Fleet-Wide Prognostic and Health Management Suite: Asset Fault Signature Database

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***Abstract*—Proactive online monitoring in the nuclear industry is being explored using the Electric Power Research Institute's Fleet-Wide Prognostic and Health Management (FW-PHM) Suite software. The FW-PHM Suite is a set of web-based diagnostic and prognostic tools and databases that serves as an integrated health monitoring architecture. The FW-PHM Suite has four main modules: (1) Diagnostic Advisor, (2) Asset Fault Signature (AFS) Database, (3) Remaining Life Advisor, and (4) Remaining Useful Life Database. This paper focuses on the AFS Database of the FW-PHM Suite, which is used to catalog asset fault signatures. A fault signature is 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. The fault signatures developed to assess the health status of generator step-up transformers are described in this paper. The developed fault signatures capture this knowledge and implement it in a standardized approach, thereby streamlining the diagnostic and prognostic process. This will support the automation of proactive online monitoring techniques in nuclear power plants to diagnose incipient faults, perform proactive maintenance, and estimate the remaining useful life of assets.**[1]

***Keywords*—generator step-up transformer; fault signatures; fleet-wide monitoring; diagnostics.**

I. Introduction

The average age of existing commercial nuclear power plants (NPPs) in the United States is 35 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. Implementing advanced, predictive online monitoring would minimize these limitations and enhance plant safety by enabling plant maintainers to diagnose incipient faults and estimate the remaining useful life (RUL) of their assets, reducing operational costs by optimizing maintenance activities. Predictive online monitoring techniques include advanced diagnostic and prognostic techniques.

The U.S. Department of Energy (DOE) Office of Nuclear Energy funds the Light Water Reactor Sustainability 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 Light Water Reactor Sustainability Program is collaborating with the Electric Power Research Institute's (EPRI's) Long-Term Operations Program to conduct research and development on technologies that can be used to enhance the long-term reliability, productivity, and safety of aging light water reactors. One of the primary areas of focus for the Light Water Reactor Sustainability and Long-Term Operations Programs is online monitoring of active assets in the nuclear industry.

An important objective of the 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. EPRI and Idaho National Laboratory (INL) are working with nuclear utility partners to develop asset fault signatures in the FW-PHM Suite software for generator step-up transformers (GSUs) and emergency diesel generators (EDGs). The nuclear utility

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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 a detailed description of fault signature development and the attributes of fault signatures. Examples of fault signatures are presented that show different fault signature attributes and their structure in the Asset Fault Signature (AFS) Database. The paper is organized as follows. Section II describes the FW-PHM Suite software architecture. Section III describes different attributes associated with a fault signature and steps involved in developing a fault signature. Section IV presents a representative fault signature for GSUs. Section V presents conclusions and future FW-PHM Suite software research.

II. Fleet-wide Prognostic and Health Management Suite Software

The FW-PHM Suite software, shown in Fig. 1, is a comprehensive asset health management solution that supports Condition-Based Maintenance (CBM) activities common to the power generation industry. The FW-PHM Suite was developed by Expert Microsystems, Inc., for EPRI's Fossil Generation and Nuclear Sectors [1]. The software is designed to support all types of generating and transmission assets, including passive and active assets in nuclear, coal, combined cycle, co-generation, wind, hydro, and switchyard facilities.

The FW-PHM Suite has four primary modules: the AFS Database, the Diagnostic Advisor, the RUL Database, and the Remaining Life Advisor. The AFS Database organizes fault signatures and troubleshooting information for power plant assets. At the most basic level, a fault signature is 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. The Diagnostic Advisor accurately identifies faults and impending failure conditions in plant assets by comparing known asset fault signatures with operating data, sensor values, nondestructive examination (NDE) results, and expert opinions from power plant personnel.

The RUL Database collects and organizes power plant asset life model information, and archives and shares that information to make accurate prognostic projections. The Remaining Life Advisor uses plant information to determine how long an aging asset will provide reliable service. For additional details on the FW-PHM Suite, refer to EPRI's 2012 report and manual [1, 2].

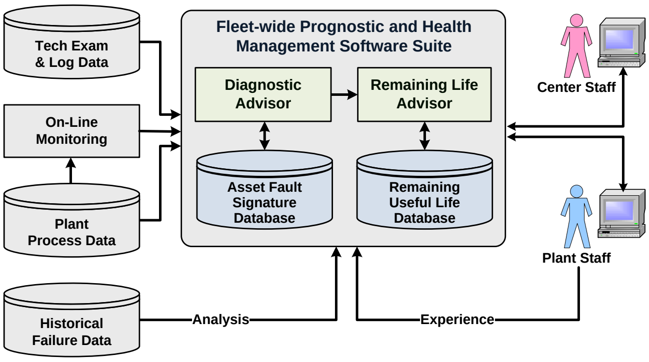

Fig. 1. FW-PHM Suite software architecture [1].

III. Asset Fault Signature Database

Diagnostic fault signature information for high-priority power plant equipment is elicited from industry experts and captured in the AFS Database of the FW-PHM Suite software [2]. A methodical approach is required to develop content for the AFS Database. The following subsections provide a detailed explanation of the terminology and structure of fault signatures, along with a procedure for preparing fault signatures for implementation in the FW-PHM Suite.

A. Asset Fault Signature Database Terminology

The AFS Database contains tables that organize and store reference information for various power plant assets. This information can be represented using an asset subtype and a reference asset-type hierarchy as shown in Fig. 2. Asset subtypes represent a generalized definition of an asset, without specifying contextual information such as the nature of its use in service within a particular kind of plant or the plant application. Asset types represent a more specific definition of an asset subtype, including information related to its use in service within a particular kind of plant or plant application.

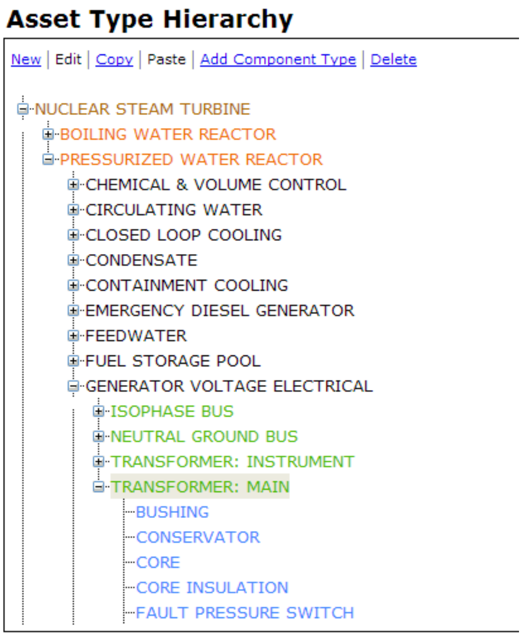

Fig. 2. An example of asset types.

Asset subtypes and asset types are organized into five discrete levels within the AFS Database: plant, unit, system, equipment, and component. Asset types are additionally organized within a set of reference asset hierarchies for various kinds of power generating plants. The collection of reference asset hierarchies is called the reference asset taxonomy.

A fault is a particular mode of degradation that can be detected by analyzing plant information before the asset fails to meet its service requirement. Fault types represent a specific definition of a fault, including contextual information such as its location and the nature of its use within a particular kind of power plant application. Fault information tables are used to organize and store information for the different fault types associated with plant assets. Paper insulation degradation in a transformer winding is an example of a fault type (Fig. 3). Attributes associated with fault types can be used to tailor how the fault applies. Fault attributes and their values also provide a way to discriminate specific fault causes (e.g., arcing and cellulose degradation are two of the fault attributes associated with paper insulation degradation).

Technology examination tables organize and store information about technology examinations performed for various plant assets. Here, the term technology examination is not limited to its common use, but is broadened to mean any form of examination of plant information, including operator examinations such as inspections, and even maintenance actions that can influence a fault diagnosis, such as on oil analysis that counts the number of particles found in a sampled volume of oil.

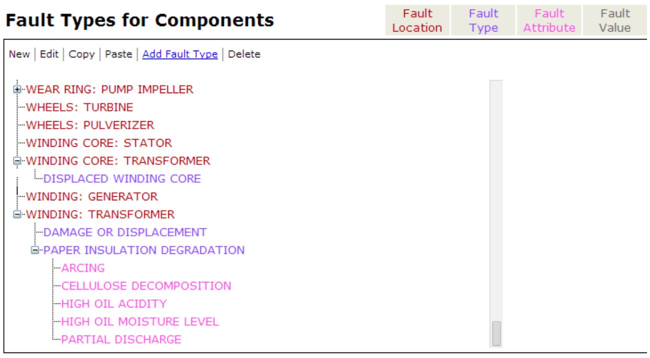

Fig. 3. An example of fault types at the component level for transformer winding.

Technology subtypes represent the various technologies available to observe degradation indications. Examples of technology subtypes include vibration, oil analysis, and temperature. Exam subtypes represent the various exams associated with technology subtypes that can be performed to measure or observe the degradation indicators. An acid number is an exam subtype associated with oil analysis.

Result types define the possible set of outcomes for a technology examination. Each technology examination is associated with a single result type. The term exam result refers to the possible outcome of a technology examination. Exam results can be represented as categorical values or non-categorical values. Non-categorical values can include numeric values, a time series of numeric values, or a vector of numeric values.

B. Asset Fault Signatures

Asset fault signature tables, the backbone of the AFS Database, are used to organize diagnostic fault signature information. At a minimum, a fault signature is comprised of an asset type, a fault type and a set of one or more observable features that may indicate the presence of the associated fault. Optionally, the fault signature can specify one or more fault types that can either cause or be caused by the specified fault. Corrective actions or a list of possible remedies can also be included in a fault signature.

Fault feature tables organize and store information for the fault features associated with various fault signatures. A fault feature definition includes a technology examination type, the location for the technology examination, and the results from the examination that indicate the possible presence of the fault. Additionally, a fault feature describes the effectiveness of the associated technology examination. Finally, a fault feature contains the technology examination result that indicates the presence of the asset fault. For example, a high-temperature measurement is a highly effective fault feature for a bearing damage fault in a pump.

C. Gathering Fault Signature Information

A step-by-step procedure for developing a fault signature includes the following four steps [2]:

- Specify the asset type for which the fault signature(s) is to be developed. For the specified asset type, gather information on its operating range, mechanisms of degradation, and observable features that can be used to detect degrading conditions. The information can be gathered from multiple sources such as EPRI's Preventive Maintenance Basis Database, Fossil Maintenance Application Center and Nuclear Maintenance Application Center reports, and from other sources (e.g., textbooks, equipment guide, and publications).
- Specify the fault type and any narrowing attributes that can be used to make the fault more specific. For example, the most common fault type associated with transformer winding is paper insulation degradation. Fault attributes such as arcing, cellulose decomposition, high oil acidity, high oil moisture level, and partial discharge are commonly used to identify the root cause of paper insulation degradation in a transformer winding.
- For each fault type, specify one or more fault features comprised of information on (1) location where the plant data are collected; (2) technology or technologies used to identify the fault (e.g., oil analysis in transformers); (3) examination (e.g., particle content, gas analysis, or moisture content) and outcome of examination (i.e., the result, whether normal, abnormal, high, low, marginal, or unacceptable); and (4) the effectiveness (e.g., low, medium, high, or very high) of the fault feature in detecting the fault condition. A specific fault feature can be associated with one or more fault signatures.
- Provide a description of the fault condition, possible causes, remedies, and effects on the asset (if left uncorrected).

Several fault signatures have been developed and implemented in the AFS Database as part of a knowledge transfer exercise with utility partners for GSUs [3, 4] and EDGs [3, 5]. Twenty-three fault signatures have been implemented in the AFS Database for GSUs. The following section discusses fault signatures developed for transformer bushings and insulating oil.

D. GSU Fault Signatures

High-voltage transformer bushings are used to connect overhead power lines to transformers. Badly degraded bushings may explode, causing extensive damage to the transformer. One of the most common degradations observed in the majority of bushing types is loss of dielectric strength. There are several causes for loss of dielectric strength that include moisture ingress, loss of oil from the bushing, and oil contamination. Technology examinations such as capacitance tests, power factor tests, tan delta tests, and oil level inspections are widely used to monitor loss of dielectric strength in transformer bushings. Fig. 4 shows the bushing fault signature for low dielectric strength developed and implemented in the AFS Database.

Signature List

945(Master)-LOW DIELECTRIC STRENGTH

Summary for 945(Master)-LOW DIELECTRIC STRENGTH

Signature Source

GSU Diagnostic Workshop at Shearon Harris NPP, Raleigh, NC, September 2012.

Fault Features

Exam Location	Technology	Exam	Fault Value	Effectiveness
BUSHING	DIELECTRIC STRENGTH	CAPACITANCE: TAP (C2)	UNACCEPTABLE	High
BUSHING	INSPECTION	OIL LEVEL	ABNORMAL	High
BUSHING	DIELECTRIC STRENGTH	POWER FACTOR	ABNORMAL	High
BUSHING	DIELECTRIC STRENGTH	TAN DELTA / DISSIPATION FACTOR	ABNORMAL	High

Fault Descriptions

Abnormal dissipation factor is indicative of oil contamination.

Indication of dielectric losses.

Causes

Fault Location	Fault Type	Description
INSULATING OIL	CONTAMINATION	Oil contamination, moisture ingress, or loss of oil from the bushing can cause a loss of dielectric strength.

Effects

Fault Location	Fault Type	Description
TRANSFORMER: MAIN	INTERRUPT TRANSFORMER OPERATION	Arcing and possibly transformer damage.

Remedies

Refurbish or replace bushing.

Fig. 4. Transformer bushing low dielectric strength fault signature and associate fault features.

Signature List

948(Master)-CONTAMINATION
947(Master)-HIGH ACIDITY
949(Master)-LOW DIELECTRIC STRENGTH
1090(Master)-THERMAL DEGRADATION

Summary for 948(Master)-CONTAMINATION

Signature Source

GSU Diagnostic Workshop at Shearon Harris NPP, Raleigh, NC, September 2012.

Fault Features

Exam Location	Technology	Exam	Fault Value	Effectiveness
INSULATING OIL	INSULATING OIL ANALYSIS	COLOR VARIATION	CHANGE	High
INSULATING OIL	INSULATING OIL ANALYSIS	OXYGEN CONCENTRATION LEVEL	ABNORMAL	High
INSULATING OIL	DIELECTRIC FREQUENCY RESPONSE	DISSIPATION FACTOR	MARGINAL	High
INSULATING OIL	INSULATING OIL ANALYSIS	SULFUR CONTENT	ABNORMAL	Medium
INSULATING OIL	INSULATING OIL ANALYSIS	INTERFACIAL TENSION	ABNORMAL	High

Fault Descriptions

High levels of oil contamination.

Increase in moisture level indicates oil contamination.

Due to chemical bonds breakage, oxygen is generated along with hydrocarbons, as a result the concentration of oxygen increases.

Causes

Fault Location	Fault Type	Description
N/A	N/A	Water ingress during installation or repair.
N/A	N/A	After years of operation, malfunction in winding leading to paper insulation wear out.

Effects

Fault Location	Fault Type	Description
N/A	N/A	Reduces the dielectric strength of the oil. Sludge formation in the tank.

Remedies

Reclaim or replace oil.

Fig. 5. Insulating oil degradation due to contamination and associated fault features.

Transformer insulating oil functions both as an electrical insulation and as a heat transfer fluid. Transformers are expected to function reliably and efficiently. The quality of the insulating oil plays an important role in performing this function for extended periods. Chemical compounds of the oil disintegrate over time when the transformer is subject to various operating conditions. These chemical changes degrade the quality of the oil, thereby leading to contamination, an increase in oil acidity, a decrease in dielectric strength, and degraded thermal properties. These changes impact the oil's electrical insulating and heat transfer properties. If left to degrade beyond allowed limits, the degradation could cause potentially catastrophic electrical faults inside the transformer. Therefore, it is important to monitor oil quality and diagnose any impending failure in a timely manner. Fig. 5 shows one of four fault signatures (contamination, high acidity, low dielectric strength, and thermal degradation) developed and implemented in the AFS Database for GSUs.

Note that some of the fault features might be common to more than one fault signature. In the case of GSUs, the interfacial tension of the transformer insulating oil is a common fault feature for two fault signatures: contamination and low dielectric strength. In this situation, the effectiveness of the fault feature serves as a differentiating factor and is used by the Diagnostic Advisor to rank the possible diagnoses.

The implemented GSU fault signatures in the AFS Database were verified and validated by EPRI subject matter experts. A demonstration showing the ability of the FW-PHM Suite to diagnose a developing fault is documented in a report [6] and in a video [7]. Emerging faults were simulated by adding drifts to plant data. The demonstration highlighted the software's ability to identify faults based on evolving symptoms, using both online and offline data sources. Additionally, some of these GSU fault signatures were used to demonstrate the prognostic ability of the FW-PHM Suite to estimate the remaining useful life of transformer winding paper insulation, using two well-established approaches [8].

IV. Conclusions and Future Work

This paper discussed the AFS Database of the FW-PHM Suite that is used to store fault signatures for different asset types. Fault signatures allow a structured representation of the information captured from multiple plant sources. Representative GSU fault signatures implemented in the AFS Database were presented; these fault signatures served as a foundation for demonstrations of the diagnostic and prognostic capabilities of the FW-PHM Suite.

As part of the future work, EPRI and INL will continue to develop and implement fault signatures for different asset types. For example, fault signatures for large electric motors are of great interest in the industry.

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References

[1] Electric Power Research Institute (EPRI). *Fleet-Wide Prognostics and Health Management Application Research*. Report EPRI 1026712. Electric Power Research Institute, Charlotte, NC, 2012.

[2] Electrical Power Research Institute (EPRI). *Asset Fault Signature Requirements. Software Manual*. Electric Power Research Institute, Charlotte, NC, 2012.

[3] V. Agarwal, N. J. Lybeck, B. T. Pham, R. Rusaw, and R. Bickford, “Online monitoring of plant assets in the nuclear industry,” Annual Conference of the Prognostics and Health Management Society, October, New Orleans, USA, 2013.

[4] N. J. Lybeck, V. Agarwal, B. T. Pham, H. Medema, and K. Fitzgerald, “Online Monitoring Technical Basis and Analysis Framework for Large Power Transformers,” Interim Report INL/EXT-12-27181. Idaho National Laboratory, Idaho Falls, ID, 2012.

[5] B. T. Pham, N. J. Lybeck, and V. Agarwal, “Online Monitoring Technical Basis and Analysis Framework for Emergency Diesel Generators,” Interim Report INL/EXT-12-27754. Idaho National Laboratory, Idaho Falls, ID, 2012.

[6] V. Agarwal, N. J. Lybeck, L. C. Matacia, and B. T. Pham, “Demonstration of Online Monitoring for Generator Step-up Transformers and Emergency Diesel Generators,” Technical Report INL/EXT-13-30155. Idaho National Laboratory, Idaho Falls, ID, 2013.

[7] http://www.youtube.com/watch?v=8JCchydWlcg&feature=c4-overview&list=UUctcciH1NrAGpwMnKwvnLgQ

[8] V. Agarwal, N. J. Lybeck, and B. T. Pham, “Diagnostic and Prognostic Models for Generator Step-up transformer,” INL/EXT-14-33124 Rev. 0, September 2014.

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