

Design and Analysis of Improved Alarm Delay-Timers

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Abstract: Alarm systems play an important role in industry to notify operators of abnormal or fault situations. In real industrial plants, however, a majority of nuisance alarm signals, including false alarms and missed alarms, interfere with operators' judgment. The technique of delay-timers, a common means to reduce both false alarm rate (FAR) and missed alarm rate (MAR), is widely performed, yet it suffers from a delayed response. In this paper we propose an improved delay-timer annunciation and clearance method to enhance the performance of conventional delay-timers via bypassing some states in state switch under some conditions. Also the improved delay-timer performance indices are calculated by using Markov chains.

Keywords: Alarm systems, Markov processes, Delay-timers, False alarm rate, Missed alarm rate, Average alarm delay.

1. INTRODUCTION

In large modern industrial plants, abnormal situations not only affect their efficiency, but also bring a lot of safety issues, even major accidents or disasters, leading to casualties and economic losses. According to the Abnormal Situation Management (ASM) Consortium statistics, for the petrochemical industry, the amount of economic losses in the US is about 10 to 20 billion \$ due to abnormal situations, and a major accident occurs every three years in average. Alarm systems are an important means to detect and annunciate abnormal production situations so that operators can take actions immediately, and play an irreplaceable role in ensuring both safety and efficiency in industrial plants. A large number of safety incidents have fully demonstrated the importance of alarm systems in safe operation, such as the nuclear power accident occurred at Three Mile Island in 1979, which is the worst nuclear accident in the US history.

Design of alarm systems has attracted great attention of academia and industry in recent years, and becomes one of the emerging research field in the process control and automation community (Izadi et al., 2009). A major problem of the current embodiment of alarm systems is the lack of efficient and specific industrial techniques to meet the standard requirements, including ISA 18.2 (International Society of Automation, 2009) and EEMUA 191 (Engineering Equipment and Materials Users' Association 2013). A lot of research has been done, such as alarm system monitoring (Ahmed et al., 2013, Kondaveeti et al., 2013, Wang et al., 2014), alarm system performance evaluation and alarm systems design and optimization (Zang and Li, 2014). Alarm annunciation and clearance is an important task of alarm system optimal design. At the present stage, we focus on two aspects: univariate methods and multivariate methods (Yang et al., 2012a, Kondaveeti et al., 2012, Yang et al.,

2012b, Yang et al., 2013, Zhu et al., 2005), as shown in Fig. 1.

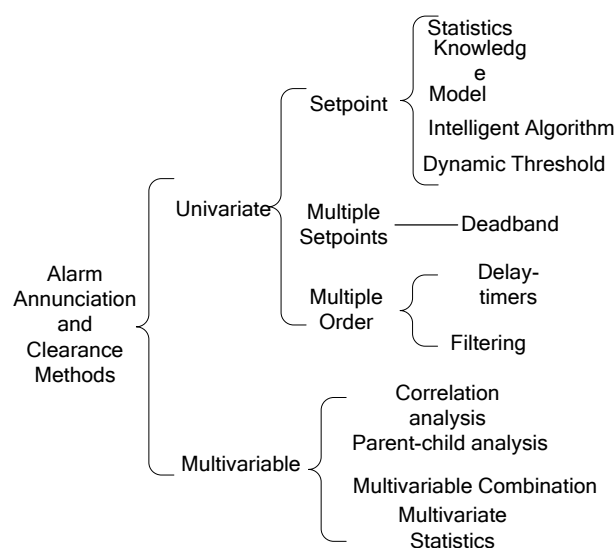


Fig. 1. Annunciation and clearance methods of alarm system design.

Univariate methods have reported wide range of applications, because they are easy to design and implement, and the alarm information is clear for operator's decision-making. The multivariate methods can control the number of alarms and alarm delay, especially alarm floods (Schleburg et al., 2013).

Univariate methods are based on the signal of the process variable; it generates an alarm status information by process data of a single variable through discrete or continuous function calculation. Alarm setpoint comparison is the most

common design approach – it is the method with a single order (only the current state is considered) and single alarm setpoint in essence, and it identifies alarm status by comparison of real-time data and setpoints. Reasonable setpoint is the key factor for alarm system efficiency and can be obtained by statistics, models, knowledge, or some intelligent algorithms. In some special conditions, the setpoint corresponding alarm state is changed, the dynamic threshold design can solve such problems effectively (Zhu et al., 2014). The traditional setpoint method is unable to meet operators' requirements for alarm systems with increasing complexity of industrial systems in recent years, some univariate methods with multiple orders or multiple setpoint methods have obtained more extensive research and applications. Multiple order methods denote that an alarm setpoint is obtained by a function transformation of several measured values in the past; whilst multiple setpoint methods denote that the annunciation and clearance of an alarm state corresponds to multiple setpoints. Alarm deadband is a two-setpoint method, where different values are used as alarm annunciation and alarm clearance setpoints (Adnan et al., 2013). Alarm delay-timers (Adnan et al., 2011, Kondaveeti et al., 2011, Xu et al., 2012) and alarm filters have been applied in industrial processes; they are multiple order methods (Yue et al., 2013). Alarm delay-timers are transformation of discrete functions, whilst filters use a continuous function transformation. Multiple setpoints and multiple order methods increase the number of design parameters, and thus can better control the performance indicators such as FAR, MAR and AAD. Among all these methods, delay-timers are commonly used for its simplicity and efficiency; however, their disadvantage is the evident time delays.

2. DELAY-TIMERS

Any method to detect alarms must be fast and accurate. A widely used method is comparison between the real-time process data and alarm setpoint to determine alarm status. Fig. 2 shows the annunciation mechanism of the false alarms and missed alarms, where X_T is the alarm setpoint. When the system is in normal state, the value of the process variable may exceed X_T , resulting in a false alarm; and when the system is in abnormal state, the value of the process variable may return to the region within X_T , then a missed alarm is generated.

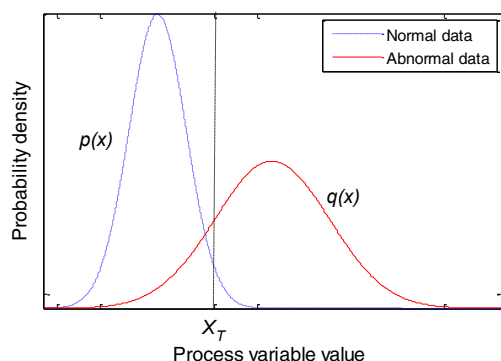


Fig. 2. Probability distributions of process data in normal and abnormal status.

False alarms and missed alarms are a pair of contradictions. The receiver operating characteristic (ROC) curve in Fig. 3 shows that it is difficult to control the false alarm rate (FAR) and missed alarm rate (MAR) within acceptable levels (Kondaveeti et al., 2011).

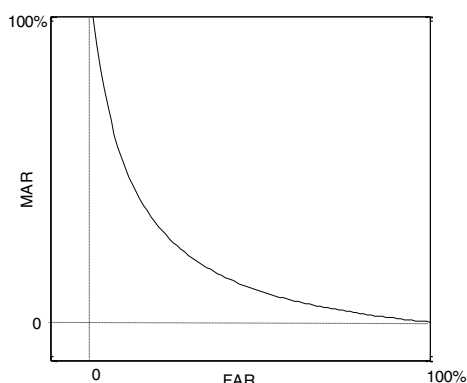


Fig. 3. The ROC curve of the alarm detection.

A delay-timer annunciation and clearance method was proposed for this situation (Xu et al., 2012). It classifies the alarm status and non-alarm status into n and m sub-states, respectively. When the process variable value exceeds X_T n times consecutively after a period of time in the normal state, the system state switches from non-alarm state NA_1 to alarm state A_1 eventually (via $NA_2, \dots, NA_n$); if the value goes within the alarm limit at any sample in this accumulation procedure, the state of the alarm tag immediately returns to state NA_1 . On the other hand, when the value is within X_T n times consecutively after a period of time in the abnormal state, the state switches from alarm state A_1 to non-alarm state NA_1 eventually (via $A_2, \dots, A_n$), otherwise jumps back to the alarm state A_1 .

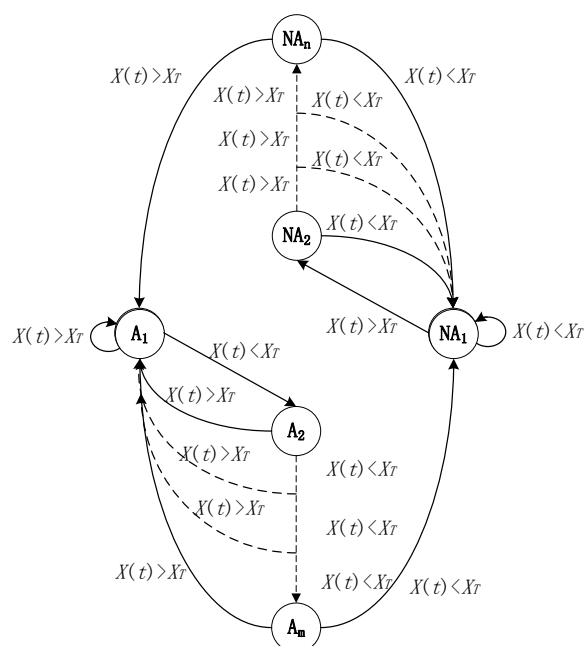


Fig. 4. Markov chain diagram of n - m -order alarm delay-timers.

The ROC curves of alarm delay-timers (in Figs. 5 and 6) show that the MAR and FAR significantly reduce when the delay-timer order increases, yet the average alarm delay (AAD) is also increased dramatically (Xu et al., 2012). The essence of delay-timers is to increase the accuracy by sacrificing on the detection delay.

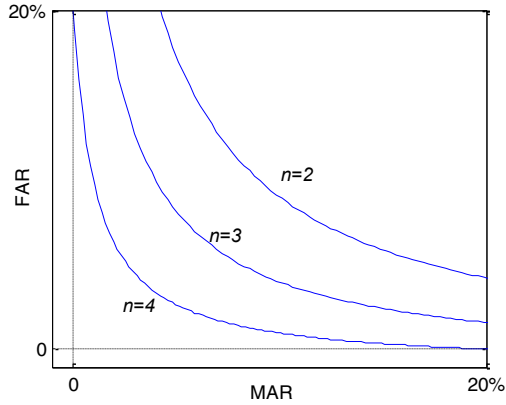


Fig. 5. The ROC curves of alarm delay-timers.

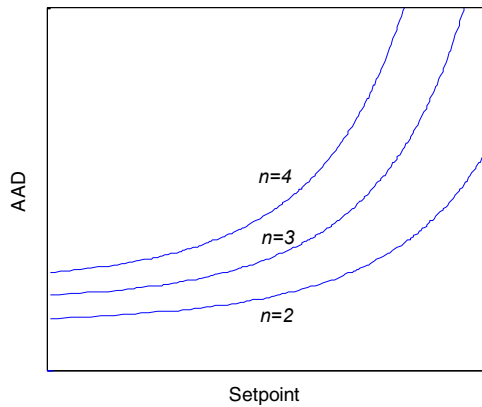


Fig. 6. AADs of alarm delay-timers with different orders.

3. IMPROVED DELAY-TIMERS

For an improved alarm delay-timer, Fig. 7 shows the probabilities and probability density functions of process values in normal and abnormal situations. Equations (1-10) give the results of these probabilities.

$$p_1 = \int_{x_{NL}}^{x_{AL}} p(x) dx \quad (1)$$

$$p_2 = \int_{x_{AL}}^{x_T} p(x) dx \quad (2)$$

$$p_3 = \int_{x_T}^{x_{NH}} p(x) dx \quad (3)$$

$$q_1 = \int_{x_{AL}}^{x_T} q(x) dx \quad (4)$$

$$q_2 = \int_{x_T}^{x_{NH}} q(x) dx \quad (5)$$

$$q_3 = \int_{x_{NH}}^{x_{AH}} q(x) dx \quad (6)$$

$$P_1 = p_1 S_N \quad (7)$$

$$P_2 = p_2 S_N + q_1 S_A \quad (8)$$

$$P_3 = p_3 S_N + q_2 S_A \quad (9)$$

$$P_4 = q_3 S_A \quad (10)$$

where $p(x)$ and $q(x)$ are probability density functions of alarm tag x in normal and abnormal situations, respectively, with arbitrary distributions with different means. where NL NH denote low and high limits of normal distribution, and AL and AH denote low and high limits of abnormal distribution. S_N and S_A are the statistical probabilities of process operating in normal and abnormal states, respectively, and $S_N + S_A = 1$.

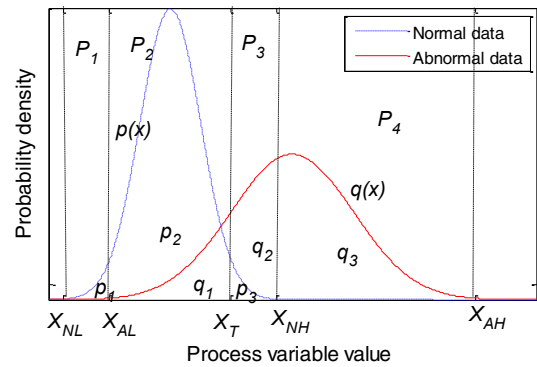


Fig. 7. Probability distributions of process data in normal and abnormal status, .

Through analysis of the alarm delay-timer topology, we notice one cause of the significant increase of AAD. When the process variable exceeds x_{NH} suddenly, the process has been in an abnormal state, and thus the alarm tag should immediately switch to the alarm state; however, the traditional alarm delay-timer has to wait for state transitions through all the sub-states step by step (n steps). In the improved alarm delay-timer, the transition from non-alarm state to alarm state in this case is immediate (one step). For the improved alarm delay-timer, we analyse the probability space on the basis of the traditional alarm delay-timer, and add two direct state transitions between the alarm state and the non-alarm state.

3.1 Improved Alarm On-Delay-Timers

Fig. 8 shows an improved on-delay-timer. The difference is additional jumps from each non-alarm sub-state to the alarm state compared with the traditional alarm on-delay-timer.

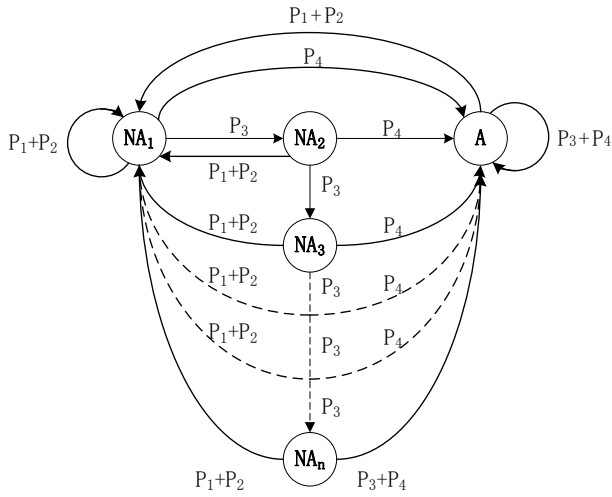


Fig. 8. Markov chain diagram of the n -order improved alarm on-delay-timers.

For the Markov chain in Fig. 8, the matrix $\mathbf{Q} \in R^{(n+1) \times (n+1)}$ of one step transition probability is

$$\mathbf{Q} = \begin{bmatrix} P_1+P_2 & P_3 & 0 & 0 & 0 & \cdots & 0 & P_4 \\ P_1+P_2 & 0 & P_3 & 0 & 0 & \cdots & 0 & P_4 \\ P_1+P_2 & 0 & 0 & P_3 & 0 & \cdots & 0 & P_4 \\ P_1+P_2 & 0 & 0 & 0 & P_3 & \cdots & 0 & P_4 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ P_1+P_2 & 0 & 0 & 0 & 0 & \cdots & P_3 & P_4 \\ P_1+P_2 & 0 & 0 & 0 & 0 & \cdots & 0 & P_3+P_4 \\ P_1+P_2 & 0 & 0 & 0 & 0 & \cdots & 0 & P_3+P_4 \end{bmatrix} \quad (11)$$

Here, the element locating at the i th row and the j th column of the matrix $\mathbf{Q}$ is the one step transition probability of the state from i to j .

When the process is in normal state, we define

$$\begin{cases} S_A = 0 \\ S_N = 1 \end{cases} \quad (12)$$

From (1-10) and (12), we have

$$\text{FAR} = p_3^n \quad (13)$$

When the process is in abnormal state, we define

$$\begin{cases} S_A = 1 \\ S_N = 0 \end{cases} \quad (14)$$

From (1-10) and (12), the solving process details can refer to references (Xu. et al., 2012), we have

$$\text{MAR} = \frac{q_1(1-q_2^n)}{1-q_2} \quad (15)$$

$$\text{ADD} = h \left(\frac{-q_1 q_2^{2n} + (-q_2 - 2q_3 + 1)q_2^n + q_3}{(q_1 q_2^n + q_3)^2} - 1 \right) \quad (16)$$

3.2 Improved Alarm Off-Delay-Timers

Fig. 9 shows an improved off-delay-timer Markov chain. The difference is additional jumps from each alarm sub-state to the non-alarm state compared to the traditional alarm off-delay-timer.

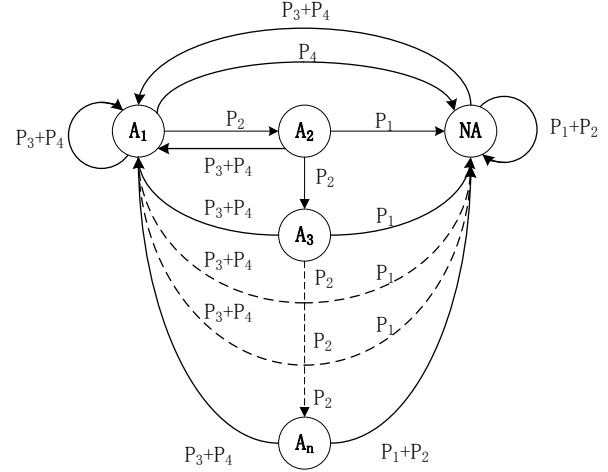


Fig. 9. Markov chain diagram of the n -order improved alarm off-delay-timers.

For the Markov chain in Fig. 9, the matrix $\mathbf{Q} \in R^{(n+1) \times (n+1)}$ of the one step transition probability is

$$\mathbf{Q} = \begin{bmatrix} P_3+P_4 & P_2 & 0 & 0 & 0 & \cdots & 0 & P_1 \\ P_3+P_4 & 0 & P_2 & 0 & 0 & \cdots & 0 & P_1 \\ P_3+P_4 & 0 & 0 & P_2 & 0 & \cdots & 0 & P_1 \\ P_3+P_4 & 0 & 0 & 0 & P_2 & \cdots & 0 & P_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ P_3+P_4 & 0 & 0 & 0 & 0 & \cdots & P_2 & P_1 \\ P_3+P_4 & 0 & 0 & 0 & 0 & \cdots & 0 & P_1+P_2 \\ P_3+P_4 & 0 & 0 & 0 & 0 & \cdots & 0 & P_1+P_2 \end{bmatrix} \quad (17)$$

According to the characteristics of the Markov chain, we obtain the performance indicators as follows:

$$\text{FAR} = \frac{p_3(1-p_2^n)}{1-p_2} \quad (18)$$

$$\text{MAR} = q_1^n \quad (19)$$

$$\text{ADD} = h \frac{q_1}{q_2 + q_3} \quad (20)$$

3.3 Improved Alarm Delay-Timers

Fig. 10 is the Markov chain of an n -order improved delay-timer.

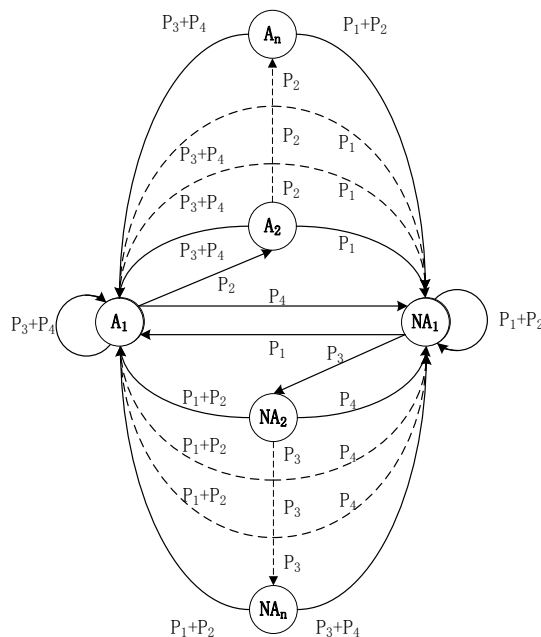


Fig. 10. Markov chain diagram of the n -order improved alarm delay-timers.

For the Markov chain in Fig. 10, the matrix $Q \in R^{2n \times 2n}$ of one step transition probability is

$$Q = \begin{bmatrix} P_1+P_2 & P_3 & 0 & \cdots & 0 & 0 & P_4 & 0 & 0 & 0 & \cdots & 0 \\ P_1+P_2 & 0 & P_3 & \cdots & 0 & 0 & P_4 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & P_3 & 0 & P_4 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & P_3 & P_4 & 0 & 0 & 0 & \cdots & 0 \\ P_1+P_2 & 0 & 0 & \cdots & 0 & 0 & P_3+P_4 & 0 & 0 & 0 & \cdots & 0 \\ P_1 & 0 & 0 & \cdots & 0 & 0 & P_3+P_4 & P_2 & 0 & 0 & \cdots & 0 \\ P_1 & 0 & 0 & \cdots & 0 & 0 & P_3+P_4 & 0 & P_2 & 0 & \cdots & 0 \\ P_1 & 0 & 0 & \cdots & 0 & 0 & P_3+P_4 & 0 & 0 & P_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ P_1 & 0 & 0 & \cdots & 0 & 0 & P_3+P_4 & 0 & 0 & 0 & \cdots & P_2 \\ P_1+P_2 & 0 & 0 & \cdots & 0 & 0 & P_3+P_4 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \quad (21)$$

According to the characteristics of the Markov chain, we obtain the performance indicators as follows:

$$FAR = \frac{p_3^n \sum_{i=0}^{n-1} p_2^i}{\sum_{i=0}^{n-1} p_3^i (1-p_3 \sum_{j=0}^{n-1} p_2^j) + p_3^n \sum_{i=0}^{n-1} p_2^i} \quad (22)$$

$$MAR = \frac{q_1^n \sum_{i=0}^{n-1} q_2^i}{\sum_{i=0}^{n-1} q_1^i (1-q_1 \sum_{j=0}^{n-1} q_2^j) + q_1^n \sum_{i=0}^{n-1} q_2^i} \quad (23)$$

$$ADD = h \left(\frac{-q_1 q_2^{2n} + (-q_2 - 2q_3 + 1) q_2^n + q_3 - 1}{(q_1 q_2^n + q_3)^2} \right) \quad (24)$$

4. SIMULATION STUDY

Apply the following mechanism to produce a single-variable data series involving two states. Assume that it follows the $N(1,1)$ normal distribution in the normal condition, and the $N(3,1)$ normal distribution in the abnormal condition. Generate 100000 data, including 50000 normal data points and 50000 abnormal data points.

$$\begin{cases} x(t) \sim N(1,1), & 100(n-1) < t \leq 50(2n-1) \\ x(t) \sim N(3,1), & 50(2n-1) < t \leq 100n \end{cases} \quad (25)$$

$$t, n \in N^+, 1 \leq n \leq 1000$$

Table 1. Definition of false and missed alarms

Alarm Situation	No alarm(0)	Alarm(1)
Normal(0)	correct	false alarm
Abnormal(1)	missed alarm	correct

Generate alarm data via a simple setpoint comparison, a 3rd-order conventional delay-timer, and an improved delay-timer, and then calculate MAR, FAR, and AAD, as shown in Table 2.

Table 2. Performance comparison

method	MAR	FAR	AAD
Threshold ($X_T=2$)	0.15684	0.15864	0.207
3rd-order delay-timer ($X_T=2$)	0.0273	0.02668	1.113
3rd-order improved delay-timer ($X_T=2$, $X_{NH}=4.5$, $X_{AL}=-0.5$)	0.01968	0.01968	0.679

From Table 2, we see that the improved alarm delay-timer has better performance in all indicators compared to the conventional alarm delay-timer. It can make the alarms more accurate and timely.

5. CONCLUDING REMARKS

The proposed improved alarm delay-timers are essentially a univariate alarm configuration method with multiple orders and setpoints. The problem of AAD excessive growth with order increases is overcome by adding an alarm annunciation setpoint and an alarm clearance setpoint on the basis of conventional alarm delay-timers. Improved alarm delay-timers have more parameters to be designed, and thus how to improve the alarm system operating efficiency by designing each parameter requires in-depth study.

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