INL/EXT-13-30155

Light Water Reactor Sustainability Program

Demonstration of Online Monitoring for Generator Step-up Transformers and Emergency Diesel Generators

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September 2013

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ABSTRACT

The online monitoring (OLM) of active components project under the Light Water Reactor Sustainability program at Idaho National Laboratory (INL) implemented fault signatures for generator step-up transformers (GSUs) and emergency diesel generators (EDGs). INL, in collaboration with Electric Power Research Institute (EPRI), demonstrated the OLM capabilities for GSUs and EDGs using the EPRI Fleet-Wide Prognostic and Health Management (FW-PHM) Suite software.

The content developed (i.e., fault signatures, fault features, and technical examinations) in the Asset Fault Signature Database of the FW-PHM Suite for GSUs and EDGs is presented in this report. In order to demonstrate the concept of OLM, fault models for GSUs and EDGs were developed to simulate faults in actual performance data of GSUs and EDGs using an advanced pattern recognition tool. The output of the tool was synchronized with the FW-PHM Suite to trigger the Diagnostic Advisor when the actual data crosses the user-defined threshold value. The Diagnostic Advisor outcome suggests possible diagnoses and troubleshooting advices to the maintenance engineer. The automated OLM capability of the FW-PHM Suite was successfully demonstrated at the 2013 August Utility Working Group Meeting, Idaho Falls, Idaho, to representatives from different utilities, EPRI, and Halden Research Project.

SUMMARY

As nuclear power plants (NPPs) continue to age and their components degrade, it is important to understand their condition and be proactive in maintenance and replacement in order to improve plant reliability, productivity, and reduce operational cost. 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 unexpected component failure and/or forced outage. Implementation of advanced predictive online monitoring (OLM) would minimize these concerns and enhance plant safety, reliability, and productivity by enabling plant maintenance engineers to diagnose incipient faults and estimate the remaining useful life (RUL) of their assets.

The U.S. Department of Energy's Office of Nuclear Energy funds the Light Water Reactor Sustainability (LWRS) Program to develop the scientific basis for extending the operation of commercial light water reactors beyond the current 60-year license period. The program is operated in collaboration with the Electric Power Research Institute's (EPRI's) research and development efforts in the Long-Term Operations (LTO) Program. The LTO Program is managed as a separate technical program operating in the Plant Technology Department of the EPRI Nuclear Power Sector with the guidance of an industry advisory integration committee. Both the LWRS and LTO programs work closely with nuclear utilities to conduct research and development in technologies which can be used to ensure long-term reliability, productivity, safety, and security of aging light water reactors.

One of the main areas of focus within these programs is online monitoring (OLM) of active components. The knowledge gained from application of OLM to active components will also apply to the implementation of OLM for large passive components and structures (e.g., concrete, cables, etc.) which would be economically challenging to replace. EPRI is leading the effort to achieve the project objective in collaboration with the Idaho National Laboratory (INL), using EPRI's Fleet-Wide Prognostic and Health Management (FW-PHM) Suite (Beta Version 1.1.2) for predictive OLM of active assets in the nuclear industry. The FW-PHM Suite software is an integrated suite of web-based diagnostic and prognostic tools and databases which allows maintenance staff to perform diagnosis and prognosis at different hierarchical levels, from the component level to the plant level, across a fleet of power units.

The research activities associated with OLM of active components are presented here. INL performed beta testing of the FW-PHM Suite software (Beta Version 1.1.1), which included installation and configuration process evaluation; content-based testing; data synchronization; and a human factors evaluation. INL documented all the testing results and provided recommendations in a report published as an EPRI Technical Update in April 2013. Based on suggested recommendations, EPRI improved the FW-PHM Suit software and released an updated beta version of the software (Beta Version 1.1.2) in May 2013.

INL performed content development for generator step-up transformers (GSUs) and emergency diesel generators (EDGs), which involved implementation of technical examinations, fault features, and fault signatures (explained in detail in Section 3) in the FW-PHM Database. The goal of content

development is to capture the rich operating knowledge of technical experts in the industry, creating a set of asset fault signatures organized in a standardized structure. The FW-PHM Suite software for automatic asset health monitoring uses fault signatures and associated fault features.

The diagnosis capability of the FW-PHM Suite software was demonstrated successfully at the 2013 Summer Utility Working Group meeting held in Idaho Falls, Idaho. In the demonstration, INL researchers along with EPRI showed the ability of the FW-PHM's Diagnostic tool to automatically diagnose possible faults in GSUs and EDGs, based on data injected with simulated faults and the fault signatures implemented in the FW-PHM Database. Shearon Harris Nuclear Station operated by Duke Energy provided INL and EPRI with different gas concentration data collected between April 2012 and April 2013 using the Kelman dissolved gas analyzer installed on Harris main transformers. Braidwood Nuclear Generating Station operated by Exelon Nuclear provided INL and EPRI with 20 cylinder temperatures, exhaust manifold temperature, and fuel line pressure data collected from one 24-hour test run of an EDG on November 28, 2012.

INL will continue content development for GSUs and EDGs in fiscal year 2014. INL, EPRI, and the partner utilities will be involved in the validation and verification of implemented fault signatures in the FW-PHM Suite software. In addition INL will research prognostic models for GSUs and EDGs.

ACKNOWLEDGEMENTS

The authors thank Rick Rusaw (EPRI) for providing the FW-PHM Software Suite (Beta Version 1.1.2) and recognize his efforts in obtaining asset data from partner utilities. They are grateful to Randy Bickford (Expert Microsystem Inc.) for providing the advanced pattern recognition tool SureSense®, along with technical support and training on SureSense®.

They thank Kirk Fitzgerald (INL) and Rahul Patlinkar (Expert Microsystems) for all the technical support with the FW-PHM Suite and SureSense®. They extend their appreciation to Chris Morgan (INL) for his technical expertise and contribution in the production of the Online Monitoring Demonstration video. Finally, the authors also thank Misty Benjamin (INL) for her voice-over narration in the video.

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FIGURES

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ACRONYMS

AFS	Asset Fault Signature
ASTM	American Standards of Testing and Maintenance
DGA	dissolved gas analysis
EDG	emergency diesel generator
EPRI	Electric Power Research Institute
FW-PHM	Fleet-Wide Prognostic and Health Management
FY	fiscal year
GSU	generator step-up transformer
IEEE	Institute of Electrical and Electronics Engineer
INL	Idaho National Laboratory
LTO	Long-Term Operations (Program)
LWRS	Light Water Reactor Sustainability (Program)
NPP	nuclear power plant
OLM	online monitoring
RUL	Remaining Useful Life
TDCG	Total Dissolved Combustible Gases

Demonstration of Online Monitoring for Generator Step-Up Transformer and Emergency Diesel Generators

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 in order to improve plant reliability, productivity, and reduce operational cost. 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 component failure or forced outage. Implementation of advanced predictive online monitoring (OLM) would minimize these concerns and enhance plant safety, reliability, and productivity by enabling plant maintenance engineers to diagnose incipient faults and estimate the remaining useful life (RUL) of their assets. Predictive OLM would reduce maintenance costs by optimizing maintenance activities.

The U.S. Department of Energy's Office of Nuclear Energy funds the Light Water Reactor Sustainability (LWRS) Program to develop the scientific basis for extending the operation of commercial light water reactors beyond the current 60-year license period. The program is operated in collaboration with the Electric Power Research Institute's (EPRI's) research and development efforts in the Long-Term Operations (LTO) Program. The LTO Program is managed as a separate technical program operating in the Plant Technology Department of the EPRI Nuclear Power Sector with the guidance of an industry advisory integration committee. Both LWRS and LTO programs work closely with nuclear utilities to conduct research and development in technologies which can be used to ensure long-term reliability, productivity, safety, and security of aging light water reactors.

One of the main focus areas under the LWRS and LTO programs is OLM of active components in nuclear industry. Generator step-up transformers (GSUs) and emergency diesel generators (EDGs) are the active components selected for initial demonstration of OLM. An important objective of the OLM of active components project is to implement predictive OLM for GSUs and EDGs in the existing fleet of NPPs, which is in-line with the long-term objective of both the programs. Predictive (also known as proactive) maintenance involves predicting the future-operating state of an asset based on the current state and operating conditions. For example, if the top insulating oil temperature in a transformer is high, and the temperature is predicted to remain high for an extended period of time, the maintenance engineer might conclude that the expected conditions would lead to an unacceptable loss of dielectric strength of insulating oil. Maintenance staff then can take appropriate actions to prevent the problem.

EPRI is leading the effort to achieve the project objective in collaboration with the Idaho National Laboratory (INL). EPRI has developed the Fleet-Wide Prognostic and Health Management (FW-PHM) Suite software (Beta Version 1.1.2) for predictive OLM of assets in the power industry. The FW-PHM Suite software is an integrated suite of web-based diagnostic and prognostic tools and databases which allows maintenance staff to perform diagnosis and prognosis at different hierarchical levels, from the component level to the plant level, across a fleet of power units.

The fiscal year (FY) 2013 activities associated with the project included:

- Performing beta testing of the FW-PHM Suite software (Beta Version 1.1.1)
- Submitting a beta testing report to EPRI
- Developing content for GSUs and EDGs in the FW-PHM Suite

- Simulating faults using an advanced pattern recognition software and actual plant data obtained from partner utilities to mimic a developing fault scenario in GSUs and EDGs
- Demonstrating the diagnosis capability of the FW-PHM Suite software's Diagnostic Advisor in real time when connected to an online data source embedded with simulated faults for GSUs and EDGs.

INL performed extensive beta testing of the FW-PHM Suite software, which included installation and configuration evaluation, content based testing, data synchronization, and a human factors evaluation. INL documented all the outcomes of beta testing and recommendations in the beta testing report [EPRI 2013, Agarwal et al., 2013]. Based on suggested recommendations, EPRI improved the FW-PHM Suit software and released an updated beta version of the software (Beta Version 1.1.2) in May 2013.

The content development exercise involved implementation of technical examinations, fault features, and fault signatures (explained in detail in Section 3) in the FW-PHM Database. INL is working with subject matter experts from industry, partner utilities, EPRI, and EPRI's partners/subcontractors to develop content in the FW-PHM Database for GSUs and EDGs. The goal of content development is to capture the rich operating knowledge of technical experts from industry, creating a set of asset fault signatures organized in a standardized structure. The FW-PHM Suite software for automatic asset health monitoring uses fault signatures and associated fault features. 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.

The diagnosis capability of the FW-PHM Suite software was demonstrated at the 2013 Summer Utility Working Group meeting, which was held in Idaho Falls, Idaho. In the demonstration, INL researchers along with EPRI showed the ability of the FW-PHM's Diagnostic Advisor to diagnose possible faults in GSUs and EDGs, based on actual data infused with simulated faults and fault signatures implemented in the FW-PHM Database. Shearon Harris Nuclear Station, operated by Duke Energy, provided INL and EPRI with gas concentration data collected between April 2012 and April 2013 using the Kelman dissolved gas analyzer installed on Harris main transformers. Braidwood Nuclear Generating Station, operated by Exelon Nuclear, provided INL and EPRI with 20 cylinder temperatures, exhaust manifold temperature, and fuel line pressure data collected from one 24-hour test run of EDG on November 28, 2012.

The project progress and status of research activities for the FY 2013 are presented in this report. The FW-PHM Suite Software is described in Section 2. Diagnostic fault signatures, fault features, and technical examinations implemented as part of content development in the FW-PHM Database for GSUs and EDGs are presented in Section 3. The actual operating data for GSUs and EDGs obtained from partner utilities, along with advanced pattern recognition software used to simulate faults, are described in Section 4. The demonstration of OLM for GSUs and EDGs using the diagnostic tools in the FW-PHM Suite is summarized in Section 5. The status of the pilot project and progress made with partner utilities is provided in Section 6. Summary and future plans are summarized in Section 7.

2. FLEET-WIDE PROGNOSTIC AND HEALTH MANAGEMENT SUITE SOFTWARE

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 [Lybeck et al., 2011; EPRI, 2011]. The FW-PHM Suite consists of four main modules: the Diagnostic Advisor, the Asset Fault Signature (AFS) Database, the RUL Advisor, and the RUL 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.

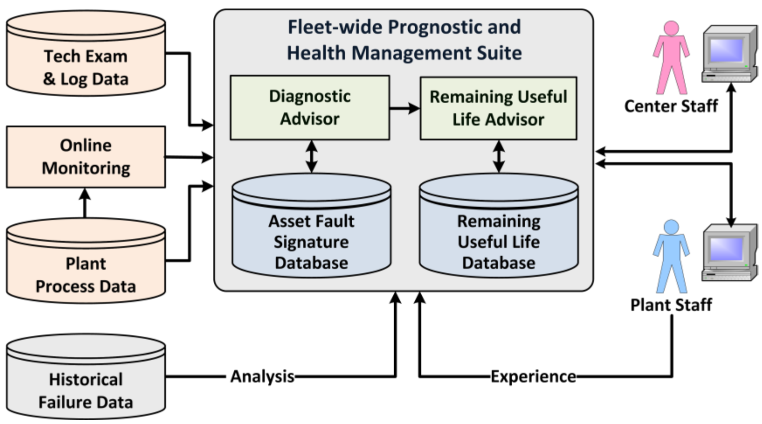


Figure 1. Data flow in the EPRI FW-PHM Suite [EPRI 2011b].

Asset Fault Signature Database

The AFS 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.

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 entered 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.

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 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.

Remaining Useful Life Advisor

The RUL Advisor calculates RUL for an asset based on the model type, model parameters, input process parameters, and diagnostic information (from the Diagnostic Advisor). The engineering staff and plant management who plan long-term corrective or replacement actions would use the RUL Advisor.

Figure 2. FW-PHM Suite main page.

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 [EPRI, 2012]. A fault describes a particular mode of degradation that can be detected by analysis of plant information before the asset fails 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 condition.

Diagnostic 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 research can be applied to comparable assets used in similar service environments.

3. CONTENT DEVELOPMENT FOR THE ASSET FAULT SIGNATURE DATABASE

Content development involves implementation of technical examinations, fault features, and fault signatures in the AFS Database of the FW-PHM Suite. INL is working with subject matter experts from industry, EPRI, and EPRI's partners/subcontractors to develop content 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. These fault signatures and associated fault features are used by the Diagnostic Advisor for automatic asset health monitoring. 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 examinations for GSUs and EDGs are presented in following sections.

3.1 Technical Examinations of Generator Step-Up Transformers

The technical examinations listed below are commonly used to monitor the condition/health of GSUs. 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 (i.e., dielectric strength), chemical properties (e.g., water content, acidity), and the physical property (i.e., interfacial tension). Insulating oil loses its dielectric strength either due to increase in the moisture content or due to thermal aging. High acidity of insulating oil causes the solubility of the water in the oil to increase, and also deteriorates the winding insulation paper strength. Acidity is measured in terms of milligrams of potassium hydroxide present in one gram of oil. Interfacial tension measures molecular attractive forces between oil and water, and is measured in Dyne/cm. A decrease in interfacial tension indicates the presence of contaminants in the oil.
3. *Dissolved gas analysis (DGA)*. 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. The key gases 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, CO_2/CO, C_2H_2/H_2, Doernenberg Ratios [IEEE, 2008], Duval triangle [Duval, 2002], and Rogers Ratios [IEEE, 2008] indicate different types of degradation inside transformers. Figure 3 shows some of the technical examinations implemented in the AFS Database for insulating oil.
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. Figure 4 shows the technical examinations implemented in the AFS Database for bushings.

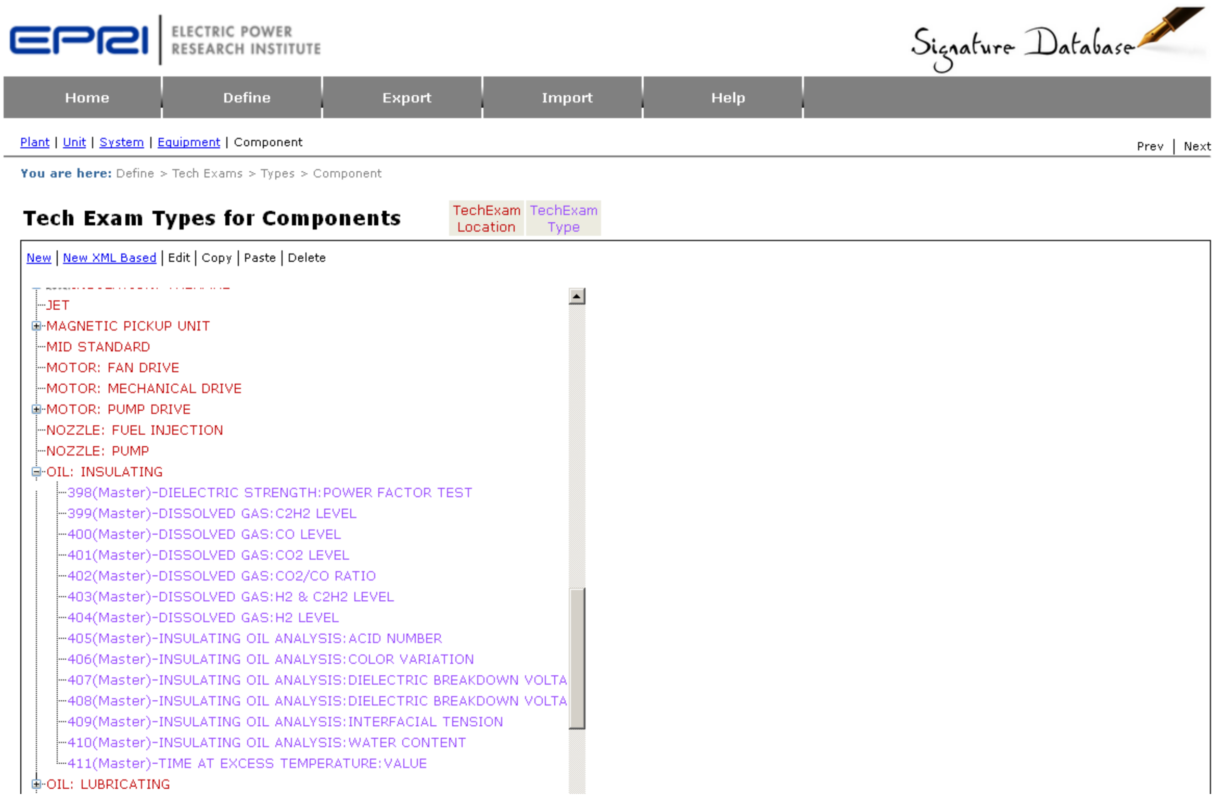


Figure 3. Insulating oil technical examinations implemented at the AFS database for GSU.

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.

3.2 Technical Examinations of Emergency Diesel Generators

The technical examinations listed below are commonly used to monitor diesel engine operation. 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]. Figure 5 shows the technical examinations implemented in the AFS Database for EDG based on engine cylinder neck and exhaust temperatures.

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, 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 pump failure or system leakage of fuel, oil, water, or air.

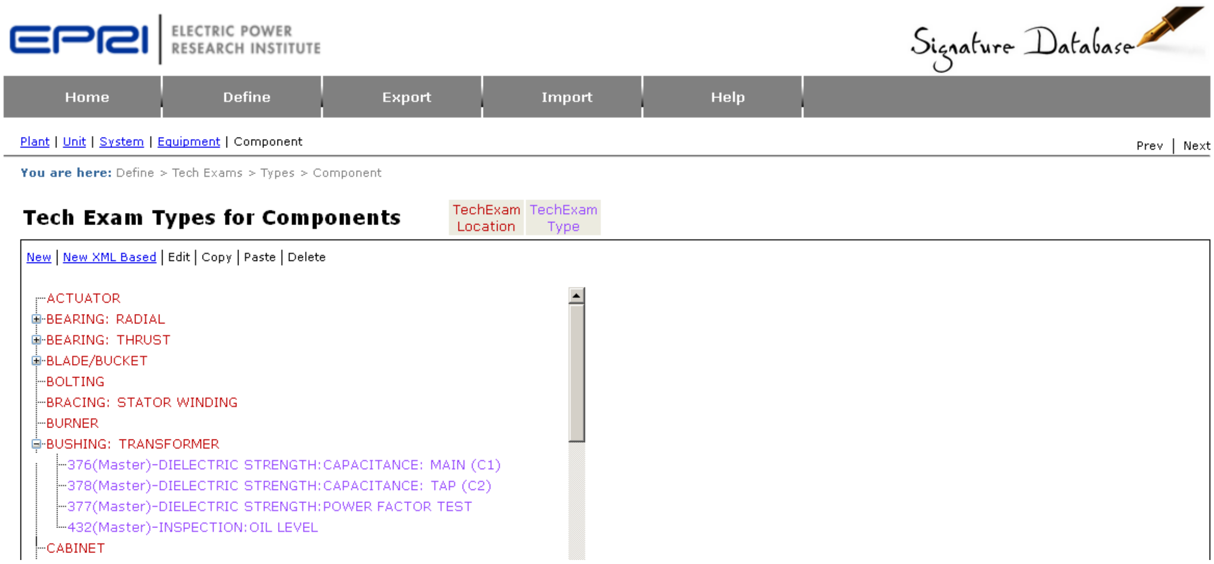


Figure 4. Technical examinations related to bushing implemented in the AFS database for GSU.

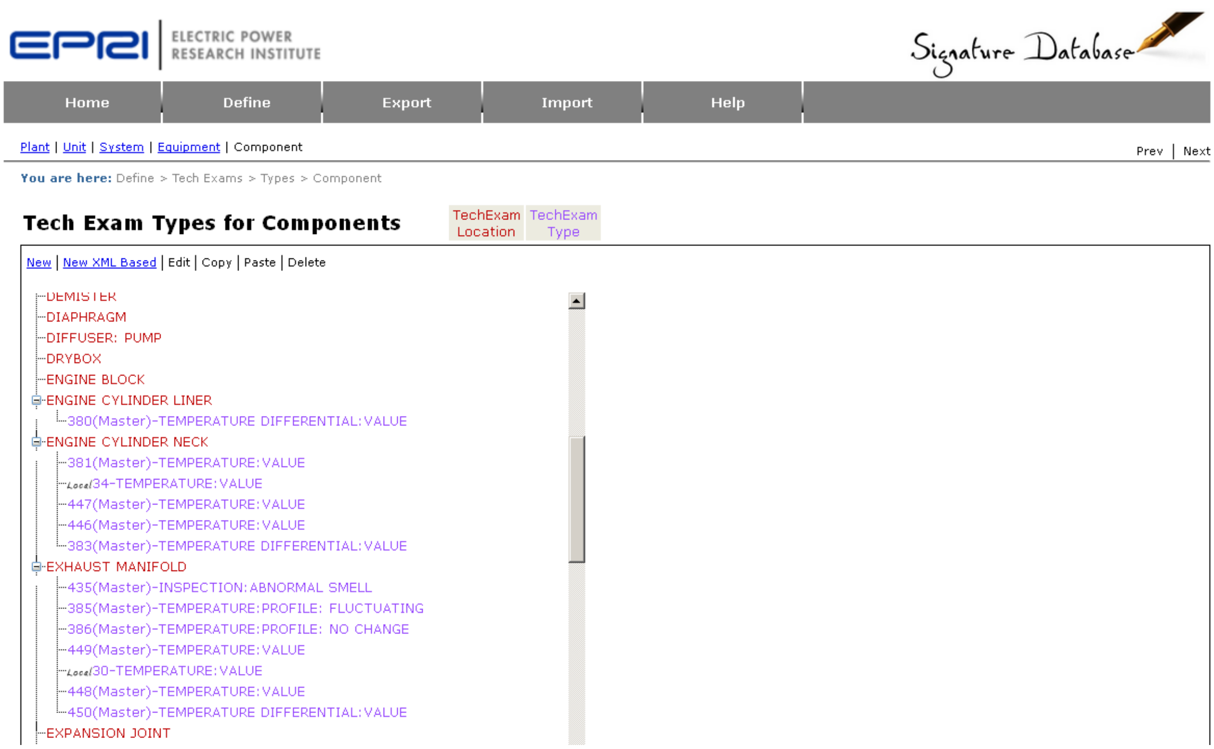


Figure 5. Technical examinations for diesel engine implemented in the AFS database for EDG.

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 greater than twice 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. This indicates problems in the diesel engine, including mechanical wear of components, bearing failure, and leaking seals [Banks, 2001]. There are three basic technical examination methods for oil analysis:

   Ferrography: Ferromagnetic particles in the lubricating oil are counted using a magnetic field to separate the particles according to size. The ferrography oil analysis includes 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 (type of material).

   Spectroscopy (American Standards of Testing and Maintenance [ASTM] D6224-09): 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 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.

3.3 Fault Signatures

The representation of fault signatures in the AFS Database captures the essential information used by experts to solve a particular type of problem. The two primary elements of a fault signature are the *Asset Types* and the *Fault Types*. For a particular asset type and a fault type, the characteristics of the plant information that can be used to detect and verify that the fault is occurring are defined. These characteristics of the plant information are called *Fault Features* and typically involve some kind of analysis of raw plant data. For example, raw plant data might comprise a temperature reading of 100°C and an analysis of that data might comprise a determination of whether that data was *Low*, *Normal* or *High* in the operating context of the asset. A fault feature might then be expressed by stating that a high value of this particular type of temperature measurement is an indicator that the fault type of the fault signature is occurring.

From the above discussion it becomes clear that a fault feature has more details implicit in its definition. For example, where was the measurement taken? What technique was used to make the measurement? How effective is this particular measurement for indicating the occurrence of this particular type of fault? It is the role of a fault signature to structure all of these details. Combining the attributes of an asset type, a fault type, and a set of fault features establishes the minimum amount of information needed to define a fault signature. The fault signature also provides the means to create a relationship of fault *Cause* and *Effect* by specifying other types of faults that the asset might experience in combination with the type specified in the signature. Additionally, the ability to specify remedial action advice is included.

The fault signature definition process in the AFS Database leads the user through the following sequence of steps. The steps are summarized in Figure 6.

- Specify the asset type for the fault signature.
- Specify the source of the fault signature information.

- Specify the fault type and any narrowing attributes making the fault more specific
- Specify the plant data features that indicate the occurrence of the fault (the fault features) including the following steps:
    - Specify the location where the plant data feature indicating the fault is acquired
    - Specify the technology (e.g., oil analysis) that underlays the fault feature
    - Specify the examination (e.g., particle content) and result (e.g., high value) that underlay the fault feature and any narrowing attributes making the examination more specific
    - Specify the effectiveness of the fault feature for detecting the fault condition
    - Describe the application of the fault feature for detecting the fault condition.
- Describe the fault condition and mechanism and provide reference information.
- List or link other faults that can cause this fault.
- List or link other faults that can result from (i.e., be an effect of) this fault.
- List possible remedies or corrective actions for the fault.
-

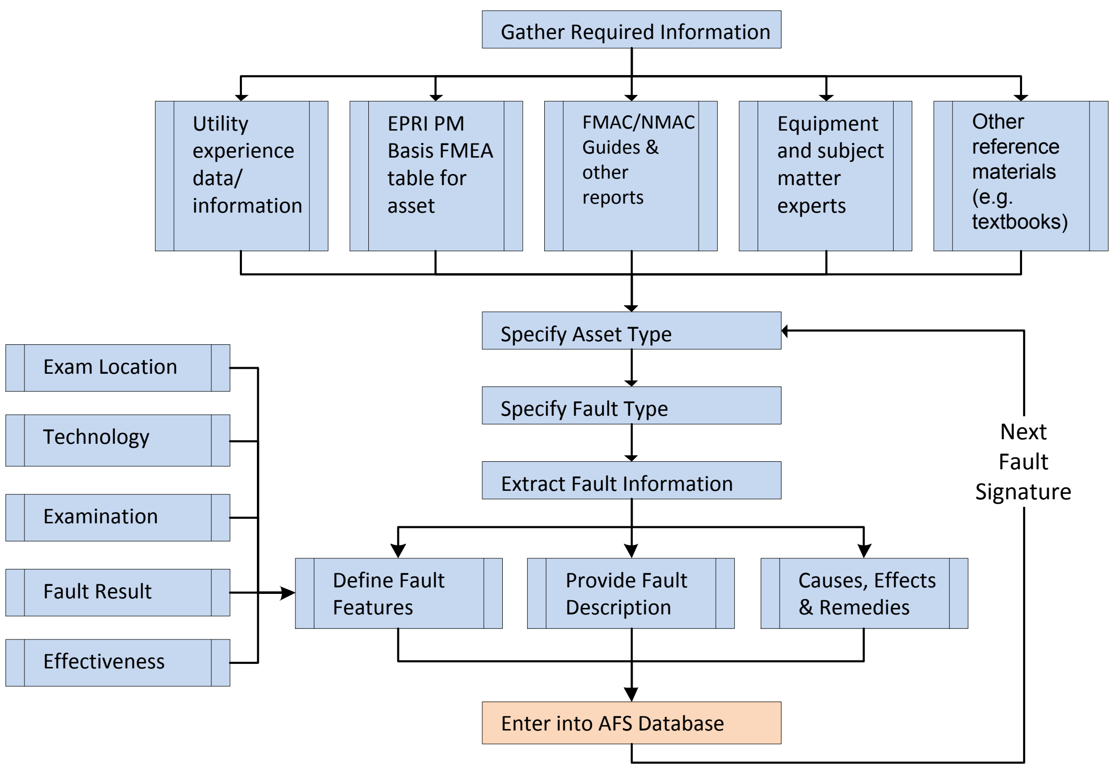


Figure 6. Steps involved in gathering asset fault signatures [EPRI, 2012].

The process of defining a fault signature can be described as the steps of (1) gathering the needed information and (2) entering the information into the AFS Database. The most complete resources are often the Preventive Maintenance Basis Database along with the Fossil Maintenance Application Center and Nuclear Maintenance Application Center Maintenance and Troubleshooting Guides published by EPRI. Used in combination, these resources can provide a sound basis for an accurate and useful fault signature. However, some additional expertise and judgment must be provided to interpret and combine the above information. The Preventive Maintenance Basis Database content and the Nuclear Maintenance Application Center/Fossil Maintenance Application Center guides are the work products of focused teams of industry experts assembled to accomplish related but different sets of objectives. For detailed discussion on the step-by-step procedure for developing an asset fault signature for the AFS Database, refer to [EPRI, 2012].

Several fault signatures have been developed for GSUs and EDGs based on the step-by-step procedure described above and as part of knowledge transfer exercises with partner utilities. In Appendix A, the implemented fault signatures in the AFS Database for GSUs and EDGs are summarized in Tables 3 and 4 respectively. The last column of Tables 3 and 4 (i.e., the 5th column) lists the effectiveness of each technical examination. Effectiveness is used in ranking possible diagnoses provided by 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

Example fault signatures for the primary winding paper insulation in GSUs are *Paper Insulation Degradation: Electrical* (due to electrical discharges) and *Paper Insulation Degradation: Thermal* (due to thermal degradation), as seen in Figure 7 and Figure 8, respectively. Significant fault features associated with the primary winding paper insulation degradation due to electrical discharges involve monitoring individual gas concentration levels of acetylene and hydrogen, both individually and jointly. An increase in the acidity level of the insulating oil will lead to insulation degradation, which in turn would accelerate the possibility of electrical discharge as the dielectric strength of the paper insulation decreases. Observe that the fault features in Figure 7 have information on *Exam Location*, *Technology*, *Exam*, *Fault Value*, and *Effectiveness* defined for each fault feature as discussed above.

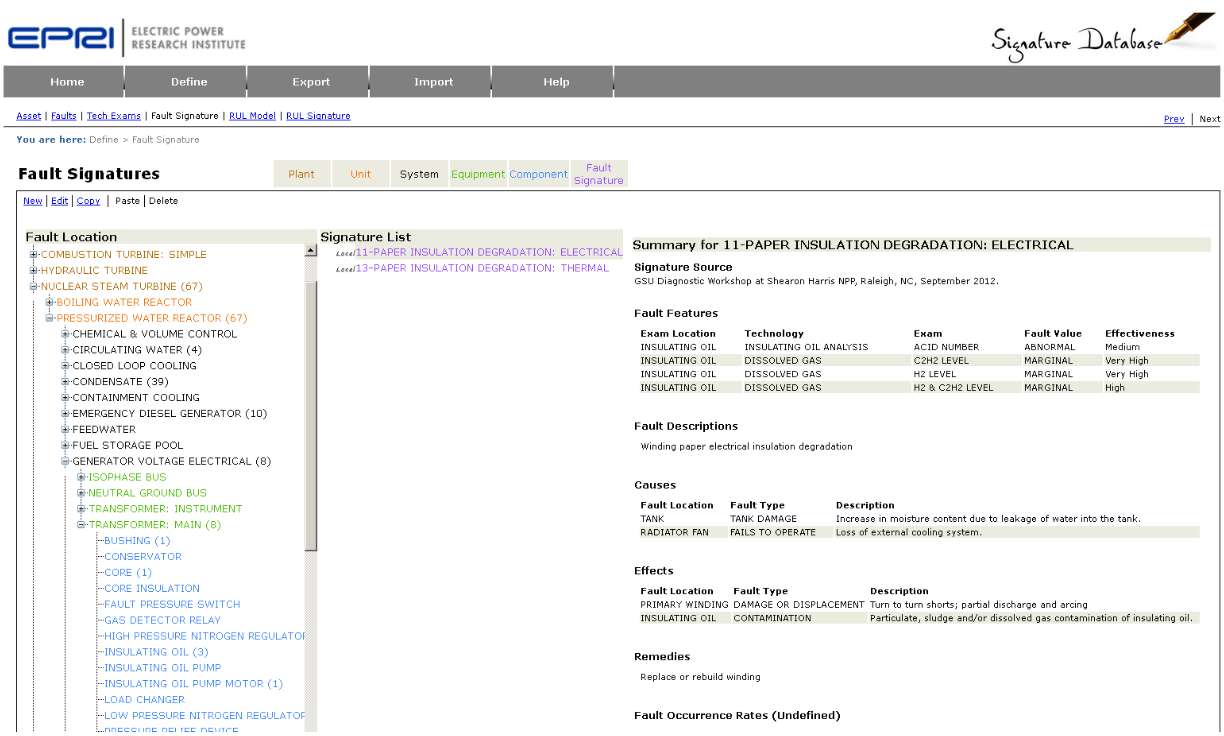


Figure 7. Paper insulation degradation: electrical fault signature and associated fault features.

Signature List

Local 11-PAPER INSULATION DEGRADATION: ELECTRICAL

Local 13-PAPER INSULATION DEGRADATION: THERMAL

Summary for 13-PAPER INSULATION DEGRADATION: THERMAL

Signature Source

PAPER INSULATION DEGRADATION: THERMAL

Fault Features

Exam Location	Technology	Exam	Fault Value	Effectiveness
INSULATING OIL	DISSOLVED GAS	CO LEVEL	MARGINAL	Very High
INSULATING OIL	DISSOLVED GAS	CO2/CO RATIO	MARGINAL	High
PRIMARY WINDING	TIME AT EXCESS TEMPERATURE	VALUE	ABNORMAL	Medium

Fault Descriptions

Winding paper thermal insulation degradation

Causes

Fault Location	Fault Type	Description
TANK	TANK DAMAGE	Increase in moisture content due to leakage of water into the tank.
RADIATOR FAN	FAILS TO OPERATE	Loss of external cooling system.

Effects

Fault Location	Fault Type	Description
PRIMARY WINDING	DAMAGE OR DISPLACEMENT	Turn to turn shorts; partial discharge and arcing.
INSULATING OIL	CONTAMINATION	Particulate, sludge and/or dissolved gas contamination of insulating oil.

Remedies

Rebuild or replace winding.

Fault Occurrence Rates (Undefined)

Figure 8. Paper insulation degradation: thermal fault signature and associated fault features.

Similarly, significant fault features associated with the paper insulation degradation due to thermal processes involve monitoring the concentration level of carbon monoxide and the ratio CO_2/CO. An increase in temperature inside the transformer due to localized heating, or due to loss of cooling systems for an extended period, causes the cellulose material of the primary winding paper insulation to degrade and generate carbon monoxide (primarily) and carbon dioxide gases.

Example EDG fault signatures *Improper Valve Timing* and *Low/No Output of fuel oil supply pump* are shown in Figure 9 and Figure 10 respectively. Cylinder temperature is the significant fault feature for both *Improper valve timing* and *Fuel oil supply pump low/no outpu*t. Other fault features such as *Diesel Engine maintenance* (Figure 9) and *Fuel metering rod position* (Figure 10) can be used to differentiate between the two fault signatures (demonstrated in Section 5.3).

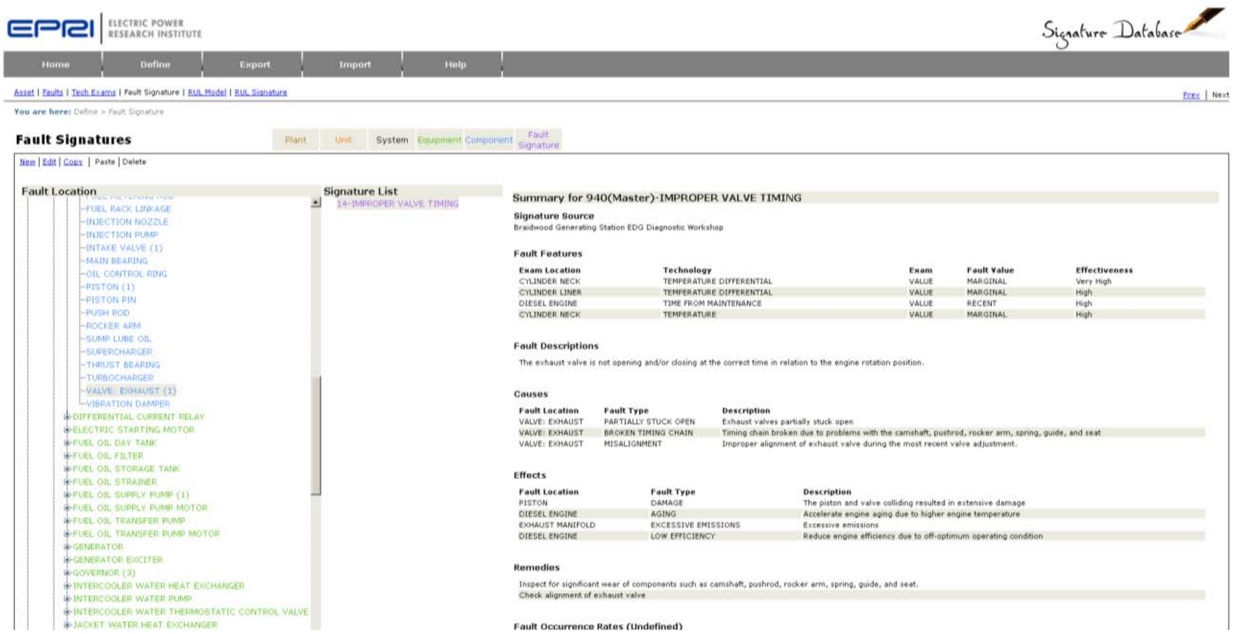


Figure 9. Diesel engine improper valve timing fault signature and associated fault features.

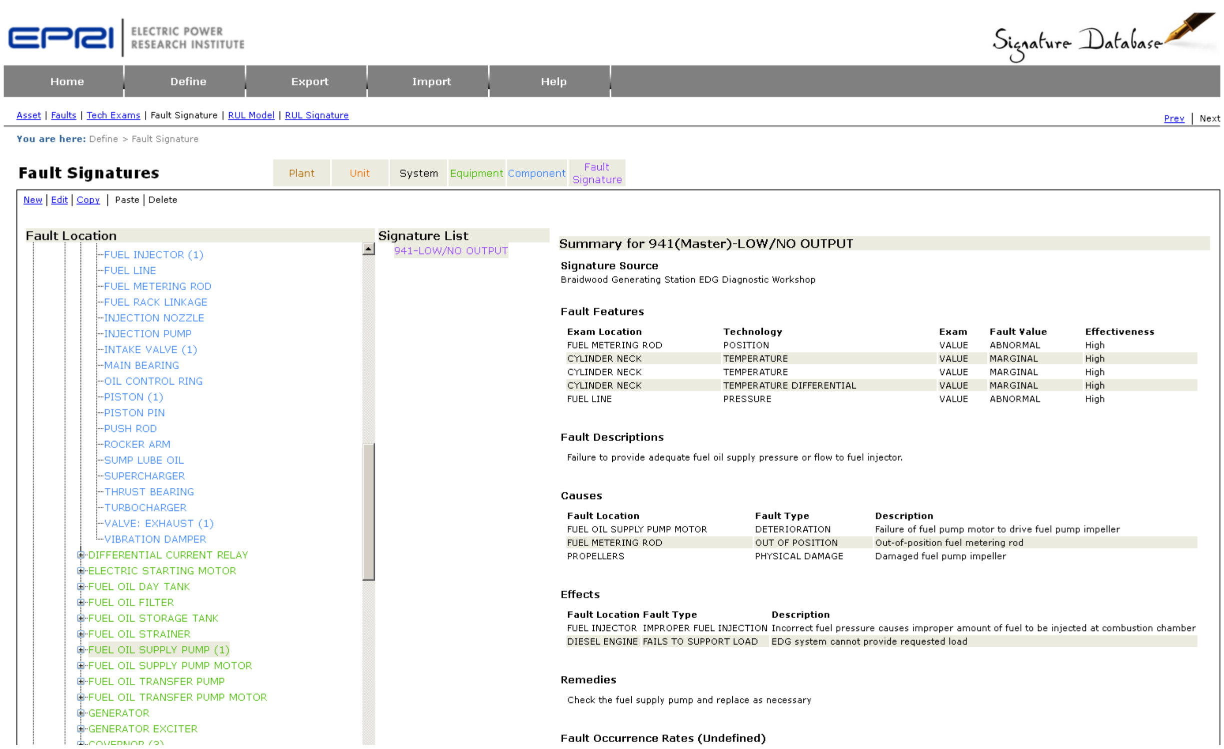


Figure 10. Diesel engine fuel oil supply pump fault signature and associated fault features.

4. ACTUAL OPERATING GSU AND EDG DATA FROM PARTNER UTILITIES

4.1 Generator Step-Up Transformer Data

Shearon Harris Nuclear Station, operated by Duke Energy, provided INL and EPRI with gas concentration data collected between April 2012 and April 2013 using the Kelman dissolved gas analyzer, (seen in Figure 11) installed on the Harris main transformers. The data also includes top insulating oil temperature, water concentration level in the insulating oil, and fan and motor ampere information for the transformer cooling system.

Figure 11. Kelman Transformer Gas Analyzer installed on Harris transformer.

A positive drift was introduced in both the acetylene and carbon monoxide concentration levels to simulate primary winding insulation degradation, a common failure mode in GSU (explained in detail in Section 5.2). As a result of the increase in the carbon monoxide concentration level, a decrease in the CO_2/CO ratio is observed. The introduction of the drift in the actual data was performed using SureSense®, an advanced pattern recognition software developed by Expert Microsystems.

The gas concentration data with drift reflect 3-out-of-4 classification criteria (Condition 1 through Condition 3) developed by the Institute of Electrical and Electronic Engineering (IEEE) to classify risk to transformers. Table 1 lists the dissolved gas concentrations for the individual gases for Condition 1 through Condition 4. This table is used to make the original assessment of a gassing condition on a new or recently repaired transformer if there are no previous tests on the transformer for dissolved gases or if there is no recent history.

Condition 1: Total Dissolved Combustible Gases (TDCG) below this level indicates the transformer is operating satisfactorily. Any individual combustible gas exceeding specified levels should prompt additional investigation.
Condition 2: TDCG within this range indicates greater than normal combustible gas level. Any individual combustible gas exceeding specified levels should prompt additional investigation. Action should be taken to establish a trend. Fault(s) may be present.
Condition 3: TDCG within this range indicates a high level of decomposition. Any individual combustible gas exceeding specified levels should prompt additional investigation. Immediate action should be taken to establish a trend. Fault(s) are probably present.
Condition 4: TDCG exceeding this value indicates excessive decomposition. Continued operation could result in failure of the transformer.

Table 1. Dissolved gas concentrations [IEEE, 2008]

Status	Dissolved key gas concentration limits							
	Hydrogen	**Methane**	**Acetylene**	**Ethylene**	**Ethane**	**Carbon monoxide**	**Carbon dioxide**	
Condition 1	100	120	1	50	65	350	2500	720
Condition 2	101-700	121-400	2-9	50-100	66-100	351-570	2500-4000	721-1920
Condition 3	701-1800	401-1000	10-35	101-200	101-150	571-1400	4001-10000	1921-4630
Condition 4	>1800	>1000	>35	>200	>150	>1400	>10000	>4630

Figures 12 and 13 show increasing levels of acetylene and carbon monoxide gas concentrations, respectively. The increase in the carbon monoxide concentration level results in decrease in the CO_2/CO ratio, as seen in Figure 14. The increase in acetylene and carbon monoxide concentration levels individually represent different phenomena leading to primary winding paper insulation degradation.

Condition 1, Condition 2, and Condition 3 in Table 1 for individual gas concentration are mapped to *Normal* (white), *Warning* (yellow), and *Alarm* (red), respectively, in SureSense® (see Figure 15), and are mapped to *Normal*, *Watch List*, and *Marginal,* respectively, in the FW-PHM Suite. Condition 4 is mapped to *Unacceptable* in the FW-PHM Suite. Individual gas concentration levels and gas ratios are monitored using SureSense®. When the gas concentration level of any gas enters Condition 2 or Condition 3, the concentration indicator in SureSense® turns yellow or red accordingly, as shown in Figure 15.

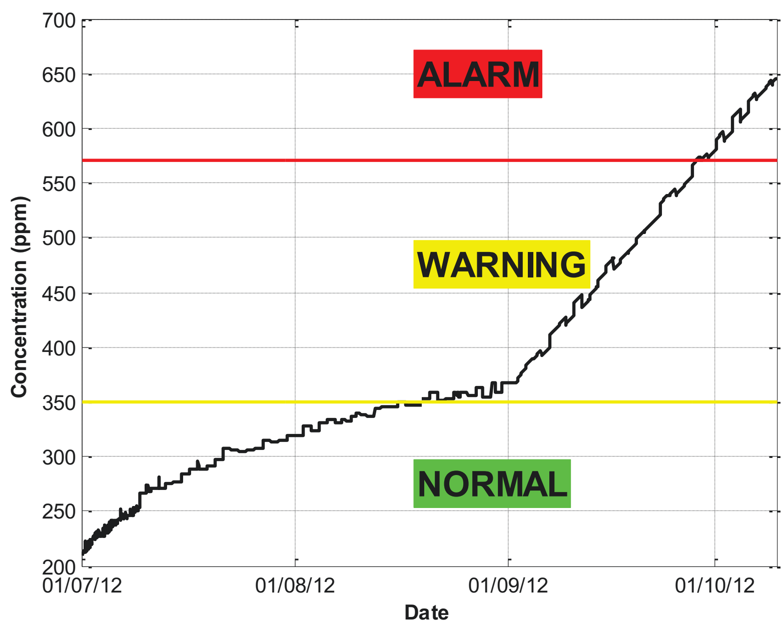


Figure 12. Simulated positive drift in the acetylene concentration level.

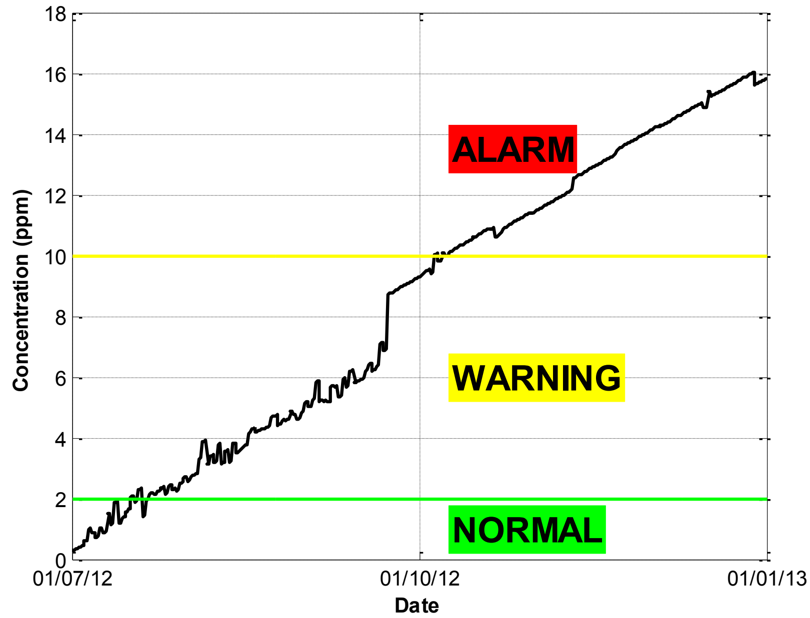


Figure 13. Simulated positive drift in the carbon monoxide concentration level.

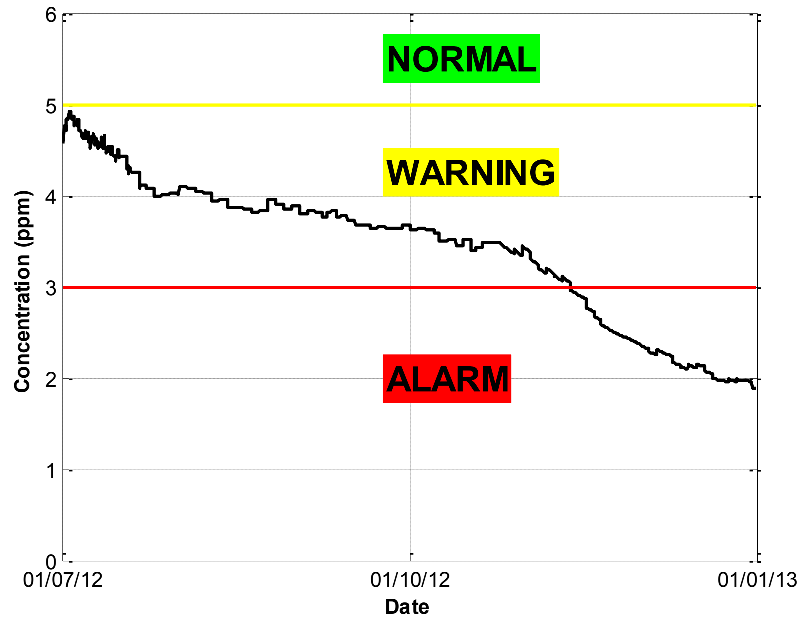


Figure 14. Decrease in CO2/CO ratio as carbon monoxide level increases.

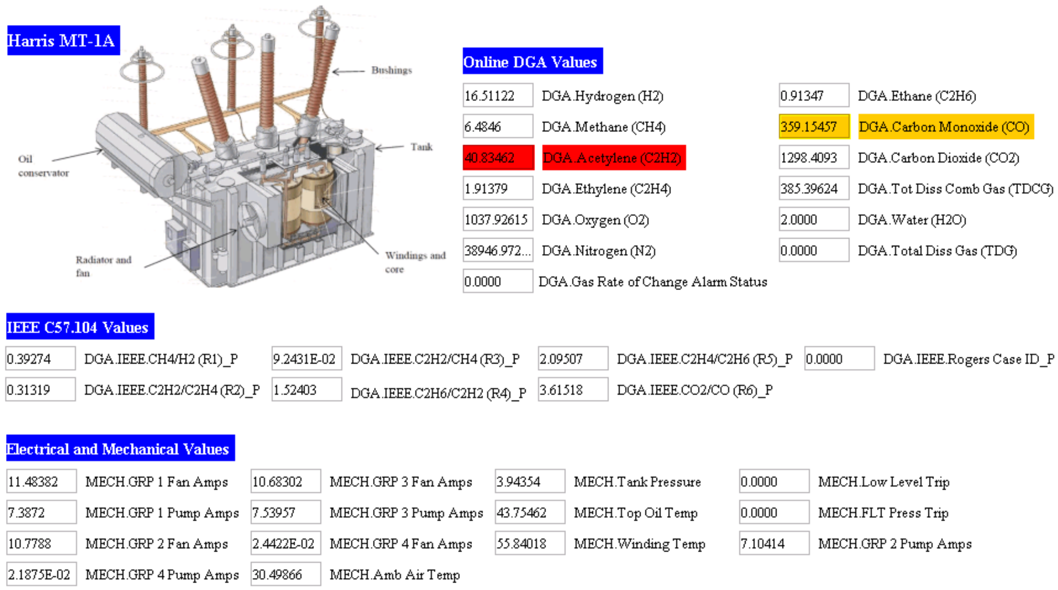


Figure 15. SureSense® interface highlighting a GSU monitored parameters.

4.2 Emergency Diesel Generator Data

Braidwood Nuclear Generating Station operated by Exelon Nuclear provided INL and EPRI with 20 cylinder temperatures, exhaust manifold temperature, and fuel line pressure data collected during one 24-hour test run of EDG on November 28, 2012. The average temperature from the 10 left and 10 right cylinders during the 24-hour run is shown in Figure 16. The two most common features used to identify improper valve timing are maximum cylinder temperature and cylinder temperature differential.

During simulation in SureSense®, a negative temperature drift was introduced in the 1st left cylinder and a positive temperature drift was introduced in the 6th right cylinder. The cylinder temperature differential was computed. The drifts in cylinder temperature and corresponding variation in the cylinder temperature differential are shown in Figures 17 and 18, respectively.

The variation in each cylinder temperature (and in cylinder temperature differential) is mapped to *Normal* (white), *Warning* (yellow), and *Alarm* (red) in SureSense® as shown in Figure 19. When the individual cylinder temperature or the cylinder temperature differential exceeds the recommended threshold limit, the indicator turns yellow or red accordingly.

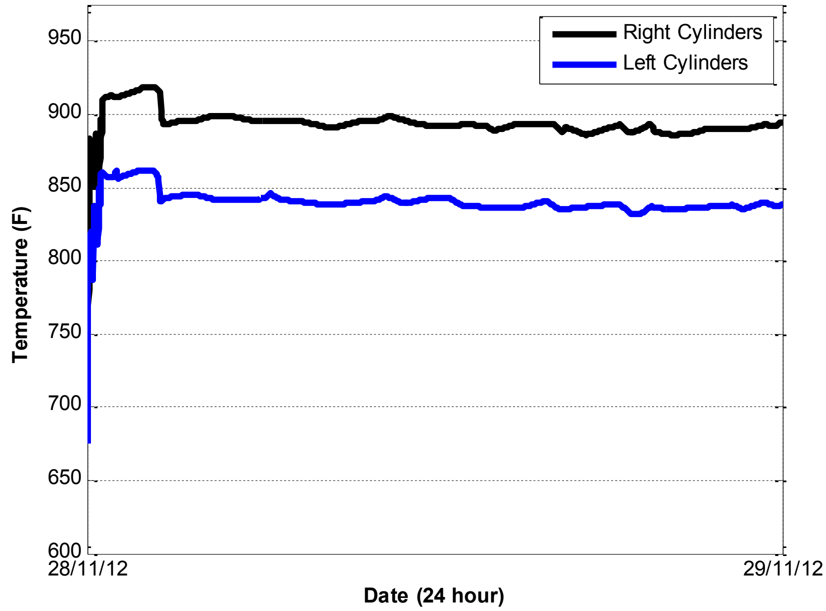


Figure 16. Average cylinder temperature profile obtained during one 24-hour run on November 28, 2012.

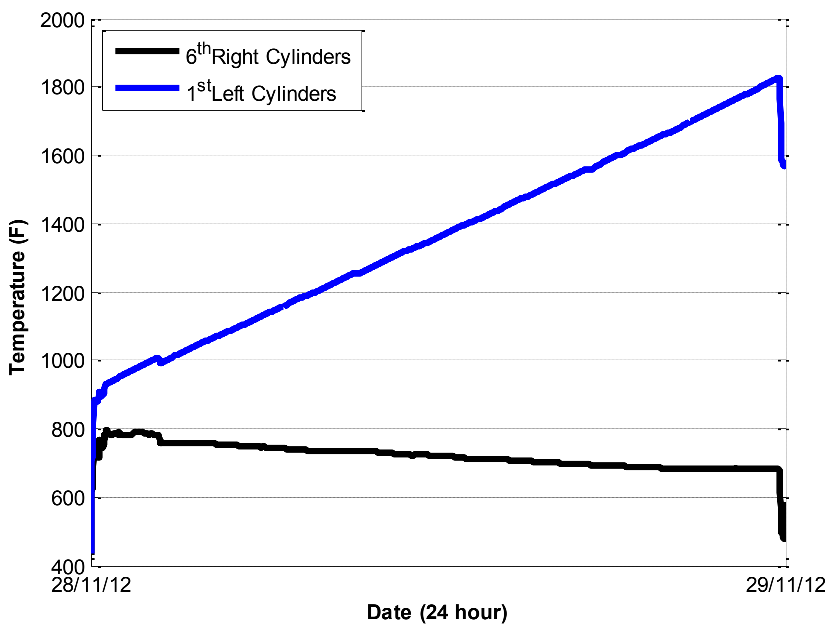


Figure 17. Deviation in the cylinder temperature indicating potential fault.

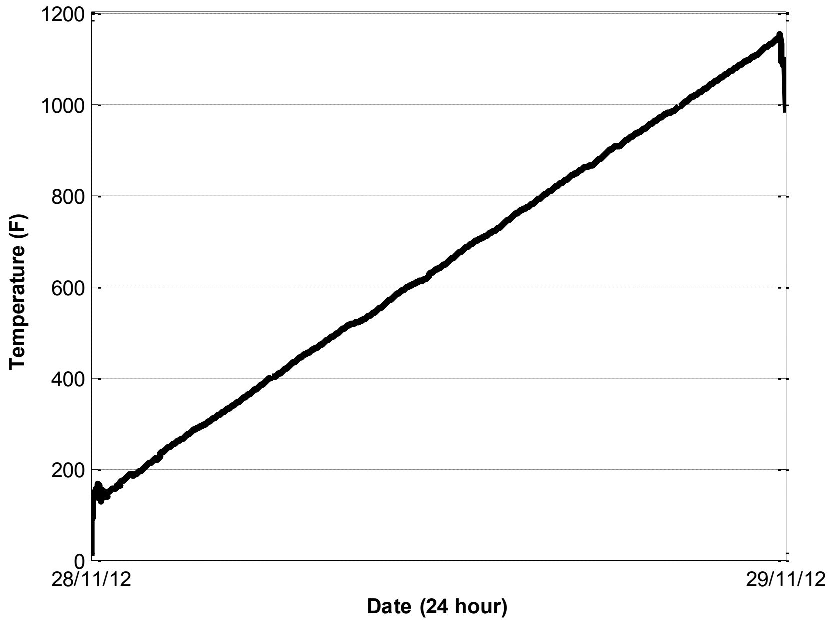


Figure 18. Simulated cylinder temperature differential as a result of drift in cylinder temperatures.

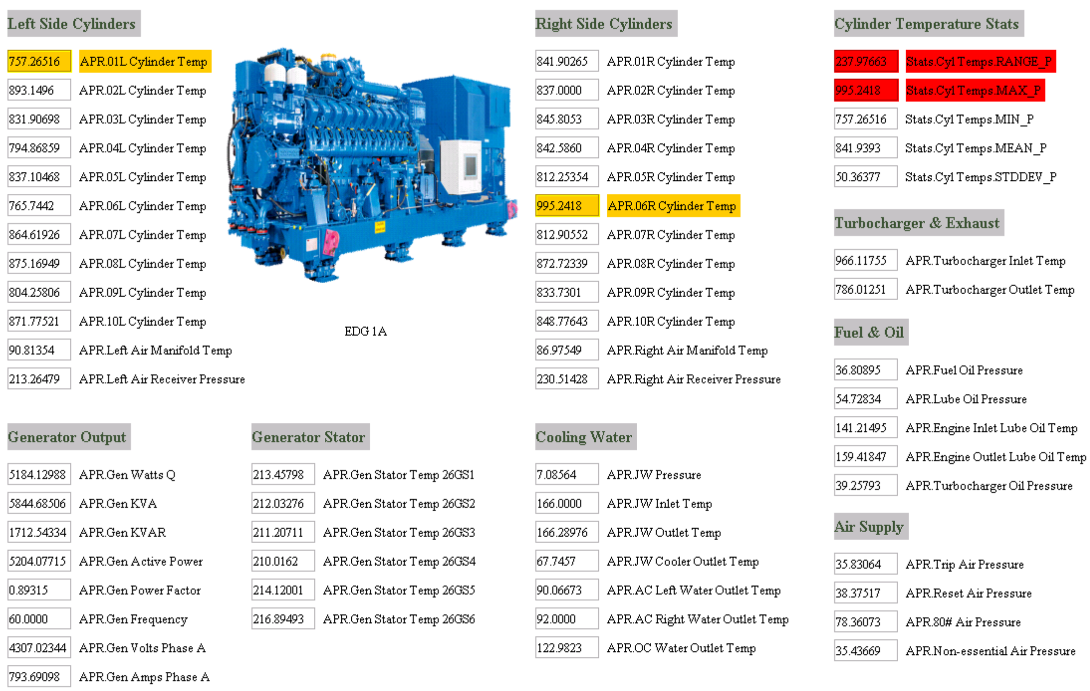


Figure 19. SureSense® interface highlighting EDG monitored parameters.

5. DEMONSTRATION OF DIAGNOSTIC CAPABILITIES OF THE FW-PHM SUITE SOFTWARE

The diagnostic capability of the FW-PHM Suite's Diagnostic Advisor was demonstrated at the 2013 Summer Utility Working Group meeting in Idaho Falls, Idaho. In the demonstration, EPRI and INL researchers used the Diagnostic Advisor to diagnose *primary winding paper insulation degradation fault* in a GSU transformer and *improper valve timing* in an EDG when connected to an online data stream embedded with simulated faults.

5.1 Information Communication Pathway

As described earlier, the faults were simulated using SureSense®, an advanced pattern recognition software. SureSense® writes the simulation outputs to an Oracle 11g Database. The Diagnostic Advisor in the FW-PHM Suite is configured to read information from the database, creating a communication pathway, as shown in Figure 20. The Diagnostic Advisor of the FW-PHM Suite utilizes the communication pathway to periodically update its online data query and perform diagnoses. If the updated information identifies any potential fault, the Diagnostic Advisor generates a new diagnosis result and sends an email notification to the person in charge.

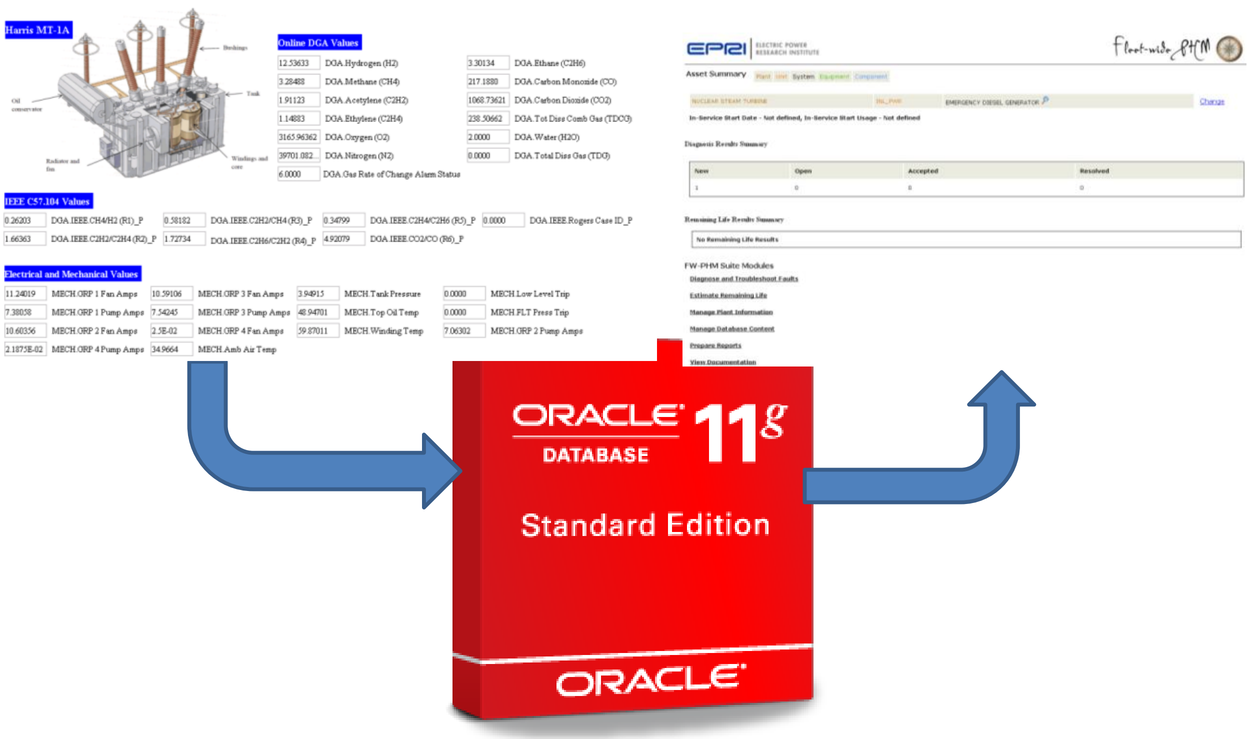


Figure 20. Information communication pathway between the SureSense® software and the AFS database.

5.2 Generator Step-Up Transformer Demonstration

GSUs are one of the most highly valued assets in power industry. Any unexpected GSU downtime results in financial losses, as it would prevent a power utility from supplying power to the grid. A new GSU costs more than $1M and acquisition may require a lead-time of approximately one year. Therefore, it is important to monitor health of GSUs and provide early diagnosis so that appropriate maintenance action can be taken before any catastrophic failure occurs.

5.2.1 Demonstration of Primary Winding Paper Insulation Degradation Fault

Primary winding insulation degradation is one of the common faults in transformers [Bartley, 2003]. The two main modes of primary winding paper insulation degradation are electrical and thermal. The Diagnostic Advisor of the FW-PHM Suite utilizes the communication pathway described in Section 5.1 and the simulated primary winding fault data (from SureSense®) described in Section 4.1 to diagnose primary winding paper insulation degradation. The ability of the Diagnostic Advisor to diagnose the degradation is described in detail here via a demonstration process. In the demonstration, gas concentration levels and gas ratios are played back at an accelerated pace and monitored continuously. In practice, changes in gas concentration and gas ratios are slow and might take several months to reach the *Warning* stage.

Paper insulation degradation due to electrical discharge represents either the occurrence of a partial discharge phenomenon or an arcing phenomenon. A steep increase in the hydrogen concentration level compared to other dissolved gases in the transformer insulating oil is an indication of partial discharge. Similarly, an increase in the hydrogen and acetylene concentration levels combined compared to other dissolved gases is an indication of arcing. Electrical discharge can create localized hotspots, causing an increase in the top insulating oil temperature.

Paper insulation degradation due to thermal phenomena can be diagnosed when a steep increase in the carbon monoxide concentration level is observed. The rate of increase of carbon monoxide and carbon dioxide are different, so a decrease in the CO_2/CO ratio also indicates thermal degradation of primary winding paper insulation.

5.2.2 Diagnostic Advisor Diagnosis of Paper Insulation Degradation

The demonstration begins with monitoring acetylene and carbon monoxide concentration levels as well as the CO_2/CO ratio. Figure 21 shows the SureSense® screen with all the individual gas concentration levels and gas ratios within the normal operating range. As long as the monitored gases are within normal range, no *New* diagnoses are observed in the FW-PHM Suite. As the monitoring continues, the acetylene concentration level indicator reaches the *Warning* level (turns yellow), indicating that the acetylene gas level has entered IEEE Condition 2, i.e., *Watch List*. This information is continuously logged into the Oracle Database. The Diagnostic Advisor of the FW-PHM Suite, via the information communication pathway, reads the updated information from the Oracle Database. At this point, the Diagnostic Advisor immediately records the change in the acetylene concentration level, creates a *New* diagnosis, as seen in Figure 22, and sends an email notification to the person in charge that includes the Fault Diagnosis Summary (Figure 23).

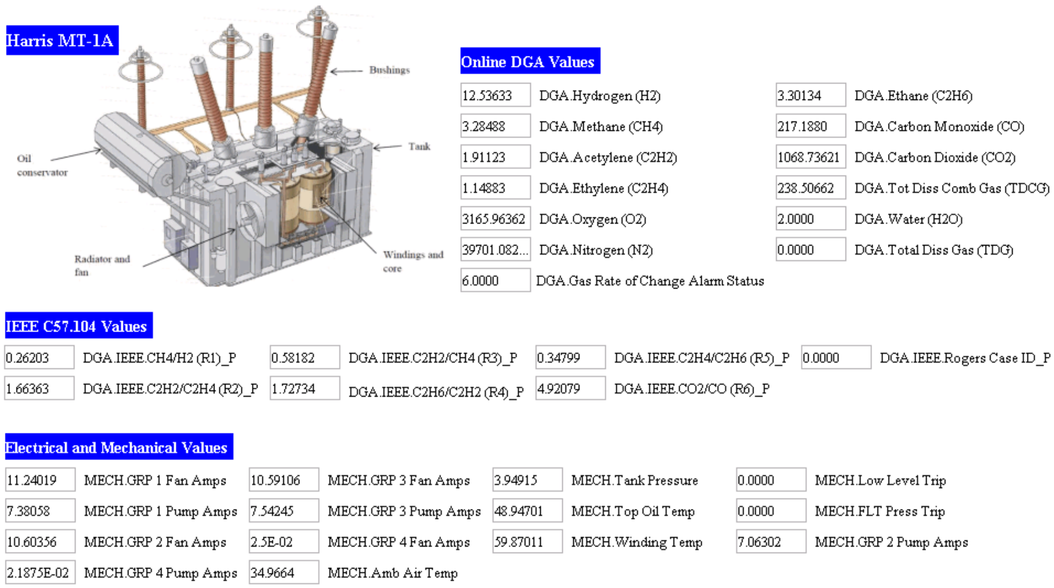


Figure 21. SureSense® screen showing all gas concentration levels and ratios within normal operating range.

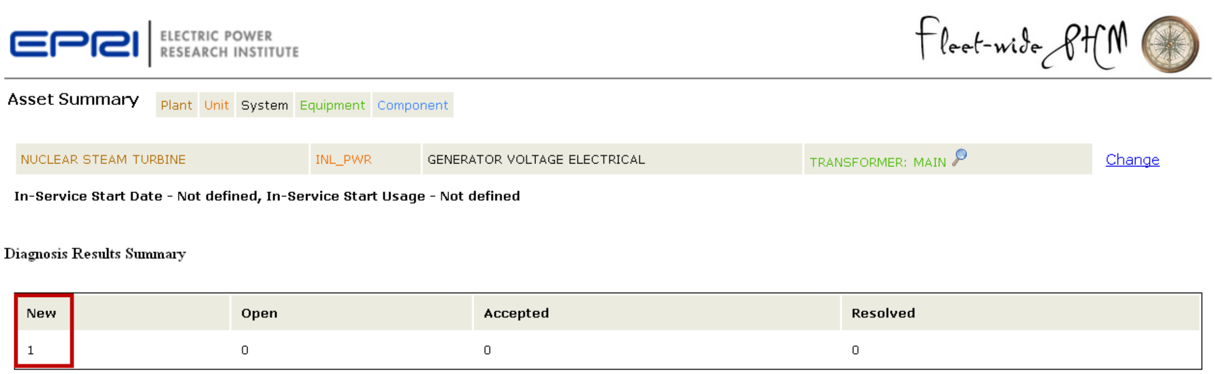
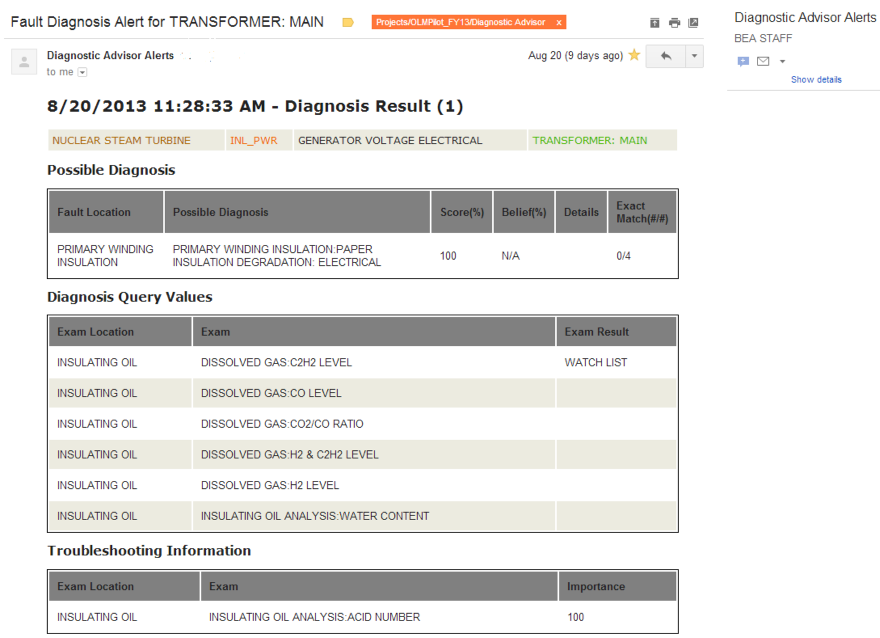


Figure 22. New diagnosis result is created by the Diagnostic Advisor.


Fault Diagnosis Alert for TRANSFORMER: MAIN Projects/OLMPilot_FY13/Diagnostic Advisor

Diagnostic Advisor Alerts
to me

Aug 20 (9 days ago)

Diagnostic Advisor Alerts
BEA STAFF
Show details

8/20/2013 11:28:33 AM - Diagnosis Result (1)

NUCLEAR STEAM TURBINE	INL_PWR	GENERATOR VOLTAGE ELECTRICAL	TRANSFORMER: MAIN

Possible Diagnosis

Fault Location	Possible Diagnosis	Score(%)	Belief(%)	Details	Exact Match(#/#)
PRIMARY WINDING INSULATION	PRIMARY WINDING INSULATION:PAPER INSULATION DEGRADATION: ELECTRICAL	100	N/A		0/4

Diagnosis Query Values

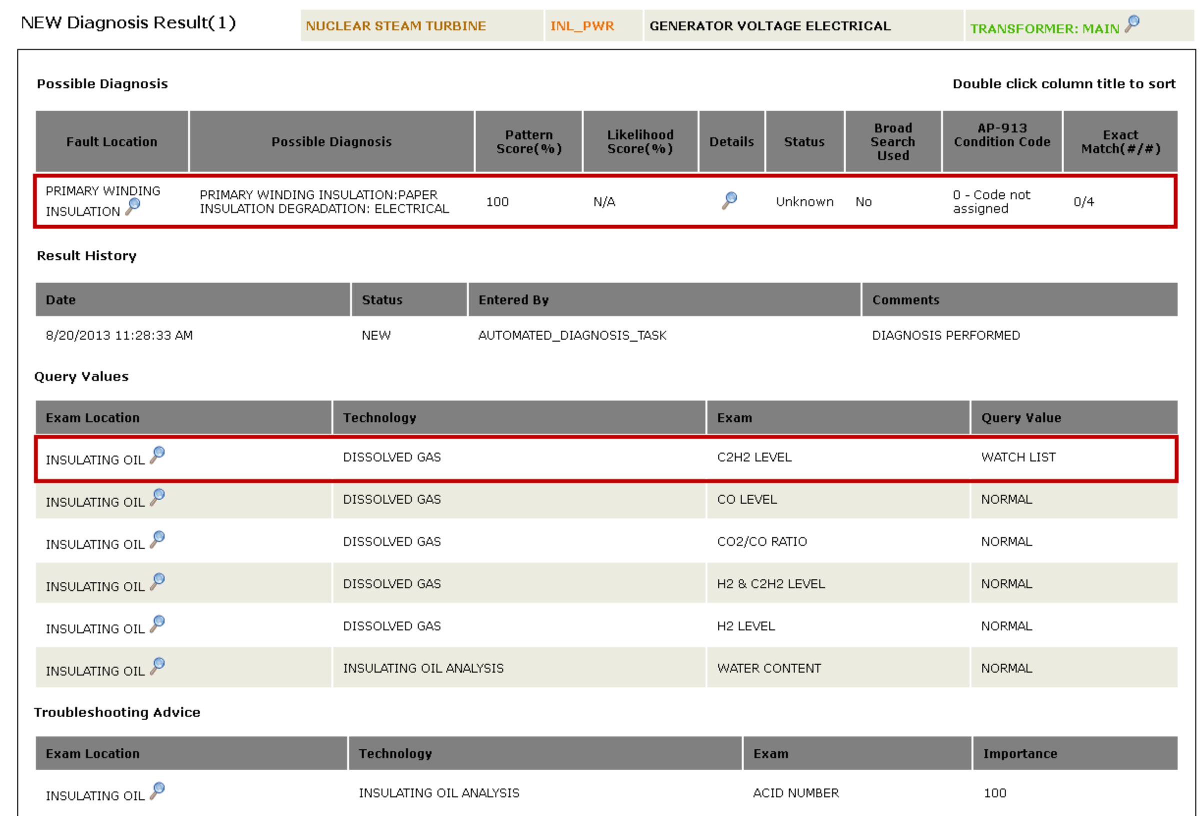
Exam Location	Exam	Exam Result
INSULATING OIL	DISSOLVED GAS:C2H2 LEVEL	WATCH LIST
INSULATING OIL	DISSOLVED GAS:CO LEVEL	
INSULATING OIL	DISSOLVED GAS:CO2/CO RATIO	
INSULATING OIL	DISSOLVED GAS:H2 & C2H2 LEVEL	
INSULATING OIL	DISSOLVED GAS:H2 LEVEL	
INSULATING OIL	INSULATING OIL ANALYSIS:WATER CONTENT	

Troubleshooting Information

Exam Location	Exam	Importance
INSULATING OIL	INSULATING OIL ANALYSIS:ACID NUMBER	100

Figure 23. An example of email notification received by the person in charge.

By clicking the *Diagnose and Troubleshoot Faults* link under the FW-PHM Suite Modules on the main page and the *Edit* link on the following page, the person in charge navigates to the *New Diagnosis Results* page as shown in Figure 24. The *Diagnosis Result Page* has different information sections. The *Possible Diagnosis* section displays the latest diagnosis results with information on *Fault Location*, *Possible Diagnosis*, *Pattern Score*, *Likelihood Score*, *Details*, *Status*, *Broad Search Used*, *AP-913 Condition Code*, and *Exact Match*. At present, only information on Fault Location, Possible Diagnosis, and Pattern Score are of interest. Fault Location communicates the location of the fault; in this case, it says *Primary Winding Insulation* (as expected). Possible Diagnosis identifies the most likely fault based on the current available information. In this example demonstration, *Paper Insulation Degradation: Electrical* is identified as the most likely diagnosis based on the current acetylene concentration level (as expected). Pattern Score is a percentage indicating the relative likelihood of the fault based on the current information.



NEW Diagnosis Result(1) | NUCLEAR STEAM TURBINE | INL_PWR | GENERATOR VOLTAGE ELECTRICAL | TRANSFORMER: MAIN

Possible Diagnosis — Double click column title to sort

Fault Location	Possible Diagnosis	Pattern Score(%)	Likelihood Score(%)	Details	Status	Broad Search Used	AP-913 Condition Code	Exact Match(#/#)
PRIMARY WINDING INSULATION	PRIMARY WINDING INSULATION:PAPER INSULATION DEGRADATION: ELECTRICAL	100	N/A		Unknown	No	0 - Code not assigned	0/4

Result History

Date	Status	Entered By	Comments
8/20/2013 11:28:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	DIAGNOSIS PERFORMED

Query Values

Exam Location	Technology	Exam	Query Value
INSULATING OIL	DISSOLVED GAS	C2H2 LEVEL	WATCH LIST
INSULATING OIL	DISSOLVED GAS	CO LEVEL	NORMAL
INSULATING OIL	DISSOLVED GAS	CO2/CO RATIO	NORMAL
INSULATING OIL	DISSOLVED GAS	H2 & C2H2 LEVEL	NORMAL
INSULATING OIL	DISSOLVED GAS	H2 LEVEL	NORMAL
INSULATING OIL	INSULATING OIL ANALYSIS	WATER CONTENT	NORMAL

Troubleshooting Advice

Exam Location	Technology	Exam	Importance
INSULATING OIL	INSULATING OIL ANALYSIS	ACID NUMBER	100

Figure 24. New Diagnosis Result summary page created by the Diagnostic Advisor when acetylene level reaches Watch List.

The *Result History* section lists all the diagnoses performed by the Diagnostic Advisor. The *Query Values* section lists query values for the mapped technology. In this case, observe that the query values for all the exams are *Normal* except for acetylene, which reads *Watch List*. The *Troubleshooting Advice* section lists other fault features that could be mapped to the Oracle Database or could be entered manually, to further refine the diagnosis result. In this case, the suggested troubleshooting advice is to analyze the *Acid Number* of the insulating oil.

As monitoring continues, the acetylene concentration level indicator in SureSense® turns red indicating that the concentration level has reached IEEE Condition 4, i.e., *Unacceptable* (see Table 1), as seen in Figure 25. After a short time interval of monitoring, the carbon monoxide concentration level indicator in SureSense® turns yellow indicating that the concentration has reached IEEE Condition 2, i.e., *Watch List*, also seen in Figure 25 This new information is updated in the Oracle Database; the Diagnostic Advisor reads the updated information, updates the previous diagnoses result based on new information, and sends a new email notification.

The following changes are observed in the updated New Diagnosis Result page, as shown in Figure 26:

1. Two possible diagnoses are now listed: *Primary Winding Insulation Degradation: Electrical* and *Primary Winding Insulation Degradation: Thermal.* The previous results seen in Figure 24 only listed the electrical degradation.

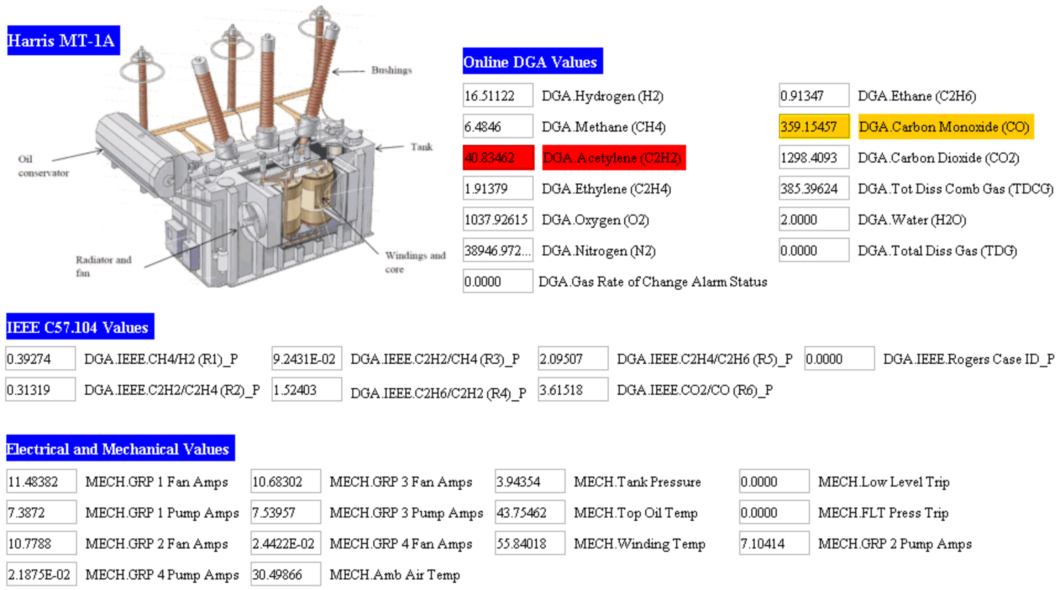


Figure 25. SureSense® screen showing increase in acetylene and carbon monoxide concentration levels to IEEE Condition 4 and IEEE Condition 2 respectively.

2. The pattern score for electrical degradation in Figure 26 has reduced from 100% to 63.16%, with thermal degradation listed at 36.84%.
3. In the *Result History* section, observe that the Diagnostic Advisor updated twice. The first update result is due to acetylene concentration reaching IEEE Condition 4, and the second update result is due to carbon monoxide concentration reaching IEEE Condition 2.
4. In the *Query Values* section, observe the query value column. For acetylene it reads *Unacceptable* and for carbon monoxide it reads *Watch List*.
5. In the *Troubleshooting Advice* section, a new exam appears. The Diagnostic Advisor now suggests an additional fault feature, *Time at Excess Temperature*, as information that might be useful in further differentiating two possible diagnoses.

As monitoring continues, the concentration level of carbon monoxide reaches IEEE Condition 3, i.e., *Marginal*. After a short time interval it is observed that CO_2/CO ratio indicator turns red, suggesting that the ratio has reached IEEE Condition 4. This new information is logged into the Oracle Database. The Diagnostic Advisor reads the updated information from the Oracle Database and updates the previous diagnoses result, sending a new email notification. The New Diagnosis Result page in Figure 27 has the following updates:

1. The pattern score for thermal degradation increased from 36.84% (as observed in Figure 26) to 67.74% and now is the most likely fault.
2. The pattern score for electrical degradation decreased from 64.16% (as observed in Figure 26) to 32.26% and is no longer the most likely fault.
3. In the *Result History* section, two additional updates are recorded. The third update result represents the change in carbon monoxide concentration level from IEEE Condition 2 to IEEE Condition 3. The fourth update result represents the change when the CO_2/CO ratio reaches IEEE Condition 4.
4. In the *Query Values* section, the query value of carbon monoxide reads *Marginal* compared to *Watch List* in Figure 26 and the query value of the CO_2/CO ratio reads *Unacceptable* compared to *Normal* in Figure 26.

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Diagnostic Advisor

NEW Diagnosis Result(3) | NUCLEAR STEAM TURBINE | INL_PWR | GENERATOR VOLTAGE ELECTRICAL | TRANSFORMER: MAIN

Possible Diagnosis — Double click column title to sort

Fault Location	Possible Diagnosis	Pattern Score(%)	Likelihood Score(%)	Details	Status	Broad Search Used	AP-913 Condition Code	Exact Match(#/#)
PRIMARY WINDING INSULATION	PRIMARY WINDING INSULATION:PAPER INSULATION DEGRADATION: ELECTRICAL	63.16	N/A		Unknown	No	0 - Code not assigned	1/4
PRIMARY WINDING INSULATION	PRIMARY WINDING INSULATION:PAPER INSULATION DEGRADATION: THERMAL	36.84	N/A		Unknown	No	0 - Code not assigned	0/3

Result History

Date	Status	Entered By	Comments
8/20/2013 11:37:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	UPDATED RESULT 2
8/20/2013 11:36:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	UPDATED RESULT 1
8/20/2013 11:28:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	DIAGNOSIS PERFORMED

Query Values

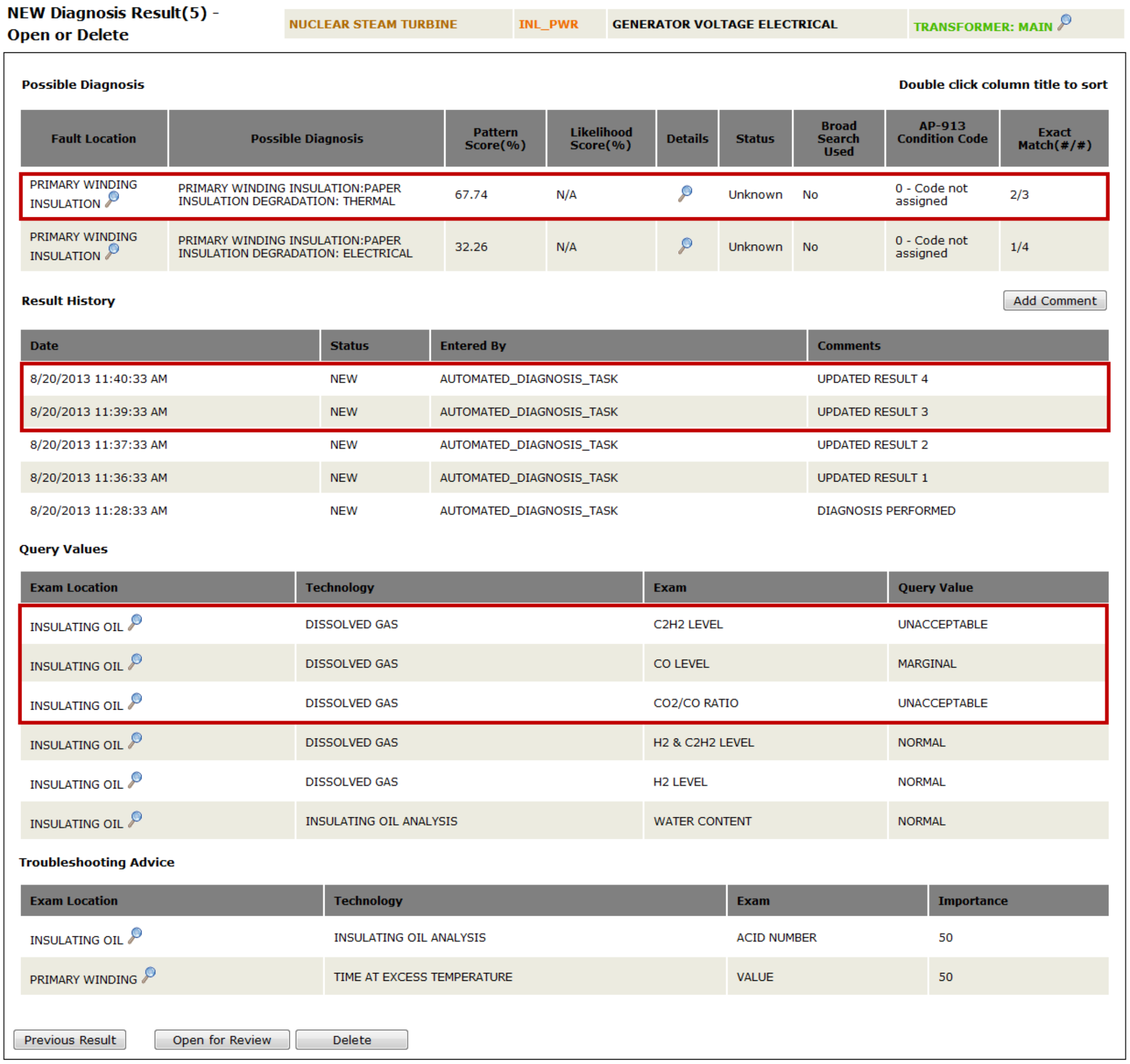
Exam Location	Technology	Exam	Query Value
INSULATING OIL	DISSOLVED GAS	C2H2 LEVEL	UNACCEPTABLE
INSULATING OIL	DISSOLVED GAS	CO LEVEL	WATCH LIST
INSULATING OIL	DISSOLVED GAS	CO2/CO RATIO	NORMAL
INSULATING OIL	DISSOLVED GAS	H2 & C2H2 LEVEL	NORMAL
INSULATING OIL	DISSOLVED GAS	H2 LEVEL	NORMAL
INSULATING OIL	INSULATING OIL ANALYSIS	WATER CONTENT	NORMAL

Troubleshooting Advice

Exam Location	Technology	Exam	Importance
INSULATING OIL	INSULATING OIL ANALYSIS	ACID NUMBER	50
PRIMARY WINDING	TIME AT EXCESS TEMPERATURE	VALUE	50

Previous Result

Figure 26. Updated New Diagnosis Result Page indicating primary winding paper insulation degradation due to electrical discharges as most likely diagnosis.



NEW Diagnosis Result(5) - Open or Delete

NUCLEAR STEAM TURBINE | INL_PWR | GENERATOR VOLTAGE ELECTRICAL | TRANSFORMER: MAIN

Possible Diagnosis

Double click column title to sort

Fault Location	Possible Diagnosis	Pattern Score(%)	Likelihood Score(%)	Details	Status	Broad Search Used	AP-913 Condition Code	Exact Match(#/#)
PRIMARY WINDING INSULATION	PRIMARY WINDING INSULATION:PAPER INSULATION DEGRADATION: THERMAL	67.74	N/A		Unknown	No	0 - Code not assigned	2/3
PRIMARY WINDING INSULATION	PRIMARY WINDING INSULATION:PAPER INSULATION DEGRADATION: ELECTRICAL	32.26	N/A		Unknown	No	0 - Code not assigned	1/4

Result History

Add Comment

Date	Status	Entered By	Comments
8/20/2013 11:40:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	UPDATED RESULT 4
8/20/2013 11:39:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	UPDATED RESULT 3
8/20/2013 11:37:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	UPDATED RESULT 2
8/20/2013 11:36:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	UPDATED RESULT 1
8/20/2013 11:28:33 AM	NEW	AUTOMATED_DIAGNOSIS_TASK	DIAGNOSIS PERFORMED

Query Values

Exam Location	Technology	Exam	Query Value
INSULATING OIL	DISSOLVED GAS	C2H2 LEVEL	UNACCEPTABLE
INSULATING OIL	DISSOLVED GAS	CO LEVEL	MARGINAL
INSULATING OIL	DISSOLVED GAS	CO2/CO RATIO	UNACCEPTABLE
INSULATING OIL	DISSOLVED GAS	H2 & C2H2 LEVEL	NORMAL
INSULATING OIL	DISSOLVED GAS	H2 LEVEL	NORMAL
INSULATING OIL	INSULATING OIL ANALYSIS	WATER CONTENT	NORMAL

Troubleshooting Advice

Exam Location	Technology	Exam	Importance
INSULATING OIL	INSULATING OIL ANALYSIS	ACID NUMBER	50
PRIMARY WINDING	TIME AT EXCESS TEMPERATURE	VALUE	50

Previous Result | Open for Review | Delete

Figure 27. Updated New Diagnosis Result page indicating paper insulation degradation: thermal as the most likely fault.

5.2.3 Summary

The GSU demonstration described above highlights the Diagnostic Advisor ability to:

1. Capture the changes in the mapped fault features on a continuous basis and update the possible diagnoses result
2. Automatically generate an email notification to the person in charge with detailed diagnosis summary
3. Maintain diagnosis history
4. Provide troubleshooting advice that, if used, could assist the person in charge to differentiate between different possible diagnoses.

5.3 Emergency Diesel Generator Demonstration

EDGs are safety-related assets that are necessary to operate reliably if the external grid power supply to the plant is interrupted. EDGs are required to start, run, and take the basic loads that are essential for safe shut-down of the plant. There are many faults that could lead to EDG failure; improper valve timing in the diesel engine is a common fault that is discussed in the following section. In section 5.3.2, the ability of the Diagnostic Advisor to diagnose the improper valve timing based on individual cylinder temperatures, cylinder temperature differentials, and maintenance actions is demonstrated.

5.3.1 Improper Valve Timing on Diesel Engine Cylinder

For an EDG to start, run, and take the basic loads, proper valve timing (alternately referred to as ignition timing) is essential. An increase or decrease in cylinder temperature may be indicative of improper valve timing. Lower and upper threshold limits are defined to monitor the change in cylinder temperature value. As the individual cylinder temperature varies, the differential value is also computed. For the sake of simplicity, cylinder temperature and cylinder temperature differential will be referred to simply as temperature and temperature differential respectively from here on, unless stated otherwise. Temperature differential is the difference between the maximum and minimum temperature values. Threshold limits are defined to monitor the changes in the temperature differential. A drift in temperature values was simulated in SureSense® for the demonstration purpose.

5.3.2 Diagnostic Advisor Diagnosis of Improper Valve Timing on Diesel Engine

A demonstration exercise is presented here to show the ability of the Diagnostic Advisor to diagnose improper valve timing on a diesel engine.

The demonstration focuses on monitoring individual temperature values and temperature differential values. The SureSense® screen in Figure 28 shows that all the individual temperature and temperature differential values are within normal operating limits. Note that the diesel engine in this demonstration has 10 cylinders on the left and 10 cylinders on the right. Under normal operating conditions, no *New* diagnosis is generated by the Diagnostic Advisor, as observed in Figure 29.

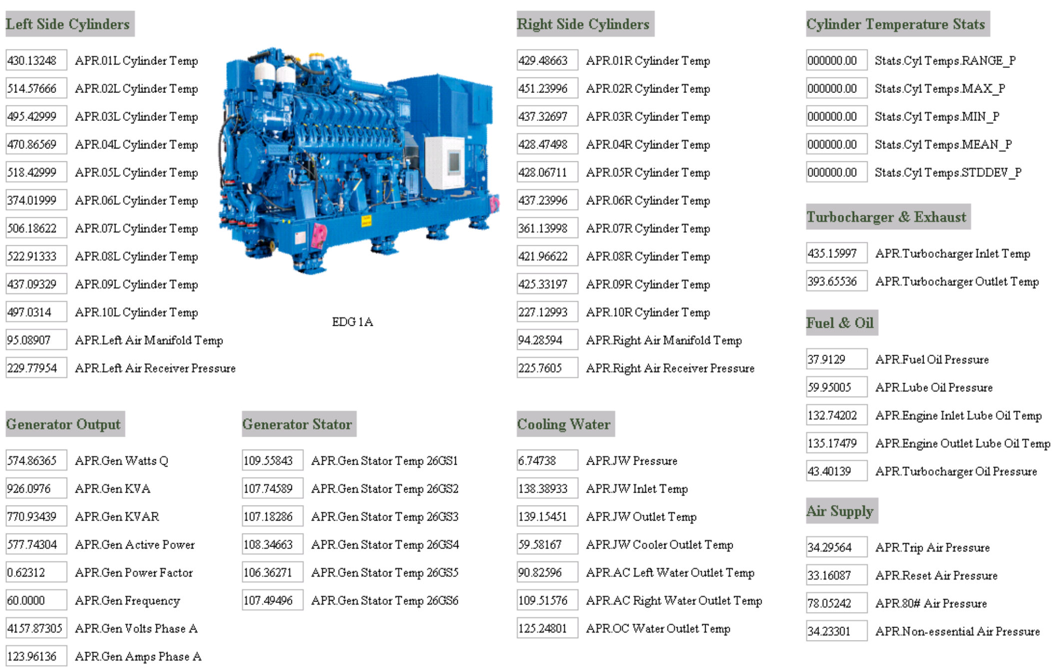


Figure 28. The SureSense® scene showing monitored EDG parameters under normal operating condition.

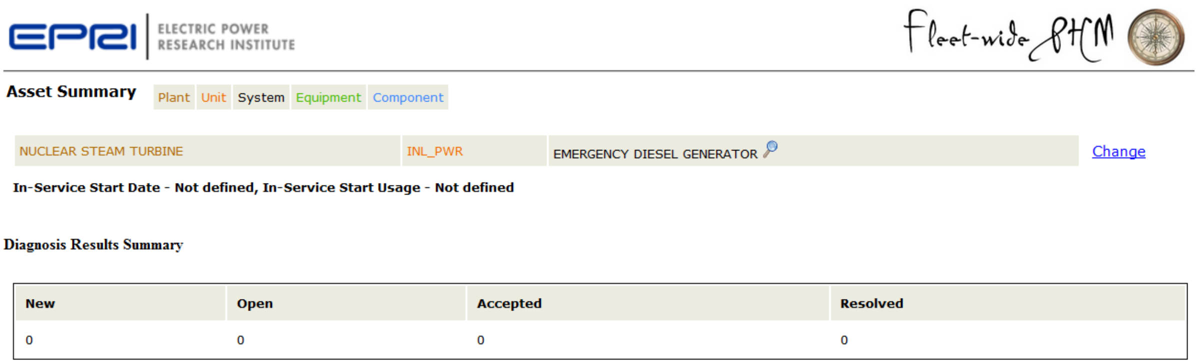


Figure 29. The FW-PHM Suite software main page showing no new diagnosis available for EDG.

After a short duration of monitoring, a drift is observed in two temperature values along with an increase in temperature differential. The temperature of the cylinder labeled APR.01L (L stands for left) is decreasing and the temperature of the cylinder labeled APR.06R (R stands for right) is increasing (see Figure 30). The temperature differential indicator labeled as Stats Cyl Temps RANGES_P starts to increase as a result of drifts in the temperature values. From the SureSense® screen in Figure 30, observe that temperature and temperature differential values are above user-defined threshold limits and the indicators turn red. This information is logged into the Oracle Database. The Diagnostic Advisor reads the information from the database and performs the diagnosis. At this instance, a *New* diagnosis result is generated as seen in Figure 31 and an email notification is sent.

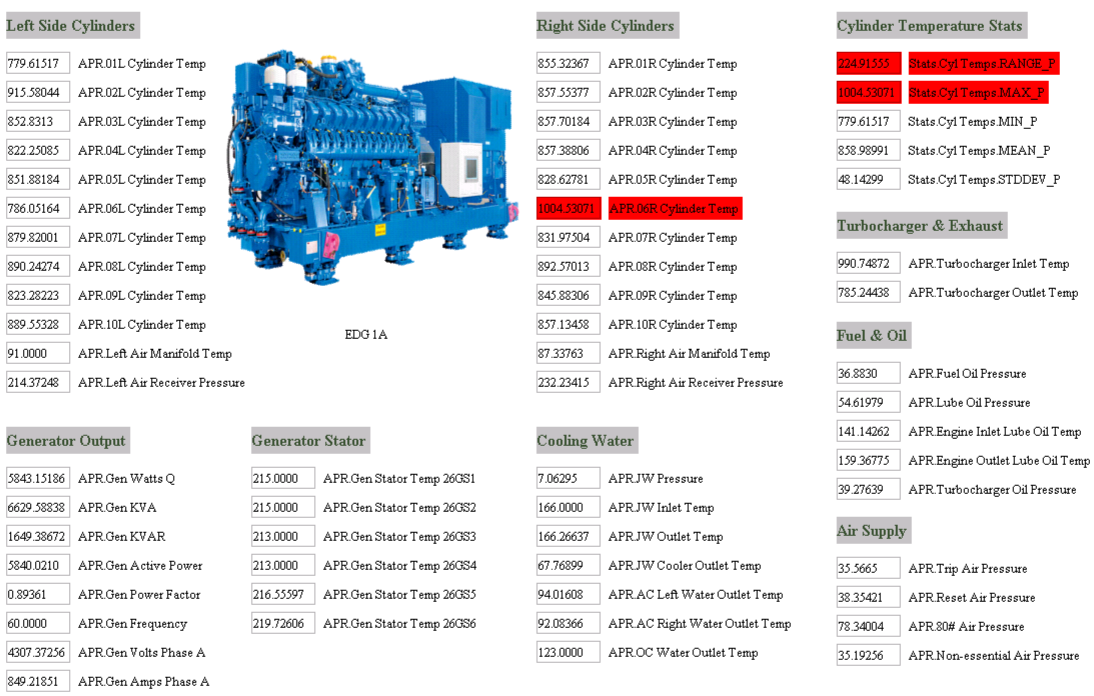


Figure 30. The SureSense® screen showing abnormal temperature and temperature differential values.

Figure 31. The FW-PHM Suite software main page showing new diagnosis for EDG.

The *New Diagnosis Result page* in Figure 32 highlights two possible diagnoses: *Valve: Exhaust: Improper Valve Timing* and *Fuel Oil Supply Pump*, with pattern scores of 52.94% and 47.06% respectively based on current query values. The pattern scores of the two faults are very close and further evidence is required to identify the most likely fault type.

The *Troubleshooting Advice* section suggests that information on maintenance activity could be used to improve the diagnosis. This additional information can be manually entered, and diagnosis can then be updated. In order to enter the information manually, the person in charge must first open the current diagnosis for review by clicking on the *Open for Review* option at the bottom of the New Diagnosis Page and by entering text in the comment area. At this stage, the current diagnosis is opened for review, as seen in Figure 33.

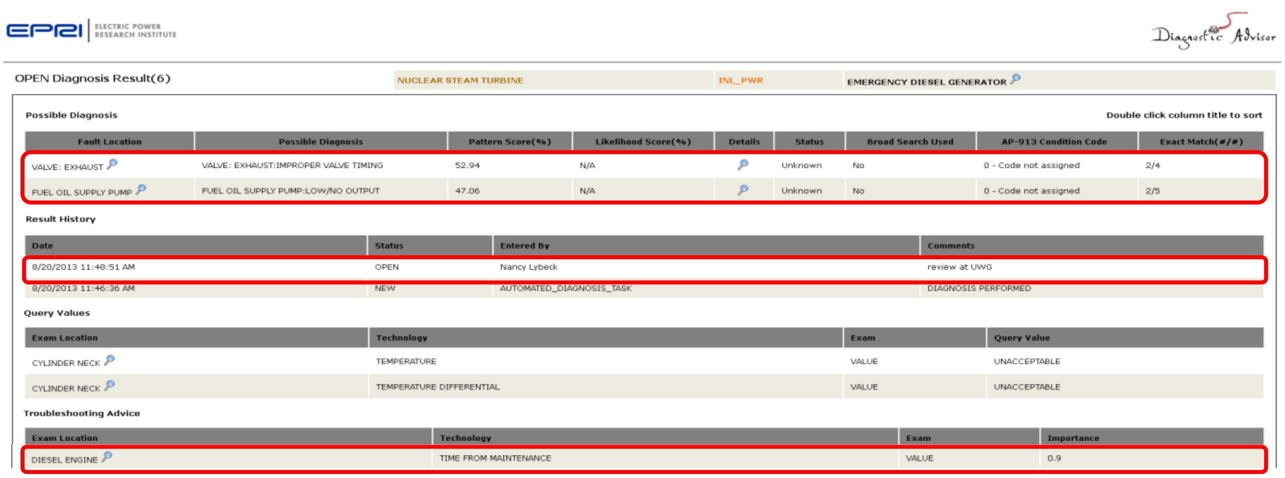


Figure 32. The New Diagnosis Result page of EDG.

Figure 33. The FW-PHM Suite software main page showing that the diagnosis is open for review.

Once the diagnosis is open for review, it is updated by navigating to the *Open Diagnosis Result* page and clicking the *Update* option at the bottom of the page as shown in Figure 34. Also observe that the *Result History* section in Figure 34 captures the current status of the diagnosis. By clicking the Update option, the *Update Query for OPEN Diagnosis Result* page shown in Figure 35 allows the person in charge to enter the *Time From Maintenance* information manually by selecting a suitable option from the drop-down menu under the Query Value column. In this demonstration, *Very Recent* query value is selected from the drop-down menu and the diagnosis result is updated by clicking *Update Diagnosis* option.

The following changes are observed from the updated diagnosis result in Figure 36:

1. The pattern score for improper valve timing increases to 56.52% compared to 52.94%
2. The pattern score for degraded fuel oil supply pump decreases to 43.48% compared to 47.06%
3. In the *Result History* section, the updated result is recorded
4. In the *Query Values* section, the person in charge enters the maintenance information manually.

Based on the updated result, *Valve: Exhaust: Improper Valve Timing* is diagnosed as the most likely fault by the Diagnostic Advisor.

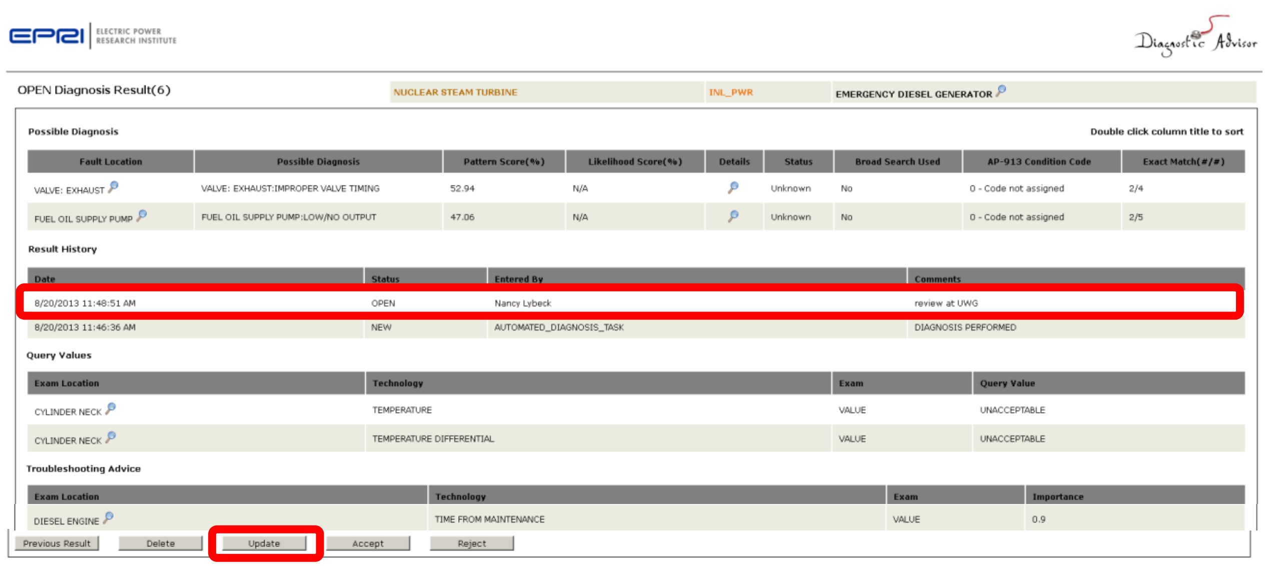


Figure 34. The OPEN Diagnosis Result page with an update option.

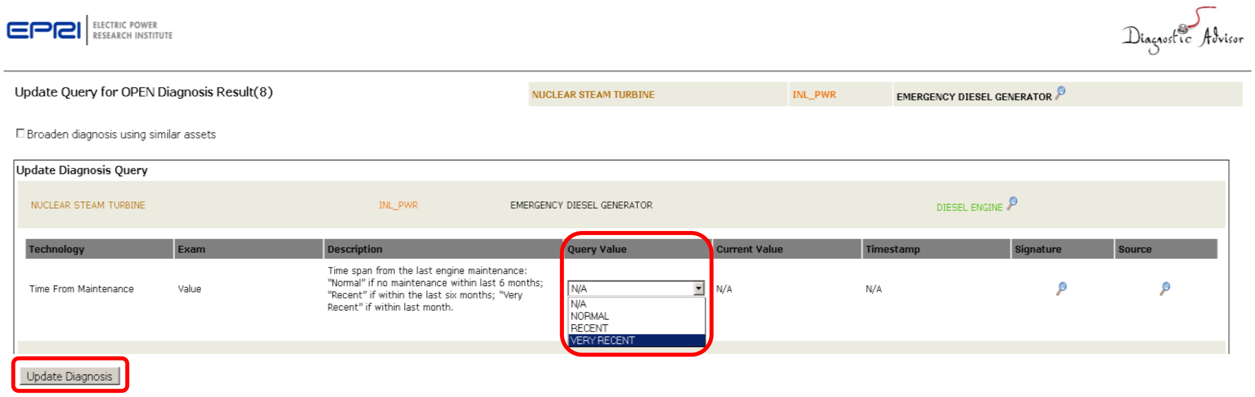


Figure 35. The Update Query for OPEN Diagnosis Result page allows manual entry of information.

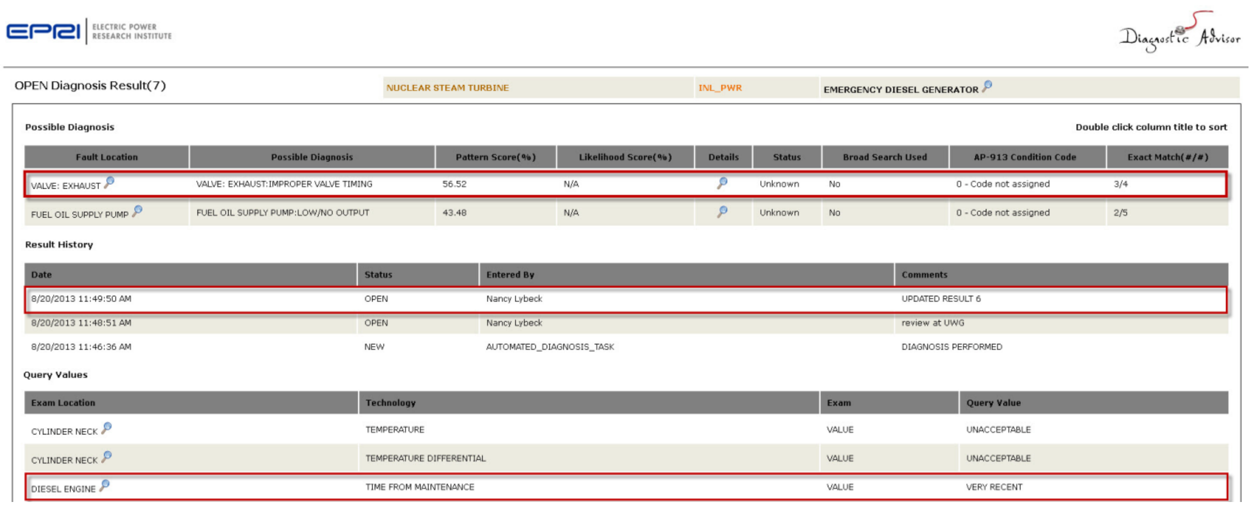


Figure 36. Diagnosis Result page identifying Valve: Improper Timing as the most likely fault based on manual entry of maintenance data.

5.3.3 Summary

The EDG demonstration highlighted the ability to:

1. Open any diagnosis result for review
2. Update any open diagnosis result with additional offline information that can be entered manually.

5.4 Closing Remarks

The Diagnostic Advisor of the FW-PHM Suite, when connected to an online data source embedded with simulated faults, provides the person in charge with accurate diagnoses and updates via email on a periodic basis. The demonstration presented above has validated the concept of using real plant data with fault simulation. It has also demonstrated the operational aspects of the system, first alerting the responsible engineer and then leading the user through a successful diagnosis by suggesting additional data to be acquired to refine the diagnosis.

This automatic diagnosis allows timely prevention of equipment failure and can optimize maintenance activity, thereby reducing operational and maintenance costs.

6. PILOT PROJECT STATUS

Table 2 shows the progress of the project in the FY 2013 and different tasks completed.

Table 2. Online monitoring pilot progress in FY 2013.

Task	Status	Period
Implementation of fault signatures for GSUs and EDGs	Complete[a]	October 1, 2013 – April 30, 2013
Level 4 Milestone Report: Online Monitoring Technical Basis and Analysis Framework for Emergency Diesel Generators – Interim Report for FY 2013.	Complete	October 1, 2012 – December 2012
Beta testing of the FW-PHM Suite software.	Complete	January 2013 – March 2013
Beta testing report to EPRI	Complete	March 2013 – April 2013
A conference paper for publication to 2013 Annual Conference on Prognostic and Health Management	Complete	June 14, 2013
Demonstration of online monitoring for GSUs and EDGs using the FW-PHM Suite software	Complete	May 2013 – August 2013
Level 2 Milestone Report: Demonstration of Online Monitoring on GSUs and EDGs	Complete	August 2013 – September 2013

[a] Important fault signatures based on discussions with partner utilities for GSUs and EDGs are implemented in the Asset Fault Signature Database of the FW-PHM Suite software. However, in future as per partner utility and project requirements, additional fault signatures will be identified and implemented.

7. SUMMARY AND FUTURE PLANS

This report presented the FY 2013 research activities associated with OLM of GSUs and EDGs, which included:

- Beta testing of the FW-PHM Suite software
- Beta testing report for EPRI
- Content development for GSUs and EDGs in the FW-PHM Suite software
- Real-time demonstration of diagnostic capability of the FW-PHM Suite software's Diagnostic Advisor when connected to an online data source with simulated faults for GSUs and EDGs.

Overall, 44 technical examinations, 30 fault features, and 8 fault signatures were implemented in the AFS Database of the FW-PHM software as part of the content development. Beta testing recommendations by INL researchers allowed EPRI to improve the FW-PHM Suite and release an updated version of the software in May 2013. EPRI and INL demonstrated the diagnosing capabilities of the FW-PHM to diagnose faults in GSU and EDG.

In FY 2014, INL will continue to work with the Shearon Harris Nuclear Generating Station and Braidwood Generating Station to populate the AFS Database with new fault signatures for GSU and EDGs respectively. The partner utilities will be hosting INL and EPRI to perform verification and validation of the implemented fault signatures. INL will research prognostic models for GSUs and EDGs.

8. REFERENCES

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Appendix A

Technical Exams and Fault Signatures added to AFS Database for GSUs and EDGs

Table 3. GSU fault signatures developed and entered 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: Thermal	*DGA:* CO_2/CO ratio in insulating oil	High ratio of CO_2/CO	High
		DGA: levels of CO gas in insulating oil	High levels of CO	Very High
		Temperature analysis: time at excess temperature at transformer winding	Long time at excessive temperature	Medium
	Paper insulation degradation: Electrical	*DGA:* levels of C_2H_2 gas in insulating oil	High levels of C_2H_2	Very High
		DGA: levels of H_2 and C_2H_2 gas in insulating oil	High levels of H_2 and C_2H_2	High
		Insulating oil analysis: Acid number of insulating oil	High acid number	Medium
		DGA: 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 millinewtons/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

Equipment or Component	**Fault Type**	**Technical Exam and Location**	**Fault Feature**	**Effectiveness**
		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
Core	Displaced winding core	*Sweep frequency response analysis:* captures the core capacitance across different frequencies	Change in the capacitance across different frequencies	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
Insulating oil pump motor	Loss of performance	*Inspection:* measure the oil level	Low level of oil	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 4. EDG fault signatures developed and entered into the AFS data [Pham et al., 2013].

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**
Diesel engine crankshaft	Crack in Crankshaft	*Angular Speed:* of crankshaft	High MAFSO	High
Lube Oil	Inadequate Lubrication	*Pressure Analysis*: of lube oil supply line	Low value of pressure	Very High
		Temperature Analysis: of lube oil	High value of temperature	High
		Pressure Differential: at the lube oil pump	Pressure differential is lower than lower bound value	Very High
Intake Valve	Improper Valve Clearance	*Vibration Analysis:* in cylinder head	High vibration magnitude	Very High
		Pressure analysis: in cylinder combustion chamber	High value of peak pressure	High
		Ultrasonic Noise Analysis: at intake valve	High noise amplitude	High