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Application of Petri nets to performance evaluation of subsea blowout preventer system

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ABSTRACT

This paper presents an application of deterministic and stochastic Petri nets (DSPN) to evaluate the performance of subsea blowout preventer (BOP) system. The overall subsea BOP system is comprised of five mechanical subsystems and five electrical subsystems, which can be viewed as a series-parallel system. In regard to common cause failures, TimeNET 4.0 toolkit is utilized to develop and analyze the DSPN models. Availability and reliability of the subsea BOP system and its subsystems are obtained. Besides, the effects of failure rate and repair time of each component on system performance are researched.

1. Introduction

Offshore drilling for oil and gas is a complex process that depends on careful coordination of hardware and control strategies. Subsea blowout preventer (BOP) system plays an important role in providing safe working conditions during the subsea drilling activities. It is developed to cope with extreme erratic pressures and uncontrolled flow emanating from a well reservoir during drilling processes. Devastating consequences could be caused by the failures of subsea BOP system, for example, the Deepwater Horizon accident occurred in the Gulf of Mexico on April 20, 2010. Eleven workers were killed in the explosions and oil caused by the blowout gushed out of the damaged well for two months, which was the worst environmental disaster in US history [1,2]. During the accident, BOP system fails to function. Recently, reliability issues of subsea BOP system attract more and more attentions, which are not studied extensively enough.

Several reliability measures have been proposed for performance evaluation of subsea BOP system. Fowler et al. [3] uses failure modes and effects analysis (FMEA) and fault tree analysis (FTA) techniques for reliability analysis of a BOP and a hydraulic control system. The results demonstrated that notwithstanding human error, the ram BOP and its associated controls constitute a highly reliable system. Holand et al. [4,5] collected the data about subsea BOP failures and malfunctions, and estimated the availability of the subsea BOP system by using the FTA method. But, the two methods are only suitable for non-repair systems and lack of time element is their limitation [6,7]. Besides, FMEA technique cannot differentiate situation of common failures or severe failure caused by compound failures [8]. Owing to their flexibility, Markov and semi-Markov methods are widely used for performance evaluation of various systems. Semi-Markov method has no limits on types of transition time distributions compared with Markov method. The authors have presented a Markov based model for performance evaluation of subsea BOP stack configuration and mounting types for control pods [9]. Bieth et al. [10] presented an extended semi-Markov model to find the limiting proportions of time the system sojourns in each state and other limiting characteristics for a two-identical-unit cold standby repairable system with two kinds of repairmen. However, impossible to derive a qualitative analysis is one drawback for both methods [6]. Moreover, state enumeration cannot be elegantly depicted when they are applied for complex system with lots of components [11]. Fortunately, Petri net-based modeling method has the potential to overcome the limitations mentioned above. It is very popular and powerful for modeling and analysis of systems that exhibit parallelism, synchronization, non-determinism and resource sharing features [12]. Some verification and analysis methods have been developed around them and many mature analysis tools are available [13,14]. They provide convenience for qualitative and quantitative analysis for the system. A system model using Petri nets is easily extended and it can provide visual and hierarchical modeling methodologies [15].

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A large variety of systems can be modeled by Petri nets. It is often employed in evaluation of manufacturing systems, safety critical on-demand systems, redundant systems, and so on [16–18]. Mujica et al. [19] presented a timed state space approach dealing with timed colored Petri nets with new algorithms for properties verification and optimization of manufacturing systems. A new class of Petri nets with parallel process net with resources was introduced by Ahmad et al. [20] for modeling flexible manufacturing systems so that multiple resource-sharing issues could be alleviated. Zhong et al. [21] proposed a Petri nets model to study the performance of China typical Urban Emergency Response System and the results are in conformity with practical operations. Kaakai et al. [22] presented a simulation model based on hybrid Petri nets in order to help transit authorities to carry out performance evaluation procedures, which can validate design projects of new stations or evaluate the existing stations for safety and security purposes. Renganathan et al. [23,24] described a technique for on-line fault diagnosis of continuous systems modeled using Petri nets, and fault tolerant control for systems has also been provided which are modeled using timed hybrid Petri nets. Miyagi et al. [25] introduced a methodology for modeling fault-tolerant manufacturing systems based on the hierarchical and modular integration of Petri nets, which can optimize normal productive processes and perform detection and treatment of faults.

This paper presents models based on DSPN for the evaluation of subsea BOP system. Aspect of common cause failures is considered. Besides, the effects of changes of failure rate and repair time on system performance are researched. The remainder of this paper is structured as follows: Section 2 describes the subsea BOP system in detail. In Section 3, DSPN models for the system are developed. Section 4 covers the analytical results and discussions. Finally, Section 5 summarizes the paper.

2. System description

The subsea BOP system is mainly made up of subsea BOP stack and subsea BOP control system. The subsea control system consists of electrical system and hydraulic system. The hydraulic control system is comprised of pumps, valves, accumulators, fluid storage, piping, manifold and so on [26], which is out of the scope of our research. Therefore, it is worth to note that the subsea BOP system consists of subsea BOP stack and subsea BOP electrical control system in this paper. A typical subsea BOP system is shown in Fig. 1.

The BOP stack is between the Lower Marine Riser Package (LMRP) connector and wellhead connector in the seafloor [9]. It mainly includes four ram BOPs, two annular BOPs, a wellhead connector and a LMRP connector. A ram BOP uses rams to seal off pressure in the wellbore. Annular BOP is a device with a generally annular shaped steel-reinforced elastomeric packing element that is hydraulically operated to close and seal around any drill pipe size or to provide full closure of the wellbore. There are two kinds of hydraulic connectors, wellhead connector and LMRP connector, which are activated hydraulically and connect the BOP stack to the wellhead or the LMRP to the BOP stack. Great damages to the riser, stack, or wellhead will likely result if the connector does not release and the rig moves off location [27].

For redundancy, a subsea BOP system has two complete control pods, subsea blue pod and subsea yellow pod, which are mounted on the lower riser package on the BOP stack. Each pod is able to perform all necessary functions on the BOP. Each pod contains a subsea electronic module (SEM) which is in a three-inch thick steel domed container to protect electrical control system of subsea BOP from the surrounding water pressure. Any major problem associated with one pod will cause it to be retrieved to the surface for repair and the control of the subsea BOP is transferred to the other pod [28].

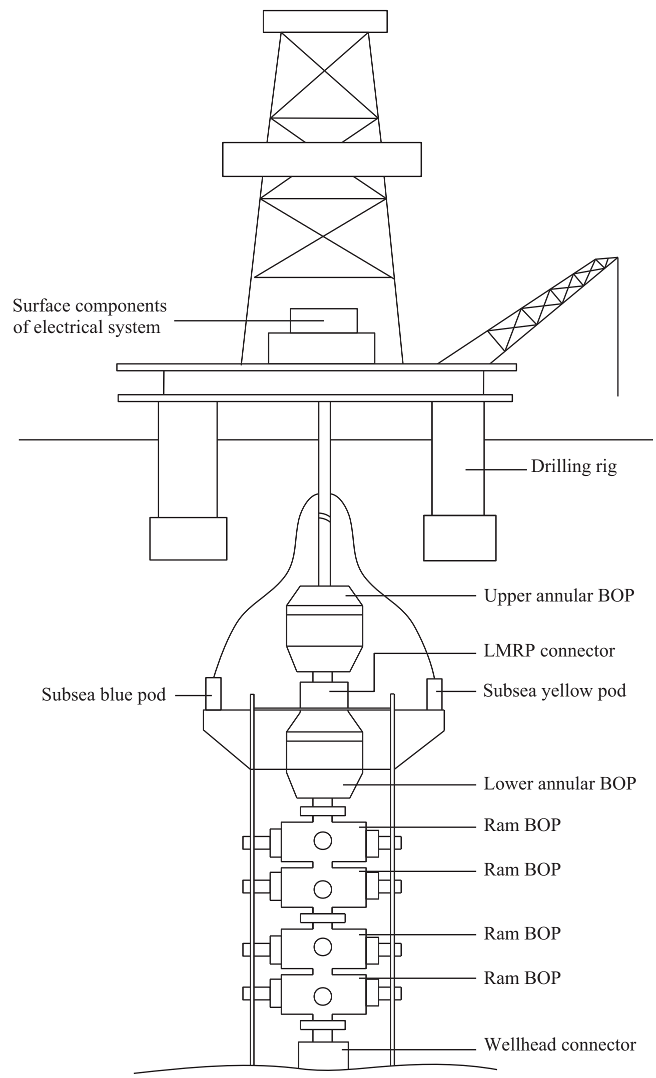

Fig. 1. Architecture of a subsea BOP system.

The subsea BOP control system is associated predominantly with technical factors like offset distance, water depth and required response speed [29]. Therefore, multiplex electro-hydraulic control systems have been developed for subsea BOP stack [30]. The subsea BOP electrical control system, as a distributed system, mainly consists of the central control unit (CCU), the connecting umbilical cable and subsea components, as shown in Fig. 2. CCU is located in drilling rig and belongs to the surface components. It houses the central processing units, programs, and other components that control communications and functions between the surface and the pods. There are three control stations in CCU, which are Driller's panel, Toolpusher's panel and work station. The three control stations compose a redundant subsystem, which are mainly industrial computers with the same functionality. Processor subsystem includes three identical processors. All three processors run the same application programs, processing data and send command signals. The system will not fail even when only a single processor works. Ethernet switches are used to connect the control stations to the processors. In order to enhance the reliability of the communication, two Ethernet switches are applied.

Two complete independent subsea umbilical cables including optical fibers and electronic wires are applied to provide power and communications paths from the surface to the SEMs. Fiber optic repeaters (FOR) are adopted for transformation of electronic signals and optical signals.