones, which are calculated on the basis of pole voltage measurements. To localize the faulty switch the mentioned voltage errors must be monitored, taking into account the location of the reference voltage vector on the α-β plane. As a consequence of previously described methods the technique presented in [7] utilizes an average values of the errors between reference and the estimated voltages, which can be calculated from a current based flux estimator. Compared to the mentioned strategies this solutions requires no additional hardware, namely voltage sensors. As prove the subsequent inverter fault diagnostic system examples, it is possible to abandon a demand to utilize more sensors than in case of the classical drive control structures, like DTC (Direct Torque Control) or FOC (Field Oriented Control). For instance in the paper [8] an observer based transistor fault monitoring system was proposed.

Further, accordingly to the previously assumed classification of the inverter diagnosis methods a majority of the current based techniques can be also classified as no additional sensor demanding algorithms from which the leading ones utilize well known Clark’s and Park’s transformation. These methods has been successfully developed and improved in many works, like [9]-[11]. Accordingly to this approach the diagnostic procedure comes down to the analysis of the current vector hodograph function on the α-β complex plane. Compared to a healthy inverter mode, after the inverter failure depending on a faulty transistor localization, some characteristic parts of the pictures formed with the result of the current vector hodograph disappear. This observation constitutes a basis for the further current phase signals processing, which can be realized in a more or less complicated way. The main problem for this group of diagnostic systems is tendency to false diagnosis under transient states of the drive, namely load or speed reference variations. Undesirable a so-called „false alarms” phenomenon can be overcome with artificial intelligence methods applications, like based on the fuzzy logic [11] or artificial neural network systems.
Another way to achieve a high quality inverter failure monitoring system is a diagnostic signal normalization [7].

Nevertheless, from an industrial point of view a real application of the high computationally demanding inverter diagnostic methods are acceptable only if they are able to assure not only an effectiveness in wide range of the drive conditions but also a possibly fast failure device identification, namely no longer than one current period.

The aim of this paper is to compare two original open-switch fault diagnostic algorithms in two-level voltage inverter-fed direct field oriented controlled induction motor drive. The first proposed technique is based on reference voltage signals but the second one relay on an utilization of the rotor flux current based simulator. In the first case, the inverter failures extraction procedure is carried out by using simple arithmetic calculations, but in the second algorithm a fuzzy logic based solution is proposed. The presented results were obtain by simulations in MATLAB/Simulink software.

2. Inverter fault diagnostic methods

The scheme of the two-level voltage source inverter topology, whose failures are taken into consideration in this paper, is shown in Figure 1a.

![Fig.1. Standard three-phase voltage source inverter topology (a) and the interpretation of its voltage space vectors (b).](image-url)

In the following sections of this chapter two original open-transistor faults diagnostic procedures are formulated.

2.1 Sector and Normalized Presence Time of the Reference Voltage Vector

The method of the Sector and Normalized Presence Time of the Reference Voltage Vector (SNPTRVV) relies on a monitoring the normalized reference voltage vector \( V_s \) presence time \( t_{th} \) in specific sectors of the complex \( \alpha-\beta \) plane. As can be seen in Figure 1b, these sectors’ borders are determined by available in two-level voltage inverter (Fig.1a) six active voltage vectors \( (V_{1}, \ldots, V_{6}) \) and they can be described by an angle \( \gamma_s \) accordingly to the Table 1. These active vectors as well as so cold „zero vectors” \( (V_{0} \) and \( V_{6} \)) are created by appropriate inverter switch command signals. For instance, in order to achieve \( V_{1} \) the logic inverter reference signal sequence 1, 0, 0 is applied, that means only T1, T6 and T2 transistors are able to conduct the current. In an accordance with the modulation technique, the average reference voltage vector \( V_{ref} \) can be obtained by applying the adjoining voltage vectors during calculated time, depending on modulation technique.

<table>
<thead>
<tr>
<th>Sector's number</th>
<th>Area of the ( \alpha-\beta ) plane defined by ( \gamma_s ) [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>((0, \pi/3))</td>
</tr>
<tr>
<td>II</td>
<td>((\pi/3, 2\pi/3))</td>
</tr>
<tr>
<td>III</td>
<td>((2\pi/3, \pi))</td>
</tr>
<tr>
<td>IV</td>
<td>((\pi, 4\pi/3))</td>
</tr>
<tr>
<td>V</td>
<td>((4\pi/3, 5\pi/3))</td>
</tr>
<tr>
<td>VI</td>
<td>((5\pi/3, 2\pi))</td>
</tr>
</tbody>
</table>

As a result of the transistor faults, some from the mentioned voltage vectors cannot be achieved, therefore rotational movement of the reference voltage vectors is slower in those sectors which are indicated by previously mentioned unavailable inverter states (unavailable voltage vectors). Taking into account this observation and the actual angular motor speed direction, the diagnostic method rules were formulated and described in Table 2.

<table>
<thead>
<tr>
<th>Faulted switch</th>
<th>Motor drive speed direction</th>
<th>Characteristic sector of the ( \alpha-0 ) plane (longer time-period of the voltage ( V_{ref} ) presence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>( \omega &gt; 0 )</td>
<td>sector I</td>
</tr>
<tr>
<td>T2</td>
<td>( \omega &lt; 0 )</td>
<td>sector VI</td>
</tr>
<tr>
<td>T3</td>
<td>( \omega &gt; 0 )</td>
<td>sector II</td>
</tr>
<tr>
<td>T4</td>
<td>( \omega &lt; 0 )</td>
<td>sector IV</td>
</tr>
<tr>
<td>T5</td>
<td>( \omega &gt; 0 )</td>
<td>sector V</td>
</tr>
<tr>
<td>T6</td>
<td>( \omega &lt; 0 )</td>
<td>sector VI</td>
</tr>
</tbody>
</table>

To improve the robustness of the proposed method to false alarms, the diagnostic signal \( I_{th} \) has to be normalized, according to (1):

\[
I_{th_{norm}} = \frac{I_{th}}{a \cdot \omega_{b}}
\]

where:

\( I_{th_{norm}} \) — normalized diagnostic signal,
\( \omega_{b} \) — angular velocity of the drive,
\( a, b \) — parameters dependent on utilized sampling period of a time \( I_{th} \) measurement system.

An implementation of the proposed algorithm can be realized on basis of the block diagram presented in Figure 2.
where:

\[ T_N = \frac{1}{2f_{\text{in}}} \cdot f_{\text{in}} \]

- \( f_{\text{in}} \) - nominal frequency;
- \( r \) - normalized rotor resistance,
- \( \infty \) - normalized rotor reactance, \( \infty_M \) - normalized mutual reactance, \( i_{\alpha} \cdot i_{\beta} \) = \( \alpha \cdot \beta \) stator current components.

For an explanation of the proposed diagnostic technique, the \( \alpha \cdot \beta \) complex plane was divided between 6 sectors, like in Table 1. Further, in Table 3 the basis diagnostic rules were formulated.

For example, if the minimum of the \( \hat{\psi}_r \) is detected in the sector 1 and simultaneously \( \omega_r > 0 \), the fault of T1 is ascertained (T1r). The rules of the proposed technique could be easily implemented by using the classical arithmetic. Nevertheless, to improve robustness of the proposed method to false diagnosis, some part of this algorithm was realized using artificial intelligence technique. In the first stage of this algorithm, the local minimum or maximum of the rotor flux \( \hat{\psi}_r \) magnitude have to be detected, e.g., by comparing values of the few consecutive \( \psi_r \) samples. Afterwards, it has to be decided whether \( \psi_r \) value related to the extreme deviates from the norm (some threshold has to be specified). For further signal processing a hybrid sequential system based on the fuzzy logic and competitive Petri net was implemented. A scheme of this system is depicted in Figure 3.

Accordingly to the Figure 3, the input signals of the diagnosis system are: \( \gamma_{r \text{ min, \text{max}}} \) - a value of the angle \( \gamma_r \) related to the moment of the \( \psi_r \) local minimum (\( \gamma_{r \text{ min}} \)) or maximum (\( \gamma_{r \text{ max}} \)), \( \beta_{r \text{ min, \text{max}}} \) - parameters of the fuzzy membership functions related to the moment of the \( \psi_r \) local minimum (\( \beta_{r \text{ min}} \)) or maximum (\( \beta_{r \text{ max}} \)), \( \omega_{r \text{ min, \text{max}}} \) - a value of the angular motor speed related to the moment of the \( \psi_r \) local minimum (\( \omega_{r \text{ min}} \)) or maximum (\( \omega_{r \text{ max}} \)). Providing that the deviation of the \( \psi_r \) is detected, the \( \gamma_{r \text{ min, \text{max}}} \) values are analyzed in

\[
\psi_r = \sqrt{\psi_r^{\alpha 2} + \psi_r^{\beta 2}}
\]

\[
\gamma_r = \arctan \left( \frac{\psi_r^\beta}{\psi_r^\alpha} \right)
\]

where the rotor flux \( \alpha \cdot \beta \) components can be obtained by (4) and (5) [13]:

\[
\psi_r^{\alpha} = \frac{1}{T_N} \left[ \sum_{r} \left( x_M i_{\alpha} - \psi_r^{\alpha} \right) - \omega_h \psi_r^{\beta} \right] dt
\]

\[
\psi_r^{\beta} = \frac{1}{T_N} \left[ \sum_{r} \left( x_M i_{\beta} - \psi_r^{\beta} \right) + \omega_h \psi_r^{\alpha} \right] dt
\]
the first fuzzy logic based system stage (Fig.3) whose membership functions parameters \( b_{\text{min, max}} \) accordingly to the \( \omega_{m_{\text{min, max}}} \) were calculated. For the inference process, which is carried out in the second layer, the speed \( \omega_{m_{\text{min, max}}} \) has to be analyzed by using fuzzy logic functions. The scheme and distribution of the system membership functions are presented in Figure 4 and Figure 5.

![Fig.4. Trapezoidal membership functions for \( \gamma_{\text{min, max}} \), set](image)

![Fig.5. Triangular membership functions for \( \omega_{m_{\text{min, max}}} \), set](image)

Depending on a value and a direction of the motor speed all related to \( \gamma_{\text{min, max}} \) membership functions are translated by a vector \( \mu = [b_{\text{min, max}}, 0] \), that means

\[
\mu_{C1}(\gamma_{\text{min, max}}) \rightarrow \mu_{C2}(\gamma_{\text{min, max}} - b_{\text{min, max}}) \quad \text{and} \quad b_{\text{min, max}} \in (-0.07, 0.37).
\]

The second layer of the diagnostic system (Fig.3) consists of inference subsystems for each transistor. As an example, the rules of the T1 monitoring subsystem were presented in Table 4 and Table 5. For the defuzzification process the singleton method was utilized. Accordingly to the Figure 3, the output signals of the diagnostic system second layer are \( T1_a, ..., T6_a \), and they correspond to previously mentioned transistor faults monitoring subsystems. These signals are compared in the third layer which is based on a competitive Petri net realizing a following algorithm (4):

\[
\text{max}[T1_a, ..., T6_a] \quad (4)
\]

This net delivers an information \( T_{n_{\text{fault}}} \) about faulty transistor, where \( n \in \{1, ..., 6\} \).

### 3. Simulation results

The effectiveness of the diagnostic methods was confirmed by simulation model of the direct field oriented controlled induction motor drive, designed in the MATLAB/Simulink software. The power converter was modeled using SimPower System toolbox, which allowed simple fault simulations by applying 0 logic signal on transistor gates permanently.

A following part of this work focuses on the analysis of some simulation results involving the effectiveness and robustness against false alarms of the proposed diagnostic methods. In particular, the times taken to localize the faulty transistor are considered. Additionally, in case of the two algorithms the implementation and tuning effort were compared.

#### 3.1 Robustness against to false alarms

The vast majority of the open-switch fault diagnosis systems require to tune same parameters which have an important influence not only on the speed of the diagnostic algorithm, but also its tendency to false alarms. Therefore, an appropriate analysis of the diagnostic system under critical drive operations should be also considered. In Figure 6 the simulation results of the motor drive operation during fast transients with a very high speed acceleration/deceleration rate approximately up to 1086 rad/s² are presented. Shortly after the start-up the motor obtained the nominal speed \( \omega_m = 60 \text{N} \) (at \( t=0,166 \)). Afterwards, at \( t=0,35 \) s a load step variation from no-load \( m_L=0 \) to full load \( m_L=m_N \) was applied. Next, the motor was braked to zero speed (and then accelerated with nominal load torque \( m_L=m_N \) up to the nominal speed but in its opposite angular direction \( \omega_m=-\omega_N \)). Further, at \( t=1,15 \) s the load torque was rapidly changed from \( m_L=-m_N \) up to \( m_L=m_N \). In Figure 6c the output signals \( f_{D_{\text{SNPTRVV}}} \) of the individual transistor condition monitoring subsystems related to the SNPTRVV method are presented.

### Tab.4.

<table>
<thead>
<tr>
<th>( \omega_{m}&gt;0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_1 )</td>
</tr>
<tr>
<td>( B_2 )</td>
</tr>
<tr>
<td>( B_3 )</td>
</tr>
</tbody>
</table>

### Tab.5.

<table>
<thead>
<tr>
<th>( \omega_{m} \leq 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_1 )</td>
</tr>
<tr>
<td>( B_2 )</td>
</tr>
<tr>
<td>( B_3 )</td>
</tr>
</tbody>
</table>
As can be seen the diagnostic signals reach the highest value $|R_{\text{norm}}|\approx1.51$ during the abrupt motor braking with full load ($t=0.59s$). So due to this fact, the fault threshold $T=1.6$ was constituted for each subsystem referred to all transistor switches.

As previously mentioned, in case of the AVPERFV method the diagnostic signal is the absolute value of the rotor flux vector, which transient is presented in Figure 6d. The deviations of the $\hat{\psi}_r$ are negligible, so that they do not have any impact on the proper diagnosis system operation. The fault thresholds $T_{\text{max}}$ and $T_{\text{min}}$ can be easily assumed as constant values, nevertheless to avoid unforeseen disturbances in this work depending on $\omega_m$ the $T_{\text{min}}$ is changed (Fig.6d). The function $T_{\text{min}}=f(\omega_m)$ was empirically formulated.

### 3.2 Effectiveness

To prove the effectiveness of both diagnostic techniques and the proposed of the diagnosis systems to the correct inverter faults detection and localization ability, some simulation results for different faulty operating conditions of the drive are presented.

Figure 7 presents the results achieved for the nominal motor speed $\omega_N$ and the nominal load torque $m_N$ during T1 fault. In Figure 7a and 7b only the fault indicating signal $|R_{\text{norm}}|$ and absolute value of the estimated rotor flux $\hat{\psi}_r$ are presented.
Furthermore, to rate the speed of the proposed diagnostic methods, the current transient of the faulty inverter phase and the diagnosis systems output signals $T_n$ are shown in Figure 7c and Figure 7d, respectively. In Figure 8 the simulation results regarding to the low speed $\omega_m=0,3 \omega_N$ and the load torque $m_L=0,25 m_N$ are presented similarly.

Comparing the results in Figure 7 and Figure 8, it can be noticed that the detection speed of the SNPTRVV and AVPERFV methods is higher if the fault affects a transistor through which the current flows during the failure moment (Fig.7c). Further, it is seen, that the proposed diagnostic methods guarantee the inverter fault localization time shorter than one current period.

4. Inverter fault diagnostic methods

This paper deals with the open-circuit faults diagnostic methods for a two level voltage inverter-fed in the field oriented controlled induction motor drive. The proposed diagnosis systems do not require additional hardware, so that extra implementation costs can be avoid.

The main ideas of the diagnostic methods, which were proposed in this paper, are relatively simple. Nevertheless, the diagnosis systems implementation can be realized by using less or more computationally demanding and sophisticated mathematical tools. To implement the SNPTRVV method, the simple diagnosis system was design but in case of the AVPERFV method the more sophisticated and computationally demanding solution based on fuzzy logic was utilized. The great advantage of the proposed fuzzy logic system is its intuitive, linguistic scheme, which simplify design process.

The proposed diagnostic methods guarantee the inverter fault localization time shorter than one current period, therefore considering the diagnostic methods survey was presented in the first part of this paper, both proposed techniques meet industrial requirements.

Bibliography


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