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Research article

Abnormal condition identification and safe control scheme for the electro-fused magnesia smelting process

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ABSTRACT

This paper presents a control framework to identify the abnormal condition and make safe control scheme by fusing the related multi-source information based on the analysis of the abnormal exhausting condition in the electro-fused magnesia smelting process. For the abnormal condition identification, the case-based reasoning is used to infer the degree of the abnormal condition. When the similarity of the matched case doesn't exceed the set threshold, Bayesian network is used to infer the degree. For the safe control scheme, taking advantage of the idea of the remaining lifetime predicting, and the adjustment of the control variables is obtained. The application results show that the proposed method is effective and it owns better performance than the manual and the existing research results.

1. Introduction

The electro-fused magnesia is an important refractory. It has been applied in a variety of industries such as glass industry, electric apparatus, aerospace industry, chemical industry, metallurgical industry and cement industry, etc. In China, the raw material of the electro-fused magnesia is magnesite. But in most cases, the raw material grade is low and the mineral composition is complex. Therefore, the unique three-phase ac fused magnesium furnace (FMF) is applied to produce high-purity fused magnesia. Many researches on the FMF have been proposed from the different aspects [1–6].

The FMF completes the smelting process by the control system tracking the different current setpoints based on the different conditions. When the raw material granule size and the impurity constituent change, the previous setpoints will not adapt to the changed condition any more. If the setpoints of electrode currents are not properly adjusted in time, the abnormal conditions will happen. The abnormal exhausting condition is one of the main abnormal conditions in the electro-fused magnesia smelting process. When the abnormal exhausting condition is serious, the melt splashing will happen. This condition will result in high energy consumption, the performance deterioration or even safety threat. To identify the abnormal condition and make suitable decision, the common method is to establish the mechanism model. However, due to the strong nonlinearity and coupling among the variables, it is difficult to obtain accurate mechanism model for the abnormal condition. Therefore, many research results are proposed to analyze the fault by the data-based methods [7–10]. The paper [7] proposes an online fault prognostic method by analyzing the critical variables for the fault-degradation and extracting their directions. The paper [8] analyzes the fault characteristics by combining the algorithms of the fisher discriminant and relative changes for two typical disturbances in the fault process, bias of data location and increase in data variations. A probabilistic fault diagnosis method is proposed to identify fault cause for the online applications. For the fault diagnosis problem in the nonstationary industrial processes, the paper [9] proposes the sparse reconstruction strategy to isolate and diagnose the fault variables. The strength of the method is that it does not require any historical fault data.

On site, the abnormal exhausting condition of the FMF are identified and controlled by manual way based on the experience, memory and knowledge of the operators. By observing the special phenomena including the current, sound and image information, the operators identify the abnormal condition and make suitable decisions to get the system out of abnormal condition. Unfortunately, when the operators identify the abnormal condition, the

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decisions are always qualitative. The manual operation way is susceptible to human errors. The operators often ignore the interactions among the variables. At the same time, the ability of the operators to deal with multi-source information is limited. When a large amount of information is triggered at the same time, it is difficult for the operators to adjust the setpoints and control the currents within the desired range. Therefore, to reduce the workload of operators and improve the performance, it is necessary to identify the abnormal condition and make control strategy by automatic way.

By simulating the actions that the operators identify and remove the abnormal exhausting condition, the paper [11] analyzes the causes of the abnormal conditions and presents a data-driven abnormal condition identification and self-healing control method. The abnormal condition identification is based on the rule-based reasoning and the self-healing control is developed using case-based reasoning (CBR). However, the paper [11] only analyzes the current information which is the only one aspect of the focused information. When the abnormal exhausting condition happens, the operators often hear different sound information compared with the normal exhausting condition. The main sound sources of FMF are from the arcs between the electrodes and the molten pool. The change of arc sound signal reflects the change of the physical states in fused magnesia production. When the abnormal exhausting condition is serious, the high-temperature melts will spurt out of the furnace together with the CO_2 gas. The operators will observe that the brightness is bigger than the normal condition in the opening of the furnace. Therefore, in practice, the operators fuse the multi-source information (current information, sound information and image information) to identify the abnormal exhausting condition. The information fusion is a very important method to improve the performance, which has attracted more and more attention recently [12,13].

The motivation of this paper is to obtain the better performance than the manual way and the existing research results for the abnormal exhausting condition identification and safe control. This paper simulates the actions of the operators to identify and remove the abnormal exhausting condition by fusing the multi-source information. In the electro-fused magnesia smelting process, the existing data and expert knowledge lay foundation for proposing new method. The CBR has a huge advantage in taking advantage of the existing knowledge included in the historical data. At the same time, there is a large amount of uncertain information in the electro-fused magnesia smelting process. Many qualitative relationships among the variables for the abnormal exhausting condition are obtained. The Bayesian network (BN) is an important and effective tool for the uncertain knowledge representation and reasoning. The CBR and the BN have been applied in all kinds of fields [14–18]. Therefore, in this paper, the CBR and BN are introduced to identify the abnormal exhausting condition.

Based on the research results in the paper [11], this paper proposes a multi-source information fusion method to identify and control the abnormal exhausting condition. By analyzing the characteristics of the abnormal exhausting condition, this paper sums up the experience of the operators, and the case data base and the BN are established based on the historical data and expert knowledge. For the abnormal condition identification, the CBR is used to identify the abnormal condition by fusing the multi-source information including the image, sound and current information. When the similarity of the matched case doesn't exceed the set threshold, the BN is used to obtain the identification result. The verified identification result from the BN is used to update the case data base. For the safe control scheme, the concept of the remaining lifetime is introduced and the relationship between the remaining lifetime and the related control variables is established. According to the abnormal condition identification result, the remaining lifetime is obtained. Based on the relationship between the remaining lifetime and the related control variables, the safe control scheme can be made to adjust the current setpoints automatically. The current control system will track the revised setpoints to make the smelting process return to normal. The simulation result shows that the proposed method is effective to identify the abnormal condition and make safe control scheme. By the comparison with the traditional method which only uses the current information, the proposed method in this paper has better performance.

The innovations of this paper reflect the following some aspects. First of all, the general framework is proposed for the abnormal exhausting condition identification and the safe control. The method can be generalized to the other abnormal conditions in the electro-fused magnesia smelting process or even other similar industrial processes. Furthermore, this paper fuses the multi-source information to identify the abnormal exhausting condition. The proposed method is more reasonable to analyze the abnormal exhausting condition and owns better performance than the manual way and the existing research results. Finally, by taking advantage of the idea of the remaining lifetime predicting, the new safe control scheme is proposed to remove the abnormal condition.

The organization of this paper is as follows. Section 2 analyzes the abnormal exhausting condition in the electro-fused magnesia smelting process. The experience of the operators to identify and control the abnormal exhausting condition is extracted. In Section 3, the proposed framework is described including the abnormal condition identification and the safe control scheme. In Section 4, the simulation results are shown and analyzed. Finally, the conclusions are presented in Section 5.

2. The abnormal exhausting condition in the electro-fused magnesia smelting process

In this section, the electro-fused magnesia smelting process will be described. The experience of the operators will be extracted for the abnormal exhausting condition.

2.1. Process description

The electro-fused magnesia smelting process is shown in Fig. 1 [11]. In general, the process of the smelting includes the following three operating conditions: heating and melting, feeding, and exhausting [3]. The operators need to determine the setpoints of the current by their experience based on different conditions. The control system tracks the setpoints of the current and makes sure the process run smoothly.

2.2. The analysis of the abnormal exhausting condition

During the smelting process, a certain amount of CO_2 gas will produce and exhaust from the FMF. The setpoints of the current will be adjusted. The control system will track the new current setpoints to increase the motion of the electrodes and produce a gap between the electrodes and the raw materials to make the gas out of the FMF. When the raw material particle size changes and exceeds the normal range, the CO_2 gas will not be exhausted appropriately. The abnormal exhausting condition will happen. When the pressure inside the FMF increases and exceeds a limited range, the high-temperature melts will spurt out of the furnace together with the CO_2 gas. The splashing high-temperature melts will result in serious safety threat for the equipment and the operators. Meanwhile, a great deal of energy is wasted, which increases the energy consumption per ton for the FMF. The energy consumption is the