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Information Sciences

• **Supplementary File** •

Incipient fault diagnosis on active disturbance rejection control

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Appendix A Proof of Theorem 2

There is a matrix exists defined as

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1,(n+1)} \\ -d_{12} & d_{22} & \cdots & d_{2,(n+1)} \\ \vdots & \vdots & \ddots & \vdots \\ -d_{1,(n+1)} & -d_{2,(n+1)} & \cdots & d_{(n+1),(n+1)} \end{bmatrix},$$

which the principal diagonal is positive and the formula $DA(e)$ positive definiteness to keeps the zero solution of this systems in (9) is Lyapunov's stability.

Proof.

In order to verify the conclusion in Lemma 1, according to the reference [**?**], the Lyapunov function can be chosen as:

$$V = \int_0^t (DA(e)e, \dot{e}), d\tau.$$

Then, taking derivatives of (8) with time can get the following formula:

$$V^{'} = -(DA(e)e, A(e)e) < 0.$$

Therefore, the zero solution of the system (8) is Lyapunov stable needs only the D is a matrix which all elements on the primary diagonal are positive number to made $DA(e)$ is a symmetric positive definite matrices and the observer state values $z_1, z_2, \cdots, z_{n+1}$ can tracking the $x_1, x_2, \cdots, x_{n+1}$.

In conclusion, we need to find the D satisfying the criteria to prove the rationality of the Lemma 2. Then, calculating the matrix $DA(e)$ as follows:

$$DA(e) = \begin{bmatrix} D_1 & -d_{11} & -d_{12} & \cdots & -d_{1n} \\ D_2 & d_{12} & -d_{22} & \cdots & -d_{2n} \\ D_3 & d_{13} & d_{23} & \cdots & -d_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ D_n & d_{1n} & d_{2n} & \cdots & -d_{nn} \\ D_{n+1} & d_{1,n+1} & d_{2,n+1} & \cdots & d_{n,n+1} \end{bmatrix}, \tag{A1}$$

where,

$$\begin{aligned} D_1 &= d_{11}\beta_{01} + d_{12}\beta_{02}b(\alpha_1) + \cdots + d_{1,n+1}\beta_{0n+1}b(\alpha_n), \\ D_2 &= -d_{12}\beta_{01} + d_{22}\beta_{02}b(\alpha_1) + \cdots + d_{2,n+1}\beta_{0n+1}b(\alpha_n), \\ D_3 &= -d_{13}\beta_{01} - d_{23}\beta_{02}b(\alpha_1) + \cdots + d_{3,n+1}\beta_{0n+1}b(\alpha_n), \\ &\cdots\cdots, \\ D_n &= -d_{1,n+1}\beta_{01} - d_{2,n+1}\beta_{02}b(\alpha_1) + \cdots + d_{n+1,n+1}\beta_{0n+1}b(\alpha_n), \end{aligned} \tag{A2}$$

$b(\alpha_i)$ is bounded and

$$0 < b(\alpha_i) < \frac{1}{\gamma^{1-\alpha_i}} \approx 1.$$

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Therefore, at the condition of the instance for a symmetric positive definite matrix, to making sure that the $DA(e)$ is symmetric positive definite matrix, it's symmetric elements are equal and the determinant of the sequential dominant is greater than zero.

Further, the following equations must be satisfied.

$$\begin{aligned}
&D_2=-d_{11}, D_3=-d_{12}, \cdots, D_{n+1}=-d_{1n},\\
&d_{13}=-d_{22}, d_{14}=-d_{23}, \cdots, d_{1,n+1}=-d_{2n},\\
&d_{24}=-d_{33}, d_{25}=-d_{34}, \cdots, d_{2,n+1}=-d_{3n},\\
&\cdots\cdots,\\
&d_{n-2,n}=-d_{n-1,n-1}, d_{n-2,n+1}=-d_{n,n-1}, d_{n-1,n-1}=-d_{nn},
\end{aligned} \tag{A3}$$

and

$$\begin{gathered}
D_1>0,\\
\begin{vmatrix} D_1 & -d_{11}\\ -d_{11} & d_{12}\end{vmatrix}>0,\\
\begin{vmatrix} D_1 & -d_{11} & -d_{12}\\ -d_{11} & d_{12} & -d_{22}\\ -d_{12} & -d_{22} & d_{23}\end{vmatrix}>0,\\
\vdots\\
\begin{vmatrix} D_1 & -d_{11} & -d_{12} & \cdots & -d_{1n}\\ -d_{11} & d_{12} & -d_{22} & \cdots & -d_{2n}\\ -d_{12} & -d_{22} & d_{23} & \cdots & -d_{3n}\\ \vdots & \vdots & \vdots & \ddots & \vdots\\ -d_{1n} & -d_{2n} & -d_{3n} & \cdots & d_{n,n+1}\end{vmatrix}>0.
\end{gathered} \tag{A4}$$

When $n=2$, assume $d_{11}=1$, $d_{22}=\tau$. and τ is a positive number bordering on zero boundlessly.

Calculating of $DA(e)$ as follows:

$$DA(e)=\begin{bmatrix} D_1 & -d_{11}\\ D_2 & d_{12}\end{bmatrix}, \tag{A5}$$

where,

$$\begin{aligned}
D_1&=\beta_{01}d_{11}+\beta_{02}b(\alpha_1)d_{12},\\
D_2&=-\beta_{01}d_{12}+\beta_{02}b(\alpha_1)d_{22}.
\end{aligned} \tag{A6}$$

Combine with the formula(15) and $d_{11}=1$, the following formula can get:

$$D_2=-d_{11}=-1. \tag{A7}$$

Hence, d_{12} is represented as shown below:

$$d_{12}=\frac{1+\tau\beta_{02}b(\alpha_1)}{\beta_{01}}. \tag{A8}$$

Further, the formulas of D_1 can get and need to satisfied $D_1>0$:

$$D_1=\beta_{01}+\frac{[1+\tau\beta_{02}b(\alpha_1)]\beta_{02}b(\alpha_1)}{\beta_{01}}>0, \tag{A9}$$

Since the $b(\alpha_i)$ is bounded and τ is a positive number bordering on zero boundlessly. So, D_1 and d_{12} can translate to (19):

$$\begin{aligned}
D_1&\approx\beta_{01}+\frac{\beta_{02}b(\alpha_1)}{\beta_{01}}>0,\\
d_{12}&\approx\frac{1}{\beta_{01}}>0.
\end{aligned} \tag{A10}$$

Obviously, $D_1>0$ because of all the parameter greater than zero.

Then, second order determinant can be found as:

$$\begin{vmatrix} D_1 & -d_{11}\\ -d_{11} & d_{12}\end{vmatrix}=d_{12}D_1-d_{11}^2=\frac{\beta_{02}b(\alpha_1)}{\beta_{01}^2}>0.$$

So, When n=2, we can find the D to satisfied the Lemma 2.

The next, when n=3, assume $d_{11} = 1, d_{22} = d_{33} = \tau$.

Calculating of $DA(e)$ and written as:

$$DA(e) = \begin{bmatrix} D_1 & -d_{11} & -d_{12} \\ D_2 & d_{12} & -d_{22} \\ D_3 & d_{13} & d_{23} \end{bmatrix}, \tag{A11}$$

where,

$$\begin{aligned} D_1 &= \beta_{01}d_{11} + \beta_{02}b(\alpha_1)d_{12} + \beta_{03}b(\alpha_2)d_{13}, \\ D_2 &= -\beta_{01}d_{12} + \beta_{02}b(\alpha_1)d_{22} + \beta_{03}b(\alpha_2)d_{23}, \\ D_3 &= -\beta_{01}d_{13} - \beta_{02}b(\alpha_1)d_{23} + \beta_{03}b(\alpha_2)d_{33}. \end{aligned} \tag{A12}$$

Combine with the formula(21), $d_{11} = 1, d_{22} = d_{33} = \tau$, the following formula can get:

$$D_2 = -d_{11} = -1, d_{13} = -d_{22} = -\tau, D_3 = -d_{12}. \tag{A13}$$

So, combine with the D_3 and formula(22), the d_{12} can be described as follows:

$$d_{12} = -\tau\beta_{01} + \beta_{02}b(\alpha_1)d_{23} - \tau\beta_{03}b(\alpha_2). \tag{A14}$$

Further, according to formula(22),formula(23) and D_2, the d_{23} is obtained as:

$$d_{23} = \frac{1 + \tau\beta_{01}^2 + \tau\beta_{01}\beta_{03}b(\alpha_2) + \tau\beta_{02}b(\alpha_1)}{\beta_{01}\beta_{02}b(\alpha_1) - \beta_{03}b(\alpha_2)}. \tag{A15}$$

Then, the D_1 depend on (21)∼(24) can be translated to following form:

$$\begin{aligned} D_1 = {} & \beta_{01} - \tau\beta_{03}b(\alpha_2) + \tau\beta_{01}\beta_{02}b(\alpha_1) - \tau\beta_{02}\beta_{03}b(\alpha_1)b(\alpha_2) \\ & + \beta_{02}^2 b^2(\alpha_1)\frac{1 + \tau\beta_{01}^2 + \tau\beta_{01}\beta_{03}b(\alpha_2) + \tau\beta_{02}b(\alpha_1)}{\beta_{01}\beta_{02}b(\alpha_1) - \beta_{03}b(\alpha_2)} > 0. \end{aligned} \tag{A16}$$

As the $b(\alpha_i)$ is bounded and τ is a positive number bordering on zero boundlessly. So, D_1 can translate as follow:

$$D_1 \approx \beta_{01} + \frac{\beta_{02}^2}{\beta_{01}\beta_{02} - \beta_{03}} > 0, \tag{A17}$$

as shown above, conditions for the establishment of the above equation is $Q = \beta_{01}\beta_{02} - \beta_{03} > 0$ or stated as follows:

$$\begin{aligned} & Q < 0, \\ & \beta_{01}Q + \beta_{02}^2 < 0. \end{aligned} \tag{A18}$$

Refer to the approach of reference [7], the inequations of (27) could be ruled out at once and the following arrays are grearter than zero under the condition of $Q > 0$.

$$D_1 > 0,$$

$$\begin{vmatrix} D_1 & -d_{11} \\ -d_{11} & d_{12} \end{vmatrix} > 0,$$

$$\begin{vmatrix} D_1 & -d_{11} & -d_{12} \\ -d_{11} & d_{12} & -d_{22} \\ -d_{12} & -d_{22} & d_{23} \end{vmatrix} > 0.$$

So, we can find the D when n=3.

On the basis of analyses above, supposed that the D were founded when $n = n$.

Now, when $n = n + 1$, we still need to prove the inequations in (13) greater than zero.

When $n = n + 1$, the D_1 translate to:

$$D_1 = d_{11}\beta_{01} + d_{12}\beta_{02}b(\alpha_1) + \cdots + d_{1,n+1}\beta_{0n+1}b(\alpha_n), \tag{A19}$$

Actually, the $d_{1,n+1} > 0$, $\beta_{0n+1} > 0$ and $b(\alpha_n) > 0$. Thus, n-th order sequential master-child always greater than zero due to the above analysis when $n = n$.

Therefore, it only need to find the condition to guarantee the value of $n+1$-th array are more than zero.

$$\begin{vmatrix} D_1 & -d_{11} & -d_{12} & \cdots & -d_{1n} \\ -d_{11} & d_{12} & -d_{22} & \cdots & -d_{2n} \\ -d_{12} & -d_{22} & d_{23} & \cdots & -d_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -d_{1n} & -d_{2n} & -d_{3n} & \cdots & d_{n,n+1} \end{vmatrix} > 0.$$

As we all know from the advanced algebra theory, term for the formula true: matrix eigenvalues of above array do not contain zero, and negative real eigenvalues must occur in pairs, then the determinant is greater than zero.

Therefore, the eigenvalues could be shown as follow:

$$\begin{vmatrix} \lambda - D_1 & -d_{11} & -d_{12} & \cdots & -d_{1n} \\ -d_{11} & \lambda - d_{12} & -d_{22} & \cdots & -d_{2n} \\ -d_{12} & -d_{22} & \lambda - d_{23} & \cdots & -d_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -d_{1n} & -d_{2n} & -d_{3n} & \cdots & \lambda - d_{n,n+1} \end{vmatrix} = (\lambda - \varphi)^{n+1},$$

where, λ is matrix eigenvalues and $\varphi > 0$.

On the basis of φ, to determine the value of D. So, we can find the D when n=n+1.

In conclusion, we can find the D which satisfied the Lemma 2 to made the $DA(e)$ is symmetric positive definite under the certain conditions. Then the state in observer $z_1(t), \ldots, z_{n+1}(t)$ can track the system state $x_1(t), \ldots, x_{n+1}(t)$. So, The proof is ended.

Appendix B Design and implementation of algorithm

In order to applied these process in practice, the reasonable analysis of algorithm according to the aforementioned analysis are depicted as follows:

Algorithm B1 The ADRC algorithm

1: System initialization, on the basis of above study, design the ADRC controller for the incipient fault diagnosis.
2: According to (1), gives the suitable parameters of TD, ESO and NSELF.
3: Display the effection, if the fitting effect is good, go to next step. Nor back to the first step.
4: Output results and get the error curve, failure estimation curve and state estimation curve.

Based on the above analysis, the simulation flow chart is shown below.

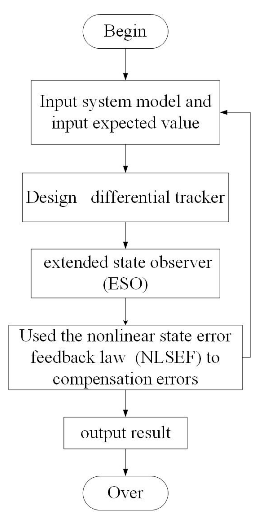

Figure B1 the ADRC simulation flow chart.

Appendix C Simulation analysis

Appendix C.1 Incipient fault classification

In order to verify the validity of the proposed algorithm and model, two kinds of incipient fault models are used for verification and the definition of the incipient fault model are as follows [?]:

1. The soft incipient fault: It is characterized with small amplitude and slow development. This type of fault impact on the system is hard to see at an early stage. But, as time going on, it has certain influence or even serious consequence on the system. Such as bearing wear fault in equipment.

2. The abrupt incipient fault: It is characterized with small amplitude and rapid instantaneous change. The failure process can reach its maximum value in a few microseconds. For example, a short circuit fault in a circuit element.

In view of the above incipient fault classification, the research on the soft incipient fault and the abrupt incipient fault has been discussed in this work. To make this discussion more objective and concrete, the two types of incipient fault mathematical expressions has been described in remark 2, remark 3.

Remark 1. Aiming at the characterize of the soft incipient fault, its analytic expression form can be described as follows:

$$f_s(t) = \begin{cases} 0, \quad if\ t < T, \\ (1 - e^{-k(t-T)})f_j(t), \quad if\ t \geqslant T, \end{cases} \tag{C1}$$

where, $T > 0$ is soft incipient fault happening time, $k > 0$ is constant, $f_j(t)$ represents a non-constant fault which affecting the system.

Remark 2. For the abrupt incipient fault, its analytic expression form can be described as follows:

$$f_a(t) = \begin{cases} 0, \quad if\ t < T, \\ M, \quad if\ t \geqslant T, \end{cases} \tag{C2}$$

where,$M \geqslant 0$ meets the conditions in remark 1.

Therefore, the superiority of ADRC in incipient fault diagnosis will be validated in the next subsection.

Appendix C.2 Numerical verification

Table C1 ADRC simulation parameters

	Symbols for quantities	The soft incipient fault	The abrupt incipient fault
TD	r	15000	15000
	h	0.01	0.01
	R	2	2
	g_1	0.05	1.5
	g_2	1	2
ESO	β_{01}	0.1	15000
	β_{02}	1	0.01
	β_{03}	0.05	1
	α_1	0.0035	0
	α_2	0.0005	1
	γ	0.02	1
NLSEF	β_1	0.1	0.0012
	β_2	1	167
	β_3	0.05	0.0005
	α_3	0.0005	1.4
	α_4	0.0035	0.85
	α_5	0.00165	4.3
	b	3	3
	γ	0.02	0.02

Through the analysis of the previous article, the second-order model is described to illustrate the effectiveness of the proposed methods, and the ADRC simulation parameters are listed as the table 1.

Consider the system (1), the second-order mode is depicted to verified the availability of the proposes methods, the system model with incipient fault and disturbance are given as follows:

$$\begin{cases} \dot{x}_1(t) = x_2(t), \\ \dot{x}_2(t) = f(t) + u(t) + d(t), \\ y(t) = x_1(t). \end{cases} \tag{C3}$$

Select the soft incipient function model as Remark 2

$$f_s(t) = (1 - e^{-k(t-T)})f_j(t),\ and\ |f_s(t)| \leqslant 1,$$

where, $f_j(t) = sint$,$k = 0.1$, $T = 1s$ means the time to fault is 1s and the disturbance can be described as following:

$$d(t) = 0.5(1 - e^{-k(t-T)})cost.$$

According to (4), the new system can be got as follows:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = x_3 + u(t) + d(t), \\ \dot{x}_3 = \dot{f}(t) = \sigma(t), \\ y = x_1. \end{cases} \tag{C4}$$

Furthermore, based on the extended state observer construct in this paper. the incipient fault curve and the tracking curve in system (36) under fault condition can be depicted in figure 1.

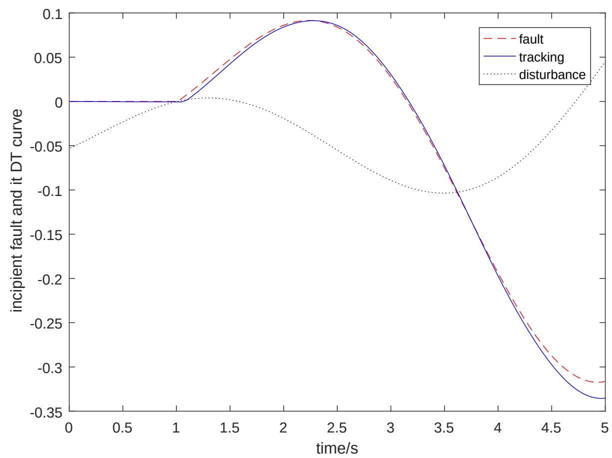

Figure C1 Fault, Fault tracking and disturbance curve for soft incipient fault.

It can be seen that this tracking curve is fast overfitting to fault curve, it means that the observer demonstrated in this paper is available and reasonable. Meanwhile, the differential tracker can follow the incipient fault well in the case of perturbations. The result indicated that the method of ADRC applying to soft incipient fault diagnosis is feasible and effective.

Otherwise, the observer error curves in system (36) can be shown in Fig.3.

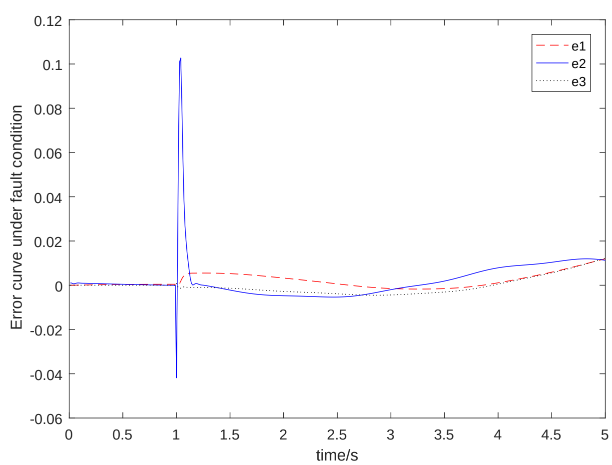

Figure C2 Error curve under the soft incipient fault condition.

As shown in the Fig.3, the error dynamic equation as given by (4) is fast tends to zero when the soft incipient fault happens in the system. Although when time to 1 second, there have a shock, but it can return to normal range. In general, this errors curve shown that the observer demonstrated in this paper is preferably.

Besides, in order to further prove the perfection of this method, the system state values and their estimations have been tried. The output curve are presented in Fig.4, Fig.5.

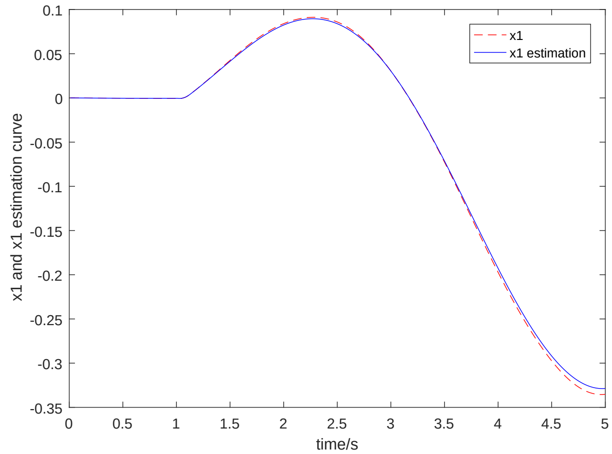

Figure C3 x_1 and x_1 estimation under the soft incipient fault condition.

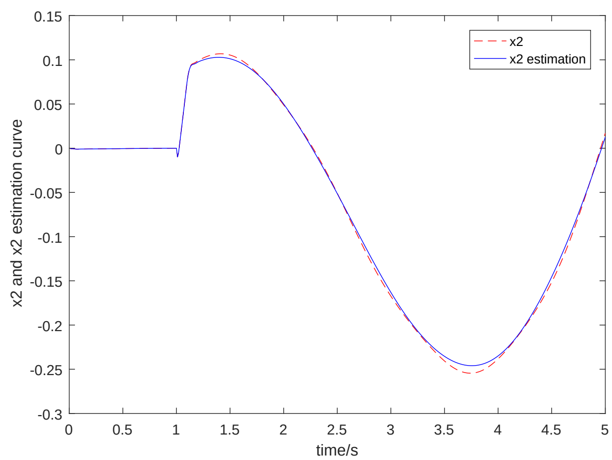

Figure C4 x_2 and x_2 estimation under the soft incipient fault condition.

As shown in Fig.4 and Fig.5, the state estimations can tracking the true values achieve a high fitting condition, it means that, this incipient fault diagnosis method not only could tracking our incipient fault value, but also could estimations our state values well.

Then, when the abrupt incipient fault happens in the system (36), based on remark 3, the incipient fault function can be selected as:

$$f_a(t) = \begin{cases} 0, & if \quad t < T, \\ 1, & if \quad t \geqslant T, \end{cases}$$

where, $M = 1$, $T = 1s$ and the disturbance can be described as follows:

$$d(t) = 0.5(1 - e^{-k(t-T)})cost.$$

Closely, the abrupt incipient fault in system (1), its estimation and the differential tracker curve can be depicted in Fig.6.

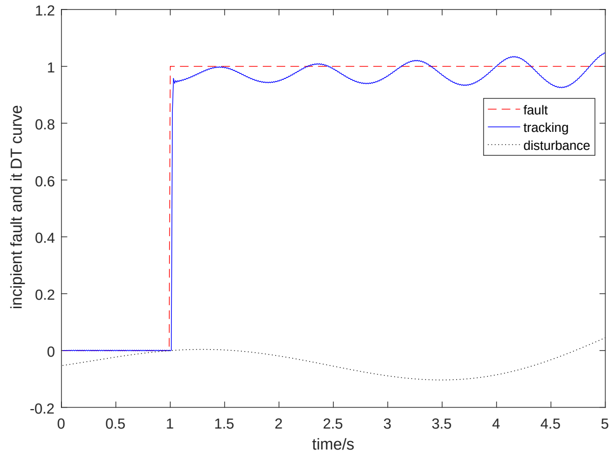

Figure C5 Fault, Fault tracking and disturbance curve for abrupt incipient fault.

As shown in Fig.6. Obviously, the estimation named tracking can trace the abrupt incipient fault value well, despite the tracking value is showing state of fluctuating, but this variation state has been around the true value all the time.

Further, the observer error curves under the abrupt incipient fault condition were be shown in Fig.7

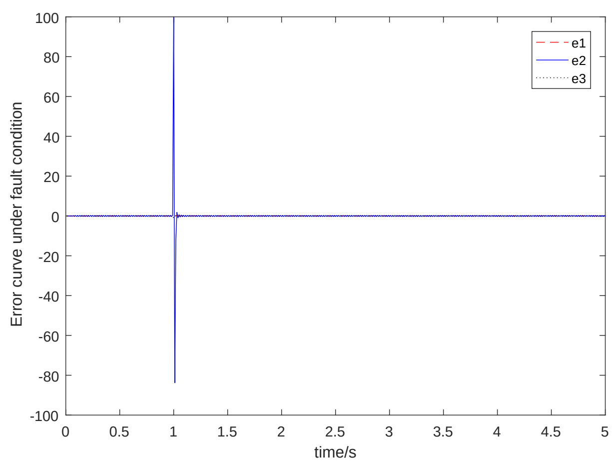

Figure C6 Error curve under the abrupt incipient fault condition.

In addition, in order to verified this method, the system state values and their estimations curves have been show in Fig.8, Fig.9.

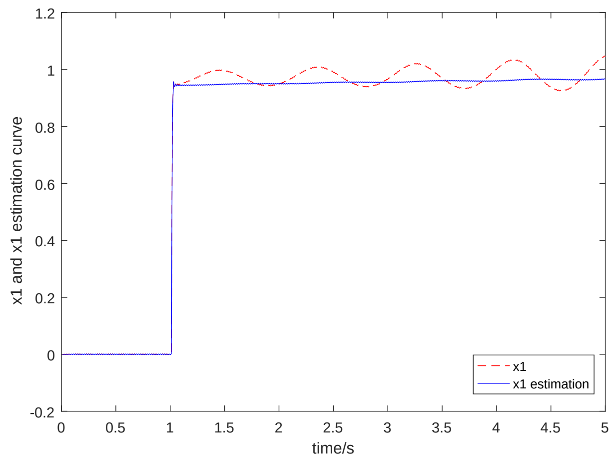

Figure C7 x_1 and x_1 estimation under the soft incipient fault condition.

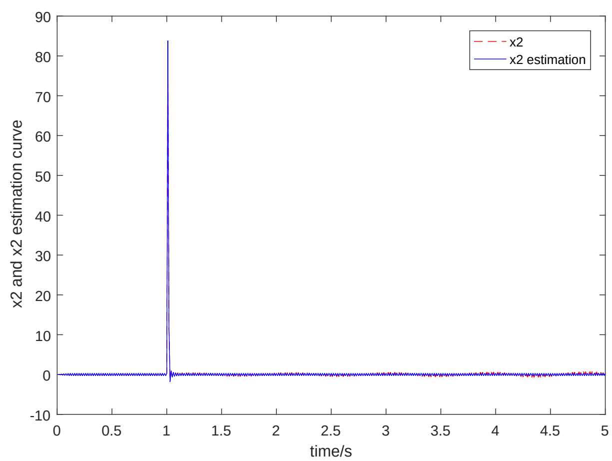

Figure C8 x_2 and x_2 estimation under the soft incipient fault condition.

From the Fig.7, it is observed that the error dynamic equation is close to zero except for the 1s. This result shows that the observer demonstrated in this paper has the good stability when it diagnoses the abrupt fault.

From the Fig.8 and Fig.9, it can be seen that the state estimations can tracking the system state well outside the initial moment of the incipient fault .

To sum up, the simulation experiments indicated that the tracking curve can track the real values of fault was verified to be a good result and reached the goal of the designed ADRC for fault diagnosis obviously.

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