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Safety prognostic technology in complex petroleum engineering systems: progress, challenges and emerging trends

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Abstract: Oil and gas facilities used in the petroleum industry can be considered as complex dynamic systems in that they require different types of equipment with various causal relationships among components and process variables under monitoring. As the systems grow increasingly large, high speed, automated and intelligent, the nonlinear relations among these process variables and their effects on accidents are to be fully understood for both system reliability and safety assurance. Failures that occur during the process can both cause tremendous loss to the petroleum industry and compromise product quality and affect the environment. Therefore, failures should be detected as soon as possible, and the root causes need to be identified so that corrections can be made in time to avoid further loss, which relate to the safety prognostic technology.

By investigation of the relationship of accident causing factors in complex systems, new progress into diagnosis and prognostic technology from international research institutions is reviewed, and research highlights from China University of Petroleum (Beijing) in this area are also presented. By analyzing the present domestic and overseas research situations, the current problems and future directions in the fundamental research and engineering applications are proposed.

Key words: Oil and gas facility, complex system, diagnostic and prognostic, coupling faults, predictive maintenance

1 Introduction

Modern petroleum technological advances are creating a rapidly increasing number of complex engineering systems, processes, and products, such as oil-gas gathering and transporting system, pumps and compressors in long-distance pipelines, and various chemical equipment, which have close relationship to the oil and gas production, transportation and processing stages. Such complex systems widely used in petroleum industry pose considerable challenges in ensuring their proper design, control, safety, and management for successful and continuous operation over their life cycles. It is their scale, nonlinearities, interconnectedness, and interactions with humans and the environment that can make these complex systems fragile, when the cumulative effects of multiple abnormalities can propagate in numerous ways to cause systemic failures.

With long-term operation, usually more than 30 years, of complex petroleum engineering systems, it is quite hard to avoid accidents. On the other hand, with characteristics that hazards could spread to the outside environment, once an accident happens, it could lead to a great loss, so such systems are also typical high risk systems. For instance, in the cases of the explosion in the BP Texas City refinery, “11.13” Jilin petrochemical explosion, “7.16” Dalian oil pipeline explosion, and “6.11” Penglai 19-3 oilfield spill, postmortem investigations of above disasters have shown that systemic failures rarely occur due to a single failure of a component or personnel, and in particular the main reason causing accidents and their consequences lies in the complex nonlinear interactions among a large number of failure causing factors.

A complexity adaptive system (CAS) theory proposed by Prof. Holland (1992) is relatively new, and important progress is being made. Researchers in the field of oil and gas safety science began to focus on complexity science (CS) and are trying to use it to address the above challenges, including accident-causing theory, safety evaluation system, intelligent fault diagnosis and trend forecasting. On the other hand, as the concept of the predictive maintenance was proposed, instead of the corrective maintenance, condition based maintenance and preventive maintenance, the focus of the maintenance of petroleum facilities is beginning to understand when complex systems could fail or be vulnerable to certain kinds of faults and failures, and the different kinds

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of fault modes. Appropriate predictive maintenance strategies and contingency plans can be prepared in advance this way, avoiding unplanned shutdown or even disastrous accidents.

Therefore, the combination of the complex science and predictive maintenance technology makes a contribution to the development of safety prognosis of complex systems. However, there still exist many challenges in this subject. What are development directions in the future? These are urgent problems that need to be addressed. If one can anticipate problems, rather than relying on the current "react-and-fix" methodology for managing systemic risks, it will be extremely helpful to ensure the safe operation of complex petroleum engineering systems, and reduce or avoid the risk of calamitous accidents.

2 Failure propagation behavior in complex petroleum engineering systems

The complexity of accident causes and consequences in a complex petroleum engineering system is related to the limitation of subjective cognitive ability and also the objective complexity of accidents themselves. Both aspects have a close relationship to all kinds of sophisticated nonlinear interactions among parts or units in the system. Based on the study of the principle of integration and interconnection, it is indicated that the interaction is the true ultimate cause of the system failures. Complex unsafe situations are likely to arise from undesirable and dysfunctional interactions among the components, subsystems, feedback loops, humans, and the environment—not just from the failure of a single component or an operator mistake. Therefore, investigation into the interaction of structures and hierarchy in systems becomes the premise and foundation to analyze the safety situation of complex systems.

Again and again, investigations have shown that the number of accidents caused by coupling factors is alarming. There are always several layers of failures, ranging from low-level components to senior units to subsystems, which have led to major disasters. Surveys showed that 92% accidents were caused by multiple factors, and on average each accident were caused by more than 4.4 basic abnormal events, and the highest was caused by 20 basic abnormal events (Liu et al, 2013). The failure propagation behavior caused by interactions and presented by multiple basic abnormal events has some characteristics such as strong randomness and elusiveness, which can lead to disastrous consequences.

The failure propagation behavior can be explained as a complicated and dynamic network of activities of multiple basic abnormal events both in time and space. For instance, first an abnormal event happens and affects a few subsystems which have a close relation with it in the complex system; then these affected subsystems fail or become degraded and will further influence other related subsystems by certain coupling interaction; further some key subsystems, which play an important role in keeping the system's main function, will fail caused by former multiple factors. Therefore, as the number of failed key subsystems increases, the whole system will partly lose control or finally become paralyzed, which could lead to a disastrous accident with inestimable loss.

Clearly, to cope with such complexity, methodologies and automation tools to model, analyze, explain, predict, and control the behavior of such multiple factors as faults or failure in complex systems and in various environments are badly needed. One central benefit that has come through from the study of the failure propagation behavior in complex petroleum engineering systems, is the need for a prognostic approach, with which one can anticipate faults or failures to help managing systemic risks. In other words, one needs real-time safety prognostic technology that can effectively monitor various aspects of process operations, and detect, diagnose, predict and advise operators and engineers about incipient abnormal events. In this way, the root causes of accidents can be restrained, and the hazard effect can be reduced by controlling its failure propagation behavior, so the safety resilience of the complex system can be improved.

3 International research progress and challenges in safety prognostic technology

According to the definition of the united nations international strategy for disaster reduction early warning is the emergency warning of impending disasters. In safety engineering discipline, its connotation includes emergency warning against possible impending accidents, and it can also include the extension of warning against secondary accidents after a period of time which would be caused by the first accident. Therefore, one needs safety prognostic technology to model and predict emergent behavior in complex systems and evaluate the future hazard effects caused by an initial abnormal event to provide early warning, and offer adequate methods or action to control accidents with minimum losses.

In order to ensure system safety by early warning, one needs to address the crucial challenge of being able to predict how changes or dysfunctional interactions in a complex engineering system or its environment would propagate through the entire system, i.e., how one makes a prediction of the future event consequences from the behavior of the parts to an effective description of the whole system behavior.

Safety prognostic technology includes prognostic analysis and prognostic control. Prognostic analysis is the activity by monitoring, identifying, diagnosis, assessment and giving early warning alarm of the complex system when there exist fault phenomena. The prognostic control is the reaction of prognostic analysis, through a series of management activities such as correction, prevention and control for a degrading trend caused by an initial abnormal event.

Recent progress has promising implications for fundamental research and engineering application of safety prognosis in complex petroleum engineering systems for better product quality, inherently safer designs, abnormal events management and reliable process operations.

3.1 Failure dynamics and fragility in complex adaptive systems

For the past twenty years, the LIPS (Laboratory for Intelligent Process Systems) group at Purdue University has focused on risk identification, analysis and management in complex systems, developing a variety of solutions using knowledge-based systems, neural networks, statistical methods, analytical models and hybrid systems (Venkatasubramanian, 2005). By investigation into various accidents in different forms in different domains, the failure patterns and their interactions have been explored and investigated in a broader perspective of the potential fragility of all complex engineering systems. We need to go beyond analyzing these events as independent one-off accidents and to study all these accidents from a common systems engineering perspective so that the commonalities as well as the differences in failure propagation behavior can be thoroughly understood, in order to have safer design and better risk control in the future.

The research by LIPS proclaimed that the next grand challenge is in the creation of next generation prognostic and diagnostic systems can sense and monitor complex equipment and processes in real time, identify degradation in performance, predict potential failure scenarios, diagnose actual failures, recommend and/or take corrective maintenance or control actions (Venkatasubramanian, 2011).

3.2 Prognostics and decision support tools for predictive maintenance

The Center for Intelligent Maintenance Systems (IMS) at the University of Cincinnati is focused on frontier technologies in remote monitoring, prognostics technologies, and intelligent decision support tools (DST) and has developed the trademarked Watchdog Agent® prognostics tools for e-maintenance systems (Djurdjanovic et al, 2003; Lee et al, 2006). Its prognostic technology contains four categories of analytical tools that assess and predict performance or failures of machines and processes, by extracting and analyzing performance-related features from inputs such as sensor data, controller signals, expert knowledge, etc. Prediction results are then used for maintenance decision making and infrastructure operations.

Decision Support Tools (DSTs) developed by IMS facilitate maintenance operations in the most production-efficient manner when one or more machines are likely to fail, according to the prediction made by prognostic algorithms (Lee et al, 2010; Wu et al, 2010; Xia et al, 2011). They prioritize maintenance work-orders and balance limited resources by minimizing possible losses in productivity due to unplanned downtime. Future challenges indicated by IMS will focus on degradation analysis and prediction to achieve and sustain near-zero breakdown performance with self-maintenance capabilities for improved reliability, productivity, and asset utilization.

3.3 Resilience engineering in complex systems

The Mary Kay O'Connor Process Safety Center (MKOPSC) at Texas A & M University is world-renowned in process safety, develops safe processes, equipment, procedures and management strategies to minimize losses within the processing industry. It has been focusing on risk management, consequence analysis and risk resilience engineering (Mitchell and Mannan, 2006). They are engaged in improving existing methods to handle the relatively large uncertainty, which causes loss of confidence in the results (Rajaraman et al, 2004; Wang et al, 2004; Markowski et al, 2010), and also to perform dynamic operational risk analysis (Yang and Mannan, 2010a; 2010b) considering effect of aging of equipment, duration of testing intervals, and the capability of a system to recover from disturbances to the normal state. For instance, Bayesian belief net (BBN), LOPA, fuzzy logic method (Yun et al, 2009; Markowski et al, 2009) has been used by MKOPSC for data processing to simulate causal chains for the study of failure propagation behavior.

In order to prevent disastrous accidents, MKOPSC presented that real-time decision making for risk management needed to be developed based on progress of complexity science, multi-perspective modeling and hybrid intelligent systems. Research into safety prognostic, high-level prediction and control are required for: 1) safe component functioning; and 2) correct and safe interaction between components.

3.4 Intelligent operation support system for chemical equipment

By studying the major chemical accidents which have happened in recent years in Japan, Suzuki and Munesawa (2012) proposed an intelligent operation support system, which can effectively prevent accidents. The intelligent operation support system is able to calculate the effect of fault propagation in abnormal situations and give appropriate information to operators. It will help operators to make quick judgments for safety. This system predicts process variables in abnormal situations using a simulator. The states of all equipment are input to the simulator in order to calculate process variables correctly.

Although in many aspects good progress has been made overseas, there are few reports or literature in China concerning the development of safety prognostic in complex petroleum engineering systems. However, with growing demands for oil and natural gas in China, system risk continuously increases, which leads to major accidents occurring frequently, so it is quite obvious that in every aspect of China's petroleum industry further development of safety prognostic technology is greatly needed.

Considering the characteristics of petroleum equipment and oil and gas production, operations and processing procedures, the future research focus of safety prognostic technology in complex systems in China should pay attention to: 1) the discovery of incipient faults or indistinct abnormal events; 2) the prediction of multiple fault propagation paths; 3) the prediction of the future developing trends of single or combined abnormal states according to relative variables; and 4) the reduction of the consequences of failure interaction by dynamic approaches.

4 Achievements in safety prognostic technology in China University of Petroleum (Beijing)

In recent years, considerable progress has been made in safety prognostic technology in China University of

Petroleum (Beijing). In this paper, we summarize our contributions to this industrially important and intellectually exciting area. These contributions are aimed at improving the accuracy of fault diagnosis in complex systems, rationality of fault causal reasoning, and the promptness of accident consequence control. The main progress lies in early incipient fault prediction and diagnosis methods, multilevel integrated diagnosis and prognosis technology for coupling faults, and dynamic safety assessment and predictive maintenance technology and engineering applications.

The results of these studies can have two layers of meaning: 1) the application of the integrated diagnosis and prognosis technologies in the specific complex petroleum engineering systems to obtain specific and useful hazard scenario and safety pre-control measures, and promotes the research progress in the discipline of the complex petroleum engineering systems; 2) by the study of as much specific failure propagation behavior in complex systems as possible, the prognostic mechanisms summarized from them can be popularized in more complex engineering systems in the petroleum industry. This becomes the theoretical foundation for research into universal nonlinear interaction mechanisms of multiple faults and failures.

4.1 Early incipient fault diagnosis and prediction methods

With the exception of a few sudden failures, most failure processes occurring in complex systems are gradual, as the component function will deteriorate gradually until control is totally lost, but the components can still continue to work before final failure. The nonlinear interaction among multiple failures can be induced when there exist incipient faults, which will cause more components even the whole system to fail with great loss.

Therefore, in order to implement early incipient fault diagnosis, two problems should be recognized: 1) the characteristics of early fault phenomena are usually very weak, and often submerged in heavy noise, which cause the incipient faults to be hard for field engineers to notice and identify; and 2) the samples corresponding to abnormal or fault states are quite hard to obtain, which make the identification model very difficult to establish accurately.

Aiming to overcome above challenges, novel effective prognostic and diagnostic systems for monitoring, analyzing incipient faults and predicting their degradation trend has been proposed and applied in complex petroleum engineering systems (Hu et al, 2009a) (shown in Fig. 1). These approaches can be used to identify early incipient faults effectively, and to help to control the development of failure propagation behavior.

The significance of the research can be presented as follows:

1) For the first time a quantitative diagnosis index based on multifractal spectra and generalized dimensions for incipient faults in complex systems has been put forward considering the multifractal features of early incipient faults. The relationship between the local scaling and the overall characteristics of the fractal phenomena of incipient fault has

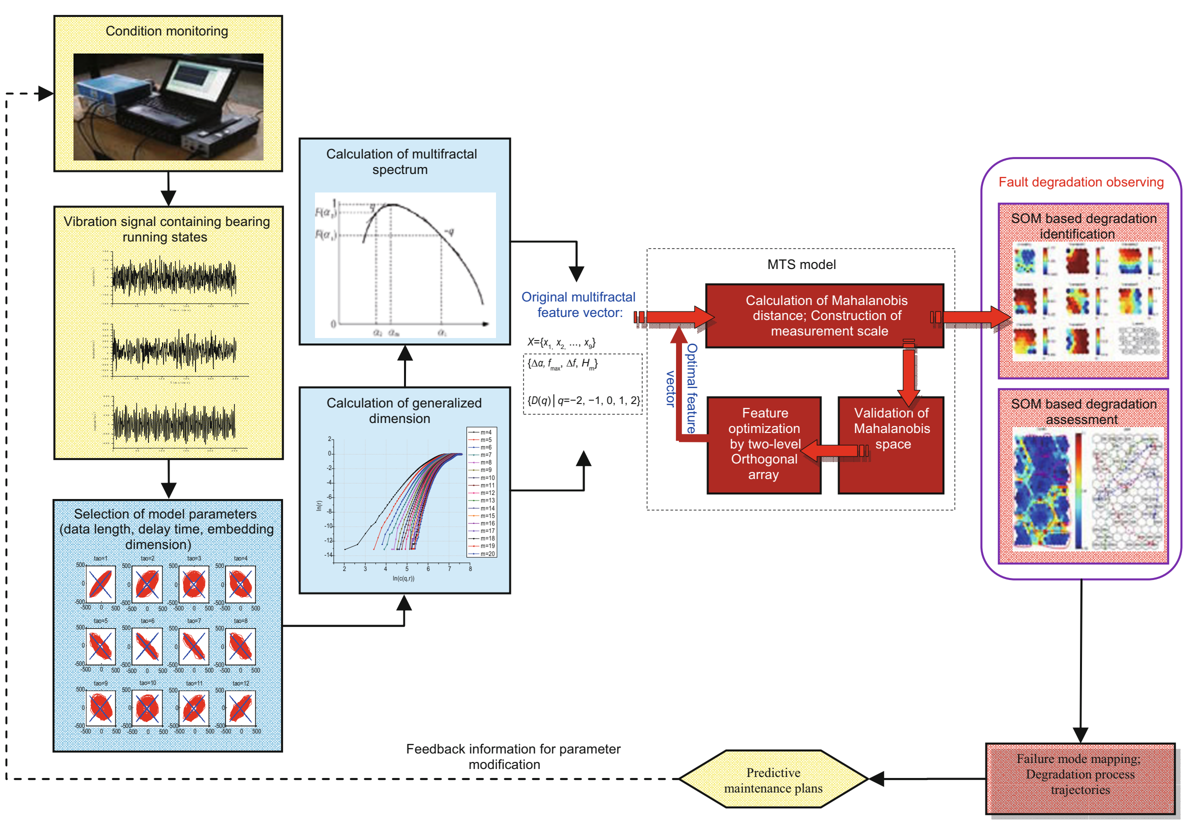

Fig. 1 Schematic of the early incipient fault diagnosis and prediction methods

been established.

2) The nonlinear relationship between the selection scheme of multifractal features and diagnosis accuracy has been established, based on which a statistic optimization method that only uses a few samples with abnormal states is also implemented, and hence the influence that the diagnostic process is affected by the number of samples and personal subjective factors can be largely reduced.

3) A diagnostic and prognostic method based on self-organization mapping (SOM) for early degradation in complex mechanical systems has been further established (Hu et al, 2013). Multifractal features also play an important role in the degradation observing process for the identification of incipient faults. By self-organization mapping the current degradation state can be identified and the degradation trend can be tracked dynamically which will help to predict future hazards or failures in advance.

4) An integrated diagnostic platform has been established for incipient faults in oil pipelines and transferring pump units (Hu et al, 2009b) , which can be used to simulate different fault modes, positions and various levels of degradation.

4.2 Multilevel integrated diagnosis and prognosis technology for coupling faults

In order to control the probability of fault occurrence, system reliability or performance prediction is an effective way to track the degradation of systems in the future and make a proper proactive maintenance plan to avoid failure or reduce the fault influential range. In complex engineering systems, most single faults have multiple propagation paths, and different propagation paths may lead to different consequences, some of which may gradually recover by its self-control system, while others may further cause adjacent components' failure and eventually lead to catastrophic accidents by failure propagation behavior. Meanwhile not all of the compatible fault propagation pathways derived from traditional risk analysis would happen in the real world, since a considerable proportion of them have a very low occurrence probability, which usually make it hard for safety engineers to find the actual fault root causes and to choose the best time for repair.

To meet the urgent need to solve the above challenges, we proposed multilevel integrated diagnosis and prognosis technology for coupling faults (shown in Fig. 2), which can effectively identify the real root causes of multiple faults in complex systems, and predict the residual life under the conditions of components with dependent failures.

The significance of the contribution can be presented as follows:

1) The interaction and dependency among entities in specific complex systems are considered and then presented by the model of multiple failure propagation paths.

2) By integrating the HAZOP model, degradation model, dynamic Bayesian network (DBN) model, monitoring model, assessment model, risk evaluation model and the prediction model, a hybrid and integrated safety prognosis model (ISPM) is developed based on dynamic Bayesian networks (Hu et al, 2010) to reduce fault occurrence probability effectively no longer relying on the assumptions of failure independence.

3) An ant colony algorithm is further used on the basis of the DBN model in ISPM to search for the most probable fault propagation path with an estimated risk value (Hu et al, 2011), which helps to take safety-related actions in time to control fault influential ranges and reduce the fault consequences.

4) This technology has been largely applied on many complex petroleum engineering systems, such as gas turbine compressor systems in long transportation pipelines (Hu et al, 2012c), large scale chemical facilities, oil-gas gathering and transporting systems. These cases show that this technology is able to improve the accuracy and efficiency of safety management for multi-component and multi-hazard complex systems, providing adequate advised safety-related actions, contingency plans and proactive maintenance plans.

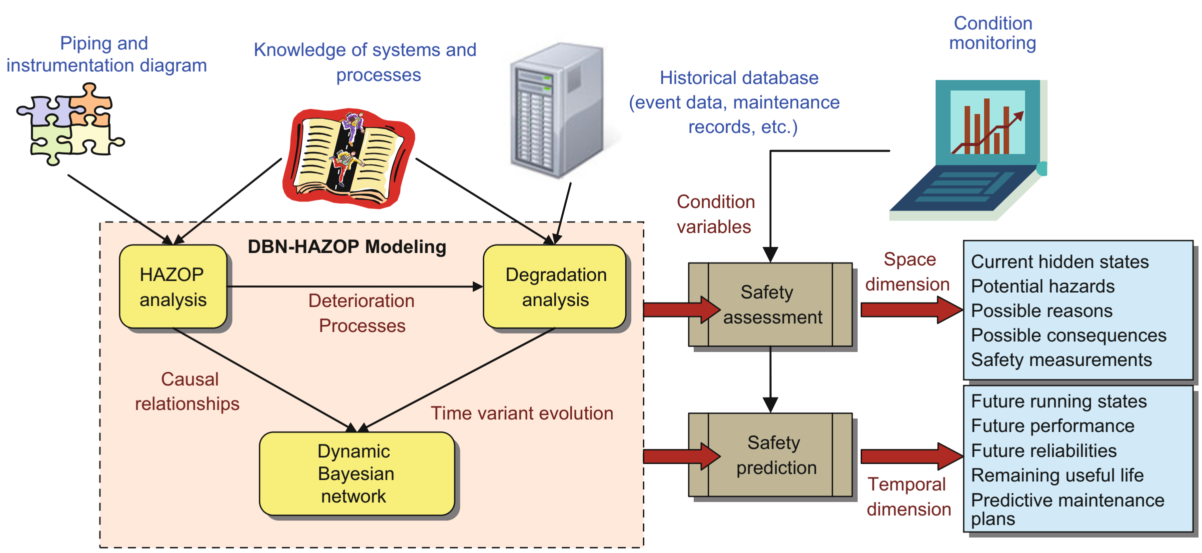

Fig. 2 Multilevel integrated diagnosis and prognosis technology for coupling faults

4.3 Dynamic safety assessment and predictive maintenance technology of complex system

The safety status of a complex system is usually determined by its historical, current and future states together. The safety assessment process of such system should have dynamic and time variant characteristics, which helps to track the dynamic states of the system and predict future probable danger in advance. In order to overcome the disadvantages of traditional static safety assessment approaches, the results from which are often delayed and prone to produce false alarms, an adaptive online safety assessment method is proposed (shown in Fig. 3), which consists of a dynamic adaptive weighting scheme.

An integrated dynamic assessment model based on “3-D” time perspective is further presented to integrate the historical, current and future safety performance of the system in a unit framework, considering both assessment and pre-warning of the system functions (Hu et al, 2012a). Other technologies are the quantitative safety evaluation model based on fuzzy information fusion (Hu et al, 2009c), intelligent risk assessment for pipeline third-party interference (Hu et al, 2012b) and a new opportunistic maintenance model with a fault preventive defense function (Hu et al, 2012c). These technologies are helpful to track and predict the safety status of a system dynamically and to discover potential faults in time, and to help to restrain the fault symptoms successfully by proactive maintenance.

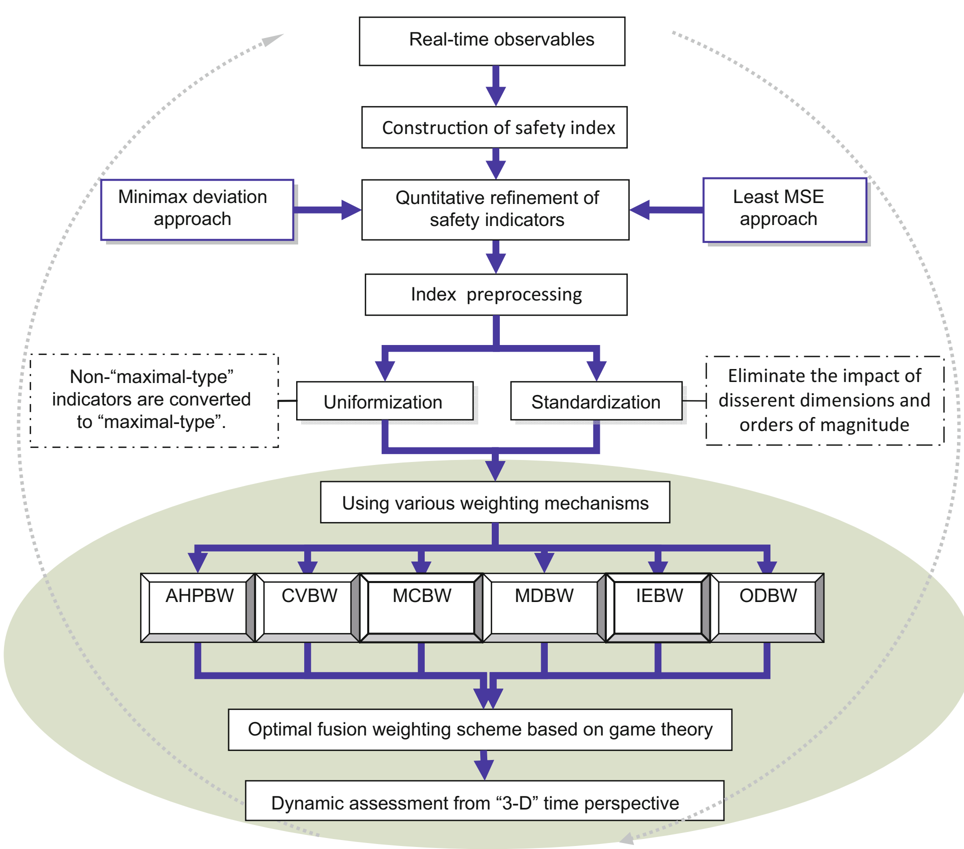

Fig. 3 Dynamic safety assessment and predictive maintenance technology of complex systems (AHPBW: Analytic hierarchy process-based weighting, CVBW: Coefficient of variation-based weighting, MCBW: Multiple correlation coefficient-based weighting, MDBW: Maximum deviation-based weighting, IEBW: Information entropy-based weighting, ODBW: Optimal distance-based weighting)

5 Conclusions and future directions

Although in many aspects good progress has been made, incidents have not stopped occurring and it is quite obvious that in every aspect further development of knowledge and technology of safety prognostic is needed. The problems existing in current research work can be summarized as “five more five less” phenomena: more focus on component faults, less on system faults; more focus on qualitative study, less on quantitative analysis; more focus on single faults, less on multiple faults; more focus on static risk, less on dynamic risk; more focus on current risk assessment, less on risk prediction. Therefore, further progress is needed to address newer aspects of the safety prognostic in these petroleum engineering systems. The intellectual challenges associated with these questions can be categorized into four classes.

1) The breakthrough from qualitative to quantitative research

The research of safety prognostic usually can be divided into five levels: first, to monitor the fault symptoms, secondly to identify the fault modes, on the third level root cause of the fault should be diagnosed, on the fourth level the damage degree of fault should be evaluated, and on the fifth level the future developing trend of the current fault will be predicted and the residual life will be calculated to give warning in advance.

If the first to the third level of study can be called qualitative research, then the fourth and fifth level are considered as quantitative research. On the basis of qualitative analysis, quantitative safety prognostic research can reveal the regularity of the occurrence, development, evolution and propagation of fault states in complex systems. This provides a foundation for further reliability assessment and life prediction for complex systems.

Further research is needed to pursue this line of quantitative safety prognosis using online monitoring and fault or abnormal event identification, model-driven or data-driven evaluation of degradation, prediction of fault trends and their effect on other related units and the remaining useful life.

2) The breakthrough from research on single faults to multiple fault prognostics

The prognostic of single faults is now mainly to rely on signal processing methods, which are usually easy to implement, however in industrial uses, there are strong limitations of its low accuracy, weak generalization ability and bad versatility, which severely restricts its application especially in complex engineering systems.

For such complex systems, the causes of the failure are usually not single, but include many factors which associate and interact with each other, which bring more difficulties for the prognostic work. Therefore, from the perspective of single faults, it will lead to overlooked risks or false alarms. Further research is needed to pursue this line to accurately identify composite faults and predict their mutual influence trend and impact on the overall operation of the system.

3) The breakthrough from the research on component faults to system faults

Another area where progress is needed is multi-perspective modeling for system failures, as interactions among the units of the complex system are the essential reason of the occurrence of a failure or accident. Component based prognostic analysis can usually identify induced faults, while the inherent hazard still exists without elimination. The reason is that component based prognostic studies often ignore the interaction among components, the external environment and the operation adjustment, which have a lot influence on the degradation process of components, making the results too optimistic and unrealistic.

Further research is needed to pursue this line of multi-perspective modeling of complex petroleum engineering systems, developing different views of complex systems from the perspectives of structure, behavior and function, predicting the failure propagation behavior of the system under various conditions, both normal and abnormal, and its final impact on the intended function.

4) The breakthrough from static to dynamic risk prediction

As noted earlier, the prognostic work, which is different from traditional fault diagnosis and assessment, aims to carry out proactive control before the incipient fault stage, and to establish a consciousness of failure prevention defense. Therefore, the dynamic tracking of the logistics, energy coordination and harmful energy conversion of system input and output, will be the focus of safety prognosis in complex systems.

Because all of the operation processes, environmental factors, operation and the degradation processes of units in complex systems are dynamic, further research is needed to study deeply how to automatically update the forecasting methods and the model structure and parameters according to changes in the external environment, operation adjustment and its dynamic degradation processes. By understanding the mapping relationship between the evolution and phenomena of failure or degradation, the safety prognostic work can be able to reflect the safety characteristics of the system dynamically in real time.

In brief, in the long run considerable technological help will come from the above future progress in taming the complexity of petroleum engineering systems, which will result in more effective safety prognostic and diagnostic systems for monitoring, analyzing, and controlling systemic risks, implementing the transformation from the traditional “fail & fix” maintenance practices to “predict & prevent”. However, getting there will require innovative thinking, bolder vision, and realizing some breakthroughs in and about the petroleum safety engineering industry.

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References

Djurdjanovic D, Lee J and Ni J. Watchdog Agent—an infotronics based prognostics approach for product performance assessment and prediction. International Journal of Advanced Engineering Informatics, Special Issue on Intelligent Maintenance Systems. 2003. 17(3-4): 109-125

Holland J H. Complex adaptive systems. Daedalus. 1992. 121(1): 17-30

Hu J, Zhang L, Liang W, et al. Mechanical incipient fault detection based on multifractal and MTS method. Petroleum Science. 2009a. 6(2): 208-216

Hu J, Zhang L, Liang W, et al. The application of integrated diagnosis database technology in safety management of oil pipeline and transferring pump units. Journal of Loss Prevention in the Process Industries. 2009b. 22(6): 1025-1033

Hu J, Zhang L, Liang W, et al. Quantitative HAZOP analysis for gas turbine compressor based on fuzzy information fusion. Systems Engineering—Theory & Practice. 2009c. 29(8): 153-159

Hu J, Zhang L, Liang W, et al. An integrated method for safety pre-warning of complex system. Safety Science. 2010. 48(5): 580-597

Hu J, Zhang L, Liang W, et al. An integrated safety prognosis model for complex system based on dynamic Bayesian network and ant colony algorithm. Expert Systems with Applications. 2011. 38(3): 1431-1446

Hu J, Zhang L, Liang W, et al. An adaptive online safety assessment method for mechanical system with pre-warning function. Safety Science. 2012a. 50(3): 385-399

Hu J, Zhang L, Liang W, et al. Intelligent risk assessment for pipeline third-party interference. Journal of Pressure Vessel Technology, Transactions of the ASME. 2012b. 134(1): 165-173

Hu J, Zhang L, Liang W, et al. Opportunistic predictive maintenance for complex multi-component systems based on DBN-HAZOP model. Process Safety and Environmental Protection. 2012c. 90(5): 376-388

Hu J, Zhang L and Liang W. Dynamic degradation observer for bearing fault by MTS-SOM system. Mechanical Systems and Signal Processing. 2013. 3(2): 385-400

Lee J, Deng C L, Tsan C H, et al. Product life cycle knowledge management using embedded Infotronics: methodology, tools and case studies. International Journal of Knowledge Engineering and Data Mining. 2010. 1(1): 20-36

Lee J, Ni J, Djurdjanovic D, et al. Intelligent prognostics tools and e-maintenance. Computers in Industry. 2006. 57(6): 476-489

Liu D, Xu H, Zhang J. Quantitative risk evaluation methods for multi-factor coupling complex flight situations. Acta Aeronautica et Astronautica Sinica. 2013. 34(3): 509-515

Markowski A S, Mannan M S and Bigoszewska A. Fuzzy logic for process safety analysis. Journal of Loss Prevention in the Process Industries. 2009. 22(6): 695-702

Markowski A S, Mannan M S, Bigoszewska A, et al. Uncertainty aspects in process safety analysis. Journal of Loss Prevention in the Process Industries. 2010. 23(3): 445-454

Mitchell S M and Mannan M S. Designing resilient engineered systems. Chemical Engineering Progress. 2006. 102(4): 39-45

Rajaraman S, Hahn J and Mannan M S. A methodology for fault detection, isolation, and identification for nonlinear processes with parametric uncertainties. Industrial and Engineering Chemistry Research. 2004. 43(21): 6774-6786

Suzuki K and Munesawa Y. How to prevent accidents in process industries? Recent accidents and safety activities in Japan. The 4th World Conference of Safety of Oil and Gas Industry, June 27-30, 2012, Seoul, Korea

Venkatasubramanian V. Prognostic and diagnostic monitoring of complex systems for product life cycle management: challenges and opportunities. Computers & Chemical Engineering. 2005. 29(6): 1253-1263

Venkatasubramanian V. Systemic failures: challenges and opportunities in risk management in complex systems. AIChE Journal. 2011. 57(1): 2-9

Wang Y, West H H and Mannan M S. The impact of data uncertainty in determining safety integrity level. Process Safety and Environmental Protection. 2004. 82(B6): 393-397

Wu F, Wang T and Lee J. An online adaptive condition-based maintenance method for mechanical systems. Mechanical Systems and Signal Processing. 2010. 24(8): 2985-2995

Xia T, Xi L, Lee J, et al. Optimal CBPM policy considering maintenance effects and environmental condition. International Journal of Advanced Manufacturing Technology. 2011. 56(9-12): 1181-1193

Yang X and Mannan M S. An uncertainty and sensitivity analysis of dynamic operational risk assessment model: a case study. Journal of Loss Prevention in the Process Industries. 2010a. 23(2): 300-307

Yang X and Mannan M S. The development and application of dynamic operational risk assessment in oil/gas and chemical process industry. Reliability Engineering and System Safety. 2010b. 95(7): 806-815

Yun G W, Rogers W J and Mannan M S. Risk assessment of an LNG importation terminal using Bayesian-LOPA methodology. Journal of Loss Prevention in the Process Industries. 2009. 22(1): 91-96

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