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Real-time diagnosis and alarm of down-hole incidents in the shale-gas well fracturing process

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ABSTRACT

Detecting down-hole incidents in the shale-gas well fracturing process plays an important role in ensuring that the fracturing operations are carried out smoothly. This paper proposes a method to monitor down-hole incidents by extracting the qualitative trend of process variables (QTPV) using qualitative trend analysis. This is based on the consideration that QTPV is similar at different magnitudes of down-hole incidents and that deviations from the normal pattern may indicate a possible incident. Based on this, this paper presents a real-time diagnosis and alarm method of down-hole incidents using a multi-class support vector machine (MCSVM) model for qualitative trend classification in real-time. Compared with the traditional modelling process in which process data is directly used as the input item to develop the MCSVM classifier, the proposed method can achieve higher global accuracy, as well as lower false and missing alarm rates, even with limited incident cases. Moreover, successful real-time diagnosis and alarm of down-hole incidents (cracks forming in the strata, channelling near the wellbore area, and sand plugs) are demonstrated. The results suggest that the presented method is a reasonable starting point for monitoring down-hole incidents during the shale-gas well fracturing process. This approach can be integrated into a real-time monitoring and alarm device for field application during fracturing operations.

1. Introduction

Exploitation and utilisation of shale gas alleviate the shortage of oil and gas resources and increase the supply of clean energy. To enhance the output of shale gas, advanced fracturing technology has been applied to promote the fast development of shale gas. However, shale-gas well fracturing is a high-cost and high-risk process in which many factors, such as tubing washout and insufficient crack width, can result in abnormal down-hole incidents. Three down-hole incidents are of specific concern and are studied in this paper: 1)*cracks forming in the strata* caused by a higher pressure at bottom hole than in the formation. Forming suitable cracks is beneficial for the smooth process of fracture construction but improper cracks may destroy the stratum; 2) *channelling near the wellbore area* refers to a connection between the tubing and the casing, which is commonly caused by a tubing washout or casing packer failure; 3) *sand plugs* are a build-up of support particles in the cracks that partially or fully block the flow of fracturing fluid. All of these down-hole incidents may damage the stratum or lead to blowout, causing severe casualties and property loss, as well as environmental pollution. Therefore, controlling and preventing down-hole incidents during the shale-gas well fracturing process (SGWFP) is crucial to avoid injury, to eliminate property damage and to minimise non-productive time.

Few studies about down-hole incidents in SGWFP have been reported, but many studies focusing on incident prevention related to chemical processes and drilling engineering have been published. These studies are mainly concerned with dynamic risk management (DRM), early warning system design and alarm management.

Dynamic risk management that integrates the dynamic risk assessment with the management system is an effective way to control and prevent industrial incidents (Abimbola et al., 2014; Khakzad et al., 2013; Khan et al., 2016; Meel and Seider, 2008, 2006; Paltrinieri et al., 2014; Pariyani et al., 2012a, 2012b). Paltrinieri et al. (2014) defined a dynamic approach to risk management that takes into account new risk notions and early warnings to systematically calculate the real-time risk. This method can be applied throughout the system lifetime as a support to robust decision-

Abreviations: SGWFP, shale-gas well fracturing process; DRM, dynamic risk management; PDCA, Plan-Do-Check-Adjust; AIS, artificial immune system; ANN, artificial neural network; QTPV, qualitative trend of process variables; QTA, qualitative trend analysis; SVM, support vector machine; BSVM, binary support vector machine; MCSVM, multi-class support vector machine; RBF, radial basis kernel function; GA, global accuracy; FAR, false alarm rate; MAR, missing alarm rate.

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making processes. To enhance this method, Khan et al. (2016) proposed a novel DRM framework that is an integration of dynamic risk assessment and Plan-Do-Check-Adjust (PDCA) management. Dynamic risk management can ensure constant improvement of the risk management process by repeating the PDCA cycle and further foster a 'zero-incident' culture for process operations. However, implementing DRM effectively is a complex, time-consuming and resource-consuming process in which a stronger safety culture is necessary to ensure an effective DRM program.

An alarm system responsible for detecting an abnormal state and communicating the indication of such a state to the operators is also a critical safety barrier to preventing incidents in chemical facilities and drilling engineering (Kujath et al., 2010; Stauffer and Clarke, 2016). To improve the management level of abnormal conditions, intelligent alarm management of alarm systems has become a hot issue (Cai et al., 2015; Chang et al., 2011; Dalpatadu et al., 2015; Hu and Yi, 2016; Rodrigo et al., 2016). For example, in the area of chemical industry, Chang et al. (2011) applied a multi-alert voting mechanism and a risk-based quantitative method to design a warning system that can effectively reduce the possibility of false alarms and alarm flooding. Dalpatadu et al. (2015) provided a Bayesian network event-based alarm system design approach for alarm management. This approach not only diagnoses root causes of an alarm, but also predicts the probabilities of abnormal events and reduces redundant alarms. For alarm management in drilling engineering, accurate diagnosis of down-hole incidents is the basis of performing early warning. There have been several studies that propose different diagnosis methods of down-hole incidents in the drilling process (Hauge et al., 2013; Willersrud et al., 2015a, 2015b, 2015c, 2015d). For instance, Willersrud et al. (2015b) showed that multi-incidents can be isolated if simultaneous changes in physical parameters are detected by a multi-variable statistical change-monitoring approach. However, for SGWFP with high non-linearity, strong coupling and noise, such approaches may not be the most practical solution since it is difficult to establish accurate mathematic models using these methods.

On the other hand, artificial intelligence techniques have been applied for condition classification including incident diagnosis (Garrouch and Lababidi, 2001; Guilherme et al., 2011; Serapiao et al., 2006; Serapião et al., 2007; Yılmaz et al., 2002). For example, Serapião et al. (2007) applied an artificial immune system (AIS) to classify stages during petroleum well drilling. Yılmaz et al. (2002) utilised an artificial neural network (ANN) to monitor the drilling process and to determine the optimal drill bit. Guilherme et al. (2011); Serapiao et al. (2006) used a multi-class support vector machine (MCSVM) for classifying drilling conditions. With respect to the aforementioned techniques, the MCSVM has some advantages, such as superior generalisation ability and the ability to overcome the non-linear separable problem, compared with the ANN (Boser et al., 1992). However, the abovementioned works directly utilise the process data from sensors as the input item to train the classifier for detecting the drilling process and, therefore, a large amount of process data of different magnitudes of an incident (or an abnormal condition) is necessary to build an accurate classifier. In reality, the process data generated by down-hole incidents in SGWFP is very limited due to the fact that down-hole incidents are rare. Consequently, the obtained classifier can be imprecise.

At the construction site of a shale-gas well, the existing alarm systems use a single variable-based design approach, in which any of the process variables that exceed their predefined threshold limits will activate the alarm. Such an alarm system results in two problems: a delayed alarm and no alarm. If a down-hole incident does not cause the process variables to exceed the threshold, no alarm will be given during the down-hole incident while if the process variables exceed their threshold at an intense or later stage of the incident, a delayed alarm will occur. These two problems make it difficult for operators to judge the type of down-hole incident accurately and to take corresponding measures to control incidents in a timely fashion. However, although process variables are still in the normal range during the early stage of down-hole incidents, they exhibit different variation trends. What's more, the variation trends of process variables in the same kind of down-hole incident behave similarly over time. The variation trend, also called the qualitative trend of process variables (QTPV), has been extracted and utilised for fault diagnosis in chemical processes (Nan et al., 2008). The qualitative trend of process variables qualitatively describes the changes of real-time process data over a long time using a sequence of primitives that express the same behaviour – e.g. increasing, constant and decreasing – of process variables in a short time. The primitives can be extracted by means of qualitative trend analysis (QTA) (Dash et al., 2003; Maurya et al., 2007). The main idea of QTA is firstly to determine suitable primitives to represent the trend and then to divide the analysed process variables in a certain length of time into a series of segments and, finally, to use a fitting function to fit each segment and further identify each primitive. As indicated earlier, QTPV at different magnitudes of the same down-hole incident behave similarly. If the QTPV rather than the process data itself is used as the input of the MCSVM, the established classifier could achieve better diagnosis performance even without a large number of down-hole incident cases. Therefore, to improve the accuracy of down-hole incidents detection in the case of fewer incident cases, this paper proposes a new approach based on QTA and MCSVM for real-time diagnosis and alarm of down-hole incidents during the shale-gas well fracturing process. The QTPV is extracted using QTA and then fed into the MCSVM model to infer the actual type of down-hole incident in real-time.

The main contribution of this study rests on the following: 1) the QTPV is introduced into the area of real-time diagnosis and alarm of down-hole incidents in SGWFP for the first time. Taking the QTPV as the input item, MCSVM classifiers can be trained by fewer incident cases and can accurately detect down-hole incidents at an early stage of an abnormal condition, which is beneficial to early warning of down-hole incidents. When the proposed method is applied for MCSVM classifier development, it is not necessary to collect substantial process data generated by down-hole incidents of different magnitudes. On the contrary, the existing researches using artificial intelligence techniques require large amounts of process data related to down-hole incident to develop classifiers in order to detect an incident accurately; and 2) the presented method is a reasonable starting point for monitoring down-hole incidents during the SGWFP, and can be integrated into a real-time monitoring and alarm device for field application during fracturing operation, which helps operators detect the down-hole incidents in time and take corrective measures to control the down-hole incidents.

The rest of this paper is organized as follows. Section 2 describes the theoretical framework, including the basic QTA and SVM concepts. Section 3 provides a real-time diagnosis and alarm framework for down-hole incidents with detailed step-by-step procedures. In Section 4, the performance assessment of proposed method and three real-time diagnosis cases are shown. The conclusions are discussed in Section 5.

2. Theoretical framework

This section will briefly present the qualitative trend analysis that is responsible for extracting the qualitative trend of process variables, as well as the support vector machine responsible for mapping the extracted qualitative trends into the corresponding incidents.