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An online method to remove chattering and repeating alarms based on alarm durations and intervals☆

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ABSTRACT

Chattering and repeating alarms, which repeatedly make transitions between alarm and non-alarm states without operators' response, are the most common form of nuisance alarms encountered in industrial plants. The paper formulates two novel rules to detect chattering alarms caused by random noise and repeating alarms by regular patterns such as oscillation, and proposes an online method to effectively remove chattering and repeating alarms via the m-sample delay timer. Industrial examples are provided to support the formulated rules and to illustrate the effectiveness of the proposed method.

1. Introduction

Alarm systems are critical assets for process safety and efficient operation of modern industrial plants. However, industrial plant operators often receive many more alarms than they can handle promptly, mainly due to the excessive large number of nuisance alarms (Bransby and Jenkinson, 1998; Rothenberg, 2009).

Chattering and repeating alarms refer to the alarms that repeatedly make transitions between alarm and non-alarm states without operators' response. They are the most common forms of nuisance alarms (EEMUA-191, 2007), and may account for 10–60% of the alarm annunciations (Rothenberg, 2009). Hence, one basic task in alarm rationalization is to eliminate chattering and repeating alarms in order to avoid distraction for operators. In addition, removing these nuisance alarms is a prerequisite for advanced alarm rationalization tasks such as alarm flood analysis (Ahmed et al., 2013).

Chattering and repeating alarms have received an increasing attention from both industrial and academic communities. Burnell and Dicken (1997) introduced an auto-shelving facility and changed the alarm display list to handle repeating alarms. Bransby and Jenkinson (1998, Appendix 10) and EEMUA-191 (2007, Appendix 9) discussed several mechanisms commonly used in practice to remove repeating alarms, including filtering, deadband, delay timer, and shelving. Hugo (2009) designed adaptive alarm deadbands to reduce the number of chattering alarms via a time-series modeling technique. Kondaveeti et al. (2013) proposed a chattering index to quantify the degree of chattering alarms based on the run lengths of alarms. Naghoosi et al. (2011) developed a method to estimate the chattering index based on statistical properties of process variables, and applied the analytical relation between the chattering index and the parameters of alarm limits and deadbands for an optimal design. Wang and Chen (2013) proposed a revised chattering index and an online method to detect and remove the repeating alarms due to oscillation.

This paper is a continuing study of our previous work (Wang and Chen, 2013). We have applied the chattering index in Kondaveeti et al. (2013), and the revised one in Wang and Chen (2013) to dozen of industrial alarm signals. Both indices have been successful in detecting chattering and repeating alarms for many cases. However, two drawbacks have also been realized. First, the rate of missing detection sometimes is large, that is, some chattering/repeating alarms that can be easily spotted by visual inspection cannot be detected by the chattering indices. Second, both chattering indices can only tell if chattering alarms are present or absent in a set of collected alarm samples, but cannot indicate

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which one of alarms is chattering; as a result, it is hard to evaluate whether the removed alarms (e.g., by using alarm deadbands) are indeed chattering.

The contribution of this paper is twofold. First, two rules are formulated to detect the chattering and repeating alarms. They are based on the alarm durations and intervals, while the chattering indices in Kondaveeti et al. (2013) and Wang and Chen (2013) are on the run lengths of alarms. The formulated rules can resolve the above-mentioned drawbacks of the existing chattering indices. Second, a novel online method is proposed to remove the chattering and repeating alarms by exploiting the two formulated rules and the m-sample delay timer. The proposed method is designed in a systematic manner by considering requirements on three performance indices, namely, the false alarm rate (FAR), missed alarm rate (MAR) and averaged alarm delay (AAD). It is worthy to point out that the methods to handle chattering/repeating alarms in Burnell and Dicken (1997), Bransby and Jenkinson (1998), EEMUA-191 (2007), Hugo (2009), Kondaveeti et al. (2013), and Naghoosi et al. (2011) are rather empirical, lack of quantitative measures on the benefits and costs. The proposed method has also some important differences with the method in our earlier work (Wang and Chen, 2013), in terms of applicability and effectiveness, as clarified later at Remark 5 in Section 5.

The rest of the paper is organized as follows. Section 2 is on the definition and causes of chattering and repeating alarms. Section 3 formulates two rules based on the alarm durations and intervals to detect the chattering and repeating alarms. Section 4 investigates the mechanisms to remove chattering and repeating alarms. The proposed online method is presented in Section 5, and its effectiveness is illustrated via industrial examples in Section 6. Section 7 adds some concluding remarks.

2. Basics of chattering and repeating alarms

This section discusses the definition and causes of chattering and repeating alarms.

The definitions of chattering and repeating alarms have been given in industrial standards. The industrial standard ISA-18.2 (2009) says “a chattering alarm repeatedly transitions between the alarm state and the normal state in a short period of time.” The repeating is defined as “the same alarm raising and clearing repeatedly over a period of time” from an industrial guide EEMUA-191 (2007). Synonyms of chattering and repeating alarms include fleeting alarms and oscillating alarms, e.g., repeating alarms are defined as “alarms come in and clear very quickly, but do not necessarily repeat” (Hollifield and Habibi, 2010). These definitions contain some vagueness that comes from the uncertainty of the period of time that a chattering/repeating alarm is raised and cleared. ISA-18.2 (2009) and Hollifield and Habibi (2010) suggest the first pass identification of the worse chattering alarms as the alarms that repeat more than three times per minute, i.e., the short period is 20 s. Rothenberg (2009) defines a chattering/repeating alarm as the one that is activated and cleared 10 or more times within 1 min/15 min, i.e., the short period is 6 s for chattering alarm, and 90 s for repeating alarms. Such a period of 6 s, 20 s or even 90 s may be too short for operators taking action and adjusting the process to clear alarms. Thus, the alarms being activated and cleared within such a short period are very likely to be nuisance alarms, because a well-accepted key criterion to distinguish nuisance alarms is that an informative alarm must require an operator response ISA-18.2 (2009).

There are several causes of chattering and repeating alarms, including the presence of random noise and some regular patterns such as the oscillatory phenomena or the repeated action of on–off control loops. For instance, Fig. 1 presents 1-h samples

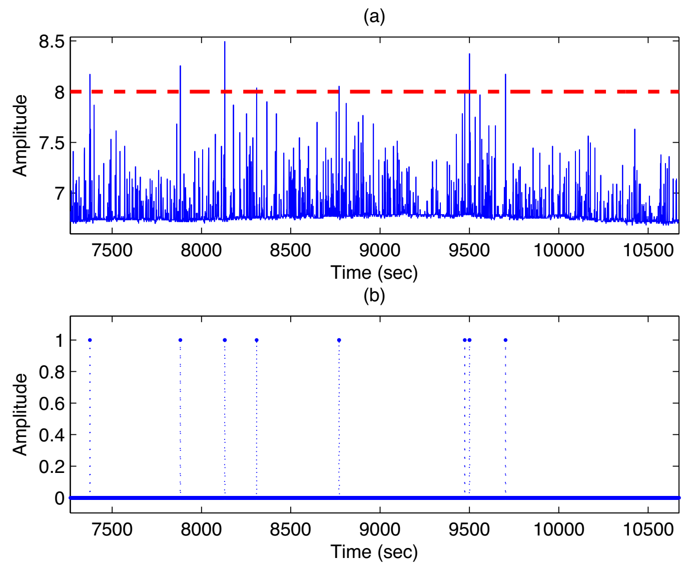

Fig. 1. Chattering alarms caused by random noise: (a) process variable (solid) and alarm trippoint (dash), (b) alarm signal.

of an industrial process variable and the associated alarms; due to the measurement noises, the alarms in Fig. 1 are raised and cleared quickly, all within 6 s, so that they are chattering alarms. As another example, Fig. 2 gives 1-h samples of a process variable and the associated alarms. The oscillation causes the alarms appeared in Fig. 2 that are raised and cleared with a regular period of 200 s, but no operator response is made for these alarms so that they are repeating alarms. These two industrial examples are further elaborated later in Section 6. Bransby and Jenkinson (1998, Appendix 10 therein) also discussed some industrial examples where the chattering alarms were caused by the noise on a process variable that is operating close to the alarm trippoint, and the repeating alarms (referred to as oscillating alarms therein) by the oscillations from repeated on–off control actions having a cycle time of 43 min.

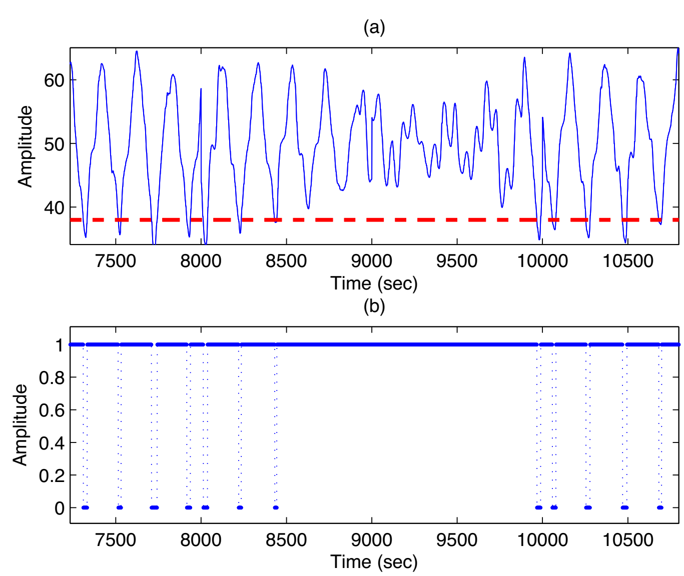

Fig. 2. Repeating alarms caused by oscillation: (a) process variable (solid) and alarm trippoint (dash), (b) alarm signal.

3. Rules to detect chattering and repeating alarms

This section discusses some drawbacks of the existing chattering indices, and formulates two novel rules to detect the presence of chattering and repeating alarms.

In order to detect chattering alarms, a chattering index was proposed by Kondaveeti et al. (2013), and was later revised to take the length of collected alarm samples into consideration by Wang and Chen (2013). The chattering indices are based on the alarm run length, which is defined based on a particular form of alarm signals.

The measurements of alarm signals in most industrial databases are in the following form, namely, the alarm signal $x_a(t)$ takes the value of '1' ('0') for the entire period of the alarm (non-alarm) state. To be more precisely, suppose that the process variable $x(t)$ is available, and is configured with a high alarm with trippoint x_{tp}. Then the alarm signal $x_a(t)$ is generated as

$$x_a(t) = \begin{cases} 1, & \text{if}\, x(t) \geq x_{tp} \\ 0, & \text{if}\, x(t) < x_{tp} \end{cases}. \tag{1}$$

Another form of the alarm signal takes the value of '1' only at the time instant when the non-alarm state is switched to the alarm state, i.e.,

$$x'_a(t) = \begin{cases} 1, & \text{if}\, x(t-1) < x_{tp}\ \text{and}\ x(t) \geq x_{tp} \\ 0, & \text{otherwise} \end{cases}. \tag{2}$$

Clearly, $x'_a(t)$ can be obtained from $x_a(t)$ in (1), while the converse transform is infeasible, because $x'_a(t)$ does not contain the information of time instants of $x_a(t)$ from '1' to '0'.

The run length, denoted as r, is defined as the number of samples between two adjacent '1's in the alarm signal $x'_a(t)$ in (2), i.e.,

$$r := t_2 - t_1 - 1, \tag{3}$$

where

$$x'_a(t_1) = 1,\ x'_a(t_2) = 1,\ \sum_{t=t_1}^{t_2} x'_a(t) = 2, \quad \text{for}\, t_2 > t_1.$$

The chattering index in Kondaveeti et al. (2013) is

$$\psi = \frac{\sum_r AC_r / r}{\sum_r AC_r}, \tag{4}$$

where r is the run length in (3) and AC_r is the total number of r in a certain period of time. A cutoff threshold of ψ is 0.05 alarms/s, determined by a rule of thumb from ISA-18.2 standard that alarms repeating more than three times per minute are considered chattering. Thus, the next rule is used in Kondaveeti et al. (2013) for the detection of chattering alarms:

Rule 1 (Kondaveeti et al., 2013). Chattering alarms are claimed to be present when $\psi \geq 0.05$.

To incorporate the length of collected alarm samples, a revised chattering index was proposed by Wang and Chen (2013),

$$\eta = \frac{2\sum_r AC_r / r}{N}, \tag{5}$$

where N is the data length of $x'_a(t)$ in (2). The index η is mainly used to detect the repeating alarms caused by oscillation; the cutoff threshold is $\eta = 0.005$, which is based on the same rule of thumb from ISA-18.2 standard that three alarms are evenly spread in 1 min. Therefore, the detection rule in Wang and Chen (2013) is

Rule 2 (Wang and Chen, 2013). Repeating alarms due to oscillation are claimed to be present when $\eta \geq 0.005$.

Both ψ in (4) and η in (5) have been demonstrated to be the valid measures of chattering and repeating alarms in some industrial examples; however, more experience of applying them to industrial alarm signals reveals that both indices have certain drawbacks. First, as weighted averages, both indices may miss the detection of chattering/repeating alarms. As a simple example, if there are two alarm run lengths 21 s and 20 s, then $\psi = ((1/20) + (1/21))/2 = 0.0488$; by contrast, if both run lengths are equal to 20 s, then $\psi = 0.05$. Rule 1 gives controversial conclusions for the two similar cases. Second, the run length cannot truly represent the essence of chattering and repeating alarms, and as a result, the two indices ψ and η may fail in detecting chattering/repeating alarms. This is clearly explained via the industrial alarm signal $x_a(t)$ shown earlier in Fig. 1, where the 7 run lengths are 505, 247, 178, 460, 703, 25, 201. The calculated chattering index is $\psi = 0.0086$, less than the cutoff threshold 0.05, so that no chattering alarms are detected by Rule 1. However, each alarm arises and clears in a short period less than 6 s so that the chattering alarms are obviously present. The failure of detection is due to a fact the Rule 1 uses the run lengths, which are quite large for the alarms in Fig. 1. Finally, both indices only tell if a set of collected alarm samples contains chattering/repeating alarms, but cannot pinpoint which alarms to be chattering/repeating. In the process of removing nuisance alarms, it is necessary to tell which one is the chattering/repeating alarm and thus should be removed.

In this context, we advocate the detection of chattering and repeating alarms based on two other metrics, namely, the alarm duration and the alarm interval, instead of the run length. The alarm duration, denoted as T_1, is the time duration of adjacent '1's for $x_a(t)$ in the first form (1), i.e.,

$$T_1 := t_2 - t_1 + 1, \tag{6}$$

where

$$x_a(t_1 - 1) = 0,\ x_a(t_2 + 1) = 0,\ \sum_{t=t_1}^{t_2} x_a(t) = t_2 - t_1 + 1, \quad \text{for}\, t_2 > t_1.$$

The alarm interval, denoted as T_0, is the time interval from the clearance of an alarm to the occurrence of the next alarm, i.e.,

$$T_0 := t_2 - t_1 + 1, \tag{7}$$

where

$$x_a(t_1 - 1) = 1,\ x_a(t_2 + 1) = 1,\ \sum_{t=t_1}^{t_2} (1 - x_a(t)) = t_2 - t_1 + 1, \quad \text{for}\, t_2 > t_1.$$

Clearly, the relation among the alarm duration T_1, the alarm interval T_0 and the run length r is $r = T_0 + T_1 - 1$. The physical interpretations of T_1 and T_0 are easy to understand. An alarm with short duration T_1 may require no response from operators to clear the alarm, e.g., the alarms given in Fig. 1. On the other hand, a small alarm interval T_0 says that the alarm clearance is only temporary so that the short-time non-alarm state should be removed as well, e.g., the alarms in Fig. 2.

Next, we present the following proposition associated with Rules 1 and 2.

Proposition 1. *If the alarms with run lengths no larger than* r_0 *are removed, then the chattering index* ψ *in (4) is always smaller than* $1/r_0$, *and the revised chattering index* η *in (5) is always smaller than* $2/r_0^2$.

Proof of Proposition 1. If all run lengths are larger than r_0, then

$$\psi = \frac{\sum_r AC_r/r}{\sum_r AC_r} < \frac{\sum_r AC_r/r_0}{\sum_r AC_r} = \frac{1}{r_0}.$$

The inequality $r > r_0$ implies that $\sum_r AC_r < N/r_0$, $\forall\, r > r_0$, leading to,

$$\eta = \frac{2\sum_r AC_r/r}{N} < \frac{2N/r_0^2}{N} = \frac{2}{r_0^2}.$$

□

Even though the proof of Proposition 1 is rather simple, the practical implication of Proposition 1 is significant. That is, there is no need to introduce the chattering indices ψ in (4) and η in (5) as well as Rules 1 and 2 to detect chattering and repeating alarms. All the chattering and repeating alarms detected by Rules 1 and 2 can always be found by directly looking at whether there are alarms having the run lengths less than $r_0 = 1/0.05 = 20$ s. However, the converse statement is not true, namely, some chattering/repeating alarms with run lengths less than 20 s may be missed by Rules 1 and 2 that are based on the averaged statistics ψ and η, respectively.

Based on Proposition 1, we formulate a new rule to detect chattering alarms.

Rule 3a. If the alarm duration T_1 or the alarm interval T_0 is less than 20 s, then the chattering alarm is present.

Rule 3a is a hard classification of chattering alarms. The threshold 20 s is based on the same rule of thumb from ISA-18.2 standard used for Rules 1 and 2. The threshold 20 s can be regarded as a default choice, and is certainly is not unique. In practice, the threshold could be adapted to the character of alarm signals; see Examples 1 and 2 in Section 6 for illustration.

Rule3a covers chattering alarms with short alarm duration or interval, possibly caused by random noise. To detect repeating alarms caused by regular patterns such as oscillation, a complementary rule is proposed along with Rule 3a,

Rule 3b. If the alarm duration T_1 or the alarm interval T_0 is kept constant, then the repeating alarm is present.

If T_1 or T_0 is constant in a long period of time, then it is very likely that no operator responses are involved, and the appearance and clearance of alarms are on their own, so that these alarms are repeating. A typical example is shown in Fig. 2, where the repeating alarms are caused by oscillatory behaviors of $x(t)$. A regularity test will be presented later in Section 5 to perform a statistical test on whether T_1 or T_0 is kept constant.

4. Mechanisms to remove chattering alarms

After chattering/repeating alarms are detected, a proper alarm generation mechanism can be exploited to remove these nuisance alarms.

There are several mechanisms commonly adopted in practice to reduce the number of chattering/repeating alarms, namely, the shelving operation, the filtering, the deadband, the delay timer, and the adjustment of the alarm trippoint x_{tp}. Among them, only the shelving operation and delay timer work directly on the alarms, while the rest mechanisms are applicable only to analog values of the process signal to generate alarms. However, some alarm signals do not have associated process variables, e.g., the alarms from digital input modules. Hence, the shelving operation and delay timer are investigated here.

The shelving operation may lead to a potentially dangerous situation, namely, when the abnormal condition occurs during the time

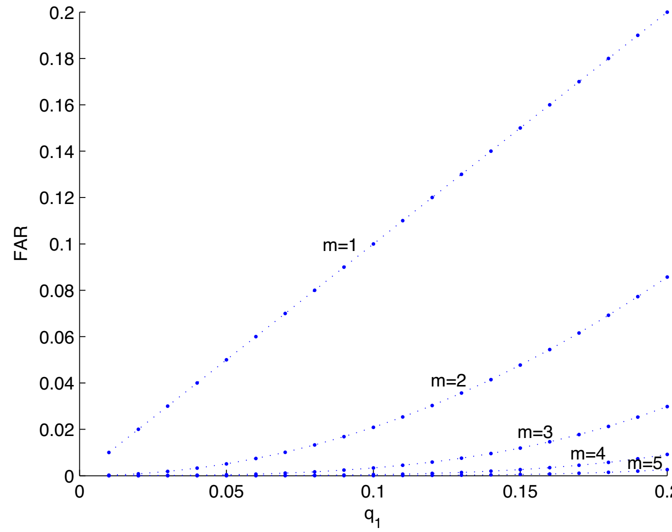

Fig. 3. The variation of FAR as a function of q_1 for several values of m.

that $x_a(t)$ is under the shelving operation, no alarms will be given. As stated in the guide EEMUA-191 (2007, p. 104), an important issue in dealing with chattering alarms is to "provide the operator with a good warning of the alarm that repeats for a period and then moves significantly into the alarm region". Clearly, this issue cannot be resolved by the shelving operation.

The m-sample delay timer raises (clears) an alarm if and only if m consecutive samples of the alarm signal $x_a(t)$ are '1's ('0's). Thus, the delay timer is indeed based on the alarm duration and interval, the same metrics used in Rules 3a and 3b. In addition, the above issue of not missing true alarms stated in the guide EEMUA-191 (2007) can be resolved by the delay timers with a proper design. Hence, the delay timer is a good choice.

A proper design of the m-sample delay timer, namely, the selection of the factor m, should meet with the requirements on the FAR, MAR and AAD (Xu et al., 2012). If $x_a(t)$ is an independent and identically distributed (IID) sequence, the FAR, MAR and AAD for the m-sample delay timer are (Xu et al., 2012)

$$\mathrm{FAR} = \frac{q_1^{m-1}(1-q_2^m)}{q_1^{m-1}(1-q_2^m) + q_2^{m-1}(1-q_1^m)}, \tag{8}$$

$$\mathrm{MAR} = \frac{p_2^{m-1}(1-p_1^m)}{p_2^{m-1}(1-p_1^m) + p_1^{m-1}(1-p_2^m)}, \tag{9}$$

$$\mathrm{AAD} = \frac{1-p_1^m}{p_2 p_1^m}, \tag{10}$$

where q_1 and p_2 respectively are the FAR and MAR for the case that no delay timer is used (or equivalently speaking, the delay timer with $m = 1$ is applied), and $p_1 := 1 - p_2$ and $q_2 := 1 - q_1$. It is straightforward to see from (8)–(10) that there exist some tradeoffs among the FAR, MAR and AAD. That is, as m increases, the FAR and MAR are monotonically decreasing, while the AAD is monotonically increasing. Since the chattering/repeating alarms are indeed the false or missed alarms, reducing the number of chattering/repeating alarms requires a larger value of m, which leads to a tradeoff in increasing AAD.

Based on Rules 3a and 3b, the factor m of the delay timer is selected as $m = 20$ s as a default value. The chattering alarms with alarm duration or interval less than m s are removed by using the m-sample delay timer. Hence, the FAR or MAR will be reduced significantly, as revealed from Fig. 3 that presents the curves of FAR vs. q_1 for several values of m. Meanwhile, the increment of AAD needs to be controlled. In practice, the value of p_2 can be estimated from

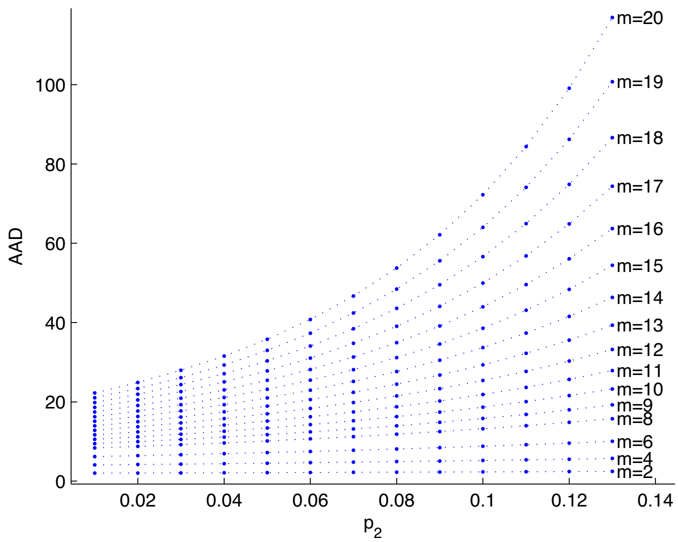

Fig. 4. The variation of AAD as a function of p_2 for several values of m.

historical data, and an upper bound of m, denoted as m_U, can be obtained from (10) based on the largest AAD acceptable to users. If the selected value of m is not larger than m_U, then the m-sample delay timer can be exploited. Fig. 4 depicts the variation of the AAD as a function of p_2 for several values of m. It is clear that the AAD is not deviated too much from m if p_2 is small, but the AAD increases very quickly with the increment of m for a large value of p_2.

5. The proposed method

This section proposes an online method that can effectively reduce the number of chattering and repeating alarms by exploiting the m-sample delay timer, while the requirements on the FAR, MAR and AAD are satisfied. Note that removing chattering/repeating alarms by the m-sample delay timer can significantly improve the FAR and MAR, so that the main concern is to control the increment of AAD within an acceptable level.

The following assumptions are assumed to be hold:

A1. The past samples of the alarm signal $x_a(t)$ in the normal and abnormal conditions are available.
A2. The upper limits of FAR, MAR and AAD, respectively denoted as RFAR, RMAR and RAAD, are known *a priori*.
A3. The alarm signal $x_a(t)$ is IID.
A4. The alarm signal $x_a(t)$ is in the non-alarm state for the majority of time.

The past samples of $x_a(t)$ in Assumption A1 is used to estimate the FAR q_1 and MAR p_2 of $x_a(t)$ where the m-sample delay timer is not used. Thus, owing to Assumptions A2 and A3, the requirement of RFAR or RMAR impose the lower bound m_L of the factor m for the delay timer from (8) or (9), while the RAAD gives the the upper bound m_U of m from (10). Rules 3a and 3b say that m is always equal to or greater than 20; thus, the lower bound m_L is usually satisfied, as revealed by Fig. 3. Therefore, the main concern for m is to satisfy the upper bound m_U. In practice, the samples required in Assumption A1 may not be available; in this case, if the MAR p_2 is believed to be small, the upper bound m_U can be taken the same as the RAAD, as implied by Fig. 4. Assumption A3 is a statistical requirement from (8)–(10) for the design of m. It can be satisfied in many cases, e.g., the underlying process variable $x(t)$ is generated as $x(t) = x_d(t) + e(t)$, where $x_d(t)$ is a deterministic component such as an oscillatory sine wave and $e(t)$ is the IID noise. Assumption A4

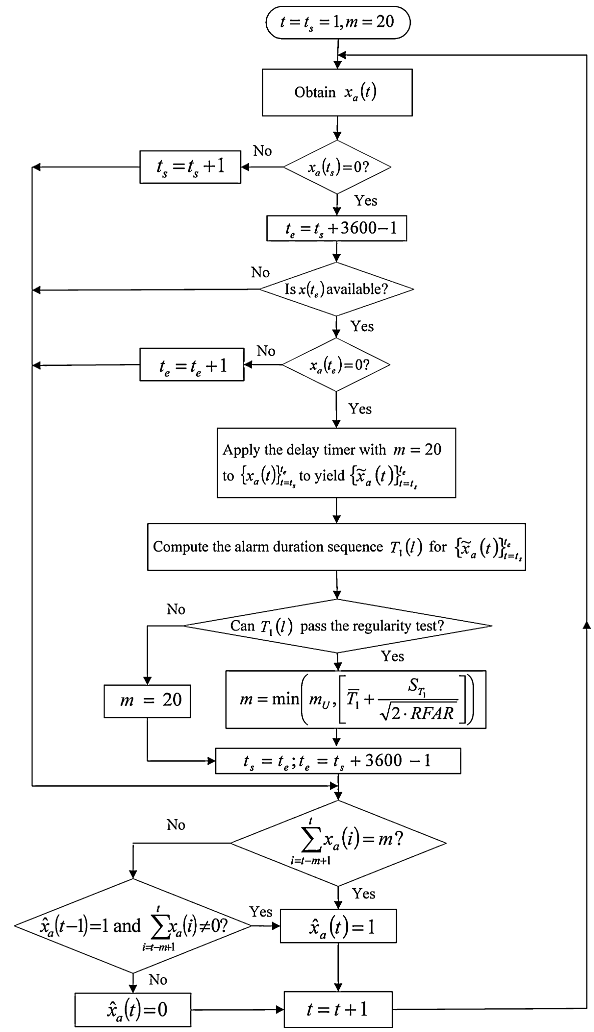

Fig. 5. The flowchart of the proposed online method.

is easy to be verified in practice by looking at the past samples of $x_a(t)$. If Assumption A4 is not hold, then the proposed method is applicable with minor modifications; see Remark 4 presented later in this section.

The proposed method consists of the following steps, shown at the flowchart in Fig. 5.

Step 1. Initialize the factor $m = 20$ for the m-sample delay timer based on Rule 3a, and set the starting position t_s of the most-recent alarm data segment $\{x_a(t)\}_{t=t_s}^{t_e}$ as the current time index t, i.e., $t_s = t$. The alarm data segment acts as the information source used for updating m later in Step 3.

Step 2. Select the time window of the alarm data segment $\{x_a(t)\}_{t=t_s}^{t_e}$ as 1 h, i.e., $t_e = t_s + 3600 - 1$, and check whether the alarm data segment starts and ends with '0'; otherwise, goes to Step 4, since the last sample $x_a(t_e)$ is in the alarm state and more alarm samples are required till the clearance of the alarm state.

Step 3a. If $\{x_a(t)\}_{t=t_s}^{t_e}$ is ready, then apply the delay timer with $m = 20$ to the segment to yield a new set of alarm samples denoted as $\{\tilde{x}_a(t)\}_{t=t_s}^{t_e}$.

Step 3b. Compute the alarm duration sequence $T_1(l)$ in (6) for $\{\tilde{x}_a(t)\}_{t=t_s}^{t_e}$, and perform the regularity test on $T_1(l)$. If the regularity test is passed, then update the factor m as $m = \min(m_U, \overline{T}_1 + S_{T_1}/\sqrt{2 \cdot \text{RFAR}})$, where m_U is the upper bound of m confined by the requirement on the RAAD in Assumption A2, and $\overline{T}_1$ and S_{T_1} are respectively the sample mean and standard deviation of $T_1(l)$. The regularity test and the update of m are defined/clarified at Remarks 2 and 3 respectively later in this section. If the regularity test fails, then there is no need to update $m=20$.

Step 3c. Update the starting and ending positions, i.e., $t_s=t_e$ and $t_e=t_s+3600-1$.

Step 4. Apply the m-sample delay timer to the current alarm sample $x_a(t)$ to yield the alarm signal to be presented to users, denoted as $\hat{x}_a(t)$. Note that the previous samples $x_a(t-m+1), \ldots, x_a(t-1)$ as well as $\hat{x}_a(t-1)$ are required by the delay timer.

Step 5. Wait for the next alarm sample $x_a(t)$ with $t=t+1$ and repeat Steps 2–4.

There are several remarks to be made for the above steps.

Remark 1: In Step 2, the window length of the segment $\{x_a(t)\}_{t=t_s}^{t_e}$ is chosen as 1 h. This choice is based on the following balance. If a smaller window length such as 10 min is used, then larger alarm durations that may pass the regularity test cannot be found in Step 3; on the other hand, if the window length is too large, then the update of m is not prompt enough so that some chattering/repeating alarms may not be removed.

Remark 2: In Step 3b, the regularity test is performed for Rule 3b in order to tell whether the alarm duration is kept constant. The idea of the regularity test is inspired from the oscillation detection methods in Thornhill et al. (2003) and Wang et al. (2013). The coefficient of variation (CV) of the alarm duration sequence $T_1(l)$ is introduced, i.e., $\mathrm{CV} := \sigma_{T_1}/\mu_{T_1}$, where μ_{T_1} and σ_{T_1} are the mean and standard deviation of $T_1(l)$, respectively. A hypothesis test is formulated based on the CV,

$$H_0 : \mathrm{CV} = 1, H_1 : \mathrm{CV} > 1, \tag{11}$$

where H_0 and H_1 represent the null and alternative hypotheses, respectively. Gulhar et al. (2012) compared fifteen confidence intervals for the CV for various population distributions and sample sizes, and recommended the following one, namely, the $(1-\alpha)100\,\%$ confidence interval for CV,

$$\frac{\sqrt{L-1}\hat{\mathrm{CV}}}{\sqrt{\chi^2_{L-1,1-\alpha/2}}} < \mathrm{CV} < \frac{\sqrt{L-1}\hat{\mathrm{CV}}}{\sqrt{\chi^2_{L-1,\alpha/2}}}, \tag{12}$$

where $\hat{\mathrm{CV}} = S_{T_1}/\overline{T}_1$ and $\chi^2_{L-1,\alpha/2}$ is the $100\alpha/2$th percentile of a chi-square distribution with $L-1$ degree of freedom. Here α is a small positive real number, e.g., $\alpha=0.05$. Symbols $\overline{T}_1$ and S_{T_1} respectively stand for the estimates of μ_T and σ_T from the collected samples $\{T_1(l)\}_{l=1}^{L} := \{T_1(1), \ldots, T_1(L)\}$, i.e.,

$$\overline{T}_1 = \frac{1}{L}\sum_{l=1}^{L} T_1(l),\ S_{T_1} = \sqrt{\frac{1}{L-1}\sum_{l=1}^{L}(T_1(l)-\overline{T}_1)^2}. \tag{13}$$

From (11) and (12), if the inequality

$$R_{T_1} := \frac{\sqrt{\chi^2_{L-1,\alpha/2}}}{\sqrt{L-1}S_{T_1}/\overline{T}_1} > 1 \tag{14}$$

holds, then H_0 is rejected with the type-I error equal to α, so that the alarm duration $T_1(l)$ is claimed to be non-constant.

Remark 3: If the alarm duration $T_1(l)$ passes the regularity test, then the factor m of the delay timer needs to be updated according to Rule 3b. The update of m is done as follows. Under Assumption A4, $x_a(t)$ is in the non-alarm state for the majority of time, so that the updated value of m should meet with the requirement on the FAR, i.e.,

$$Pr(T_1(l) > m) \leq \mathrm{RFAR}.$$

With a symmetric distribution of T_1, Chebyshev's inequality is applied to the sequence $T_1(l)$ to yield

$$Pr(T_1 - \mu_{T_1} > \gamma_{T_1}) \leq \frac{\sigma^2_{T_1}}{2\gamma^2_{T_1}}.$$

Thus, γ_{T_1} is obtained as

$$\gamma_{T_1} = \frac{\sigma_{T_1}}{\sqrt{2\cdot\mathrm{RFAR}}},$$

In practice, μ_{T_1} and σ_{T_1} are replaced by their estimates $\overline{T}_1$ and S_{T_1} in (13), respectively. Then, the value of m is updated as

$$m = \min(m_U, \overline{T}_1 + \frac{S_{T_1}}{\sqrt{2\cdot\mathrm{RFAR}}}). \tag{15}$$

Remark 4: If the opposite of Assumption A4 is true, i.e., $x_a(t)$ is in the alarm-state for the majority of time, then the proposed method is applicable with the following minor modifications. First, the alarm data segment in Step 2 should start and end with '1's instead of '0's. Second, the alarm interval sequence $T_0(l)$ in (7) should replace the alarm duration sequence $T_1(l)$ in Step 3b. That is, the regularity test in (14) becomes

$$R_{T_0} := \frac{\sqrt{\chi^2_{L-1,\alpha/2}}}{\sqrt{L-1}S_{T_0}/\overline{T}_0} > 1, \tag{16}$$

where $\overline{T}_0$ and S_{T_0} are the counterparts of $\overline{T}_1$ and S_{T_1} in (13) for $T_0(l)$, respectively; the update of m is made to satisfy the requirement on the MAR, i.e., the counterpart of (15) is

$$m = \min\left(m_U, \overline{T}_0 + \frac{S_{T_0}}{\sqrt{2\cdot\mathrm{RMAR}}}\right).$$

Remark 5: The proposed method has some important differences from our earlier work (Wang and Chen, 2013). First of all, the applicability in broaden to chattering alarms due to random noise and repeating alarms caused by regular patterns such as oscillation, not limited to repeating alarms caused by oscillation. This is owing to a fact that the method in Wang and Chen (2013) is based on the chattering index η in (5), while the proposed method here is on Rules 3a and 3b. Proposition 1 justifies the classification of chattering alarms based on Rule 3a, which overcomes the drawbacks of Rules 1 and 2 that are based on chattering indices (see Section 3). Second, the proposed method is more effective. The update of alarm parameters in the method in Wang and Chen (2013) relies upon the detection of oscillation in the process variable $x(t)$, while the proposed method here performs the regularity test directly on the alarm durations or intervals of the alarm signal $x_a(t)$. As an illustration, consider again $x(t)$ and $x_a(t)$ in Fig. 1. The oscillation behavior of $x(t)$ varies from time to time; in particular, $x(t)$ around [9000, 10,000] s has a different pattern with the rest parts. As a result, no oscillation is detected by the method in Wang and Chen (2013). By contrast, the alarm interval sequence $T_0(l)$ passes the regularity test with the statistics, $\overline{T}_0 = 23.6$, $S_{T_0} = 2.0736$, and $R_{T_0} = 3.9606$, so that the repeating alarms in Fig. 1(b) are successfully detected by Rule 3b.

6. Examples

Three industrial examples are presented here to support Rules 3a and 3b, and to illustrate the effectiveness of the proposed method. The data samples in these examples are collected with the sampling period $h=1$ s at a large-scale thermal power plant at

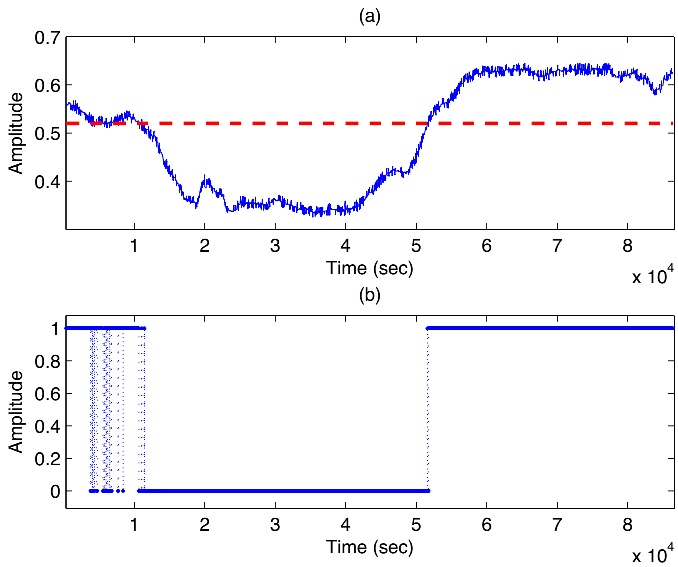

Fig. 6. (a) Process variable $x(t)$ (solid) and its alarm trippoint x_{tp} (dash) and (b) alarm signal $x_a(t)$ in Example 1.

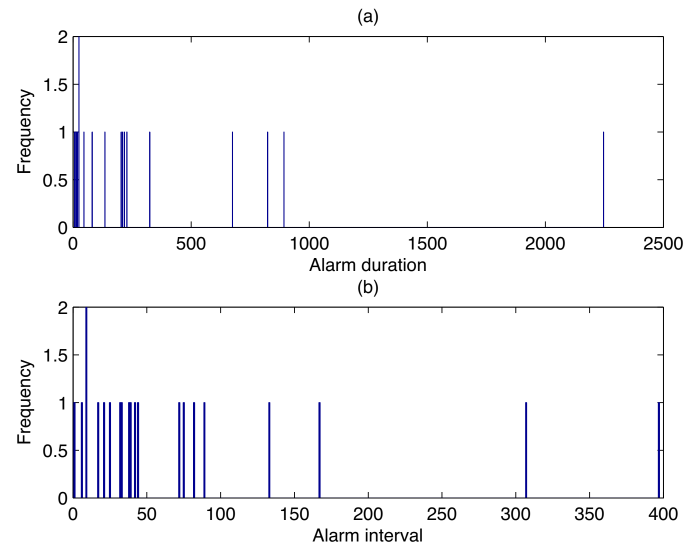

Fig. 7. Histograms of the alarm duration (a) and alarm interval and (b) in Example 1.

Shandong Province in China. The data samples can be downloaded for academic studies on the web.[1]

In the first two examples, the delay timer with $m = 20$ is effective in removing the chattering alarms therein. In addition, the two examples illustrate that it is straightforward to adapt the factor m to the character of signals under study, in order to be more effective in removing chattering alarms or to have a smaller increment of the AAD.

Example 1. The process variable $x(t)$ is the steam pressure inside an inlet pipe to a deaerator, and a high alarm will be raised if $x(t)$ is larger than the alarm trippoint 0.52. The samples of $x(t)$ and $x_a(t)$ are shown in Fig. 6.

Since the total duration for $x_a(t)$ in the alarm-state dominates, i.e., Assumption A4 is invalid, the proposed method is implemented with the modifications mentioned in Remark 4 (Section 5), and the alarm interval is the metric to look at. However, for the purpose of illustration, both the histogram of alarm interval and that of alarm duration are given in Fig. 7. Note for a better view, the large alarm duration 2247 s and the alarm interval 40, 121 s, which are clearly visible in Fig. 6, are not shown in Fig. 7. As the alarm intervals do not pass the regularity test, the factor m is kept with the default choice $m = 20$. By using the delay timer with $m = 20$, the total number of alarms is reduced from 22 in $x_a(t)$ to 12 in $\hat{x}_a(t)$. Here $\hat{x}_a(t)$ is the alarm signal in Step 4 of the proposed method in Section 5, and the number of alarms is equal to the number of '1's in $x'_a(t)$ defined in (2). Fig. 8(b) and (c) compare $x_a(t)$ and $\hat{x}_a(t)$ in the time range involving the chattering alarms.

The time trend of $x(t)$ in Fig. 6 reveals that quite a few chattering alarms, whose alarm duration or interval are larger than 20 s, are raised at the beginning part when the steam pressure is close to the alarm trippoint. Thus, in order to remove these chattering alarms, a larger factor m may be used to adapt to the character of $x(t)$ here. However, the value of m should be confined by the upper bound m_U to meet with the requirement on the AAD. The upper bound m_U can be obtained as follows. Let us take the measurements of $x(t)$ and $x_a(t)$ in the previous 24 h shown in Fig. 9 as the samples required by Assumption A1. By exploiting the method of estimating normal and abnormal distributions in Xu et al. (2012, Section V therein),

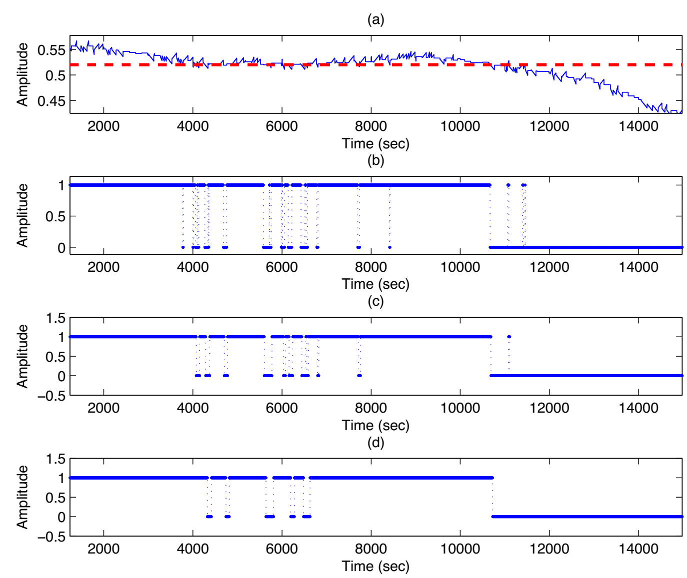

Fig. 8. (a) Process variable $x(t)$ (solid) and its alarm trippoint x_{tp} (dash), (b) alarm signal $x_a(t)$, (c) $\hat{x}_a(t)$ with $m = 20$ and (d) $\hat{x}_a(t)$ with $m = 58$ in Example 1.

the FAR and MAR are estimated as $\hat{q}_1 = 0.1266 \times 10^{-3}$ and $\hat{p}_2 = 0.7582 \times 10^{-3}$, respectively. With the estimated MAR $\hat{p}_2$, the upper bound m_U is readily obtained from (10), e.g., if the requirement on the AAD in Assumption A2 is AAD $\leq$ RAAD = 60 s, then (10) leads to $m_U = 58$. If the delay timer with $m = 58$ is used, then the total number of alarms is reduced from 22 in $x_a(t)$ to 6 in $\hat{x}_a(t)$. Fig. 8(d) presents $\hat{x}_a(t)$ from the delay timer with $m = 58$.

Example 2. The process variable $x(t)$ is the range of measurements from 54 temperature sensors installed at stator outlet pipes for a power generator; a high alarm arises if the temperature range is larger than 8 degrees. Due to the measurement noise aggregation in 54 sensors, the temperature range $x(t)$ contains high-frequency noise components. The alarms in Fig. 10 are raised and cleared quickly for 1117 times in 24 h; see Fig. 1 for a detailed visualization of these signals in 1 h. Fig. 11 presents the number of alarms per hour and the histogram of the alarm durations. All the 1117 alarm durations are less than 6 s – a short period that power plant

[1] http://www.mech.pku.edu.cn/robot/teacher/wangjiandong/research.htm.

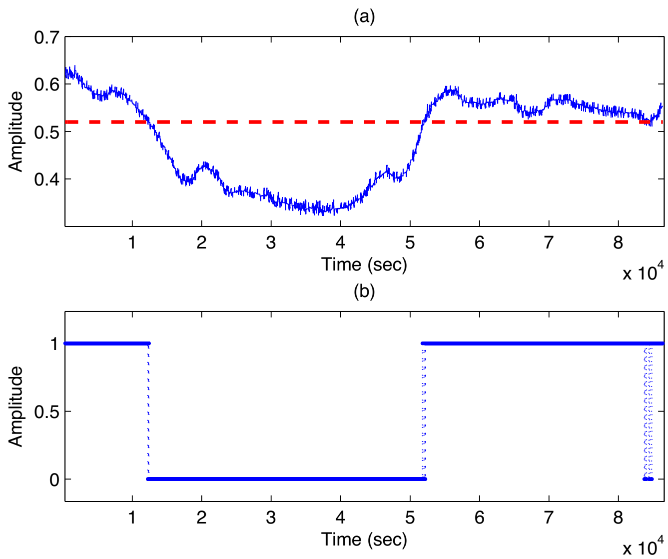

Fig. 9. Measurements of $x(t)$ (a) and $x_a(t)$ (b) in the previous 24 h for Example 1.

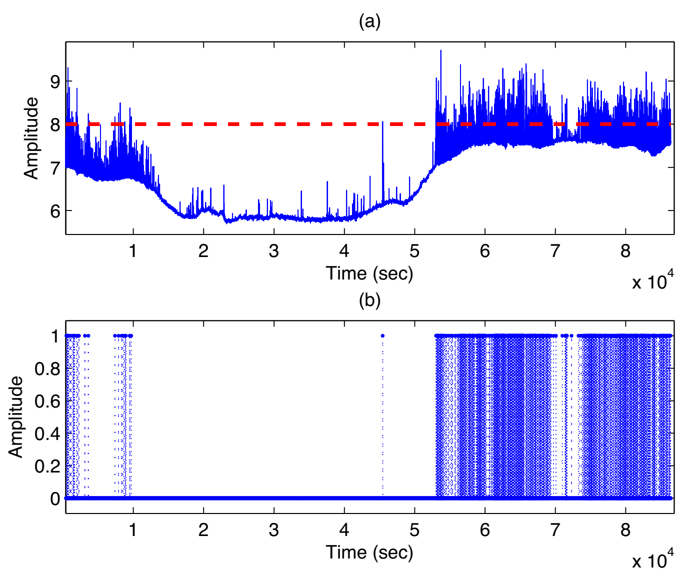

Fig. 10. (a) Process variable $x(t)$ (solid) and alarm trippoint x_{tp} (dash) and (b) alarm signal $x_a(t)$ in Example 2.

operators cannot make any response. Hence, according to Rule 3a, all the 1117 alarms are regarded as chattering, and can be removed via the m-sample delay timer with the default choice $m = 20$. Since the fluctuation in $x(t)$ is with high frequencies and all the alarm durations are less than 6 s, a much smaller factor $m = 6$ could be used in order to have a smaller value of the AAD.

The next example demonstrates that the proposed method can promptly detect the regularity of alarm durations or intervals so that the factor m is updated accordingly. Chattering and repeating alarms are present simultaneously here, and are removed successfully by m-sample delay timer.

Example 3. The process variable $x(t)$ is the water level in a low-pressure heater depicted in Fig. 12. If the level is higher than 38 mm, a high alarm arises. Fig. 13 presents the samples of the water level and its alarm signals in 24 h; see also Fig. 2 for a detailed visualization of these signals in 1 h.

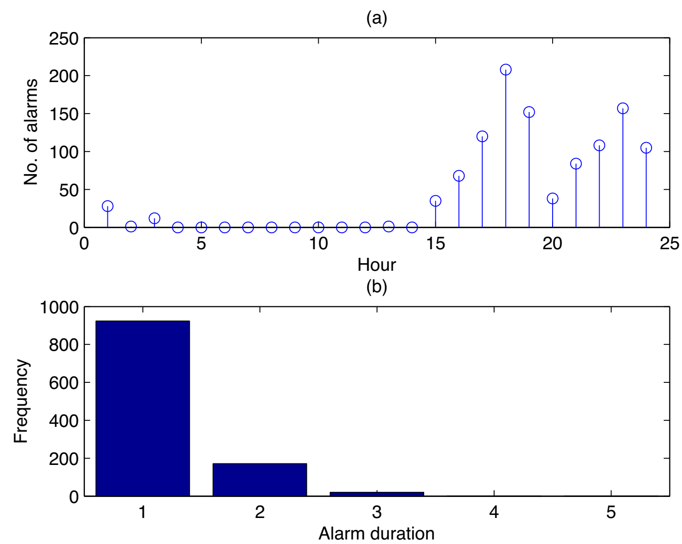

Fig. 11. (a) Number of alarms per hour and (b) histogram of the alarm duration in Example 2.

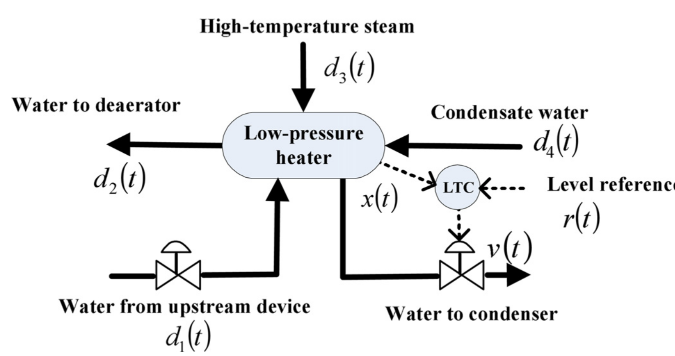

Fig. 12. Diagram of low-pressure heaters for Example 3.

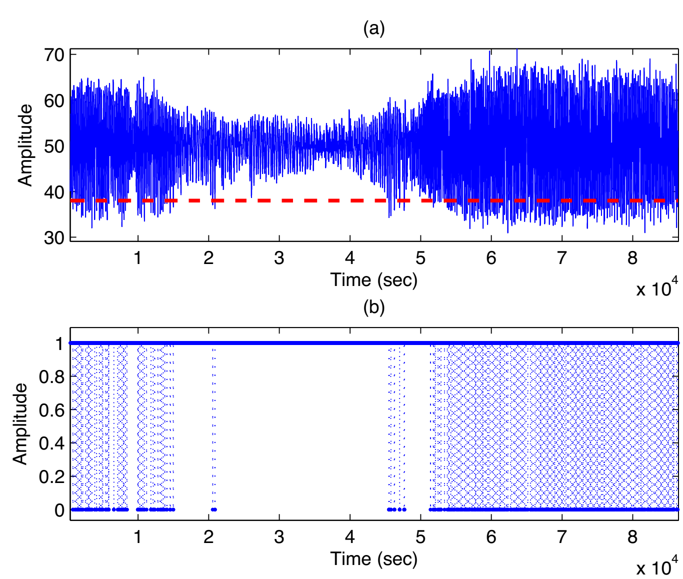

Fig. 13. (a) Process variable $x(t)$ (solid) and its alarm trippoint x_{tp} (dash) and (b) alarm signal $x_a(t)$ in Example 3.

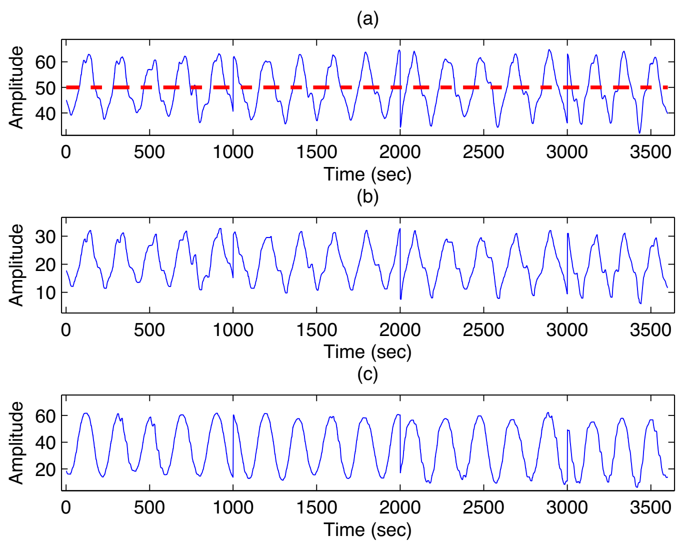

Fig. 14. Signals in the level control loop: (a) the water level $x(t)$ (solid), the setpoint (dash), (b) the control valve opening $v(t)$ and (c) the control valve opening $d_1(t)$.

The water level $x(t)$ is oscillatory due to the fluctuation of an inlet water flow from the upstream device, controlled by a control valve's opening $d_1(t)$ in Fig. 12. The water level $x(t)$ is under a feedback control with the controller denoted by LTC in Fig. 12, so that a control valve responses automatically to the level oscillation by varying the outlet flow. Fig. 14 presents 1-h measurements of the variables in the level control loop, namely, the water level $x(t)$, the level reference $r(t)$, and the control valve opening $v(t)$, as well as the oscillatory inlet valve opening $d_1(t)$. The other related variables $d_2(t)$, $d_3(t)$ and $d_4(t)$ of the heater in Fig. 12 are almost constant and are not presented here. It is clear that no operator response is made for the alarms associated with $x(t)$; thus, they are nuisance alarms. As a matter of facts, these nuisance alarms have been present for more than 6 months ever since the power plant is in operation.

Since the water level is above the alarm trippoint 38 mm for the majority of the time (i.e., Assumption A4 is invalid), the alarm interval T_0, instead of the alarm duration T_1, is the information source to update the factor m of the delay timer, and the proposed method

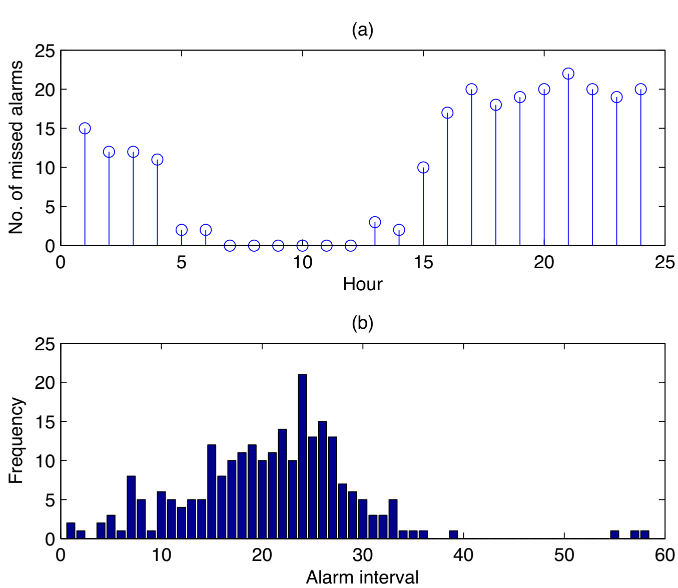

Fig. 15. (a) Number of alarms per hour and (b) histogram of the alarm intervals in Example 3.

Table 1
Results of the proposed method for Example 3.

$x_a(t)$	N_{x_a}	$N_{\hat{x}_a}$	$N_{\tilde{x}_a}$	$\overline{T}_0$	S_{T_0}	R_{T_0}	m
1	15	4	4	24.7500	2.5000	2.6552	20
2	12	1	8	25.7500	3.3700	3.7542	33
3	12	0	8	24.3750	3.9256	3.0508	36
4	11	0	8	27.0000	3.7417	3.5455	37
5	2	1	1	39.0000	0	NaN	39
6	2	1	1	33.0000	0	NaN	20
7	0	0	0	NaN	NaN	NaN	20
8	0	0	0	NaN	NaN	NaN	20
9	0	0	0	NaN	NaN	NaN	20
10	0	0	0	NaN	NaN	NaN	20
11	0	0	0	NaN	NaN	NaN	20
12	0	0	0	NaN	NaN	NaN	20
13	3	3	3	49.3333	14.1539	0.5546	20
14	2	2	2	45.5000	13.4350	0.1061	20
15	10	1	1	27.0000	0	NaN	20
16	17	6	6	20.6667	0.8156	10.3202	20
17	20	7	8	24.2500	3.1053	3.8370	23
18	18	0	15	24.4667	2.9729	5.2184	34
19	19	0	15	26.3571	3.2959	4.9639	34
20	20	0	14	25.2143	2.6070	6.0033	37
21	22	1	16	25.2667	4.0083	3.9969	33
22	20	0	14	24.7143	2.8937	5.3013	38
23	19	1	12	25.7500	3.8406	3.9489	34
24	20	0	7	26.8571	4.5617	2.6736	38

is implemented with the modifications mentioned in Remark 4 (Section 5). Fig. 15 presents the number of alarms per hour and the histogram of the alarm interval of $x_a(t)$ in Fig. 13. There are 244 alarms in 24 h, among which 101 alarms have the alarm intervals less than 20 s, and many other alarms with intervals larger than 20 s are caused by oscillations. The proposed online method is applied, with the detailed results for each data segment listed in Table 1, where N_{x_a}, $N_{\hat{x}_a}$ and $N_{\tilde{x}_a}$ are the number of alarms in $x_a(t)$, $\hat{x}_a(t)$ and $\tilde{x}_a(t)$, respectively. Here $\tilde{x}_a(t)$ and $\hat{x}_a(t)$ are defined in Steps 3a and 4 in Section 5, respectively; see also Fig. 5. In Table 1, the statistics R_{T_0} is defined in (16), and $\overline{T}_0$ and S_{T_0} are the sample mean and standard deviation for $T_0(l)$, respectively. Table 1 shows that the regularity of the alarm interval is promptly detected, and the factor m is updated in the way consistent with the variation of alarm intervals. The total number of alarms is reduced from 244 in $x_a(t)$ to 28 in $\hat{x}_a(t)$ by the proposed method. By contrast, if only the delay timer with $m = 20$ were used, the total number of alarms in $\tilde{x}_a(t)$ would be 143.

7. Conclusion

The paper formulated two rules, namely, Rules 3a and 3b, to detect the presence of chattering and repeating alarms, based on alarm durations and intervals. The two rules were shown to be capable of overcoming the drawbacks of the existing chattering indices that are based on the run lengths of alarms. An online method, as shown by the flowchart in Fig. 5, was proposed to remove chattering and repeating alarms by exploiting the m-sample delay timer, subject to the requirements on the FAR, MAR and AAD. The proposed method can handle chattering alarms caused by random noises and repeating alarms by more regular patterns such as oscillation. The effectiveness of the proposed method was illustrated via three industrial examples.

References

Ahmed K, Izadi I, Chen T, Joe D, Burton T. Similarity analysis of industrial alarm flood data. IEEE Trans Autom Sci Eng 2013;10:452–7.

Bransby ML, Jenkinson J. The management of alarm systems. Sheffield: Health and Safety Executive; 1998.

Burnell E, Dicken CR. Handling of repeating alarms. London: IEE Colloquium on Stemming the Alarm Flood; 1997.

EEMUA-191. Alarm systems – a guide to design, management and procurement, Version 2. London: EEMUA (Engineering Equipment and Materials Users' Association); 2007.

Gulhar M, Kibria BMG, Albatineh AN, Ahmed NU. A comparison of some confidence intervals for estimating the population coefficient of variation: a simulation study. Stat Oper Res Trans 2012;36:45–68.

Hollifield B, Habibi E. The alarm management handbook. 2nd ed. Houston: PAS; 2010.

Hugo AJ. Estimation of alarm deadbands. In: Proceedings the 7th IFAC SAFEPROCESS; 2009.

ISA-18.2. Management of alarm systems for the process industries. North Carolina: ISA (Instrumentation, Systems & Automation Society); 2009.

Kondaveeti S, Izadi I, Shah SL, Shook D, Kadali R, Chen T. Quantification of alarm chatter based on run length distributions. Chem Eng Res Des 2013;91:2550–8.

Naghoosi E, Izadi I, Chen T. Estimation of alarm chattering. J Process Control 2011;21:1243–9.

Rothenberg D. Alarm management for process control. New Jersey: Momentum Press; 2009.

Thornhill NF, Huang B, Zhang H. Detection of multiple oscillations in control loops. J Process Control 2003;13:91–100.

Wang J, Huang B, Lu S. Improved DCT-based method for online detection of oscillations in univariate time series. Control Eng Pract 2013;21:622–30.

Wang J, Chen T. An online method for detection and reduction of chattering alarms due to oscillation. Comput Chem Eng 2013;54:140–50.

Xu J, Wang J, Izadi I, Chen T. Performance assessment and design for univariate alarm systems based on FAR, MAR and AAD. IEEE Trans Autom Sci Eng 2012;9:296–307.