A generalized alarm delay-timer’s performance indices computing method

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ABSTRACT

With the rapid development of the modern process industry, the importance of the alarm system has become significant. In general, too many nuisance alarms exist in alarm systems and distract operators’ attention from paying attention to the real abnormal situation. As an effective technique to remove nuisance alarms, the alarm delay-timer is applied extensively in practice. Due to the defects of the alarm delay-timer, the generalized alarm delay-timer is proposed recently as an improvement. But the alarm performance indices alarm rate (FAR), missed alarm rate (MAR), and average alarm delay (AAD) for the generalized alarm delay-timer are not obtained easily so far. In view of this fact; first, a generalization computing method is proposed in the form of three formulas based on the Markov models. Second, the application range of the generalized alarm delay-timer and conventional alarm delay-timer are compared through a numerical simulation. Finally, the procedures of applying the generalized alarm delay-timer are illustrated by a simulation example.

KEYWORDS

Generalized alarm delay-timer; false alarm rate (FAR); missed alarm rate (MAR); averaged alarm delay (AAD); computing method

1. Introduction

In a modern industrial process, the most desirable thing is that all equipment can run smoothly, efficiently and continuously. Thus, thousands of sensors are installed in different sections of the process to monitor the production process running (Adnan, Izadi, & Chen, 2011), thereby facilitating the reliable control on the system (Sheng, Zhang, & Gao, 2014). If there is an abnormal situation occurring, then an alarm will appear in an alarm system.

The alarm system is a collection of hardware and software that detects abnormal situation, communicates the detecting result to the operators and records all results according to the industrial standard (ANSI/ISA-18.2, 2009). Now, the alarm system is the first protective layer and the core component of modern industry safety. However, an unreasonable alarm system configuration may result in alarm floods and reduce its performance as a safeguard for plant operations (Folmer, Pantförder, & Vogel-Heuser, 2011; Rothenberg, 2009; Yuki, 2002).

Now-days, the number of nuisance alarms in almost every alarm system is huge, which is far more than the operators’ ability to handle. Nuisance alarms do not indicate any abnormal situation in the production process. But these nuisance alarms send the wrong impression to operators about the process situation. If this situation continues, operators will lose their confidence about alarm system gradually. When there is a real abnormal situation occurring, it may be missed by operators and leads to a catastrophe. For example, the accident in the Three Mile Island nuclear power station in the United States. Before the accident, the alarm system was flooded with a lot of alarms, but most of them were nuisance alarms. These nuisance alarms caused the operators to be unable to find the equipment failure timely. Thus, it is important to remove nuisance alarms in an alarm system.

Nearly all the existing alarm systems are beset by numerous nuisance alarms. The most obvious feature of poor performance is alarm overloading. Some industrial associations have formulated several industrial standards to guide alarm system optimization. All of these standards and guidelines set specific requirements for the performance of the alarm system. For example, the average number of alarms per day should not exceed 144 (EEMUA, 2013). However, there is not any corresponding methods or techniques provided to practice these requirements.

In order to remove nuisance alarms and improve the performance of an alarm system, some research topics related to alarm system optimization have become an
area of focus such as alarm system monitoring (Ahmed, Izadi, Chen, Joe, & Burton, 2013; Wang & Chen, 2014), alarm system performance evaluation, and alarm systems design and optimization (Zang & Li, 2014). The alarm delay-timer can be regarded as an effective technical tool for nuisance alarm removing. Xu, Wang, Izadi, and Chen (2012) proposed a novel method for configuring the alarm delay-timer based on probability distribution change detection. Adnan, Cheng, Izadi, and Chen (2013) proposed a design procedure for the purpose of reducing nuisance alarms and improve the performance of the alarm system by compromising the alarm performance indices AAD, FAR and MAR. Zang, Yang, and Huang (2015) proposed delay-timer performance indices based on Markov chains. Afzal, Chen, Bandehkhoda, and Izadi (2018) proposed a novel method for configuring time-deadbands for nuisance suppressing. In Tulsyan, Alrowaie, and Gopaluni (2017), a novel method for alarm delay-timer configuration has been proposed by taking the minimization of the rate of false and missed alarm rates into consideration. The effectiveness of this method has been validated by an industrial case also. Afzal and Chen (2017), a hidden Markov model with Markov chain observations is used as a process model, and the alarm delay-timer configuration is studied thoroughly based on the process model.

Although there is a large amount of research results about the alarm delay-timer, all of them have not proposed a generalized alarm delay-timer’s performance indices computing method to the best of our knowledge. So it is very necessary to formulate a set of formulas to facilitate the alarm delay-timer’s performance computing.

The contribution of this paper is twofold. First, a generalized computing method for FAR, MAR and AAD is proposed in the form of three formulas based on a Markov model. And the application range of the generalized alarm delay-timer and conventional alarm delay-timer is compared through a numerical simulation. Second, the procedures for applying a generalized alarm delay-timer in practice are formulated and illustrated through a simulation example.

The rest of this paper is organized as follows. The concept of the three alarm performance indices is introduced in detail in Section 2. In Section 3, the three formulas, which can be applied to compute alarm performance indices of generalized alarm delay-timer directly, are summarized after a series of careful deduction based on a Markov model. The application range of the conventional alarm delay-timer and generalized alarm delay-timer is compared in Section 4. A numerical simulation example is provided in Section 5 to illustrate the procedure of the generalized alarm delay-timer application. Finally, some concluding remarks are given in Section 6.

### 2. Performance assessment of alarm systems

This section introduces three performance indices for the alarm performance measurement in industrial practice, namely FAR, MAR and AAD.

The indices FAR and MAR mainly indicate the accuracy of the alarm system in detecting the abnormal situation in production process variables. If FAR is too large, it means that there is a large amount of false alarm in an alarm system. If MAR is too large, it means that the alarm system may miss some real abnormal situations. The index AAD indicates the necessary time of the alarm system to detect an abnormal situation. If AAD is small, alarm events will be activated more quickly after the process variable runs into an abnormal situation, and leaves more time for the operators to deal with the abnormal situation.

Suppose the process variable is generated as a white Gaussian random process, denoted by \( x(t) \), which has a different mean value in a normal situation and abnormal situation. Then the probability density functions (PDFs) of \( x(t) \) are known. The corresponding high alarm threshold is denoted as \( x_{tp} \). The PDFs of \( x(t) \) under normal and abnormal conditions can be depicted by curves as Figure 1 shows. Thus, for a process signal which satisfies the assumption above and fixed threshold, it misses alarm rate \( p_2 \) and false alarm rate \( q_1 \) can be regarded as a constant respectively.

If the probability density curve of process data in a normal condition is denoted as \( q(x) \) (solid line in Figure 1). Then FAR is the integral result of \( q(x) \) from \( x_{tp} \) to infinite, i.e.

\[
FAR = q_1 = \int_{x_{tp}}^{+\infty} q(x) \, dx. \tag{1}
\]

![Figure 1. The PDFs of x under normal and abnormal conditions.](image)}
Similarly, the MAR is

$$\text{MAR} = p_2 = \int_{-\infty}^{x_{tp}} p(x) \, dx \quad (2)$$

In (2), the $p(x)$ is the probability density curve of the process data in an abnormal condition (dashed line in Figure 1).

Besides FAR and MAR, the other important performance index for alarm system is the AAD. It implies the time span from the abnormal situation occurring till the alarm event arising. As depicted in Figure 2, the process variable undergoes a change from a normal situation to an abnormal situation at time $t_0$. Denote $t_a$ as the time instant when the first sample point is equal to or larger than the alarm threshold $x_{tp}$ to raise the alarm. The time interval between $t_0$ and $t_a$ is called alarm delay (Xu et al., 2012), i.e.

$$T_d = t_a - t_0 \quad (3)$$

The AAD is defined as the expected value of $T_d$, that is,

$$T_d = E(T_d). \quad (4)$$

3. Generalized alarm delay-timer

The conventional alarm delay-timer works in this manner, an alarm is only raised if there are $n$ consecutive samples above the threshold. In other words, the process remains in the alarm state for $n$ sampling time before activating an alarm. With off-delay, a raised alarm is to be cleared if $n$ consecutive samples are below the alarm threshold.

In many cases, the conditions for the conventional alarm delay-timer are hardly to be satisfied. For example, suppose an alarm delay-timer has 8 samples on-delay. When the process data enters from the normal situation to the abnormal situation, it needs continuous 8 samples to exceed the threshold to arise an alarm. Otherwise, the beginning 8 sample data may not satisfy the conditions stringently caused by noise, etc. It is very likely that the alarm will be delayed several sample periods during this transition period. However, if the condition is relaxed to 6 out of 8 sample data above the threshold, the AAD will be smaller than the previous one. This alarm arising mechanism is defined as the generalized alarm delay-timer.

For the generalized alarm delay-timer, an alarm will be raised when $m$ out of $n$ consecutive samples cross the threshold. And an alarm will be cleared when $m$ out of $n$ consecutive sample data fall below the threshold.

3.1. False alarm rate

The working principle of $m$ out of $n$ samples generalized alarm delay-timer under normal conditions can be described by the Markov model in Figure 3.

In Figure 3, the state $NA_{w,v}$ is indicated that there are $w$ sample data above the alarm threshold and $v$ sample data below the alarm threshold, here $w = 1, 2, \ldots, m - 1$ and $v = 1, 2, \ldots, n - m$. The state $A_{w,v}$ is defined as the alarm state with $w$ samples above the threshold and $v$ samples below the threshold, $w = 1, 2, \ldots, n - m$, $v = 1, 2, \ldots, m - 1$. The $NA_{0,0}$ is the initial no-alarm state and $A_{0,0}$ are the initial alarm state.

In order to explain the state implication in Figure 3, an example is provided here. Suppose a start segment of the values of a process variable is $[2.8, 3.2, 3.5, 2.9, 3.1]$. The threshold is 3, and the delay-timer rule is 3 out of 4 on-delay. In this case, the value of sample 1 is smaller than the threshold and the generalized alarm delay-timer will not work, the process will remain in the no-alarm state $NA_{0,0}$. If the value of sample 2 is higher than the threshold, then the generalized alarm delay-timer starts to work and enters the no-alarm state $NA_{1,0}$. If the value of sample 3 is higher than the threshold, then the process jumps into the no-alarm state $NA_{2,0}$. If the value of sample 4 is smaller than the threshold, then the process jumps into the no-alarm state $NA_{2,1}$. If the value of sample 5 is higher than the threshold, then the process jumps into the alarm state $A_{0,0}$.

The false alarm rate refers to the probability of alarm arising under normal conditions. According to the Markov
model of generalized alarm on-delay, the probability of the initial state transited to each of the intermediate states is
\[
P(NA_{0,0} \rightarrow NA_{1,0}) = q_1; \\
\vdots \\
P(NA_{0,0} \rightarrow NA_{m-1,0}) = q_1^{m-1}; \\
P(NA_{0,0} \rightarrow NA_{1,1}) = q_1 q_2; \\
P(NA_{0,0} \rightarrow NA_{2,1}) = 2 q_1^2 q_2; \\
\vdots \\
P(NA_{0,0} \rightarrow NA_{m-1,1}) = (m-1) q_1^{m-1} q_2; \\
\vdots \\
P(NA_{0,0} \rightarrow NA_{m-1,n-m}) = \frac{(m-2)!}{(m-1)!} q_1^{m-1} q_2^{n-m}; \\
P(NA_{0,0} \rightarrow NA_{m,0}) = q_1^n \\
+ \frac{1}{(m-2)!} q_1^{m} q_2^{n-m} \left[ q_1^{m-1}(1-q_2^{n-m}) q_2^{n-m} \right].
\]

For generalized alarm off-delay, the probabilities between intermediate states and the initial state are
\[
P(A_{0,0} \rightarrow A_{0,1}) = q_2; \\
\vdots \\
P(A_{0,0} \rightarrow A_{m-1,1}) = q_1 q_2^{m-1}; \\
P(A_{0,0} \rightarrow A_{1,1}) = q_1 q_2; \\
P(A_{0,0} \rightarrow A_{1,2}) = 2 q_1^2 q_2; \\
\vdots \\
P(A_{0,0} \rightarrow A_{1,m-1}) = (m-1) q_1 q_2^{m-1}; \\
\vdots \\
P(A_{0,0} \rightarrow A_{n-1,m-1}) = \frac{(m-2)!}{(m-1)!} q_1^{m-1} q_2^{n-m}; \\
P(A_{0,0} \rightarrow NA_{0,0}) = q_2^n \\
+ \frac{1}{(m-2)!} q_2^{m} q_2^{n-m} \left[ q_1^{m-1}(1-q_2^{n-m}) q_2^{n-m} \right].
\]

Taking the probability of the initial state into consideration, then the false alarm rate can be calculated according to the Markov model. Thus, the sum of all the probability that the state transits from state $NA_{0,0}$ to state $A_{n-m,m-1}$ indicates the no-alarm probability proportion for the Markov model in Figure 3, and is denoted as $P_n(NA)$, i.e.

\[
P_n(NA) = [P(NA_{0,0} \rightarrow NA_{1,0}) + \cdots + P(NA_{0,0} \rightarrow NA_{m-1,n-m})] \\
\times P(A_{0,0} \rightarrow NA_{0,0})
\]

The sum of all the probability that state transit from state $A_{0,0}$ to state $A_{n-m,m-1}$ indicates the false alarm probability proportion for the Markov model, and denoted as $P_n(A)$, i.e.

\[
P_n(A) = [P(A_{0,0} \rightarrow A_{0,1}) + \cdots + P(A_{0,0} \rightarrow A_{n-m,m-1})] \\
\times P(NA_{0,0} \rightarrow A_{0,0})
\]

\[
= \left\{ q_2^n + \frac{1}{(m-2)!} q_2^n q_2^{m-2} d(m-2) \left[ q_1^{m-1}(1-q_2^{n-m}) q_2^{n-m} \right] \right\} \\
\times \left\{ 1 + \sum_{i=2}^m \frac{1}{(i-2)!} q_2^{i-2} d(i-2) \left[ q_1^{i-2}(1-q_1^{n-m+1}) q_2^{n-m+1} \right] \right\}.
\]

Thus, the false alarm rate can be calculated as
\[
FAR = \frac{P_n(A)}{P_n(A) + P_n(NA)}.
\]

### 3.2 Missed alarm rate

The missed alarm rate can be calculated based on the Markov model of abnormal conditions in Figure 4. The calculation process of the missed alarm rate is similar to the false alarm rate. Thus, the sum of all the probabilities that the process transits from state $A_{0,0}$ to state $A_{n-m,m-1}$ indicates the alarm probability proportion of the Markov model, and is denoted by $P_o(A)$, i.e.

\[
P_o(A) = [P(A_{0,0} \rightarrow A_{0,1}) + \cdots + P(A_{0,0} \rightarrow A_{n-m,m-1})] \\
\times P(NA_{0,0} \rightarrow A_{0,0})
\]

\[
= \left\{ p_0^n + \frac{1}{(m-2)!} p_0^n p_2^{m-2} d(m-2) \left[ p_1^{m-1}(1-p_2^{n-m}) p_2^{n-m} \right] \right\} \\
\times \left\{ 1 + \sum_{i=2}^m \frac{1}{(i-2)!} p_2^{i-2} d(i-2) \left[ p_1^{i-2}(1-p_1^{n-m+1}) p_1^{n-m+1} \right] \right\}.
\]

The sum of all the probabilities that process transits from state $NA_{0,0}$ to state $NA_{n-m,m-1}$ indicates the miss
alarm probability proportion of the Markov model in Figure 4, and is denoted by \( P_a(NA) \), i.e.

\[
P_a(NA) = [P(NA_{0,0} \rightarrow NA_{1,0}) + \cdots + P(NA_0 \rightarrow NA_{m-1,n-m})] \times P(A_0 \rightarrow NA_{0,0})
\]

\[
= \left\{ p_2^n + \frac{1}{(m-2)!} p_2^{m-2} d^{(m-2)} \frac{p_1^{n-1}(1-p_1^{m-n})}{1-p_1} \right\} \times \left\{ 1 + \sum_{i=2}^{m} \frac{1}{(i-2)!} d^{(i-2)} \frac{p_1^{i-1}(1-p_1^{m-i+1})}{1-p_2} \right\}
\]

The false alarm rate can be calculated as

\[
MAR = \frac{P_a(NA)}{P_a(NA) + P_a(A)}.
\]

### 3.3. Averaged alarm delay

The calculation of the average alarm delay is based on the Markov model in Figure 4. According to the definition in (3), the AAD for \( m \) out of \( n \) samples generalized alarm delay-timer is

\[
T_d = E(T_d) = hE(T_{1,m(n-m)-n+2m}) - h = h \frac{d}{dz} \Gamma_{1,m(n-m)-n+2m}(z) \bigg|_{z=1}
\]

where \( T_{1,m(n-m)-n+2m} \) is the number of steps taken from 1 to \( m(n-m) - n + 2m \). \( \Gamma_{1,m(n-m)-n+2m}(z) \) is the moment generating function of the discrete random variable \( T_{1,m(n-m)-n+2m} \). \( z = e^t \) (Papoulis & Saunders, 1989), \( h \) is the sampling period.

\( \Gamma_{1,m(n-m)-n+2m} \) can be calculated by the following formula (Xu et al., 2012):

\[
\Gamma_{1,m(n-m)-n+2m}(z) = \sum_{j=l} \frac{z^{p_{ij}^{(1)}}}{(n+2m)!} \Gamma_{1,m(n-m)-n+2m}(z)
\]

where \( l \) is the state space, \( p_{ij}^{(1)} \) represents transition probability from state \( i \) to \( j \) in just 1 step.

According to the theory of the Markov chain and the Markov model under the abnormal condition, the following can be obtained

\[
\begin{align*}
\Gamma_{1,m(n-m)-n+2m}(z) &= z p_2 \Gamma_{1,m(n-m)-n+2m}(z) + z p_1 \Gamma_{2,m(n-m)-n+2m}(z) \\
\Gamma_{2,m(n-m)-n+2m}(z) &= z p_2 \Gamma_{2,m+1,m(n-m)-n+2m}(z) + z p_1 \Gamma_{3,m(n-m)-n+2m}(z) \\
&\vdots \\
\Gamma_{m(n-m)-n+2m}(z) &= z p_2 \Gamma_{m-1,m(n-m)-n+2m}(z) + z p_1 \\
&\vdots \\
\Gamma_{m(n-m)-n+2m}(z) &= z p_2 \Gamma_{1,m(n-m)-n+2m}(z) + z p_1.
\end{align*}
\]

Through the iterative calculation of equations in formula (8), then AAD can be obtained as

\[
\Gamma_{1,m(n-m)-n+2m}(z) = z^n p_1^n + z^m p_1^m d^{(m-2)} \frac{(z p_2)^{n-1}}{(m-2)!} \frac{1 - (z p_2)^{n-m}}{1 - z p_2}
\]

\[
1 - z p_2 - \sum_{j=2}^{m} \frac{(n-m+i-2)!}{(i-2)!(n-m)!} z^{n-m+i} p_1^{i-1} p_2^{n-m+1}.
\]

Taking the expression \( \Gamma_{1,m(n-m)-n+2m} \) in formula (9) into formula (7), the following can be obtained:

\[
AAD = \frac{-h + h \frac{d}{dz} \Gamma_{1,m(n-m)-n+2m}(z)}{1 - z p_2 - \sum_{j=2}^{m} \frac{(n-m+i-2)!}{(i-2)!(n-m)!} z^{n-m+i} p_1^{i-1} p_2^{n-m+1}}\bigg|_{z=1}.
\]

### 4. Application range comparing

The generalized alarm delay-timer is an optimization of the conventional alarm delay-timer. Therefore, the applicable condition of the generalized alarm delay-timer should be more broader than the conventional alarm delay-timer in common sense. In this section, the application ranges of conventional alarm delay-timer and generalized alarm delay-timer are compared. The three performance indices FAR, MAR and AAD are set.
\text{FAR} \leq 1\%, \text{MAR} \leq 1\%, \text{AAD} \leq 10h \quad \text{according to the calculation formulas of FAR, MAR and AAD obtained in the previous section. From formulas (5), (6) and (10), it can be seen directly that FAR is only related to } q_1, \text{MAR and AAD are related to } p_2 \text{ merely. Therefore, when the request of FAR is determined, the range of } q_1 \text{ for the alarm delay-timer with different parameters can be determined according to the calculation formula of FAR. When the MAR and AAD are determined, the value of } p_2 \text{ for the alarm delay-timer with different parameters can be determined according to the calculated formulas of MAR and AAD.}

For the conventional alarm delay-timer, the satisfied range of \( q_1 \) can be computed through formula (5) on the condition that FAR satisfied the requirements at different values of \( n \), \( n = 1, 2, \cdots, 10 \), \( m = n \). Similarly, the satisfied range of \( p_2 \) can be computed through formulas (6) and (10) also. For a special \( n \), the intersection area of the \( p_2 \) interval and the \( q_1 \) interval in the two-dimensional plane is a rectangle. For all the \( n \) from 1 to 10, there will 10 layers in the three-dimensional space, as shown in Figure 5(i). The corresponding top view of Figure 5(i) is Figure 5(ii). Each layer in Figure 5(i) represents the intersection area of values \( q_1 \) and \( p_2 \) for the corresponding \( n \) when the FAR, MAR and AAD are satisfied. Figure 5(ii) is a projection of the 10 layers in Figure 5(i) in a two-dimensional plane, that is, the scope of application that meets the FAR, MAR and AAD requirements when \( n \leq 10 \).

For the generalized alarm delay-timer, the satisfied range of \( q_1 \) can be computed through formula (5) on the condition that FAR satisfied the requirement at different values of \( n \) and different \( m \), \( n = 1, 2, \cdots, 10 \), \( m = 1, 2, \cdots, n \). Similarly, the satisfied interval of \( p_2 \) can be computed through formulas (6) and (10) also. For a special \( n \), the intersection areas of the \( p_2 \) interval and the \( q_1 \) interval in the three-dimensional plane is a series rectangle in the \( n \)-direction. For all the \( n \) from 1 to 10, there will a set of layers in the three-dimensional space, as shown in Figure 5(iii). The corresponding top view of Figure 5(iii) is Figure 5(iv). Figure 5(iv) shows the application range of FAR, MAR and AAD for \( n \leq 10 \) and \( m \leq n \).

By comparing the intersection area of \( q_1 \) and \( p_2 \) in Figure 5(ii) and Figure 5(iv), it can be seen clearly that the generalized alarm delay-timer has a wider application range than the conventional alarm delay-timer.

5. Simulation of example

In order to illustrate the procedures of applying the generalized alarm delay-timer in practice, a set of concrete design procedures is given here based on a set of simulation data. Suppose the sampling period \( h \) is 1 s.

\textbf{Step 1:} Obtain process data. The process data are the base of all the work. Thus, this work should be done first. Estimate \( q_1 \) and \( p_2 \) through these data. The simulation data are generated by a random variable \( x(t) \) which follows normal distribution. In the normal situation \( x(t) \sim N(3.58, 1) \), and in the abnormal situation \( x(t) \sim N(5, 1) \). The probability density curves in normal and abnormal situations are shown in Figure 6.

\textbf{Step 2:} Confirm the performance requirements. The value of performance indices must be determined according to the actual needs of the industrial plant. For this example, the range of the performance index \( \text{FAR} \leq 1\%, \text{MAR} \leq 1\% \) and \( \text{AAD} \leq 10h \) are adopted.

\textbf{Step 3:} Determine the parameters. Try to meet the requirements of alarm performance FAR, MAR and AAD by moving the alarm threshold \( x_{tp} \) from the lower boundary to upper boundary with a reasonable interval. For each time of moving \( x_{tp} \), select different values of \( n \) and \( m \), and compute the value of FAR, MAR and AAD. The results of Step 3 are depicted in Figures 7–9.

![Figure 5](image1.png)  
*Figure 5. The range of \( q_1 \) and \( p_2 \) that satisfies the performance requirements.*

![Figure 6](image2.png)  
*Figure 6. The probability density curves of simulation data in different conditions.*
Figure 7. The FAR curves corresponding to different \( n \) and \( m \).

Figure 8. The MAR curves corresponding to different \( n \) and \( m \).

Figure 9. The AAD curves corresponding to different \( n \) and \( m \).

According to the computing results of FAR, MAR and AAD, the effective interval of \( x_{tp} \) for satisfying the requirements of FAR are obtained from the corresponding curves shown in Figure 7; in order to satisfy the requirements of MAR, the effective value interval of \( x_{tp} \) is obtained from Figure 8 and the effective value interval of \( x_{tp} \) for satisfying the requirements of AAD is obtained from Figure 9.

Table 1. Different types of the alarm delay-timer satisfy the required threshold range.

| \( m/n \) | FAR \( x_{tp} \) | MAR \( x_{tp} \) | AAD \( x_{tp} \) |
|---------|----------------|----------------|----------------|
| 6/6     | [4.14, 5]     | [3, 4.44]      | [3, 3.96]      |
| 6/7     | [4.23, 5]     | [3, 4.44]      | [3, 4.27]      |
| 7/7     | [4.05, 5]     | [3, 4.45]      | [3, 3.72]      |
| 7/8     | [4.13, 5]     | [3, 4.43]      | [3, 4.06]      |
| 7/9     | [4.2, 5]      | [3, 4.38]      | [3, 4.24]      |
| 7/10    | [4.27, 5]     | [3, 4.31]      | [3, 4.37]      |

Table 2. Optimal threshold for different types of alarm delay-timer devices to meet the requirements.

| \( m/n \) | \( x_{tp} \) | \( \text{Argmin}(J) \) |
|---------|-------------|------------------|
| 6/7     | 4.27        | 2.227            |
| 7/9     | 4.24        | 2.002            |
| 7/10    | 4.28        | 2.612            |

The valid ranges of \( x_{tp} \) are listed in Table 1, we can select the intersection of the effective intervals in the second, third, and fourth columns of Table 1 as the proper range of \( x_{tp} \) for each value of \( n \) and \( m \).

Table 1 provides the valid ranges of \( n \), \( m \) and \( x_{tp} \). However, only one pair of values of \( n \), \( m \) and \( x_{tp} \) can be implemented in the alarm system. In order to choose the optimal values of \( n \), \( m \) and \( x_{tp} \), we choose the weighted-sum loss function as

\[
J = \omega_1 \text{FAR} + \omega_2 \text{MAR} + \omega_3 \text{AAD}.
\]

Here, \( \omega_1 \), \( \omega_2 \) and \( \omega_3 \) are the weights of FAR, MAR and AAD. The value of \( \omega_1 \), \( \omega_2 \) and \( \omega_3 \) should be determined according to the requirements of the industrial process. Here, let the FAR, MAR and AAD be equal in proportion, that is, \( \omega_1 = \omega_2 = \omega_3 = 1 \). The optimal values of \( n \), \( m \) and \( x_{tp} \) are the ones minimizing the loss function in (11), i.e.

\[
[\hat{n}, \hat{m}, \hat{x}_{tp}] = \text{arg min}(J).
\]

For different types of the alarm delay-timer, the corresponding optimal of \( x_{tp} \) and the minimal loss function \( J \) are listed in Table 2. In this simulation example, \( \hat{n} = 9 \), \( \hat{m} = 7 \) and \( \hat{x}_{tp} = 4.24 \).

**Step 5:** Configure the generalized alarm delay-timer. First, set the alarm trip-point as same as value of \( \hat{x}_{tp} \). Second, let the generalized alarm delay-timer with parameters \( \hat{n} \) and \( \hat{m} \).

**Step 6:** Run in practice. After all the steps above are finished, the configured generalized alarm delay-timer can be applied in an online manner.

Through the procedures above, it easily to find that the conventional alarm delay-timer cannot satisfy the performance requirements. From the simulation running results, it can be found easily that the generalized alarm
delay-timer satisfied the performance requirements well and removed all the nuisance alarm.

6. Conclusion

The generalized alarm delay-timer provides a more suitable solution for nuisance alarm elimination than the conventional delay-timer in practice. In order to simplify the application process of the generalized alarm delay-timer, three formulas are summarized in this paper, which are helpful for generalized alarm delay-timer parameter fixing. The effective procedures for the generalized alarm delay-timer configuration and applying are illustrated step by step through a simulation example.

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