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Risk based opportunistic maintenance model for complex mechanical systems

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ABSTRACT

The essence of the complex mechanical system can be considered as an open system. There exist coupling relationships between various parts in the system and also between different fault modes, which result in multiple fault propagation paths. Considering the safety, benefits and maintenance loss, parameters such as downtime losses, minimal repair costs, corrective, preventive and opportunistic maintenance costs, should be analyzed comprehensively to investigate the influence of different maintenance strategies.

A new risk based opportunistic maintenance (RBOM) model considering failure risk is proposed in the paper. It helps to convert the negative random factors caused by single faults to a favorable opportunity of preventive defense against failure for other slight degraded components in advance, so the overall economic losses could be reduced. The global optimization algorithm is further developed to realize RBOM policy. Case studies are provided to illustrate the proposed approaches, with sensitivity analysis of the position, time, style and criterion of the RBOM strategy. Comparative study with the widely used maintenance policy demonstrates the advantage of the proposed method can significantly reduce the maintenance cost and failure risk, and are expected to bring immediate benefits to the energy industry.

1. Introduction

As modern machinery or equipment becoming increasingly large-scale, high speed, automatic and intelligent, complex mechanical systems such as compressors, oil pumps, gas turbine units which are widely used in energy industry, constitute an open complex giant system (OCGS). The malfunction of such OCGS may lead to serious or even catastrophic accidents causing great economic losses. However the components of these mechanical OCGS system and their failure modes highly interact and effect each other, which make up a complicated fault propagation network (FPN). The majority of single failures usually have multiple propagation paths, so any local minor deviation could be spread, diffused, accumulated and enlarged through the FPN, finally resulting in serious safety accidents and economic loss.

It is understood that conducting proper maintenance is an effective way to keep mechanical systems in good condition. A lot of efforts have been made on maintenance strategies which play great roles in improving operational safety, minimizing maintenance costs, and reducing the frequency and severity of in-service system failures.

Traditional strategies of repair and maintenance, such as time based maintenance (TBM), condition based maintenance (CBM) and detection based maintenance (DBM), can be used to temporarily repair the fault or failure parts without eliminating the root cause. Therefore in practice, these activities are generally imperfect and cannot restore the system to as good as new. Even though some degraded components are replaced, the cumulative wear on adjacent components may go unnoticed and worsen the condition of the relative parts, and the system as a whole. In this way, the repaired system still has incipient hazards which will initiate further degradation again. On the other hand, corrective maintenance after system breakdown will cause great economic loss, and interrupt the normal continuous production process of company. Simultaneously the shutdown process in maintenance may also trigger new safety troubles (Gao, 2005). Currently corrective maintenance and time-based maintenance are widely used in energy industry for complex mechanical systems, which take advantage of ease of management, particularly in the case of extreme conditions.

A new idea comes out that taking the correlation in term of FPN into account could provide favorable opportunities to reduce the probability of secondary accident. There is the reason that shutdown or decomposition of the whole system for a long period of time are usually required during the repairing process of a certain failure component, which brings a good opportunity to carry out the preventive repair of other deteriorated parts (Laggoune, Chateauneuf, & Aissani, 2009), when the whole system lies in the idle state. In this way, the corrective repair of failure component

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and the preventive repair of other degraded components with certain relevance (economy relevance, fault relevance, function relevance, structure relevance, etc.) can be performed together (Dekker & Wildeman, 1997; Nicolai & Dekker, 2006; Wang, 2002). Fortunately, opportunistic maintenance can realize this function. In opportunistic maintenance, whenever a failure occurs in the system, the maintenance team is sent onsite to perform corrective maintenance, and take this opportunity to simultaneously perform preventive maintenance on the other components in the failed systems and the running systems and their components which show relatively high risks. Economic dependencies exist among various components and systems. When a down time opportunity is created by the failed components, maintenance team may perform preventive maintenance for other components satisfying pre-specified decision conditions, such as certain age thresholds. As a result, substantial cost can be saved comparing to separate maintenance for the components. That means it can not only be used to reduce the downtime losses, make full use of maintenance resource, save the repair cost caused by disassembling and assembling, but also reduce the whole risk of failure by restore other related degraded components in complex systems.

Many kinds of opportunistic maintenance scheduling have been developed which pay much attention to the system reliability. In term of the different system configurations, different opportunistic maintenance models for multi-unit systems have been proposed. Ding and Tian (2012) proposed opportunistic maintenance policies for wind farms which are defined by the component's age threshold values, and different imperfect maintenance thresholds are introduced for failure turbines and working turbines. Laggoune et al. (2009) proposed maintenance plan which was based on opportunistic multi grouping replacement optimisation for multi-component systems. Derigent, Thomas, Levrat, et al. (2009) presented a fuzzy methodology for assessing component proximity on which can be implemented opportunistic maintenance strategy. Iung (Iung, Levrat, & Thomas, 2007) proposed an odds algorithm-based opportunistic maintenance task execution to select a production stop in order to perform a just-in-time maintenance action preserving finality performances and not only component conditions. For a certain type of large-scale mechanical system including multiple units, Liu, Zhu, and Shao (2009) put forward a kind of condition-based opportunistic maintenance strategy based on actual degradation state, considering economic relevance of repair. Chen, Jin, and Huang (2009) proposed an opportunistic maintenance control strategy using optimal repair interval as a benchmark. In his work, a simulation algorithm based on Monte Carlo method for the solution of optimal maintenance interval and opportunistic maintenance coefficient is further presented with the target of maximum availability. Zhang, Wu, and Li (2012) established a desired repair cost rate analysis model based on the renewal process theory to determine the optimal opportunistic maintenance strategy with the optimal objective of minimum expected repair cost rate of the system. Barata, Soares, Marseguerra, and Zio (2002) models continuously monitored deteriorating systems by using Monte Carlo simulation and embedding the resulting model within an "on condition" maintenance optimization scheme that aims at minimizing the expected total system cost over a given mission time. Zhou, Xi, and Lee (2007) tried to integrate sequential imperfect maintenance policy into condition-based predictive maintenance (CBPM), and presented a reliability-centered predictive maintenance policy for a continuously monitored system subject to degradation due to the imperfect maintenance. Zhou, Xi, and Lee (2009) further pays attention to the interaction among complex system components and fault modes, which help to study the multi-objective optimization on maintenance decision making.

However, two issues still need to be addressed. First, the majority of models that appear in above literatures make maintenance policies which are defined by the component's age threshold values. In many cases though, this assumption has proven to be far from the reality especially for energy industries where the safety aspect is important. The impact of an accident caused by failure is often very sensitive and significant comparing to maintenance cost.

Second, for multi-component systems, an optimal maintenance policy must take into account the combination among the various parameters of the maintenance activities, such as the position of the components which need repair, downtime losses, minimal repair costs, corrective or preventive maintenance costs, and failure risk. However, in above literatures few models analyzed all of them dynamically during the whole life cycle of systems.

To address the issues above, in this paper, a risk-based opportunistic maintenance approach is developed for complex mechanical systems to take advantage of the maintenance opportunities considering safety factors and their coupling effect. The model is established by utilizing the risk evaluation of system shutdown caused by component failure. This method overcomes the limitation that traditional model only considers component's age for decision and ignores the relationship between non-linear characteristic of the parameters corresponding to different maintenance policies. A global optimization algorithm as solution procedure is further developed for dynamic maintenance decision during the whole life cycle of the complex mechanical systems simultaneously considering various important parameters. By utilizing the proposed model the degraded components can be repaired proactively in advance with quite low economic cost during the period when failed components are under corrective maintenance. In this way, the fault coupling or propagation effects can be inhibited and the failure risk of the overall system can be reduced, so minimum failure loss could be achieved.

2. Risk based opportunistic maintenance strategy

According to the system failure model analysis, after new equipment being put into production, components which are in service will gradually deteriorate, so the corresponding failure rate and the risk level of random failure will increase (called "aging loss period") together.

When fault or failure occurs in a certain component which will cause system breakdown, the whole complex system usually has to shut down for maintenance; on the other hand when the preset preventive maintenance interval arrives, planed outage should also be carried out to perform preventive maintenance. Although above both type of maintenance strategies need to shut down system, the downtime and maintenance cost of the former one are usually more grievous than the latter, and the former situation may even lead to serious accidents and environmental pollution with high risk. During the period of system outage, the opportunity for proactive maintenance of other degraded parts (which has not met the failure threshold and could still work for a while) appears in advance. This type of work called opportunistic maintenance could reduce the possibility of future corrective maintenance and save large amounts of maintenance cost. However not all degraded parts should be repaired or replaced for opportunistic maintenance, but only the parts which meet certain prerequisites will be maintained in advance before their preventive maintenance intervals arrive, since improper proactive maintenance also makes maintenance budget added and unnecessary waste of manpower and material resources. So the problem here may lies in what kinds of preconditions (i.e. pre-specified decision conditions) are set for the implementation of opportunistic maintenance.

The determination of preconditions should concern following factors especially for complex mechanical system, which include