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# Online reduction of chattering alarms due to random noise and oscillation ⋆

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**Abstract:** Chattering alarms repeatedly make transitions between alarm and non-alarm states without response from operators, and severely deteriorate the performance of industrial alarm systems. Two rules are formulated based on the metrics of alarm durations and intervals to detect chattering alarms caused by random noise and oscillation. An online method is proposed to reduce the number of the chattering alarms via delay timers. Industrial examples are provided to illustrate the effectiveness of the formulated rules and the proposed method.

## 1. INTRODUCTION

Alarm systems are crucial assets of modern industrial plants to improve process safety and efficient operation. However, the current performance of alarm systems is far below industrial standards such the well-accepted ISA 18.2 standard [7]. In particular, the averaged and peak numbers of alarms are excessively high, so that industrial plant operators cannot handel the alarms promptly [1][10].

One of main reasons causing the excessive numbers of alarms is the presence of chattering alarms, which are the alarms that repeatedly make transitions between alarm and non-alarm states without operators' response. Chattering alarms, accounting for around 50% of the alarm annunciations, perhaps are the most common forms of nuisance alarms [3].

Chattering alarms, as well as the closely-related repeating alarms and fleeting alarms, have received an increasing attention. Burnell & Dicken [2] used an auto-shelving facility and changed the alarm display list to handle repeating alarms. Bransby & Jenkinson [1] (Appendix 10 therein) and EEMUA-191 [3] (Appendix 9 therein) exploited the filtering, deadband, delay timer, and shelving to remove repeating and fleeting alarms. Hugo [6] designed adaptive alarm deadbands to reduce the number of chattering alarms. Kondaveeti *et al.* [8] devised a chattering index to quantify the degree of chattering alarms based on the run lengths of alarms. The index was estimated by Naghoosi *et al.* [9] based on statistical properties of process variables. Wang & Chen [12] revised the chattering index and proposed an online method to detect and remove the chattering alarms due to oscillation.

This paper is a continuing study of our previous work [12], motivated by two drawbacks revealed in applying the chattering indices in [8][12] to some industrial alarm signals. First, the rate of missing detection sometimes is large, because the chattering indices are essentially weighted averages and are based on alarm run lengths that are not good measures of chattering alarms. Second, the chattering indices can only indicate the presence or absence of chattering alarms in collected alarm samples, but cannot tell which alarm sample is chattering.

This paper has two main contributions.

- Two rules are formulated to detect the chattering alarms, based on the alarm durations and intervals. The two rules resolve the above-mentioned two drawbacks of the existing chattering indices in [8][12] that are based on the weighted averages of alarm run lengths.
- A novel online method is proposed to remove the chattering alarms due to random noise and oscillation, by exploiting the two 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).

The proposed method makes significant improvements over the method in our earlier work [12]. First, the applicability is broaden to chattering alarms due to random noise and oscillation, while the method in [12] is limited to the chattering alarms caused by oscillation. Second, the proposed method is more effective, because it is based new rules in detection of chattering alarms, and looks directly at the regularity of some metrics of alarm signals, while the method in [12] is based on the revised chattering index suffering from the above-mentioned drawbacks and takes an indirect approach by detecting the oscillation in process signals in the first place.

The rest of the paper is organized as follows. Section 2 reviews the two chattering indices and formulates two rules to detect chattering alarms. The proposed online method is presented in Section 3, and its effectiveness is illustrated via industrial examples in Section 4. Section 5 concludes the paper.

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## 2. DETECTION OF CHATTERING ALARMS

This section discusses the definition of chattering alarms, and the drawbacks of the existing chattering indices. Next, two novel rules are formulated to detect chattering alarms.

### *2.1 Definition of chattering alarms*

The industrial standard ISA-18.2 [7] says "a chattering alarm repeatedly transitions between the alarm state and the normal state in a short period of time." Synonyms of a chattering alarm are the repeating and fleeting alarms, which are respectively defined as "the same alarm raising and clearing repeatedly over a period of time" and as "the alarms which are raised and cleared shortly afterwards" from an industrial guide EEMUA-191 [3].

These definitions contain some vagueness that comes from the uncertainty of the short period of time that a chattering alarm is raised and cleared. ISA-18.2 [7] and Hollifield & Habibi [5] 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 sec. Rotherberg [10] define 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 sec for chattering alarm, and 90 sec for repeating alarms. The alarms being activated and cleared within such a short period of 6 sec, 20 sec or even 90 sec, which are usually too short for operators taking action and adjusting the process to clear alarms, are very likely to be nuisance alarms, and are regarded as chattering alarms.

### *2.2 Chattering indices and their drawbacks*

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

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

The run length, denoted as $r$, is defined as

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

where

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

The chattering index proposed by Kondaveeti *et al.* [8] 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 $r$. A cutoff threshold of $\psi$ is 0.05 alarms/sec, determined by a rule of thumb from ISA-18.2 standard that alarms repeating more than three times per minute are considered chattering.

*Rule 1 [8]. 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 in [12],

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

where $N$ is the data length of $x'_a(t)$ in (2). The cutoff threshold $\eta = 0.005$ is based on the same rule of thumb from ISA-18.2 standard that three alarms caused by oscillation are evenly spread in one minute.

*Rule 2 [12]. Chattering alarms due to oscillation are claimed to be present when* $\eta \geq 0.005$.

Both $\psi$ in (4) and $\eta$ in (5) have been demonstrated to be the valid measures of chattering alarms in some industrial examples; however, the indices have the following drawbacks. First, as weighted averages, the indices may miss the detection of chattering alarms. As a simple example, if there are two alarm run lengths 21 sec and 20 sec, then $\psi = 0.0488$ so that Rule 1 detects no chattering alarms. If the two run lengths are equal to 20 sec, then a controversial conclusion is obtained from Rule 1. Second, the run length is not a good measure of chattering alarms. For instance, if an alarm rises up and disappears in a short period, and another similar alarm occurs again after a rather long time, then the run length will be quite large and these types of alarms cannot be detected as chattering ones (see Fig. 2 appeared later for an example). Finally, both indices only tell if a set of collected alarm samples contains chattering alarms, but cannot pinpoint the location of chattering alarms. In the process of removing chattering alarms, it is necessary to tell which one is the chattering alarm and thus should be removed.

### *2.3 Two rules to detect chattering alarms*

In this subsection, two rules are formulated to detect chattering alarms based on two metrics, namely, the alarm duration and the alarm interval. 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

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

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

$$x_a(t_1 - 1) = 1,\ x_a(t_2 + 1) = 1,$$

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

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 $\psi$ in (4) is always smaller than $1/r_0$, and the revised chattering index $\eta$ 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 $\psi$ in (4) and $\eta$ in (5) as well as Rules 1 and 2 to detect the chattering alarms. All the chattering 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 $r_0 = 1/0.05 = 20$ sec. However, the converse statement is not true, namely, some chattering alarms with run lengths less than 20 sec may be missed by Rules 1 and 2 that are based on the averaged statistics $\psi$ and $\eta$, respectively.

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

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

Rule 3a is a hard classification of chattering alarms. The threshold 20 sec is based on the same rule of thumb from ISA-18.2 standard used for Rules 1 and 2. The threshold 20 sec can be regarded as a default choice, and could be adapted to the character of alarm signals; see Example 1 in Section 4 for illustration.

To accommodate with the chattering alarms caused by 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 chattering 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 chattering. A regularity test will be presented later in Section 3 to perform a statistical test on whether $T_1$ or $T_0$ is a constant.

## 3. REDUCTION OF CHATTERING ALARMS

This section proposes an online method to reduce the number of chattering alarms by exploiting the $m$-sample delay timer.

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). 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.

If $x_a(t)$ is an independent and identically distributed (IID) sequence, the FAR, MAR and AAD for the $m$-sample delay timer are [13],

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

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

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

where $q_1$ and $p_2$ respectively are the FAR and MAR for the case that no delay timer is used, and $p_1 := 1 - p_2$ and $q_2 := 1 - q_1$.

Based on Rules 3a and 3b, the factor $m$ of the delay timer is selected as $m = 20$ or another larger value. The chattering alarms with alarm duration or interval less than $m$ sec are removed by using the $m$-sample delay timer. Hence, the FAR or MAR will be reduced significantly. Meanwhile, the increment of AAD needs to be controlled. Eq. (10) implies that the AAD does not deviate 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 $p_2$.

It is ready to propose the online method, by assuming the following assumptions:

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 except the deterministic components that it may contain.
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).

The proposed method consists of the following steps.

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., $t_s = t$.

Step 2. Select the time window of the alarm data segment $\{x_a(t)\}_{t=t_s}^{t_e}$ as one hour, 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 to wait for more alarm samples 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 in Remark #1 on $T_1(l)$. If the regularity test is passed, then update the factor $m$ as

$$m = \min\left(m_U, \bar{T}_1 + \frac{S_{T_1}}{\sqrt{2 \cdot \mathrm{RFAR}}}\right), \tag{11}$$

where $m_U$ is the upper bound of $m$ confined by the requirement on the RAAD in Assumption A2, and $\bar{T}_1$ and $S_{T_1}$ are respectively the sample mean and standard deviation of $T_1(l)$. 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 $x_a(t-m+1), \cdots, x_a(t-1)$ 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 3b, the regularity test is performed to tell whether the alarm duration is kept constant. The idea of the regularity test is inspired from the oscillation detection methods proposed by Thornhill *et al.* [11]. The coefficient of variation (CV) of the alarm duration sequence $T_1(l)$ is introduced, i.e., $CV := \sigma_{T_1}/\mu_{T_1}$, where $\mu_{T_1}$ and $\sigma_{T_1}$ are the mean and standard deviation of $T_1(l)$, respectively. A hypothesis test is formulated based on the CV,

$$H_0 : CV = 1, H_1 : CV > 1, \tag{12}$$

where $H_0$ and $H_1$ represent the null and alternative hypotheses, respectively. The $(1-\alpha)\,100\%$ confidence interval for $CV$ is [4],

$$\frac{\sqrt{L-1}\hat{CV}}{\sqrt{\chi^2_{L-1,1-\alpha/2}}} < CV < \frac{\sqrt{L-1}\hat{CV}}{\sqrt{\chi^2_{L-1,\alpha/2}}}, \tag{13}$$

where $\hat{CV} = S_{T_1}/\bar{T}_1$ 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 $\alpha$ is a small positive real number, e.g., $\alpha = 0.05$. Symbols $\bar{T}_1$ and $S_{T_1}$ respectively stand for the estimates of $\mu_T$ and $\sigma_T$ from the collected samples $\{T_1(l)\}_{l=1}^{L} := \{T_1(1), \cdots, T_1(L)\}$, i.e.,

$$\bar{T}_1 = \frac{1}{L}\sum_{l=1}^{L} T_1(l), \quad S_{T_1} = \sqrt{\frac{1}{L-1}\sum_{l=1}^{L}\left(T_1(l) - \bar{T}_1\right)^2}. \tag{14}$$

From (12) and (13), if the inequality

$$R_{T_1} := \frac{\sqrt{\chi^2_{L-1,\alpha/2}}}{\sqrt{L-1}S_{T_1}/\bar{T}_1} > 1 \tag{15}$$

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

*Remark #2:* If the alarm duration $T_1(l)$ passes the regularity test, then the factor $m$ of the delay timer needs to be updated 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.,

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

Applying Chebyshev's inequality to $T_1(l)$ yields

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

Thus, $\gamma_{T_1}$ is obtained as

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

In practice, $\mu_{T_1}$ and $\sigma_{T_1}$ are replaced by their estimates $\bar{T}_1$ and $S_{T_1}$ in (14), respectively. Then, the updating equation of $m$ is obtained as (11).

*Remark #3:* 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 (15) becomes

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

where $\bar{T}_0$ and $S_{T_0}$ are the counterparts of $\bar{T}_1$ and $S_{T_1}$ in (14) for $T_0(l)$, respectively; the update of $m$ is made to satisfy the requirement on the MAR, i.e., the counterpart of (11) is

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

## 4. EXAMPLES

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

**Example 1.** This example illustrates that the delay timer with $m = 20$ is effective in removing the chattering alarms therein, and it is straightforward to adapt the factor $m$ to the character of signals under study, in order to have a smaller increment of the AAD.

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. The alarms in Fig. 1 are raised and cleared quickly for 1117 times in 24 hours; see Fig. 2 for a detailed visualization of these signals

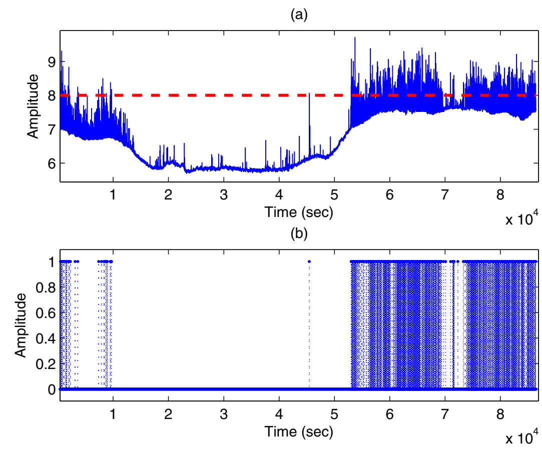


Fig. 1. (a) process variable $x(t)$ (solid) and alarm trippoint $x_{tp}$ (dash), (b) alarm signal $x_a(t)$ in Example 1

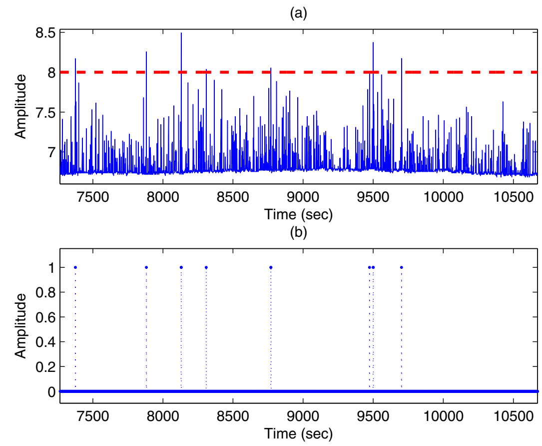


Fig. 2. (a) process variable $x(t)$ (solid) and alarm trippoint $x_{tp}$ (dash), (b) alarm signal $x_a(t)$ in 1 hour for Example 1

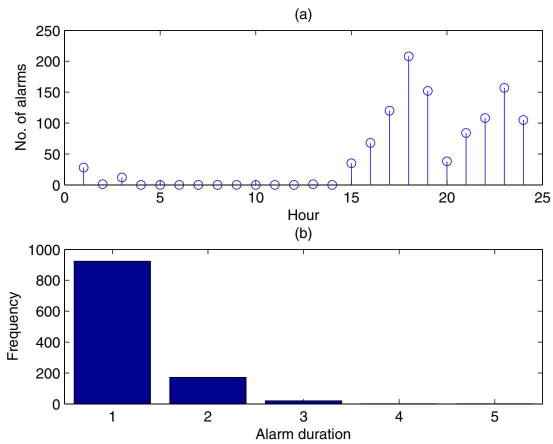


Fig. 3. (a) number of alarms per hour, (b) histogram of the alarm duration in Example 1

in 1 hour. Fig. 3 presents the number of alarms per hour and the histogram of the alarm durations. All the 1117 alarm durations are less than 6 sec. Hence, according to Rule 3a, all the 1117 alarms are regarded as chattering,

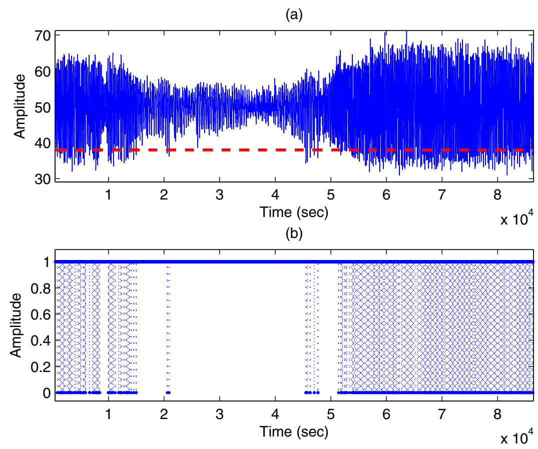


Fig. 4. (a) process variable $x(t)$ (solid) and its alarm trippoint $x_{tp}$ (dash), (b) alarm signal $x_a(t)$ in Example 2

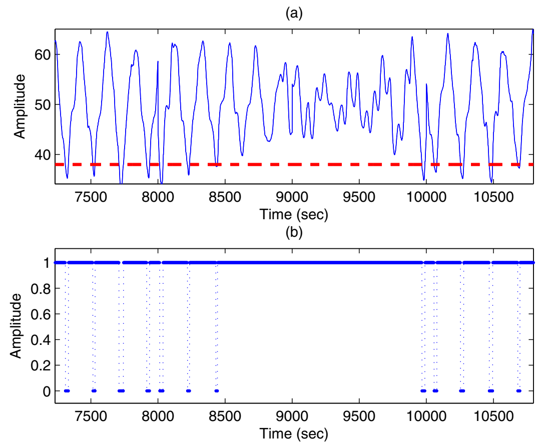


Fig. 5. (a) process variable $x(t)$ (solid) and its alarm trippoint $x_{tp}$ (dash), (b) alarm signal $x_a(t)$ in 1 hour for Example 2

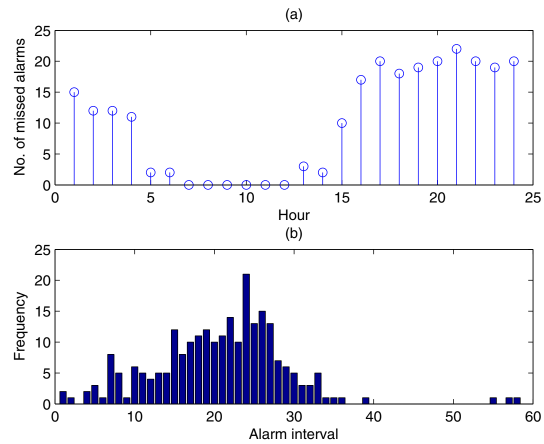


Fig. 6. (a) number of alarms per hour, (b) histogram of the alarm intervals in Example 3

and can be removed via the $m$-sample delay timer with the default choice $m = 20$. Since all the alarm durations are less than 6 sec, a much smaller factor $m = 6$ could be used in order to have a smaller value of the AAD.

**Example 2.** The example demonstrates that the proposed method can promptly detect the regularity of alarm durations or intervals so that the factor $m$ of delay timers is updated accordingly to reduce the number of chattering alarms due to oscillation.

The process variable $x(t)$ is the water level in a low-pressure heater. If the level is higher than 38 mm, a high alarm arises. Fig. 4 presents the samples of the water level and its alarm signals in 24 hours; see also Fig. 5 for a detailed visualization of these signals in 1 hour. No operator response is made for the alarms associated with $x(t)$; thus, these alarms are chattering. As a matter of facts, these chattering 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 is implemented with the modifications mentioned in Remark #3 (Section 3). Fig. 6 presents the number of alarms per hour and the histogram of the alarm interval of $x_a(t)$ in Fig. 4. There are 244 alarms in 24 hours, among which 101 alarms have the alarm intervals less than 20 sec. The oscillation causes many alarms with intervals larger than 20 sec. 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 $\hat{x}_a(t)$ and $\tilde{x}_a(t)$ are defined in Steps 3a and Step 4 in Section 3, respectively. The statistics $R_{T_0}$ is defined in (16), and $\bar{T}_0$ 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 the delay timer with $m = 20$ were used for 24 hours without updating, the total number of alarms in $\tilde{x}_a(t)$ would be 143.

Table 1. Results of the proposed method for Example 3

| $x_a(t)$ | $N_{x_a}$ | $N_{\hat{x}_a}$ | $N_{\tilde{x}_a}$ | $\bar{T}_0$ | $S_{T_0}$ | $R_{T_0}$ | $m$ |
|---|---|---|---|---|---|---|---|
| 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 |

## 5. CONCLUSION

Rules 3a and 3b were formulated to detect chattering alarms caused by random noise and oscillation, based on alarm durations and intervals. The two rules are capable of overcoming the drawbacks of the existing chattering indices that are based on the run lengths of alarms. With the consideration on the FAR, MAR and AAD, an online method was proposed to reduce the number of chattering alarms by exploiting the $m$-sample delay timer. The effectiveness of the proposed method was illustrated via two industrial examples.

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