



DESIGN OF FAULT TOLERANT CONTROL SYSTEM OF VSI-FED INDUCTION MOTOR DRIVES

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Abstract: Fault-tolerant control systems are attracting more interests due to its ability of increasing the reliability of voltage source inverts (VSI). Fault identification, localization and fault tolerant control schemes of current sensor are presented here for high fault tolerance induction motor drives. Practically three phase current sensors are used in high power inverters to read the stator currents and allow the drives to work accordingly. But on failure of current sensors it degrades the performance and reliability of drives, even it leads to the breakdown of the vector control system due to the fact that flux angle cannot be estimated correctly. The proposed scheme consists three separate observers, taking a-phase current, b-phase current and c-phase current as inputs, respectively. The observers are having ability to monitor the state of current sensors under normal operation online. Further, after one or even two current sensors getting faulty, the observers can detect and localize the faults and switch the system to tolerant vector control mode even with only one healthy phase current sensor available. Hence, it is very attractive in some safety crucial applications. Stability and convergence of the observer are mathematically derived and verified. A Matlab/Simulink based 1.1kW induction motor variable speed system is setup for the verification of the proposed algorithm.

Index Terms - Current sensor; fault diagnosis; tolerant control; full order observer.

I. INTRODUCTION

Due to the advantages of reduced size and cost, minimal maintenance and mechanical ruggedness, high-performance induction motor (IM) drives have been commercially available since field-oriented control or vector control of IM is proposed. Generally, the controllers are supported by feedback signals such as rotor speed and stator phase currents, etc. Therefore, failures of these sensors will degrade the system performance, even cause the system breakdown. One of the most attractive research method is the fault diagnosis and tolerant control of inverter. It should be noted that the high fault tolerance system includes two aspects: fault diagnosis and fault tolerant control. In this paper, current sensor fault diagnosis and tolerant control method is presented, Matlab/Simulink simulation results are given by fault tolerant algorithm which is executed through Matlab/Simulink.

Fault Tolerant Control (FTC) systems are designed to permit recovery from damage and system faults. When it comes to electrical drives used in safety critical applications or industrial processes where system faults may lead to enormous costs.

In case of VSI fed inverter continuity and reliability of drive is the main consideration in applications like engine cooling fans, heat pumps, air conditioning pumps, aircrafts, aerospace vehicles. Carryout this, it is desired that, the drive should work efficiently and effectively without discontinuity. Traditional drives operation is limited by faults developed in the sensors mounted on the motors and/or actuator. Thus Fault-tolerant control methods are becoming popular due to its capability of increasing the reliability of voltage source inverts (VSI). Fault identification, localization and tolerant control schemes of current sensor are presented for high fault

tolerance induction motor drives. In this synopsis, current sensor fault diagnosis and tolerant control method are presented and the fault tolerant algorithm was executed through Matlab/Simulink.

II. LITERATURE REVIEW:

A literature survey has been carried out including two of the most important and common databases, namely, the IEEE/IEE electronic library and Science Direct electronic databases.

Below is a literature review of works carried out in last few years –

1. IEEE PAPER on **“Design of fault tolerant controller based on observers for a PMSM drive”** BY AHMAD AKRAD, MICKAEL HILAIRET, MEMBER IEEE AND DEMBA DIALLO, SENIOR MEMBER IEEE.

In this paper author discussed about fault tolerant control system for a high performance pmsm drive. The fault tolerant control (ftc) is an observer-based structure with a voting algorithm, which selects the appropriate speed and position in case of mechanical sensor failure from two observers. A sensorless controller has been experimentally evaluated with both observers, the optimal two stage extended kalman’s filter and a back-emf adaptive observer. The transient behavior of both observers has been analyzed to extract the reliability coefficients required by the maximum-likelihood voting algorithm. The ftc has been improved by developing a new method called adapted maximum-likelihood voting algorithm. This paper presents architecture to obtain permanent magnet synchronous motor (pmmc) drive that is robust to mechanical sensor failure based on kalman filter, adaptive observer and maximum likelihood voting algorithm [1].

2. IEEE PAPER on **“Easy and fast sensor fault detection and isolation algorithm for electrical drives”** BY HANEN BERRI, MOHAMMED WISSEM NAOUAR, ILHEM SLAMA-BELKHODJA.

This paper focus on sensor fault detection and isolation (FDI). This paper proposes a new, easy and fast sensor FDI algorithm for electrical systems. The developed FDI algorithm is available for sensors measuring variables, with gradual change. So, only sudden faults are detected, even faults with low magnitude. A very low sampling time acquisition, relatively to the measured state variable time constant, is necessary. It leads to significant simplifications, and consequently to an algorithm depending only on successive readings of the concerned sensor output, with no regards to model system. So, it is not sensitive to model parameter variations as classical model-based sensor fault detection methods, neither to operating point [2].

3. IEEE PAPER ON **“A fault tolerant control Architecture for induction motor drives in automotive applications”** BY DEMBA DIALLO, MOHAMED EL HACHEMI BENBOUZID, ABDESSALAM

This paper has described a fault-tolerant control system for a high-performance induction motor drive for automotive applications. The proposed system adaptively changes control techniques in the event of sensor failures. Four control techniques have been used to ensure induction motor drive operation continuity. Among these, a practical sensorless control technique has been developed, which requires the presence of an adaptive flux observer. The speed estimator is based on the approximation of the magnetic characteristic slope of the induction motor to the mutual inductance value, which is considered constant [3].

4. IEEE PAPER ON **“Fault tolerant control design of induction motor drive in Electrical Vehicle: A hybrid control approach”** BY M. BOUCHNIFER, A. RAISEMACHE, D.DIALLO.

In this paper, architecture of a hybrid fault tolerant control has designed and used for the speed control of an induction motor drive employed in Electric Vehicles. An additional controller parameter has been introduced as the main tool to achieve fault tolerance. A feature of this structure is that it automatically includes a diagnostic signal of the speed sensor. The proposed method activates PI controller in co-ordination with H_{∞} controller when there is fault in the system and provide reliability [4].

5. IEEE PAPER ON “**Current Sensor fault detection, isolation, and reconfiguration for doubly fed induction generators**” BY KAI ROTHENHAGEN AND FRIEDRICH WILHELM FUCHS.

In this paper current sensor fault detection, isolation and reconfiguration is presented voltage oriented controlled doubly fed induction generator which is mainly used in induction generator. It is beneficial to make these DFIG systems more reliable. Fault diagnosis and monitoring are modern ways to increase reliability, and they are possible without installing extra hardware. Two Luenberger observers are used in parallel to generate residuals for the stator and rotor current sensors. In order to distinguish between stator and rotor current sensor faults, Fault Isolation Logic (FIL) is implemented. To increase the available time for FDI, the control of the DFIG is switched to open-loop control, as soon as a fault is detected. As soon as the fault is isolated, the control loops are reconfigured using observer outputs. Closed-loop control is resumed, and a flag indicates the faulty sensor. Laboratory measurements are included to verify this concept. They show very good behavior [5].

6. IEEE paper on “**Detection and isolation of speed-, DC-link voltage and current sensor faults based on an adaptive observer in induction motor drives**” by Tooraj Abbasian Najafabadi, Fazad R. Salmasi and Perviz Jabehder-Maralani.

In this author describe about, a sensor fault detection and isolation unit is considered for induction motor drives based on adaptive observer with rotor resistance estimation. In proposed paper, phase currents and rotor resistances are sent to a decision making unit which identify faulty sensor based on a deterministic rule. An Fault Detection and Isolation (FDI) unit has been considered for detection and isolation of speed or position, phase currents, and dc-link voltage-sensor faults in closed-loop induction-motor drives. An adaptive observer is used to estimate phase currents and rotor resistance. The Decision Making Unit (DMU) singles out the faulty sensor based on the observer outputs and measured signals. [6].

III. OUTLINE OF THESIS

In this thesis discussed about the introduction of Fault-tolerant control systems and its importance and also explains about the literature review which consists of related literature. It also includes conventional fault diagnosis methods and fault-tolerant control methods for current sensor overview. Paper also gives theory of Space vector pulse width modulation (SVPWM) method used in this scheme. Then it gives the overview of proposed Diagnosis method for the first current sensor fault and Diagnosis method for the second current sensor fault. Simulation model of proposed fault diagnosis and fault tolerant scheme is given. Then it is followed with the simulation results of the project. The conclusion of the project given at the end which interprets about the results.

IV. CONVENTIONAL FAULT DIAGNOSIS METHODS AND FAULT-TOLERANT CONTROL METHODS FOR CURRENT SENSOR

1. Fault Diagnosis Methods for Current Sensor:

Current sensor fault diagnosis and tolerant control methods have been reviewed in many literatures. We have seen that fault diagnosis approaches and their applications are divided into model-based and signal-based methods. In model-based methods, the models of the industrial processes or the practical systems are required, which can be obtained by using either physical principles or systems identification techniques. In signal-based methods, after the fault features have been extracted, which are incorporated in the measured signals, a diagnostic decision can be made based on the symptom analysis and prior knowledge of the healthy systems. In other method the measured currents are compared with the estimated currents in order to localize the faulty current sensor. In some cases, an adaptive gain scheduling observer is used to generate the residual, and then the faulty sensor can be identified and isolated in a direct torque controlled induction motor drive system. Some people proposed a fault diagnosis method based on three adaptive full-order observers which have different inputs. Nevertheless, this method is not applicable to realize the fault diagnosis when two current sensors are breakdown in succession. This proposed a compact and robust sensor fault detection, isolation algorithm based on extended Kalman filter, which reduced the number of adaptive observers. In some cases, they proposed diagnostic method uses the measured phase

currents only, and the merits of this method are simplicity, reliability and suitable for real-time implementation. But, it is only suitable for integration into the controller of a fault-tolerant PMSG for wind energy conversion systems. The fault detection and isolation of speed and current sensor are achieved by axes transformation, and the current estimation uses the d-axes and q-axes currents by invert park transformation. Some schemes are based on residual generation through observers or parity equations, and the average normalized machine-phase currents are used in the proposed technique, without any information about motor or inverter models. Few are reported as knowledge-based methods including expert system, fuzzy theory and artificial neural network etc., these methods require priori knowledge and large volume of historic data. In some cases, after the sensor fault is detected by the proposed artificial neural network approach, drive topology will be changed based on sensor or control topology redundancy.

2. Fault-tolerant control methods for current sensor:

There are mainly two approaches for fault tolerant control of current sensor. In the first approach, the system will switch to another controller (typically from closed-loop to open-loop control) when a fault is detected. In some cases, the simple algorithmic/logical mechanism based on the measured currents is used for current sensor fault detection. After the fault detected, drive topology is modified. In the second approach, the estimated signal replaces the faulty current signal without changing the original system structure. Therefore, the reliability and accuracy of the observers or estimators are the key points as reported in many research work. In few, an adaptive observer with online estimation of rotor and stator resistances is designed with only one healthy phase current sensor. The merit of this method is that the observer is robust to rotor and stator resistance variations. Some thesis extracts the information of the phase currents in two-phase stationary reference frame by using the corresponding synchronous reference frame variables and vector rotator. In some papers, the current estimation method combines the fault diagnosis with fault tolerant schemes. After the fault is diagnosed, computational currents are used to replace the lost currents. Estimation of phase currents based on the dc-link current measurement and switching patterns are discussed in some research work.

V. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM) THEORY

Space vector pulse width modulation (SVPWM) technique is suitable for fundamental switching frequency as well as high Frequency applications. This modulation technique produces good quality output waveforms in terms of low voltage and current THD.

A mathematical model of three-phase is presented here based on space vector representation. The power circuit topology of a three-phase VSI is shown in Figure (1). Each switch in the inverter leg is composed of two back-to back connected semiconductor devices. One of these two is a controllable device and other one is a diode for protection. Leg voltage waveforms is shown in Figure (2) for 180° conduction mode.

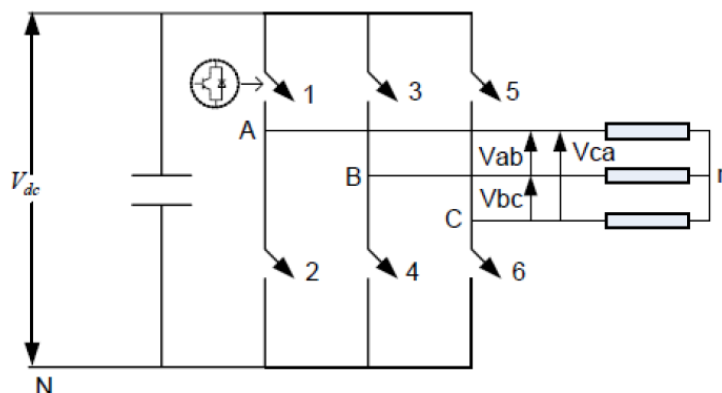


Figure (1) Power circuit of a three-phase Voltage Source Inverter.

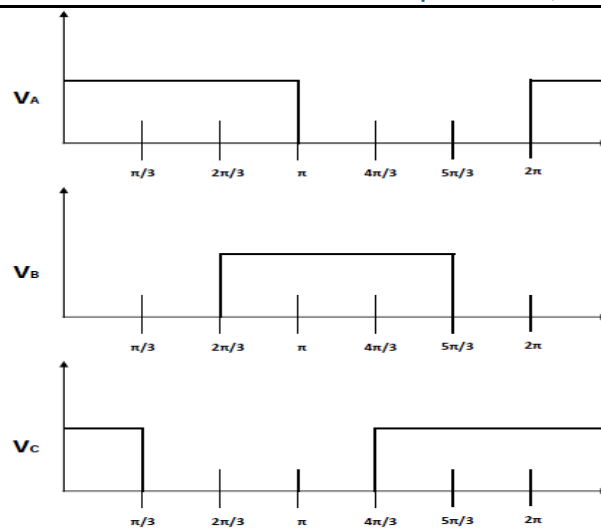


Figure (2) Leg voltage waveform of a threephase VSI for 180° conduction

It is observed from Figure (1) that one inverter leg's state changes after an interval of 60° and their state remains constant for 60° intervals. Thus it follows that the leg voltages will have six distinct and discrete values in one cycle (360°).

This section briefly discusses the space vector PWM principle. This PWM method is frequently used in vector controlled and direct torque controlled drives. In vector controlled drive this technique is used for reference voltage generation when current control is exercised in rotating reference frame. It is seen in the previous section that a three-phase VSI generates eight switching states which include six active and two zero states. These vectors form a hexagon in Fig.4 which can be seen as consisting of six sectors spanning 60° each. The reference vector which represents three-phase sinusoidal voltage is generated using SVPWM by switching between two nearest active vectors and zero vectors. To calculate the time of application of different vectors, consider Figure (3) depicting the position of different available space vectors and the reference vector in the first sector. It also describes space vector transformation of three phase voltages.

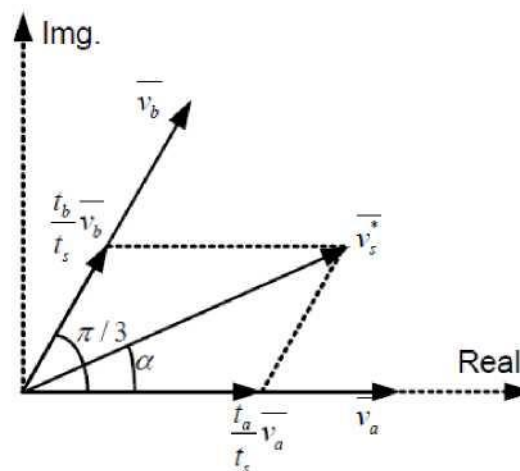


Figure (3) Principle of space vector time calculation.

Voltage vectors produced by voltage source inverters is shown in below fig. (4)

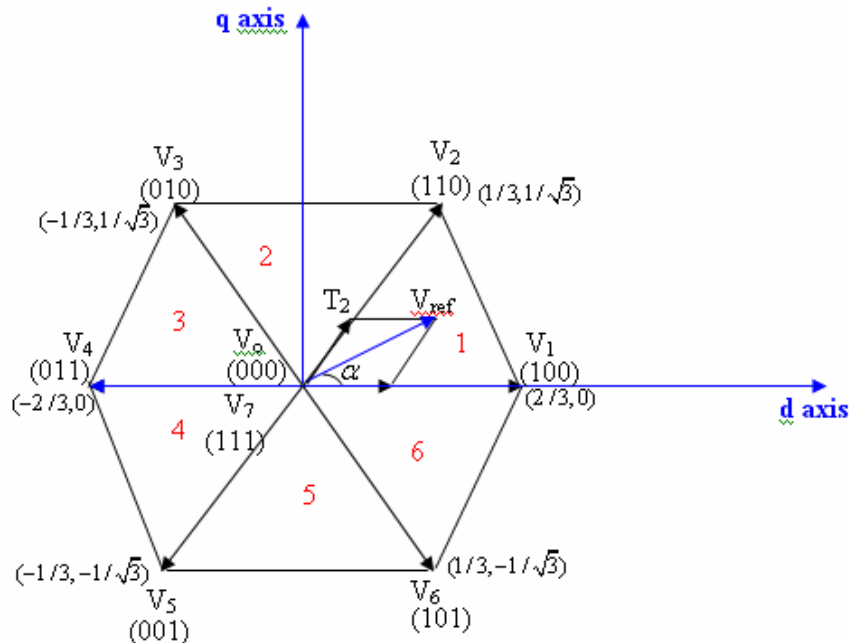


Figure (4) Basic switching, vectors and sectors.

Switching States-

Below table- 1 gives inverter switching states and corresponding output voltages for standard switching.

Table 1: Switching patterns and output vectors.

Voltage	Switching Sectors			Line to neutral voltage			Line to line voltage		
	A	B	C	V _{an}	V _{bn}	V _{cn}	V _{ab}	V _{bc}	V _o
V0	0	0	0	0	0	0	0	0	0
V1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V2	1	1	0	1/3	1/3	-2/3	0	1	-1
V3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V4	0	1	1	-2/3	1/3	1/3	-1	0	1
V5	0	0	1	-1/3	1/3	2/3	0	-1	1
V6	1	0	1	1/3	-2/3	1/3	1	-1	0
V7	1	1	1	0	0	0	0	0	0

For 180° mode of operation, there exist six switching states and additionally two more states, which make all three switches of either upper arms or lower arms ON. To code these eight states in binary (one-zero representation), it is required to have three bits (2³ = 8). And also, as always upper and lower switches are commutated in complementary fashion, it is enough to represent the status of either upper or lower arm switches. In the following discussion, status of the upper bridge switches will be represented and the lower switches will it's complementary. Let "1" denote the switch is ON and "0" denote the switch in OFF. Table-(1) gives the details of different phase and line voltages for the eight states.

VI. NOVEL FAULT TOLERANT CONTROL AND FAULT DIAGNOSIS METHOD FOR CURRENT SENSOR

A. Fault Tolerant Control for Current Sensor

1. Introduction

The fault-tolerant control algorithm plays a key role after sensor faults occurrence. When the fault diagnosis algorithm detects a fault, the control system will switch to the fault-tolerant mode. So the accuracy and stability of the fault-tolerant control system must be guaranteed. Generally, three current sensors are used to detect leakage currents and maintain high reliability in high power inverters. According to the fact that the summation of three phase currents is zero, it is recognized that two current sensors are also enough to implement vector control. Therefore, the key point of fault-tolerant control is how to keep the vector control scheme stable with only one healthy current sensor. In the following, the detailed introduction of proposed algorithm will be presented.

2. The tolerant control after one current sensor failure

According to the theory that the summation of three-phase stator current is zero, under the assumption that we have already known which current sensor is faulty, the corresponding current can be reconstructed with the other two measured stator currents. This idea can be considered to realize the fault-tolerant control system when one current sensor is faulty. It is simple and conventional so that two current sensors are generally used in low power induction motor drive systems.

3. The tolerant control after two current sensors failure

When two current sensors are faulty, the traditional vector control scheme is no longer applicable. Three-phase stator currents must be reconstructed with only one healthy current sensor. In this paper, the full-order adaptive stator current observer plays a vital role. In the following, the adaptive observer design is required. Basically two methods are used for fault tolerant, first one is to use input phase voltages and using current regulators we can implement and other method is based on SVPWM and DC bus voltage. Most adoptive observers use this method only because of simplicity and reliable.

B. Novel Fault Diagnosis Method for Current Sensor

1. Diagnosis method for the first current sensor fault

The method of state estimation with only one current signal is proposed in previous section. Based on this state observer, a novel current sensor fault diagnosis method can be achieved in this section. The basic idea of this method is that the three-phase stator current signals (i_a, i_b, i_c) and stator voltages (need to be transformed) are sent into three independent single current based state observers respectively as shown in Fig.5. Observer1,2,3 are with respect to three different α - β coordinate systems. For example, observer1 takes use of i_a as its input, so the α axis in observer-1 is aligned with i_a , and so on with observer-2 and observer-3. The angle difference between any two coordinate systems of the three state observers is 120° , as shown in Fig.2. When all the current sensors are fault-free, the three rotor flux amplitudes observed by three state observers are equal and the estimated currents ($\hat{i}_{s\alpha}^a, \hat{i}_{s\alpha}^b, \hat{i}_{s\alpha}^c$) of three state observers track three actual phase currents respectively. During any one of the three current sensors is faulty, a-phase current for example, $\hat{i}_{s\alpha}^a$ ($\hat{i}_{s\alpha}^a, \hat{i}_{s\alpha}^b, \hat{i}_{s\alpha}^c$ present the measured values of three phase current sensors) becomes null instantly and $\hat{i}_{s\alpha}^a$ only changes little in the period of estimation. By making full use of this phenomenon, one current sensor fault diagnosis is realized.

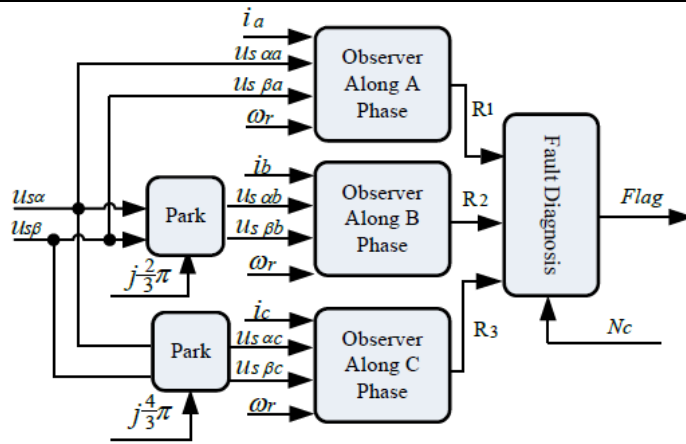


Fig.5 The block of single current sensor fault diagnosis scheme

2. The realization mechanism of one current sensor fault diagnosis method

The angle difference between i_s and ψ_r is defined as φ ranging from 0° to 90° . If the state observers are designed well and under normal conditions, the estimated values can be expressed as follows:

$$\begin{aligned} \hat{i}_{s\alpha}^a &= I_s \sin \omega t & \hat{\psi}_{r\alpha}^a &= \psi \sin(\omega t - \varphi) \\ \hat{i}_{s\beta}^a &= I_s \cos \omega t & \hat{\psi}_{r\beta}^a &= \psi \cos(\omega t - \varphi) \end{aligned} \tag{1}$$

It can be derived that

$$\begin{aligned} &\hat{i}_{s\alpha}^a * \hat{\psi}_{r\alpha}^a + \hat{i}_{s\beta}^a * \hat{\psi}_{r\beta}^a \\ &= I_s \sin \omega t * \psi \sin(\omega t - \varphi) + I_s \cos \omega t * \psi \cos(\omega t - \varphi) \\ &= I_s \psi \cos \varphi \end{aligned} \tag{2}$$

Under stable state, I_s, ψ, φ are all constant values. For simplicity, R_1, R_2, R_3 variables are introduced.

$$\hat{i}_{s\alpha}^a * \hat{\psi}_{r\alpha}^a + \hat{i}_{s\beta}^a * \hat{\psi}_{r\beta}^a = i_{s\alpha}^a * \hat{\psi}_{r\alpha}^a + i_{s\beta}^a * \hat{\psi}_{r\beta}^a = R_1 \tag{3}$$

$$\hat{i}_{s\alpha}^b * \hat{\psi}_{r\alpha}^b + \hat{i}_{s\beta}^b * \hat{\psi}_{r\beta}^b = i_{s\alpha}^b * \hat{\psi}_{r\alpha}^b + i_{s\beta}^b * \hat{\psi}_{r\beta}^b = R_2 \tag{4}$$

$$\hat{i}_{s\alpha}^c * \hat{\psi}_{r\alpha}^c + \hat{i}_{s\beta}^c * \hat{\psi}_{r\beta}^c = i_{s\alpha}^c * \hat{\psi}_{r\alpha}^c + i_{s\beta}^c * \hat{\psi}_{r\beta}^c = R_3 \tag{5}$$

Variables R_1, R_2, R_3 are obtained respectively in three independent observers which rely on different current sensors. Therefore, fault identification is straightforward: each variable is only sensitive to the corresponding current sensor.

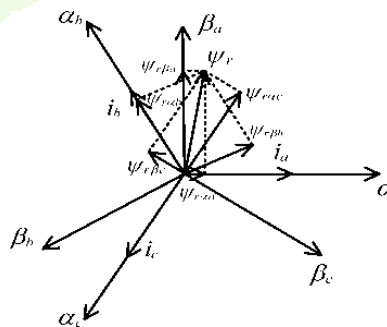


Fig. 6 The position relation of the coordinate system used by three state observers

3. Judgment basis of the first current sensor fault diagnosis

A single current sensor fault diagnosis scheme based on single current state observer is shown in Fig.5. It should be noted that the inputs of voltages need “PARK transform” in order to correspond to the $\alpha\beta$ -axis respectively. Stator voltages need to be transformed as follow:

$$\begin{aligned} u_{s\alpha}^a &= \frac{(2*u_a - u_b - u_c)}{3} & u_{s\beta}^a &= \frac{(u_b - u_c)}{\sqrt{3}} \\ u_{s\alpha}^b &= \frac{(2*u_b - u_c - u_a)}{3} & u_{s\beta}^b &= \frac{(u_c - u_a)}{\sqrt{3}} \\ u_{s\alpha}^c &= \frac{(2*u_c - u_a - u_b)}{3} & u_{s\beta}^c &= \frac{(u_a - u_b)}{\sqrt{3}} \end{aligned} \tag{6}$$

Under normal conditions, the estimations of three observers are accurate, so the values of and are equal. Assuming that a-phase current sensor is faulty, the measured current becomes null instantly, leading to the observed current decreases at the same time. Simultaneously, the three-phase currents will increase due to the inaccurate feedback current and the controller. And the value of the rotor flux remains unchanged during such short time. Therefore, the variable decreases quickly but others will become a little larger.

In order to eliminate the influence of starting up and dynamic respond, E_{ab} , E_{ac} and E_{bc} are introduced to balance such influence on R_1 , R_2 and R_3 , thus the diagnosis process can be more reliable and resistant in the starting up and load variation situations.

$$\begin{aligned} E_{ab} &= R_1 - R_2 \\ E_{ac} &= R_1 - R_3 \\ E_{bc} &= R_2 - R_3 \end{aligned} \quad (7)$$

So when a-phase current sensor gets faulty, E_{ab} , E_{ac} will go large and become bigger than a threshold N_c , but E_{bc} will not. The phase current sensor faults can be detected by this judgment rule, which is shown in Table -2.

Table 2. The Judgment Principle of First Current Sensor Fault Diagnosis

Fault Code	Judgement	Diagnosis Result
0	$ E_{ab} < N_c, E_{ac} < N_c, E_{bc} < N_c$	Healthy
1	$E_{ab} > N_c, E_{ac} < -N_c,$	a fault
2	$E_{ab} > N_c, E_{bc} < -N_c,$	b fault
3	$E_{ac} > N_c, E_{bc} > N_c,$	c fault

According to the parameters of the induction motor which are listed in Table 4. The reference value of magnetizing current and rotor flux threshold value of N_c can be chosen as 2.

4. Diagnosis method for the second current sensor fault

According to the previous part, after the first current sensor fault occurrence, the fault can be detected and localized, and the system will continue work in the fault-tolerant control mode with the other two healthy current sensors. Unfortunately, there are still some possibility that the two remaining healthy current sensors get faulty, In this part, the fault diagnosis method for the second current sensors will be explained.

For simplicity, assuming that the c-phase current sensor is faulty, the system is working in vector controlled mode with ab-phase current sensors, as shown in Fig. 7. For convenience of discussion and understanding, according to the principle of equivalence, Fig.8 is used to explain the current sensor fault diagnosis principle.

According to CLARK and PARK transform, the inputs of three-phase PI controllers in Fig. 8 can be obtained as follows:

$$\begin{aligned} \Delta i_a &= i_a^* - i_a \\ \Delta i_b &= i_b^* - i_b \\ \Delta i_c &= i_c^* - i_c = i_c^* + i_a + i_b \end{aligned} \quad (8)$$

In steady state, Δi_a , Δi_b and Δi_c are almost zero. In dynamic operating process such as accelerating or braking, the absolute value of Δi_a , Δi_b and Δi_c will change to more than zero, thus the voltage reference can be obtained through PI regulator. If the b-phase current sensor get faulty, the measured current i_{sb} becomes zero instantly, so the inputs of three phase PI controllers are changed as follows.

$$\begin{aligned} \Delta i_a &= i_a^* - i_a \approx 0 \\ \Delta i_b &= i_b^* - i_b = i_b^* \\ \Delta i_c &= i_c^* - i_c = i_c^* + i_a + 0 = -i_b \end{aligned} \quad (9)$$

From (19), it can be seen that the change of Δi_b and Δi_c is bigger than that of Δi_a so that the phase voltages u_b and u_c will change faster than u_a , and also the stator current i_b and i_c change faster than i_a . From the following state equation (20), it is known when fault occurs, the phase voltage u_{sb} plays the leading role of making the estimated value track the real value instead of the current negative feedback. Therefore, the observed current i_b will reach a threshold N_d faster than i_a .

With this idea, the method of fault diagnosis for two current sensors can be achieved.

$$\frac{di_{s\alpha}^b}{dt} = -\frac{R_s L_r^2 + R_r L_m^2}{\sigma L_s L_r^2} i_{s\alpha}^b + \frac{L_m R_r}{\sigma L_s L_r^2} \hat{\psi}_{r\alpha}^b + \frac{L_m \omega_r}{\sigma L_s L_r} \hat{\psi}_{r\beta}^b + \frac{1}{\sigma L_s} u_{s\alpha}^b + f_1(i_{s\alpha}^b - \hat{i}_{s\alpha}^b) + f_2 \text{sign}(i_{s\alpha}^b - \hat{i}_{s\alpha}^b) \quad (20)$$

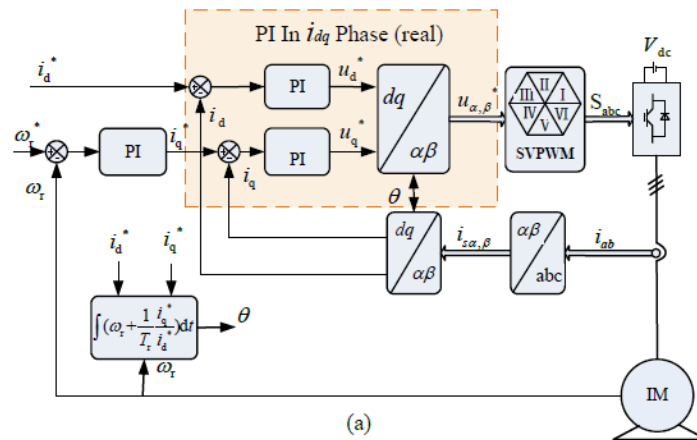


Fig.7 Real Block diagram of the vector control method with ab -phase current sensors

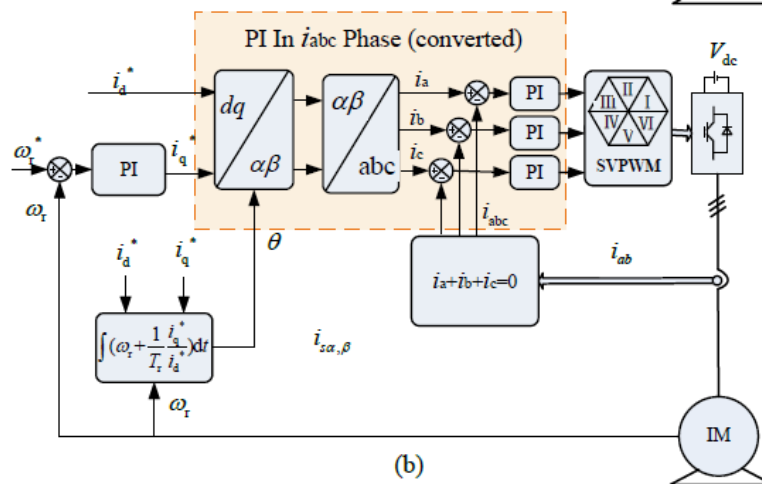


Fig. 8 Equivalent Block diagram of the vector control method with ab -phase current sensors

Similarly, the judgment rules can be concluded as shown in Table -3.

Table 3. The Judgment Principle of the Second Current Sensor Fault Diagnosis Scheme

Fault code	Condition	Judgement	Diagnosis result
3	f = 3 c fault	$ \hat{i}_{s\alpha}^a < N_d, \hat{i}_{s\alpha}^b < N_d$	c fault
4		$ \hat{i}_{s\alpha}^a > N_d, \hat{i}_{s\alpha}^b < N_d$	ac faults
5		$ \hat{i}_{s\alpha}^a < N_d, \hat{i}_{s\alpha}^b > N_d$	bc faults
2	f = 2 b fault	$ \hat{i}_{s\alpha}^a < N_d, \hat{i}_{s\alpha}^c < N_d$	b fault
6		$ \hat{i}_{s\alpha}^a > N_d, \hat{i}_{s\alpha}^c < N_d$	ab faults
7		$ \hat{i}_{s\alpha}^a < N_d, \hat{i}_{s\alpha}^c > N_d$	bc faults
1	f = 1 a fault	$ \hat{i}_{s\alpha}^b < N_d, \hat{i}_{s\alpha}^c < N_d$	a fault
8		$ \hat{i}_{s\alpha}^b > N_d, \hat{i}_{s\alpha}^c < N_d$	ab faults
9		$ \hat{i}_{s\alpha}^b < N_d, \hat{i}_{s\alpha}^c > N_d$	ac faults

The threshold N_d is chosen as 6A. As shown in Table-3, N_d relates to the second sensor fault diagnosis. For this motor, the rated current is 2.8A, the full-load peak current is 3.96A, the no-load peak current is 2A. On one hand, the threshold value N_d should be set between the rated phase current and the protective current. On the other hand, since the actual phase current depends on load, the threshold value N_d must be set to reach a compromise between no-load and full load condition, then the diagnosis method will be applicable to all load conditions. If the threshold can be applied in no-load condition with narrow margin, it can also be applied in full-load condition. In no-load condition, the error value reaches 6.3A by simulation so we set the threshold N_d at 6A.

In this section, simulation experiment on induction motor drive system are carried out to investigate the system performance. Nominal parameters of the induction motor are-

Table 4 Rated Parameters of Induction Motor

Rated Power (Pn)	1.1Kw
Rate current (An)	2.8A
Rate Voltage (Un)	380V
Stator Resistance (Rs)	6.4985 Q
Rotor Resistance (Rr)	3.4289 Q
Stator Self Inductance (Ls)	0.4113H
Rotor Self Inductance (Lr)	0.4113 H
Magnetizing Inductance (Lm)	0.3893H
Moment of Inertia (J)	0.02 kg • m2
Number of Poles (p)	2

VII. SIMULATION OF PROPOSED FAULT DIAGNOSIS AND FAULT TOLERANT SCHEME

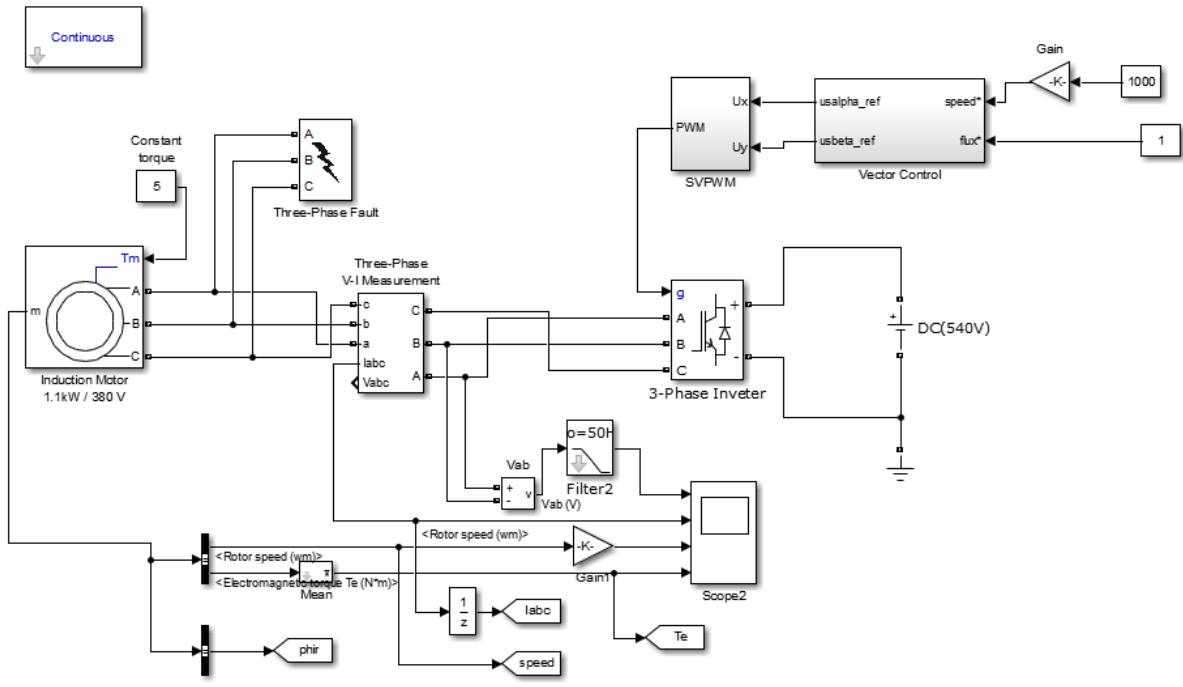


Fig. 9 Matlab/Simulink model of SVPWM –VSI induction motor drive

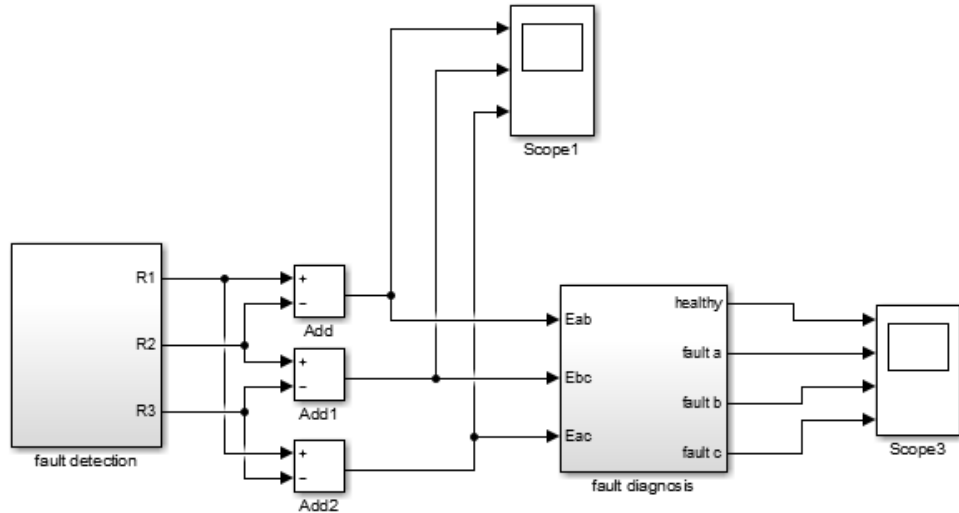


Fig. 10 Matlab/Simulink model of fault detection and fault diagnosis algorithm

VIII. SIMULATION RESULTS

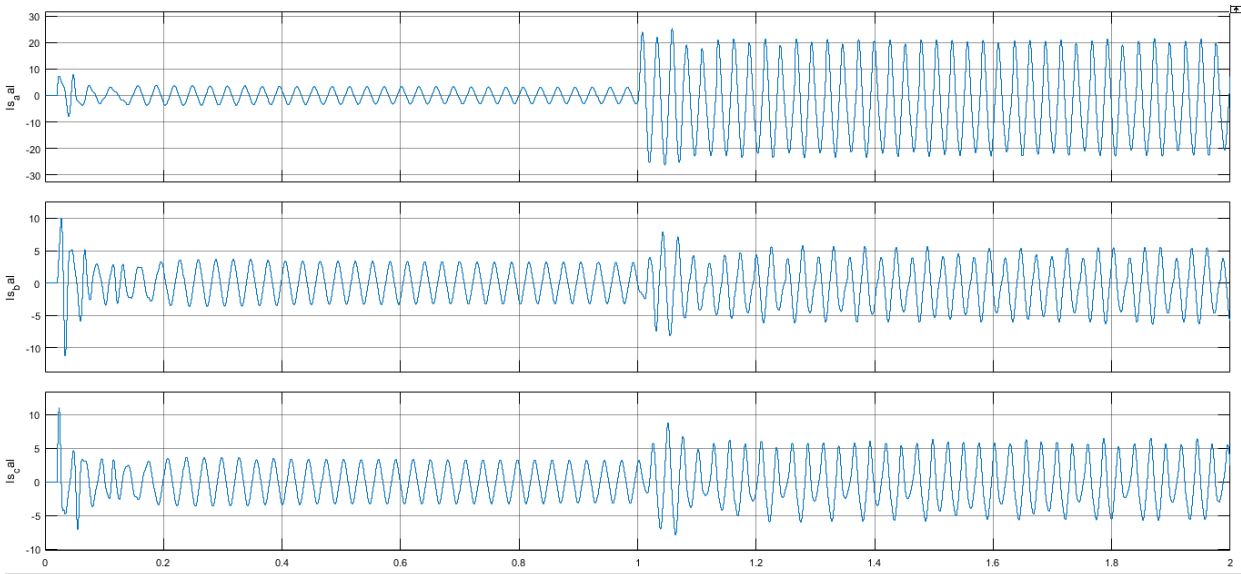


Fig. 11 Estimated Stator Currents in healthy condition and faulty condition

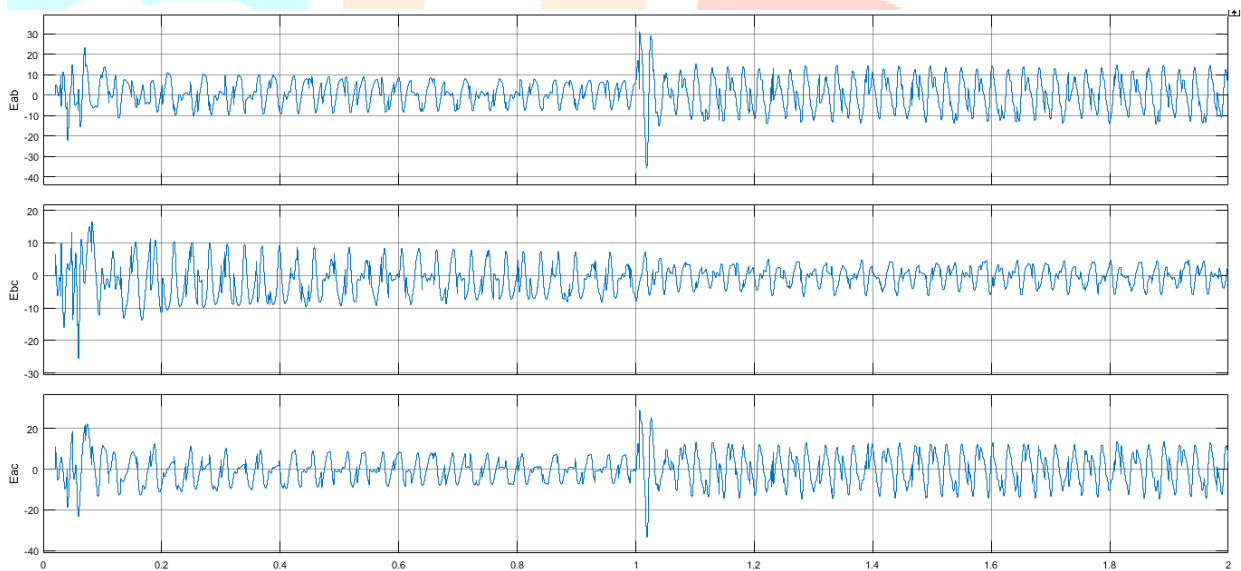


Fig. 12 Estimated stator EMF's in healthy condition and faulty condition

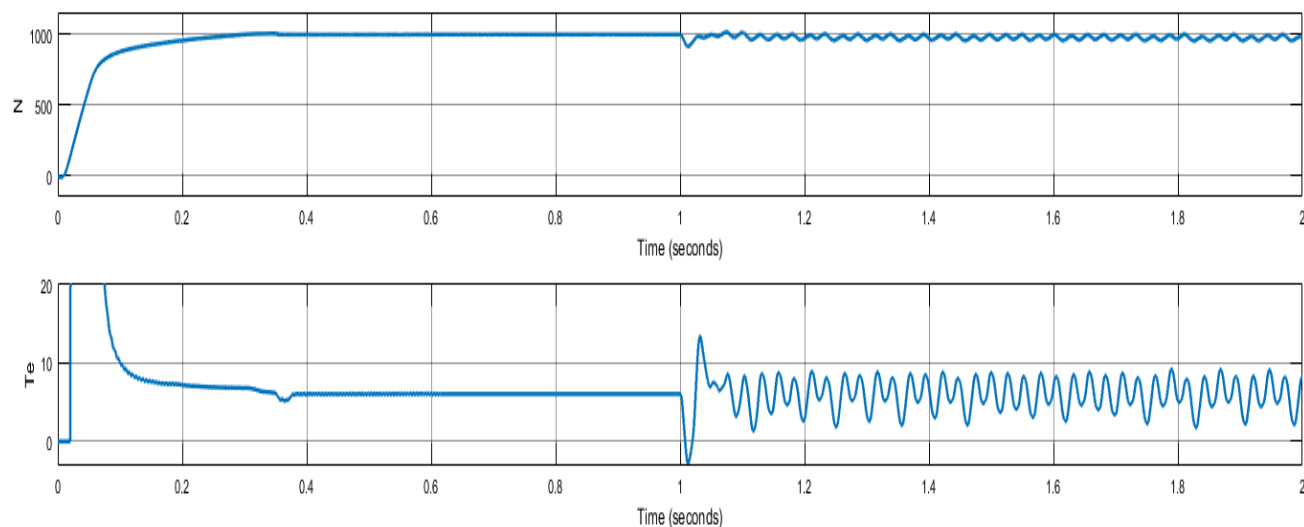


Fig. 13 Variation in speed and torque of the motor in healthy condition and faulty condition

From above results we can interpret that the SVPWM drive runs the motor continuously under healthy condition and under faulty condition also. That is when one of the current sensor or any two current sensors become faulty, the motor is operated in tolerant control mode without halting the operation. Only the small speed and torque fluctuation seen in the output when its operated in tolerant mode as shown in fig.6.4.

IX. CONCLUSION

By studying the all the chapters discussed in the report and comparing the results of simulation results we can say the following points

- a. In this report presented a new method of current sensor fault diagnosis and tolerant control for induction motor. This approach can implement the detection, localization, and tolerant control of single or two current sensors fault, even when their faults occurred in sequence.
- b. The current sensor fault diagnosis and tolerant control is based on three paralleled independent full order observers, which take a-phase current, b-phase current and c-phase current as inputs, respectively.
- c. The observers are capable of on-line monitoring the state of current sensors under normal operation. Furthermore, after one or even two current sensors getting faulty, the observers can detect and localize the faults and switch the system to tolerant vector control mode even with only one healthy phase current sensor available.
- d. The proposed method is suitable for safety crucial applications of induction motor drives; it will keep the system running even in severe failures occurrence.

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