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Fault tolerant control of induction motor through observer techniques II

Khalaf Salloum Gaeid^{1*}, Hew Wooi Ping¹, Mustafa Khalid¹, Saad M.Herdan²

¹Department of Electrical Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia.

²Department of Electrical Engineering, University of Tikrit, Iraq.

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In the design of the control law due to sensor and actuator faults, it is very important to implement the fault tolerant control system. Unknown Input Observers (UIO) can be used in model based fault detection and isolation (FDI) schemes to reduce or almost eliminate the effect of unknown disturbances on the MIMO (Multiple-Input and Multiple-Output) plant/system. Furthermore, they can be used to generate residuals that are insensitive to unknown disturbances or noise, and thus, lower the false alarm rate. Design of many faults isolation banks of UIOs has been done. To make sure the best detection and isolation of the faults is provided, these banks generate residuals which are sensitive to only one fault. Fault tolerant control is used to compensate both sensor and actuator faults.

Key words: Fault tolerant control, actuator fault, and sensor fault unknown input observer, fault detection and isolation, MIMO system, induction motor.

INTRODUCTION

Nowadays, there is a demand for high performance electric drives capable of accurately achieving speed command which necessarily leads to more sophisticated control methods. Induction motors play an important role in the industry because of advantages of size, cost and efficiency (Khalaf et al., 2009; Andrzej, 2001). Fault detection and isolation (FDI) has received a great deal of attention during the last twenty years. As control subjects, diagnosis is based on a model of the system under study. The model based FDI approach involves two main steps: residual generation and decision making. This model usually represents the normal behavior of the system in the absence of any fault. Detection of sudden or developing faults which occur in actuators, sensors, or other components may be economically reasonable and may contribute to a safe operation or provide fault ride through capabilities (Combastel et al., 2002). The implementation of an observer for a multivariable linear system partially driven by unknown inputs is immensely relevant. In the literature, linear observers which are completely independent of the immeasurable disturbances

are known as UIO. The principle of UIO is to make the state estimation error decoupled from the unknown inputs (disturbances). An observer can be defined as a UIO for the system described by Equation (1), if its state estimation error vector $e(t)$ approaches zero asymptotically, regardless of the presence of the unknown input (disturbance) in the system. The systems with UIO play a vital role in robust model based fault detection. The basic idea behind the use of observers for fault detections is to form residuals from the difference between the actual system outputs and the estimated outputs using an observer (Patton et al., 1997).

The faults of the aircraft actuator are detected and isolated using UIO (Stefan et al., 2005). The designed T-S observer is used for detection and reconstruction of faults which can affect a nonlinear model and can be applied directly for fault detection and isolation of actuator faults (Dan et al., 2006). The uncertainty of the model is still a big problem for selection and adaptation of the threshold (Mohammed et al., 2008). The fault detection and isolation problem (FDIP) in dynamical systems consists of generating a diagnostic signal, which has to be different from zero during a specific fault occurrence and insensitive to other inputs, such as disturbances and other fault signals (Guang et al., 2007).

*Corresponding author. E-mail: salimhazim2010@gmail.com.

Benloucif et al. (2006) presented a scheme of observers with nonlinear decoupling for residual generation to detect the faults in the induction machine. Sarah (2008) presented a sliding mode observer with unique properties. The ability of this observer to generate a sliding motion ensures that a sliding mode observer produces a set of state estimates that are precisely commensurate with the actual output of the plant. Chung et al. (2006) developed a fault detection procedure based on the torque observer structure and the discrete wavelet transform (DWT) method to detect servomechanism faults. Jason et al. (2006) studied the fault detection, isolation, and recovery (FDIR) system, in the case of an aircraft elevator redundancy control system, and demonstrated how to trace requirements to a design and create tests based on those requirements. Zhengang et al. (2005) proposed a novel scheme of sensor and actuator (FDI) for multivariate dynamic systems in the presence of process uncertainties.

Great efforts have been devoted to fault tolerant control to ensure the detection of all faults (actuator, sensor, incipient) as well as to maintain a pre specified performance of the system (Christopher et al., 2006). Mohamed et al. (2007) presented a fault tolerant controller for a 4Kw induction motor with a conventional and intelligent approach to maintain the specified system performance. Bennett et al. (1996); Jihen et al. (2004) presented fault tolerant control of an induction motor using direct torque control (DTC) to investigate the tolerance of the drive against sensor faults. There are two main approaches of fault tolerant control, namely passive and active control. In passive fault tolerant control (PFTC), there is no need for adaptation in the control law and so these controllers may be considered as a class of robust controllers, while active FTCS react to the detection of a fault to maintain a certain level of the system performance by either choosing pre-computed fixed control laws designed or by modifying the controller parameters. It is thus considered a class of adaptive control (Floquet et al., 2007). The work in this paper is a continuation of that published in Khalaf et al. (2010).

The aim of this paper is to implement the fault detection and isolation of induction motor observer based approaches with an emphasis on UIO as well as, FTC.

PROBLEM STATEMENT

The state space of the induction motor is given as:

$$\begin{aligned} \dot{X} &= Ax + B v_s + Ed \\ I_s &= Cx + f_s \end{aligned} \tag{1}$$

Where $x \in R^n$ is the state vector, $I_s \in R^m$ is the output

vector, $v_s \in R^r$ is the known input vector and $d \in R^q$ is the unknown input (or disturbance) vector. A, B, C, E and F is known matrices with appropriate dimensions, according to the system shown by Floquet et al. (2007); Chen (2008):

$$x = [i_s \quad \lambda_s]^T \tag{2}$$

The stator current can be expressed as:

$$i_s = [i_{sd} \quad i_{sq}]^T \tag{3}$$

The stator flux components are:

$$\lambda_s = [\lambda_{sd} \quad \lambda_{sq}]^T \tag{4}$$

λ_{sd} , λ_{sq} are direct and quadrature stator flux components respectively.

The stator voltage components are as in Equation (5):

$$v_s = [v_{sd} \quad v_{sq}]^T \tag{5}$$

The state matrix of the system can be expressed as in Equation (6):

$$A = [A_{11} \quad A_{12}; A_{21} \quad A_{22}] \tag{6}$$

$[A_{11} \quad A_{12}; A_{21} \quad A_{22}]$, can be expressed as follows:

$$A_{11} = 1/\sigma [1/\tau_s + (1-\sigma)/\tau_s] I \tag{7}$$

Where σ , τ_s are total leakage factor, stator time constant, respectively.

$$A_{12} = L_m / \sigma L_s L_r [(1/\tau_r)I - \omega_o J] \tag{8}$$

$L_m, L_s, L_r, \tau_r, \omega_o$ are the magnetizing inductance, stator inductance, rotor inductance, rotor time constant and angular velocity respectively:

$$A_{21} = (L_m / \tau_s) I \tag{9}$$

$$A_{22} = -(1/\tau_r)I + \omega_o J \tag{10}$$

I an identity matrix,

$$J = [0 \ -1; 1 \ 0]$$

The input matrix of the system can be expressed as in Equation (11):

$$B = [B_1 \ 0]^T \quad (11)$$

B_1 , can be expressed in the following form:

$$B_1 = (1/\sigma L_s)I \quad (12)$$

The output matrix of the system can be expressed as in Equation (13):

$$C = [I \ 0] \quad (13)$$

Design of the general structured UIO

The first major goal of this paper is to design a full order unknown input observer (UIO) based on the structure of Equation (14) (Hafiz, 1995). The structure of the UIO is as follows:

$$\dot{z} = Fz(t) + TBu(t) + Ky(t) \quad (14)$$

$$\hat{x} = z(t) + Hy(t) \quad (15)$$

Where \hat{x} is the estimated state vector and z is the state of this full order observer, and F , T , K , H are matrices to be designed for achieving UI decoupling and other design requirements. The observer described by Equation (14) is illustrated in Figure 4. The error between the plant state vector and estimated state vector is $e(t)$:

$$e(t) = x(t) - \hat{x}(t) \quad (16)$$

The dynamic error can be expressed as in Equation (17):

$$\dot{e}(t) = \dot{x}(t) - \dot{\hat{x}}(t) \quad (17)$$

By substituting Equation (14) to (16) in Equation (17) we can get:

$$\begin{aligned} \dot{e}(t) = & (A - HCA - K_1 C)e(t) + [F - (A - HCA - K_1 C)]z(t) \\ & + [K_2 - (HCA - K_1 C)H]y(t) + [T - (I - HC)]Bu(t) + [HC \\ & - I]Ed(t) \end{aligned} \quad (18)$$

$$K = K_1 + K_2 \quad (19)$$

The gain matrix k_1 is found using bilinear feedback to cancel the first two columns in the error dynamics.

Similarly, K_2 is calculated as in Equation (20) (Chen, 2008):

$$K_2 = FH \quad (20)$$

$$F = A - HCA - K_1 C \quad (21)$$

If all Eigen values of F are stable then the error $e(t)$ will approach zero asymptotically. This means that the observer is an UIO for the original system (Young et al., 1994). The most important aspect of the model based FDI is the generation of residuals. To provide useful information for FDI, the residual should be:

$$r_{es}(t) \neq 0 \quad \text{iff} \quad f(t) \neq 0 \quad (22)$$

Then the fault can be detected by comparing the function of the residual generated with the threshold of each parameter as can be seen in the proposed structure of the work done by (Shao et al., 1997).

Theorem1. If the following conditions are satisfied:

1. Rank (E^*C) should be equal to the rank (E). The checking proves that the rank (C^*E) = 1 and the rank of E after checking = 1, so the first condition is satisfied.
2. (A_1 , C) is detectable. Where;

$$A_1 = TA \quad (23)$$

$$T = I - HC \quad (24)$$

There is gain matrix K such that the estimation $e(t) = x(t) - \hat{x}(t)$ will converge to zero when $t \rightarrow \infty$.

Theorem 2. The second condition of Theorem 1, which states that the pair (A_1 , C) is detectable when the rank is equivalent to:

$$\begin{bmatrix} sI - A & E \\ C & 0 \end{bmatrix} = n + m \quad (25)$$

This is valid for all values of s , such that $\text{real}(s) \geq 0$. Where n and m are the order of the system and dimension of the E matrix, respectively.

FAULT DETECTION AND ISOLATION ALGORITHM

Fault detection

The classical observer based fault detection scheme is to

construct an observer, which takes the input and output of a system and generates a signal called residual. This signal is processed to decide if the system is faulty or healthy (Saverio et al., 2008). Fault detection and isolation technique for induction motor and the state space matrices of the induction motor has been mentioned earlier. Using MATLAB to find state feedback controller (K) by pole placement method:

$$[K \ l \ s] = lqr(A, B, Q, R, N) \tag{26}$$

Therefore the control law of the system becomes as follows:

$$u(k) = K_1 x(k) - K_2 Z(k) \tag{27}$$

The calculation of state gain K is chosen to minimize the following cost function:

$$j = 1/2 \sum_{k=0}^{\infty} (X^T(k)QX(k) + u^T(k)Ru(k)) \tag{28}$$

The matrix N is set to zero in this paper. Also returned are the solution l of the associated algebraic Riccati equation and the closed loop Eigen values in the following form:

$$A^T XA - X - A^T X B (B^T X B + R)^{-1} B^T X A + Q = 0 \tag{29}$$

This is solved by (dare) instruction in Matlab:

$$s = eig(A - BK) \tag{30}$$

This will be shown in Figure 11.

$$k = \begin{bmatrix} 7.69 & -0.000 & 40.208 & 5.6343 \\ -0.000 & 7.69 & -5.6343 & 40.208 \end{bmatrix}$$

$$l = \begin{bmatrix} 0.1332 & -0.0000 & 0.6968 & 0.0963 \\ -0.0000 & 0.1332 & -0.0963 & 0.6968 \\ 0.6968 & -0.0963 & 3.7181 & -0.0000 \\ 0.0963 & 0.6968 & -0.0000 & 3.7181 \end{bmatrix}$$

In the design of the UIO, the desired locations of the poles were selected at ($s = -2, -3, -4, -5$), which implies:

$$F = \begin{bmatrix} -2 & 0 & 0 & 0 \\ 0 & -3 & 0 & 0 \\ 0 & 0 & -4 & 0 \\ 0 & 0 & 0 & -5 \end{bmatrix}$$

$$s = 1.0e + 2 * \begin{bmatrix} -0.3761 + 1.5377i \\ -0.3761 - 1.5377i \\ -0.2170 + 0.0410i \\ -0.2170 - 0.0410i \end{bmatrix}$$

The rank's condition of the $(C^*E) = \text{rank}(E)$ means that the corresponding states coupled with unknown inputs must be obtainable from the measurement outputs. It is worth noticing that the number of output signals is not less than the number of unknown inputs (Julien et al., 2009). For a stable system, the following condition should be satisfied:

$$M = TA - FT - kC = 0 \tag{31}$$

$$M = 1.0e - 012 * \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -0.2274 & 0 \\ 0 & 0 & 0 & -0.0568 \\ 0 & 0 & 0 & 0 \end{bmatrix} \approx 0$$

Fault isolation

The detection of any fault should be followed by fault isolation, which will distinguish (isolate) a particular fault from others. The meaning of fault isolation is simply to find which residual does not satisfy the fault condition ($r(t) \neq 0$).

Fault isolation may be achieved by using observer schemes (Claudio et al., 2004) as can be seen in Figure 12. To prove the ability to track the outputs of the system, the controllability and the uncontrollable state in the presence of faults should be tested according to the following formula:

$$cont = ctrb(A, B) \tag{32}$$

Number of uncontrollable states (UC) is:

$$UC = \text{length}(A) - \text{rank}(cont) = 4 - 4 = 0$$

The controllability matrix is given at the bottom of the page in (33). The simulation of actuator faults as additive fault is shown in Figure 6. The bias sensor fault for the quadrature or direct components of the stator current is shown in Figure 7.

Fault tolerant control

The fault tolerant control which should be containing the above fault detection and isolation can be achieved in two ways: passive and active approaches (Hassan et al.,

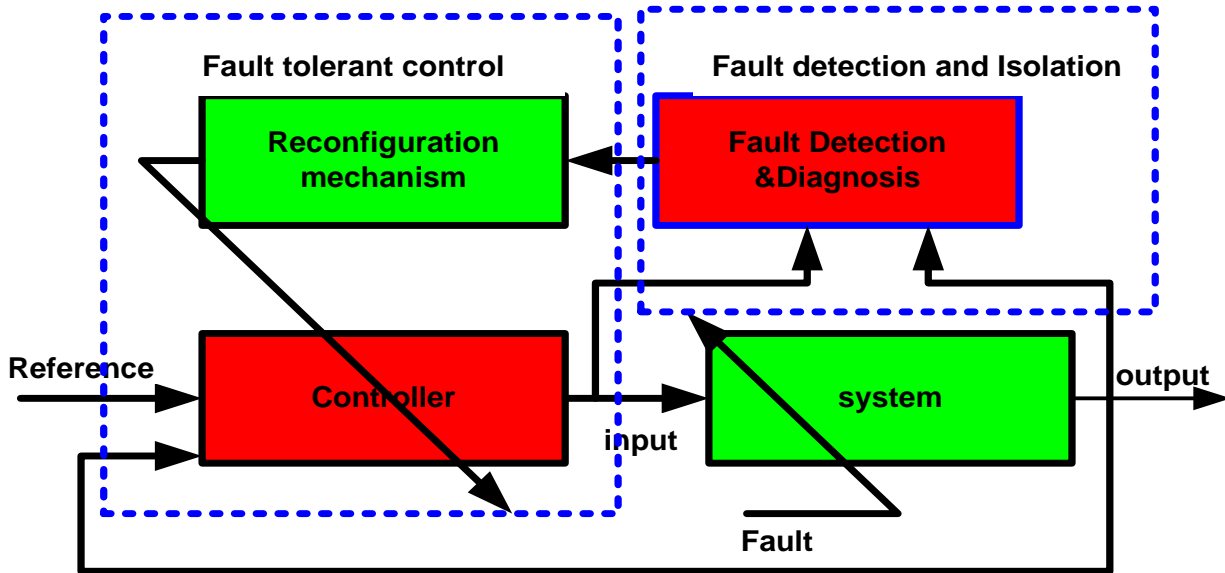


Figure 1. Complete FTC scheme.

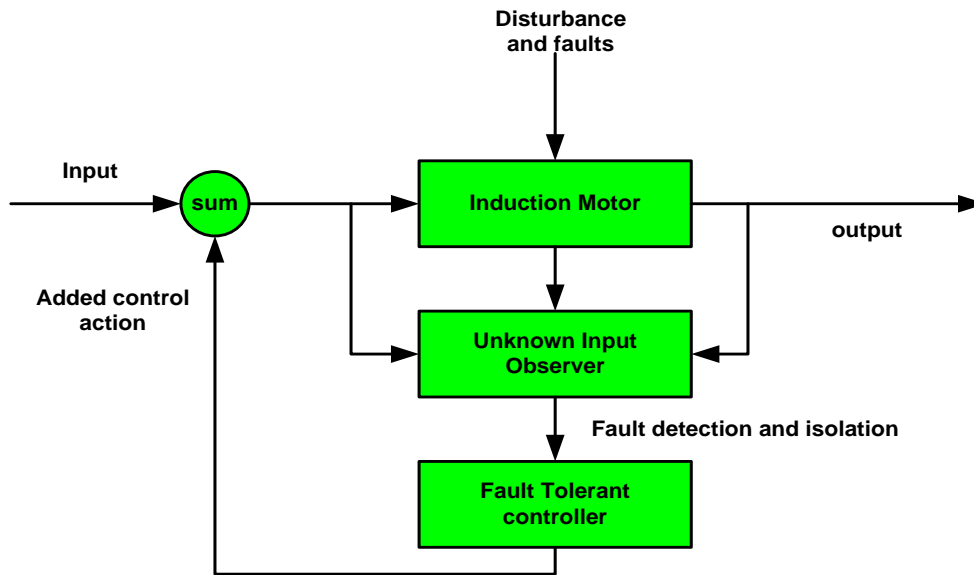


Figure 2. Fault tolerant control.

2009); also the reconfigurable controller is another part of the FTC system as is shown in Figure 1. The complete procedure used in this work is shown in Figure 2.

$$cont = e + 6^* \begin{bmatrix} 0 & 0 & 0 & 0 & 0.0018 & 0.0268 & 3.9701 & -0.8557 \\ 0 & 0 & 0 & 0 & -0.0268 & 0.0018 & 0.8557 & 3.9701 \\ 0 & 0 & 0 & 0 & -0.0005 & -0.0049 & -0.7121 & 0.2680 \\ 0 & 0 & 0 & 0 & 0.0049 & -0.0005 & -0.2680 & 0.7121 \end{bmatrix} \quad (33)$$

Good fault tolerant performance can be achieved for

many machines by adapting a flexible controller architecture that can stabilize the system performance in the event of fault occurrence (Demba et al., 2004).

Actuator and sensor mathematical models should be defined; in this paper $u(k)$ expresses the input without fault occurrence, $u_f(k)$ is the actuator fault expressed as additive noise with original input as is shown in Figure 6, while the sensor fault is expressed as an additive bias in the output measurement (Xiaodong, 2002), as can be seen in Figure 7. After the isolation of fault, a control law

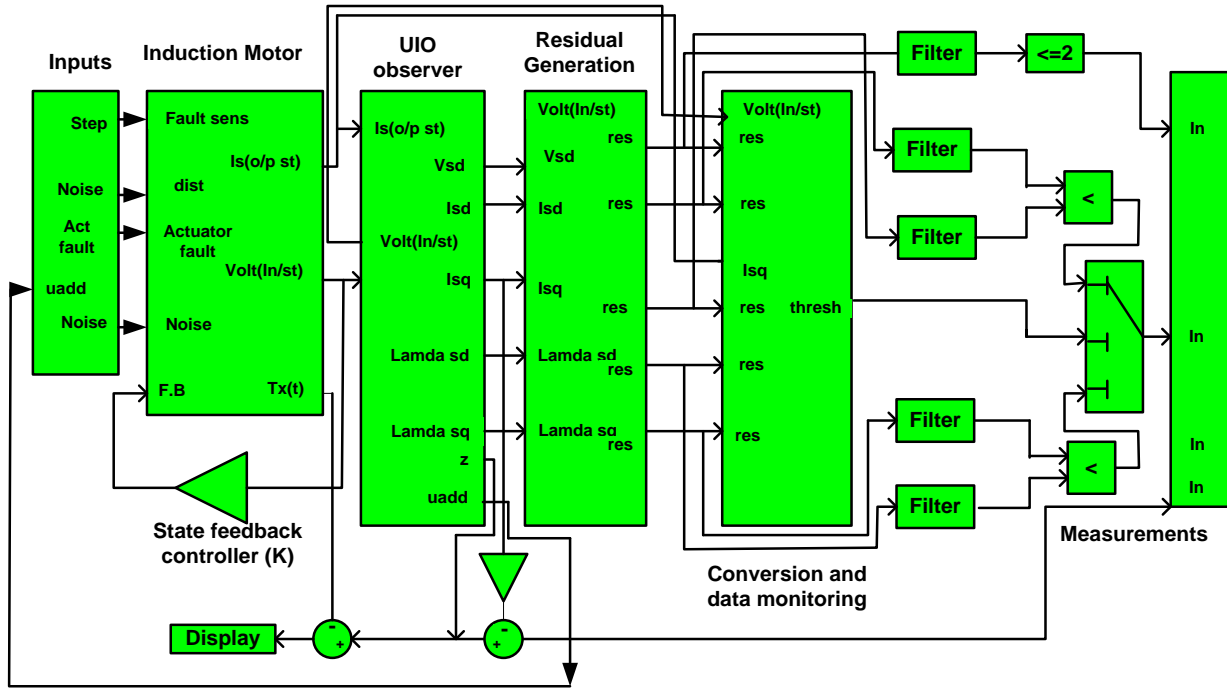


Figure 3. Proposed structure of fault tolerant control algorithm.

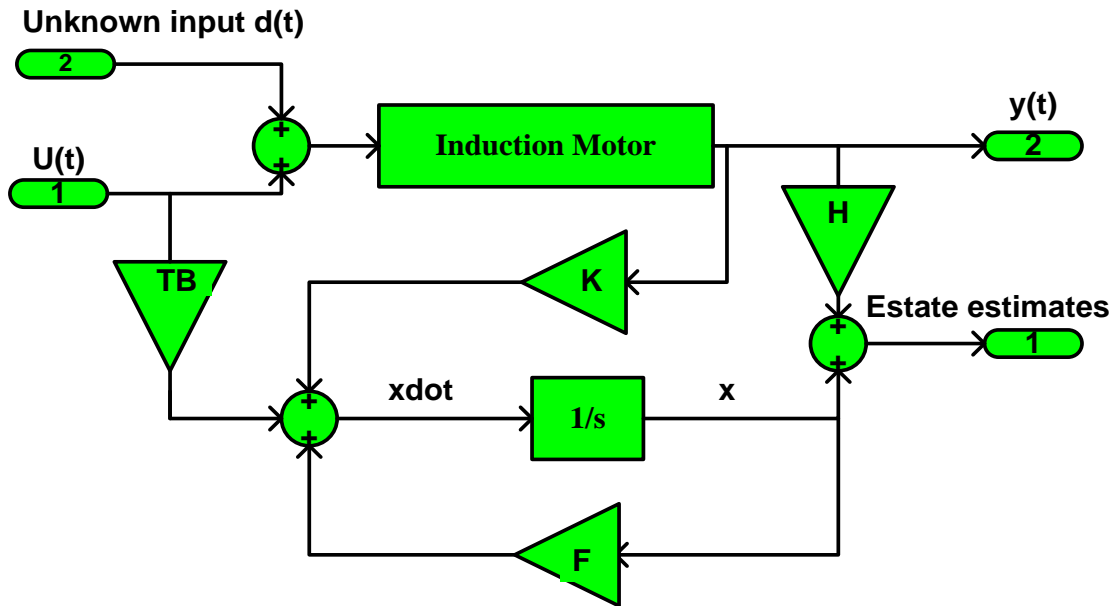


Figure 4. Induction motor coupling with UIO.

should be added to compensate this fault, so Equation (27) becomes as follows:

$$u_f(k) = K_1 x(k) - K_2 Z(k) + u_{add} \quad (34)$$

u_{add} is the control law added to compensate the fault as can be seen in Figures 3 and 8.

$$u_{add} = inv(B) * F_a * f_a(k) \quad (35)$$

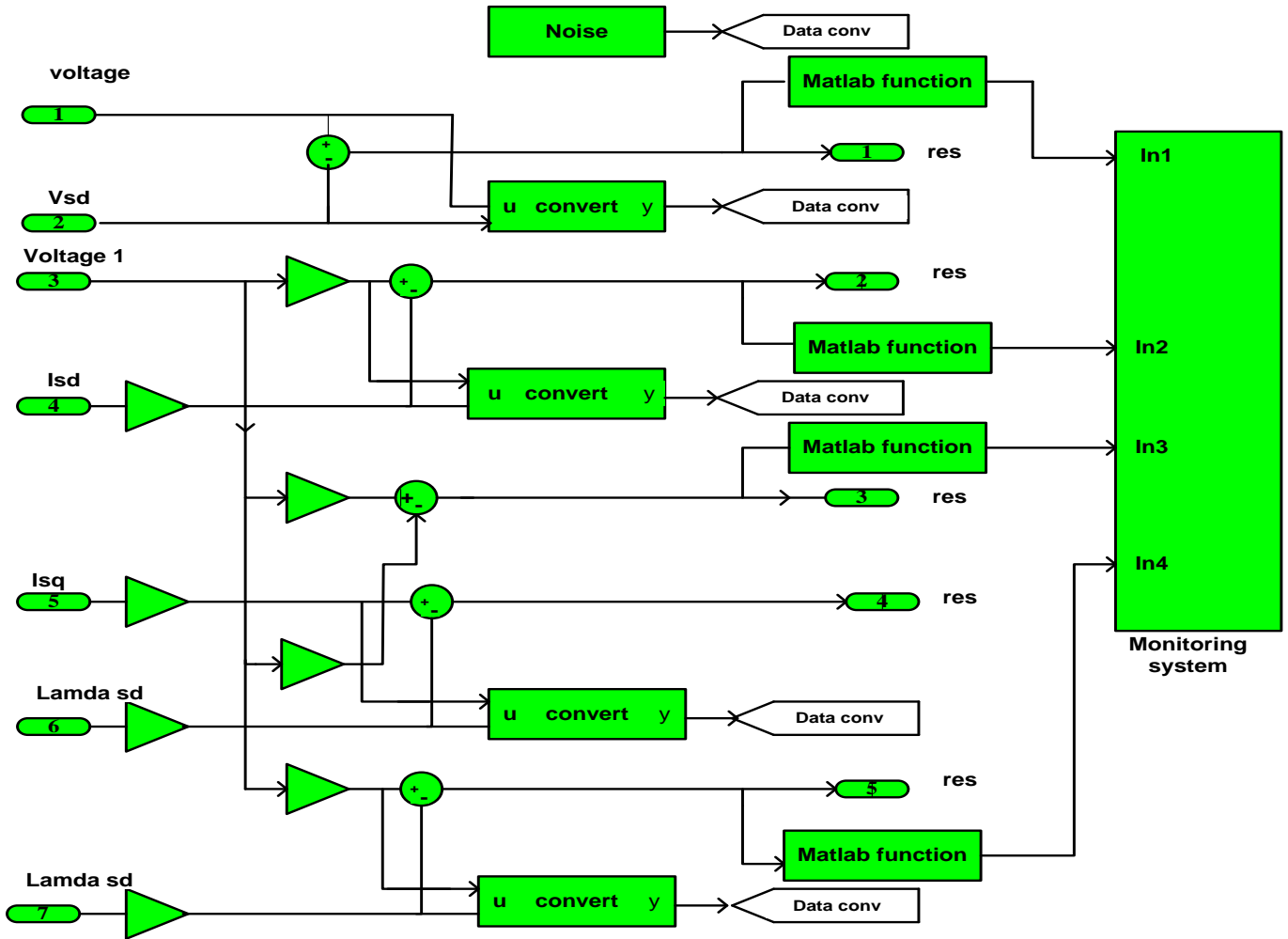


Figure 5. Residual generation and data convert.

Equation (34) and (35):

$$u(k) = K_1 x(k) - K_2 Z(k) + inv(B) * F_a * f_a(k) \tag{36}$$

The induction motor mathematical model, Equation (1) in the actuator fault takes the following form:

$$\begin{aligned} X(k+1) &= Ax(k) + Bu(k) + F_{act} f_{act}(k) \\ y(k) &= x(k) \end{aligned} \tag{37}$$

The following form in the sensor fault:

$$\begin{aligned} X(k+1) &= Ax(k) + Bu(k) \\ y(k) &= x(k) + F_s f_s(k) \end{aligned} \tag{38}$$

Where F_s, f_s are known matrices. The whole circuit of the fault tolerant controller is shown in Figure 3.

SIMULATION RESULTS

The complete structure of this work is composed of the UIO coupled with the induction motor as is shown in Figure 4; the proposed scheme is depicted in Figure 3; Figure 5 represents the residual generation and the data conversion of the proposed scheme. Figure 8 shows the UIO with fault tolerant controller, Figure 9 represents actuator fault detection after the response of the states exceeds the threshold (0.25). Consequences of a fault in the actuator would most likely be instability (fluctuation). Figure 10 represents a healthy case, with all states within the threshold, and a corresponding test of controllability as further evidence of the healthy state. The difference between the length of matrix (A) and the rank of controllability equals zero (no uncontrollable state). Also, the stability check shows all poles in the left hand of the s-plane as in Figure 11. Figure 12 shows the results of

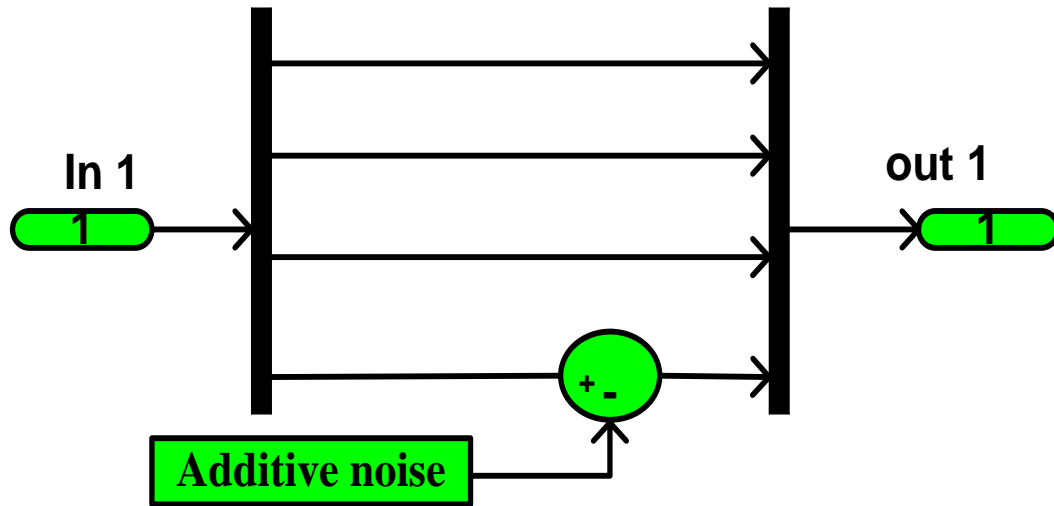


Figure 6. Additive actuator fault.

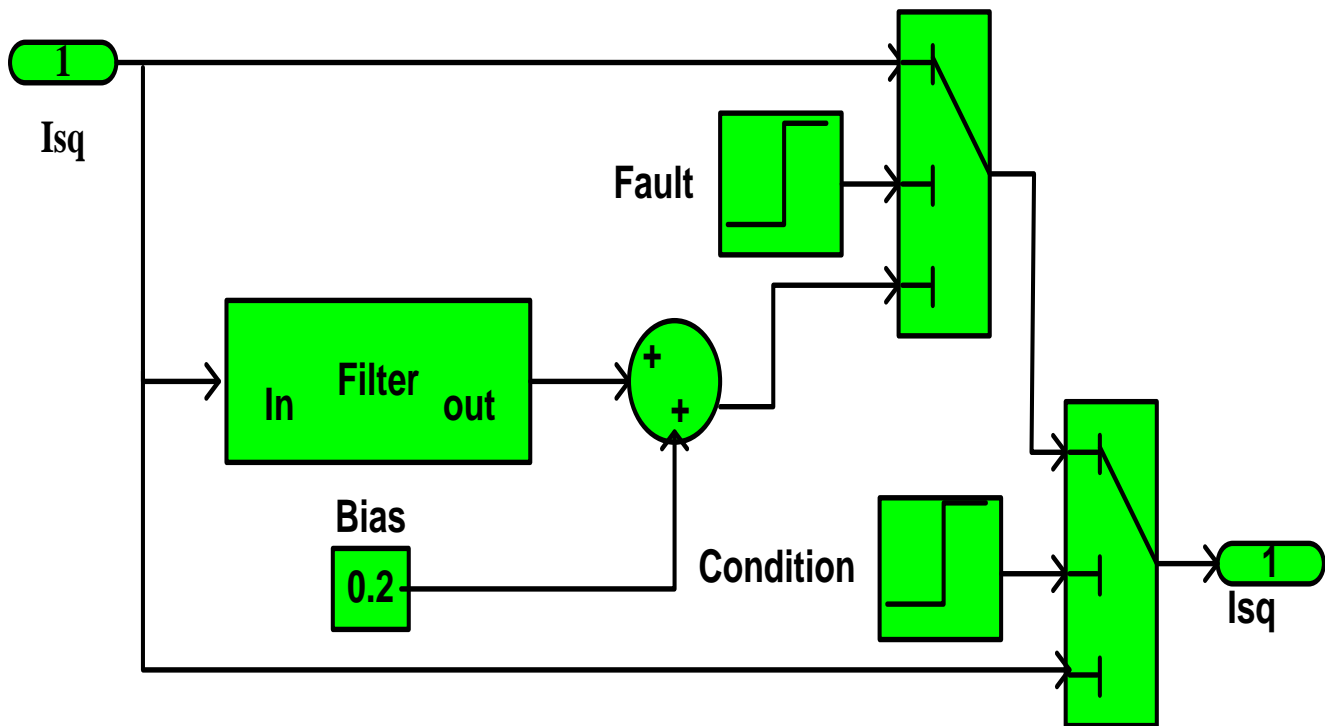


Figure 7. Sensor fault on stator current (I_{sq}).

amplitude of the fault isolation when fault occurs in actuator at 0.4 s. It is seen that the isolation increases with occurrence of fault. The nonzero (M) result of Equation (31) may be due to uncertainty of some parameter of induction motor. To test the reconfiguration circuit, two faults are tested, sensor and actuator fault and we observe the tolerance of the both components of stator current (I_{sd} , I_{sq}). These faults are tested at time 0.2

s as can be shown in Figure 13 for the I_{sd} and Figure14 for I_{sq} .

DISCUSSION

Simulink implementation of the UIO fault detection for a Multi-Input Multi-Output (MIMO) system is presented. In

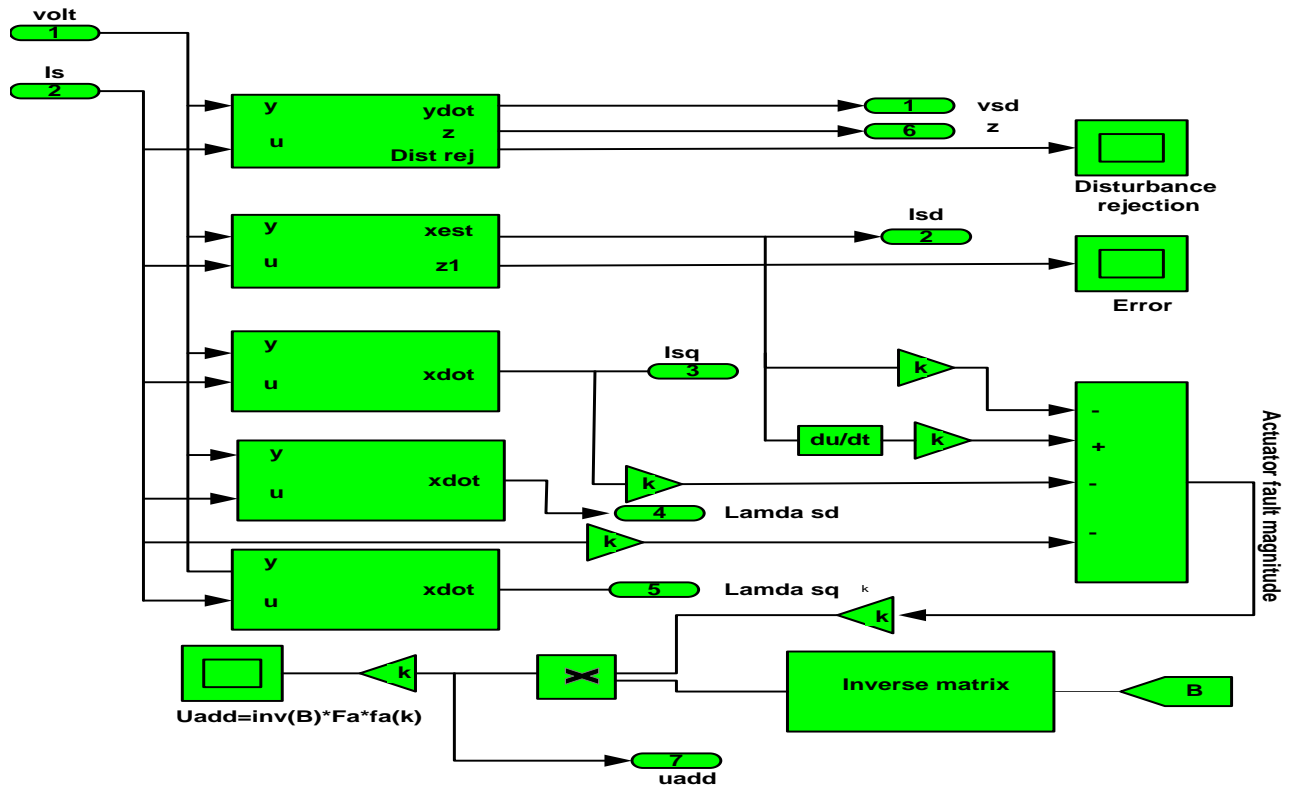


Figure 8. U I O with fault tolerant controller.

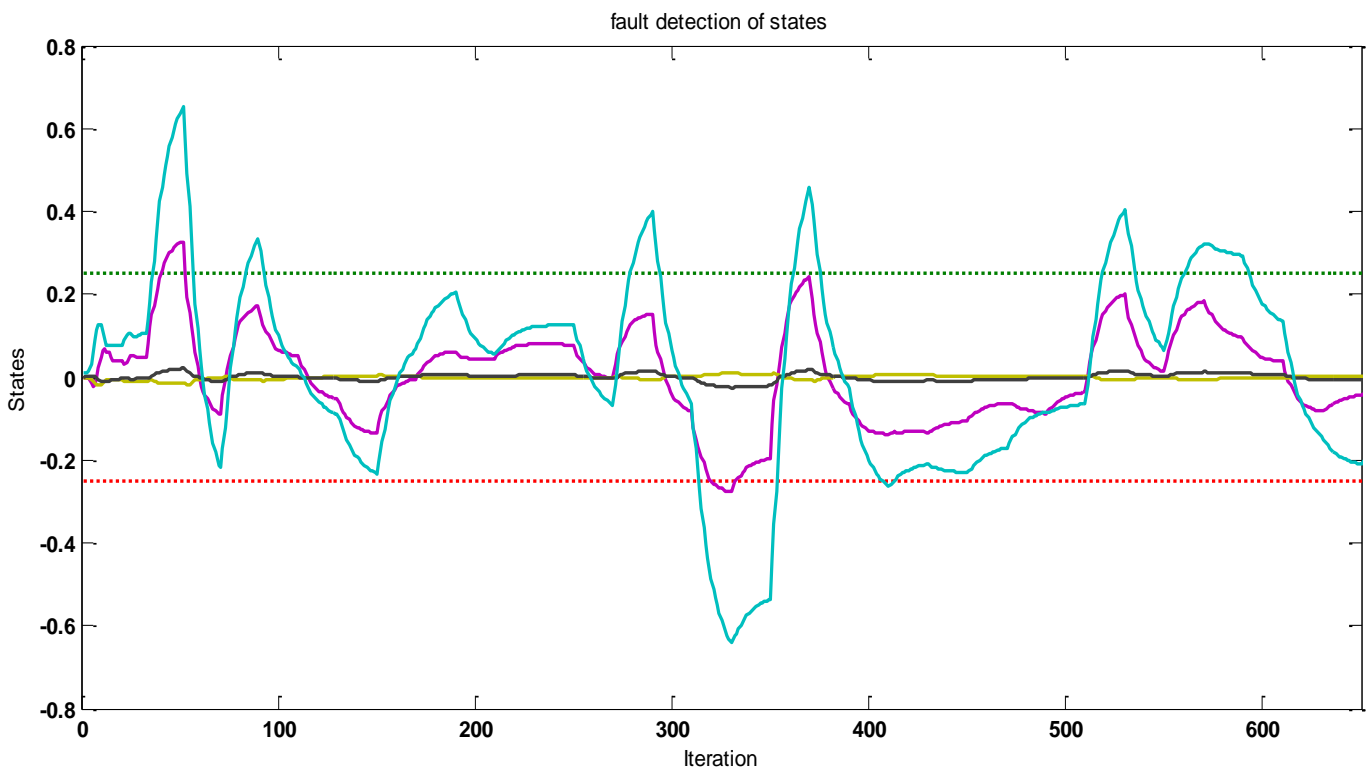


Figure 9. Actuator fault detection (pu).

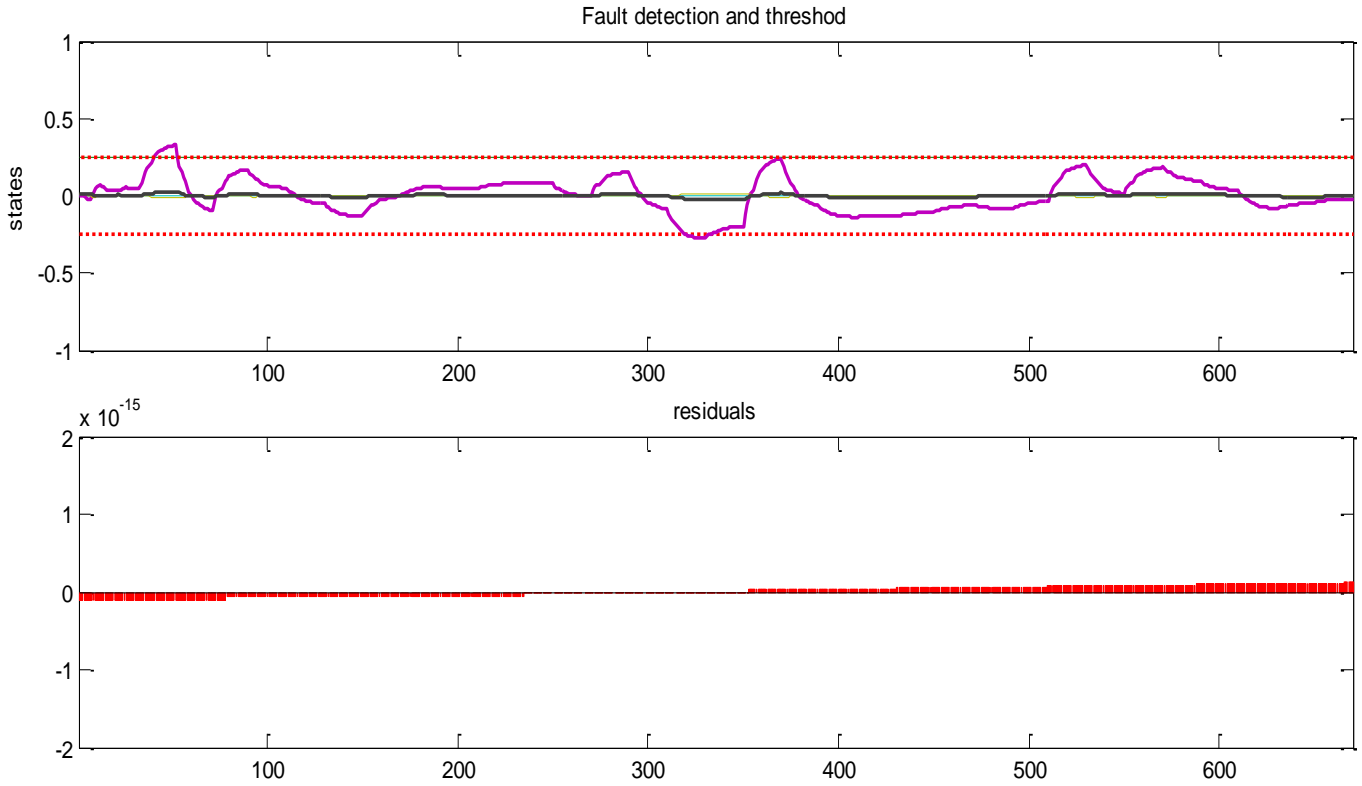


Figure 10. Healthy case output and residual within threshold (pu).

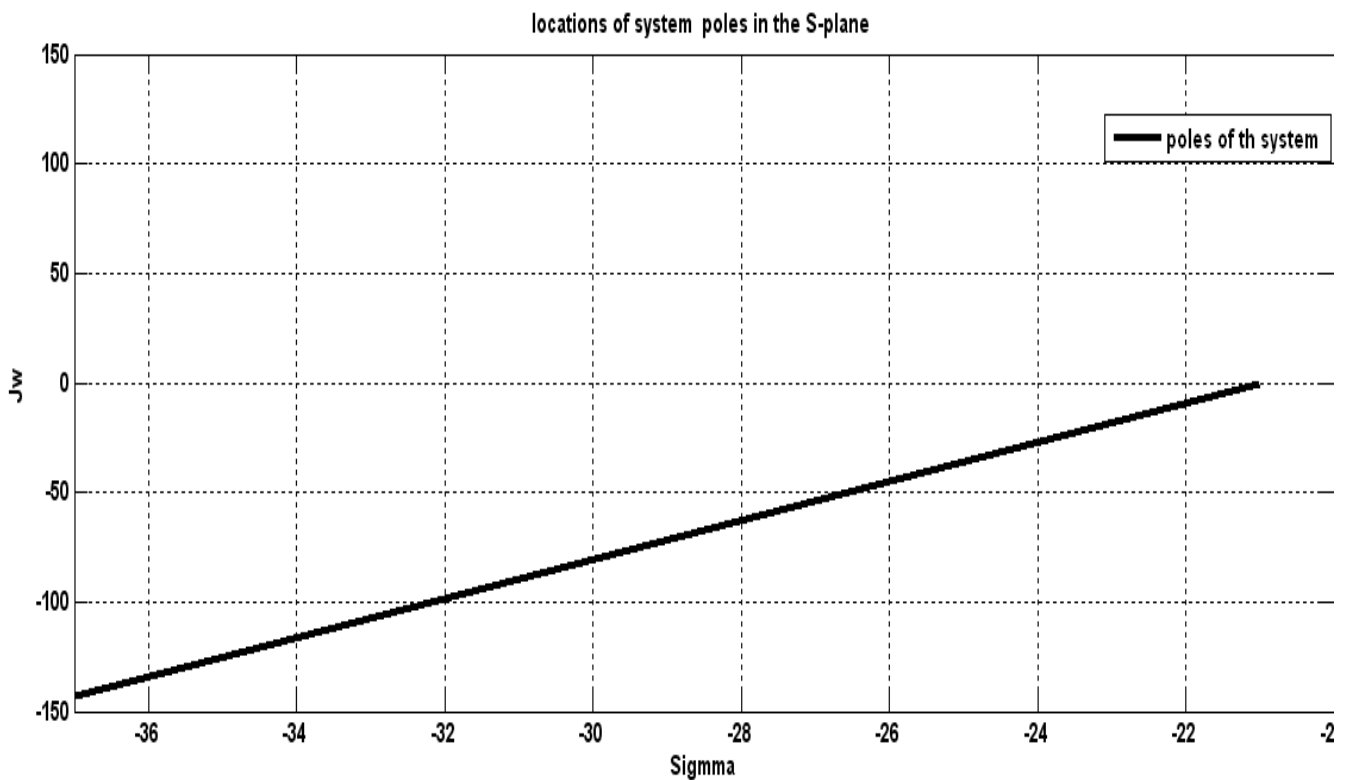


Figure 11. Stability checking after the fault isolated.

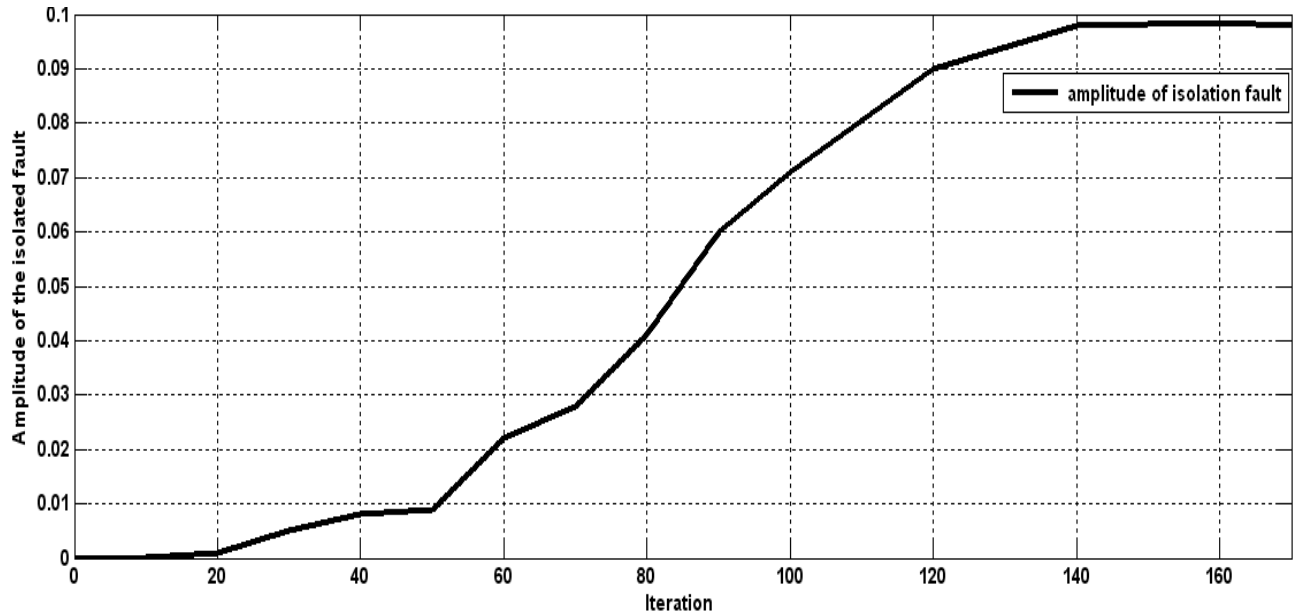


Figure 12. Actuator fault isolation.

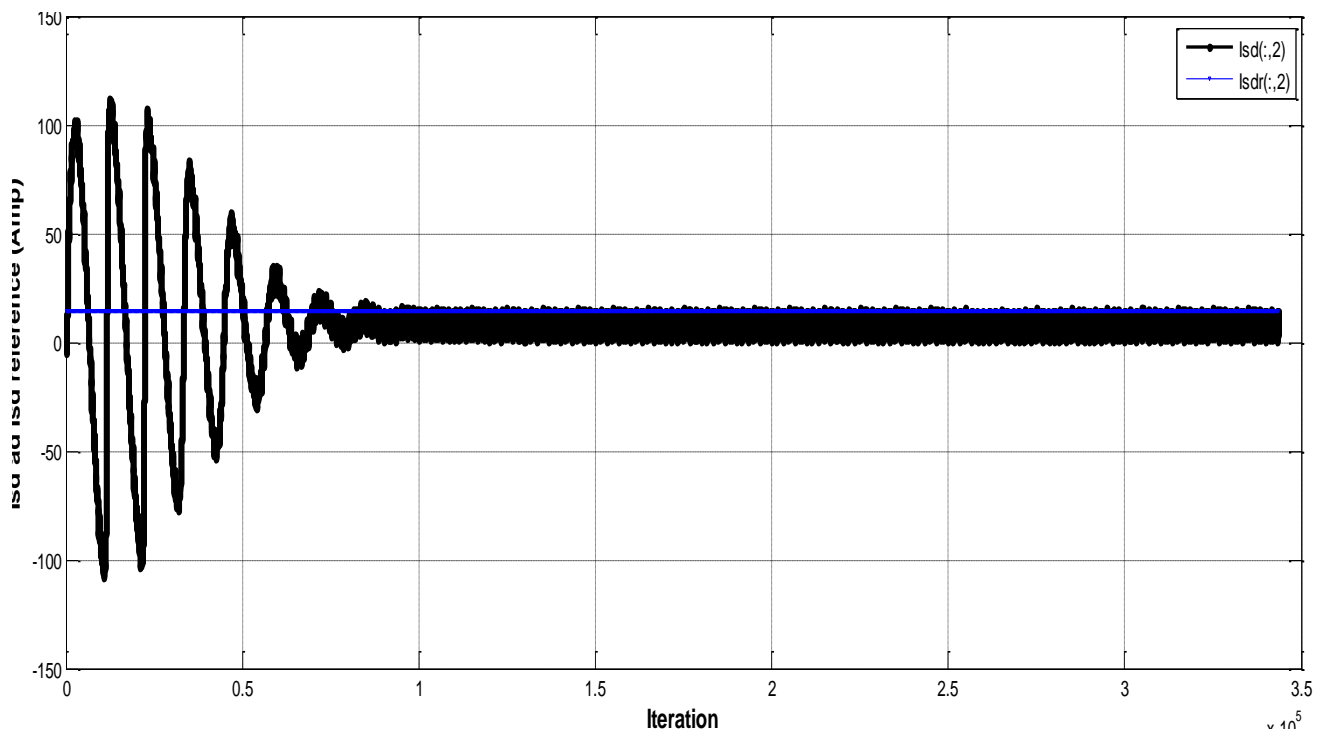


Figure 13. I_{sd} response with fault compensation.

the presence of the actuator and sensor faults, this approach was able to decouple all faults. As is seen in Figure 2, the input from the inverter is summed with the control action and provided to both the induction motor and to the UIO. The disturbances and faults are

introduced into the induction motor. Also, the induction motor output and its states are fed to the UIO. The FTC compensates for the fault and determines the right control action.

The fault tolerant control was able to compensate the

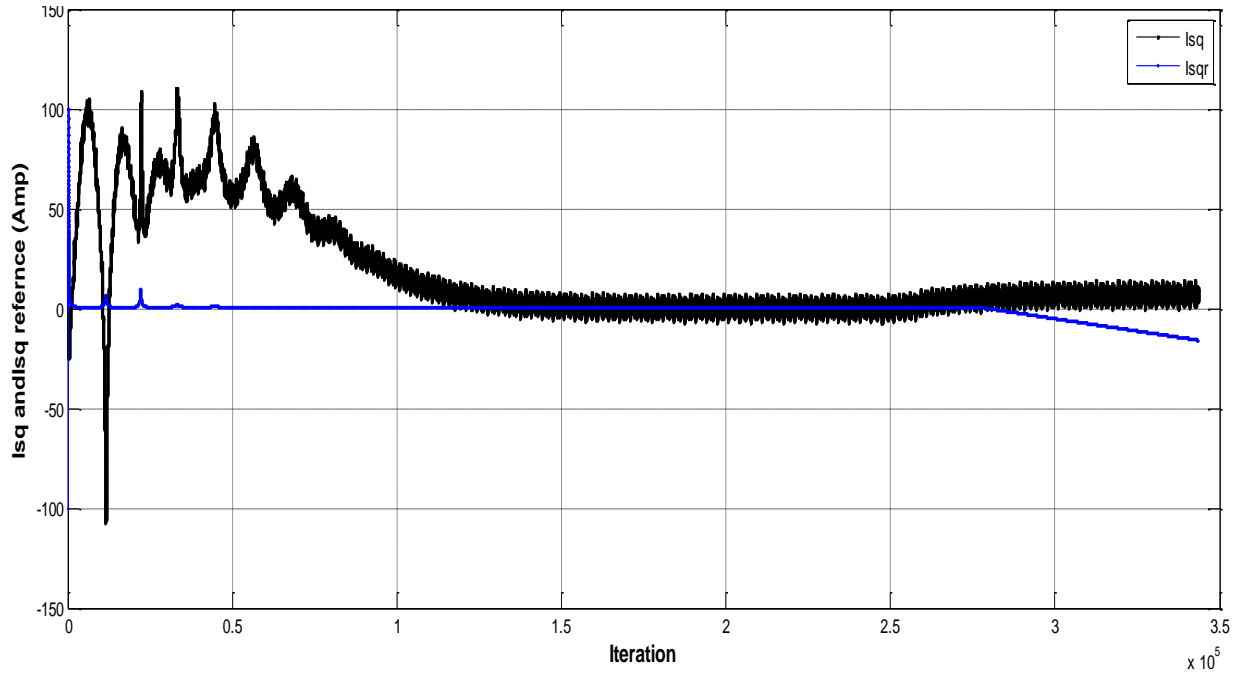


Figure 14. I_{sq} response with fault compensation.

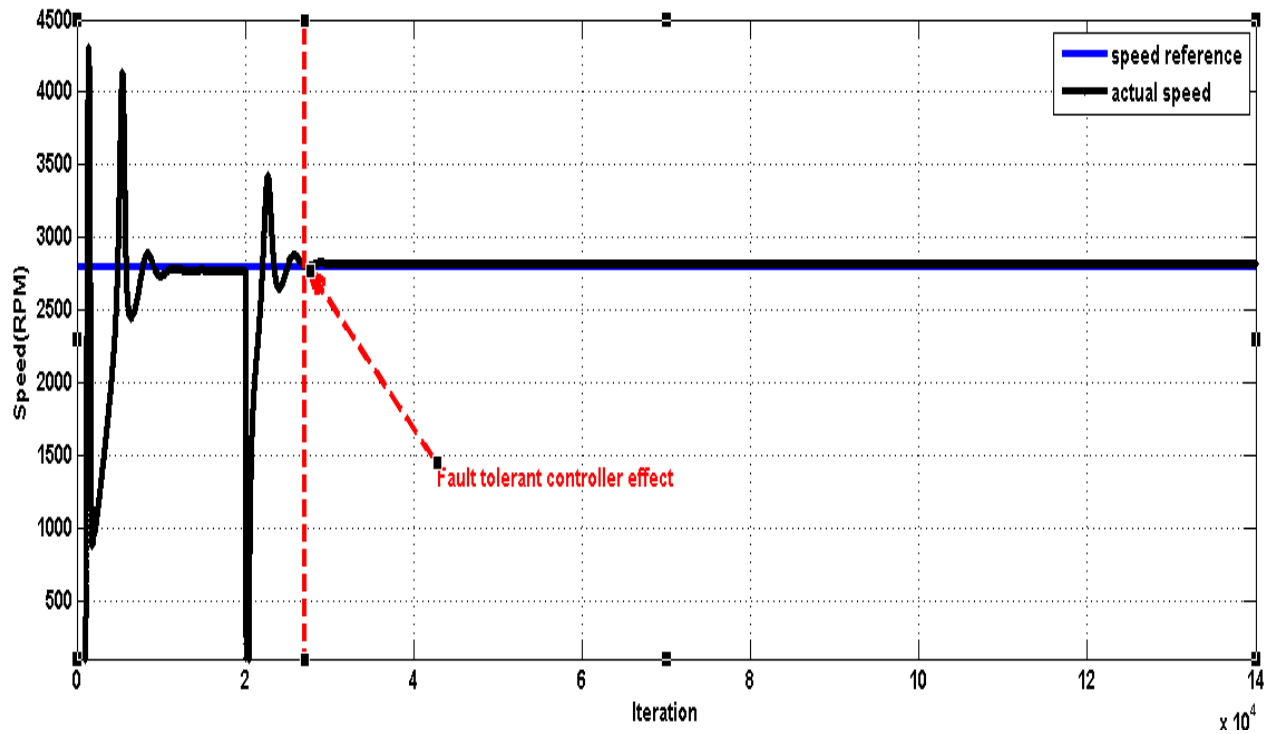


Figure 15. Speed response of reference and actual with fault compensation.

faults within 0.25 s, thereby maintaining the operational performance of the induction motor. Figure 15 shows both reference and actual speeds with fault compensation

when the system is subjected to sensor and actuator faults at the beginning of motor operation and after 2 s.

Figure 16 shows the speed response when the speed is

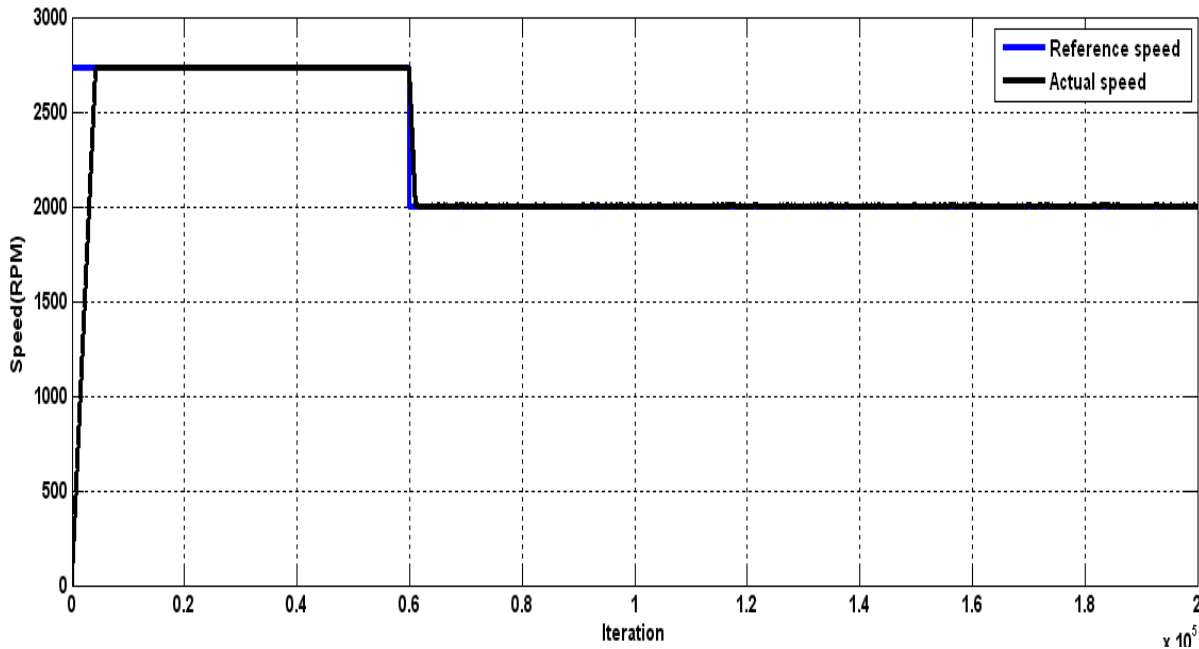


Figure 16. Reference and actual speed with fault compensation when the speed changed from (2730-2000) RPM.

changed into 2000RPM after 1.5 s. The fault tolerant control was able to compensate the faults within 0.25 s maintaining of the performance of induction motor to operate.

Conclusion

A number of qualitative and quantitative techniques have been developed for fault detection and isolation base observers over the past decade for fault detection and isolation of various systems. The systems have performance specifications and uncertain characteristics, so they cannot be modeled perfectly. This paper has introduced the UIO based approach for fault detection in induction motors. MATLAB /SIMULINK implementation of the proposed structure has confirmed the effectiveness of this UIO of the FDI method. The UIO can detect more faults, including instrument faults such as gain and bias changes. For detection of fault, one filter is enough but for isolation a set of filters bank are needed. When one or more faults in process parameters are directly isolated, the degree of those faults is estimated to take the appropriate fault accommodation action, so as to recover from the fault and maintain the system performance.

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