Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2019, 6(12):7-12

Research Article **ISSN: 2394 - 658X**

Neutral Time-Delay System: Prognosis for a Class of Neutral System with Variable Time Delay

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ABSTRACT
The present paper proposes prognosis method for class of neutral systems with variable time delay. To generate an algebraic method to achieve system prognosis will used an unknown input observer (UIO) with a new form

Key words: Neutral time delay system, Prognosis, UIO, Fault detection

1. INTRODUCTION

In the last years, the study of systems with delays has received special attention from researchers due to the fact that delays occur in the major part of the chemical, mechanical or communication systems, Their presence may lead to the deterioration of the system's performance or even its instability. For this reason, prognosis has been an essential objective of research to make model control easier. In the literature, the prognosis, as appropriate, of a process to determine the remaining life of a system [1] or the likelihood that the system will operate for a period of time. The prognosis methods can be classified according to three approaches:prognosis based on a physical model [2,3], prognosis guided by data, and data-driven prognosis approaches studying the use of data-mining and machine learning techniques for the purpose of process monitoring of industrial systems. Due to its potentials to boost efficiency and cut costs of industry, the prognosis under the data-driven framework have been an attractive research topic, and several related research results have been reported [4,5], and prognosis based on feedback data [6]. The present paper, aims at developing prognosis approach to estimate the dynamics state degradation of a neutral time delay system with variable time delay and predict its remaining life.

The remainder of the paper is organized as follows: Section 2 presents the proposed degradation prognosis method to evaluate the state of cumulative degradation and its dynamics. Section 3 illustrates the relevance of the diagnosis and the prognosis method applied to a transmission line system. Finally, the conclusions are given in section 4.

A. Prognosis for a class of neutral time delay system

1) Model class for prognosis

The prognosis turns out to be a quite promising activity for not incurring inopportims maintenance costs. The Management Prognosis Health (MPH) consist in developing degradation prognosis methodologies to estimate the dynamics of system degradation state and predict the Life Time Remaining (LTR). For this reason, a conventional general model class is used [2]:

$$\begin{cases} \dot{x} = w(\kappa, u) \\ y = f(\kappa, u) \\ \kappa \in v, u \in U, y \in \delta \\ w(.,.): v \times U \to v, y(.,.): v \times U \to \delta \end{cases} \tag{1}$$

$\kappa = [x, \dot{x}, \alpha]^T$ is associated with the state x and degradation α. f is a function which is at least class C^1. v is an open set of $x \in \mathbb{R}^n$, U is an open set of $\mathbb{R}^m$ regarding environmental and load conditions. δ is an open set of $\mathbb{R}^p$, t$\in \mathbb{R}^+$ is the time variable. In order to describe the behavior of this system, a subclass of model (1) is used:

$$\begin{cases} \dot{x} = w(x, \dot{x}, \lambda(\alpha), u); x(t_0) = x_0 \\ \dot{\alpha} = \varepsilon s(x, \dot{x}, \alpha), \alpha(t_0) = \alpha_0 \\ y = q(x, \dot{x}, \alpha, u) \end{cases} \tag{2}$$

$\lambda \in \mathbb{R}^r$ is the vector of parameters, function ofα, $u \in \mathbb{R}^m$ is the vector composed of the environmental conditions and solicitation. The ratio of separation of fast time scales and slow dynamics is described by $0 < \varepsilon << 1$.$y \in \mathbb{R}^p$ is the output vector.

Degradation is defined as a process of alteration caused by changes in the structural properties of the system, which affects present and future performances irreversiblye. It is synonymous with a slope of functionality when it reaches a critical threshold. Therefore $\dot{\alpha} = \varepsilon s(x, \dot{x}, \alpha)$,$w$, s, q are assumed as being of continuously differentiable functions of their arguments x, α, u, $\dot{x}$.

The main contribution of this paper is the introduction of models based prognostic methodology to rebuild dynamics accumulation of the degradation state, using only known system input and output measures. The method is based on the fact that the deterioration will be brought to an unknown input.

2) System Description and Problem Formulation

a. Unknown input observer (UIO) based degradation prognosis

Supposition 1: The output function is not a function of the degradation state which considers a model class in the form of system (2).

$$\begin{cases} \dot{x}(t) = A_1(\alpha)x(t) + A_2(\alpha)x(t - l(t)) + A_d(\alpha)\dot{x}(t - l(t)) + B(\alpha)u(t) \\ y(t) = Cx(t) \end{cases} \tag{3}$$

$x \in \mathbb{R}^n$, $y \in \mathbb{R}^p$, $u \in \mathbb{R}^m$, $\alpha \in \mathbb{R}^q$ and the matrices A_1, A_2, A_d, B, and C are defined with appropriate dimensions.

Supposition 2: the changes caused by degradation in the structural properties are supposed to be modeled with linear structure as follows:

$$\begin{cases} A_1(\alpha) = A_{1_0} + \sum_{i=1}^{q} A_{1_i}\alpha_i \\ A_2(\alpha) = A_{2_0} + \sum_{i=1}^{q} A_{2_i}\alpha_i \\ A_d(\alpha) = A_{d_0} + \sum_{i=1}^{q} A_{d_i}\alpha_i \\ B(\alpha) = B_0 + \sum_{i=1}^{q} B_i\alpha_i \end{cases} \tag{4}$$

Bye replacing (4) in (3) and by considering hypothesis 2, the system obtained is as follows:

$$\begin{cases} \dot{x} = A_{1_0}x(t) + A_{2_0}x(t - l(t)) + A_{d_0}\dot{x}(t - l(t)) + B_0u(t) + \Omega(x, \dot{x}, u, \alpha) \\ y = Cx(t) \end{cases} \tag{5}$$

Supposition 3: We consider a matrix J such as rank (J)≤p. In addition, rank (J)=q≤p and Ω=JΩ_1

$$\begin{cases} \dot{x} = A_{1_0}x(t) + A_{2_0}x(t - l(t)) + A_{d_0}\dot{x}(t - l(t)) + B_0u(t) \\ +J\Omega_1(x, \dot{x}, u, \alpha) \\ y = Cx(t) \end{cases} \tag{6}$$

In order to design an observer for linear systems with neutral delay, a methodology is developed in [7] with T_1 is a non-singular transformation matrix $x = T_1\bar{x}$. T_1=[N J_1] with N$\in M_{(n,(n-q))}$, $J_1 \in M_{n,q} \in$ span J_i, $i = 1 \ldots n J_i (i = 1 \ldots n)$ represent column vectors of matrix J.

By applying the state T_1 transformation, we obtain:

$$\begin{cases} \dot{\bar{x}} = \bar{A}_{1_0}\bar{x} + \bar{A}_{2_0}\bar{x}(t - l(t)) + \bar{A}_{d_0}\dot{\bar{x}}(t - l(t)) + \bar{B}_0 u \\ +T_1^{-1}J\Omega_1(\bar{x}, \dot{\bar{x}}, u, \alpha) \\ y = \bar{C}\bar{x} \end{cases} \tag{7}$$

With matrices are defined as follows

$$\begin{cases} \bar{A}_{1_0} = T_1^{-1} A_{1_0} T_1 = \begin{bmatrix} \bar{A}_{1_{11}} & \bar{A}_{1_{12}} \\ \bar{A}_{1_{21}} & \bar{A}_{1_{22}} \end{bmatrix} \\ \bar{A}_{2_0} = T_1^{-1} A_{2_0} T_1 = \begin{bmatrix} \bar{A}_{2_{11}} & \bar{A}_{2_{12}} \\ \bar{A}_{2_{21}} & \bar{A}_{2_{22}} \end{bmatrix} \\ \bar{B}_0 = T_1^{-1} B_0 = \begin{bmatrix} \bar{B}_1 \\ \bar{B}_2 \end{bmatrix} \\ \bar{A}_{d_0} = T_1^{-1} A_{d_0} T_1 = \begin{bmatrix} \bar{A}_{d_{11}} & \bar{A}_{d_{12}} \\ \bar{A}_{d_{21}} & \bar{A}_{d_{22}} \end{bmatrix} \\ \bar{C} = C T_1 \end{cases}$$

The state vector is decomposed into two parts, one part $\bar{x}_1$ that is not affected by the degradation and a second part $\bar{x}_2$ affected by the degradation.

$$\bar{x} = [\bar{x}_1 \bar{x}_2]^T,$$
$$\bar{x}_1 \in R^{n-q}, \bar{x}_2 \in R^q$$

O^{-1} is a non-singular transformation matrix for operations on the J column and rank (O) = n such that

$$\begin{cases} \dot{\bar{x}} = \bar{A}_{1_0}\bar{x} + \bar{A}_{2_0} x(t - l(t)) + \bar{A}_{d_0}\dot{\bar{x}}(t - l(t)) \\ +\bar{B}u + T_1^{-1} J O^{-1} O \Omega_1(\bar{x}, \dot{\bar{x}}, u, \alpha) \\ \bar{y} = \bar{C}\bar{x} \end{cases} \quad (8)$$

With

$$\bar{J} = T_1^{-1} J O^{-1} = \begin{pmatrix} 0_{n-q,n-q} & 0_{n-q,q} \\ 0_{q,n-q} & I_{q,q} \end{pmatrix}$$
$$\bar{J} v(\bar{x}, \dot{\bar{x}}, u, \alpha) = O\Omega_1(\bar{x}, \dot{\bar{x}}, u, \alpha)$$

System (7) can be written in the following form:

$$\begin{cases} \dot{\bar{x}} = \bar{A}_{1_0}\bar{x} + \bar{A}_{2_0}\bar{x}(t - l(t)) + \bar{A}_d\dot{\bar{x}}(t - l(t)) + \bar{J} v(\bar{x}, \dot{\bar{x}}, u, \alpha) \\ y = \bar{C}\bar{x} \end{cases} \quad (9)$$

Hence the system without faults and unknown input can be defined as follows:

$$(I_{n-q} 0)\dot{\bar{x}} = (\bar{A}_{1_{11}} \bar{A}_{1_{12}})\bar{x} + (\bar{A}_{2_{11}} \bar{A}_{2_{12}})\bar{x}(t - l(t))$$
$$+(\bar{A}_{d_{11}} \bar{A}_{d_{12}})\dot{\bar{x}}(t - l(t)) + \bar{B}_1 u \quad (10)$$

Supposition4: a transformation of the output is performed under the assumption that the CJ_1matrix is full rank column. Using the output transformation $\bar{y} = [\bar{y}_1 \bar{y}_2] = U^{-1} y$ with the following matrices U=[CJ_1 Q] with the matrices Q$\in M_{p,(p-q)}$, $U_1 \in M_{q,p}$, $U_2 \in M_{p-q,p}$
Then

$$\bar{y}_1 = U_1 y = U_1 C N \bar{x}_1 + \bar{x}_2 \quad (11)$$
$$\bar{y}_2 = U_2 y = U_2 C N \bar{x}_1 \quad (12)$$

Using expression (11), the following expression can be deduced:

$$\bar{x}_2 = U_1 y - U_1 C N \bar{x}_1 \quad (13)$$

Inserting (13) in (9), and using the output term (12) which does not include the behavior of degradation and retaining only the state $\bar{x}_1$ of(9); After transformation the obtained system is written as:

$$\begin{cases} \dot{\bar{x}}_1 = \tilde{A}_{1'}\bar{x}_1 + \tilde{A}_{2'}\bar{x}_l + \tilde{A}_{d'}\dot{\bar{x}}_{d_1} + \bar{B}_1 u + J_1 y_1 + J_2 y_{l_1} + J_d \dot{y}_d \\ \bar{y} = \tilde{C}_1 \bar{x}_1 \end{cases} \quad (14)$$

The matrices can be defined as follows:

$$\begin{cases} \tilde{A}_{1'} = \bar{A}_{1_{11}} - \bar{A}_{1_{12}} U_1 C N \\ \tilde{A}_{2'} = \bar{A}_{2_{11}} - \bar{A}_{2_{12}} U_1 C N \\ \tilde{A}_{d'} = \bar{A}_{d_{11}} - \bar{A}_{d_{12}} U_1 C N \\ J_1 = \bar{A}_{1_{12}} U_1 \\ J_2 = \bar{A}_{2_{12}} U_1 \\ J_d = \bar{A}_{d_{12}} U_1 \\ \tilde{C}_1 = U_2 C N \end{cases}$$

Under the condition that system (13) is observable, an unknown input observer can be built for the healthy system:

$$\begin{cases}\dot{\bar{z}}(t) = \hat{A}_{1'}\bar{z} + \hat{A}_{2'}\bar{z}_l + \hat{A}_{d'}\dot{\bar{z}}_d + \hat{Z}_1\bar{y}_1 \\ +\hat{Z}_2\bar{y}_l + \hat{Z}_d\dot{\bar{y}}_d \\ +\hat{B}_1 u + \hat{J}_1 y_1 + \hat{J}_2 y_l + \hat{J}_d\dot{y}_d \\ \hat{\bar{x}}_1 = \bar{z}(t) + M_1\bar{y} \\ \bar{z}(\theta) = \alpha(\theta), \forall \in [-l, 0]\end{cases} \tag{15}$$

With $z \in \mathbb{R}^g$ is the state estimate vector (g <n-q) and $\hat{A}_1, \widehat{A}_2, \widehat{A}_d, \widehat{Z}_1, \widehat{Z}_2, \hat{Z}_d, \widehat{B}_1, \widehat{J}_1, \hat{J}_2, \widehat{J}_d$ and $\widehat{M}_1$ are unknown matrices to be determined such that $\hat{\bar{x}}$ converges to $\bar{x}$.

b. Reconstruction of the degradation state and unknown input

Considering expression (11) and remembering that the state transformation T_1 has been used in expression (7), the state vector is defined as

$$\hat{x} = T_1\hat{\bar{x}} = \begin{pmatrix}\hat{\bar{x}}_1 \\ \hat{\bar{x}}_2\end{pmatrix} = T_1\begin{pmatrix}\bar{z}(t) + M_1\bar{y} \\ U_1 y - U_1 CN\hat{\bar{x}}_1\end{pmatrix} \tag{16}$$

$\hat{x}, \hat{\bar{x}}, \hat{\bar{x}}_1, \hat{\bar{x}}_2$ Are respectively the estimates of x, $\overline{x}$, $\bar{x}_1$, $\overline{x}_2$

According to equation (14), we obtain [7]:

$$\begin{aligned}\begin{pmatrix}\dot{\hat{\bar{x}}}_1 \\ \dot{\hat{\bar{x}}}_2\end{pmatrix} &= \begin{pmatrix}\bar{A}_{1_{11}} & \bar{A}_{1_{12}} \\ \bar{A}_{1_{21}} & \bar{A}_{1_{22}}\end{pmatrix}\begin{pmatrix}\hat{\bar{x}}_1 \\ \hat{\bar{x}}_2\end{pmatrix} \\ &+ \begin{pmatrix}\bar{A}_{2_{11}} & \bar{A}_{2_{12}} \\ \bar{A}_{2_{21}} & \bar{A}_{2_{22}}\end{pmatrix}\begin{pmatrix}\hat{\bar{x}}_1(t - l(t)) \\ \hat{\bar{x}}_2(t - l(t))\end{pmatrix} \\ &+ \begin{pmatrix}\bar{A}_{d_{11}} & \bar{A}_{d_{12}} \\ \bar{A}_{d_{21}} & \bar{A}_{d_{22}}\end{pmatrix}\begin{pmatrix}\dot{\hat{\bar{x}}}_1(t - l(t)) \\ \dot{\hat{\bar{x}}}_2(t - l(t))\end{pmatrix} + \begin{pmatrix}\bar{B}_1 \\ \bar{B}_2\end{pmatrix}u + \begin{pmatrix}0 \\ I_q\end{pmatrix}\hat{v}\end{aligned} \tag{17}$$

The two preceding equations gives :

$$\begin{aligned}\dot{\hat{\bar{x}}}_2 &= (\bar{A}_{1_{21}}\bar{A}_{1_{22}})\hat{\bar{x}}_2 + (\bar{A}_{2_{21}}\bar{A}_{2_{22}})\hat{\bar{x}}_2(t - l(t)) \\ &+(\bar{A}_{d_{21}}\bar{A}_{d_{22}})\dot{\hat{\bar{x}}}_2(t - l(t)) + \bar{B}_2 u + \hat{v}\end{aligned} \tag{18}$$

Therefore, the vector estimate of unknown input is expressed by:

$$\begin{aligned}\hat{v} &= \dot{\hat{\bar{x}}}_2 - (\bar{A}_{1_{21}}\bar{A}_{1_{22}})\begin{pmatrix}\bar{z}_1 + M_1 U_2 y_1 \\ U_1(I - CNM_1U_2)y_1 + U_1CN\bar{z}_1\end{pmatrix} \\ &-(\bar{A}_{2_{21}}\bar{A}_{2_{22}})\begin{pmatrix}\bar{z}_2 + M_1 U_2 y_2 \\ U_1(I - CNM_1U_2)y_2 + U_1CN\bar{z}_2\end{pmatrix} \\ &-(\bar{A}_{d_{21}}\bar{A}_{d_{22}})\begin{pmatrix}\bar{z}_d + M_1 U_2 y_d \\ U_1(I - CNM_1U_2)y_d + U_1CN\bar{z}_d\end{pmatrix} - \bar{B}_2 u\end{aligned} \tag{19}$$

The expression of the vector estimate of the unknown input is obtained by:

$$\begin{aligned}\hat{v} &= U_1\dot{y} + (\bar{A}_{1_{22}}U_1CN - U_1CN\hat{A}_{1'} - \bar{A}_{1_{21}})\bar{z}_1 \\ &+(\bar{A}_{2_{22}}U_1CN - U_1CN\hat{A}_{2'} - \bar{A}_{2_{21}})\bar{z}_2 \\ &-(\bar{A}_{1_{22}}U_1 + U_1CN\hat{J}_1)y_1 - (\bar{A}_{2_{22}}U_1 + U_1CN\hat{J}_2)y_2 \\ &-(\bar{A}_{d_{22}}U_1 + U_1CN\hat{J}_d)\dot{y}_d \\ &+(\bar{A}_{d_{22}}U_1CN - U_1CN\hat{A}_{d'} - \bar{A}_{1_{21}})\dot{\bar{z}}_d - (U_1CN\hat{B}_1 + \bar{B}_2)u\end{aligned} \tag{20}$$

Mathematically, the unknown input is built. Then, an expression of the degradation state based on the unknown input can be established. Associated with (8), matrix $\bar{J}$is developed for this purpose.

$$\bar{J} = O\Omega_1(\bar{x}, \dot{\bar{x}}, u, \alpha)$$
$$\Leftrightarrow \begin{pmatrix} 0_{n-q,n-q} & 0_{n-q,q} \\ 0_{q,n-q} & I_{q,q} \end{pmatrix} \begin{pmatrix} v_{n-q} \\ v_q \end{pmatrix}$$
$$= \begin{pmatrix} O\Omega_{1_{n-q,n-q}}(\bar{x}, \dot{\bar{x}}, u, \alpha) & O\Omega_{1_{n-q,q}}(\bar{x}, \dot{\bar{x}}, u, \alpha) \\ O\Omega_{1_{q,n-q}}(\bar{x}, \dot{\bar{x}}, u, \alpha) & O\Omega_{1_{q,q}}(\bar{x}, \dot{\bar{x}}, u, \alpha) \end{pmatrix} \quad (21)$$

Then we have:

$$O\Omega_{1_{q,q}}(\bar{x}, \dot{\bar{x}}, u, \phi) = v_q \quad (22)$$

Finally, we can deduce the following result.
Proposal: J is a solution of equation (22) with u is known input and $\bar{x}$, $\bar{x}(t-l)$and$\dot{\bar{x}}(t-l)$, v_q are estimated.

B. Transmission line diagnosis and prognosis

In this section, the example of transmission line model is presented to demonstrate the effectiveness and flexibility of the proposed observer based diagnostic and prognosis approachs. To illustrate the relevance of the proposed prognosis methodology a simulation test is performed on the transmission line system.
The model equation is given by:

$$\begin{cases} \dot{x}(t) = A_1(\alpha)x(t) + A_2(\alpha)x(t-l(t)) \\ +A_d(\alpha)\dot{x}(t-l(t)) + B(\alpha)u(t) \\ y(t) = Cx(t) \end{cases} \quad (23)$$

With

$$\begin{cases} A_1 = \frac{m - \frac{1}{z'}}{c_l} \\ A_2 = -\frac{(z'-R_0)(m+\frac{1}{z'})}{c_l(z'+R_0)} \\ A_d = \frac{z'-R_0}{z'+R_0} \\ z' = z + \alpha \\ z = \sqrt{\frac{L}{c}} \end{cases} \quad (24)$$

A transmission line is constituted by one or more conductors carrying an electrical signal from a source (transmitter) to a receiving load. If the signal conveyed meets a breakdown of characteristic impedance z=$\sqrt{\frac{L}{C}}$ part of the transmission line, it is reflected towards the emitter causing a deformation of its conductance. Therefore, the degradation primarily affects the physical parameters when the crack changes. An image of the degradation is taken into account for our study. It is assumed that z' is at a critical level when z' = 3*z. Rewrite (23) with $z' = z + \alpha$(proposition), we get:

$$\begin{cases} \dot{x}(t) = (\frac{m}{c_l} - \frac{1}{(z+\alpha)c_l})x(t) \\ +(\frac{(z+\alpha)-R_0)(m(z+\alpha)+1)}{c_l(z+\alpha)(z+\alpha+R_0)})x(t-l(t)) \\ +(1 - \frac{2R_0}{(z+\alpha+R_0)})\dot{x}(t-l(t)) + Bu(t) \\ y(t) = Cx(t) \end{cases} \quad (25)$$

The general expression of cumulative degradation is defined as follows:

$$\dot{\alpha} = \varepsilon s(x, \alpha) \quad (26)$$

The cumulative degradation(23) is estimated here by developing the methodology introduced above. The non-singular matrix of state transformation T_1 is defined by T_1 =1 O^{-1} non-singular transformation matrix is written as: O^{-1}=1. After applying the two previous transformations, system (23) can be written as:

$$\begin{cases} \dot{x}(t) = (\frac{m}{c_l} - \frac{1}{(z+\alpha)c_l})x(t) \\ +(\frac{(z+\alpha)-R_0)(m(z+\alpha)+1)}{c_l(z+\alpha)(z+\alpha+R_0)})x(t-l(t)) \\ +(1 - \frac{2R_0}{(z+\alpha+R_0)})\dot{x}(t-l(t)) + Bu(t) \\ y(t) = Cx(t) \end{cases} \quad (27)$$

Then, it is assumed that rank (J) $\leqslant p$, also there exists J such that rank (J) = q = 1$\leqslant p$ and $\Omega = J\Omega_1$

$$\dot{x} = \frac{m}{c_l}x - \dot{x}(t - l(t)) + D\Delta_1(x, \dot{x}, u) \quad (28)$$

Non singular U^{-1} output transformation is expressed as follows:

$$U^{-1} = 1$$

After the calculation of the unknown input and the degradation state based on (19), (20) and (21), the curve of the degradation is illustrated in figure 1:

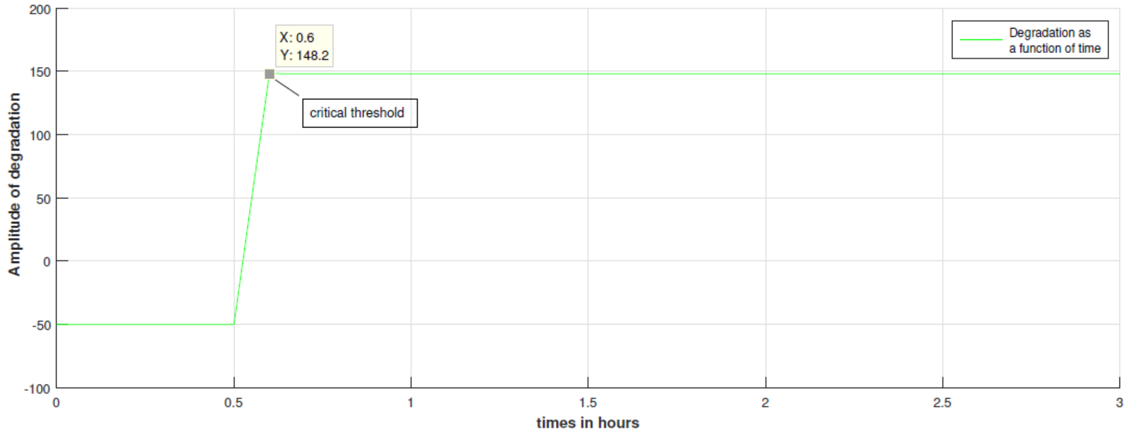

Fig. 1 Degradation as a function of time

The remaining Life Time is the time difference between the time of appearance of failure and the present time of reference when the system evolves. Therefore, the remaining time in this system is equal to 0.6s.

2. CONCLUSION

In this paper, a new prognosis approach for observer design problem of a class of neutral systems with variable delay is addressed. The main contribution of the present work lies in the use of an unknown input observer for the neutral system prognosis with variable delay.

Acknowledgment

This work was supported by the Ministry of the Higher Education and Scientific Research in Tunisia.

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