

Full Length Research Paper

Induction motor fault detection and isolation through unknown input observer

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Unknown input observers (UIO) can be used in the model-based fault detection and isolation (FDI) schemes to reduce or almost eliminate the effect of unknown disturbances on the multi input multi output (MIMO) plant/system. In this paper, a new FDI of the MIMO system was carried out in as well as the design of many fault isolation banks of UIOs has been done. These banks are used to generate residuals that are insensitive to unknown disturbances or noise. To make sure best detection and isolation of the faults, these banks generate residuals, which are sensitive to only one fault. The fault in the actuator is detected and isolated with a lower false alarm rate effectively.

Key words: Fault detection and isolation, induction motor, MIMO plant, residuals, unknown input observers.

INTRODUCTION

Nowadays, there is a demand for high performance electric drives. These derive can be capable of accurately achieving speed command. This has necessarily lead to more sophisticated control methods to deal with such an issue. Special attention was directed induction motor because of known reason such as size, cost, efficiency (Khalaf et al., 2009).

Fault detection and isolation (FDI) have received a great deal of attention in the last 20 years. As a control subject, the diagnosis is based on the 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 a fault ride through capabilities (Combastel et al., 2002).

In the literature, the linear observers who are completely independent of the immeasurable disturbances are known as unknown input observers (UIO). The principle of (UIO) is to make the state estimation

error de-coupled from the unknown inputs (disturbances).

An observer can be defined as an 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 unknown input observers play a vital role in robust model-based fault detection the basic idea behind the use of observers for fault detections to form residuals from the difference between the actual system outputs and the estimated outputs using an observer (Patton and Chen, 1997). The faults of the aircraft actuator are detected and isolated using (UIO) (Stefen et al., 2005).

The designed T-S observer is used for detection and reconstruction of faults, which can affect a non-linear model and can be applied directly for fault detection and isolation of actuator faults (Dan and Kai-Yew, 2006). The uncertainty of the model is still a big problem for selection and adaptation of threshold of the model-based fault detection and isolation (Mohammed et al., 2008).

The fault detection and isolation problem (FDIP) in dynamic 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-Hong, 2007).

Benloucif and Balaska (2006) presented a scheme of

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observers with nonlinear decoupling used for residual generation to detect the faults in the induction machine. Trzynadlowski (2001), presented nonlinear observer used in the fault diagnosis of the induction motor. Sarah K. Spurgeon (2008) presented sliding mode observers have unique properties, in that the ability to generate a sliding motion on the error between the measured plant output and the output of the observer.

Chung-Wei et al. (2006) developed a fault detection procedure based on the PI controller of the torque observer structure and the discrete wavelet transform (DWT) method to detect a servomechanism fault. Jason and Pieter (2006) studied a fault detection, isolation, and recovery (FDIR) system, in the case of an aircraft elevator redundancy control system, and demonstrate how to trace requirements to a design, create tests based on those requirements.

Zhengang et al. (2005) propose a novel scheme of sensor and actuator (FDI) for multivariate dynamic systems in the presence of process uncertainties. Wang (2010) presented new approach in sensor fault estimation of the UIO based fault class isolation and estimation. The aim of this paper is to implement fault detection and isolation of induction motor observer-based approaches using unknown input observer.

Induction motor modeling

The state space of the induction motor in the present of faults is:

$$X' = Ax + Bv_s + Ed \tag{1}$$

$$I_s = Cx + f_s$$

$x \in R^n$ 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 and F are known matrices with appropriate dimensions, according to the system shown in (S.M. Bennett et al., 2002 and Hafiz Bilal Ahmad, 2005).

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

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

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

$\lambda_{sd}, \lambda_{sq}$ are direct and quadrature stator flux components

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

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

The values of $(A_{11}, A_{12}, A_{21}, A_{22})$ as follows:

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

Where σ, τ_s, τ_r are the total leakage factor, stator time, rotor time constants 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 is the magnetizing inductance, stator inductance, and rotor inductance respectively, Andrzej, (2001).

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

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

I is an identity matrix and $J = [0 \ -1; 1 \ 0]$

$$B = [B_1 \ 0]^T \tag{11}$$

$$B_1 = (1/\sigma L_s) I \tag{12}$$

$$C = [I \ 0] \tag{13}$$

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 (2). The structure of the unknown input observer (UIO) as follows:

$$z' = Fz(t) + TBu(t) + Ky(t) \tag{14}$$

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

\hat{x} is the estimated state vector, z is the state of this full-order observer, and F, T, K, H are matrices to be designed for achieving unknown input de-coupling and other design requirements. The observer described by equation (2) is illustrated in Figure 1. The error between the plant state vector and estimated state vector is $e(t)$.

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

The dynamic error is:

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

Substituting the above equations in equation (17) yields:

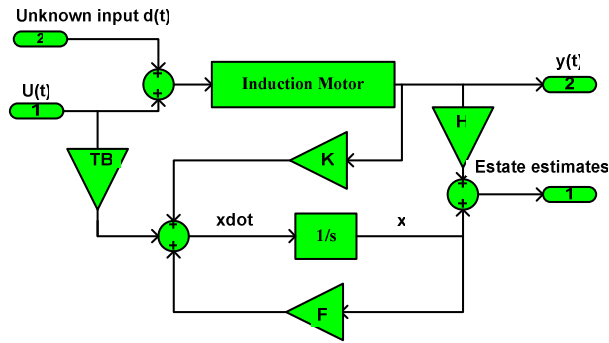


Figure 1. Induction motor with unknown input observer.

$$\begin{aligned} \dot{e}(t) = & (A - HCA - K_1C)e(t) + [F - (A - HCA - \\ & K_1C)z(t) + [K_2 - HCA - K_1C]H]y(t) \end{aligned} \quad (18)$$

$$+ [T - (I - HC)]Bu(u) + [HC - I]Ed(t)$$

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

The gain matrix K_1 is found using bilinear feedback to cancel the first two columns in the error dynamics. K_2 can be calculated using equation (21) (Zhengang et al., 2005)

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

$$F = A - HCA - K_1C \quad (21)$$

If all Eigen values of F are stable then the error $e(t)$ will approach zero asymptotically, this means that the observer is an unknown input observer for the original system (Floquet et al., 2007). The most important thing of the model-based FDI is the generation of residuals.

To provide useful information for FDI, the residual should be:

$$r_{es}(t) \neq 0 \quad \text{if and only if} \quad f(t) \neq 0 \quad (22)$$

Then the fault can be detected by comparing the function of residual generated with the threshold (J. Chen, 2008). There are two theorems control the operation conditions of the unknown input observer. Theorem1. There are two conditions should be 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 $(E = 1)$ so the first condition is satisfied. 2. (A_1, C) is detectable.

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

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

There is existing gain matrix K such that the estimation of the errors:

$$e(t) = x(t) - \hat{x}(t), \text{ will converge to zero when } t \rightarrow \infty$$

Theorem2. The second condition of Theorem 1, which states that the pair (A_1, C) is detectable, is equivalent to Rank of:

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

(n, m) is 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 Armeni et al., 2008). Fault detection and isolation technique for induction motor is described in the beginning, the state space matrices of the induction motor.

Using MATLAB to find the state feedback controller (K) by pole placement method:

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

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

$$j = 1/2 \sum_{k=0}^{\infty} (X^T(k)QX(k) + u^T(k)Ru(k)) \quad (27)$$

The matrix N in equation (26) is set to zero for simplicity. Furthermore, returned are the solution of the associated algebraic Riccati equation and the closed-loop Eigen values.

$$s = eig(A - BK) \quad (28)$$

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

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

$$s = \begin{bmatrix} 1.0e + 002 * \\ -0.3761 + 1.5377i \\ -0.3761 - 1.5377i \\ -0.2170 + 0.0410i \\ -0.2170 - 0.0410i \end{bmatrix}$$

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

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

The rank's condition of the $(C * E) = \text{rank}(E)$ means that the corresponding states coupled with unknown inputs must be obtainable through the measurement outputs. So, it should be noticed that the number of output signals no less than the number of unknown inputs (Young-Real et al., 1994). For stable system the following condition should be satisfied.

$$M = TA - FT - kC = 0 \tag{29}$$

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

Fault isolation

The detection of any fault should be followed by the fault isolation, which will distinguish (isolate) a particular fault from others, the meaning of fault isolation is simply to find which residual not satisfy the fault condition (Shao-Kung Chang et al., 1997). To prove the ability to track the outputs, controllability of the system and the uncontrollable states in the presence of faults should be tested, according to the following formula:

$$\text{cont} = \text{ctrb}(A, B) \tag{30}$$

The number of uncontrollable states (UC) is: $UC = \text{length}(A) - \text{rank}(\text{cont})$

In this paper, the length of the matrix A is 4 and the rank of the controllability matrix is 4. This mean there is

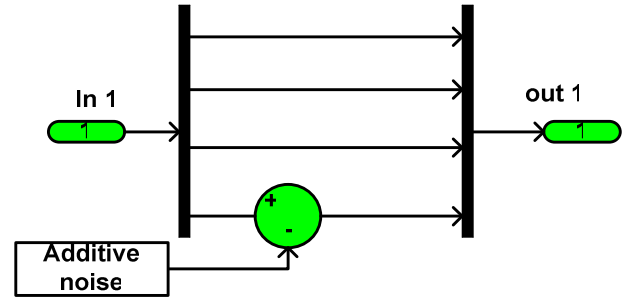


Figure 2. Additive actuator fault.

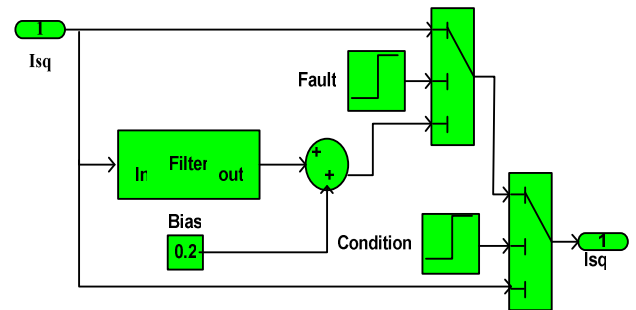


Figure 3. Sensor fault on stator current (Isq)

no uncontrollable state (healthy system). Due to equation (30), the controllability matrix is:

$$\text{cont} = 1.0e + 006 * \begin{bmatrix} 0.0000 & 0 & -0.0000 & 0 \\ 0.0018 & 0.0268 & 3.9701 & -0.8557; \\ 0 & 0.0000 & 0 & -0.0000 \\ -0.0268 & 0.0018 & 0.8557 & 3.9701; \\ 0 & 0 & 0.0000 & 0 \\ -0.0005 & -0.0049 & -0.7121 & 0.2680; \\ 0 & 0 & 0 & 0.0000 \\ 0.0049 & -0.0005 & -0.2680 & -0.7121 \end{bmatrix}$$

The simulation of actuator faults as additive fault will be shown in Figure 2, the bias fault for sensor for the quadrature or direct components of the stator current as will be shown in Figure 3.

RESULTS AND DISCUSSION

The nonlinear properties of induction motor are neglected as well as considering a pure sinusoidal input source. Simulink implementation of UIO fault detection based for (MIMO) system is carried out.

In the presence of the actuator or sensor faults, this approach could decouple any faults. Figure 1 shows the unknown input observer coupled with the induction motor.

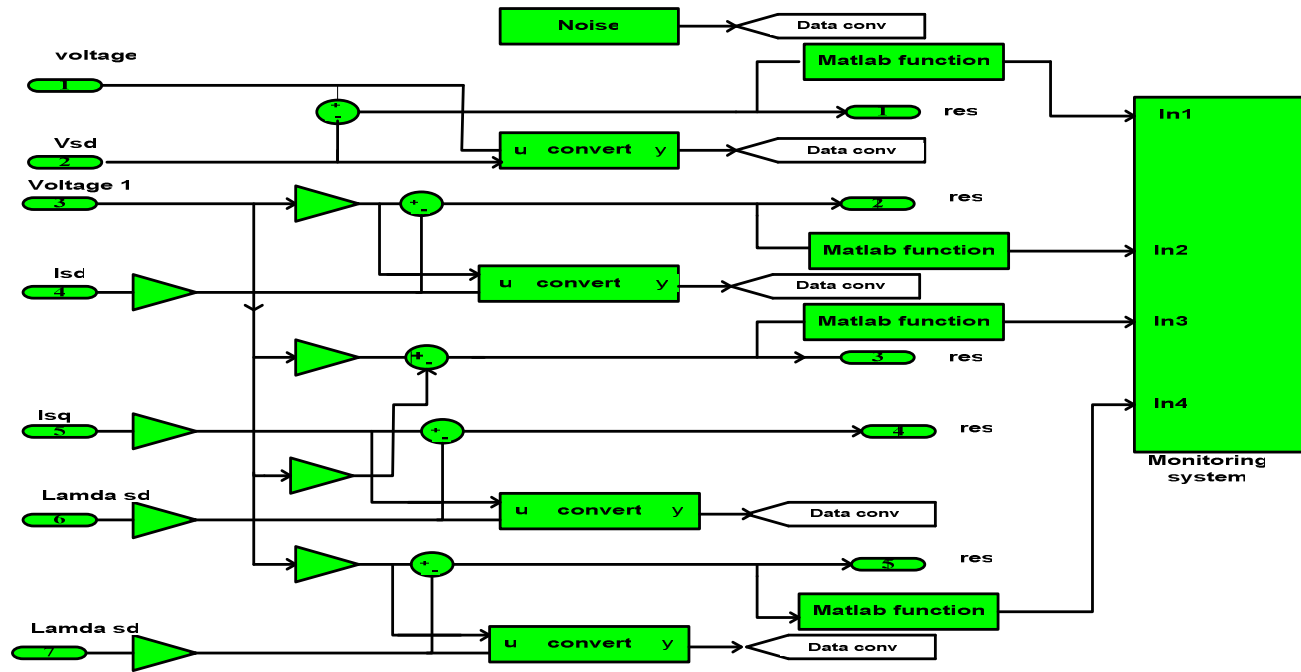


Figure 4. Residual generation and data conversion.

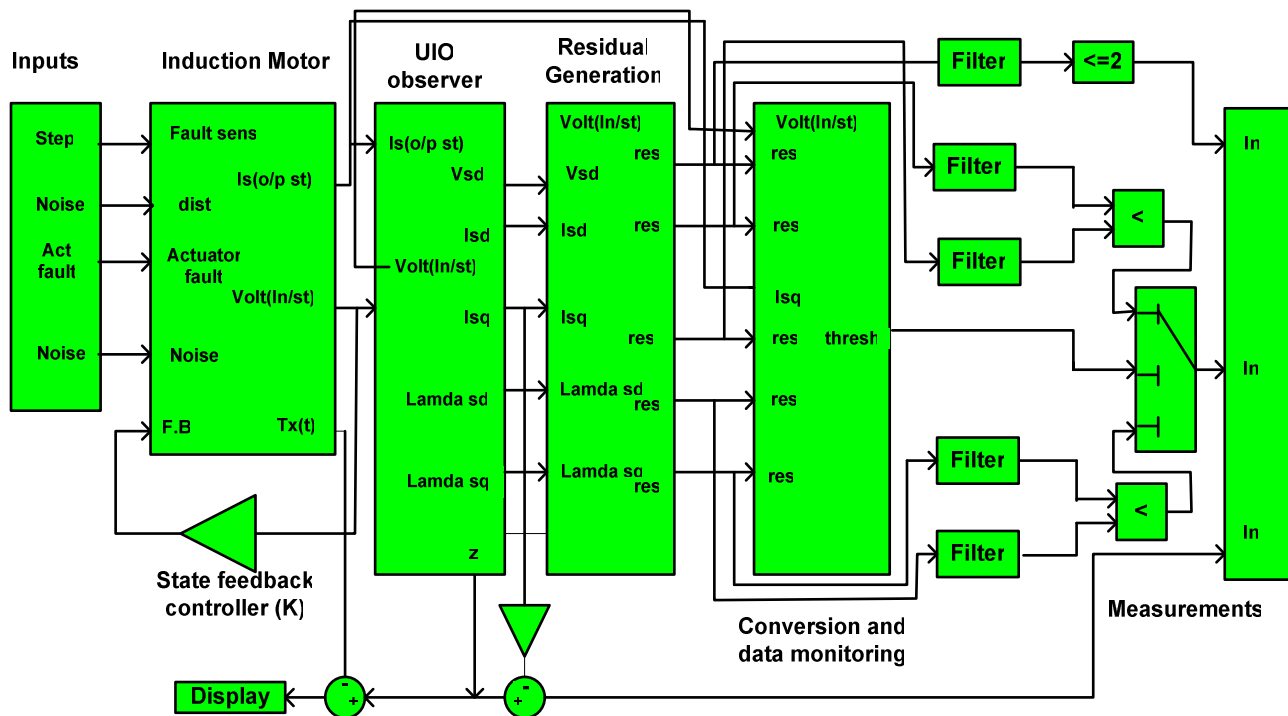


Figure 5. Proposed structure.

Figure 2 represents the additive actuator fault circuit. Figure 3 represents the stator current sensor (I_{sq}) circuit. Figure 4 shows the residual generation with the

monitoring system. Figure 5 represents the proposed structure of the system. Figure 6 represents actuator fault detection after the response of the states exceeds the

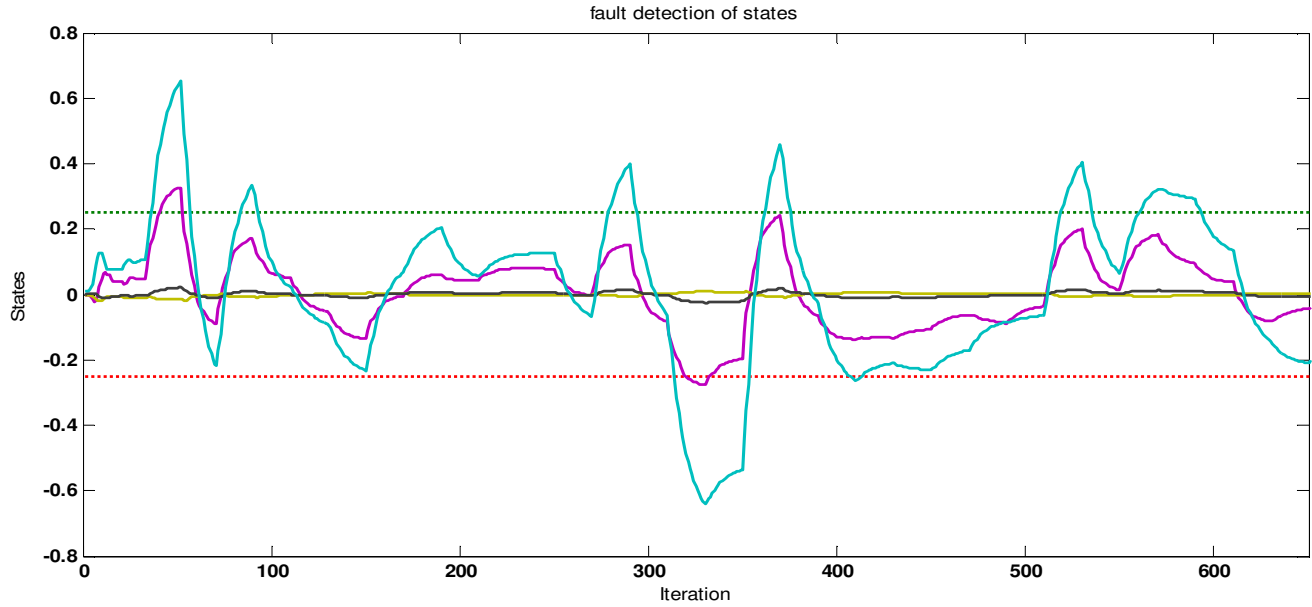


Figure 6. Actuator fault detection.

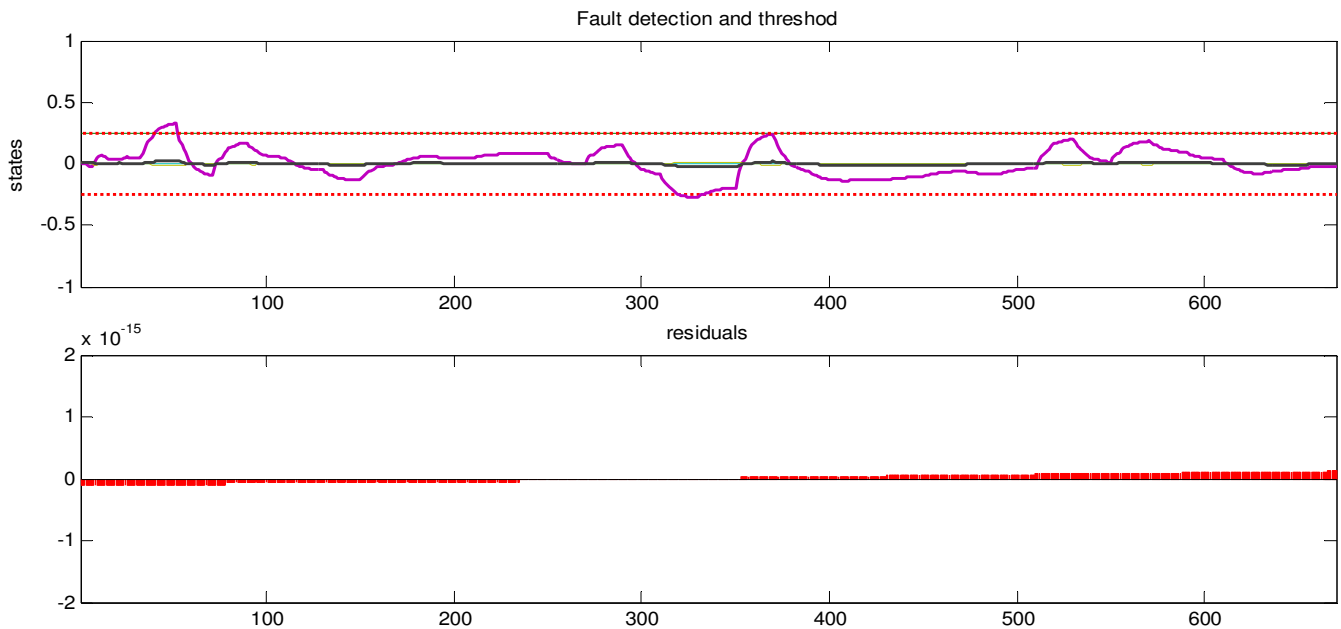


Figure 7. Healthy case output and residual.

thresholds (0.3), Consequences of a fault in the actuator would most likely be instability (fluctuation). Figure 7 represents the healthy case.

All states are within the threshold, and the test of controllability of the system proves that. To check the number of uncontrollable states for the healthy system, the difference between length of matrix (A) and rank of controllability equal zero (no uncontrollable state). According to the results of equations (26) and (27) the

system poles' locations were to left hand side of s-plane, which proves that the system stable for all value of s as in Figure 8. Figure 9 shows the results of fault isolation when the fault occurs in the actuator at 0.4 s.

It shows that the residual generation method can detect the fault with reasonable accuracy. The nonzero (M) result of equation (29) may be due to uncertainty of some parameter of induction motor. In this paper, the induction motor was 4th order. Table 1 gives the parameters of the

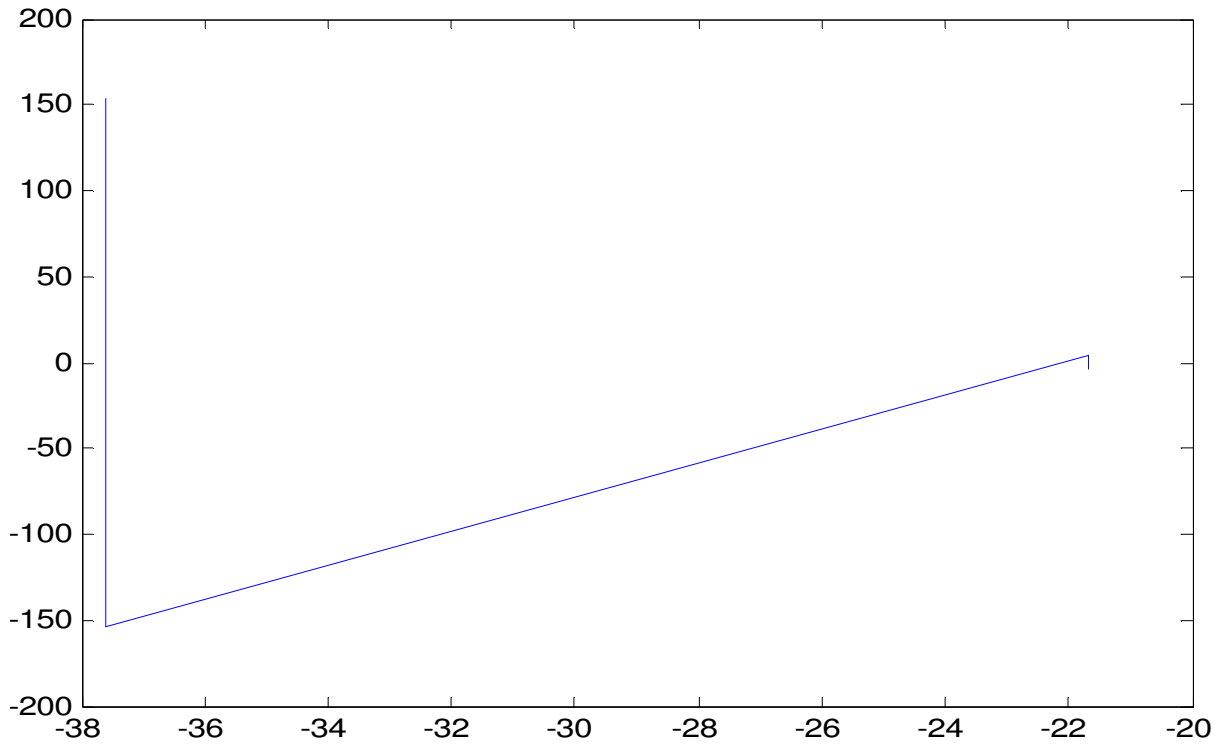


Figure 8. Stability checking after the fault isolated.

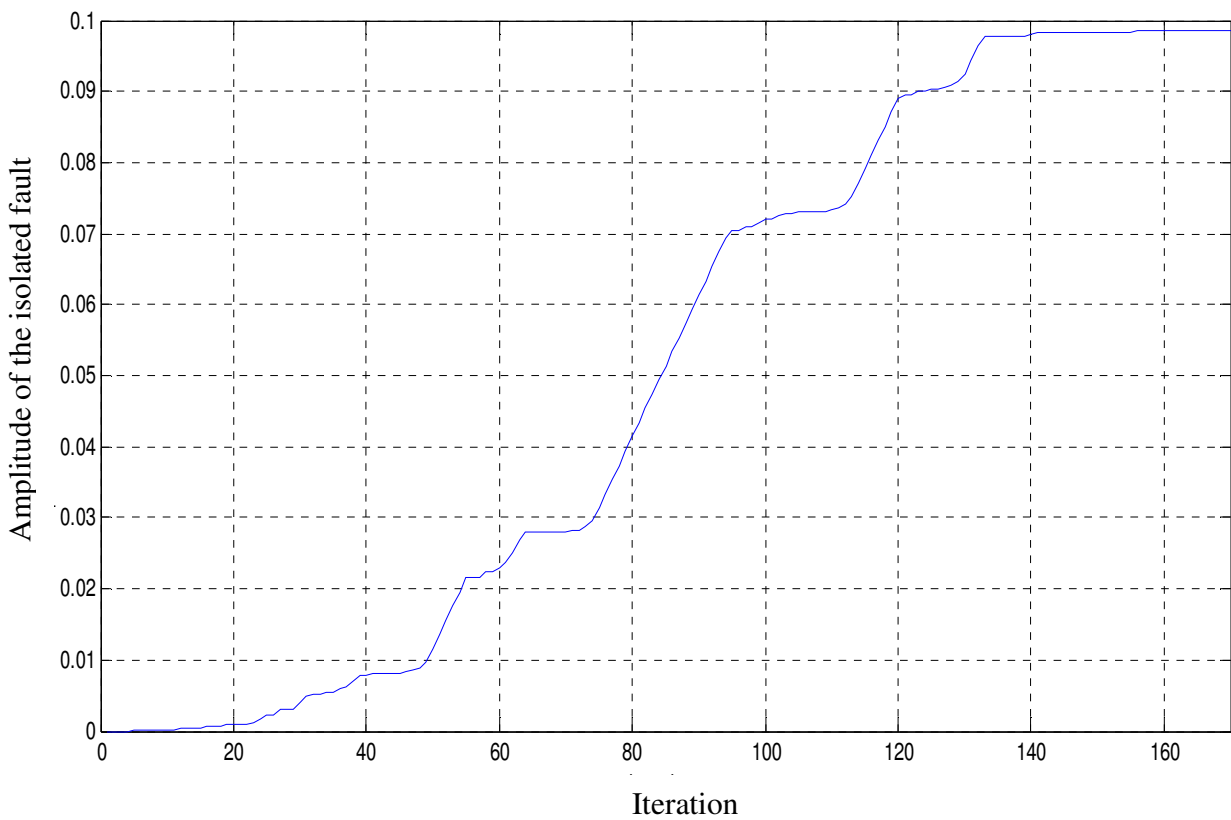


Figure 9. Actuator fault isolation.

Table 1. Induction motor parameters.

Item	Values	Units
Power	3	Hp
Stator resistance	0.534	Ohm
Rotor resistance	0.816	Ohm
Stator inductance	73e-3	Henry
Rotor inductance	71e-3	Henry
Magnetizing inductance	69e-3	Henry
frequency	50	Hz
Speed	1725	RPM
Voltage	220	volt

induction motor.

CONCLUSIONS

There have been a number of techniques developed for fault detection and isolation based observers named qualitative and quantitative over the past decade for fault detection and isolation various systems.

The systems have performance specifications and uncertain characteristics, so it cannot be modeled perfectly. This paper has introduced the unknown input observer-based approach for fault detection of induction motor. MATLAB/SIMULINK implementation of the proposed structure had confirmed the effectiveness of this UIO of the FDI method.

The unknown input observer can be detecting more faults like instrument faults such as gain and bias changes.

For detection of fault, one filter is enough but for isolation a set of a filters bank are needed. When one or more faults in process parameters are directly isolated, it is required to estimate the degree of those faults to take appropriate fault accommodation action, which is part of the fault tolerant control.

REFERENCES

- Andrzej MT (2001). Control of Induction Motor, Academic Press, University of Nevada.
- Benloucif ML, Balaska H (2006). Robust Fault Detection for an Induction Machine, IEEE Conf. (WAC), pp. 1- 6.
- Bennett SM, Patton RJ, Daley S, Newton DA (2002). Torque and Flux Estimation for Rail Traction System in the Presence of Intermittent Sensor Faults, IEE Int. Conf. Control (UKACC), pp. 72-77.
- Chen J (2008). Robust Fault Detection using Unknown Input Observers, lecture from 8th IRS course, Brunel University, UK.
- Chung-Wei C, Wen Peng T, Mi Ching T (2006). Servomechanism Fault Detection Based on Load Torque Observer and Discrete Wavelet Transform, JSME Int. J., Series C, 49(2): 418-425.
- Combastel SL, Petropoulos S, Gentil S (2002) "Model-Based and Wavelet Approaches to Induction Motor on-Line Fault Detection. Control Eng. Pract. J., 10(5): 493-509.
- Dan W, Kai-Yew L (2006). Adaptive Unknown Input Observer Approach for Aircraft Actuator Fault Detection and Isolation, Int. J. Adaptive Control Signal Process., 21: 31- 48.
- Floquet T, Edwards C, Spurgeon SK (2007). On Sliding Mode Observers for Systems with Unknown Inputs. Int. J. Adaptive Control Signal Process., pp. 1-20.
- Guang-Hong Y, Heng W (2007). An LMI-based Approach to Fault Detection for Uncertain State Feedback Control Systems, IEEE Int. Conf. Control Appl., CCA, pp. 1055-1060.
- Hafiz BA (2005). UIO based Fault Detection and Isolation in Dynamic Systems" <http://www.mathworks.com>.
- Jason G, Pieter JM (2006). Applying Model-Based Design to a Fault Detection, Isolation, and Recovery system, Military Embedded Syst. J., pp. 1-5.
- Khalaf SG, Hew WP, Haider A, Mohamed F (2009). Indirect Vector Control of a Variable Frequency Induction Motor Drive (VCIMD), IEEE Conf., ICICI-BME, pp. 36-41.
- Mohammed C, Abdelkader A, Didier M, Jose R, .Young M (2008). Fuzzy Observer for Fault Detection and Reconstruction of Unknown Input Fuzzy Models. Int. J. Modeling Identification Control, 3: 193-200.
- Patton RJ, Chen J (1997). Observer -Based Fault Detection and Isolation: Robustness Appl., Control Eng. Pract. J., 5: 671-682.
- Sarah KS (2008). Sliding Mode Observers: A survey, Int. J. Syst. Sci., 39(8): 751-764.
- Saverio A, Alessandro C, Edoardo M (2008). Robust Fault Detection and Isolation Filter Design with Sensitivity Constraint, Int. J. Adaptive Control Signal Process., 23(1): 55 -72.
- Shao-Kung C, Wen-Tong Y, Pau-Lo HSU (1997). Design of General Structured Observers for Linear Systems with Unknown Inputs, J. Franklin Institute, 334B (2): 213- 232.
- Stefen H, Stanislaw H Z, Shao-Kung C, Nicole R (2005). Observer Design for Systems with Unknown Input, Int. J. Appl. Math. Comput. Sci., 15(4): 431-446.
- Wang Z (2010). Unknown Input Observer Based Fault Class Isolation and Estimation" IEEE, Proceedings of the 29th Chinese Control Conf., pp. 29-31.
- Young-Real K, Seung-Ki S, Min-Ho P (1994). Speed Sensorless Vector Control of Induction Motor Using Extended Kalman Filter. IEEE Trans. Industry Appl., 30(5): 1225-1233.
- Zhengang H, Weihua L, Sirish LS (2005). Fault Detection and Isolation in the Presence of Process Uncertainties. Control Eng. Pract. J., 13: 587-599.