Online Monitoring of Plant Assets in the Nuclear Industry

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ABSTRACT

Today's online monitoring technologies provide opportunities to perform predictive and proactive health management of assets within many different industries, in particular the defense and aerospace industries. The nuclear industry can leverage these technologies to enhance safety, productivity, and reliability of the aging fleet of existing nuclear power plants. The U.S. Department of Energy's Light Water Reactor Sustainability Program is collaborating with the Electric Power Research Institute's (EPRI's) Long-Term Operations program to implement online monitoring in existing nuclear power plants.

Proactive online monitoring in the nuclear industry is being explored using EPRI's Fleet-Wide Prognostic and Health Management (FW-PHM) Suite software, a set of web-based diagnostic and prognostic tools and databases that serves as an integrated health monitoring architecture. This paper focuses on development of asset fault signatures used to assess the health status of generator step-up transformers and emergency diesel generators in nuclear power plants. Asset fault signatures describe the distinctive features based on technical examinations that can be used to detect a specific fault type. Fault signatures are developed based on the results of detailed technical research and on the knowledge and experience of technical experts. The Diagnostic Advisor of the FW-PHM Suite software matches developed fault signatures with operational data to provide early identification of critical faults and troubleshooting advice that could be used to distinguish between faults with similar symptoms. This research is important as it will support the automation of predictive online monitoring techniques in nuclear power plants to diagnose incipient faults, perform proactive maintenance, and estimate the remaining useful life of assets.

1. INTRODUCTION

The average age of existing commercial nuclear power plants (NPPs) in the United States is around 34 years. As these plants continue to age and their components degrade, it is important to understand their condition and be proactive in maintenance and replacement. The current periodic and condition-based maintenance practices at NPPs result in high maintenance costs and increased likelihood of human error. Additionally, the inability to identify developing faults can lead to either disabling component failure or forced plant outage. Implementation of advanced predictive online monitoring would minimize these limitations and enhance plant safety by enabling systems and maintenance engineers to diagnose incipient faults and estimate the remaining useful life (RUL) of their assets, thereby reducing operational costs by optimizing maintenance activities. Predictive online monitoring techniques include advanced diagnostic and prognostic techniques.

The U.S. Department of Energy, Office of Nuclear Energy funds the Light Water Reactor Sustainability (LWRS) program to develop the scientific basis to extend the operation of commercial light water reactors beyond the current 60-year licensing period. The Advanced Instrumentation, Information, and Control Systems pathway under the LWRS program is collaborating with the Electric Power Research Institute's (EPRI's) Long-Term Operations (LTO) program to conduct research and development on technologies that can be used to enhance long-term reliability, productivity, and safety of aging light water reactors. One of the primary areas of focus for the LWRS and LTO programs is *online monitoring (OLM) of active assets* in the nuclear industry.

An important objective of the online monitoring of active assets research is to implement predictive online monitoring for the existing fleet of NPPs. EPRI's Fleet-Wide Prognostic and Health Management (FW-PHM) Suite software was selected for use as a demonstration platform. The FW-PHM Suite was specifically developed by EPRI for use in the commercial power industry (both nuclear and fossil fuel). EPRI and Idaho National Laboratory (INL) are working with nuclear utility partners to develop diagnostic models in the FW-PHM Suite software for Generator Step-Up Transformers (GSUs) and Emergency Diesel Generators (EDGs). The nuclear utility partners include Shearon Harris Nuclear Generating Station (owned by Duke Progress Energy) for GSUs and Braidwood Generating Station (owned by Exelon Nuclear) for EDGs.

This paper presents the research and development performed to date with the GSU and EDG content development in the FW-PHM Suite and initial diagnoses. The paper is organized as follows. Section 2 summarizes some of the relevant works associated with fleet-wide monitoring. The FW-PHM Suite software architecture is briefly described in Section 3. Section 4 discusses the content development for GSUs and EDGs. Assessments of the diagnoses based on fault signatures entered in the FW-PHM Suite software are presented in Section 5. Finally, conclusions and future research are presented in Section 6.

2. Related Works

Fleet-wide diagnosis, prognosis, and knowledge management have gained significant interest across different industries. Review of some of the myriad of fleet-wide diagnosis and prognosis architectures, knowledge structures, and associated issues reported in literature is presented.

Deployment of a fleet-wide health management solution is challenging and requires a systematic approach (Johnson, 2012). The approach suggested in (Johnson, 2012) includes identifying assets and business needs, identifying critical components within assets, selecting sensory sources, and selecting prognostic methods.

Managing relevant knowledge arising both from modeling and monitoring of a fleet is essential (Monnin, Voisin, Leger, & Lung, 2011). A knowledge-structuring scheme based on ontologies for fleet-wide application of PHM in a marine domain was presented in (Medina-Oliva et al., 2012). In the case of fleets with heterogeneous assets, the knowledge-structure based on ontologies was utilized to search for assets based on similar characteristics (Monnin et al., 2011). Similarly, predictive maintenance of a fleet with homogeneous assets using an ontology based modeling approach was suggested by (Umiliacchi, Lane, & Romano, 2011).

In (Patrick et al., 2010) authors demonstrate that the threshold values indicating different fault conditions for a homogeneous fleet could be derived from statistical studies of fleet-wide behaviors of identical assets and known cases of faults. A similarity-based approach for estimating the remaining useful life of a fleet composed of similar assets was proposed by (Wang et al., 2008).

3. Fleet-Wide Prognostic and Health Management Suite

The FW-PHM Suite software is an integrated suite of web-based diagnostic and prognostic tools and databases, developed for EPRI by Expert Microsystems, specifically designed for use in the commercial power industry (for both nuclear and fossil fuel generating plants). The FW-PHM Suite serves as an integrated health management framework, as shown in Figure 1, managing the functionality needed for a complete implementation of diagnostics and prognostics (Electrical Power Research Institute, 2012). The FW-PHM Suite consists of four main modules: the Diagnostic Advisor, the Asset Fault Signature (AFS) Database, the Remaining Useful Life Advisor, and the Remaining Useful Life Database. The FW-PHM Suite has the capability to perform diagnosis and prognosis at different hierarchical levels, from the component level to the plant level, across a fleet of power units.

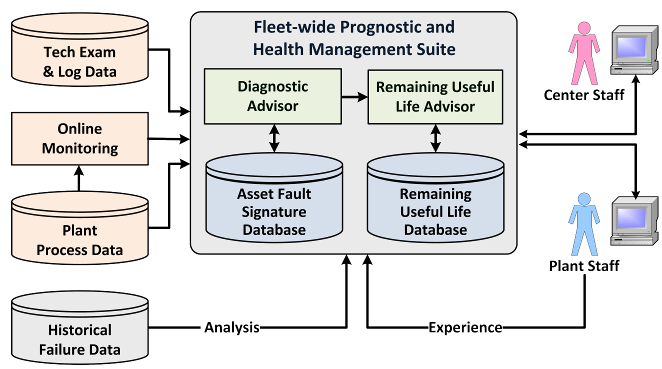

Figure 1. Data flow in the EPRI FW-PHM Suite software architecture (Electrical Power Research Institute, 2012).

The FW-PHM Suite uses fault signatures as a structured representation of the information that an expert would use to first detect and then verify the occurrence of a specific type of fault (Electrical Power Research Institute, 2012). A fault describes a particular mode of degradation that can be detected by analysis of plant information before the asset condition reaches the point of failure to meet a service requirement. Implied is an assumption that the fault is detectable by analysis of plant information and that the analysis can be performed in time to prevent or otherwise remedy the fault condition before it becomes a failure.

Fault signatures are developed for application to a specific type of asset and are therefore organized with reference to that type of asset. However, it is desirable to specify fault signatures as broadly as possible to be used in the entire industry. Many of the fault signatures defined in this paper can be applied to comparable assets used in similar service environments.

3.1. Asset Fault Signature Database

The Asset Fault Signature database organizes fault signatures collected from the many EPRI member utilities. At the most basic level, fault signatures are comprised of an asset type, a fault type, and a set of one or more fault features (symptoms) that are indicative of the specified fault. Each installation of the software has two separate database schemas: the master database maintained and distributed by EPRI, and a local database containing data developed at the plants or fleet monitoring center. Locally developed information can be exported and sent to EPRI for evaluation and possible inclusion in the master database that is shared amongst EPRI members. The AFS Database is populated via a content development exercise that is described in the following section.

3.2. Diagnostic Advisor

The Diagnostic Advisor identifies possible faults by comparing asset fault signatures with operating data. The Diagnostic Advisor is expected to be used on a daily or other periodic basis by technicians who are monitoring the health of a specific asset in the plant. Using either online data sources or information that is input manually, the Diagnostic Advisor presents the likely faults (if any), and, when appropriate, recommends additional tests that might be used to discriminate amongst the possible faults. The Diagnostic Advisor is expected to streamline the diagnosis process by helping the technician focus his/her efforts on the most likely faults and possible causes based on the operating behavior of the system.

3.3. Remaining Useful Life Advisor

The Remaining Useful Life Advisor calculates remaining useful life for an asset based on the model type, model parameters, input process parameters, and diagnostic information (from the Diagnostic Advisor). The RUL Advisor is expected to be used on a periodic basis by technicians who are monitoring the health of a specific asset in the plant.

3.4. Remaining Useful Life Database

The RUL Database organizes asset RUL signatures (i.e., models) collected from across the industry. At the most basic level, a RUL signature is comprised of an asset type, a model type, and model calibration parameters. The model type definition includes the definition of the input variables needed to run the model. Subject matter experts from the power industry, EPRI, and EPRI's partners/subcontractors will most likely develop RUL signatures. Figure 2 shows the modules available in the FW-PHM Suite software.

4. Content Development for the Asset Fault Signature Database

INL is working with subject matter experts from industry, EPRI, and EPRI's partners/subcontractors to develop content in the AFS Database for GSUs and EDGs. Currently, troubleshooting is typically a manual process that predominantly relies on expert knowledge and written documentation. The goal of content development is to capture this rich operating knowledge, creating a set of asset fault signatures organized in a standardized structure. The Diagnostic Advisor for automatic asset health monitoring uses these fault signatures and associated fault features. Content management for the asset fault signatures will be provided by EPRI.

Fault signatures for a specified asset must include, at a minimum, a fault description and associated fault features. Fault features represent a unique state of one or more parameters indicating a faulty condition; these parameters come from technical examinations of the asset. Therefore, identification of different technical examinations for a target asset is a critical step in the development of fault signatures. Some of the most common technical examination for GSUs and EDGs are presented in the following sections.

4.1. Technical Examinations of Generator Step-Up Transformers

The technical examinations listed below are commonly used to monitor the operation of GSUs (Lybeck et al., 2011). These examinations allow assessment of winding insulation degradation, loss of dielectric strength of insulating oil, cooling system effectiveness, and bushing degradation.

1. *Temperature analysis*. The top oil temperature reflects the effectiveness of a cooling system.
2. *Insulating Oil Analysis (online or offline).* Performing oil analysis allows assessment of the electrical property (e.g. dielectric strength), chemical properties (e.g., water content, acidity), and the physical property (e.g. interfacial tension (IFT)). Insulating oil loses its dielectric strength either due to increase in the moisture content or due to thermal aging. Acidity of insulating oil needs to be monitored, as an increase in acidity is harmful because if the oil becomes acidic, the solubility of the water in the oil increases and also deteriorates the winding paper insulation strength. Acidity is measured in terms of milligrams of potassium hydroxide present in one gram of oil. IFT measures molecular attractive forces between oil and water. A decrease in the IFT indicates the presence of contaminants in the oil and is measured in Dyne/cm.

Figure 2. The FW-PHM Suite main page.

3. *Dissolved gas analysis*. Another important chemical property of transformer insulating oil to be analyzed is the dissolved gas concentration. Thermal or electrical faults occurring inside the transformer decompose the hydrocarbon bonds, resulting in generation of gases within the transformer. One of the most important aspects of oil analysis is to measure the concentration of key dissolved gases, which include hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6). In addition to the key gases, carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2) are also generated, even under normal operating conditions. The gas ratios such as O_2/N_2, $CO2/CO$, C_2H_2/H_2, Doernenberg Ratios, Duval triangle (Duval, 2002), and Rogers Ratios indicate different types of degradation inside transformers.
4. *Doble Capacitance Test.* Measuring bushing capacitance is a standard technique used to determine bushing condition. The main capacitance (C1) test is conducted in the ungrounded specimen mode, i.e., the ground lead is not used for measurement, but instead the selected low voltage leads are used. The outcome of the C1 test allows assessment of contamination in the main body of the bushing. The tap capacitance (C2) test is conducted in the grounded specimen mode, i.e., at least part of the test current is measured through the grounded lead; the rest is measured through the low voltage leads, if used and not guarded. The outcome of the C2 test allows assessment of contamination in the oil and tap area.
5. *Sweep Frequency Response Test.* The frequency responses measured during a sweep frequency response test reflect the measured winding capacitance. These responses are compared to the reference sweep frequency responses. Any deviation in the measured responses from the reference indicates capacitance change that might be due to winding movement or core displacement.

4.2. Technical Examinations for Emergency Diesel Generators

The technical exams listed below are commonly used to monitor diesel engine operation (Pham, Lybeck, & Agarwal, 2012). These examinations allow assessment of degradation of valves, fuel injectors, seals, and piston rings as well as the overall health of the EDG engine.

1. *Temperature analysis.* Component temperatures (e.g., engine cylinders or exhaust manifold) indicate engine performance. Cooling water temperatures and lubricating oil temperatures (inlet, outlet, and their difference) are used to monitor the thermodynamic efficiency of the engine (Banks, 2001).
2. *Pressure and flow rate analysis.* Deviation of engine cylinder pressure (measured by a pressure transducer mounted on the cylinder head) from baseline pressure-time curves for each of the cylinders indicates a variety

of abnormal engine operating conditions. The key reference points in time are peak firing pressure, peak firing pressure crank angle, maximum pressure rise rate, start of injection, and start of combustion (Banks et al., 2001). Pressure and fluid volume measurements (inlet and outlet) from engine support systems such as the fuel oil system, lubricating oil system, cooling water system, and starting air system are used to identify leakage and component failure of the corresponding system. Abnormally low pressure in these systems usually indicates either system leakage of fuel, oil, water, or air or pump failure.

3. *Vibration analysis.* Vibration data from various engine components as a function of run time (or crankshaft angle) can be used to assess the condition of the bearing, the crankshaft, and other moving parts without physical examinations. The existence of peaks at frequencies higher than 2-times the line frequency in the engine vibration spectrum can indicate liner scuffing and blow by.

4. *Engine oil analysis (or lubricating oil analysis, online or offline)*: Oil analysis is used to detect metal particles (e.g., particle count according to size), fuel oil, water, or combustion products in the lubricating oil, indicating problems in the diesel engine, including mechanical wear of components, bearing failure, and leaking seals (Banks et al., 2001). There are three basic technical examination methods for oil analysis.

   Ferrography (International Standards Organization, 1999)*:* Ferromagnetic particles in the lubricating oil are counted using a magnetic field to separate the particles according to size. The ferrography oil analysis includes the following operations: collection of wear particles according to size on a transparent substrate; selection and separation of significant particles; inspection and evaluation of the particles and their morphology and nature; and identification of particles (i.e., type of material).

   Spectroscopy (American Society for Test and Materials, 2009): The frequency and intensity of light emitted from electrically excited particles are measured using a spectrometer to detect particles in the lubricating oil.

   Particle count: Particles are counted in the engine lube oil using a particle counter. The nature of particle counting is based on light scattering, light obscuration, or direct imaging when the particle passes through a high-energy light beam.

5. *Power analysis.* Voltage and frequency measurements at the outlets of an EDG potential transformer can be used to assess its performance and detect faults when these parameters are not within specified ranges.

4.3. Fault Signatures

A step-by-step procedure for developing and implementing an asset fault signature in the AFS Database is described in EPRI (2012) and shown in Figure 3. Several fault signatures have been developed and implemented in the AFS Database as part of a knowledge transfer exercise with utility partners for GSUs and EDGs. Two representative fault signatures are described below.

Primary winding paper insulation degradation is one of the common faults in transformers (Bartley, 2003). The two most common modes of primary winding paper insulation degradation are electrical and thermal.

Paper insulation degradation due to electrical discharges represents the occurrence of either a partial discharge phenomenon or an arcing phenomenon. A steep increase in the H_2 concentration level compared to other dissolved gases in the transformer insulating oil is an indication of partial discharge. Similarly, an increase in the H_2 and C_2H_2 concentration levels combined compared to other dissolved gases is an indication of arcing.

Paper insulation degradation due to thermal phenomenon can be diagnosed when a steep increase in the carbon monoxide concentration level is observed. As a result, a decrease in the CO_2/CO ratio is observed. Therefore, a decrease in the CO_2/CO ratio also indicates thermal degradation of primary winding paper insulation.

EDGs are safety-related assets that are required to operate reliably if the external grid power supply to a plant is interrupted. It is required to start, run, and take the basic load that is essential for safe shutdown of the plant. There are many faults that could lead to EDG failure. One of the faults is *improper valve timing* (alternately referred as ignition timing) for the diesel engine cylinder. An increase or decrease or both in cylinder temperature may be due to improper value timing. Lower and upper threshold limits are defined to monitor the change in cylinder temperature.

In Appendix A, the currently implemented fault signatures for GSUs and EDGs are summarized in Tables A1 and A2 respectively. The last column of Tables A1 and A2 (i.e., the 5^{th} column) lists the effectiveness of each technical examination. Effectiveness is used in ranking possible diagnosis of the Diagnostic Advisor, especially in a situation where the same technical examination is used to diagnose different fault types. These fault signatures represent the initial effort to create useful fault signatures for GSUs and EDGs, but do not create a complete diagnostic system for GSUs and EDGs.

5. Diagnosis Process

In this section, the ability of the Diagnostic Advisor to diagnose a developing fault in a GSU and an EDG is presented. The Diagnostic Advisor compares the simulated

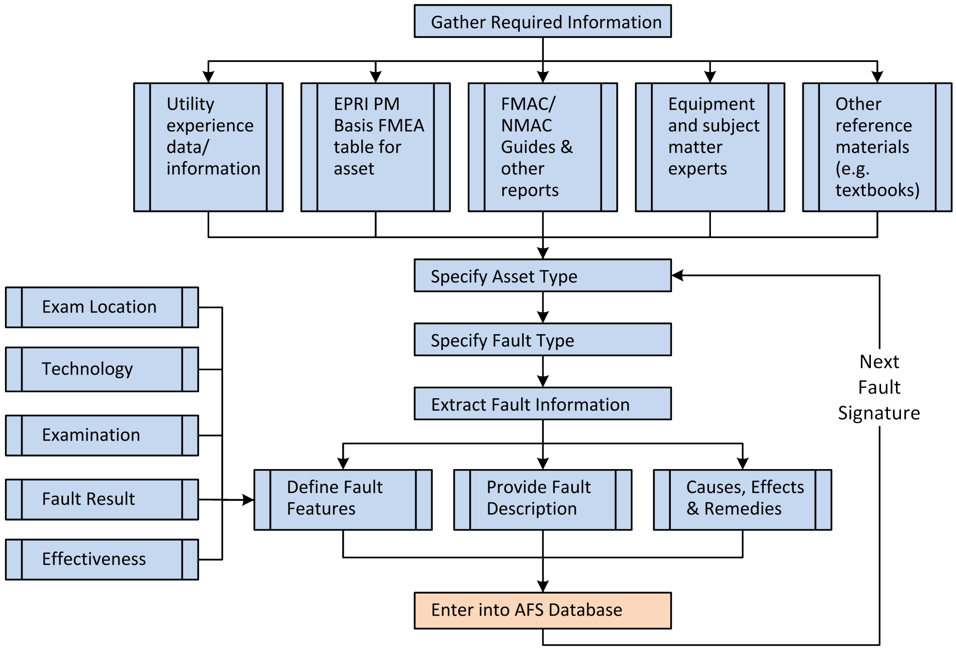

Figure 3. Steps involved in gathering asset fault signatures (EPRI, 2012).

operating data with the established fault signatures in the AFS Database, to assess the health of a plant asset. The diagnosis of primary winding paper insulation degradation in a GSU and of improper valve timing in an EDG is discussed.

5.1. GSU Primary Winding Paper Insulation Diagnosis

The Diagnostic Advisor's ability to diagnose the primary winding paper insulation degradation is discussed in detail in Agarwal et al. (2013). For the purpose of testing, the Diagnostic Advisor is connected to a simulated data stream in which an initial increase in the acetylene concentration level is followed by an increase in the carbon monoxide concentration level and a decrease in the CO_2/CO ratio. The threshold limits in the Diagnostic Advisor for each monitored gas level are mapped to 3-out-of-4 classification criteria (Condition 1 through Condition 3) developed by the Institute of Electrical and Electronics Engineers (IEEE) to classify risk to transformers (IEEE, 2008). Table 1 in IEEE (2008) lists the dissolved gas concentration for the individual gases for Condition 1 through Condition 4.

During simulation, when the acetylene concentration enters Condition 2, the Diagnostic Advisor identifies the change and generates a possible diagnosis result. It identifies primary winding paper insulation degradation due to electrical phenomena, as shown in Figure 4, as the most likely fault (as expected based on technical examinations and fault signatures implemented in the AFS Database). As the simulation continues, the carbon monoxide gas level enters Condition 2 and soon enters Condition 3. As the carbon monoxide gas level increases to Condition 3, the CO_2/CO ratio reduces below 3 (i.e., below the recommended level (IEEE, 2008)). The Diagnostic Advisor records these changes and updates its previous possible diagnosis results. Based on the updated diagnoses, as shown in Figure 5, primary winding paper insulation degradation due to thermal phenomena is now the most likely fault.

The key observation is that the Diagnostic Advisor updates its possible diagnosis outcomes as new information becomes available.

5.2. EDG Improper Valve Timing Diagnosis

A 20 cylinder EDG is considered in this diagnosis example. As stated earlier, improper valve timing in a diesel engine can lead to either an increase or decrease in cylinder temperature, or both. To mimic improper valve timing, a positive drift and a negative drift are simulated in two randomly selected cylinders. During simulation, when the cylinder temperature and the cylinder temperature differential (i.e., difference between the maximum and the minimum temperature) exceed the user-defined threshold limits, the Diagnostic Advisor recognizes the change and diagnoses the possible fault. Figure 6 shows the possible diagnosis result. Observe that the two possible diagnoses are close in terms of pattern score (i.e., the percentage indicating the relative likelihood of the fault based on the current information) and further evidence is required to identify the most likely fault type.

One of the additional evidences that can be used to update the diagnosis result is the information on recent maintenance. The Diagnostic Advisor provides an option to manually update the previous diagnosis result. By utilizing the option, recent maintenance information was manually

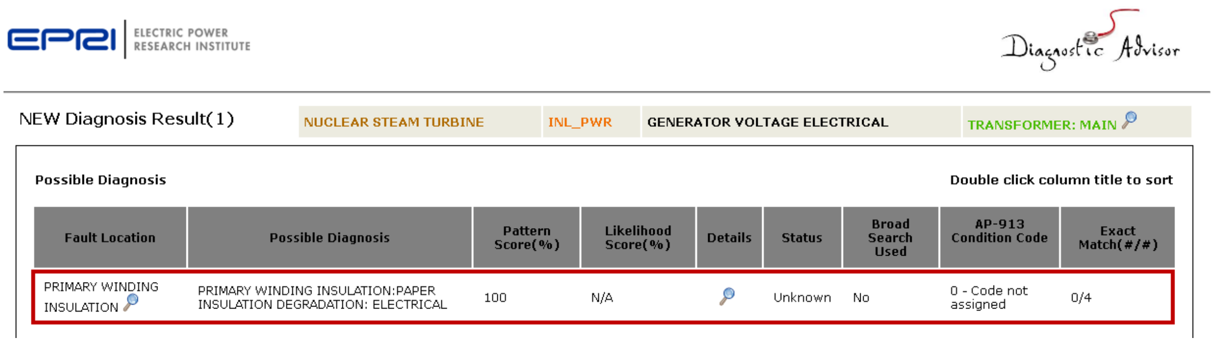

Figure 4. New Diagnosis Result page created by the Diagnostic Advisor when the acetylene level reaches IEEE Condition 2.

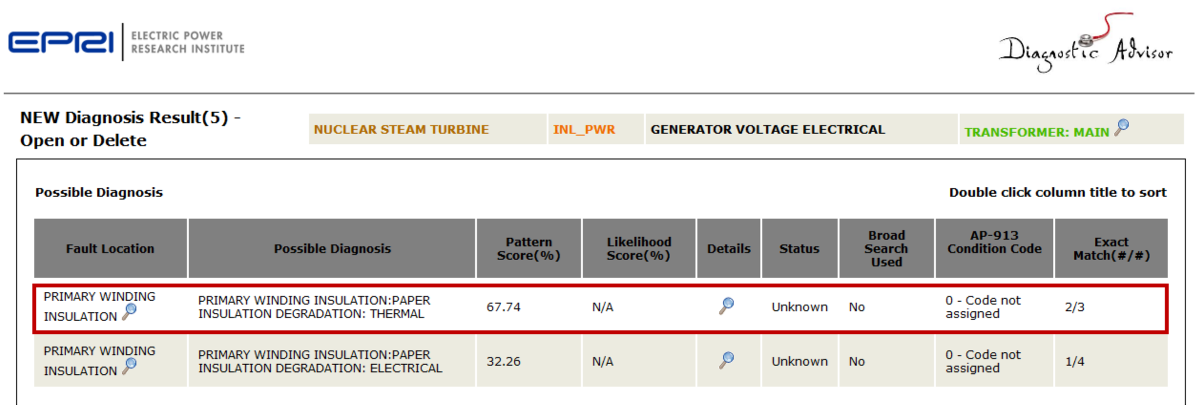

Figure 5. Updated New Diagnosis Result page indicating paper insulation degradation: thermal as the most likely fault.

entered and the previous diagnosis result was updated. Based on the updated result, as shown in Figure 7, it can be observed that the pattern score for improper valve timing has increased to 56.52% compared to the previous score of 52.94% (Figure 6).

This example demonstrates that same technical examination can be used to diagnose different fault types. In such situation, additional evidence can be included manually (if available) to clearly identify the most likely fault type.

6. Conclusions and Future Research

The paper presented research and development performed to date towards implementation of predictive online monitoring for existing nuclear power plants using the FW-PHM Suite software. Several fault signatures were developed for common faults observed in GSUs and EDGs based on the results of technical research and on the knowledge and experience of technical experts. After a thorough verification and validation process, these fault signatures will serve as a foundation for implementation of automated online monitoring for GSUs and EDGs in the nuclear industry. The discussion of diagnosis results highlights the ability of the Diagnostic Advisor to identify the most likely fault type based on the currently implemented fault signatures.

In the future, EPRI and INL will continue to work with nuclear utility partners to develop and verify a full set of fault signatures covering a wide range of recognized faults for GSUs and EDGs, enabling implementation in NPPs. Ultimately, prognostic models based on physics of failure will be developed and implemented in the FW-PHM Suite to predict the remaining useful life of GSUs and EDGs.

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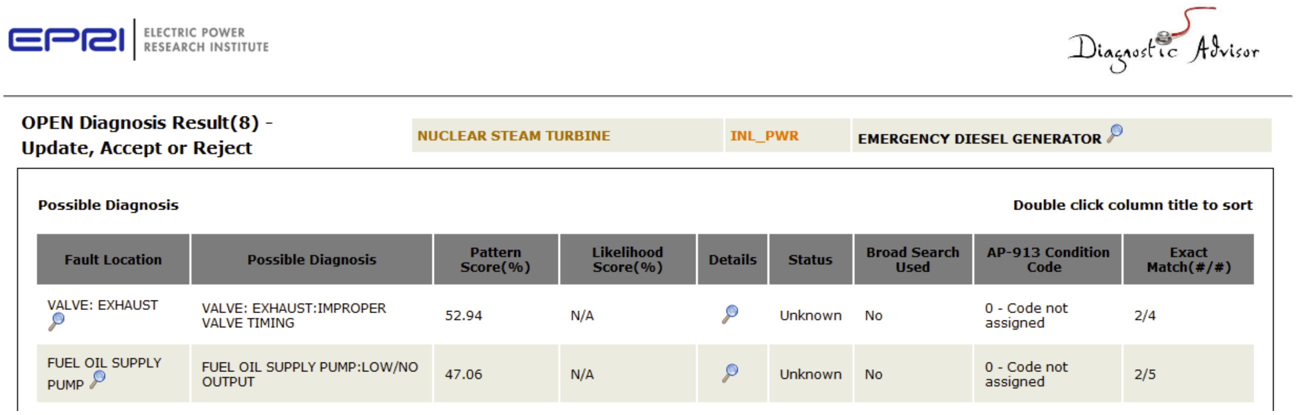
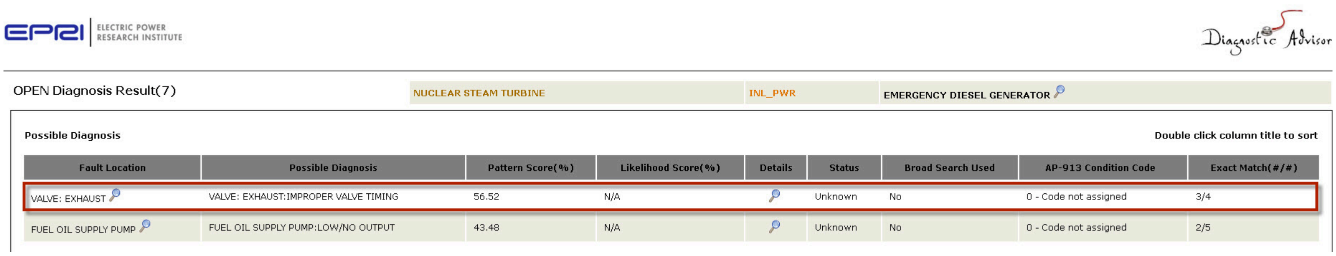


Fault Location	Possible Diagnosis	Pattern Score(%)	Likelihood Score(%)	Details	Status	Broad Search Used	AP-913 Condition Code	Exact Match(#/#)
VALVE: EXHAUST	VALVE: EXHAUST:IMPROPER VALVE TIMING	52.94	N/A		Unknown	No	0 - Code not assigned	2/4
FUEL OIL SUPPLY PUMP	FUEL OIL SUPPLY PUMP:LOW/NO OUTPUT	47.06	N/A		Unknown	No	0 - Code not assigned	2/5

Figure 6. New Diagnosis Result page created by the Diagnostic Advisor when the cylinder temperature and the cylinder temperature differential exceed threshold limits.



Fault Location	Possible Diagnosis	Pattern Score(%)	Likelihood Score(%)	Details	Status	Broad Search Used	AP-913 Condition Code	Exact Match(#/#)
VALVE: EXHAUST	VALVE: EXHAUST:IMPROPER VALVE TIMING	56.52	N/A		Unknown	No	0 - Code not assigned	3/4
FUEL OIL SUPPLY PUMP	FUEL OIL SUPPLY PUMP:LOW/NO OUTPUT	43.48	N/A		Unknown	No	0 - Code not assigned	2/5

Figure 7. Updated Diagnosis Result page after manual entry of recent maintenance information.

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APPENDIX A: TECHNICAL EXAMS AND FAULT SIGNATURES ADDED TO AFS DATABASE FOR GSUS AND EDGS

Table A1. GSU fault signatures developed and implemented into the AFS Database (Lybeck et al., 2012).

Equipment or Component	Fault Type	Technical Exam and Location	Fault Feature	Effectiveness
Winding insulation	Paper insulation degradation	*Dissolved gas analysis:* levels of H_2 and C_2H_2 gas in insulating oil	High levels of H_2 and C_2H_2	High
		Dissolved gas analysis: levels of C_2H_2 gas in insulating oil	High levels of C_2H_2	Very High
		Dissolved gas analysis: CO_2/CO ratio in insulating oil	High ratio of CO_2/CO	High
		Temperature analysis: time at excess temperature at transformer winding	Long time at excessive temperature	Medium
		Insulating oil analysis: Acid number of insulating oil	High acid number	Medium
		Dissolved gas analysis: levels of H_2 gas in insulating oil	High levels of H_2	Very High
Insulating Oil	High acidity	*Insulating oil analysis*: level of KOH per gram of oil	High value of KOH	Very High
	Contamination	*Insulating oil analysis*: the value of IFT measured in Dynes/cm or in mN/m	Low IFT value	Very High
		Insulating oil analysis: color variation	Distinct color change	High
	Low dielectric strength	*Insulating oil analysis*: to measure the dielectric breakdown voltage (ASTM D877-02)	Low value of breakdown voltage	Very High
		Insulating oil analysis: measure the moisture content in the oil	High value of moisture	High
		Insulating oil analysis: the value of IFT measured in Dynes/cm or in mN/m	High value of KOH	Medium
		Dielectric strength: measure the power factor of the oil in the bushing	High value of power factor	Very High
Bushing	Low dielectric strength	*Dielectric strength*: measure the main capacitance	High value of main capacitance	High
		Dielectric strength: measure the tap capacitance	High value of tap capacitance	High
		Dielectric strength: measure the power factor of the oil in the bushing	High value of power factor	High
		Inspection: measure the oil level	Low level of oil	High
Core	Displaced winding core	*Sweep frequency response analysis:* captures the core capacitance across different frequencies	Change in the capacitance across different frequencies	Very High

Equipment or Component	Fault Type	Technical Exam and Location	Fault Feature	Effectiveness
Insulating oil pump motor	Loss of performance	*Insulating oil motor pump:* measure electric voltage	High value of electric voltage	High
		Insulating oil motor pump: measure electric current	High value of electric current	Very High
		Insulating oil motor pump: measure electric resistance	High value of electric resistance	High

Table A2. EDG fault signatures developed and implemented into the AFS Database (Pham, Lybeck, & Agarwal, 2012).

Equipment or Component	Fault Type	Technical Exam and Location	Fault Feature	Effectiveness
Diesel engine fuel injector	Improper fuel injection	*Temperature analysis:* temperature at the exhaust manifold	Abnormal temperature (too high or too low)	High
		Temperature analysis: temperature at the exhaust manifolds	High temperature differential between exhaust manifolds	High
		Inspection: unpleasant odor of fuel	Unpleasant smell of fuel	Very High
Diesel engine piston	Excessive wear	*Lubricating oil analysis:* evaluate chromium and aluminum content in lube oil sampled from the sump	High value of chromium and aluminum	Very High
		Temperature analysis: temperature at the cylinder neck	Low value of temperature	High
Fuel oil supply pump	Fuel pump failure	*Temperature analysis:* temperature at the cylinder neck	High value of temperature	Medium
		Temperature analysis: temperature at the cylinder neck	Low value of the temperature	Medium
		Temperature analysis: temperature at the cylinder neck	High temperature differential between cylinder necks	High
		Inspection: position of fuel metering rod	Displacement in the position	High
		Pressure analysis: of fuel line	Abnormal value of pressure	Very High
Diesel engine exhaust valve	Improper valve timing	*Temperature analysis:* temperature at the cylinder neck	High value of temperature	High
		Temperature differential: between the cylinder necks	High temperature differential	Very High
		Maintenance activity: on the diesel engine	Time from maintenance	High

Equipment or Component	**Fault Type**	**Technical Exam and Location**	**Fault Feature**	**Effectiveness**
Governor	Unresponsive governor	*Power analysis:* power (KW) at Potential Transformer inlets	KW power unchanged in response to demand change	High
		Power analysis: power frequency at potential Transformer inlets	Frequency fluctuating in response to demand change	High
		Inspection: position of fuel rack linkage	Position unchanged in response to demand change	High
		Power analysis: Voltage across governor outlets	Voltage unchanged in response to demand change	High
		Power Analysis: Voltage at Magnetic Pickup Unit	Voltage changed with demand change	Medium
		Temperature analysis: Temperature at the Exhaust Manifold	Temperature does not change in response to demand change	Very High
	Intermittent control signal	*Power analysis:* power (KW) at Potential Transformer inlets	KW power profile fluctuating	High
		Power analysis: power frequency at potential Transformer inlets	Frequency profile fluctuating	High
		Power analysis: Voltage across governor outlets	Voltage profile fluctuating	Very High
		Temperature analysis: temperature at the exhaust manifold	Temperature profile fluctuating	High
		Inspection: position of fuel rack linkage	Position profile fluctuating	High
		Power Analysis: Voltage at Magnetic Pickup Unit	Voltage profile fluctuating	High
	Intermittent MPU signal	*Power analysis:* power (KW) at Potential Transformer inlets	KW power profile fluctuating	Medium
		Power analysis: power frequency at potential Transformer inlets	Frequency profile fluctuating	Low
		Power analysis: Voltage across governor outlets	Voltage profile fluctuating	High
		Temperature analysis: temperature at the exhaust manifold	Temperature profile fluctuating	High
		Inspection: position of fuel rack linkage	Position profile fluctuating	High
		Power Analysis: Voltage at Magnetic Pickup Unit	Voltage profile fluctuating	Very High