FAULT DETECTION IN A DC MOTOR USING THE ADAPTIVE THRESHOLD LMS (ATLMS) TECHNIQUE

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Abstract— Any engineering application is susceptible to fault occurrence which can cause a major damage on processes. This paper discusses the application of detection fault theory on DC motor using the ATLMS, and adaptive threshold technique, with structured residual generation. Here, three different faults were studied and evaluated with regard to fault detection promptness on the proposed system. Fault 1 results in RPM deviation from normal to zero value; fault 2 describes a situation where the RPM value at the time of fault occurrence is kept fixed for the rest of the simulation no matter how the input signal changes; and fault 3 presents an exceeding RPM value.

Keywords— Fault Detection, ATLMS, Adapatative Threshold, Structured Residuals, DC Motor

Resumo— As aplicações de engenharia são sucetiveis à ocorrência de falhas que podem causar danos severos nos processos. Esse artigo irá abordar a aplicação da teoria de detecção e diagnóstico de falhas em um Motor DC usando o ATLMS, combinado com a geração de resíduos estruturados. Serão abordados três falhas que foram estudadas e avaliadas, sendo feita a detecção de cada uma delas. A Falha 1 em situação de falha onde o motor se encontra em 0 RPM; Falha 2 onde o valor de RPM se encontra fixo em um valor até o final da simulação, independente da mudança nos valores de entrada; Falha 3 demonstra uma situação onde o valor de RPM excede o máximo permitido.

Palavras-chave— Detecção de Falhas, ATLMS, Limiar Adaptativo, Residuos Estruturados e Motor DC.

1 Introduction

Fault detection and diagnosis plays an important role in complex systems. Some of the advantages of FDD applications rely on enhanced system reliability, lifetime expansion of monitored components and failure probability reduction of the overall system (Gertler, 2015),(Chiang, Russel, 2001). The main requirements of fault detection systems are based on early detection and lower rates of missed / false alarms. In many cases, diagnosis is based on hardware redundancy which brings additional complexity and cost to the system (Isermann, 2005). Another common approach is based on limit checking of specific variables. With respect to model-based diagnosis, mathematical models do not perfectly describe the system. For this reason, generated residuals might suffer from deviations even in fault-free cases and threshold boundaries may not satisfy both false and missed alarm rates. Ideally, the dynamic behavior of the thresholds should present (*i*) low sensitivity to control signal variation, (*ii*) low sensitivity to noise, and (*iii*) high sensitivity to fault residuals. These three requirements might be reached with the use of suitable adaptive thresholds. This paper uses the ATLMS, an adaptive threshold technique based on the Sequential Probability Test Ratio (SPRT) and the Least Mean Square (LMS) filter, in order to detect three different faults applied to a DC motor. Fault 1 results in RPM deviation from normal to zero value; fault 2 describes a situation where the RPM value at the time of fault occurrence is kept fixed for the rest of the simulation no matter how the input signal changes; and fault 3 presents an exceeding RPM value.

2 Background Concepts

2.1 Fault Detection and Diagnosis

With the constant growth of industry and the influence that automation has on its technical processes, it became a need to develop sensors, actuators, bus-communication systems and supervisory control in order to optimize its tasks and likewise provide more reliable systems. However, as the number of elements on a structure increases, the more is likely the occurrence of faults.(Isermann,2005)

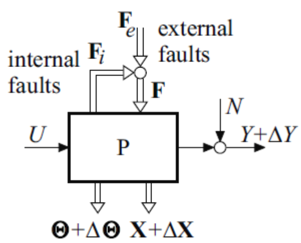

Figure 1: Scheme of process influenced by faults, (Isermann, 2005)

As shown on figure 1, a system can have a fault due to the action of an internal or external cause. Fault Detection and Fault Diagnosis methods are used to give to the operator a better understanding of the fault before deciding the best operational action to take. The Fault Detection determines whether if a fault has happened or not and Fault Diagnosis aims to figure out the type of the fault.

There are several approaches to the fault detection,some of them are:

- Fault and Process models, which are based on the mathematical approximated models of the system and its faults;
- Limit checking, which basically registers when a threshold value of a measurement is exceeded ;
- Signal models, based on periodic, non-periodic and stochastic signals;
- Process identification, applying a parameter estimation method;
- State Observers and Estimation, based on a State-space system representation;
- Parity equations, which uses residuals to determine, by comparison,when the system model is described by a nominal or faulty behaviour;

The present work is restrained to the application of the Fault Detection method of structured residuals, a branch of the Parity Equation method, to characterize faulty behaviour on a DC motor system.

Figure 2 shows an overview of Fault Detection techniques.

2.2 Residual Generation

Residuals play an essential role in fault detection algorithms and techniques. Generally speaking, residuals are used to compare faulty and non-faulty process behavior (Frisk, 2001), (Isermann, 2005), and (Nyberg,1999). In this way, residuals are designed to be zero in the fault-free case and non-zero when a fault occurs. However, residuals tend to vary due to model uncertainties, disturbances and noise. Some of the ways to minimize such deviations are maximizing fault sensitivity, robustness against modelling errors, generation of enhanced residuals and use of adaptive thresholds, depending on input signals. In order to generate residuals, the following approaches can be used:

- Directional residuals: the main idea is to generate a residual vector that varies its directions according to different faults.
- Structured residuals: the main idea is designing a set of residuals that are sensitive to some faulty behaviors and insensitive to others.

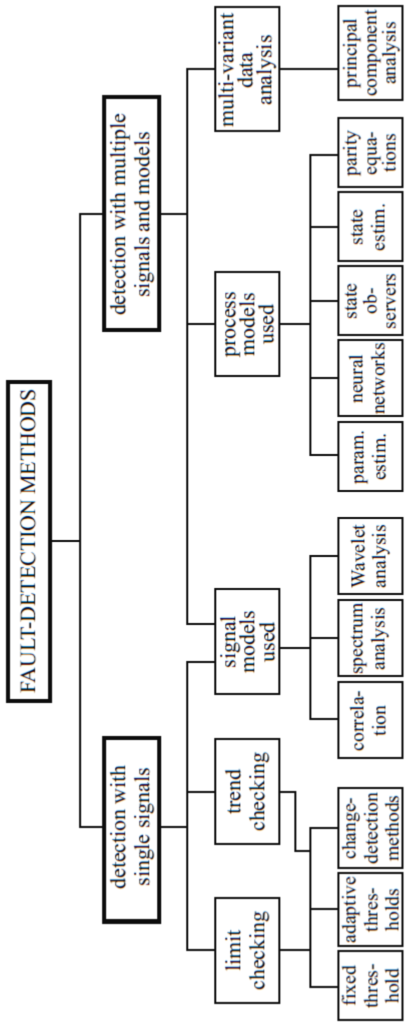

Figure 2: Fault Detection techniques (Isermann, 2005)

From now on, the present article will focus on the generation of structured residuals as presented in (Isermann, 2005). Consider a linear process described by

$$G_p(s) = \frac{y_p(s)}{u(s)} = \frac{B_p(s)}{A_p(s)} \tag{1}$$

and the respective process model - assumed to be known and with fixed parameters - described by

$$G_m(s) = \frac{y_m(s)}{u(s)} = \frac{B_m(s)}{A_m(s)} \tag{2}$$

Then the linear process is defined as

$$G_p(s) = G_m(s) + \Delta G_m(s) \tag{3}$$

where $\Delta Gm(s)$ accounts for model errors. Figure 3 presents the system block diagram

The residuals are then formulated as

$$r(s) = A_m(s)y_p(s) - B_m(s)u(s) \tag{4}$$

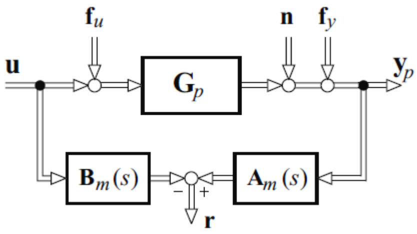

Figure 3: Block diagram for polynomial error (Isermann, 2005)

and should be decoupled from the faults to be detected. Finally, the structured residuals are defined by

$$r^*(s) = W(s)\left\{\begin{bmatrix} A_1(s) & 0 & \cdots & 0 \\ 0 & A_2(s) & & \\ & & \ddots & \\ 0 & 0 & \cdots & A_r(s) \end{bmatrix}\begin{bmatrix} y_1(s) \\ y_2(s) \\ \vdots \\ y_r(s) \end{bmatrix} - \begin{bmatrix} B_1(s) & 0 & \cdots & 0 \\ 0 & B_2(s) & & \\ & & \ddots & \\ 0 & 0 & \cdots & B_p(s) \end{bmatrix}\begin{bmatrix} u_1(s) \\ u_2(s) \\ \vdots \\ u_p(s) \end{bmatrix}\right\} \tag{5}$$

where $W(s)$ is the generating residual matrix, often called residual generator.

2.3 ATLMS Technique

One way to achieve robustness against modeling errors is using adaptive thresholds. Since residuals may oscillate even in a fault-free case, pre-defined thresholds may not accomplish either missed or false alarm requirements. In this case, the behavior of the adaptive threshold should present low sensitivity to control signal variation and noise and high sensitivity to fault signatures.

The ATLMS (Adaptive Threshold Least-Mean Squares) technique was introduced by (Leite, 2012). It allows the threshold tuning by changing well known parameters independently of the case study. This signal-based approach does not require a-priori knowledge either of the fault models or plant, but relies on a suitable set of fault signatures delivered by residual generators. The ATLMS technique is based on the Sequential Probability Ratio Test (SPRT) and an adaptive non-recursive filter. Alarm activation results from a comparison between signal y_0, non-sensitive to the applied fault, and adaptive threshold (function of y_0).

The adaptive threshold is computed at each sample period as:

$$f = \phi^T \theta$$

$$f = \begin{bmatrix} u_1 & \cdots & u_{Nc} & y_{0k} & \cdots & y_{0k-m} & 1 \end{bmatrix}\begin{bmatrix} \theta_1 \\ \cdot \\ \cdot \\ \theta_{Nc+m+2} \end{bmatrix} \tag{6}$$

Figure 4 presents the structure of the adaptive threshold.

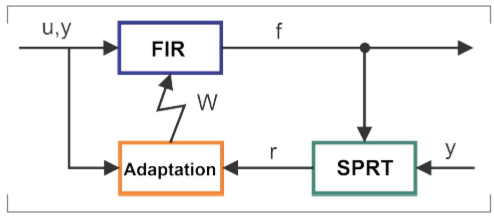

Figure 4: ATLMS Structure (Leite, 2012)

- u: control signal vector;
- y_0: insensitive residue to the fault to be detected (obtained as in [Isermann]);
- y_1: sensitive residue to the fault to be detected;
- r: instantaneous $SPRT$;
- W: weight vector of the non-recursive filter.

2.4 DC Motor System and Model

The DC motor studied on this article is part of the Mechanical Unit of the Digital Servo Kit shown in figure 6. The system model was based on a simplification made by (Leite, Kuga and Lopes, 2006) of the model of a DC motor presented on (Dorf, 2011) as in figure 5.

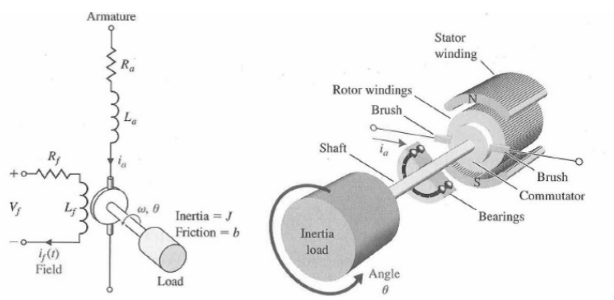

Figure 5: Simplified scheme of a DC motor. (Dorf,2011)

Equation 7 describes the relation between the motor input voltage, $V_{in}(s)$, and the motor angular velocity, $\Omega(s)$, as presented in (Dorf, 2011) .DC

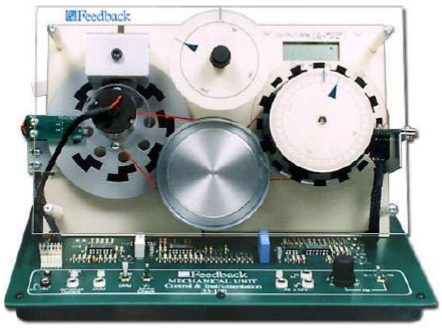

Figure 6: Mechanical Unit of the Digital Servo Kit, (Feedback, 2007)

Motor Model Parameters table shows the model's variables

$$\frac{\Omega(s)}{V_{in}(s)} = \frac{K_A K_T}{(L_A J_T)s^2 + (R_A J_T + L_A b)s + (R_A b + K_B K_T)} \tag{7}$$

Basing on parameter estimation, (Leite, Kuga and Lopes, 2006) the model presented in equation 7 can be simplified by neglecting the effects of the armature inductance, L_A. Therefore, the first-order simplified DC motor model is described by equation by 8

$$\frac{\Omega(s)}{V_{in}(s)} = \frac{K_A K_T}{(R_A J_T + L_A b)s + (R_A b + K_B K_T)} \tag{8}$$

DC Motor Model Parameters	
$V_{in}(t)$	Motor Input Voltage (Volts)
$\Omega(t)$	Motor Angular Velocity
$i_A(t)$	Armature Current (Ampères)
b	Motor Viscous Friction Constant
J_T	Rotor Moment of Inertia ($Kg.m^2$)
K_A	Gain on the Amplifier
K_B	emf Constant ($Volt.s/rad$)
K_T	Motor Torque Constant ($N.m/A$)
L_A	Armature Inductance (Henry)
R_A	Armature Resistance (Ohms)

3 Fault Modeling

To ensure the reliability of the fault detection method, different faults were applied to the system and simulation results were analyzed with respect to residuals behavior and ATLMS response.

3.1 Fault 1: Rotation Approaching Zero

This fault describes a failure wheel situation. This means that no matter which is the input signal, the wheel does not respond and its angular velocity remains very close to zero. Therefore, the mathematical model of fault 1 is presented as follows:

Variables List	
$T(s)$	Torque provided by the motor
$U_e(s)$	Torque reference
K	Gain $K = 7.510^{-3}$
Ω	Angular Velocity
t_{f1}	Time when the fault occurs
d_{f1}	Duration of the Fault

When the fault occurs the system do not respond to any change in input voltage, resulting in a null torque:

$$T(s) = K\left[U_e(s)\frac{1 - e^{-t_{f1}s} + e^{-(t_{f1}+d_{f1})s}}{s}\right] \tag{9}$$

3.2 Fault 2: Last Value Memory

Consider the shifted time step:

$$1(t-a) = \begin{cases} 0, & if \ t < a \\ 1, & if \ t \geq a \end{cases} \tag{10}$$

This fault keeps the output value fixed when $t = t_{f2}$. This value is the step amplitude applied at time t_{f2}. For this reason, shifting property was used to model the fault behavior.

$$\int_{-\infty}^{\infty} f(t)\delta(t-a)dt = f(a) \tag{11}$$

In this case, $d_{f2} \to \infty$ since the fault remains through the rest of simulation after ocurring at t_{f2}, (Leite, 2007). Therefore, fault model is described by:

$$Y_{f2}(t, t_{f2}) = \theta Y_0(t) - Y_z(t) + Y_{se}(t) \tag{12}$$

Variables List	
$Y(t)$	Output's sensor
$Y_{F2}(t)$	Failed output's sensor
$Y_0(t)$	Real fisical input
Y_z	Angular Velocity
$Y_{se}(t)$	When the fault occurs
t_{f2}	When the fault occours
d_{f2}	Duration of the Fault

3.3 Fault 3: Exceeding Maximum RPM Value

The maximum speed value allowed by the equipment manual is $8000RPM$ and the system has an automatic protection to avoid this situation (FBK, 2001). However, as this fault occurs, the motor produces a resulting torque that exceeds the limiting values. The main cause for this behavior may be a problem in the control circuit. Hence, the fault model is developed as follows.

Variables List	
$T(s)$	Torque provided by the motor (Nm)
I_z	Moment of inertia of the wheel rotor
$U_e(s)$	Torque's reference
f_3	Angular Velocity
K	Gain $= 7.510^{-3}$
$\Omega(s)$	Speed of the wheel
t_{f3}	Time when the fault occurs
d_{f3}	Duration of the Fault

When the fault occurs at t_{f1} the control circuit will saturate the torque reference (V) and this continue while the fault last:

$$T(s) = K\left[U_e(s)\frac{1 - e^{-t_{f3}s} + e^{-(t_{f3}+d_{f3})}}{s} + \frac{e^{-t_{f3}s} - e^{-(t_{f3}+d_{f3})s}}{s}f_3\right] \quad (13)$$

As the fault happens on the control circuit, the angular velocity is described as:

$$\Omega(s) = T(s)\frac{1}{I_z}\frac{1}{s} \quad (14)$$

4 Results & Discussion

4.1 Structured Residuals for the DC Motor

The transfer function of the DC motor can be divided into two different intermediate functions as shown in equations 15 and 16. As the first intermediate function relates the armature current of the motor and its input voltage signal, and the second one relates the angular velocity (Ω) with the armature current.

$$\frac{I_a(s)}{U_A(s)} = \frac{s}{Ts+1} \quad (15)$$

$$\frac{\Omega(s)}{I_a(s)} = \frac{k}{s} \quad (16)$$

Thus, the armature current and voltage of the DC motor is defined as in equations 17 and 18

$$I_a(s) = \frac{1}{kT}\left[kU_a(s) - \Omega(s)\right] \quad (17)$$

$$U_a(s) = TI_a(s) + \frac{I_a(s)}{s} \quad (18)$$

Rewriting equations 17 and 18 in matrix form

$$\begin{bmatrix}0\\0\end{bmatrix} = \begin{bmatrix}-1\\ \frac{1}{T}\end{bmatrix}U_a(s) + \begin{bmatrix}T+\frac{1}{s}\\ -1\end{bmatrix}I_a(s) + \begin{bmatrix}0\\ -\frac{1}{kT}\end{bmatrix}\Omega_a(s) \quad (19)$$

In order to achieve decoupling characteristics with respect to $U_a(s)$, $I_a(s)$, and $\Omega(s)$, structured residuals are then calculated as follows

$$r(s) = W(s)\begin{bmatrix}0 & T+\frac{1}{s}\\ \frac{-1}{kT} & -1\end{bmatrix}\begin{bmatrix}\Omega_a(s)\\ I_a(s)\end{bmatrix} + \begin{bmatrix}-1\\ \frac{1}{T}\end{bmatrix}U_a(s) \quad (20)$$

where

$$W_1^T(s) = \begin{bmatrix}-1\\ \frac{1}{T}\end{bmatrix} = 0 \Rightarrow W_1^T(s) = \begin{bmatrix}\frac{1}{T} & 1\end{bmatrix} \quad (21)$$

$$W_2^T(s) = \begin{bmatrix}T+\frac{1}{s}\\ -1\end{bmatrix} = 0 \Rightarrow W_2^T(s) = \begin{bmatrix}1 & T+\frac{1}{s}\end{bmatrix} \quad (22)$$

$$W_3^T(s) = \begin{bmatrix}0\\ \frac{-1}{kT}\end{bmatrix} = 0 \Rightarrow W_3^T(s) = \begin{bmatrix}1 & 0\end{bmatrix} \quad (23)$$

Finally, applying equation 5

$$\begin{bmatrix}r_1^*\\ r_2^*\\ r_3^*\end{bmatrix} = \begin{bmatrix}\frac{1}{T} & 1\\ 1 & T+\frac{1}{s}\\ 1 & 0\end{bmatrix}\begin{bmatrix}-U_a(s) + TI_a(s) + \frac{I_a(s)}{s}\\ \frac{1}{T}U_a(s) - I_a(s) - \frac{\Omega(s)}{kT}\end{bmatrix} \quad (24)$$

Therefore,

$$r_1^* = \frac{I_a(s)}{Ts} - \frac{\Omega(s)}{kT} \quad (25)$$

$$r_2^* = \frac{(-Ts-1)\Omega(s)}{kTs} + \frac{kU_a(s)}{kTs} \quad (26)$$

$$r_3^* = -U_a(s) + \frac{(Ts+1)I_a(s)}{s} \quad (27)$$

4.2 Fault 1 Simulation: Zero DC Motor Rotation

Situation 1 represents a fault on the wheel. When this occurs, motor speed speed reduces gradually until reaching a zero value, as shown on figure 7:

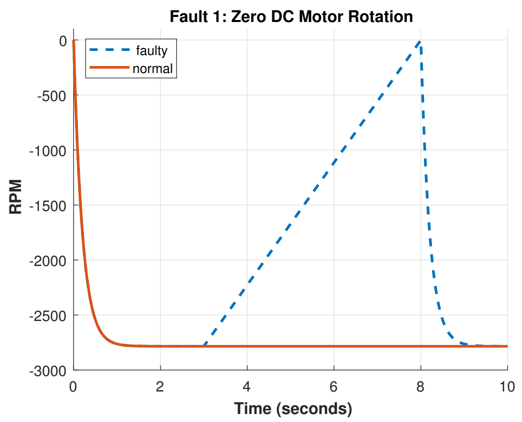

Figure 7: Profile of Fault 1

At $t = 3s$, fault appears and the wheel ignores any signal coming from the control circuit.

In order to analyze this fault, sensitive and insensitive structured residuals were generated. Figure 8 shows residuals 1 to 3 and the ATLMS response. Residual 3 is insensitive to the fault applied whereas residuals 1 and 2 are sensitive. The ATLMS technique produces an adaptive threshold which is determined by the signal behavior of sensitive and insensitive residuals. Figure 9 shows the flag response for fault occurrence (flag = 1). With respect to fault 1, the ATLMS detected a deviation from normal behavior at 3.01 seconds, resulting in a 0.01s delay after fault occurrence.

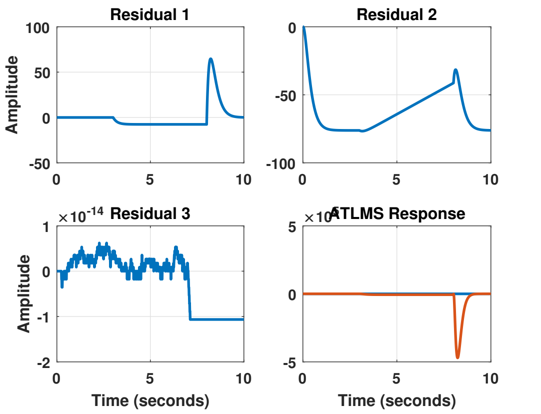

Figure 8: Structured Residuals for Fault 1

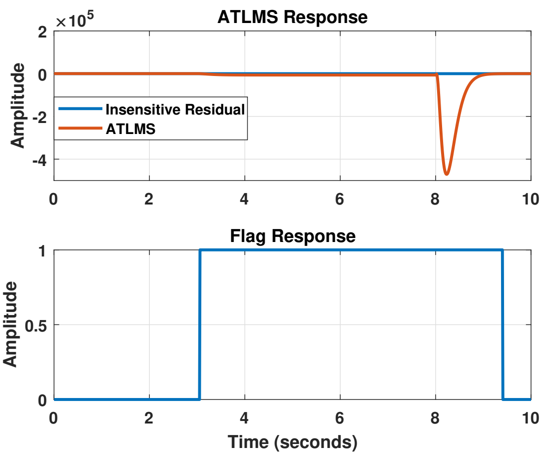

Figure 9: ATLMS Flag Response for Fault 1

4.3 *Fault 2 Simulation: RPM Last Value*

As described by figure 10, the motor receives an input signal from the control circuit but the wheel is kept in a failure state, showing the last RPM value before fault occurs. On figure 11, the structured residuals generated for fault 2. Residuals 2 and 3 are sensitive to the applied fault whereas residual 1 is insensitive. Figure 12 shows the flag response for fault occurrence (flag = 1). With respect to fault 2, the ATLMS detected a deviation from normal behavior at 0.21 seconds, again resulting in a 0.01s delay after fault occurrence.

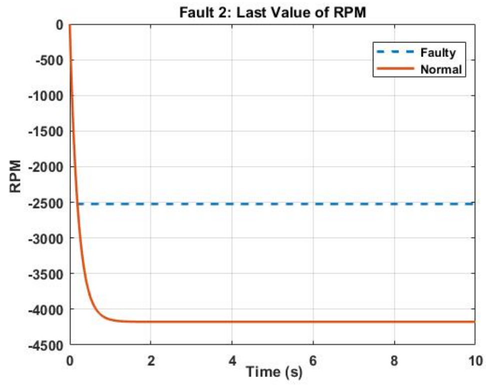

Figure 10: Profile of Fault 2

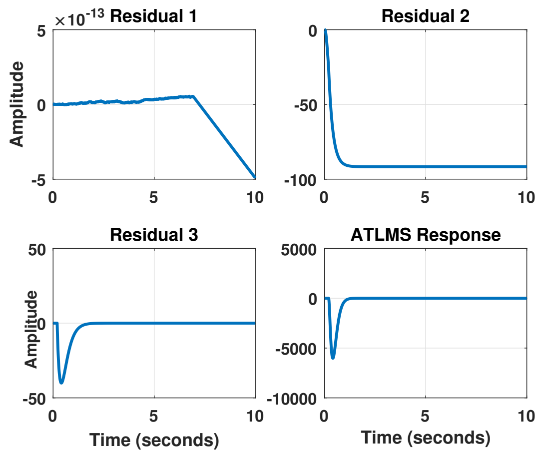

Figure 11: Structure Residuals for Fault 2

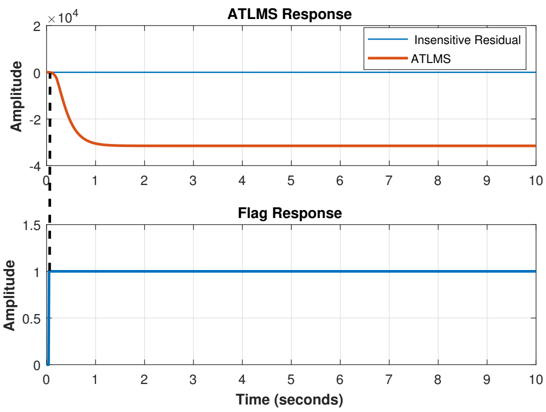

Figure 12: ATLMS Flag Response for Fault 2

4.4 *Fault 3 Simulation: Exceeding RPM Maximum Value*

Fault 3 can be described by a malfunction on the control circuit which results in a voltage error. The motor cannot exceed 8000RPM as specified by (FBK, 2001). Fault profile is presented in figure 13:

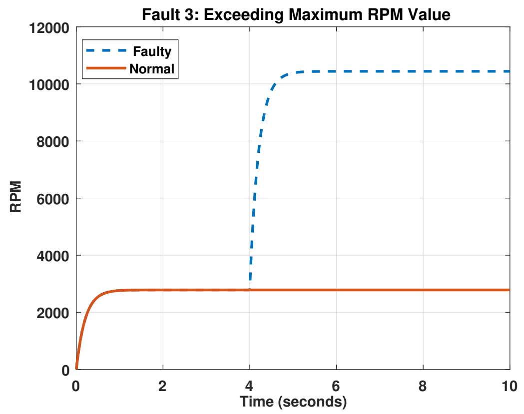

Figure 13: Profile of fault 3

During fault occurrence, input voltage goes from 8V to 30V, causing a critical impact on motor speed. Fault 3 produces a significant variation on the residuals as in figure 14. Residuals 1 and 2 are sensitive and residual 3 is insensitive to the applied fault. Fault 3 was injected at $t = 4s$ and the ATLMS detected a deviation from normal behavior at $4.3s$, resulting in a $0.3s$ delay after fault occurrence as represented in figure 15

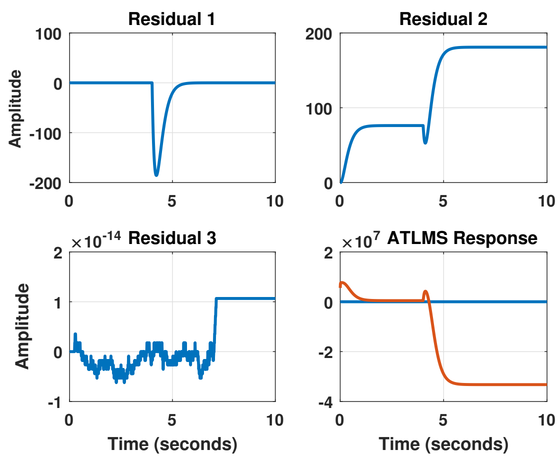

Figure 14: Structured Residuals for Fault 3

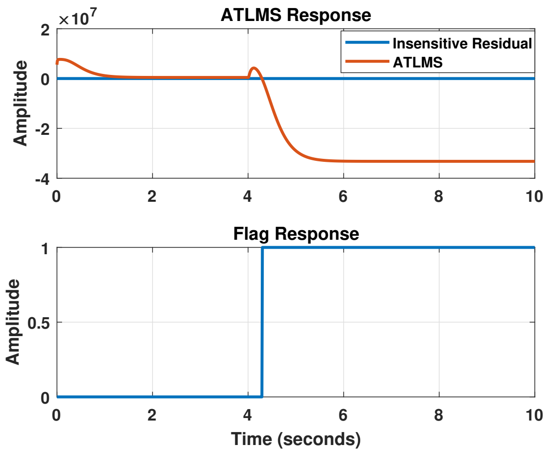

Figure 15: ATLMS Flag Response for Fault 3

5 Conclusions

The ATLMS technique was proven to be a very useful tool for detecting faults. Three different situations were proposed and structured residuals were designed in order to satisfy ATLMS requirements i.e. sensitive and insensitive residuals with respect to applied faults. All proposed faults were detected within a range from 0.01s to 0.3s and there was no missed/false alarms. Better results might also be achieved through a detailed analysis of ATLMS parameters such as filter convergence and suitable SPRT parameters.

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