Performance comparison of various delay timers on alarm system design

R. KACED[1], A. KOUADRI[1], K. BAICHE[2]

Abstract – *Alarm systems are critically important for safety and efficiency of industrial plants. Not designed properly or not receiving the attention they deserve, alarm systems suffer from poor performances. Alarms notify the operator of the abnormality on the plant. Unfortunately, most of these alarms are false and nuisance, they can be a real distraction to the operator and may additionally mask vital alarms. Deadbands, filters and delay timers are industrial techniques proposed by the industrial community to reduce false and nuisance alarms. In this paper, we investigate the use of three different delay timers; conventional delay timer, generalized delay timer and multi-setpoint delay timer; in the process and compared their effects on accuracy and detection delay. False alarm rate (FAR), Missed alarm rate (MAR) and average alarm delay (AAD) are the three performance indices used to design optimal alarm system. Simulation results show that alarm performances can be improved and even optimized via delay-timer with proper choice of the delay timer order.*

***Keywords**: Alarm systems, Average alarm delay, False alarm rate, Generalized delay timer, Markov chains, Missed alarm rate, Multi-setpoint delay timer.*

I. Introduction

The inefficiency of alarm systems is the main cause of incidents and accidents such as the explosion of BP Texas City refinery in March 2005[13] and the Buncefield incident in December 2005[14]. Alarm system design has received substantial interest from industrial practices and academic researchers. The primary objective of an alarm system is to alert, inform and guide the plant operator who must decide about what to do during plant upset.

Many organizations developed and published some standards and guidelines to be used for designing and managing alarm systems. The Engineering Equipment and Materials Users' Association produced the document EEMUA-191 *Alarm Systems: A Guide to Design, Management, and Procurement* [9]. The standards ANSI/ISA-18 were proposed by the International Society of Automation [8]. Investigation reports that many industrial plants annually lose millions of dollars because of unexpected shutdown, damage of equipment and operation failures. Most plants prefer to avoid a shutdown if it could be done without risk [18].

Timely detection and isolation of a fault are essential functional requirements for good alarm system. Yet, it is rarely the case in reality; alarm systems suffer from low executions, misleading, and markedly alarm overloading where a large number of alarms are raised and thus difficult to be handled (ten, hundreds of alarms per hour). Most of those alarms are nuisance (false) alarms. Some modifications on the alarm generation are needed to reduce the occurrence of these alarms.
Deadbands [10], [15], filters [16], delay timers [19] are some of the simple industrial techniques deployed in practice to get rid of chattering and nuisance alarms, improve alarming accuracy and sensitivity.

Delay timers are extensively utilized in distributed control systems (DCS) for their ease of use and straightforward work on alarms. In [19], the authors presented a procedure for designing a conventional on/off alarm delay based on FAR, MAR and EDD. In paper [17], a new procedure is introduced to appropriately select the delay timer when the historical data of the alarm event and the corresponding 'Back to Normal' (RTN) information are used.

Accuracy is significantly better when using a (combined) delay timer rather than using on-delay timer or off-delay timer of the same length [17]. In this paper, three different delay timers, namely, conventional delay timer, generalized delay timer [11] and multi-setpoint delay timer [12], have been used and modeled via Markov chains. We will evaluate and discuss the performance of these delay timers by comparison using a simple case study. The main goal here is to find the best delay timer for designing an optimal alarm system under some specifications.

II. Markov chain

Markov chain, known as a Discrete-Time Markov Chain (DTMC) or Markov process, is the simplest mathematical model for random phenomenon evolving in time [1]. It is a system of countable states set $S = \{ i_0, i_1, \ldots, i_n \}$ and probabilities. The transition to the future state is essentially dependent on its current state and not on how the system attained the current state.

Markov chains have been applied in various fields; chemistry [2], biology [3], economics [4] and finance [5].

A Discrete-Time Markov Chain is a stochastic process satisfying the Markov property:

$$P(X_n = i_n | X_0 = i_0, \ldots\ldots X_{n-1} = i_{n-1}) = P(X_n = i_n | X_{n-1} = i_{n-1}) \quad (1)$$

$X_0, X_1, \ldots, X_n$ are random variables and t=0, 1, 2, …, n is the discrete-time interval of Markov chain [6]. The jump from state i to state j is characterized by the one-step transition probability:

$$p_{ij} = P(X_n = j | X_{n-1} = i) \quad (2)$$

The p_{ij} is the ij^{th} element of the $n\times n$ matrix **P** known as the transition probability matrix. **P** is a stochastic matrix where its entries are the one-step transition probabilities and satisfying:

$$0 \le p_{ij} \le 1, 1 \le i, j \le n \quad (3)$$

$$\sum_{j=1}^{n} p_{ij} = 1, 1 \le i \le n \quad (4)$$

Thus, **P** is given as:

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1j} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2j} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ p_{i1} & p_{i2} & \cdots & p_{ij} & \cdots & p_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nj} & \cdots & p_{nn} \end{bmatrix} \quad (5)$$

Rows represent the actual state and columns the next state. After n-step transitions, the transmission probability matrix will be $\mathbf{P}^n$.

The stationary distribution $\boldsymbol{\pi}$ is a probability vector satisfying the equation:

$$\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P} \quad (6)$$

Where

$$\boldsymbol{\pi} = [\pi_1, \pi_2, \cdots, \pi_n] \quad (7)$$

$\boldsymbol{\pi}$ is the left eigenvector of the matrix **P** with unity eigenvalue [7].

Direct graphs are used to represent Markov chain by defining all states and the one step probability hopping.

III. Conventional delay timer

A delay timer is a simple technique used in practice to reduce chattering and nuisance alarms [8].

ON delay timer is deployed to get rid of nuisance alarms; an alarm is raised if and only if n consecutive samples overshooting the alarm limit. OFF delay timer is utilized to avoid chattering alarms; the alarm status returns to the no alarm state if m consecutive samples go below the established alarm limit. Hence, some delays have been introduced in raising and clearing an alarm.

The main design parameter in delay timer is the length of the ON/OFF delay timer.

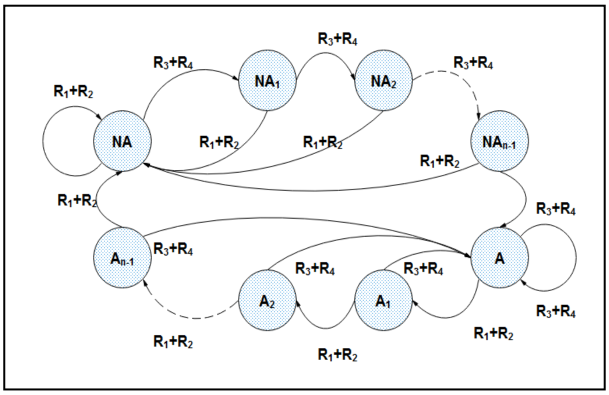

Fig.1. Markov chain of n samples ON\OFF delay timer.

According to the type of process signal, some delays have been proposed in [9].

Table 1 highlights the EEMUA recommendations [9].

Table-1: EEMUA recommendation for delay timer

Signal type	Delay
Flow	15 sec
Level	60 sec
Pressure	15 sec
Temperature	60 sec

In this work, we consider the process variables independent and identically distributed (*i.i.d*) and the probability distribution of normal and abnormal statuses are known.

Fig. 2 shows two distribution functions (PDFs) of one process variable under normal (solid) and abnormal (dashed) situations. Five set points, X_{NL}, X_{AL}, X_{tp}, X_{NH}, and X_{AH} are selected where NL and NH refer to the low and high limits of process variable operating under normal conditions, respectively. In a similar way, respectively, AL and AH represent the low and high limits for which the process is considered abnormal.

If the plant is operating under the normal conditions and an alarm is raised, the probability managing this situation is called a False Alarm Rate (FAR) whereas the probability when an alarm is not activated in the presence of a fault is a Missed Alarm Rate (MAR).

Detection Delay is the time difference between the particular moment of fault incident (t_f) and the time an alarm is activated (t_a) [10].

$$T_d = t_a - t_f \quad (8)$$

Fig. 2 shows an example of a distribution function of a process variable under normal and abnormal conditions where it is configured for a high alarm limit. The Probability calculation of variable in each range is demonstrated in equations (9)-(14):

$$q_1 + q_2 + q_3 \cong 1 \quad (9)$$

$$p_1 + p_2 + p_3 \cong 1 \quad (10)$$

$$q_1 = \int_{X_{NL}}^{X_{AL}} f(x)dx \quad (11)$$

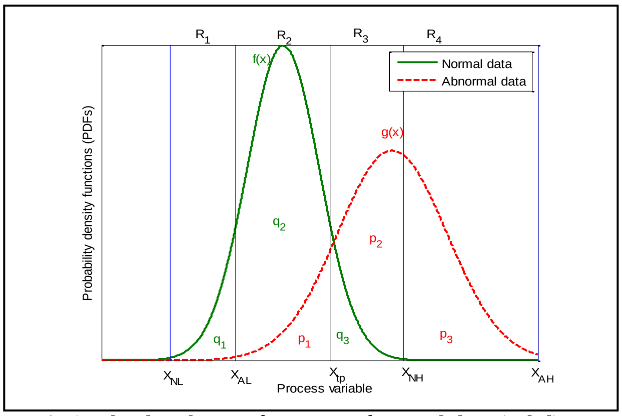

Fig.2. The distribution functions of normal data (solid), abnormal data (dashed) and alarm limits (vertical lines).

$$q_2 = \int_{X_{AL}}^{X_{tp}} f(x)dx \tag{12}$$

$$q_3 = \int_{X_{tp}}^{X_{NH}} f(x)dx \tag{13}$$

$$p_1 = \int_{X_{AL}}^{X_{tp}} g(x)dx \tag{14}$$

$$p_2 = \int_{X_{tp}}^{X_{NH}} g(x)dx \tag{15}$$

$$p_3 = \int_{X_{NH}}^{X_{AH}} g(x)dx \tag{16}$$

q_3 denotes the probability of false alarms whereas p_1 the probability of missed alarms.

$$R_1 = q_1 S_N \tag{17}$$

$$R_2 = q_2 S_N + p_1 S_A \tag{18}$$

$$R_3 = q_3 S_N + p_2 S_A \tag{19}$$

$$R_4 = p_3 S_A \tag{20}$$

S_A and S_N are the statistical probabilities of process operating in a normal and abnormal manner, respectively [12].

According to (11)-(20), the one step transition probability matrix $\mathbf{Q} \in R^{2n\times 2n}$ of the Markov chain in Fig.1 is:

Q=

$$\begin{bmatrix} R_1+R_2 & R_3+R_4 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ R_1+R_2 & 0 & R_3+R_4 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\ R_1+R_2 & 0 & \cdots & 0 & R_3+R_4 & 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & R_3+R_4 & R_1+R_2 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & R_3+R_4 & 0 & R_1+R_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & R_3+R_4 & 0 & 0 & \cdots & R_1+R_2 \\ R_1+R_2 & 0 & 0 & \cdots & R_3+R_4 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

(21)

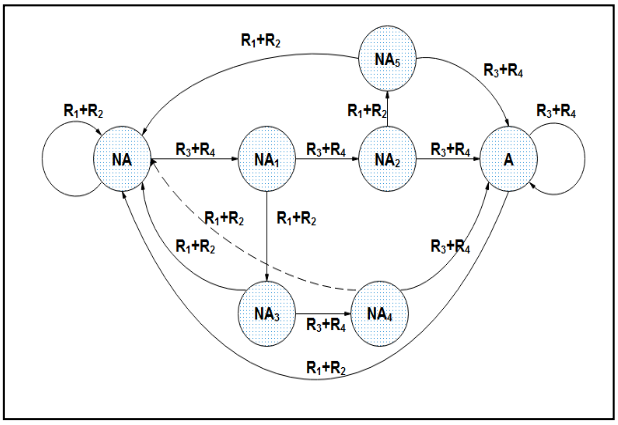

Fig.3. 3 out of 4 generalized on-delay timer.

To find the *FAR* formula, we use the one step transition probability matrix **Q** in normal condition (21) which is obtained by setting S_N=1 and S_A=0.

The analytic expression of FAR for the n-sample delay timer is:

$$FAR = p(A) + P(A_1) + \ldots + P(A_{n-1}) \tag{22}$$

$$FAR = \frac{q_3^{\,n-1}(1-(q_1+q_2)^n)}{q_3^{\,n-1}(1-(q_1+q_2)^n) + (q_1+q_2)^{n-1}(1-q_3^{\,n})} \tag{23}$$

MAR and *AAD* are related with p_1, p_2 and p_3. The one step transition probability matrix **Q** in abnormal condition where S_N=0 and S_A=1.

The analytic expression of MAR and AAD for the n-sample delay timer are:

$$MAR = p(NA) + P(NA_1) + \ldots + P(NA_{n-1}) \tag{24}$$

$$MAR = \frac{p_1^{\,n-1}(1-(p_2+p_3)^n)}{p_1^{\,n-1}(1-(p_2+p_3)^n) + (p_2+p_3)^{n-1}(1-p_1^{\,n})} \tag{25}$$

$$AAD = h\left(\frac{(1-(p_2+p_3)^n - p_1(p_2+p_3)^n}{p_1(p_2+p_3)^n} - 1\right) \tag{26}$$

Where *h* is the sample period.

IV. Generalized delay timer

The condition of n consecutive samples above the alarm limit for alarm annunciation is difficult to satisfy since chattering and repeating alarms exists in process plant. Adnan, et al. introduced a new delay timer by relaxing the condition to n_1 out of n samples exceeding the alarm limit [11]:

- n_1 out of n samples generalized on-delay: if n_1 out of n consecutive samples cross the alarm limit, an alarm will be raised.
- m_1 out of m samples generalized off-delay: if m_1 out of m consecutive samples fall below the alarm limit, an alarm will be cleared.

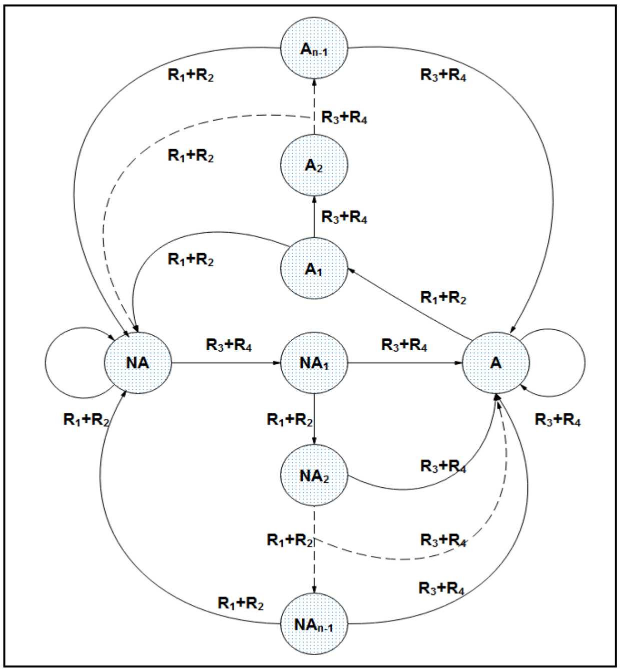

Fig.4. 2 out of n generalized delay timer.

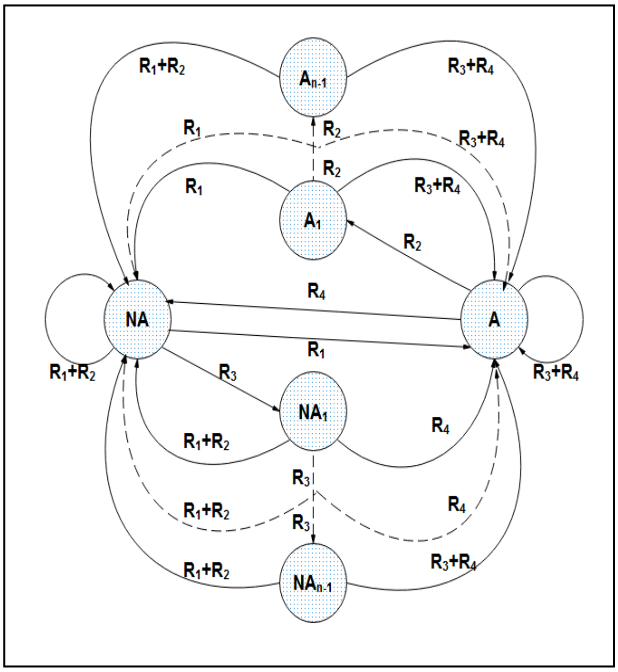

Fig.5. n-sample multi-setpoint delay timer.

Fig. 3 presents information about the generalized on-delay timer with n_1=3 and n=4. The conventional 3 on-delay timer has only one path to reach the alarm state (A) from no alarm state (NA_1) in contrary of the 3 out of 4 generalized on-delay timer which has three different paths. The generalized delay timer is more complex than the traditional one since it has more paths and intermediate states as we increase n.

In this paper, we will take the case 2 out of n generalized delay timer for simplicity. Based on equations (9)-(18), the one step transition probability matrix $\mathbf{P} \in R^{2n \times 2n}$ of Fig. 4 is:

P=

$$\begin{bmatrix} R_1+R_2 & R_3+R_4 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & R_1+R_2 & \cdots & 0 & R_3+R_4 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & R_1+R_2 & R_3+R_4 & 0 & 0 & \cdots & 0 \\ R_1+R_2 & 0 & 0 & 0 & 0 & R_3+R_4 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & R_3+R_4 & R_1+R_2 & 0 & \cdots & 0 \\ R_1+R_2 & 0 & 0 & \cdots & 0 & 0 & 0 & R_3+R_4 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ R_1+R_2 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & R_3+R_4 \\ R_1+R_2 & 0 & 0 & \cdots & 0 & R_3+R_4 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

(27)

The analytic expression of *FAR* for the 2 out of n generalized delay timer:

$$FAR = \frac{q_3(2-q_3^{\ n-1})(1-(q_1+q_2)^{n-1})}{q_3(2-q_3^{\ n-1})(1-(q_1+q_2)^{n-1})+(q_1+q_2)(1-q_3^{\ n-1})(2-(q_1+q_2)^{n-1})} \quad (28)$$

$$MAR = \frac{p_1(2-p_1^{\ n-1})(1-(p_2+p_3)^{n-1})}{p_1(2-p_1^{\ n-1})(1-(p_2+p_3)^{n-1})+(p_2+p_3)(1-p_1^{\ n-1})(2-(p_2+p_3)^{n-1})} \quad (29)$$

$$AAD = h\left(\frac{(2-(n+1)p_1^{\ n-1})(1-p_1-p_2p_1^{\ n-1})+(2p_1+p_1^{\ n-1}(n-(n+1)p_1))(1-p_1^{\ n-1})}{(1-p_1)(1-p_1^{\ n-1})^2}-1\right) \quad (30)$$

V. Multi-setpoint delay timer

Su et al. proposed another delay timer in order to improve alarming accuracy and alarming sensitivity. By employing the additional set points shown in Fig.2, the transition in Markov chain from no alarm state (NA) to alarm state (A) is direct and in one step. This will improve the flexibility of status transitions. Markov chain of an n-m-order multi-set point delay timer is demonstrated in Fig.5. If the process variable goes above (below) the alarm limit with probability q_3 (p_1), an alarm will be raised (cleared) immediately [12].

The one step transition probability matrix $\mathbf{K} \in R^{2n \times 2n}$ of Fig. 5 is:

K=

$$\begin{bmatrix} R_1+R_2 & R_3 & 0 & \cdots & 0 & R_4 & 0 & 0 & \cdots & 0 \\ R_1+R_2 & 0 & R_3 & \cdots & 0 & R_4 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ R_1+R_2 & 0 & 0 & \cdots & R_3 & R_4 & 0 & 0 & \cdots & 0 \\ R_1+R_2 & 0 & 0 & \cdots & 0 & R_3+R_4 & 0 & 0 & \cdots & 0 \\ R_1 & 0 & 0 & \cdots & 0 & R_3+R_4 & R_2 & 0 & \cdots & 0 \\ R_1 & 0 & 0 & \cdots & 0 & R_3+R_4 & 0 & R_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ R_1 & 0 & 0 & \cdots & 0 & R_3+R_4 & 0 & 0 & \cdots & R_2 \\ R_1+R_2 & 0 & 0 & \cdots & 0 & R_3+R_4 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

(31)

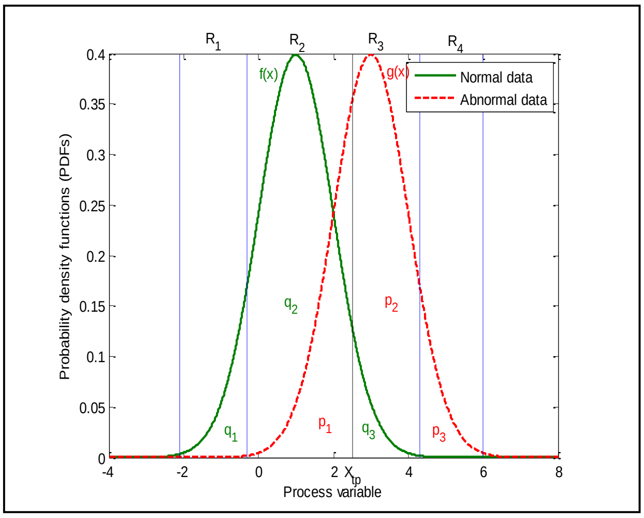

Fig.6. Probability distribution functions of the process variable in normal and abnormal conditions.

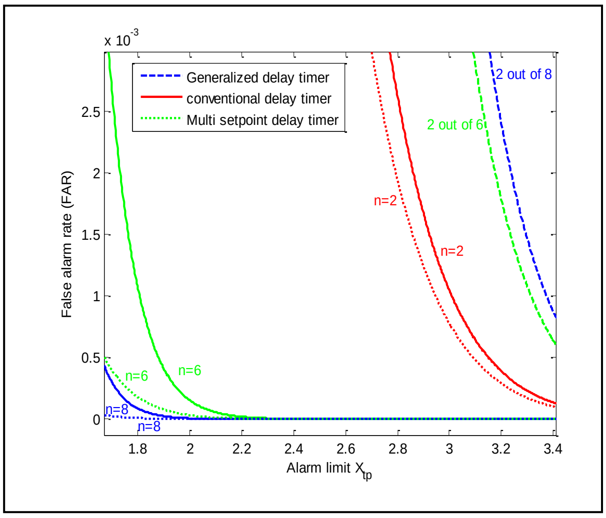

Fig.7. *FAR* vs x_{tp} with the use of various delay timers.

The *FAR*, *MAR* and *AAD* equations for the n-sample multi-set point delay timer [12]:

$$FAR = \frac{q_3^n \sum_{i=0}^{n-1} q_2^i}{\sum_{i=0}^{n-1} q_3^i (1 - q_3 \sum_{i=0}^{n-1} q_2^i) + q_3^n \sum_{i=0}^{n-1} q_2^i} \tag{32}$$

$$MAR = \frac{p_1^n \sum_{i=0}^{n-1} p_2^i}{\sum_{i=0}^{n-1} p_1^i (1 - p_1 \sum_{i=0}^{n-1} p_2^i) + p_1^n \sum_{i=0}^{n-1} p_2^i} \tag{33}$$

$$AAD = h\left(\frac{-p_1 p_2^{2n} (-p_2 - 2p_3 + 1) p_2^n + p_3}{(p_1 p_2^n + p_3)^2} - 1 \right) \tag{34}$$

VI. Alarm system design

Designing an alarm system using delay timer requires finding an optimal delay timer as well as the alarm limit that improves significantly the accuracy and latency of this system.

Adding delay timers to a system with bad design of alarm limit will aggravate the situation.

This work examines the performance of the three techniques commonly used to reduce nuisance alarms. We can determine the optimal parameter (the alarm delay) to reach the desired probabilities in case the wanted probabilities of the three performance indices are available.

To find the optimal design, we will use a weighted-sum loss function *J*.

$$J = c_1 \frac{FAR}{mFAR} + c_2 \frac{MAR}{mMAR} + c_3 \frac{AAD}{mAAD} \tag{35}$$

Where *mFAR*, *mMAR* and *mAAD* are the requirements of *FAR*, *MAR* and *AAD* respectively. c_1, c_2 and c_3 are the weights of *FAR*, *MAR* and *AAD* respectively. 'Optimality' means that *J* is minimal.

For simplicity, let the process variable X follows a normal distribution with a mean change at t_0,

$$X(t) = N(1,1), t \prec t_0$$
$$X(t) = N(3,1), t \geq t_0 \tag{36}$$

The PDFs of the process variable in normal and abnormal conditions is shown in Fig. 6.

The performances of the three delay timers are shown in Fig.7, Fig.8 and Fig.9.

When increasing the order (n) of the delay timers in Fig.7 and Fig.8, two striking observations can be drawn from these figures. The first observation is that conventional and multi-setpoint delay timer will significantly reduce FAR and MAR in contrary of the generalized one which will increase FAR and MAR for fixed n1=2. The second observation is that the multi-setpoint delay timer has far more effect on FAR/MAR compared to the conventional delay timer. We can explain this by the direct (one step) transition from NA (A) state to A (NA) state when condition is satisfied.

It is clear from Fig.9 that the generalized delay timer is much better in terms of latency compared to the two other delay timers. It can be justified by the property of the generalized delay timer; having different path to reach the A state (NA) from NA (A) state.

The trade-off between FAR/MAR and AAD always hold; better accuracy (less FAR/MAR) induces bad latency (more delay).

We can design the alarm delay so that the alarm system requirements are met.

Let's assume the alarm limit to be X_{tp}=2.5 $mFAR \leq 0.1$ $mMAR \leq 0.1$ $mAAD \leq 2h$.

The objective is to choose an optimal delay timer that ensures false and missed alarms less than 1% and average alarm delay less than 2*h*.

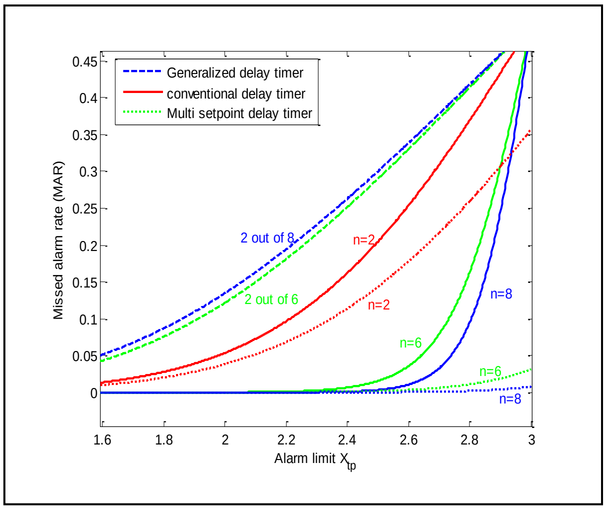

Fig.8. *MAR vs x_{tp} with the use of various delay timers.*

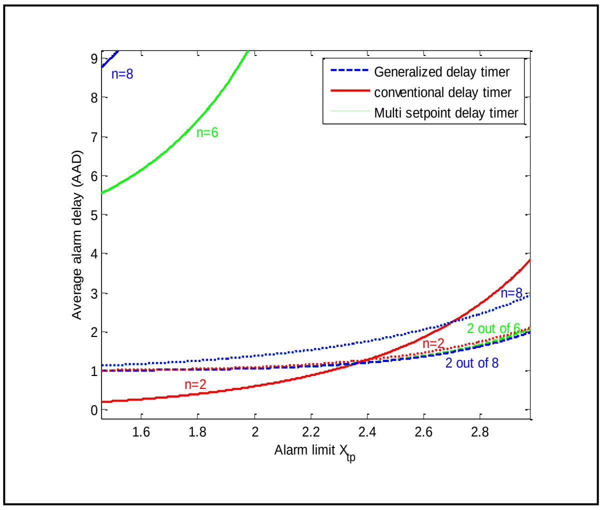

Fig.9. *AAD* vs x_{tp} with the use of various delay timers.

Table-2: optimal design of various delay-timers.

Delay timer	n	*FAR*	*MAR*	*AAD*	*J*
Conventional delay timer	n=3 n=6 n=8	9.624×10^{-4} 6.426×10^{-7} 4.129×10^{-9}	0.1205 0.0155 0.0033	4.5586 24.380 56.682	3.493 12.34 28.37
2 out of n Generalized delay timer	n=3 n=6 n=8	0.0162 0.0314 0.0382	0.2434 0.2898 0.2999	1.4917 1.2833 1.2759	3.341 3.854 4.019
Multi setpoint delay timer	n=3 n=6 n=8	5.296×10^{-4} 1.768×10^{-7} 7.981×10^{-10}	0.0529 0.0017 1.63×10^{-4}	1.689 1.882 1.890	1.379 0.958 0.946

Using the weighted-sum loss function defined in (35), we can find the optimal design of alarm delay where *FAR*, *MAR* and *AAD* are equally treated; the weights are chosen as $c_1 = c_2 = c_3 = 1$.

For X_{tp}=2.5, the resulting *FAR*, *MAR* and *AAD* are shown in table-2. It is observed that the 8-sample multi setpoint delay timer gives the best performances where the function *J* is minimal.

Considering the priority given to *FAR*, *MAR* and *AAD* for different situations in practice, several optimization criteria can be developed. If we are more interested on the *AAD* (setting c_3 larger) , the generalized delay timer will give more choices to satisfy requirements.

VII. Conclusion

In this paper, we reviewed three different delay timers; conventional delay timer, generalized delay timer and multi-setpoint delay timer. The effect of adding those techniques on alarm system performances was discussed. It has been shown that the performance of multi-setpoint delay timer is much better than the two other delay timers when it comes to accuracy (less *FAR*, less *MAR*). On the other hand, generalized delay timer performs better results when it comes to latency by efficiently reducing the *AAD*. The weighted-sum loss function *J* has been used to choose the efficient delay timer where *FAR*, *MAR* and *AAD* are equally treated, we concluded with the multi-setpoint as a best choice for optimal design.

Nomenclature	
S	Countable set of states.
X_i	Random variable.
p_{ij}	Transition probability from i[th] state to j[th] state.
P	Stochastic transition probability matrix.
$\boldsymbol{\pi}$	Left eigenvector of the stochastic matrix ***P***.
n	Number of consecutive samples exceeding the alarm limit in a delay timer.
A	Alarm state.
NA	No alarm state.
X_{NL}	Low limit of probability density function of normal data.
X_{AL}	Low limit of probability density function of abnormal data.
X_{tp}	Alarm limit.
X_{NH}	High limit of probability density function of normal data.
X_{AH}	High limit of probability density function of abnormal data.
FAR	Probability of false alarms.
MAR	Probability of missed alarms.
AAD	Average alarm delay
f(x)	Probability density function (PDF) of normal data.
g(x)	Probability density function (PDF) of abnormal data.
h	Sample period.
R_1	Range between the low limits of probability density functions of normal and abnormal data.
R_2	Range between the low limit of probability density function of normal data and the alarm limit.
R_3	Range between the alarm limit and high limit of probability density function of normal data.

R_4	Range between the high limits of probability density functions of normal and abnormal data.
S_A	Statistical probability of process operating under normal condition.
S_N	Statistical probability of process operating in an abnormal manner.
J	Weighted-sum loss function.
$mFAR$	Required FAR value to satisfy.
$mMAR$	Required MAR value to satisfy.
$mAAD$	Required AAD value to satisfy.

References

[1] J. R. Norris. Markov Chains. Cambridge University Press, 1997.

[2] A. Tamir: "Applications of Markov Chains in Chemical Engineering". Elsevier Science, 1998.

[3] A.Swaminathan, R. M.Murray: "Identification of Markov Chains From Distributional Measurements and Applications to Systems Biology". Proceedings of the 19th World Congress The International Federation of Automatic Control Cape Town, South Africa. August 24-29, 2014.

[4] J. G. Cabello: "The future of branch cash holdings management is here: New Markov chains". European Journal of Operational Research, Volume 259, Issue 2, pp 789-7991, June 2017.

[5] G. D'Amicoa F. Petroni : "Copula based multivariate semi-Markov
models with applications in high-frequency finance". European Journal of Operational Research, Volume 267, Issue 2, pp 765-7771, June 2018.

[6] A. Papoulis, S.U. Pillai, Probability, Random Variables and Stochastic Processes, 4th ed., Tata Mcgraw-Hill Publishing Company Ltd., New Delhi, 2002.

[7] G.F. Lawler, Introduction to Stochastic Processes, 2nd ed., Chapman & Hall/CRC, Boca Raton, 2006.

[8] ISA, 2009, ANSI/ISA-18.2: "Management of Alarm Systems for the Process Industries". International Society of Automation. Durham, NC, USA.

[9] EEMUA. Alarm Systems: "A Guide to Design, Management and Procurement". EEMUA Publication No. 191 Engineering Equipment and Materials Users Association, London, 2 edition, 2007.

[10] N.A. Adnan, I. Izadi, T. Chen: "On expected detection delays for alarm systems with deadbands and delay-timers", Journal of Process Control, vol 2, pp 1318–1331, 2011.

[11] Naseeb Ahmed Adnana, Yue Chenga, Iman Izadi b, Tongwen Chena: "Study of generalized delay-timers in alarm configuration", Journal of Process Control, vol 23, pp 382– 395, 2013.

[12] Jianjun Sua, Cen Guob, Hao Zangb, Fan Yangb, Dexian Huangb, Xiaoyong Gaob, Yan Zhaoa: "A multi-setpoint delay-timer alarming strategy for industrial alarm monitoring", Journal of Loss Prevention in the Process Industries, vol 54, pp1-9, 2018.

[13] Health and Safety Executive 100021025. The Buncefield investigation: Third progress report. December 2008.

[14] United States Chemical Safety and Hazard Investigation Board. Investigation report, refinery explosion and fire. March 2007.

[15] Muhammad Shahzad Afzal, Tongwen Chen a, Ali Bandehkhoda b, Iman Izadi: "Analysis and design of time-deadbands for univariate alarm systems", Control Engineering Practice, vol 71, pp 96–107, 2018.

[16] Wen Tana,c, Yongkui Sunb,c, Ishtiza Ibne Azadc, Tongwen Chenc: "Design of univariate alarm systems via rank order filters", Control Engineering Practice, vol 59, pp 55–63, 2017.

[17] Sandeep R. Kondaveeti, Iman Izadi, Sirish L. Shah and Tongwen Chen: "On the Use of Delay Timers and Latches for Efficient Alarm Design".19th Mediterranean Conference on Control and Automation Aquis Corfu Holiday Palace, Corfu, Greece June 20-23, 2011.

[18] Rothenberg D. Alarm Management for Process Control: A Best-practice Guide for Design, Implementation, and Use of Industrial Alarm Systems. Momentum Press, Highland Park, NJ. 2009.

[19] J. Xu, J. Wang, I. Izadi, T. Chen: "Performance assessment and design for univariate alarm systems based on FAR, MAR, and AAD", IEEE Transactions on Automation Science and Engineering, vol 9, pp 296-307, 2012.

[1] Signals and Systems Laboratory, Institute of Electrical and Electronics Engineering, University M'Hamed Bougara of Boumerdes, Av. De l'indépendance, 35000 Boumerdes, Algeria.

[2] Applied Control Laboratory, University of Boumerdes, Av. De l'indépendance, 35000 Boumerdes, Algeria.