Research Status of Prognostics and Health Management in Nuclear Field

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ABSTRACT

Recently, the concerns of Nuclear Power Plants (NPPs) safety and reliability have increasing because of Fukushima disaster and NPPs increasing operating years. Operational experience has shown that greater situational awareness of the state of safety-critical nuclear plant System, Structure, and Components (SSCs) is necessary, particularly as they age due to exposure to harsh service conditions. While replacement of a subset of components is possible, and may even be economically attractive, it may be economically prohibitive to replace several of the lager components, including the reactor pressure vessel and primary piping. Thus, characterization, management, and mitigation of aging-related degradation in these critical passive components become important to maintain safety margins.

In order to deal with these problem above mentioned, thus, it is necessary to develop Prognostics and health Management (PHM) technology. The key technology in PHM is to detect degradation and anomalies and to determine Remaining Useful Life (RUL) and Probability of Failure (POF) of SSCs. The prognostics results can be used to manage the evolving health and condition of nuclear plant SSCs. The prognostics information is used in a Probabilistic Safety Assessment (PSA) model to assess the risk significance of the degradation and the corresponding reduced safety margin. In this paper, the review of the state of the art in PHM for nuclear industry was summarized. In addition, the prognostics application in case of Nuclear filed and technical gap for NPPs were described.

1. INTRODUCTION

Recently, the concerns of Nuclear Power Plants (NPPs) safety and reliability have increasing because of Fukushima disaster and NPPs increasing operating years. Operational experience has shown that greater situational awareness of the state of safety-critical nuclear plant SSCs is necessary, particularly as they age due to exposure to harsh service conditions. In order to deal with these problem above mentioned, thus, it is necessary to develop Prognostics and health Management (PHM) technology.

The PHM refers specifically to the phase involved with predicting future behavior, including Remaining Useful Lifetime (RUL), in terms of specific data for current operating conditions (run-time data) and components (or plant), and then required maintenance actions to maintain system health are scheduled. Therefore, as mentioned above, PHM can apply to Long Term Operation (LTO) of existing NPPs above as well as Small Modular Reactor (SMR) which is new designed as Generation-IV. In case of SMR, SSCs will be designed as integrated type. Therefore, establishing maintenance period is most important than existing NPPs. In order to establish proper maintenance period, PHM techniques will be applied and be utilized.

In this paper, the research statue in NPPs is described in chapter 2. In the chapter 3, as an application, reliability data update method is suggested by using prognostics. Finally, technical gaps are described to apply PHM for NPPs.

2. RESEARCH STATUE IN NPPS

For the sensors, monitoring techniques have been proposed to assess the calibration of sensors using data collected during plant operation (Bickford, Davis, Rusaw, and Shankar, (2002)). In 2000, the U.S.NRC accepted the generic concept of monitoring for sensor calibration assessment and calibration interval extension (U.S. NRC (2000)). However, no U.S. plant successfully obtained the license amendment necessary to implement calibration interval extension. The Sizewell BNPP in the United Kingdom does employ monitoring for sensor calibration.

Motors were applied for monitoring and diagnostics. Induction motors are commonly monitored online through vibration testing, electrical signature analysis, and temperature monitoring. Motor Current Signature Analysis (MCSA) monitors specific frequencies for sign of impending anomalies and faults (IAEA, (2013)), (Korkua, Jain, Lee, and Kwan, (2010)), (Thomson & Fenger, (2001)). In addition, vibration monitoring can detect and diagnose mechanical issues. Deployed motor monitoring systems do not currently extend to prognostics of motor life.

The Reactor Coolant Pump (RCP) has received significant research attention for fault detection and diagnostics. The degradation and failure of RCPs and casing are commonly monitored through the RCP Vibration Monitoring System (RCPVMS) (Koo & Kim, (2000)), (Jarrell, Sisk, and Bond, (2004)). As an alternative to the current RCPVMSs, it developed a Sequential Probabilistic Ratio Test (SPRT)-based fault detection and diagnostic system.

For the valve, there are a verity of type of valve, thus a review of monitoring and diagnostic method for check valves was performed. Several studies have looked at using acoustic emission signals for valve health monitoring (Lee, Lee, Kim, Luk and Jung, (2006)). A check valve monitoring system using ultrasonic transducers coupled to a pipe was developed and patented. The remote testing methods that rely on accurate first principle models of the induction machine in the Motor Operate Valve (MOV) and an online valve diagnostic monitoring system was patented (Ghosh, Varde, and Stheesh, (2013)). In addition, monitoring and diagnostic system applied to a turbine control valve during transient operation.

In the Control Rod and Element Drive Mechanisms (CEDMs), recent work has focused on developing monitoring and diagnostics for CEDMs. The enhancement of the Digital Rod Position Indication (DRPI) resulted in single step accuracy; in-situ health assessment of the coil, cable, connectors, and power supply. The DRPI data can be used for performance testing, anomaly detection, and diagnostics for the CEDMs (McCulley, Morton, Caylor, and Hashemian, (2013)).

The passive SSCs can be further divided totally passive system (pipes, reactor vessel, etc.) and semi-passive (heat exchanger). The reason of divided that may be monitored through performance assessments and process parameters. These semi-passive components can be monitored and prognosed in much the same way that active components are considered (Kim, Kang, Heo, and Song, (2014)). Passive structures require alternate data collection methods that typically interrogate the structure and record responses. Thus, the research for the passive SSCs is ongoing. On the other hands, monitoring, diagnostics, and prognostic have been performed (Kim & Heo, (2016)).

The applications of PHM for NPPs are summarized as table 1. In the table 1, the target components for NPPs express status of maturity of each technology.

Table 1. The Application of SSCs in NPPs

Component	Monitoring	Diagnostics	Prognostics
Sensor	***	*	*
Motor	***	**	*
Pump	***	***	*
Valve	***	**	*
CEDM	***	**	*
Heat Exchanger	**	*	**
Passive Structure	**	*	*

***: Technology available for NPPs

** : Technology available further qualifications are required for specific applications

* : Technology in R&D domain, feasibility demonstrated

3. PHM APPLICATION IN NPPS

Prognostics was used to estimate reliability of Structure, SSCs, however, the concept of updating the Probabilistic Safety Assessment (PSA) model using monitoring and prognostics was proposed (Varde & Pecht (2012)) and performed (Ramuhalli, Ivans, Hirt, Wootan, Coles, Mitchell and Bonebrake, (2014)). By applying the characteristics of prognostics to the PSA, uncertainty in the PSA is reduced. A method for integrating prognostics can reduce the distinctions between beginning-of-cycle (BOC) and end-of-cycle (EOC) by using plant-specific data and effects on areas that require a periodic update of the PSA model, such as a Periodic Safety Review (PSR), continuous operation of NPPs, and Risk Informed Applications (RIAs). Figure 1 shows the concept of integrating prognostics and PSA model.

The PSA is one of the main safety assessment for NPPs, uses the Event Tree and Fault Tree (ET/FT) method. The ET/FT method was developed with each accident scenario and correlation of systems. The frequency of the end state of a specific accident scenario is calculated by combining an event tree and a fault tree. Also, using suggested method, the prognostics that estimate reliability of single SSC can estimate system wide reliability. These methods have been studying and the authors suggested more specific method.

The study that initiating event frequency for steam generator tube rupture was updated considering reliability steam generator tube was performed by using proposed methodology (Kim (2016)).

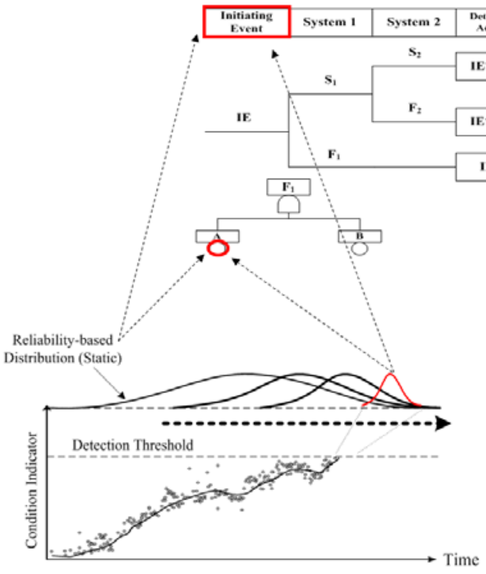

Figure 1. Concept of integrating prognostics and PSA model

The results shown in Figure 2 were obtained by assuming that plugging (repairing) is performed on tubes that exceed the threshold value upon the subsequent update cycle (15 Effective Full Power Year; EFPY) using a prognostics model. Figure 2 shows a graph before repairing the steam generator tube. The NUREG frequency (i.e., the conventional Initiating Event(IE) frequency) was calculated when there was no data for steam generator tube. If the reliability for steam generator tube was calculated in 5 EFPY, a new SGTR IE frequency value that considered the NUREG frequency was calculated. The frequencies are very close to the values of the prognostics in the early stage because the uncertainty of the prognostics is low; however, this uncertainty increased with time. Additionally, the mean and uncertainty values decreased when the part was changed by the monitoring value.

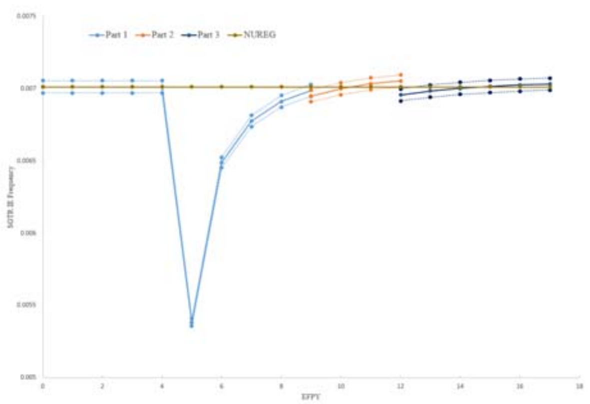

Figure 2. Updated Frequency of Initiating Event for Steam Generator Tube Rupture

4. TECHNICAL GAPS

PHM technology in the field of nuclear energy currently stays on a level of introduction the research. Most studies in the nuclear field are only focusing on the application and performance enhancement of fault detection and diagnosis. As PHM technology is still on a level of application and verification in other fields, the technical gaps such as uncertainty analysis and propagation, performance metrics, and verification and validation of PHM algorithms and models will be described. Specific problems in applying PHM technology to the nuclear energy are mainly sensor arrangement, sensor design, online monitoring & metrics.

First, a NPP is a large system, consisting of various devices. Most of the sensors in a NPP are installed with thermal-hydraulic consideration for nuclear safety, and mostly for an active system and process variables. Even though multiple sensor is set in place for various measurement in the thermos-hydraulically important parts, uncertainty is included in reality as the measured values are different depending on position even in the same part. Additional sensor can be added according to equipment reliability and LTO for PHM technology application, but it involves economic problem. Therefore, the existing sensors, as well as additional sensors, need to be given an optimal position for equipment reliability and LTO. It requires enhancement of monitoring function by adopting some technologies including a virtual sensor and sensor network, in addition to more sensors.

Secondly, a NPP is operated under harsh conditions such as high temperature, high pressure, and high radiation. Therefore, it requires the design of sensors that withstand such sever accident conditions. In addition, it is necessary to develop advanced sensor of load following operation and automation operation because of LTO and new reactor types which recently have become issues and high survivability sensor to maintain under severe conditions. In case of severe accident, core and parts of related primary side are inappropriate for the application of PHM due to transient. However, for the SSCs that play a role of safety barrier even in severe accident such as containment building, PHM can be applied, contributing to the safety of NPPs and supporting long term recovery action after a severe accident. Therefore, it should be developed not only with sensors capable of withstanding high temperature, high pressure and high radiation but also with circuit design and self-harvesting technology capable of operating at low or no power.

Finally, online monitoring & metrics needs to be set up. As mentioned above, most of the measuring instruments in NPPs are generally installed for active components and process monitoring. However, in the case of accident of NPPs, the accidents of a passive component such as piping and structure are often dealt with. Currently, nondestructive testing and risk-informed in-service inspection (RI-ISI) are conducted, but they are not reflecting the characteristics of each individual power plant. While performance indices for monitoring and diagnosis are well established, the one for failure prediction is not yet. Therefore, either online monitoring technology for a passive system needs to be applied, or semi-online monitoring should be carried out by a sequence of data acquisition from an overhaul. In addition, most of the safety equipment of NPPs is standby component. With the standby components, it's not easy to seek data for PHM as it operates only when necessary. Therefore it is in need of the technological support.

ACKNOWLEDGEMENT

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (No. 2014M2A8A2074105)

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