FACTOR DIAGNOSIS OF VSI-FED THREE-PHASE INDUCTION MOTOR

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Abstract- This paper aims at developing an efficient tool for the fault diagnosis of VSI-fed 3-phase Induction motor. The considered faults include stator winding faults of the induction motor and open power switch faults in the voltage source inverter. Any single phasing situation creates the stator fault that may result in opening of one or more phase windings. In this work, the induction motor model is modified for analyzing the open circuit fault of the stator phase winding and the current patterns obtained using Park’s Vector Approach are compared. The power switch faults in the converter are analyzed using Normalized Currents Average Values method.

Index Terms- Fault diagnosis, Induction motor, Normalized Current Average Values, Park’s Vector Approach.

I. INTRODUCTION

Induction motor is the most commonly used, robust and fault tolerant motor in industries. The failure of the induction motor may be caused due to many reasons like manufacturing fault, designing fault of the engineer, overloading, environment and poor technical knowledge in handling the machine. It is necessary to diagnose the fault at the preliminary stage. Any fault left without finding at the early stage may lead to large losses in man power, profit and precious time.

For the purpose of detecting motor faults, many diagnostic methods have been developed so far. These methods to identify the faults may involve several different types of fields of science and technology. They can be enumerated as follows [1], [2], [3]:
1. Electromagnetic field monitoring, search coils, coils wound around motor shafts (axial flux-related detection);
2. Temperature measurements;
3. Infrared recognition;
4. Radio-frequency (RF) emissions monitoring;
5. Noise and vibration monitoring;
6. Chemical analysis;
7. Acoustic noise measurements;
8. Zero crossing time method

The above mentioned techniques can be used to detect only one type of fault each. For example, the noise and vibration monitoring technique can be used to detect only bearing and vibration faults; the zero crossing time method can be used to detect only stator faults. Moreover, these methods require sensors to be placed in the machine at the time of construction itself and the location of the sensor determines the area in which it can detect faults. Hence, on-line diagnosis of fault is important. On-line diagnosis refers to the identification of fault while the machine is running, by monitoring the motor current signature [4].

The technique we are proposing in this paper is the Park’s Vector Approach for fault diagnosis. The Park’s Vector approach can be used to detect both stator as well as rotor faults and hence is a better technique than the above mentioned. However, in our paper, only the open circuit stator fault in the motor is analyzed.

Furthermore, for critical applications where fault tolerant systems are highly recommended, temporary remedial actions that allow the system to continue operating under faulty conditions, are also based on real-time diagnostic algorithms. They can be integrated into the drive controller, thus helping to increase the reliability and reduce the negative consequences of unintentional stoppages [5]. Some statistical studies show that about 38% of faults in variable ac speed drives are found in power equipment and 53% in control circuits [6]. Also, a survey regarding the reliability of power electronic converters show that power devices, capacitors and gate control circuits are the most susceptible to faults [7]. Another recent study shows that semiconductor, soldering and printed circuit board failures amount to 60% of the converter system failures [8]. Hence it can be inferred that a very high percentage of failures are due to power switch faults, since a failure in the gate control circuit results in a switch open-circuit fault [9].

Power switch failures can broadly be classified as open-circuit faults and short circuit faults. Typical inverter protection methods include protection against short-circuit or overcurrent, but they do not incorporate open circuit faults. Thus, open-circuit faults can remain undetected for an extended period of time leading to potential secondary faults in the converter [10].
Based on the aforementioned facts, it can be understood that reliable fault diagnostic techniques for open-circuit faults are significant. The current Park’s vector approach can be used as a fault diagnostic tool for inverter faults [11]. Although this approach allows for the visualization of all the possible distinguishable inverter fault modes, it requires very complex pattern recognition algorithms which are not suitable for the integration into the drive controller.

In this paper, a simple diagnostic and detection method is proposed that allows the real time detection and localization of single and multiple open-circuit faults in VSI-fed three phase induction motor, using only the motor phase currents. Simulation results are presented showing the performance of the algorithm under distinct operating conditions.

II. DIAGNOSTIC METHODS DESCRIPTION

A. Park’s Vector Approach

The ac supply applied to the stator terminals are \(V_{as}, V_{bs}, \) and \(V_{cs}\).

\[
\begin{align*}
V_{as} &= V_m \sin \omega t \\
V_{bs} &= V_m \sin(\omega t - 120) \\
V_{cs} &= V_m \sin(\omega t - 240)
\end{align*}
\]

\(V_m\) is the maximum voltage in phases a, b and c of the supply voltage. The phase voltages \(V_{as}, V_{bs}, \) and \(V_{cs}\) are given as inputs to the three phase asynchronous motor model inherently present in MATLAB/SIMULINK.

The Park’s transform allows the representation of the variables of a 3-phase machine through a co-ordinate system with 2 perpendicular axes; direct and quadrature axes. The measured motor phase currents are \(i_{as}, i_{bs}, \) and \(i_{cs}\). These currents are transformed into qdo axis as \(i_{qs}, i_{ds}, \) and \(i_{os}\). The zero sequence current \(i_{os}\) is always zero for a healthy machine [12].

The transformation equations are as follows:

\[
\begin{align*}
i_{qs} &= \frac{1}{\sqrt{2}} i_{bs} - \frac{1}{\sqrt{2}} i_{cs} \\
i_{ds} &= \frac{2}{\sqrt{3}} i_{as} - \frac{1}{\sqrt{6}} i_{bs} - \frac{1}{\sqrt{6}} i_{cs} \\
i_{os} &= (i_{as} + i_{bs} + i_{cs}) / 3
\end{align*}
\]

The Park’s current pattern drawn using the Park’s current vector components, which are obtained from equations (2) and (3), is analyzed.

B. Normalized Currents Average Values Open Transistor Faults:

A schematic of the considered system is shown in Fig. 1. It is primarily composed of a three phase voltage source inverter and an induction motor.

A failure of several transistors leads to deformations in two or three phase currents. In the considered inverter topology, one can identify 39 different failure combinations which permit continued operation of the drive with limited torque production capability. However, the combinations reduce to only 27 faulty modes that can be distinguished from one another based on the current analysis.

The method of the normalized currents average values (NCAV) for inverter open-circuit fault diagnosis was firstly proposed in [13], where the motor phase currents average values were normalized by the corresponding fundamental component value. In this paper, the diagnostic variables are reformulated by using the currents average absolute values as normalizing quantities, thereby providing the capability of multiple fault diagnosis. A block diagram of this algorithm is presented in Fig. 2 [14].

The main diagnostic variables \(r_n\) are obtained from the three motor phase currents \(i_n\) by:

\[
r_n^* = \left\langle W_n \right\rangle \left\langle i_n \right\rangle = \left\langle i_n \right\rangle
\]

where the subscript \(n\) represents the phase symbol (a, b and c), \(\left\langle W_n \right\rangle\) are the near zero variables average values, \(\left\langle i_n \right\rangle\) the motor phase currents average values and \(\left\langle f_n \right\rangle\) are the currents average absolute values.
Fault Diagnosis of VSI-FED Three-Phase Induction Motor

R_n is a measure of robustness against false alarms and is formulated according to the following expression:

\[
R_n = \begin{cases} 
  P & \text{for } r_n > K_r \\
  Z & \text{for } -K_r \leq r_n \leq K_r \\
  N & \text{for } r_n < -K_r
\end{cases}
\]  

where K_r is the threshold value which can be empirically established by taking into account a safety margin for a more robust diagnostic.

The near-zero variables \( w_n \) are used to take advantage of the fact that the output currents in faulty phases have long intervals of near-zero values. Therefore, they are defined by classifying each sample of \( |\tilde{i}_n| \) using the relationship:

\[
w_n = \begin{cases} 
  1, & \text{if } |\tilde{i}_n| \leq K_0 \\
  0, & \text{otherwise}
\end{cases}
\]

where K_0 is a threshold value empirically chosen to be equal to 5% of the motor rated current.

In the case of a double fault in the same inverter leg, the variables \( r_n \) are ill-conditioned since the corresponding value of \( |\tilde{i}_n| \) is close to zero. With the aim to handle with these specific faults, additional auxiliary variables can be defined as:

\[
S_n = \frac{2\langle |\tilde{i}_n| \rangle}{\langle |\tilde{i}_l| \rangle + \langle |\tilde{i}_m| \rangle}
\]

where \( l, m, n \in \{a, b, c\} \) and \( l \neq m \neq n \). A low value of \( S_n \) indicates lack of current flow in phase \( n \).

The fault variables can be formulated according to the following expression:

\[
S_n = \begin{cases} 
  LL & \text{for } \langle i_n \rangle \leq -K_s \\
  L & \text{for } \langle i_n \rangle < 0 \\
  H & \text{for } \langle i_n \rangle > 0 \\
  HH & \text{for } \langle i_n \rangle \geq K_s
\end{cases}
\]

where K_s is the threshold value which can be empirically established by simply analyzing the variables’ behavior for different faulty operating conditions.

The values taken by \( S_n \) allow generating a distinct fault signature which corresponds to a specific faulty operating condition. Taking this into account and considering a typical motor drive system with a voltage source inverter supplying an ac motor (Fig. 1.), the generated fault signatures allow to detect and localize 27 possible combinations of faulty IGBTs, as shown in Table 1.

III. SIMULATION AND RESULTS

A. Park’s Vector
Using Park’s Vector Approach, the healthy condition and motor open-circuit faulty condition of the induction motor are analyzed.

The Park’s Vector approach gives two dimensional representations of three phase currents. The stator three phase quantities can be converted to two phase quantities and the current pattern can be drawn using the Park’s current vector components, \( i_q \) and \( i_d \).

The stator fault is created by the single phasing situation in which any one of the phases is open, so that the phase currents may be unbalanced, indicating the open circuiting fault in the induction motor. The induction motor with stator winding single phasing fault condition is simulated in MATLAB.

From the current pattern of the Park’s Vector, the healthy and faulty conditions of the induction motor are analyzed. The healthy condition of the induction motor is having a circular pattern which is centered at the origin of the coordinates, as shown in Fig. 3. Any faulty condition of the induction motor results in a deviation in the Park’s current pattern. The resulting pattern is an ellipse.

The observed results from the healthy and faulty motors are as follows: The elliptical pattern has an axis length equal to the diameter of the circular pattern obtained in healthy condition. But the angle of the axis of the ellipse is changing as the single phasing occurs in the various phases. The current pattern obtained while single phasing the A-phase, B-phase and C-phase are shown in Fig. 4. When A-phase is open, the ellipse has its axis along the y-axis; when B-phase is open, the axis of the ellipse is shifting 45 degrees in the clockwise direction from the y-axis; when C-phase is open, the axis of the ellipse is shifting 45 degrees in the counter-clockwise direction.
For all the considered operating conditions, the threshold values $K_r$ and $K_s$ were set to be 0.2 and 0.3 respectively. The correct algorithm diagnostic performance is dependent on the correct selection of the threshold values. In a similar way to the majority of the existing open-circuit fault diagnostic techniques, the definition of the threshold values is accomplished by analyzing the diagnostic variables behavior for the healthy case and all faulty modes. These thresholds can be considered universal since they do not depend on the motor rated power, its operating load level and speed.

### Table 1. Diagnosis signatures of faulty switches identification

<table>
<thead>
<tr>
<th>Faulty Switches</th>
<th>$S_a$</th>
<th>$S_b$</th>
<th>$S_c$</th>
<th>$R_a$</th>
<th>$R_b$</th>
<th>$R_c$</th>
</tr>
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<tbody>
<tr>
<td>T1</td>
<td>L</td>
<td>N</td>
<td>Z</td>
<td>Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>H</td>
<td>P</td>
<td>Z</td>
<td>Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>L</td>
<td>Z</td>
<td>N</td>
<td>Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>H</td>
<td>Z</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>L</td>
<td>Z</td>
<td>Z</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>H</td>
<td>Z</td>
<td>Z</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1,T4</td>
<td></td>
<td>P</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3,T6</td>
<td></td>
<td>P</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5,T2</td>
<td></td>
<td>N</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1,T3</td>
<td>L</td>
<td>L</td>
<td>H</td>
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<td>HH</td>
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<td>P</td>
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<tr>
<td>T1,T2</td>
<td>LL</td>
<td>HH</td>
<td>N</td>
<td>Z</td>
<td>P</td>
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</tr>
<tr>
<td>T5,T4</td>
<td>HH</td>
<td>LL</td>
<td>P</td>
<td>Z</td>
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<tr>
<td>T3,T2</td>
<td>LL</td>
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<tr>
<td>T5,T6</td>
<td>HH</td>
<td>LL</td>
<td>Z</td>
<td>P</td>
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</tr>
<tr>
<td>T1,T3,T2</td>
<td>LL</td>
<td>HH</td>
<td>Z</td>
<td>N</td>
<td>N</td>
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</tr>
<tr>
<td>T4,T5,T6</td>
<td>HH</td>
<td>H</td>
<td>LL</td>
<td>P</td>
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<tr>
<td>T1,T5,T6</td>
<td>L</td>
<td>HH</td>
<td>LL</td>
<td>N</td>
<td>N</td>
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</tr>
<tr>
<td>T4,T2,T3</td>
<td>H</td>
<td>LL</td>
<td>HH</td>
<td>N</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>T3,T5,T4</td>
<td>HH</td>
<td>LL</td>
<td>L</td>
<td>N</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>T6,T2,T1</td>
<td>LL</td>
<td>HH</td>
<td>H</td>
<td>P</td>
<td>N</td>
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</tr>
</tbody>
</table>

### Table 2. Induction Motor Parameters

- Nominal power (VA) = 3730
- Rated line voltage (V) = 460
- Supply frequency (Hz) = 60
- No. of pole pairs = 2
- Stator resistance (Ω) = 0.01909
- Rotor resistance (Ω) = 0.01909
- Stator leakage inductance (H) = 0.0397
- Rotor leakage inductance (H) = 0.0397
- Mutual inductance (H) = 1.354
- Inertia (Kgm²) = 0.1
- Friction factor (N.m.s) = 1000
Single IGBT Open-Circuit Fault
The single IGBT open-circuit fault is created by removing the gate signal from IGBT T1. The main diagnostic variables $r_1$, $r_2$, and $r_c$ attain values -0.308, 0.1771 and -0.0506 respectively. From equation (5), $R_4$, $R_5$, and $R_c$ are formulated to be N, Z and Z respectively. Similarly, from equation (8), the fault variable $S_a$ is found to be L by comparing the average value of current in the respective phases with the threshold $K_c$. In this case, fault variables $S_b$, $S_c$ are irrelevant.

Single-Phase Open-Circuit Fault
The single-phase open-circuit fault is created by removing the gate signals from IGBTs T1 and T4. The main diagnostic variables $r_2$, $r_3$, and $r_c$ attain values -0.0157, 0.3554 and -0.3555 respectively. From equation (5), $R_4$, $R_5$, and $R_c$ are formulated to be Z, P and N respectively. The additional auxiliary variable $s_a$ assumes an extremely low value and is computed to be 0.000189 from equation (7). The information provided by the fault variables $s_1$ is irrelevant in this case.

Double power switch Open-Circuit Fault
The double power switch open-circuit fault is created by removing the gate signals from IGBTs T1 and T3. The main diagnostic variables $r_2$, $r_3$, and $r_c$ attain values -0.3265, -0.3809 and 0.0303 respectively. From equation (5), $R_4$, $R_5$, and $R_c$ are formulated to be N, N and Z respectively. Similarly, from equation (8), the fault variables $s_a$, $s_b$, and $s_c$ are found to be L, L and H respectively, by comparing the average values of current in the respective phases with the threshold $K_c$.

Cross Double Fault in two different legs
The cross double fault is created by removing the gate signals from IGBTs T1 and T6. The main diagnostic variables $r_2$, $r_3$, and $r_c$ attain values -0.3077, 0.2764 and -0.0523 respectively. From equation (5), $R_4$, $R_5$, and $R_c$ are formulated to be N, P and Z respectively. Similarly, from equation (8), the fault variables $s_a$ and $s_b$ are found to be LL and HH respectively, by comparing the average values of current in the respective phases with the threshold $K_c$. $S_c$ is irrelevant in this case.

Triple power switch open-circuit Fault
The triple power switch open-circuit fault is created by removing the gate signals from IGBTs T1, T3 and T2. The main diagnostic variables $r_2$ and $r_3$ attain values -0.3358 and -0.3626 respectively. From equation (5), $R_4$ and $R_5$ are formulated to be N and N respectively. $R_c$ is irrelevant in this case. Similarly, from equation (8), the fault variables $s_a$, $s_b$ and $s_c$ are found to be LL, L and HH respectively, by comparing the average values of current in the respective phases with the threshold $K_c$.

CONCLUSION
In this paper, simple real-time fault diagnostic methods to detect open-circuit motor and inverter faults of a VSI-fed three phase induction motor have been presented.

The motor is analyzed for healthy and faulty conditions using the stator current signatures with the help of Park’s Vector Approach. This approach is a powerful method in fault diagnosis of the motor faults in the induction motor. The current pattern obtained gives a clear indication of the presence of an open circuit fault. The advantage of this approach over the others is that it can diagnose incipient faults.

The open power-switch faults in the voltage source inverter are diagnosed using Normalized Currents Average Values (NCAV) method. The fault diagnostic algorithm can be easily integrated into the main control system without great effort. It does not require the use of extra voltage or additional sensors because it incorporates only the motor phase current signals. Thus, subsequent increase of the drive system cost and complexity is avoided. Also, the diagnostic algorithm has other advantages such as the independence against load and speed transients, and a relatively fast diagnosis. The presented simulation results allow successful verification of the proposed diagnostic method effectiveness.

REFERENCES

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