Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2016

Online Monitoring of Large Centrifugal Pumps in Nuclear Power Plants

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1. Introduction

Online Monitoring detects and diagnoses incipient faults, performs predictive maintenance, and can estimate the Remaining Useful Life (RUL) of Active and Passive Components before they fail. In an effort towards assisting Utility Partners to be proactive in the management of their Assets, the Electric Power Research Institute (EPRI) collaborated with the Idaho National Laboratory (INL) to develop a Fleet-Wide Prognostic and Health Monitoring (FW-PHM) Software Suite [1]. The FW-PHM is a web based diagnostic tools and databases designed for use in commercial NPP. As a result, Fault Signatures for the Generator Step-Up Transformers (GSU) and the Emergency Diesel Generators have been developed for further validation and incorporation into the Asset Fault Signatures (AFS) Database of the FW-PHM Architecture [1].

The AFS development process as designed by EPRI can be adapted to Large Centrifugal Pumps (LCP) in Nuclear Power Plants (NPP). For the purpose of this endeavor, the set of LCP considered are Safety Class-Motor Driven-Vertical Centrifugal Pumps for primary flow which includes Safety Injection, Containment Spray, and Residual Heat Removal. These are designed to be identical and functionally interchangeable. This paper presents Fault Signatures for the Safety Injection Pump, the Containment Spray Pump, and the Residual Heat Removal Pump.

2. Methods and Results

The International Council on Systems Engineering (INCOSE) V-model for systems development [Vee Model (ISO/IEC 15288)] has been tailored for the development of FS for the LCP (fig 1). The model identifies seven stages of system development beginning from the conception stage to final disposal. The first four stages of the V-model have been applied to this work.

2.1 Technology Exploration

The LCP are safety-related components which need to be monitored closely in order to detect fault and possibly preclude failure before they occur. The monitoring techniques that could be used for the

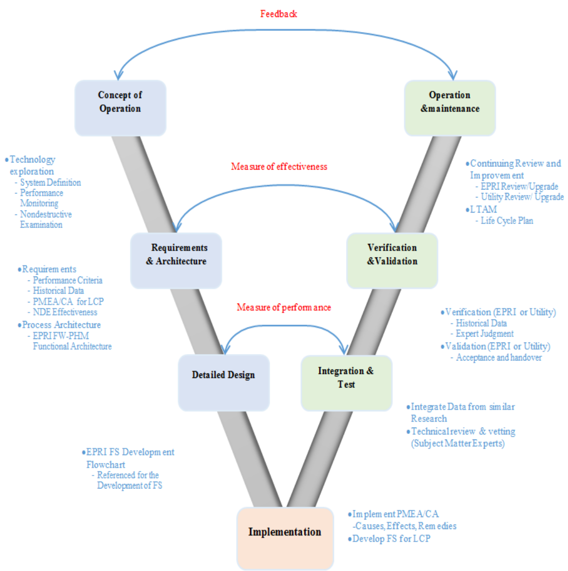

Figure 1: INCOSE V-model for FS development process

LCP are to be predictive in nature (condition based) and should be capable of identifying degradation with minimal or no risks added to the system. According to the ASME Code Section XI (in-service inspection of NPP components), Pumps of code class 1&2 should be subjected to volumetric, surface, internal surface, and visual examinations. The KEPIC Code MOB (in-service test of pumps) also provides for vibrational examination for these set of pumps.

Five non-destructive examinations (NDE) were selected based on the degradation mechanism of the LCP by referencing literature. These NDE technologies are: (1) Vibration Analysis, (2) Motor Circuit Analysis, (3) Infrared Thermography, (4) Ultrasonic Analysis, and (5) Oil Analysis.

2.2 Requirements and Architecture

2.2.1. Historical data. These are failures and operational experiences of LCP which have been documented over time. They include LCP failure mechanisms, failure indicators, failure causes, failure effects, time to failure, etc. The information was sourced from Literature, Plant O&M Documents, EPRI Guidance Documents, and Technical Reports.

2.2.2. Preventive Maintenance based 'Failure Mode and Effect Analysis' (PMEA). This is developed independent of service conditions and duty cycle. The analysis was done referencing historical data and also utilizing inputs from Subject Matter Experts [3]. The Time to Failure [4] and the Failure Occurrence as per the pump driver [5] were used as the bases for establishing the Criticality of the degradation identified for LCP. The 36 month period, recommended in NUMARC 93-01 for the evaluation of SSC performance, was adopted as the baseline to classify the pump failures. Also, a 10% Failure Occurrence was used as the basis for classifying the driver's degradation modes.

2.2.3. Non-Destructive Examination Effectiveness (NDE). The Effectiveness of the NDE selected for the various faults associated with LCP was determined by referencing Literature [6]. The Grades allocated were High, Medium or low depending on how reliable they are in diagnosing the associated faults.

2.2.4. Architecture. The Remaining Useful Life (RUL) Database as reflected in the figure (2) below is not covered in this work, because the technology is not completely ready for verification and validation [2].

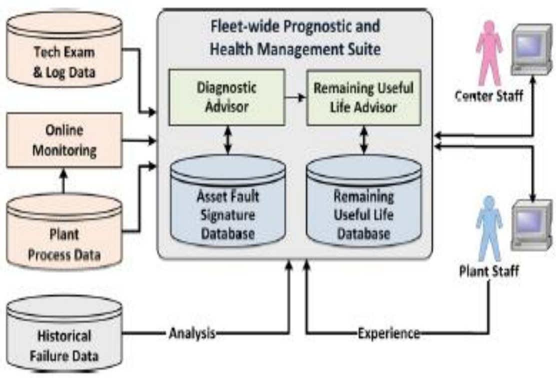

Figure 2: Functional architecture of the EPRI FW-PHM suite software [1]

2.3 Detailed Design

This states the details involved in the development of Fault Signatures (FS) for onward population of the AFS Database. This process was followed meticulously to define FS for the LCP (Fig.3).

2.4 Implementation

2.4.1 Discussion of Results. The PMEA as presented in table 1 shows the LCP fault types, their

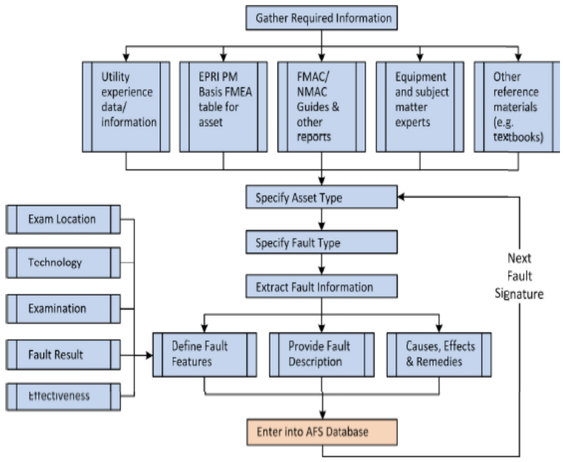

Figure 3: EPRI flowchart for asset fault signatures development [1]

causes, their effects, and their corresponding corrective actions. Failures of the Pump components that could occur within a 36 month period were classified Critical, while those that could occur much greater than 36 months were considered Minor. Also, the average failures for the Driver parts (thrust bearing, stator, rotor, others) that have below 10% probable occurrence were classified as Minor, while those that have greater than 10% were considered Critical. In Table 2, the Fault Features (FS), the NDE, and the NDE mode of application is presented. These NDE identified were then categorized as High, Medium, or Low. High signifies greater reliability in detecting the associated faults, while Low signifies a minimal reliability.

For the purpose of optimization, the data on table 1 should be compared with the results of table 2. Therefore, failures which have been categorized as 'Critical' and whose NDE effectiveness are 'High', should be selected for predictive monitoring (OLM). Other alternate combinations should be left to Planned Overhaul Maintenance (Disassemble).

3. Conclusion

Fault Signatures of the LCP for OLM has been developed following the INCOSE V-model systems development approach. The fault types, fault features, and their detection methods and effectiveness for the LCP were established by diligently following the guidelines recommended by EPRI. An optimization of the FS for OLM has been suggested for implementation. As a way of extending this work, a Cost-Benefit Analysis between OLM and the conventional Periodic Maintenance for the LCP in NPP is proposed.

Table 1: PMEA for LCP

Item	**Degradation**	**Causes**	**Effects**	**Remedies**	**Time to Failure (month)**	**Criticality**
Radial Bearing	Wear	Vibration, Design	Low efficiency	Use adequate Lubricant	36	Critical
	Fatigue/age	Design, Vibration	Excessive Vibration	Lubricate Bearings	34	Critical
Mechanical Seal	Wear	Vibration	Low efficiency	Replace seal	38	Critical
Impeller	Rubbing with casing	Design, Operation	Vibration	Lubricate Thrust Bearing	20	Critical
	Wear	Operation, Impeller lift	Low efficiency	Change Impeller	84	Minor
Shaft	Cracked	Design, Misalignment	Low efficiency, Vortexing	Replace Shaft	43	Minor
	Wear	Corrosion, Vibration	Low efficiency, Abnormal noise	Replace Shaft and Seal	105	Minor
Coupling	Cracked	Corrosion, Vibration	Low efficiency, Abnormal noise	Replace Coupling	60	Minor
Casing	Vanes fatigue	Design, Vibration	Reduced flow rate	Change Casing	127	Minor
	Wear	Corrosion,	Crack,	Change casing	144	Minor
Item	**Degradation**	**Causes**	**Effects**	**Remedies**	**Average Failure %**	**Criticality**
Thrust Bearing	Wear	Excessive vibration	High Bearing Temperature	Change Bearing	42	Critical
	Failure	Insufficient lubrication	Corrosion	Use adequate Lubricant		
Stator	Winding insulation degradation	Persistent overload	Motor overheating	Change Insulation of Lamination	33	Critical
	Lamination insulation degradation	Normal deterioration	Motor short circuit	Change Insulation of lamination		
	Loose bracing & blocking	Normal deterioration	Motor vibration and noise	Tighten/replace block		
Rotor	Failed Rotor Shorting Rings	Excessive vibration	Motor shutdown	Change rotor shorting rings	9	Minor
	Loose Lamination	Insufficient lubrication	Low motor efficiency	Change lamination		
Others					16	Minor

Table 2: LCP fault signatures and NDE effectiveness

Component	**Fault**	**NDE and Location**	**Fault Feature**	**Effectiveness**
Radial Bearing	Wear	*Vibration analysis*: Measure loading & vibration	High Loading & Vibration	High
	Fatigue or age	*Vibration analysis*: Measure Bearing housing vibration	High Bearing housing vibration	High
Mechanical Seal	Wear	*Ultrasonic analysis*: Measure Oil level	Low Oil level	Low

Component	**Fault**	**NDE and Location**	**Fault Feature**	**Effectiveness**
Impeller	Rubbing with casing	*Vibration analysis, Ultrasonic analysis*: Measure Impeller vibration & ultrasonic level	High Impeller vibration & Ultrasonic level	High
	Wear	*Vibration analysis*: Measure Pump head & flow rate	Low Pump head & Flow rate	High
Shaft	Cracked	*Vibration analysis, Ultrasonic analysis*: Measure Shaft vibration & ultrasonic	High Vibration & Ultrasonic level	High
	Wear	*Vibration analysis, Ultrasonic analysis*: Measure Shaft vibration & ultrasonic	High Vibration & Ultrasonic level	High
Coupling	Cracked	*Vibration analysis, Ultrasonic analysis*: Measure Coupling vibration & ultrasonic level	High Vibration & Ultrasonic level	High
Casing	Vanes fatigue/Wear	*Vibration & Ultrasonic analysis, Performance Trending*: Measure Casing vibration & performance	High Vibration Level, and reduced Performance	Medium
Thrust Bearing	Wear	*Vibration analysis, Ultrasonic analysis*: Measure bearing housing vibration, ultrasonic level, & lube oil contamination	High Vibration, Ultrasonic level, & contamination level	High
	Failure	*Vibration analysis, Ultrasonic analysis:* Measure Bearing housing vibration, Ultrasonic level	High Vibration & Ultrasonic level	High
Stator	Winding insulation degradation	*Infrared-thermography, Motor current signature analysis, Motor circuit analysis*: Measure Winding temperature	High Winding Temperature	Low
	Lamination insulation degradation	*Infrared-thermography, Motor current signature analysis, Motor circuit analysis*: Measure Stator insulation	High Core Temperature	Low
	Loose bracing & blocking	Scheduled restoration	High Core Temperature	Low
Rotor	Failed rotor band/shorting rings	*Infrared-thermography, Motor current signature*: Measure Circuit resistance	High Circuit Resistance	Medium
	Loose Lamination	*Infrared-Thermography, Motor current signature Analysis*: Measure Winding temperature	High Winding Temperature	Medium

ACKNOWLEDGEMENT

This research is supported by the 2016 research fund of the KEPCO International Nuclear Graduate School, Republic of Korea.

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