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Main causes of long-standing alarms and their removal by dynamic state-based alarm systems☆

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A B S T R A C T

Long-standing alarms are those in the alarm state continuously for a long period of time. Some long-standing alarms belong to nuisance alarms, playing a detrimental role to the performance of industrial alarm systems, and hence they should be removed. The paper analyzes the main causes leading to long-standing alarms as nuisance ones; industrial examples from a large-scale thermal power plant are provided as supportive evidences of the main causes. A dynamic state-based alarm system is designed to remove long-standing alarms caused by the inconsistency between the alarm design and discrete-valued operating states. The design is based on two rules formulated to select state variables and a novel alarm generation mechanism to generate state-based alarm variables. Industrial case studies illustrate the effectiveness of the dynamic state-based alarm system in significantly reducing the severity of long-standing alarms.

1. Introduction

An industrial alarm system is the collection of hardware and software that generates, records and communicates alarm states to operators (ISA, 2009). Alarm systems are the safeguards to prevent the deterioration of near misses to accidents. As implied by the safety pyramid in Fig. 1, almost every accident is associated with a number of near misses as precursors. Alarm systems are the tools for industrial plant operators to promptly detect the occurrences of near misses and take corrective actions to drive processes back to normal operating ranges. Retrospective investigation on a large number of accidents also support the importance of alarm systems for the safety of industrial plants. For instance, in the final report of the Buncefield accident (HSE, 1997, 2008), which is by far the most severe industrial accident in Europe, the 8th recommendation was to develop high-high level alarms for oil overfill prevention, and the 23rd recommendation was to collect accident data to find the defects of the installed alarm system. Therefore, industrial alarm systems have been well recognized as the critical assets for process safety of modern industrial plants in many industries such as power, chemical, oil-gas, petrochemical, and pulp and paper (Bransby and Jenkinson, 1998; Macdonald, 2004; Rothenberg, 2009; Pariyani et al., 2010; Stauffer and Clarke, 2016).

Despite the importance of alarm systems, industrial surveys showed that industrial alarm systems often suffered from poor performance in terms of having too many alarms to be promptly handled by industrial plant operators (Bransby and Jenkinson, 1998; Rothenberg, 2009). This phenomenon of alarm overloading is clearly revealed from Table 1 (Rothenberg, 2009), which is based on a study of 39 industrial plants ranging from oil and gas, petrochemical, and power industries. The statistics of performance metrics such average alarms per day are much larger than the benchmarks from the Engineering Equipment and Materials Users' Association (EEMUA).

The occurred alarms include an excessive large number of nuisance alarms that are not associated with any abnormalities so that no corrective actions are required from industrial plant operators. By contrast to the nuisance alarm, an informative alarm does require operators to take some corrective action; otherwise, abnormalities associated with informative alarms would have negative effects on operation safety and/or efficiency. Nuisance alarms is extremely detrimental to the important role played by alarm systems. Due to "cry wolf" effect, operators do not trust alarm systems and are very likely to miss informative alarms that are buried

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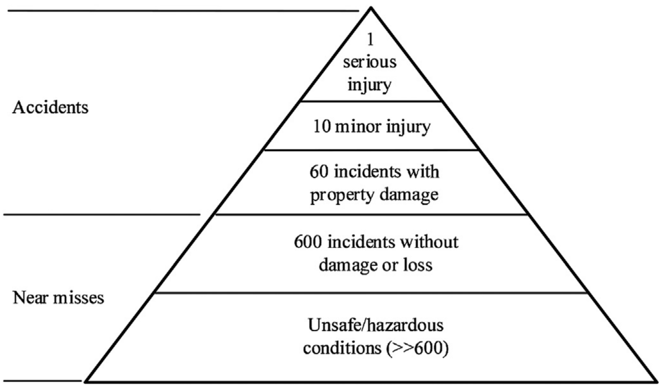

Fig. 1. Safety pyramid with typical historical data Pariyani et al. (2010).

Table 1
Cross-industry study Rothenberg (2009).

	EEMUA	Oil-gas	PetroChem	Power
Average alarms/day	144	1200	1500	2000
Peak alarms/10 min	10	220	180	350
Average standing alarms/day	9	50	100	65

among a large amount of nuisance alarms. In order to remove nuisance alarms and achieve desired performance benchmarks, ANSI/ISA-18.2 presented ten stages for an alarm management lifecycle, namely, alarm philosophy, identification, rationalization, detailed design, implementation, operation, maintenance, monitoring and assessment, management of change, and audit (ISA, 2009).

Long-standing alarms are the ones continuously remaining in the alarm state for a long period of time, e.g., 24 h. As clarified later in Section 3, many long-standing alarms are the nuisance ones, so that they are culprits for poor performance of industrial alarm systems. For the long-standing alarms that do not belong to nuisance alarms, they have to be checked and understood regularly, so that operators are aware of the ongoing abnormal situations causing the long-standing alarms. Thus, the long-standing alarms being nuisance ones add extra workloads to operators; as a result, the operators may overlook the ongoing abnormal situations if the number of long-standing alarms is large. For example, an emergency shutdown of a power generation unit occurred at 23:49:13 on January 24, 2014 at a large-scale thermal power plant in Shandong Province in China; during the incident, there were 348 alarm variables in the alarm state, among which 96 alarm variables had been continuously in the alarm state for more than 24 h. Therefore, ANSI/ISA-18.2 imposed a performance metric that "there should be less than five long-standing alarms on any given day, with action plans to address them" (ISA, 2009). EEMUA-191 required a usability metric that the average number of long-standing alarms per day is no larger than nine as given in Table 1 (EEMUA, 2013).

There are very few methods in handling long-standing alarms, despite a well recognition of their importance in practice. The industrial standard ANSI/ISA-18.2 stated that logic, programmatic, or state-based methods could be used to eliminate long-standing alarms (ISA, 2009). The guide EEMUA-191 suggested the usage of a maintenance shelf or one-shot shelving to deal with long-standing alarms (EEMUA, 2013). Hollifield and Habibi (2010) and Jerhotova et al. (2013) mentioned the implementation of some logic or state-based alarm methodologies, especially for shutdown states. Kim (1994), Hatch (2005), Arjomandi and Salahshoor (2011) and Beebe et al. (2013) recommended state-based alarming based on different operation modes such startup, shutdown, full-rate and half-rate modes. However, no technical details were provided in these references. One possible reason for the shortage of related studies is that the state-based alarming seems rather straightforward, e.g., if the device is in the shutdown state, then the alarm is turned off; however, such an intuitive design is associated with a serious flaw that mistakenly ignores the previous status of alarm variables (to be clarified later in Example 4). There are also some related works on the design of alarm systems based on different process states, but they are not specific for handling the long-standing alarms. Ghetie et al. (1998) used multiple binary decisions to generate an alarm signal with five states. Nihlwing and Kaarstad (2012) designed a state-based alarm system for the Halden Boiling Water Reactor Simulator, based on a number of well-defined process states, in order to detect the secondary disturbances earlier and more often. Ragsdale et al. (2012) showed that operators performed better and had more trust in three-state alarms ('OK', 'Warning', 'Alarm') than two-state alarms ('OK', 'Alarm'). Zhu et al. (2014a) obtained dynamic alarm trippoints depending upon multiple steady states and transitions between these states. Blaauwgeers et al. (2013) and Zhu et al. (2014b) recommended using dynamic alarm priorities for different process states and operational scenarios.

This paper presents two main contributions on the study of long-standing alarms. First, three main causes of long-standing alarms are identified, with a focus on those leading long-standing alarms to nuisance ones. Industrial examples are provided as supportive evidences of the identified causes. Second, a dynamic state-based alarm system is designed to remove long-standing alarms caused by the inconsistency between the alarm design and discrete-valued operating states. In particular, two rules are formulated to select state variables based on historical data samples; a dynamic alarm generation mechanism is proposed to generate a state-based alarm variable by taking the previous status of the original alarm variable into consideration. To the best of our knowledge, the two rules and the dynamic state-based alarm generation mechanism are the first systematic techniques to handle long-standing alarms.

The rest of the paper is organized as follows. Section 2 gives some basic information of long-standing alarms. Section 3 analyzes the main causes of long-standing alarms. The dynamic state-based alarm system is designed in Section 4. Section 5 provides industrial case studies as illustrations. Some concluding remarks are presented in Section 6. A nomenclature section is given at the end of the paper.

2. Basics of long-standing alarms

This section presents the definitions of long-standing alarms, and proposes an index to quantify the severity level of long-standing alarms.

There are several closely-related definitions of long-standing alarms. Hollifield and Habibi (2010) treated long-standing alarms as those in the alarm state continuously for more than 24 h. ANSI/ISA-18.2 had a similar definition as "an alarm that remains in the alarm state for an extended period of time (e.g., 24 h)" (ISA, 2009). Rothenberg (2009) separated the definitions of stale alarms and long-standing alarms: the former as the alarms acknowledged but uncleared for 8–12 h, and the latter as the alarms acknowledged but uncleared for 24 or more hours. EEMUA-191 regarded a long-standing alarm as any alarm active for a full operating shift or longer (EEMUA, 2013). These definitions have a common feature of having large alarm durations, but are different in alarm duration thresholds.

Let $x_a(t)$ represent the value of an alarm variable at the time