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Using Bayesian networks in reliability evaluation for subsea blowout preventer control system

Baoping Cai, Yonghong Liu*, Zengkai Liu, Xiaojie Tian, Xin Dong, Shilin Yu

College of Mechanical and Electronic Engineering, China University of Petroleum, Dongying, Shandong 257061, China

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ABSTRACT

The Bayesian network models of redundant systems including parallel system and voting system, taking account of common cause failure and imperfect coverage, are proposed. The Triple Modular Redundancy (TMR) and Double Dual Modular Redundancy (DDMR) control systems for subsea Blowout Preventer (BOP) are presented. By applying the proposed Bayesian network models, the reliability of subsea BOP control systems are evaluated at any given time, and the difference between posterior and prior probabilities of each single component given the system failure is obtained. The effects of coverage factor of redundant subsystem and failure rate of single component on reliability of systems are also researched. The results show that the DDMR control system has a little higher reliability than TMR system. To improve the reliability of subsea BOP control systems, the component failure rates of Ethernet switch (ES), programmable logic controller (PLC) and personal computer (PC) should be reduced for TMR system, whereas the failure rates of ES and PC should be reduced for DDMR system. The recovery mechanism of PLC, PC and ES subsystems, and PC and ES subsystems should be paid more attention for TMR and DDMR control systems, respectively.

1. Introduction

Subsea Blowout Preventer (BOP) stack plays an extremely important role in providing safe working conditions for the drilling activities in 10,000 ft ultra-deepwater region. Failures of subsea BOP stack could cause a catastrophic accident, for example, the deep-sea petroleum drilling rig Deepwater Horizon exploded and oil spill off the coast of Louisiana on April 20, 2010. Therefore, the extreme reliability is required for subsea BOP control system, which is developed based on N-modular redundancy technique in our previous work. Triple redundant controllers, triple redundant control stations, dual redundant Ethernet networks, redundant subsea electronic modules and redundant input/output subsystems are utilized in order to improve system reliability [1]. The reliability evaluation of subsea BOP control system is becoming recognized.

Many methods have been developed such as fault tree, reliability block diagram, reliability graph and Markov chain for the purpose of reliability evaluation. Each method has its own advantages and disadvantages. Recently, Bayesian networks are more and more used in reliability analysis due to the fact that the model can perform forward or predictive analysis as well as backward or diagnostic analysis. In predictive analysis, the probability of occurrence of any node is calculated on the basis of the prior probabilities of the root nodes and the conditional dependence of each node. In diagnostic analysis, the posterior probability of any given set of variables is calculated given some observation (the evidence), represented as instantiation of some of the variables to one of their admissible values [2].

Bayesian network models for reliability evaluation can be achieved by converting the traditional reliability models. Bobbio et al. [2,3] presented an algorithm to convert a fault tree or a dynamic fault tree into a Bayesian network or dynamic Bayesian network. A software tool named RADYBAN was also developed for automatic translation. Weber and Jouffe [4] presented a methodology that help developing dynamic object oriented Bayesian networks to formalize complex dynamic models as equivalent models to the Markov chains. Torres-Toledano and Sucar [5] presented a general methodology for transforming a reliability structure represented as a reliability block diagram to a Bayesian network representation, and with this, the reliability of the system can be obtained using probability propagation techniques. Kim [6] extended the research, and provided a method of mapping a reliability block diagram with general gates model into an equivalent Bayesian network model without losing the one to-one matching characteristic for quantitative analysis.

Many application of Bayesian networks have been recently found in reliability evaluation of various redundant systems.

* Corresponding author. Tel.: +86 546 8392303; fax: +86 546 8393620.
E-mail addresses: liuyh@upc.edu.cn, liuyhupc@163.com, liuyhupc@126.com (Y. Liu).

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Kannan [7] discussed the suitability of Bayesian theory and networks for use in safety instrumented system design, proposed Bayesian belief networks to build the scenario based hazard probability model and used that in the post-design phase to track the residual risk probability. Neil and Marquez [8] presented a hybrid Bayesian network framework to model the availability of renewable systems, and showed the method to model corrective repair time, logistics delay times and scheduled maintenance time distributions and combine these with time-to-failure distributions to derive system availability. Mahadevan et al. [9] proposed a methodology to apply Bayesian networks to structural system reliability reassessment, with the incorporation of two important features of large structures including of multiple failure sequences and correlations between component-level limit states. Doguc and Ramirez-Marquez [10] presented a holistic method that used historical data about the system to be modeled as a Bayesian network and provided efficient techniques for automated construction of the Bayesian network model, and hence estimation of the system reliability.

Honari et al. [11] showed how one may use Bayesian networks as a statistical technique to develop a new approach to evaluate the reliability of an (r, s)-out-of-(m, n): F system. Wilson and Huzurbazar [12] extended the applications of Bayesian networks on binary outcomes to multilevel discrete data and discussed how to make joint inference about all of the nodes in the network. Flammini et al. [13] presented both a failure model for voting architectures based on Bayesian networks and a maintenance model based on continuous time Markov chains, and proposed to combine them according to a compositional multi-formalism modeling approach in order to analyze the impact of imperfect maintenance on the N-modular redundant computer system safety. Khakzad et al. [14] demonstrated the application of Bayesian networks in safety analysis of process systems, and compared the approaches of fault tree and Bayesian network. Jones et al. [15] applied Bayesian network modeling to a maintenance and inspection department, and established and modeled various parameters responsible for the failure rate of a carbon black producing system, in order to apply it to a delay-time analysis study.

Two important features of redundant control systems, such as common cause failure and imperfect coverage, have significant effects on the system reliability, which are studied by the traditional reliability methods [16–19]. Few researches about Bayesian networks for reliability evaluation with respect to common cause failure and imperfect coverage were reported. Liu and Singh [20] proposed a Bayesian networks based method to investigate the overall effects of hurricanes on the reliability evaluation of composite power systems. This method used the noisy OR-gate model to consider both common cause failures and independent failures of transmission lines and generating units. In addition, the Bayesian networks models for reliability analysis of series and parallel systems with dependent components are proposed in Ref. [5,21]. Langseth and Portinale [22] introduced a coverage factor, which is defined as the probability that a single failure entails a complete system failure, to Bayesian networks in order to model the inaccurate recovery mechanism of redundant system.

The reliability of subsea BOP stacks for deepwater applications was evaluated using fault tree approach [34,35]. The performance of subsea BOP systems with common-cause failures was also evaluated by merging the independent Markov models with the Kronecker product approach [36,37]. They mainly researched the subsea BOP systems, especially the BOP stacks. The reliability evaluation of subsea BOP electronic control systems has never been reported.

This work focuses on the Bayesian networks model for reliability evaluation of subsea BOP Triple Modular Redundancy (TMR) control system and Double Dual Modular Redundancy (DDMR) control system, taking into account two important features of redundant systems including common cause failure and imperfect coverage. The paper is structured as follows: Section 2 presents two hardware configurations of subsea BOP control systems. In Section 3, the Bayesian networks models for system reliability analysis are developed. In Section 4, the system reliability, difference between posterior and prior probabilities, effects of coverage factors and failure rates are investigated. Section 5 summarizes the paper.

2. System description

2.1. Subsea BOP system

The subsea BOP system consists mainly of subsea BOP control system and subsea BOP stack. A typical subsea BOP system is illustrated in Fig. 1.

The subsea BOP control system includes electric control system and fluid control system. The fluid control system consisted of pumps, valves, accumulators, fluid storage and mixing equipment, manifold, piping, hoses, control panels and other items necessary to hydraulically operate the BOP equipment [23], which is out of our research target. Only the electric control system which is developed in our previous project [1] is researched in this work; therefore, the subsea BOP control system refers particularly to subsea BOP electric control system.

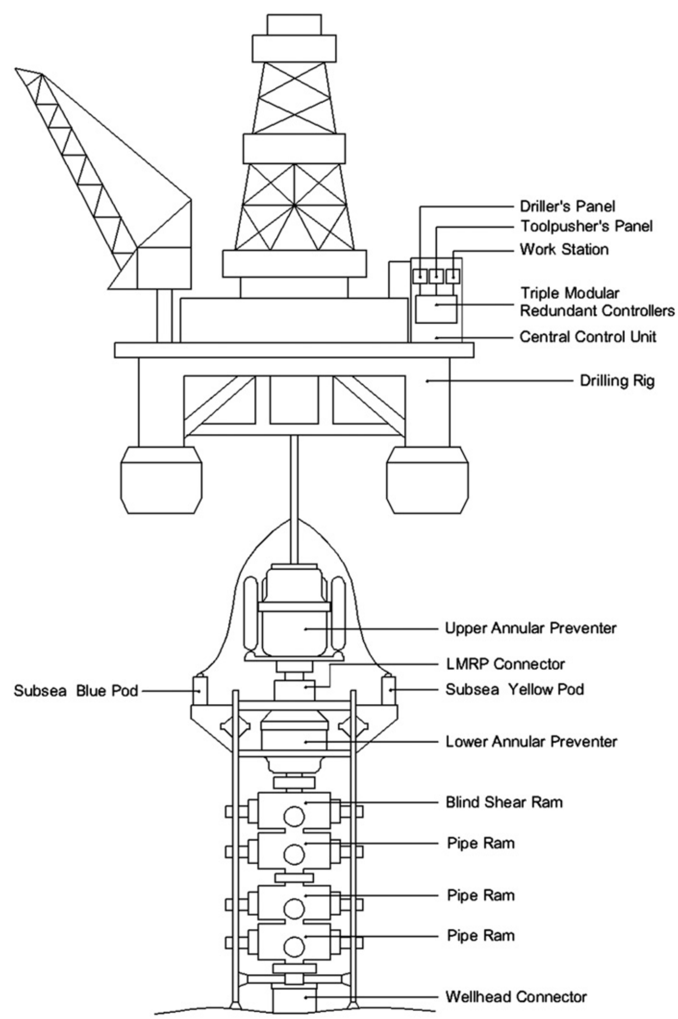

Fig. 1. Typical architecture of a subsea BOP system.