Reliability Modeling and Evaluation of Subsea Blowout Preventer Systems

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SCIENCE PRESS
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Responsible Editors: Qunxia Wan   Liwei Qiao

图书在版编目(CIP)数据

水下防喷器系统可靠性建模与评估 = Reliability Modeling and Evaluation of Subsea Blowout Preventer Systems: 英文 / 刘永红等著. —北京：科学出版社, 2015. 6

Ⅰ. ①水… Ⅱ. ①刘… Ⅲ. ①水下–防喷器–系统可靠性–系统建模–英文 ②水下–防喷器–系统可靠性–评估–英文 Ⅳ. ①P634.4

中国版本图书馆 CIP 数据核字(2015)第 062617 号

Published by Science Press
16 Donghuangchenggen North Street
Beijing 100717, P. R. China
Printed in Beijing

ISBN 978-7-03-044005-1

Foreword

China officially initiated 211 Project approved by the State Council in 1995. It was the biggest and most important project that was authorized by China in the higher education since the founding of New China. As a response to the domestic and international situation at the turn of the century, Chinese leaders made the important decision to develop the higher education 211 Project drives the overall development of participating universities through major innovations. It encompasses developing university subjects and teaching faculties, as well as other core elements aimed at improving university standards. The 211 project thereby explores successful ways to develop the high level universities.211 Project has been remarkably successful over the last 17 years. It has improved the overall educational quality of chinese higher level education, scientific research standards, and its institutional management and administration. The project has established the foundation for china to help top ranking universities operate at an advanced global level.

In 1997, the China University of Petroleum(UPC) was included in the 211 Project rankings, providing us with an opportunity to develop into a high level university. During the three phases (during the Ninth, Tenth and Eleventh Five-Year Plan periods) of 211 Project to date, the UPC has focused on improving the university's level; stated our mission to meet the needs of the petroleum and petrochemical industry; stated our goal to realize major innovative breakthroughs for national oil and gas; and aimed to improve of key discipline levels, create academic leaders, and cultivate international and innovative talents. We has adhered to the 211 Project development guidelines, and has used our advantages to drive overall improvements and developments. Our competitiveness has been significantly strengthened, and the university's administration and overall strength have noticeably improved, establishing a solid foundation for a world-class petroleum research university.

Participation in 211 Project has strengthened the university's petroleum characteristics and has highlighted our academic advantages. Moreover, we are smoothly implementing our specialty innovation platform. Five of the UPC's national key disciplines and two of our state key (cultivation) disciplines are at leading domestic/international advanced levels.

The UPC's engineering and the chemistry departments entered the Essential Science

Indicators' world rankings for the first time in March 2012, indicating that the strength and the level of the two main subjects (the petroleum and petrochemical disciplines) have significantly increased. Our high-level teaching staff structure has substantially progressed. Our staff includes members of the Chinese Academy of Science and Engineering, distinguished Changjiang Scholar professors, national science fund for distinguished young scholars winners, and national "Thousand Person Plan" and "Millions of Talents" project candidates among other high-level talents. This provides an intellectual guarantee for the university's future. Innovation ability has substantially improved, and high-level programs and achievements are constantly emerging. Our annual scientific research funds are over 400 million RMB. The UPC has preliminarily established a science and technology innovation system with distinctive petroleum features, and has become an important element of the national science and technology innovation system. Our ability to cultivate innovative talents is improving. The UPC has undertaken a plan to educate and train outstanding engineers, and established a special zone for outstanding innovative talents. We are actively exploring ways to cultivate international talents, and have reformed our postgraduate education mechanism, preliminarily formed an innovative talents cultivation method and a postgraduate education mechanism corresponding to innovative talent cultivation.

We are perfecting our public service support system, we has developed an efficient and fast public service system, significantly upgraded our software and hardware.This provides a strong support basis to develop teaching, scientific research and management levels.

The experiences gained in the 17 years that UPC has been involved in 211 Project are invaluable.First, we must adhere to our guidelines and pioneer discipline innovations by strengthening our characteristics and stressing our advantages. We can thereby realize the goal of building a world-class petroleum department. Second, we must keep abreast of ongoing developments and overall improvements to further widen our advantages. We must coordinate our development and constantly improve our overall competitiveness by promoting the whole through the key parts.Third, we must adhere to the goal of improving our educational mechanisms and establishing our research platform. We must strengthen the overall university structure, collect resources, integrate our talent teams, and optimize all of the management sessions and working systems. We will achieve this by perfecting our educational mechanisms: focusing on elements such as integration, openness, common sharing, competitiveness, information flow, and our project administration mechanisms to ensure that all project work is conducted efficiently and effectively. Fourth, we must focus on staff recruitment and development, and cultivate a talented and united workforce. We must attract outstanding talents to form a team with dedicated and innovative members to promote 211 Project development, which support all of the university's undertakings. Internal schools, disciplines and relevant departments should coordinate and cooperate with one another to form a strong joint effort and guarantee that all of the development goals are smoothly implemented.

We gained invaluable experience since the implementation of 211 Project. It is necessary to carry these experiences forward to further develop the university into an outstanding research institute. To summarize the university's 211 Project experience and its successful outcomes, the UPC initiated a special fund in 2008 to finance the publication of a series of academic monographs relating to the project. These publications relate to both the implementation of 211 Project in the UPC and the scientific research achievements of talented UPC scholars. These monographs introduce and demonstrate the subject construction, scientific innovation and talent cultivation in different categories.

I believe that this series of monographs will disseminate our advanced scientific research results and our academic thoughts from different perspectives and multiple dimensions, and demonstrate the remarkable achievements made and development route taken during our implementation of 211 Project to date. They will support our social influence, improve our academic reputation and make an important and unique contribution to our ongoing 211 Project development plans.

Finally, I am grateful to all of our scholars for their hard work and considerable efforts for 211 Project. I commend the monograph authors in the dedication of collecting and summarizing all our research results. They will leave innovative results and academic spirits, and make invaluable contributions to our university, our faculities, the staffs, and the students.

President of China University of Petroleum (East China)
September 2012

Preface

Complex mechatronic systems for critical application, such as subsea blowout preventer (BOP) systems, require a high reliability, i.e., a very low probability of failure. For this, many statistical techniques methods have been developed such as fault tree, reliability block diagram, Petri net, Markov chain and Bayesian networks that can predict the system reliability based on its structures and the reliability of each components. For improving the accuracy of reliability evaluation, some important factors and actions, such as common cause failure, imperfect coverage, imperfect repair and preventive maintenance and real-time reliability should be considered. Therefore, we write the book, focusing on Markov and Bayesian network based reliability evaluation.

The book is structured as follows.

Chapter 1 focuses on the extremely high reliability of subsea BOP control system which is designed by using hardware redundancy techniques, software redundancy techniques and a series of voting algorithm.

Chapter 2 presents two configurations of subsea BOP distributed control systems, which are triple modular redundancy control system and double dual modular redundancy control system. With respect to common cause failures, the performances of the two systems are evaluated by using Markov method with multiple error shock model.

Chapter 3 presents and discusses a Markov-based method developed for the performance evaluation of a subsea BOP system. Based on this developed model, the effects of stack configurations and mounting types of subsea control pods are evaluated.

Chapter 4 focuses on the Bayesian networks model for reliability evaluation of subsea BOP triple modular redundancy control system and double dual modular redundancy control system, taking into account two important features of redundancy systems including common cause failure and imperfect coverage.

Chapter 5 presents a quantitative reliability and availability evaluation method for subsea BOP system by translating fault tree into dynamic Bayesian networks directly, taking account of imperfect repair.

Chapter 6 focuses on the dynamic Bayesian networks modeling of series, parallel and 2oo3 voting systems, taking account of common-cause failure, imperfect coverage, imperfect repair and preventive maintenance.

Chapter 7 presents a methodology for quantitative risk assessment of subsea BOP operations in the offshore oil and gas industry by directly translating a flow chart to a Bayesian network.

Chapter 8 proposes a novel real-time reliability evaluation framework of subsea ram BOP by combining the Bayesian networks based root cause diagnosis phase and the dynamic Bayesian networks based reliability evaluation phase.

Chapter 9 proposes a conversion algorithm from defined pseudo-fault tree into dynamic Bayesian networks, taking account of repair actions, and researches the reliability of human factors on offshore blowouts.

Chapter 10 researches the reliability of software system for subsea BOP by using Bayesian networks method.

We thank our families and friends for their support, thank all persons involved in reviewing the book, and would like to thank China University of Petroleum for their support for publishing this book.

We wish to acknowledge the support of National Natural Science Foundation of China (No. 51309240), National High-Technology Research and Development Program of China (No. 2013AA09A220), Specialized Research Fund for the Doctoral Program of Higher Education (No. 20130133120007), China Postdoctoral Science Foundation (No. 2015M570624), Applied Basic Research Programs of Qingdao (NO. 14-2-4-68-jch), Fundamental Research Funds for the Central Universities (No. 13CX02077A), Science and Technology Project of Huangdao District (No. 2014-1-48), Fundamental Research Funds for the Central Universities (No.14CX02197A) and Taishan Scholar Project of Shandong Province (TS20110823).

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October, 2014

Contents

Chapter 1 Development of Automatic Subsea Blowout Preventer Stack Control System Using PLC Based SCADA

An extremely reliable remotely control system for subsea BOP stack is developed based on the off-the-shelf triple modular redundancy system. To meet a high reliability requirement, various redundancy techniques such as controller redundancy, bus redundancy and network redundancy are used to design the system hardware architecture. The control logic, human machine interface graphical design and redundant databases are developed by using off-the-shelf software. A series of experiments were performed in laboratory to test the subsea BOP stack control system. The results showed that the tested subsea BOP functions could be executed successfully. For the faults of programmable logic controllers, discrete input groups and analog input groups, the control system could give correct alarms in the human machine interface.

1.1 Introduction

Subsea BOP stack plays an extremely important role in providing safe working conditions for the drilling activities in 10000ft① 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. It was considered that on the Deepwater Horizon rig, the subsea BOP did not isolate the well before and after the explosions. The subsea BOP stack might have been faulty before the blowout or it might have been damaged due to the accident [1,2].

The BOP stack is between the lower marine riser package (LMRP) connector and wellhead connector in the seafloor [3-6]. The traditional electro-hydraulic control system transmits electrical command signals using pairs of wires. The large quantity of wires makes the armored umbilical cables and electrical interface heavy and bulky with increasing depth of water [7]. The multiplex electro-hydraulic control systems have been developed in recent years, which employ multi-conductor armored subsea umbilical

① 1ft = 0.3048m.

cables to transmit coded commands that activate solenoid operated pilot valves in the subsea pods [8,9]. An intelligent supervisory control and data acquisition (SCADA) platform, which provides economical and user-friendly solutions to subsea BOP stack management, is the kernel of the multiplex electro-hydraulic control system.

In recent years, various SCADA systems have been developed. Large numbers of programmable logic controller (PLC) based SCADA systems are used in wastewater treatment plant, cryogenic pumping facility, water pumping control system, fuzzy proportion integration differentiation controller and petroleum industry [10-14]. Chaudhuri et al. [15] developed a PLC based automation system to control the water flow in the secondary cooling zones of the strand. The automation system configuration was also given. Aydogmus [16] presented a SCADA control via PLC for a fluid level control system with fuzzy controller. Bayindir and Cetinceviz [17] described the water pumping control system that was designed for production plants and implemented in an experimental setup in a laboratory by using PLC and industrial wireless local area network technologies. Some new approaches are used for PLC software design. Kandare et al. [18] presented a model-based approach to PLC software development by introducing a new procedural modeling language called ProcGraph. In addition, PC-based SCADA systems are used in electric power system, desalination plant and laboratory testing system [19-21]. And Web-based and mobile-phone-based SCADA systems are also developed [22,23].

However, most of the SCADA systems described above are non-redundant, which can not provide high reliability. The redundancy systems are usually developed based on the chip-level processors, such as filed programmable gate array (FPGA) [24,25] or single chip microcomputer (SCM) [26,27], but not the system-level processors, such as PLC or PC. The redundancy systems based on chip-level processors are difficult to develop, which require professionals to develop the control hardware and software.

For the subsea BOP system, both of the high reliability and easy development are need, therefore, PLC based triple modular redundancy system GE Fanuc Genius modular redundancy (GMR) is chosen to provide supervisory control and data acquisition due to the fact that the system can provide the tolerance against single hardware component failures. The subsea BOP system can be developed easily based on the off-the-shelf GMR system, and the potential errors can be corrected easily and rapidly by using the off-the-shelf software.

This work focuses on the extremely high reliability of subsea BOP stack which is