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A Real Time High Performance Open Circuit Switch Fault Diagnosis for Vector Controlled VSI fed Induction Motor Drive

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ABSTRACT: Electric machines are key element in many electrical systems. Induction motors are used as standard in many industrial applications. A growing number of induction motors operates in variable speed drives where it is not directly connected to the power grid, but supplied by an inverter. These power converters are very susceptible to suffer from critical failures. Monitoring and failure detection improves the reliability and availability of an existing system. Here, a fast, real time, fair robust and 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 is proposed. According to the phase angle of one phase current, the repetitive operation process of VSI is evenly divided 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 current vector rotating angle. The stage determination part determines the faulty stages by recalculating the current vector rotating angle and the d- and q-axis current distortions. 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 simulation results shows the effectiveness of the proposed method. The simulation results are verified by MATLAB/SIMULINK.

KEYWORDS: Fault diagnosis, Open Circuit switch fault, voltage source inverter, induction motor, vector control

I.INTRODUCTION

The Induction motors are world widely used as “workhorses” in many of the industrial applications. This may be due to its rigid structure, good self starting property, reliability, low maintenance cost etc. In most of the cases, these are not directly fed from the supply, but instead fed through a inverter. Voltage source inverters, where the ac output voltage waveforms can be controlled independently are the most widely in many of the industrial and power electronics applications in which output voltages are controlled by means of pulse width modulation techniques. For a VSI or VFI(voltage fed inverter) the DC voltage remains constant. Typically an induction motor drive system consists of a controller unit 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.

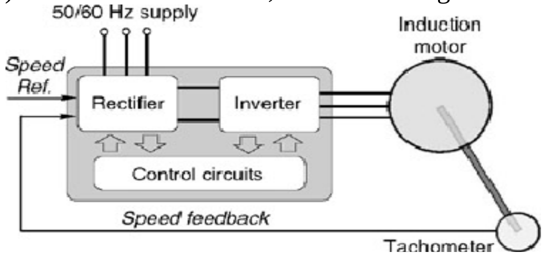

Fig. 1 General Configuration of an induction motor drive system

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Fault diagnosis of rotating electrical motors has received intense research interest. Condition monitoring leading to fault diagnosis and prediction of electrical machines and drives has attracted researchers in the past few years because of its great influence on the operational continuation of several industrial processes. Correct diagnosis and early detection of incipient faults result in fast unscheduled maintenance and short down time for the process under consideration. They also avoid harmful, sometimes devastative, consequences and help reducing financial loss. An ideal diagnostic procedure should take the minimum measurements necessary from a machine and by analysis extract a diagnosis, so that its condition can be inferred giving a clear indication of incipient failure modes in a minimum time. Safety, reliability, efficiency and performance are some of the major concerns on which researchers are interested. Fault detection and diagnosis emerges as an important field. Fault detection and isolation methodologies (FDI), an efficient diagnostic system which paves way for a fault tolerant drive which is target for future. FDI allows to ensure safe and continuous operation of the treated system and to guarantee timely maintenance to the faulty process. FDI performs the following three tasks: fault detection, fault identification, and fault isolation, which is a remedial action. But considering the implementation practically, the fault detection and identification are considered as a prime process and hence they are often called as fault diagnosis. In every industrial process electrical machines are the most critical components. The electric drive systems are exposed to overloading and hard environmental conditions which may lead to induction motor faults or inverter fault. For induction motor fault, there are both electrical and mechanical faults like stator winding short circuit, broken rotor, bearing faults etc. Statistics show that about 38% of failures in variable speed AC drives are concerned in power electronics – semiconductor, capacitors, gate drivers etc. of which 31% contributes semiconductor switch failure faults[1].

The literature on fault diagnostic methods is very much diversified. The methods based on sensing voltage, [3],[4] such as error voltage methods requires hardware requirements like voltage sensors, increases system costs. The same is the problem with current sensing methods[4]-[10] like Park's vector method, Centroid based faulty detection, Normalised DC current method, Current deviation method etc, the main problem with these are susceptible to load torque. Many other methods like Artificial intelligence method[11], wavelet fuzzy logic algorithm[12], Clustering ANFI system[13],ANN diagnostic method[14] etc have been used based on reliability and application, coming to vector controlled induction motor applications many methods fails due to dependence in load torque, complexity, high cost etc. This paper presents a very simple, robust, real time fault detection algorithm for detection of multiple open circuit switch faults in PWM voltage source inverter fed vector controlled induction motor drive. This is highly efficient in the sense that it has immunity over abrupt speed or torque change, it uses no number of extra electric devices like sensors, as it already uses from the those in vector controlled feedback. Hence this can be fitted as a sub routine of the main control unit without any much change, hence low cost.

II.SWITCH FAULT AND ITS CHARACTERISTIC ANALYSIS

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.
The stator currents are first decomposed by coordinate transformation into two synchronously rotating Cartesian vector components i_d and i_q which are controlled independently to control the rotor flux and torque respectively.

The currents i_d and i_q in the d − q frame can be derived from the currents in the α − β frame by the expressions called Park transformation defined as

$$i_d = i_\alpha \cos\theta + i_\beta \sin\theta$$
$$i_q = -i_\alpha \sin\theta + i_\beta \cos\theta$$

were θ is the rotor flux angle (also called transform angle, generated from the speed signal and slip signal) and the currents i_α and i_β in stationary frame are transformed by Clarke transformation defined as

$$i_\alpha = \frac{2}{3}\left(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c\right)$$
$$i_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}i_b - \frac{\sqrt{3}}{2}i_c\right)$$

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where i_a, i_b , and i_c 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. The phase current distribution is a sinusoid in normal and healthy condition, as is shown in Fig.2. According to the different combinations of the three-phase current flow directions, six operating stages, noted S1–S6 where the dashed lines are their boundary, are defined. According to the current vector rotating angle from 0◦ to 360◦, each stage from S1 to S6 has 60◦ in a sequence and S1 stands for the part from 0◦ to 60◦.

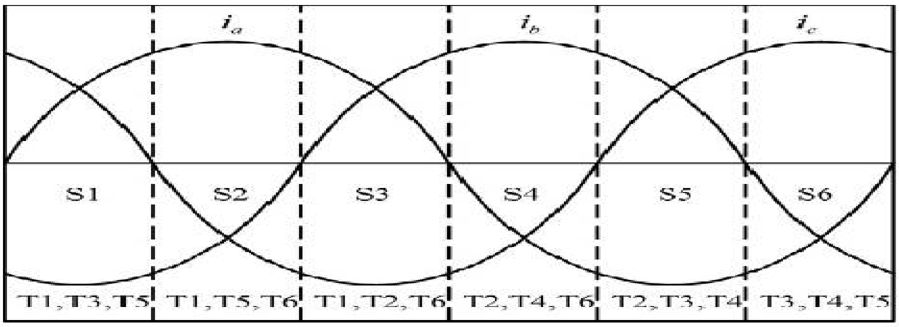

Fig.2 Three-phase currents distribution in the power switches.

At stage S1, the three-phase current flow directions are positive, negative and positive, respectively. For each stage, although all six switches are alternatively turned on and off by certain rules, only three transistors of them exert a vital influence and the others make a negligible influence, as will be explained in the next paragraphs. For example, at S1, the influential power switches are T1, T3 and T5, the negligible ones are T2, T4, and T6. Therefore, three operating transistors at each stage are obtained. In healthy condition, three influential power switches work normally at each stage and all the six power switches alternatively work healthily according to the given commands. However, when an open-circuit fault occurs, the faulty power switches will affect the operating stages where they are influential and three-phase currents get distorted during these faulty stages. So the fault can be identified according to the faulty stages. Table I presents the faulty switches in a six-stage conversion and the defined value of a fault type. For single switch open-circuit fault, such as that T1 fails, the three phase currents at the operating stages where T1 is influential are distorted. T1 makes a vital influence at stage S1, S2, and S3 and makes a negligible influence at stage S4, S5, and S6. So the three-phase currents distort at stage S1, S2, and S3 and return to normal at stage S4, S5, and S6. The current distortions last from stage S1 to S3. Therefore, the faulty power switch T1 can be judged if the current distortions last from stage S1 to S3. For double switches open-circuit fault in different legs such as T1 and T2 fail, they together make a vital influence at stage S1, S2, S3, S4, and S5 and make a negligible influence at stage S6. So the current distortions last form stage S1 to S5. The faulty power switches (T1 and T2) can be judged if the current distortions last from S1 to S5. However, for the double switches open-circuit fault in the same leg such as T1 and T4 fail, they together make a vital influence at all stages. So an additional approach is introduced for such kind of faults. As Table 5.1 shows, the arrow means the state conversion of the VSI from the start of faulty stage to the end of the faulty stage. As discussed earlier, the currents in a cycle are divided into six stages and the faulty stage can be used to identify the fault. The stage can be expressed by the current vector rotating angle. From 0◦ to 360◦, each stage from S1 to S6 has 60◦ in a sequence. The current vector rotating angle δ consists of two component (ωt and θ_c). In a vector controlled induction motor drive, ωt = θ whether faults occur in the VSI or not. As long as the induction motor operates, the rotor flux exists whether faults occur or not and its angle is θ. But when the open-circuit faults occur, the initial angle θc does not remain constant and the current vector rotating angle δ no longer changes from 0◦ to 360◦ sequentially. Therefore, the present stage determined by the current vector rotating angle is very likely to be false. So in order to determine the stage correctly, the current vector rotating angle should be calculated by another computational method and the key factor is to restore the initial angle θc . The initial angle θ_c only associates with id and iq. And the d- and q-axis currents i_d and i_q only relate to the load torque and setting speed theoretically. Therefore, the initial angle θc at faulty stages can be represented by the initial angle at healthy stages.

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III.FAULT DETECTION

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 (i_d) 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 that can be calculated by the *d*- and *q*-axis currents. Therefore, faults can be identified according to the faulty stages. In healthy condition, the actual currents can track the current commands. But an open-circuit fault makes the actual currents 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 condition, the *d*-axis current distortion Ei_d between command i^*_d and feedback i_d is nearly zero and the *q*-axis current distortion Ei_q between command i^*_q and feedback i_q is also nearly zero when the drive system is in stable state. The *d*- and *q*-axis current distortions are expressed by

$$Ei_d = i_d^* - i_d$$

$$Ei_q = i_q^* - i_q$$

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

$$boolEi_d = \begin{cases} 1, if\ |Ei_d| \geq K_d : error \\ 0, otherwise : normal \end{cases}$$

$$boolEi_q = \begin{cases} 1, if\ |Ei_q| \geq K_q : error \\ 0, otherwise : normal \end{cases}$$

where K_d and K_q are the selected threshold values and *boolEid* and *boolEiq* are the generated Boolean errors for the current distortions of i_d and i_q . Threshold values K_d and K_q are positive values and carefully selected to minimize the possibility of the false alarms mainly caused by the noises of measurement and the regulation of the controller. If they are selected too high, the *d*- and *q*-axis current distortions may not be detected. Moreover, if they are too small, the probability of false alarms increase. If the Boolean error *boolEid* has the value of 1, it means that there is a fault and the system is in faulty condition. Since the *d*-axis current distortion is zero or nonzero depending on whether the system works at healthy stage or at faulty stage, the generated Boolean error *boolEid* shows periodic square waveforms in faulty condition. The error detection is a simple and frequently used method, but has the possibility of false detection due to the generated Boolean errors jitters caused by the noise and the regulation of the controller. To guarantee the robustness against the false error detection, the proposed method employs the Counting Algorithm that looks for *COUNT* sequential stable states of the generated Boolean errors, where *COUNT* is a fault diagnosis constant number ranging from 1 (no jitters at all) to seemly infinity. Generally the algorithm detects a transition and then starts incrementing a counter till the counter reaches a jitter-free count. If the state is not stable, the counter resets to its initial value. The constant *COUNT* is defined as how long the Boolean errors are continuously generated and given by

$$COUNT = kf\ T/Ts$$

where *kf* is the sensitivity factor for the fault diagnosis, *T* denotes the current cycle of induction motor ($T = 2\pi/\omega$), and *Ts* stands for the sampling cycle of three-phase currents. If *kf* is too large, the open-circuit fault may not be detected. If *kf* is too small, the possibility of false alarms increases. Therefore, the sensitivity factor *kf* is carefully selected considering the detection time and reliability of fault detection. Then, the algorithm for the fault detection is given by

$$flagFault = 1,\ if\ counter1 \geq COUNT1$$
$$=0,\ otherwise$$

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where *counter*1 is the counter value from the beginning of the error detection in (12) to the arriving at the fault detection constant *COUNT*1 (*COUNT*1 = *kf* 1*T*/*Ts*) and *flagFault* denotes the fault detection flag indicating the fault condition. The error detection counter value *counter*1 is reset to zero when the Boolean errors are zero. If the error counter value *counter*1 is longer than the fault detection constant *COUNT*1, the fault detection flag *flagFault* is set from low to high. The identification of the faulty switch is started just after the fault detection. The value "1" of *boolEiq* only implies the faults after the occurrence of the fault has been detected by *boolEid* . Since the current distortion are zero at healthy stages and are nonzero at faulty stages when faults occur, the generated Boolean errors show periodic square waveforms. The errors *boolEid* and *boolEiq* together are applied to determine the stages which can give high reliability *boolEi* = *boolEid* |*boolEiq*

The rising edge of *boolEi* indicates the currents begin to distort while the falling edge indicates they return to normal. The same jitter-free algorithm called counting algorithm as applied to *boolEid* is used to process *boolEi* (represented by *boolEiFilter*) where *counter*2 and *COUNT2* (*COUNT*2 = *kf* 2*T*/*Ts*) have identical definitions to *counter*1 and *COUNT*1, respectively.

TABLE 1

Faulty Switches in a Six-Stage Conversion

Faulty Stage Conversion	Fault Type	Faulty Switch
NO $\rightarrow$ NO	0	NORMAL
S1 $\rightarrow$ S3	1	T1
S3 $\rightarrow$ S5	2	T2
S5 $\rightarrow$ S1	3	T3
S4 $\rightarrow$ S6	4	T4
S6 $\rightarrow$ S2	5	T5
S2 $\rightarrow$ S4	6	T6
S6 $\rightarrow$ S3	7	T1T5
S1 $\rightarrow$ S4	8	T1T6
S3 $\rightarrow$ S6	9	T2T4
S2 $\rightarrow$ S5	10	T2T6
S4 $\rightarrow$ S1	11	T3T4
S5 $\rightarrow$ S2	12	T3T5
S1 $\rightarrow$ S5	13	T1T2
S3 $\rightarrow$ S1	14	T2T3
S5 $\rightarrow$ S3	15	T1T3
S4 $\rightarrow$ S2	16	T4T5
S6 $\rightarrow$ S4	17	T5T6
S2 $\rightarrow$ S6	18	T4T6

Moreover the rising and falling edge of *boolEi* are timely stored. Fig. 3 presents the waveforms of processing *boolEi*, where the waveform *edge* is actually a matrix storing the rising and falling edge of *boolEi*. The matrix *edge* is composed of two numbers, each of which stores the time of the rising and falling edge, respectively. When *boolEiFilter* = 0, its first number of *edge* is updated every time *boolEi* rises up until *boolEiFilter* also rises up. And when *boolEiFilter* = 1, the other number of the matrix is updated every time *boolEi* falls down until *boolEiFilter* also falls down.

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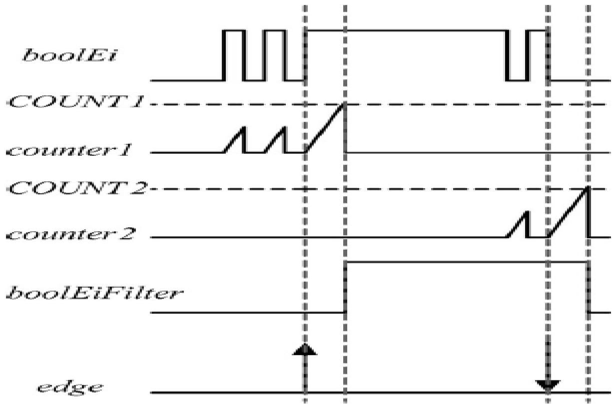

Fig.3. Process of the counting algorithm

IV.SIMULATION RESULTS

The simulation was carried out in MATLAB/Simulink environment to verify the feasibility of the proposed Fault diagnosis method. All the transistor open-circuit faults are performed by inhibiting their respective gate signals and also by keeping the bypass diodes connected. 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 (K_d,K_q , k_{f1} , and k_{f2}) of the algorithm are chosen to be 0.5 A, 0.5 A, 0.2, and 0.2 in the tests, respectively.

A) Immunity to abrupt Change of load torque and Setting speed

In this evaluation, by introducing an abrupt change of the load torque from no-load to rated load at t = 0.4 s and the setting speed from 1200 to 1100 r/min , the obtained results verify that flagFault and faultType remain unchanged despite of the strong load disturbance and speed change, proving the algorithm robustness.

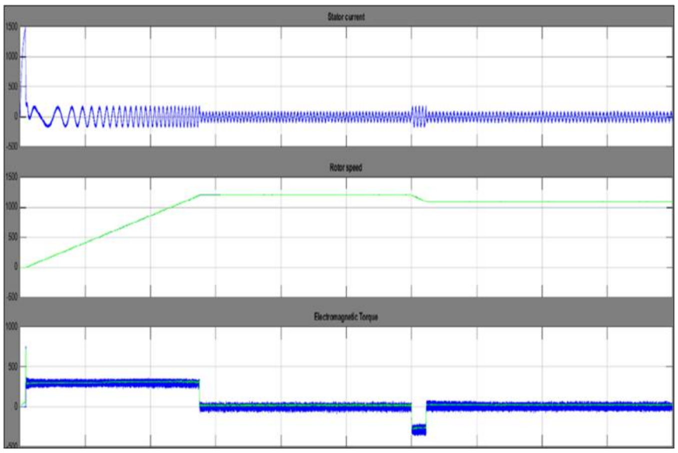

Fig.4 Simulation waveform of stator current (phase a), Speed change and change in load Torque

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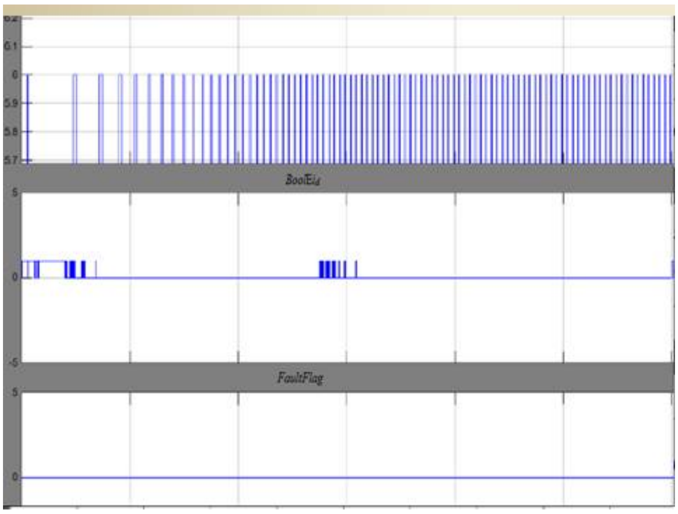

Fig.5 Simulation waveform of boolEid , faultFlag and fault type

B) Single switch fault detection:

A single transistor open-circuit fault corresponding to *T*4 is shown in Fig.8 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 Ei_d stays at zero until the distortions come. Then, the fault detection flag *flagFault* is set from low to high at t = 0.5145 s according to the value of filtered Ei_d and the fault identification is started to identify the faulty switch. In combination with the recalculated current vector rotating angle, the rising edge and falling edge of *boolEi* are obtained and thus the stages where the three-phase currents begin to distort and return to normal are determined. Therefore, according to Table, *faultType* = 4, indicating that the open-circuit fault occurs to *T*4.

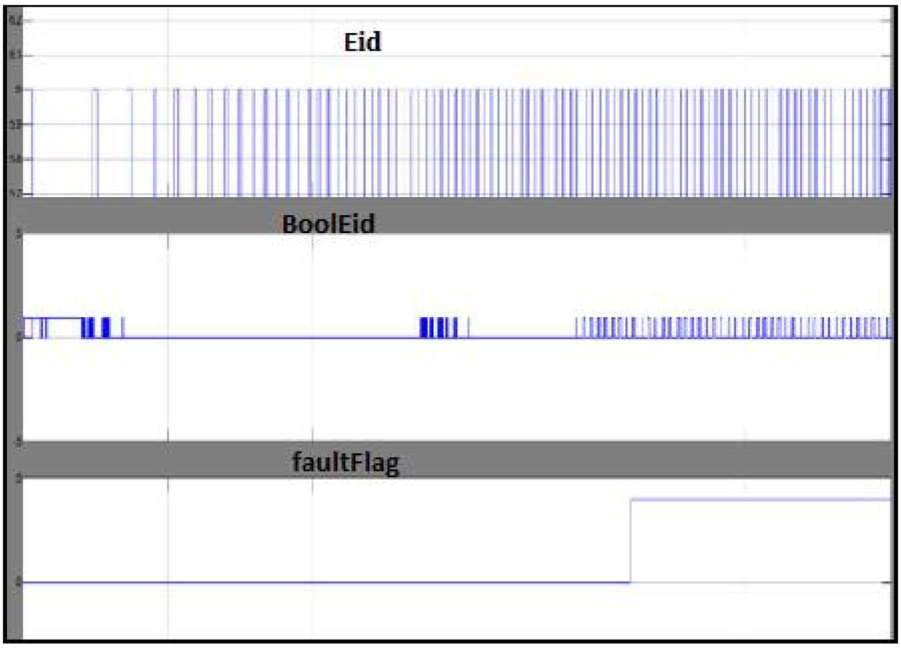

Fig6 Simulation waveform of $Ei_{d,}$ $BoolEi_d$ and faultFlag Type for single transistor fault(T4)

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C) *Multiple Transistor Fault:*

A double transistors open-circuit fault corresponding to *T*1 and *T*2 is shown in Fig. 6.3, which presents the simulation waveforms of three-phase currents, the motor speed and the diagnostic signals. It is much the same as the single transistors open-circuit fault. After the faults at $t = 0.5$ s are introduced, the fault detection flag *flagFault* is set from low to high at $t = 0.5145$ s according to the value of filtered *Eid* and then the fault identification is started to identify the faulty switch. The recalculated current vector rotating angle together with the rising edge and falling edge of *boolEi* determine the stages where the three-phase currents begin to distort and return to normal. Therefore, according to Table II, *faultType* = 13, indicating that the open-circuit fault occurs to *T*1 and *T*2.

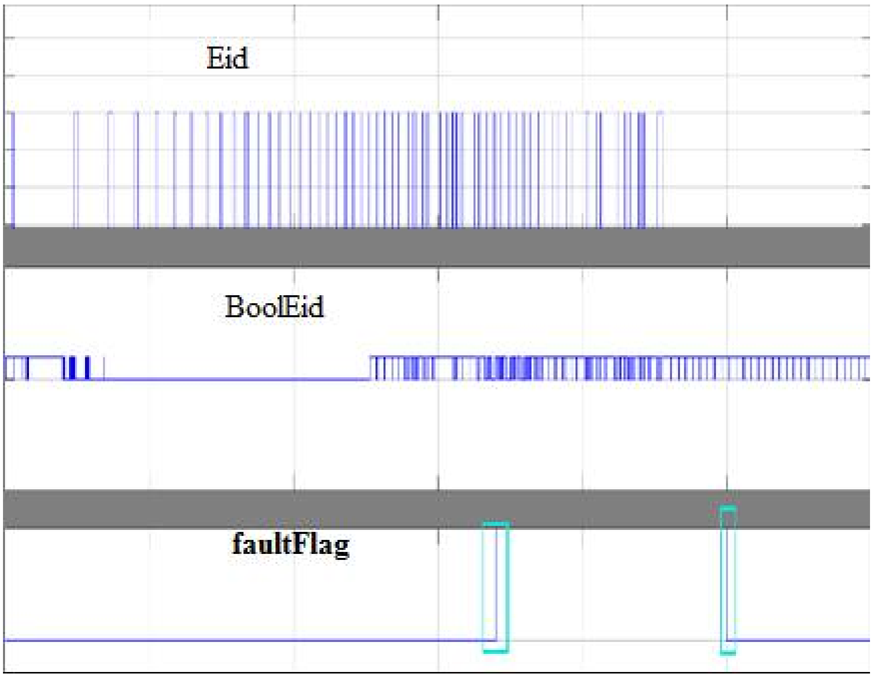

Fig.7 Simulation waveform of Ei_d, $BoolEi_d$ and *faultFlag*

VI.CONCLUSION

A simple method for single switch and double switches open circuit fault diagnosis in PWMVSIs for vector-controlled induction motor drives has been proposed in this paper. 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 previously published methods, the original method relies on the stage conversion. An open-circuit fault of power switches in the VSI changes the corresponding phase currents and introduces the periodic current distortions. When the fault occurs, the distortions are estimated and compared with the threshold value to detect the fault. And the stage is determined according to the recalculated current vector rotating angle. After the fault is detected, the faulty stages are determined in combination with the estimated distortions. Therefore, the faults are identified according to the stage conversion table. In comparison to the existing fault diagnosis, the proposed method can not only identify an initial fault, but also can identify a secondary fault fast and correctly, and show fair robustness. Moreover, it can be embedded into the existing vector-controlled induction motor drive software as a subsystem without excessive computation effort. Simulation results have validated the proposed method and show that the proposed method has good performance and practical value.

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