FAULT DETECTION AND ISOLATION BASED ON HYBRID SLIDING MODE OBSERVER and FUZZY LOGIC

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Abstract

Faults detection and isolation scheme on the bases of a hybrid Sliding Mode Observer (SMO) technique and fuzzy logic technique has been presented in this paper. The SMO technique was used for the fault detection purpose based on residual signal which represent the difference between output of the process and output of the model that used as a fault indicator, while the fuzzy logic technique was used as a fault isolator depending on fuzzy rules base and fuzzy membership functions. The performance of this hybrid technique is evaluated on a model of DC motor, the proposed scheme is illustrated on a Matlab/Simulink simulator and the results demonstrated a successful implementation of the proposed Fault Detection and Isolation FDI scheme.

Keyword: Fault Detection and Isolation, Sliding Mode Observer, Fuzzy Logic, Residual Generation, DC Motor Modeling.

كشف وعزل الاخطاء بالاستناد على هجين مراقبة النمط الانزلاقي مع المنطق الضبابي

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الخلاصة

في هذا البحث تم كشف وعزل الأخطاء على اساس هجين مراقبة النمط الانزلاقي (SMO) مع تقنية المنطق الضبابي (fuzzy logic). حيث استخدمت تقنية (SMO) لغرض الكشف عن الاخطاء بالاعتماد على الاشارة المتبقية (Residual signal) والتي تمثل الفرق بين الناتج من العملية والناتج من النموذج حيث تستخدم كمؤشر للخطأ. في حين استخدمت تقنية المنطق الضبابي كعازل للأخطاء إعتمادا على القواعد والوظائف العضوية للمنطق الضبابي. تم تقييم أداء هذه التقنية الهجينة بعد تطبيقها على نموذج من محرك تيار المستمر(DC Motor). ذو الطريقة المقترحة تم توضيحها من خلال استخدام بيئة Matlab/Simulink واظهرت النتائج المستحصلة صحة ودقة و نجاح هذه التقنية في تنفيذ الطريقة المقترحة لكشف وعزل الاخطاء.

الكلمات الدلالية: كشف وعزل الخطأ , مراقبة النمط الانزلاقي , المنطق الضبابي , توليد Residual , نمذجة DC Motor

1. Introduction

The term "fault" refers to any disturbances, errors, malfunctions or failures in the functional units that can lead to undesirable or intolerable behavior of a system **(G. Bartolini, et al, 2008).** The early detection of faults can help avoid system shut-down, breakdown and even catastrophes involving human fatalities and material damages **(R. J. Patton, et al, 2000).** Thus to ensure the normal operation, and increase the safety and reliability of the systems in many applications, the problem of fault detection, and isolation has received considerable attention over the past two decades **(G. Bartolini, et al, 2008).**

Fault detection is the first step for FDI it can inform the presence of faults, and the early detection of faults which is very important for the safety of real systems. After the detection of faults, it is often desired to locate the faults, which is the task of fault isolation **(Weitian Chen and Mehrdad Saif, 2005).**

There are many approaches appeared in the field of FDI model based is one of these approaches. The idea of model-based fault detection schemes is to compare the behavior of an actual process to that of the nominal fault-free model of the process driven by the same input.A model-based fault detection scheme it consists of two main stages, residual generation and residual evaluation. The objective of residual generation is to produce a signal, called residual signal, by comparing the measurements with their estimates and the purpose of residual evaluation is to inspect the residual signal for possible presence of faults. Model-based fault detection schemes can further be divided into two categories, the model can be an analytical model represented by a set of differential equations or it can be knowledge-based model represented by, for example, neural networks, petri-nets, experts systems, fuzzy rules….etc **(Muhammad Abid, 2010).**

The presence of uncertainties or disturbances in system can actually corrupt the functionality of the FDI scheme whereby the residual could be nonzero when there is no fault, resulting in false alarms, or worse, the residual is zero when there is a fault, thus masking the effect of the fault on the system. Therefore, there is a need for a robust FDI scheme to tackle-

this problem **(Ng Kok Yew, 2009).** In this paper, has been used a robust SMO for fault detection purpose and fuzzy logic technique for fault isolation purpose.

2. Sliding Mode Observer Based Faul Detection

The sliding mode observer (SMO) is a type of nonlinear observer introduced by Utkin that is becoming very popular in the FDI field. As the name of this observer suggests, this method adopts a sliding motion for the state estimation error of the system where finite-time convergence is attained. As long as the state estimation error is forced to slide onto and remain on a certain hyper-plane, then the observer is said to be in a sliding mode whenever there is a fault in the system, the observer will stop sliding and the residual will generate the alarm **(Ng Kok Yew, 2009).**

The linear state space of any system is as **follows (Nicola Orani, 2010 and H. Alwi, 2011)**:

$$\begin{cases} x^{\cdot}(t) = Ax(t) + Bu(t)\dots\dots\dots\dots\dots\dots\dots\dots eq.(1) \\ y^{\cdot}(t) = Cx(t) \end{cases}$$

Where:

$A \in R^{nxn}$, $B \in R^{nxm}$, $C \in R^{pxn}$, and p≤m. Assume that the matrices B and C are of full rank and the pair (A,C) is observable.

It is convenient to introduce a coordinate transformation so that the outputs appear as components of the new state vector. One possibility is to consider the non-singular transformation x →Tcx:

$$Tc. = \begin{bmatrix} N^T c \\ C \end{bmatrix}\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots eq.(2)$$

Where:

$N_c \in R^{nx(n-p)}$ and the columns span the null space of C and with respect to this new coordinate system, the distribution matrices of the similar system are:

$$\begin{cases} \tilde{A} = T_c A\, T_c^{-1} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}; & \tilde{B} = T_c B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}; \quad \dots\dots eq.(3) \\ \tilde{C} = T_c^{-1} = [0\ I_p]; \end{cases}$$

Then the nominal system (3) can be rewritten as :

$$\begin{cases} \dot{x}_1(t) = A_{11}x_1(t) \mid A_{12}y(t) \mid B_1u(t)\dots\dots\dots\dots\dots\dots\dots eq.(4) \\ \dot{y}(t) = A_{21}x_1(t) + A_{22}y(t) + B_2u(t) \end{cases}$$

The SMO can be designed as follows:

$$\begin{cases} \dot{\hat{x}}_1(t) = A_{11}\hat{x}_1(t) + A_{12}\,\hat{y}(t) + B_1u(t) + Lv \dots\dots\dots\dots eq.(5) \\ \dot{\hat{y}}(t) = A_{21}\,\hat{x}_1(t) + A_{22}\,\hat{y}(t) + B_2u(t) - v \end{cases}$$

where $(\hat{x}_1, \hat{y})$ represent the state estimates for $x_1$and y, L∈ $R^{(n-p)xp}$ is a constant feedback gain matrix and the discontinuous vector v, of appropriate dimension, is a defined component-wise by:

$$v_i = M\,sgn(\hat{y}_i - y_i)\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots eq.(6)$$

where $M \in R_+$. The errors between the estimates and the true states are written as $e_1 = \hat{x}_1 - x_1$and $e_y - \hat{y} - y$, then from eq(4) and eq(5) the following error dynamical system is obtained by:

$$\begin{cases} \dot{e}_1(t) = A_{11}e_1(t) + A_{12}e_y(t) + Lv \dots\dots\dots\dots\dots\dots\dots\dots eq.(7) \\ \dot{e}_y(t) = A_{21}e_1(t) + A_{22}e_y(t) - v \end{cases}$$

If the scalar M is large enough such that e_y will converge to zero in finite time, then a sliding motion takes place on the surface:

$$S = \{(e_1, e_y); e_y = 0\} \quad\text{..}eq.(8)$$
(8)

It follows that after some finite time, for all subsequent time, $e_y = \dot{e}_y = 0$, and $v = A_{21}e_1(t) \; \dot{e}_1(t)$ becomes:

$$\dot{e}_1(t) = (A_{11} + LA_{21})e_1(t)\text{..}eq.(9)$$

Which, by choice of L, represents a stable system and so $e_1 \to 0$ and consequently $\hat{x}_1 \to x_1$ asymptotically, eq (9) presents the reduced order sliding mode error dynamics.

The aim of SMO based fault detection is to generate residual which is called as a fault indicator, residuals are generated by comparing the measured system output y(t) and the estimated system output $\hat{y}(t)$ to detect the unpermitted behavior of the system. Hence the residual signal $r(t)$:

$$r(t) = y(t) - \hat{y}(t)$$

Then, fault detection can be carried out as follows:

$$\begin{cases} r(t) = 0, \text{ no fault occurred} \\ r(t) \neq 0, \text{ fault has occurred} \end{cases}$$

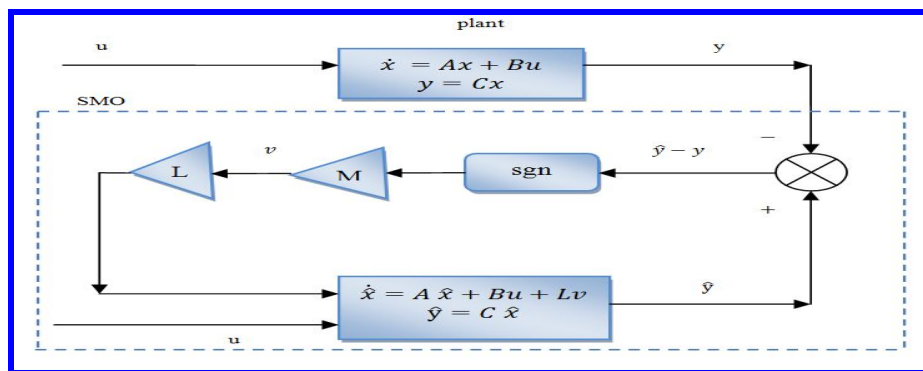The configuration of SMO based residual generator for fault detection is illustrated in **Figure 1**.

Fig.1: Sliding Mode Observer.

3. Fuzzy Logic Control Based Fault Isolation

The procedure of fuzzy logic based fault isolation which based on the residuals that generated from-

SMOs by comparing the data taken from actual process with the fault free case, the crisp value of each residual can be transformed into a linguistic variable with a degree of membership function from 0 to 1, these residual represent the input of fuzzy controller. The output of fuzzy controller reflect the location of fault that occurring in system , the membership functions of the output is defined, thus ,with all of the input and output of membership functions defined the rules base need to be defined by IF Then relations. Fuzzy rules are of the general form:

If antecedent(s) then consequent(s)

  The antecedent and consequent of a fuzzy rule are propositions containing linguistic variables **(A. P. Engelbrecht, 2007).**

4. DC Motor Modeling

    The state space format of DC motor is:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots eq.(10)$$

    The two states considered are the armature current i, and the angular velocity of the shaft speed ω of the DC motor. The input is the armature voltage u(t), Eq. (10) becomes:

$$\frac{d}{dt}\begin{bmatrix} w \\ i \end{bmatrix} = \begin{bmatrix} -\frac{b}{J} & \frac{K}{J} \\ -\frac{K}{L} & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} w \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}V \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots eq.(11)$$

$$w = \begin{bmatrix} 1 & 0 \end{bmatrix}\begin{bmatrix} w \\ i \end{bmatrix} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots eq.(12)$$

Where:

    b,J,k,R, and L are the physical parameters of DC motor listed in **Table 1 (Robert Babuska and Stefano Stramigioli, 1999),** the input to the DC motor is considered a unit step voltage (1 volt).

Table 1: Physical Parameters of the DC Motor.

Moment of inertia of the rotor	J =0.01 kg. m^2
Damping (friction) of the mechanical system	b =0.1 NMS
(back) Electromotive force constant	K =0.01 Nm/A
Electric resistance	R = 1 Ω
Electric inductance	L = 0.5 H

5. Result

DC motor has been used for detecting and isolating the faults that occur in which, in this work we imposed that the fault may occur in sensor or in actuator, first the DC motor model is built in the MATLAB/SIMULINK environment based on SMO, after the model has been built the residual is generated that used as fault indicator as shown in **Figure 2**.
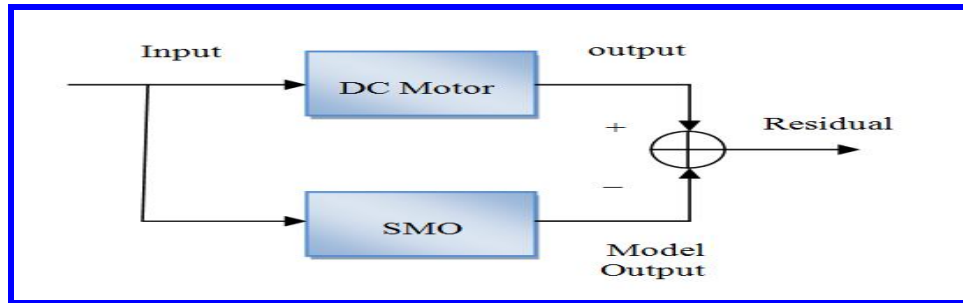

Fig.2: Residual Generated Based on SMO.

Figure 3 shows the measured and estimated speed output of the DC motor and the calculated residual is illustrated in **Figure 4** when there is no fault in the system.
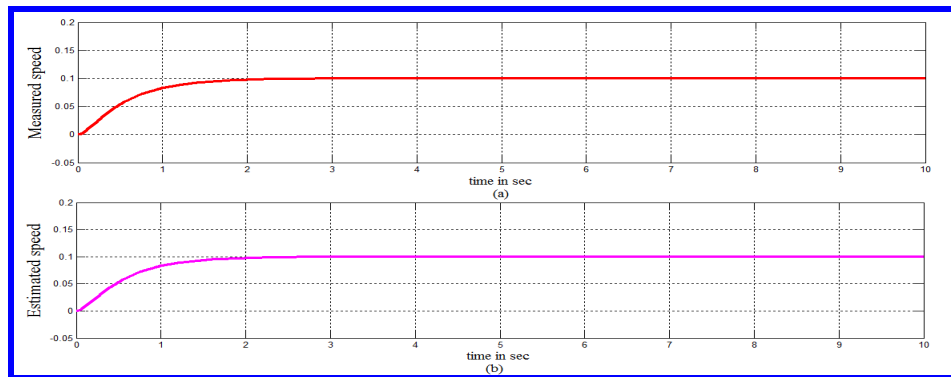

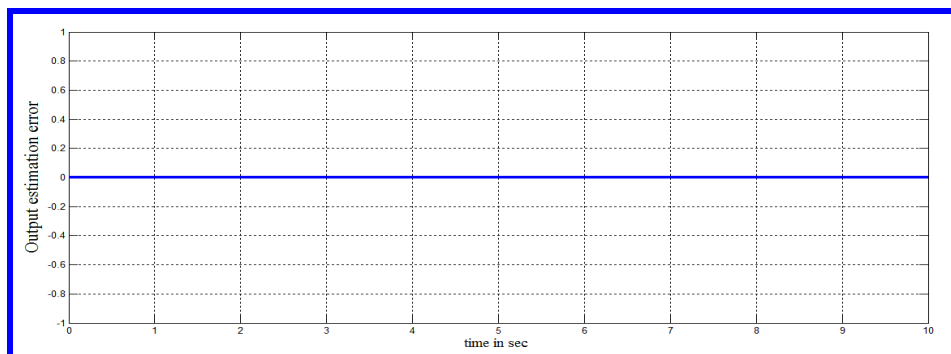**Fig.3: Measured Speed and Estimated Speed.**

Fig.4 : Residual Signal when no Fault at the System (Output Estimation Error).

After fault detection fuzzy logic technique used for fault isolation, first the two residuals, (r_1, r_2) that generated by using a bank of two SMOs, used as the input to the fuzzy controller, the universe of discourse for each residual membership functions is given by:

$r_1 \in [-1, 0.6]$ $r_2 \in [0.4, 2]$

Triangular forms are used to represent two membership functions, Low (L) and High (H) respectively. The output of the fuzzy controller gives three possibilities for the motor case, the first possibility is the motor in normal operation (free fault), the second possibility is the motor under sensor fault condition, and the third possibility is the motor under actuator fault condition, so there are three membership functions of the output of the fuzzy controller, triangular form are used to represent three membership functions, F.F(free fault), F_s (sensor fault), and F_a (actuator fault), with the universe of discourse for each membership functions is given by:

F.F $\in [-1, -0.2]$ Fa $\in [-0.4, 0.4]$ Fs $\in [0.2, 1]$

Based on the input and output membership functions the rules base is defined using IF Then relation as shown in **Table 2.**

Table 2: Rules for Fuzzy Controller.

r_1 / r_2	L	H
L	F.F	F_S
H	F.F	F_a

Figure 5 shows block diagram of FDI scheme designed based on the integration of fuzzy knowledge model with SMO model, simulated in MATLAB/SIMULIN.
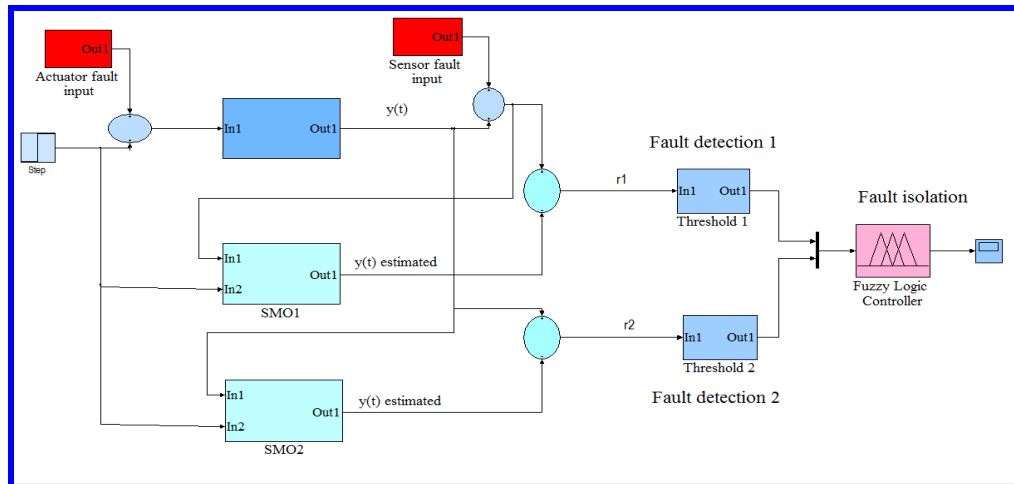

Fig.5: Block Diagram of FDI Based on the SMO and FL.

The following results shown in **Figure 6** assumed that the sensor is under fault condition and the actuator is fault free, in this case was assumed abrupt fault occurs with threshold equel to 0.1.
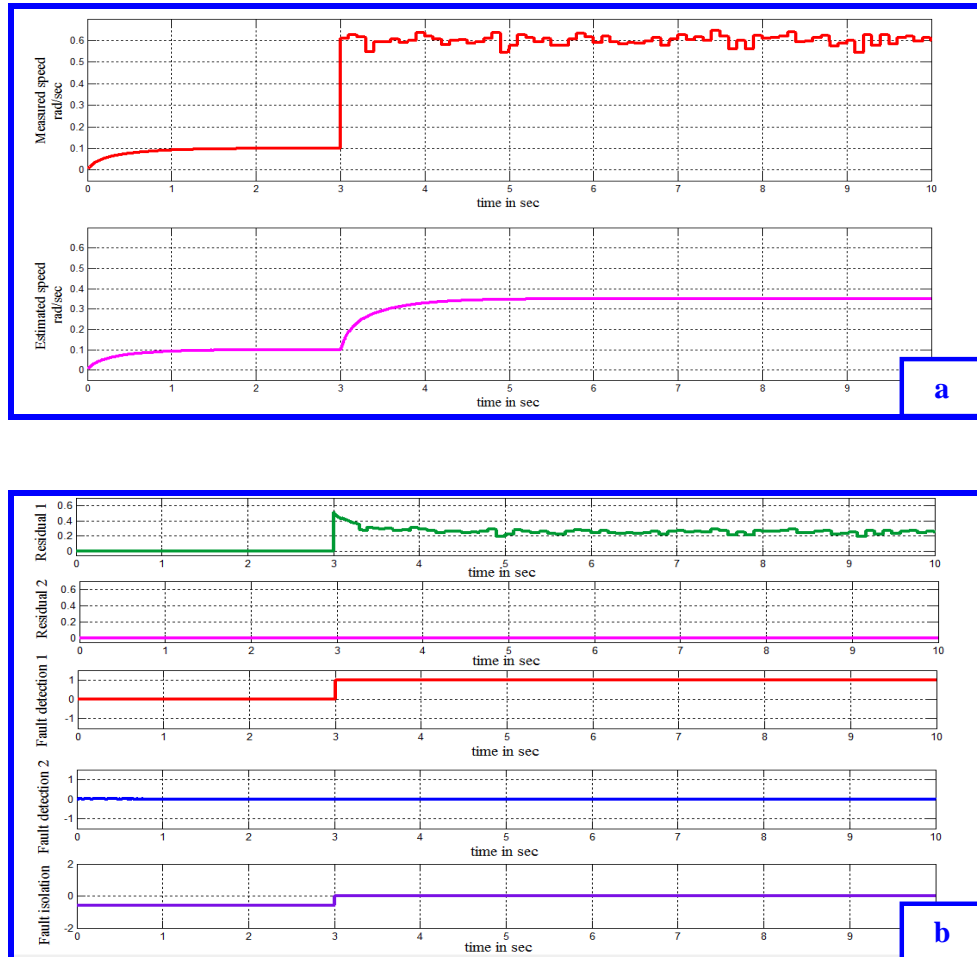

Fig.5: Abrupt FDI in Sensor Usnig SMO and FL, a)Measured Speed and Estimated Speed, b) Residual 1, Residual 2, Fault Detection 1, and Fault Detection 2

The following results shown in **Figure 7** obtained when assumed that the actuator is under fault condition and the sensor is fault free, in this case was assumed abrupt fault occurs with threshold equel to 0.1.
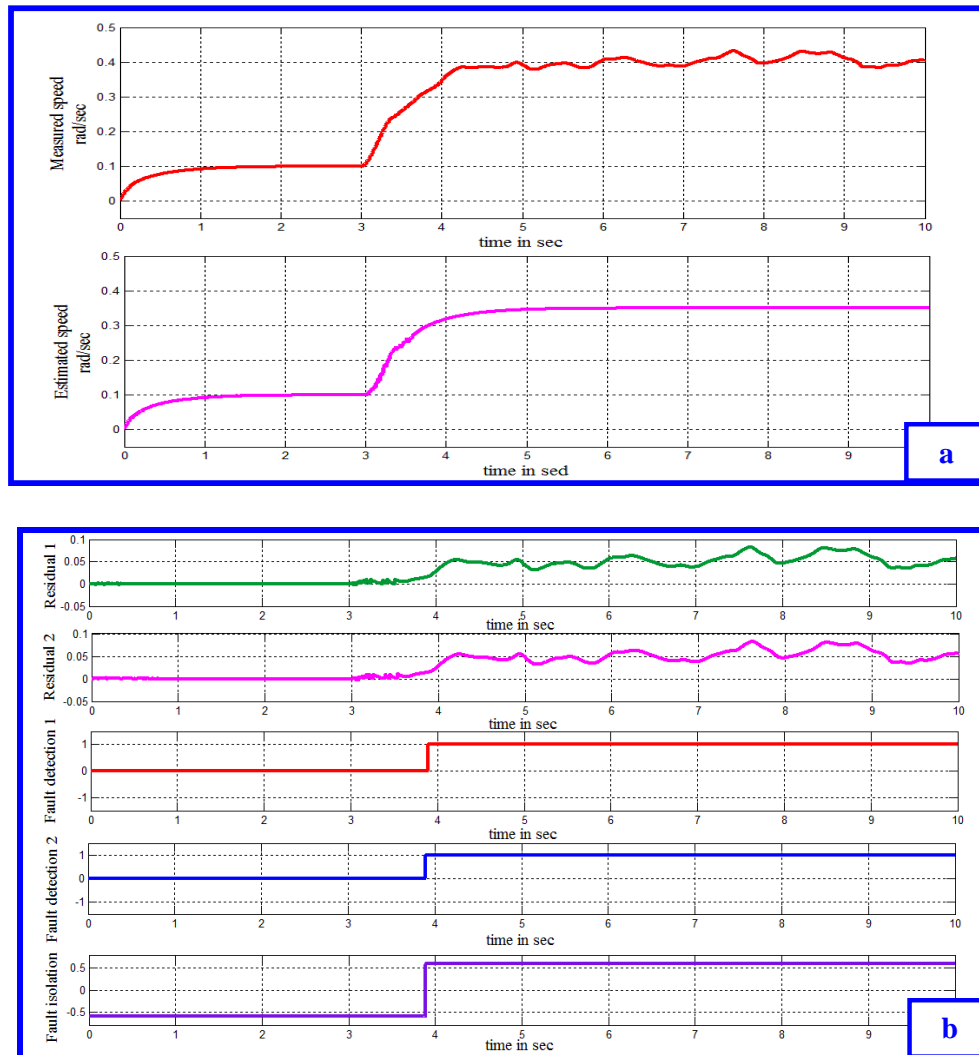
Fig.7: Abrupt FDI in Actuator Usnig SMO and FL, a) Measured Speed and Estimated Speed, b) Residual 1, Residual 2, Fault Detection 1, and Fault Detection 2

6. Conclusion

Sliding mode observer and fuzzy logic control based fault detection and isolation are proposed in this paper. From this work one can conclude that the combination between the SMO and fuzzy logic techniques exhibit a number of features that make them attractive for fault detection and isolation in different systems. The SMO and fuzzy logic control based FDI schemes were designed and tested on a DC motor model for the purpose of fault detection and isolation. Actuator and sensor of the DC motor assumed under fault conditions.

7. References

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8. List of Abbreviations

FDI: Fault Detection and Isolation
FL: Fuzzy Logic
SMO: Sliding Mode Observer