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Introduction on High-Performance Fault Diagnosis in PWM Voltage-Source Inverters for Vector-Controlled Induction Motor Drives

[#1]Rohit Khadse, [#2]Prof S.V. Murkute

[#1]Electrical Department,
[#2]Professor of Electrical Department

PES college of Engineering.
Dr.Babasaheb Ambedkar Marathwada University Aurangabad, Maharashtra, India

ABSTRACT

This paper proposes a simple method for single switch and double switches open-circuit fault diagnosis in pulse width-modulated voltage-source inverters (PWM VSIs) for vector-controlled induction motor drives, which also applies to secondary open-circuit fault diagnosis. According to the phase angle of one phase current, the repetitive operation process of VSI is evenly di-vided into six operating stages by certain rules. At each stage, only three of the six power switches exert a vital influence on this operation and the others make a negligible influence. An open-circuit fault of power switches introduces the repetitive current distortions, whose period is identical to that of the three-phase currents. The current distortions appear at faulty stages and disappear at healthy stages. The stage is determined by recalculating the cur-rent vector rotating angle. The d- and q-axis current repetitive distortions are applied to the detection of faulty switches due to its simplicity and fair robustness, while the faulty stages are used for the identification of faulty switches. The simulations and experiments are carried out and the results show the effectiveness of the proposed method.

Keywords: **Fault diagnosis, induction motor, open-circuit fault, pulse width-modulated voltage-source inverter (PWM VSI), vector control.**

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I. INTRODUCTION

In most industrial and manufacturing processes, the electric drive systems are exposed to overloading and hard environmental conditions, which may lead, in addition to the natural aging process, to many faults essentially related to the induction motor or the inverter. These faults can lead in turn to unpredicted downtime or even huge damages to human life.

Thus, the demand for reliability and maintainability is growing largely, which ha promoted the development of many fault detection and isolation (FDI) methodologies. FDI performs the following three tasks [1]: fault detection; fault identification; and remedial actions, also known as fault isolation. Among these three tasks, the fault detection and identification are considered as a prime

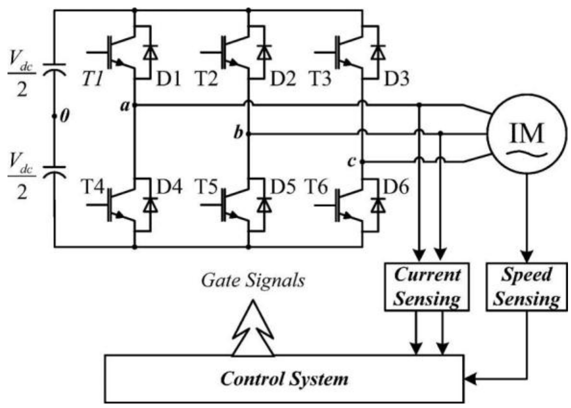

Fig. 1. General configuration of an induction motor drive system.

process for the practical implementation and are often called as fault diagnosis. FDI allows to ensure a safe and continuous operation of the treated system and to guarantee the timely maintenance to the faulty process components.Typically, a motor drive system consists of a microcontroller unit (MCU) for implementing the control algorithms, a power electronic converter such as pulse width-modulated voltage-source inverter (PWM VSI), and an induction motor as shown in Fig. 1. Within the considered drive system, faults may occur in the inverter, dc bus, or in the motor itself. The most common inverter topology used in these systems and also in power quality applications is voltage-source inverter. Taking into account their complexity, these power converters are very susceptible to suffer critical failures. In fact, statistic results show that about 38% of the failures in variable speed ac drives in industry are concentrated in power electronics [2]. More recently, an industry-based survey of reliability in power electronic converters also shows that "semiconductor power device' is the most fragile component, which is followed by "capacitors" and "gate drives" Generally, power device failures in the inverter can be broadly classified as open-circuit faults and short circuit faults. Presently, the power converters designed for industrial use are often equipped with some diagnostic units that enable protection against disturbances and execute a shutdown in case of severe faults to avoid greater damages. Although the protection against power transistor over current or short circuit by monitoring the transistor collector–emitter voltage has become a standard feature for the inverters, the open-circuit failures are often over-looked yet for its characteristic of slow response. This type of fault may result from the disconnection of the semiconductor due to lifting of bonding wires caused by thermic cycling or due to a problem in the gate control signal [4]. This kind of failure does not necessarily cause the system shutdown and can remain undetected for an extended period of time [5]. However, it causes the operating topology imbalance, raises the current pressure of healthy transistors, degrades the performance of the system, and then may lead to a secondary fault in the converter or in the remaining drive components, resulting in the total system shutdown and higher repairing costs, or even personal injury. So this paper presents a simple and effective system approach to the problem of real time detection of the open-circuit faults in inverter switches. Research works have been developed and published in the literature [1] on the subject of open-circuit fault diagnosis in the motor drive systems. The methods based on voltage, such as the error voltage method which compares the actual voltage with voltage command [1], and lower switch volt-age method, where the measurement of the voltages is used, show a fast diagnosis performance and thus reduce the time between the fault occurrence and diagnosis.

diagnosis methods use fuzzy logic to make it effective under current closed-loop condition, but still have so many uncertainties about its utility in practical drive systems for the memberships of fuzzy inference are easily influenced by parameters of environment and motor. The artificial intelligent diagnosis methods based on advanced algorithms such as neural network, wavelet neural network, wavelet fuzzy network, subtractive clustering method, and SVM have also been proposed, but an excessive amount of computation is a major drawback. The authors in detect and identify the faults by incorporating a simple switch control in the conventional method. Recently, model-base, and observer-based methods have been addressed with its high performance of immunity to the load torque and appropriate computation. However, robustness on parameter variation is issued due to nonlinear motor model.

This paper proposes a simple and low-cost fault diagnosis method for open-circuit faults of a vector-controlled induction motor drive. A deep analysis is given into the principle of vector control and thus the relative features in faulty condition are obtained to detect and identify the faults. The proposed scheme is divided into four parts: 1) error calculation; 2) fault detection; 3) stage determination; and 4) fault identification. The error calculation part generates the residual errors between the actual currents and current commands to represent the current distortions in the d–q frame. Then, the d-axis residual error is processed by a series of algorithm to detect the occurrence of the fault. The stage determination part determines the faulty stages by recalculating the current vector rotating angle and the d- and q-axis current distortions. Then, according to a stage-conversion table, the faulty switch is identified. The proposed fault diagnosis is configured without extra hardware equipment and excessive computational effort and thus allows to be em-bedded into an existing vector-controlled induction motor drive system. To test and validate the proposed method, single switch and double switches open-circuit faults are introduced in the VSI for a vector-controlled induction motor drive. Simulation and experimental results are presented to show the validity of the proposed diagnosis method.

II. CHARACTERISTIC ANALYSIS OF THE OPEN-CIRCUIT FAULT IN THE VSI

The ultimate object of vector control is to drive the induction motor as a shunt-wound dc motor, i.e., to control the field excitation and the torque-generating current separately. Fig. 2 shows an ordinary indirect vector control system of an induction motor drive without consideration of flux weakening. The stator currents are first decomposed by coordinate transformation into two synchronously rotating Cartesian vector components id and iq which are controlled independently to control the rotor flux and torque respectively. It can be expressed by the following standard set of equations with d–q axis fixed in the synchronously rotating frame with rotor-flux orientation

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where id and iq denote d- and q-axis rotor currents, ψr is the rotor flux in rotor reference frame, Te stands for the electromagnetic torque, np is the number of pole pairs, Lm and Lr are the magnetizing inductance and rotor self-inductance, respectively, Rr is the rotor resistance, and p is the differential operator d/dt.

The currents id and iq in the d − q frame can be derived from the currents in the α − β frame by the expressions called Park transformation defined as where θ is the rotor flux angle (also called transform angle, generated from the speed signal and slip signal) and the cur-rents iα and iβ in stationary frame are transformed by Clarke transformation defined as where ia , ib , and ic stand for the motor phase currents. It is shown that the vector control is based on projections that transform a three-phase time and speed dependent system into a two-coordinate (d- and q-coordinate) time invariant system. These projections lead to a structure similar to a dc machine control. The vector control machine needs two variables as input references: the torque component (i∗q) and the flux component (i∗d). As vector control is based on projections, the control structure handles the instantaneous electrical quantities. This makes the control accurate in every working operation (steady states and transient) and independent of the limited bandwidth mathematical model. Without consideration of flux weakening, the amplitude of the rotor flux (ψr) is maintained at a fixed value and thus there is a linear relationship between torque and torque component (i∗q). Thereby, the torque can be control by controlling the torque component of stator current vector. With regard to the current, the complex stator current vector is defined by

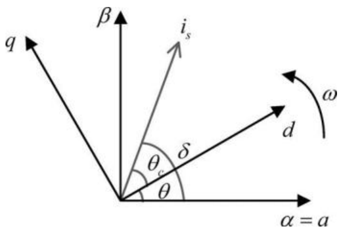

Fig. 2. Current vector in the d − q frame and its relationship with the α − β frame.

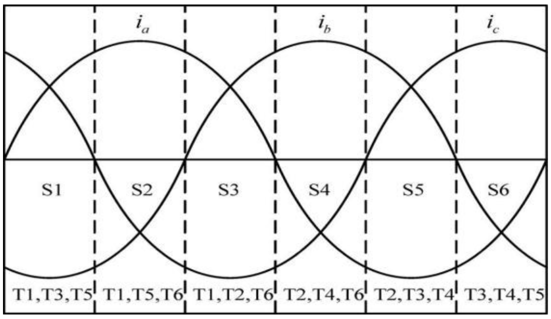

Fig. 3.Three-phase currents distribution in the power switches.

III.PROPOSED APPROACH

The currents in the a–b–c frame are transformed to the d–q frame by using the coordinate transformation of vector control. In normal and healthy condition, the actual d-axis current (id) remain unchanged for it is the flux component of the stator current. It changes only when faults occur. So the d-axis current distortion is used to detect the occurrence of faults When an open-circuit fault occurs, both the d- and q-axis currents change abnormally and show repetitive waveforms. They distort at faulty stages where the faulty power switches make a vital influence and return to normal at healthy stages where the faulty power switches make a negligible influence. The stages can be determined by the current vector rotating angle faults can be identified according to the faulty stages.

A. Error Detection

In healthy condition, the actual currents can track the cur-rent commands. But an open-circuit fault makes the actual cur-rents deviate from the current commands at faulty stages. These current deviations can be considered as "current distortions" induced by the open-circuit fault. Therefore, in healthy conditions, the d-axis current distortion Eid between command i∗d and feedback id is nearly zero and the q-axis current distortion Eiq between command i∗q and feedback iq is also nearly zero when the drive system is in stable state. The d- and q-axis current distortions are expressed by

In order to improve the robustness of the fault diagnosis algorithm, the load torque change and variable speed are taken into consideration for they will also distort the d- and q-axis currents, although the changes of the currents are not repetitive. In healthy condition, when the load torque or the setting speed change, the distortion Eiq does not remain zero for a short time during which the controller is adjusting the drive to make the induction motor work stably. However, in faulty condition, the distortions are zero at healthy stages and nonzero at faulty stages, and thus show the characteristic of periodic variation. So it is easy to distinguish whether the distortions are caused by a change of load and setting speed or open-circuit faults based on the characteristic. In a real situation, since the actual currents are not exactly identical to the corresponding applied current commands, there exist current differences between the commands and feedbacks. Therefore, the threshold value is employed to determine whether the distortions are zero or not and given by

B. Table Improvement

Since the current deviations between the actual currents and the current commands are considered as "current distortions" induced by the open-circuit fault and regulated by the regulators, there is a regulation process at the boundary between faulty stages and healthy stages. The currents distort at faulty stages and return to normal at healthy stages due to the regulation of the regulator. Right after the system crosses the boundary from faulty stages to healthy stages, the current deviations may be still so large that the system may be determined to be still at faulty stages. Then, after a while of the regulation process, the current deviations become small that can be considered as zero, indicating the system is at healthy stages. Thus, in order to avoid the false determination of operating stages, six stages are redefined, noted Stg1 − Stg6 where six longer dashed lines are their boundary in Fig 3 and the conversion table is redesigned as fig 3. Each stage from Stg1 to Stg6 has 60◦ in a sequence fig 3 represents the summary of faulty switches and the defined fault type in a six-stage conversion, where "Addition" denotes the additional requirement shows the flowchart of the proposed fault diagnosis algorithm. The fault diagnosis is accomplished in the following procedures: 1) observation of the currents distortions in the

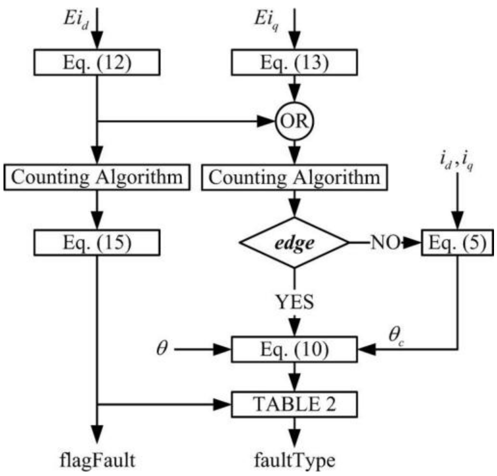

Fig.4 Flow chart of the proposed fault diagnosis Algorithm

When the open-circuit fault occurs to the transistor T 4, the distortions of currents in the d − q frame appear to have large values, and are compared with the selected threshold value as shown in and Then, they are filtered by the counting algorithm expressed in Section III for the detection of the fault and the storage of the rising edge time and the falling edge time. After the fault detection flag f lag Fault is set to high, the faulty stage conversion is determined according to the rising and falling edge time at the recalculated current vector rotating angle and the fault identification fault Type is then easily obtained from Table II.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The simulation in the MATLAB/Simulink environment and the experiment were carried out to verify the feasibility of the proposed fault diagnosis method. A rotor-field-oriented vector control strategy was applied to the inverter in order to control a squirrel-cage motor. open-circuit faults are performed by inhibiting their respective gate signals while keeping the bypass diodes still connected. The proposed approach is represented by the signal flag Fault for fault detection and the signal fault Type for fault identification.

A. Simulation Results

The motor used in the simulation was a 5.5-kW squirrel-cage motor with 380 V rated voltage, 12.5 A rated current and 1430 r/min rated speed. The PWM VSI was running with a switching frequency of 20 kHz. And the parameters (Kd , Kq , kf 1 , and kf 2) of the algorithm are chosen to be 0.5 A, 0.5 A, 0.2, and 0.2 in the tests, respectively.

1) Immunity to an Abrupt Change of Load Torque and Set-ting Speed: Fig. 5 shows the time-domain waveforms of the motor speed and three-phase currents together with the diagnos-tic signals in case of a change of load torque (all transistors are healthy in this test). In this evaluation, by introducing an abrupt change of the load torque from no-load to rated load at t = 0.4 s

2) Faults Diagnosis: A single transistor open-circuit fault corresponding to T 4 is shown in Fig. 5, which presents the simulation waveforms of three-phase currents, the motor speed and the diagnostic signals. When the fault occurs at t = 0.5 s, the characteristic variable Eid stays at zero until the distortions come. Then, the fault detection flag flag Fault is set from low to high at t = 0.5145 s according to the value of filtered Eid and the fault identification is started to identify the faulty switch. the rising edge and falling edge of boolEi are obtained and

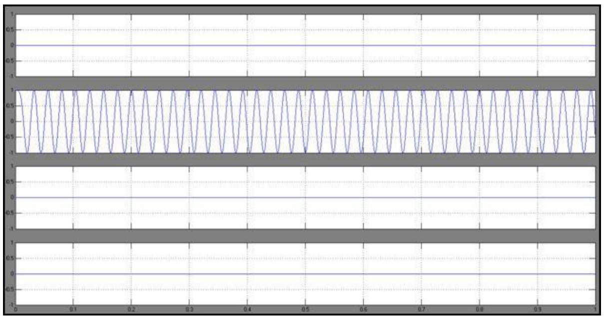

Fig. 5. Simulation results of the fault diagnosis in case of an abrupt change of load torque

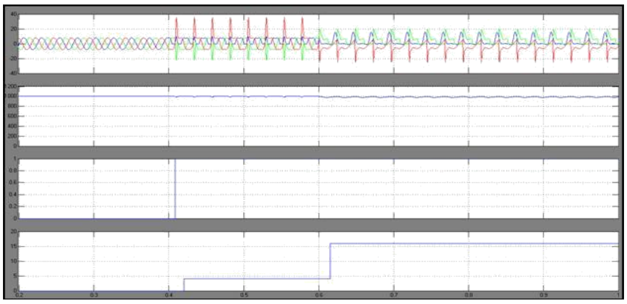

Fig.6. Simulation results of the fault diagnosis when T5 fails after T4

V. CONCLUSION

A simple method for single switch and double switches open circuit fault diagnosis in PWM VSIs for vector-controlled induction motor drives has been proposed in this paper based on fuzzy logic controller. This method uses just as inputs the three-phase currents which are already available for the main control system, avoiding the use of extra sensors and the subsequent increase of the system complexity and costs. Comparing with and show that the proposed method has good performance and practical value.

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