INL/EXT-12-27754

Online Monitoring Technical Basis and Analysis Framework for Emergency Diesel Generators—Interim Report for FY 2013

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The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

The Light Water Reactor Sustainability program at Idaho National Laboratory is actively conducting research to develop and demonstrate online monitoring capabilities for active components in existing nuclear power plants. Idaho National Laboratory and the Electric Power Research Institute are working jointly to implement a pilot project to apply these capabilities to emergency diesel generators and generator step-up transformers. The Electric Power Research Institute Fleet-Wide Prognostic and Health Management Software Suite will be used to implement monitoring in conjunction with utility partners: Braidwood Generating Station (owned by Exelon Corporation) for emergency diesel generators, and Shearon Harris Nuclear Generating Station (owned by Duke Energy Progress) for generator step-up transformers.

This report presents monitoring techniques, fault signatures, and diagnostic and prognostic models for emergency diesel generators. Emergency diesel generators provide backup power to the nuclear power plant, allowing operation of essential equipment such as pumps in the emergency core coolant system during catastrophic events, including loss of offsite power. Technical experts from Braidwood are assisting Idaho National Laboratory and Electric Power Research Institute in identifying critical faults and defining fault signatures associated with each fault. The resulting diagnostic models will be implemented in the Fleet-Wide Prognostic and Health Management Software Suite and tested using data from Braidwood. Parallel research on generator step-up transformers was summarized in an interim report during the fourth quarter of fiscal year 2012.

EXECUTIVE SUMMARY

The Light Water Reactor Sustainability Program is a research, development, and deployment program sponsored by the U.S. Department of Energy Office of Nuclear Energy. The program is operated in collaboration with the Electric Power Research Institute's (EPRI's) research and development efforts in the Long-Term Operations Program. The Long-Term Operations 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. Because both the Department of Energy Office of Nuclear Energy and EPRI conduct research and development in technologies enabling the operation of commercial light water reactors beyond the current 60-year license limits, it is important that the work be coordinated to the benefit of both organizations.

The Light Water Reactor Sustainability and Long-Term Operations Programs are working closely with nuclear utilities to develop instrumentation and control technologies and solutions to help ensure the safe life extension of current reactors, including centralized online monitoring. The current fleet of nuclear power plants (NPPs) performs periodic or condition-based maintenance of their active assets/components. The objective of centralized online monitoring (OLM) is to implement predictive online monitoring techniques that would enable NPPs to diagnose incipient faults, perform proactive maintenance, and estimate the remaining useful life (RUL) of the asset. Currently, there are two projects under centralized OLM: online monitoring of active components and online monitoring of passive components. The research activities presented here are associated with online monitoring of active components.

To implement predictive online monitoring, EPRI has developed a web-based Fleet-wide Prognostic and Health Management (FW-PHM) Software Suite (currently in Beta Version 1.1.1). The framework of the FW-PHM software consists of four main components: Diagnostic Advisor; Asset Fault Signature Database; RUL Advisor; and RUL Signature Database.

Part of the long-term strategic goal of centralized OLM of active components is to enable industry to employ online monitoring using the FW-PHM software on important active components. Emergency diesel generators (EDGs) are one of the systems selected for initial development of monitoring techniques, diagnostic and prognostic models. Idaho National Laboratory (INL) and EPRI have identified Braidwood Generating Station (owned by Exelon Corporation) as the partner utility for EDGs.

INL is performing research and working with Exelon to identify and characterize critical faults that lead to catastrophic failures in EDGs. This will allow INL to populate the asset fault signature database of the FW-PHM software. The asset fault signature database captures details about asset type, source of the fault information, and fault signatures, including features, causes, remedies, and consequences. Based on the identified fault signatures and failure modes, the Diagnostic Advisor is used to diagnose fault conditions.

INL will continue research on prognostic models for EDGs over the next two years. These models will be used to populate the RUL database and to make component life predictions using the RUL advisor. The resulting models will be

used with data from the utility partner to demonstrate the benefit of predictive OLM in NPPs. The FW-PHM software is unique in the sense that it standardizes the diagnostic and prognostic approach across assets based on fault signatures and fault features, generates a comprehensive diagnosis report, and allows information sharing between different NPPs via a master database. As valuable historical operating data accumulate, the diagnostic and prognostic performance will improve significantly. These capabilities do not currently exist in NPPs, and are expected to support safer long term operation of the NPPs.

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ACRONYMS

CCF	common cause failure
CIGRE	Conseil international des grands réseaux électriques (French) or International Council on Large Electric Systems (English)
EDG	emergency diesel generator
EPRI	Electric Power Research Institute
FOM	figure of merit
FW-PHM	Fleet-Wide and Prognostic Health Management Suite
GSU	generator step-up transformer
IEEE	Institute of Electrical and Electronics Engineer
INL	Idaho National Laboratory
LOOP	loss of offsite power
MPU	magnetic pickup unit
NPP	nuclear power plant
OLM	online monitoring
RUL	remaining useful life

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1. INTRODUCTION

The Light Water Reactor Sustainability Program is a research, development, and deployment program sponsored by the U.S. Department of Energy Office of Nuclear Energy. The program is operated in collaboration with the research and development efforts of the Electric Power Research Institute (EPRI) in the Long-Term Operations Program. The Long-Term Operations 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. Because both the Department of Energy Office of Nuclear Energy and EPRI conduct research and development in technologies that have application to establishing the feasibility of operating commercial light water reactors beyond the current 60-year license limits, it is important that the work be coordinated to the benefit of both organizations.

The Light Water Reactor Sustainability and Long-Term Operations Programs are working closely with nuclear utilities to develop instrumentation and control technologies and solutions to help ensure the safe life extension of current reactors. One of the main areas of focus is centralized online monitoring (OLM). The centralized OLM project has two subprojects: online monitoring of active components and online monitoring of passive components.

The long-term objective of the OLM pilot project for active components is to implement predictive online monitoring techniques that would enable nuclear power plants (NPPs) to diagnose incipient faults, perform proactive maintenance, and estimate the remaining useful life (RUL) of their active assets. Predictive or proactive maintenance involves predicting future parameter values (or the actual state of the equipment). This allows plants to take timely or proactive action before the occurrence of a catastrophic failure and to estimate and optimize future maintenance costs.

EPRI is leading the OLM research and implementation effort in collaboration with Idaho National Laboratory (INL). EPRI has developed the Fleet-Wide Prognostic and Health Monitoring (FW-PHM) Software Suite (Beta Version 1.1.1) for predictive online monitoring. FW-PHM 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 (both nuclear and fossil fuel). FW-PHM serves as an integrated health management framework, managing the functionality needed for a complete implementation of diagnostics and prognostics [Lybeck 2011]. The open-architecture integrated FW-PHM software has four main components:

- *Diagnostic Advisor*, which identifies impending failures by comparing asset fault signatures with operating data
- *Asset Fault Signature Database*, which organizes asset fault signatures collected from across the industry
- *RUL Advisor*, which estimates how long an aging or faulty asset will continue to provide reliable service
- *RUL Signature Database*, which organizes asset remaining life signatures collected from across the industry.

Generator step-up transformers (GSUs) and emergency diesel generators (EDGs) are the two active components selected for initial development and implementation of fault signatures, diagnostic models, and prognostic models. Implementation of the models will use the FW-PHM Software Suite. This report focuses on the interim status of research activities associated with EDGs. The interim status of research activities associated with OLM for GSUs was presented in Lybeck [2012].

Each NPP must be able to *withstand* and *recover* from a station blackout (loss of the offsite electric power system concurrent with reactor trip and unavailability of the onsite alternating current electric power system) for a specified duration. The EDGs are part of the Class 1E alternating current onsite electrical power distribution system, providing reliable emergency power to electrical buses that supply the emergency core cooling system and other systems necessary for a safe shutdown of the reactor. The unreliability of onsite alternating current power sources is one of the main factors contributing to the risk of core melt as a result of a station blackout. For this reason, the EDGs are subjected to a rigorous testing schedule. The frequent required tests and starts performed on EDGs cause accelerating aging deterioration of many of the components, making the EDG an excellent candidate for coverage by diagnostic and prognostic systems.

Monitoring capabilities for EDGs currently vary widely among the NPPs, with automated data acquisition available in some of the plants. Troubleshooting is a manual process that predominantly relies on expert knowledge and written documentation. Capturing this knowledge, and implementing it in a standardized approach based on fault signatures and fault features, enables the automation of the diagnostic process. Information gathered from different NPPs will be shared via a master database, creating a more complete knowledge base. As valuable historical operating data accumulate, the diagnostic and prognostic performance will be refined, leading to enhanced performance. These capabilities do not currently exist in NPPs, and are expected expedite the diagnosis process, as well as support safer long term operation of the NPPs.

This report introduces EDGs in Section 2, which includes conditions leading to failure, common causes of failure, and requirements for maintenance and testing; presents diagnostic fault signatures for GSUs in Section 3; and summarizes the current state of research and future plans in Section 4.

2. BACKGROUND INFORMATION FOR EMERGENCY DIESEL GENERATORS

An EDG is comprised of the diesel engine and generator with all components in the exhaust path, electrical generator, generator exciter, output breaker, combustion air, lubrication system, cooling system, fuel oil system, and the starting compressed air system, as shown in Figure 1.

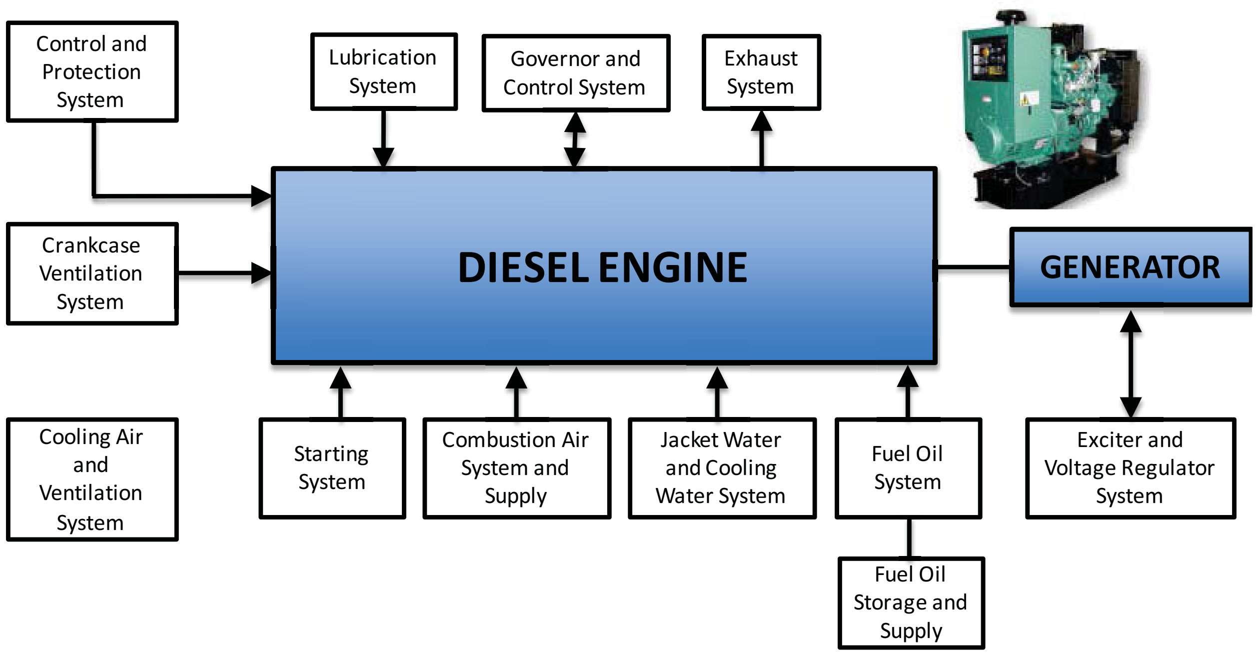

Figure 1. Emergency diesel generator components [Regulatory Guide 1.9 2007].

An emergency diesel generator selected for use in an onsite electric power system in a NPP must be able to: start and accelerate a number of large motor loads in rapid succession, while maintaining voltage and frequency within acceptable limits; provide power promptly to engineered safety features if a loss of offsite power (LOOP) and a design-basis event occur during the same time period; and supply power continuously to the equipment needed to maintain the plant in a safe condition if an extended (e.g., 30-day period with refueling every 7 days) LOOP occurs [Regulatory Guide 1.9 2007].

Although the risk of total station blackout is small, there have been numerous instances when EDGs have failed to start and run in response to tests conducted at operating plants. In addition, probabilistic risk assessment reveals EDG failure accounts for one-third of the core damage frequency [Dulik 1997]. Requirements for testing and inspecting EDGs are described in [Regulatory Guide 1.9] to ensure that the EDG unit shall be capable of operating during and after any design basis event without support from the preferred power supply. A corresponding maintenance program (periodic inspection and testing, reporting, recordkeeping and scheduled maintenance) is used to ensure the target EDG reliability is being achieved and to provide a capability for failure analysis and root-cause investigations. The EDG testing program consists of load capability, start and load acceptance, and margin tests before start of service and periodic inspection, testing, and maintenance throughout the service lifetime.

2.1 Conditions Leading to Failure

Aging has been determined to be significant factor in the degradation of EDG components—multiple components such as gaskets, insulation, and bearings have age-related failure mechanisms. Thermal and mechanical cycling associated with numerous starts and tests performed on EDGs also cause mechanical and performance degradation as if the engines had experienced many more operating hours. The components with potential age-related failure must be periodically qualified through testing and analysis, making them excellent candidates for coverage by diagnostic and prognostic systems.

The aging stressors for most EDG components, especially the mechanical components in an NPP, frequently originate from periodic tests mandated by regulations that simulate the starting and loading sequence that would be encountered during an emergency. Statistically, actual emergency (unplanned) fast-starts amount to only 2% of all starts; 98% of the fast-starts are tests. Starting the engine is a severe aging stressor for certain engine components, including the pistons and cylinder liners. During standby, oil drains away from the liners and the pistons, especially in a warm environment. Insufficient lube oil conditions, which last only seconds at startup, may cause more wear (e.g., scuffing of piston and cylinder liners) than many hours of normal operation. Additionally, aging stressors associated with fast loading in response to accident signals are also significant. Rapid loading of the engines without allowing time for normal thermal equilibration applies thermal stresses to the engine components. When the engine delivers several megawatts of power in less than 60 seconds, the pistons thermally expand very rapidly, while the water-cooled cylinder liners expand more slowly. As a result, the cylinder piston clearance gap may be lost, causing metal-to-metal contact that can lead to piston and cylinder liner scuffing. Under emergency power conditions, this scuffed metal can reach temperatures in the range of 600 to 700°F, which can result in a crankcase explosion.

According to Hoopingarner et al. [1987], the age-related stressors for an EDG are:

- *Cooling water*: Degraded water chemistry can cause sludge, hard water inorganic deposits, and rust of intercoolers, heat exchangers, and other engine components.
- *Lubricating oil:* Aging oil contains increased organic impurities (or bacteria content), water contamination, wear metal, and corrosion products, which can impact the oil's ability to prevent corrosion, carbon deposits, sludge formation, and varnish buildup.
- *Fuel oil:* Storing distillate fuel oil for extended periods can result in physical separation, thickening, water accumulation, and microbial growth, potentially causing filters to plug rapidly and injection system components to corrode and seize.
- *Starting air:* Water condensate in the starting air system may degrade components such as valves, orifices, and controls because of corrosion.
- *Intake and exhaust systems:* Dust, moisture, other air contaminants, thermal stresses, vibration, and corrosion may degrade intake and exhaust systems.
- *Nonmetallic deterioration:* Nonmetallic materials used in seals, gaskets, and hoses are subject to aging by oxidation, oil-induced degradation, thermal cycling, and frequent component removal for inspection.
- *Hydraulic deterioration:* Aging caused by hydraulic forces (e.g., cavitation) affects cylinder heads and liners, water pumps, bearings (especially connecting rod bearings), high pressure lines, fuel lines (fatigue because of pulsation), and the hydraulic loading of air start controls, valves, and lines.
- *Electrical deterioration:* Oxidation, commutator and slip ring wear acceleration caused by dust accumulation and corrosion, and aging of probes, lines, contacts, connections, and diodes caused by vibration, heat, and chemical attack will result in damage to electrical insulation.
- *Dynamic stresses (electrical, mechanical, electro-mechanical):* Extreme dynamic loading, especially during fast-start conditions, place unusual demands on components such as crankcases, cylinder blocks, pistons, heads, gears, cams, bearings, rollers, crankshafts, connecting rods, electrical components, and controls.

- *Vibration stresses:* Vibration stress can affect the crankshaft, flanges, gears, bolts, pipes, supports, and pumps.
- *Thermal stresses and thermal fatigue:* Thermal stresses and fatigue can affect cylinder liners and exhaust manifolds.

The myriad of age-related stressors in EDGs provides a strong justification for the use of online monitoring to identify and correct problems before failure occurs.

2.2 Failure Events Analysis

Wierman, Rasmuson, and Stockton [2003] reported insights related to EDG common-cause failure (CCF) events obtained from the U.S. Nuclear Regulatory Commission's CCF Database. CCFs can be thought of as resulting from the coexistence of two main factors: susceptibility to fail or become unavailable because of a particular cause of failure, and the presence of a coupling factor or mechanism that allows multiple components to be affected by the same cause. Because many of the age-related stressors in EDGs affect multiple components, CCFs are of interest to this work. Wierman's study identified 138 events occurring at U.S. NPP units during the period from 1980 through 2000. The causes and coupling factors highlight the importance of maintenance in the EDG CCFs. Testing (65%) and inspection (20%) are most effective at discovering CCFs; only 9% of failures were discovered during actual demand.

2.2.1 EDG Failure Modes

The failure modes used in evaluating the EDG failure data [Wierman, Rasmuson, and Stockton 2003] are:

1. *Fail-to-start (57%)*: A successful start encompasses starting the motor, closing the output breaker, and loading to the requirement for the current configuration. For example, if the start is in response to an actual loss of power, the full sequence of loading must be completed in order for the start to be considered successful. If only partial loading occurs before the failure, the failure mode will be *Fail-to-Start*. If the start requires no loading (e.g., a test), the success criteria only includes starting the motor.
2. *Fail-to-Run (43%)*: Failure to run involves a successful start with a subsequent failure to run for the duration of the mission time.

The EDG failures represent malfunctions that hindered or prevented successful operation of the EDG system. In 2003, a modification to the EDG failure mode classification was proposed by the International Council on Large Electric Systems (CIGRE) as follows (CIGRE 2003): (1) *Fail-to-Start* as failure to start until the EDG output breaker receives a signal to close; (2) *Fail-to-Load* as failure to take loads and run for 1-hour after breaker has received a signal to close; and (3) *Fail-to-Run* as failure of the EDG to be able to run for 24 hours. The new classification scheme is used in annual studies based in EPIX results, which are available for EDGs on [http://nrcoe.inel.gov/resultsdb/CompPerf/].

2.2.2 Subsystem Contribution to EDG Failure

The EDG CCF data were reviewed to determine the affected subsystem to provide insight into the most vulnerable areas of the EDG component with respect to common-cause failure events [Wierman, Rasmuson, and Stockton 2003]. Figure 2 shows the distribution of the EDG CCF events by affected subsystem (the set of 138 EDG CCF events is based on industry data from 1980 to 2000). The highest number of events occurred in the instrumentation and control subsystem (41 events or 30%). The engine, fuel oil, generator, and cooling subsystems are also significant contributors. More recent EPIX results indicate that these systems are still significant contributors.

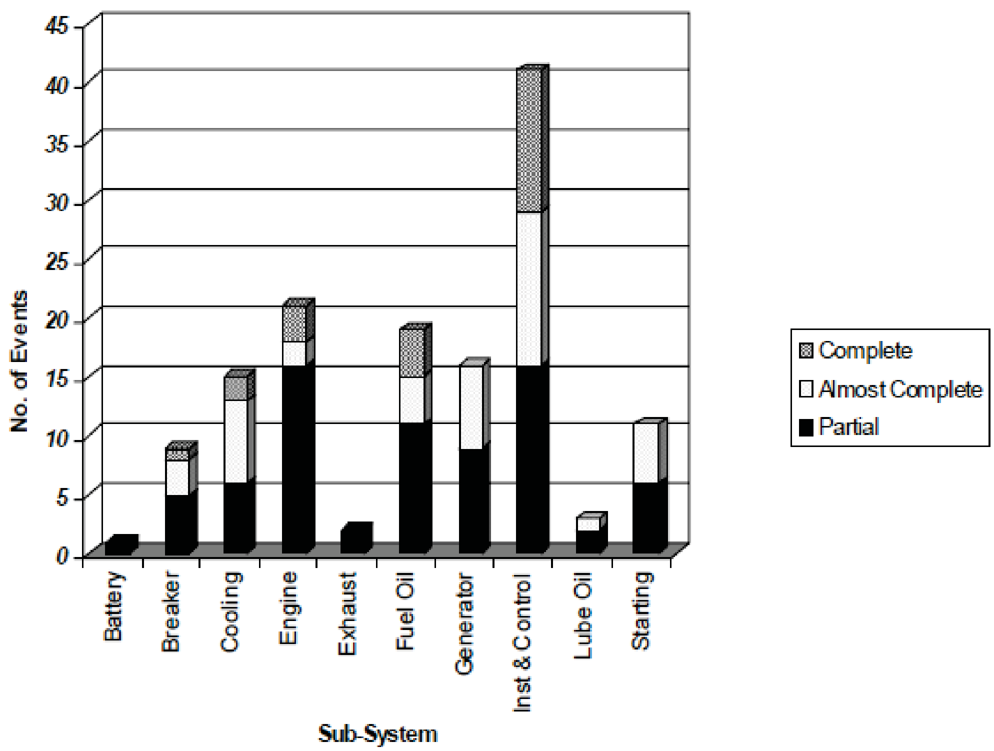

Figure 2. Subsystem distribution for all EDG CCF events [Wierman, Rasmuson, and Stockton 2003].

2.2.3 CCF Proximate Causes

A **proximate cause** of a failure event is the condition that is readily identifiable as leading to the failure. The proximate cause can be regarded as a symptom of the failure cause and does not, in itself, necessarily provide a full understanding of what led to that condition. The proximate cause classification consists of six major groups or classes [Wierman, Rasmuson, and Stockton 2003]:

- ***Design****/Construction/Installation/Manufacture Inadequacy*: Errors in equipment and system specifications, material specifications, and calculations
- *Operational/****Human*** *Error*: Omission or commission on the part of plant staff or contractor staff
- *Internal to the* **component***, including hardware-related causes and internal environmental causes*: malfunctioning of hardware internal to the component because of physical mechanisms such as erosion, corrosion, internal contamination, fatigue, wear-out, and end of life
- ***External environmental*** *causes*: Harsh environment that is not within the component design specifications
- ***Other*** *causes*: Set point drift and the state of other components
- **Unknown** causes.

Figure 3 shows the distribution of CCF events by proximate cause. The leading proximate cause was design/construction/installation/manufacture inadequacy which accounted for about 33% of the total events. Internal to component faults accounted for 30% of the total. Human error accounted for 22% of the total events. To a lesser degree, *external environment* and the *other* proximate cause categories were assigned to the EDG component. A successful OLM system can prevent most of these causes from becoming catastrophic events.

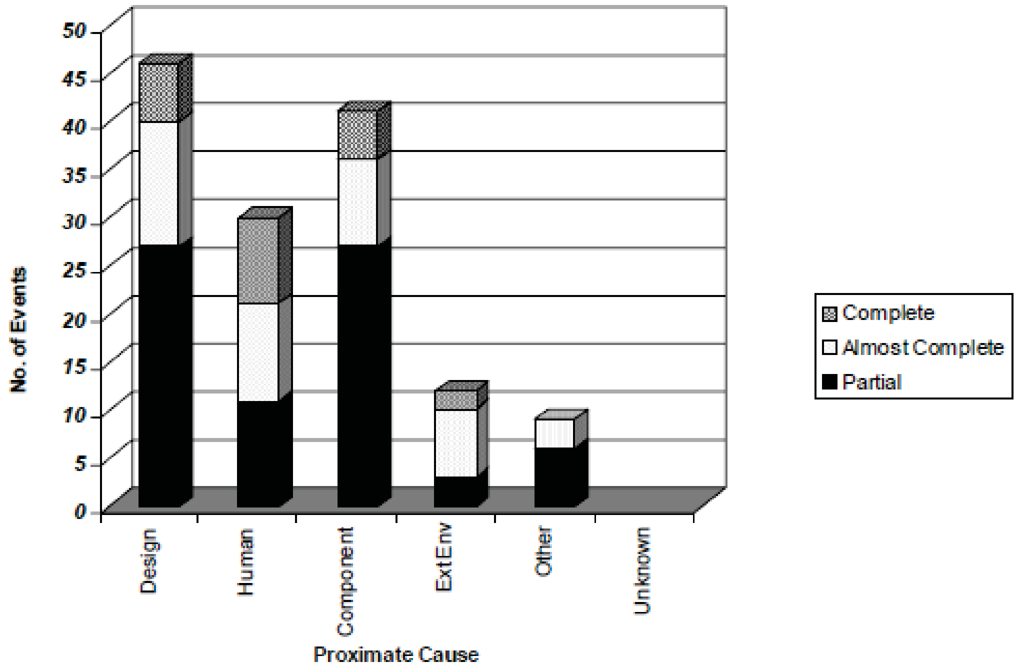

Figure 3. Proximate cause distribution for all EDG CCF events [Wierman, Rasmuson, and Stockton 2003].

2.2.4 CCF Coupling Factors

A **coupling factor** is a characteristic of a component group or linked parts making them more susceptible to the same causal mechanisms of failure. Such factors include similarity in design, location, environment, mission, and operational, maintenance, design, manufacture, and test procedures. The coupling factor classification consists of five major classes:

- **Environmental** coupling factors, propagate a failure mechanism via identical external or internal environmental characteristics
- **Design**-based coupling factors, the design was inadequate and was the link between the events
- Hardware **Quality** based coupling factors, propagate a failure mechanism among several components because of manufacturing and installation faults
- **Maintenance** coupling factors, the maintenance frequency, procedures, or personnel provided the linkage among the events
- **Operational** coupling factors, propagate a failure mechanism because of identical operational characteristics among several components.

Figure 4 shows the coupling factor distribution for these events. Design is the leading coupling factor with 66 events (48%). Design coupling factors result from common characteristics among components determined at the design level. Maintenance accounts for the majority of the remaining events, with 39 events (28%). Maintenance also has a higher proportion of *complete* events (failure events where all components failed because of a single cause in a short period of time) than any other coupling factor [Wierman, Rasmuson, and Stockton 2003]. These two coupling factors account for the top 76% of the events.

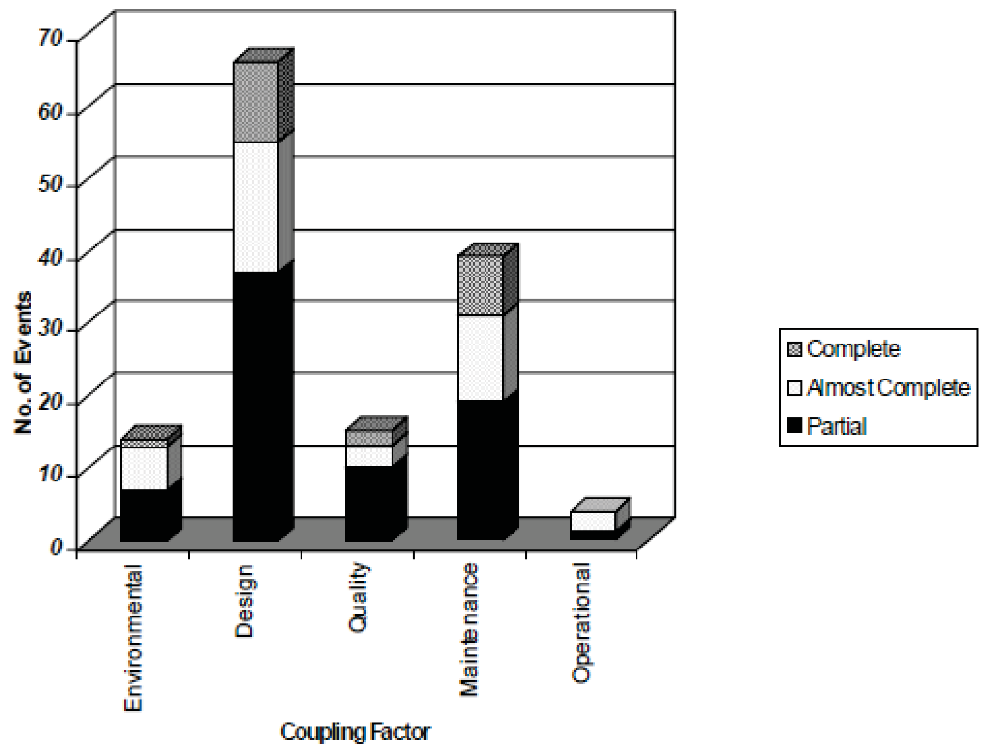

Figure 4. Coupling factor distribution for all EDG CCF events [Wierman, Rasmuson, and Stockton 2003].

2.3 Requirements for Testing and Maintenance

Because EDGs in NPPs do sometimes fail during demand, requirements for ongoing surveillance, including the periodic tests used as a basis for the identification of equipment degradation and validation of the results of the aging and aged equipment testing, are presented in the Institute of Electrical and Electronics Engineer (IEEE) Std 387-1995 [IEEE 1995]. After being placed in service, the diesel-generator unit is tested periodically, including monthly 1-hour runs, to demonstrate that the continued capability and availability of the unit to perform its intended function is acceptable. Individual test requirements are listed in Table 1.

The testing and surveillance of EDG systems are established in two places: the technical specifications (virtually the same for all NPPs) and the vendor recommendations (plant-specific depending on manufacturer). The monthly one-hour runs are not sufficient to guarantee zero unavailability; the vendor recommended maintenance includes highly intrusive inspection and tear-down during refueling outages. Failures to start, run, or accept load during any of these periodic tests may mandate accelerated testing frequency until the failure rate complies with specifications.

2.3.1 EDG Preoperational Testing Requirements

EDGs are designed to allow tests that simulate the parameters of operation (e.g., manual start, automatic start, load sequencing, load shedding, and operation time), normal standby conditions, and environments (e.g., temperature, humidity) that would be expected if actual demand were placed on the system as listed in Table 1. For example, the LOOP testing simulates a loss of offsite power in order to demonstrate:

- The emergency buses are deenergized and the loads are shed from the emergency buses.

Table 1. Testing requirements for EDGs [IEEE 1995].

Test	Site Acceptance	Pre-operational	Availability: Monthly	Availability: Semi-annually	System Operation – Shutdown/ Refueling	Independent 10 years
Starting	X					
Load acceptance	X					
Rated load	X					
Load rejection	X					
Electrical	X					
Subsystem	X					
Reliability		X				
Start			X			
Load run			X	X		
Fast start				X		
LOOP		X				
SIASa		X				
Combine SIAS and LOOP		X			X	
Largest load rejection		X			X	
Design load rejection		X			X	
Endurance and load		X			X	
Hot restart		X			X	
Synchronizing		X			X	
Protective trip bypass		X			X	
Test mode override		X			X	
Independence		X				X

a. *Safety injection actuation signal (SIAS)*: EDG starts on the auto-start signal from its standby conditions, attains the required voltage and frequency within acceptable limits and time, and operates on standby for a minimum of 5 minutes.

- The diesel-generator unit starts on the auto-start signal from its standby conditions, attains the required voltage and frequency in an acceptable time frame, energizes the auto-connected shutdown loads through the load sequencer, and operates for a minimum of 5 minutes.

2.3.2 In-Service Preventive Maintenance, Inspection, and Testing Requirements

Separate preventive maintenance, inspection, and testing programs have been established for the diesel-generator unit and all supporting systems based on the manufacturer's recommendations; these guidelines include replacement intervals for components with a qualified life less than the objective life of the power plant. Manufacturer's recommendations may be based on operating hours, fixed time intervals, or both. Procedures must, where applicable, include specific programs for each portion of the unit as follows:

1. The engine, including the governor, over-speed trip device, internal components to the maximum extent practical, turbocharger, lube oil components, fuel oil components, jacket water components, starting components, cleaning, adequate lubrication, and water chemistry

2. The generator and rotating exciter (if used), including insulation condition, bearings, cooling system, lubricating system, and space heaters (if applicable)
3. Electrical auxiliary equipment, including local engine and generator control, exciter and voltage regulator, and protection and surveillance components
4. Subsystems, including:
    a. Starting energy, typically consisting of air receiver tanks, compressors, piping, valves, and associated instrument and control devices
    b. Fuel oil, typically consisting of pumps, filters, strainers, piping, valves, and associated instrument and control devices
    c. Lube oil, typically consisting of pumps, filters, strainers, keep-warm heaters and pumps, coolers, sump tanks, piping, valves, and associated instrument and control devices
    d. Cooling water, typically consisting of expansion tanks, heat exchangers, pumps, keep-warm heaters and pumps, piping, valves, and associated instrument and control devices
    e. Intake air, typically consisting of filters, silencers, expansion joints, and piping
    f. Exhaust, typically consisting of silencers, expansion joints, and piping
    g. Crankcase ventilation components, if applicable.

3. CONDITION MONITORING AND FAULT DIAGNOSIS FOR EDGS

The unexpected and sometimes catastrophic failure of an EDG during demand in a NPP can result in the reactor core damage associated with severe consequences. Generally, the function of the monitoring system is to prevent EDG operation in conditions that could cause severe damage to the EDG train (by fault protective devices), and to notify plant operators of the generator system status by annunciated alarms. However, the monitoring currently in place does not provide the opportunity to trend EDG performance or to carry out preventive maintenance.

The major contributors to EDG failures are the engine with associated components, control system (including governor), service water pumps, ventilation dampers, sequencers and output breakers, contact pairs, and service water connection valves. These contributors are predominantly mechanical systems. Aging components in these systems are suitable candidates for predictive monitoring and preventive maintenance. The proposed monitoring procedure uses component fault signatures to identify failure precursors. The fault signature is established from historical operating data, expert experiences, and physical simulation results (commonly used in other industries), against which a failure mode and possible associated causes are identified based on the actual measurements.

Fault diagnostic techniques compare measured operational parameters to normal baseline levels, often relying on the residual to indicate a possible fault condition. Understanding the correlation between the parameter and the components or mechanical functions that they represent provides insight into the root cause of machinery faults. The operational parameters are results of technical examinations at various locations of machine components (e.g., temperature and pressure measurements at the cylinder head). Engine performance state parameters are also useful for diesel engine fault diagnosis, including fuel consumption, maximum combustion cylinder pressure, exhaust temperature, and input and output cooling water temperatures. Combustion cylinder pressure is used to estimate the power ability. Exhaust gas temperature is used to estimate emission ability. Fuel consumption is used to estimate fuel economy. Diagnosis of the engine and the generator are discussed in this section.

3.1 Engine Diagnosis

Figure 5 shows a cross section of the Cooper EDG engines (4-stroke cycle Enterprise KSV V16 and V20 cylinder engines) used in many NPPs. In each EDG engine, there are as many as 20 cylinders arranged in pairs located on directly opposite sides of the V-shape. This cylinder arrangement allows the use of a single crankshaft journal without offset for both cylinders in a pair. There is a master connecting rod that provides the bearing and transmits both connecting rod load/power into the single crankshaft journal.

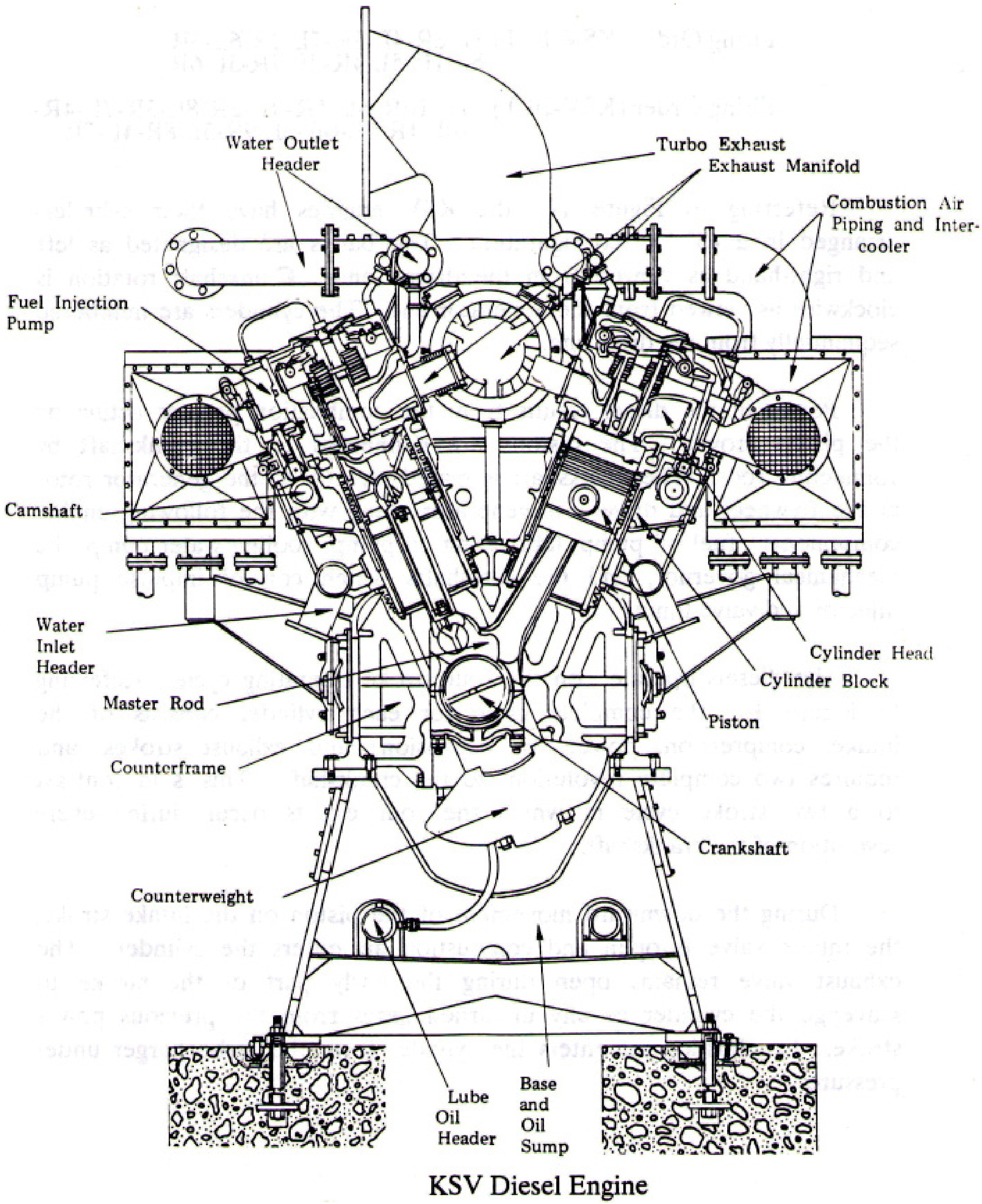

Figure 5. Cooper engine cross section [Hoopingarner et al. 1987].

3.1.1 Technical Examinations

The parameters listed in Table 2 [Dulik 1997] are commonly used to monitor diesel engine operation. These parameters allow assessment of degradation of valves, fuel injectors, seals, and piston rings as well as the overall health of the EDG engine. Other EDG performance indicators (engine horsepower efficiency, fuel consumption, exhaust emissions, etc.) can also be used to assess an engine's condition. Possible crosstalk between sensors and sensor integrity should be monitored to ensure accurate performance prediction of component health [Banks 2001]. Commonly used technical examinations for an EDG engine include:

1. *Temperature analysis:* component temperatures (e.g., engine cylinders or exhaust manifold) indicate engine performance. Cooling water temperatures and lubricating oil temperatures (inlet, outlet, and their difference) are used to monitor the thermodynamic efficiency of the engine (Banks 2001).
2. *Pressure and flow rate analysis*:
   a. Engine cylinder pressure (measured by a pressure transducer mounted on the cylinder head): deviation 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].
   b. Pressure and fluid volume measurements (inlet and outlet) from engine support systems such as the fuel oil system, lubricating oil system, cooling water system, and starting air system are used to identify leakage and component failure of the corresponding system. Abnormally low pressure in these systems usually indicates either system leakage of fuel, oil, water, or air or pump failure.
3. *Vibration analysis*:
   a. *Time domain 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.
   b. *Spectral analysis*: the existence of peaks at frequencies higher than 2-times the line frequency in the engine vibration spectrum (resulting from a fast Fourier transformation) can indicate liner scuffing, blow by, and improper fuel injection. This method requires high frequency vibration transducers (e.g., 35–45 kHz range).
4. *Engine oil analysis (or lubricating oil analysis on-line or off-line)*: detect metal particles (e.g., particle count according to size), fuel oil, water, or combustion products in the lubricating oil, indicating problems in the diesel engine, including mechanical wear of components, bearing failure, and leaking seals [Banks 2001]. The technical examination methods are:
   a. *Ferrography (ISO 4406)*: ferromagnetic particles in the lubricating oil are counted using a magnetic field to separate the particles according to size. The ferrography oil analysis includes the following operations: collection of wear particles according to size on a transparent substrate; selection and separation of significant particles; inspection and evaluation of the particles and their morphology and nature; and identification of particles (type of material).
   b. *Spectroscopy (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.
   c. *Particle count (ASTM D6224-09)*: 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.

Table 2. Monitoring parameters for diesel engine systems of an EDG in NPP [Dulik 1997].

System	Component	Monitoring parameter
Engine	Cylinder	Pressure
		Exhaust temperature
		Vibration
	Fuel rack	Position
	Crankshaft	Position
	Bearings	Vibration
		Temperature
Fuel oil	Tanks	Level
	Fuel lines	Pressure
	Pumps	Differential pressure
		Vibration
Cooling water	Tanks	Level
	Line	Pressure
	Pumps	Differential pressure
		Vibration
	Coolant to engine	Temperature
	Coolant from engine	Temperature
Lubrication oil	Oil	Chemical analysis
	Tanks	Level
	Line	Pressure
	Pumps	Differential pressure
		Vibration
	Oil to engine	Temperature
	Oil from engine	Temperature
Starting air	System	Pressure
	Compressor	Differential pressure
		Vibration
Turbocharger or Supercharger	Boost	Differential pressure
	Intercooler	Inlet temperature
		Outlet temperature
	Charger	Vibration
Service water	Pumps	Differential pressure
		Vibration
Ventilation	Blowers	Air flow
		Vibration
	Dampers	Vibration

3.1.2 Engine 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 common faults of an EDG engine identified from a literature review are firing pressure imbalance, inferior fuel injection, leaking power cylinder valves, leaking piston rings, worn or scored cylinder liners, intake/exhaust port or bridge wear, worn or rocker arms, defective valve filters, worn valve guides, worn cam surfaces, damaged connecting rods and wrist pins, damaged bearings, turbocharger defects, jacket water and lube oil pump faults, excessive frame vibration, and foundation and grout damage.

EPRI, INL, and Expert Microsystems team members travelled to the Braidwood Generating Station for a project meeting on September 6, 2012. The Monitoring Program Manager for Exelon, Mohammed Yousuf, and the Braidwood EDG System Engineer provided expert guidance in defining the initial fault signatures for implementation in the FW-PHM Software Suite. The EDGs installed at Braidwood are Cooper-Bessemer KSV 20-cylinder generators. Sixteen and 20 cylinder Cooper-Bessemer EDGs are installed in 31 plants at eight sites in the United States. The following fault signatures were identified during the meeting (for completeness, the worksheet used to develop the fault signatures is included in Appendix A):

1. *Fault*: Governor not responsive

   Asset type: Electronically controlled governor

   Fault feature: Power output, exhaust temperature, crankshaft speed, fuel linkage position, or voltage unchanged in response to a demand change; oscillating output frequency as the governor tries to meet the load demand

   Possible causes: Failure of speed sensor, control signal, bad electrical circuit

   Consequences: Governor prevents EDG from providing requested load

2. *Fault*: Intermittent control signal to governor

   Asset type: Governor

   Fault feature: Output power, frequency, exhaust temperature, crankshaft speed, or voltage fluctuating while demand is unchanged; governor fuel linkage hunting (jittery)

   Possible causes: Bad internal circuits; bad electrical connection on inputs; faulty magnetic pickup unit (MPU); unreliable power supply

   Consequences: Governor wear or failure

3. *Fault*: Intermittent MPU signal to governor

   Asset type: Governor

   Fault feature: Output power, frequency, exhaust temperature, crankshaft speed, or voltage fluctuating while demand is unchanged; governor fuel linkage hunting; MPU signal is oscillating or intermittent

   Possible causes: Bad internal circuits; bad electrical connection on inputs; bad speed sensor; unreliable power supply

   Consequences: Governor wear or failure

4. *Fault*: Improper exhaust valve timing

   Asset type: Exhaust valve

   Fault feature: High exhaust temperature for the affected cylinder with elevated exhaust temperature for the adjacent cylinders; high exhaust temperature differential between cylinders; high intake air temperature differential for the affected cylinder and possibly adjacent cylinders; recent engine maintenance

   Possible causes: Improper alignment during the most recent valve adjustments; problems with the camshaft, pushrod, rocker arm, spring, guide, and seat

   Consequences: Accelerate engine aging because of higher engine temperature, lower engine efficiency because of off-optimum operating condition, and excessive emissions

5. *Fault*: Fuel pump degradation

   Asset type: Fuel pump

   Fault feature: Low exhaust temperature for the cylinder with low fuel supply; high exhaust temperature for adjacent cylinders; high exhaust temperature differential for the affected cylinder and possibly adjacent cylinders; abnormal fuel metering rod position

   Possible causes: Fuel pump crosshead failure; internal failure of fuel pump; plugged or broken fuel injector; plugged or broken high pressure fuel line pump; fuel metering rod is out of position

   Consequences: Accelerate engine aging because of higher engine temperature, lower engine efficiency because of off-optimum operating condition, and may prevent EDG from providing requested load.

Additional fault signatures were obtained via a literature search. These fault signatures will further evaluated for inclusion in the FW-PHM Software Suite:

1. *Fault*: Thermal overload [Jones and Li 2000]

   Asset type: Combustion housing

   Fault feature: High cylinder wall temperatures

   Possible causes: Unsuitable fuel quality; leaking injection valves; low injection pressure; eroded or clogged injector holes; carbon formation on injector nozzle; high fuel/air ratio; worn or failed piston ring-cylinder; air cleaner or exhaust silencer blockage; blocked intercooler; inadequate coolant flow; high coolant or lubricant temperature; high engine friction; incorrect timing; misfiring; leaking intake or exhaust manifold; leaking intake or exhaust valves

   Consequences: Increased rate of high temperature corrosion on the combustion chamber surfaces; Crack development in the piston crown, cover, and liner; destruction of the oil film in the upper part of the liner, increased wear rate of the liner and ring; excessive emissions

2. *Fault:* Blow-by [Dulik 1997]

   Asset type: Oil injectors

   Fault feature: High vibration level of engine cylinders that coincides with high cylinder pressures

   Possible causes: Piston ring or cylinder wear

   Consequences: Reduced engine efficiency

3. *Fault:* Large valve clearance [Cai 2011]

   Asset type: Valves

   Fault feature: High amplitude and high frequency of the engine cylinder head vibration

   Possible causes: Excessive valve wear

   Consequences: Engine knocking because of abnormal combustion caused by increased peak cylinder pressure, increasing wear

4. *Fault*: Small valve clearance [Cai 2011]

   Asset type: Valves

   Fault feature: Low amplitude and low frequency of the engine cylinder head vibration

   Possible causes: Corrosive or clogged valves

   Consequences: Engine knocking because of abnormal combustion caused by reduced peak cylinder pressure, increasing wear

5. *Fault*: Excessive wear rates

   Asset type: Metallic components

   Fault feature: High metal content in engine oil (the concentration of a particular element can provide information about the origin of the particles); for the ferrous metals, chromium comes from the surface coating of the first piston ring, manganese comes from cylinder liner, and nickel comes from transmission gears; for the nonferrous metals, aluminum comes from piston, copper primarily comes from the connecting rod bearing, lead comes from crankshaft bearing, and silicon comes from pistons or contamination

   Possible causes: Excessive mechanical wear of moving components

   Consequences: Reduced engine efficiency, EDG failure

6. *Fault*: Leakage [Cai 2011]

   Asset type: Fuel oil system, lubricating oil system, cooling water system, and starting air system

   Fault feature: Low pressure and loss of fluid (fuel, oil, water, and air) volume more than expected amounts consumed by the system

   Possible causes: Wear of bearings and other moving parts; aging/deterioration of nonmetallic materials used in seals gaskets and hoses because of oxidation; reduced life of nonmetallic sealing components because of thermal cycling and frequent component removal; wear of packing glands because of continuous operation in narrow bands of motion while in standby and/or constant load conditions

   Consequences: Reduced engine efficiency, EDG failure (failed-to-start or failed-to-run).

7. *Fault*: Pump degradation [Cai 2011]

   Asset type: Pumps in engine supporting systems

   Fault feature: Low fluid pressure and/or differential pressure, abnormal vibration levels

   Possible causes: Degradation of bearing and other moving parts

   Consequences: Reduced engine efficiency, EDG failure

8. *Fault:* Cooling failure

   Asset type: Cooling water system

   Fault feature: High jacket water temperature

   Possible causes: Dirty heat exchanger, air in the system, clogged water passage

   Consequences: Reduced engine efficiency, EDG failure

9. *Fault*: Air dryer degradation

   Asset type: Air dryer in starting air system

   Fault feature: High air moisture content (relative humidity)

   Possible causes: Air dryer failure

   Consequences: Increased corrosion of engine metal components

10. *Fault*: Turbocharger failure

    Asset type: Turbochargers

    Fault feature: Vibration, inlet and outlet air temperatures, and pressure gain across the charger

    Possible causes: Chemical: corrosion of tri-metal bearing because of oil breakdown; Mechanical: stresses on casing, plugging of vanes, bearing lubrication loss

    Consequences: Reduced power output

11. *Fault*: Excessive piston to head clearance [Krawczak and Wilson 1993]

    Asset type: Combustion chamber

    Fault feature: High piston to head clearance measured by a lead wise test

    Possible causes: Bent connecting rod

    Consequences: Reduced engine efficiency, EDG failure

12. *Fault*: Scuffed or scored cylinder liners [Krawczak and Wilson 1993]

    Asset type: Cylinder liners

    Fault feature: High chrome and iron content in the engine lube oil; abnormal vibration pattern (typical vibration profile is shown in Figure 6, where TDC stands for Top Dead Center and BDC for Bottom Dead Center), including ultrasonic spikes that are not correlated with distinct mechanical events (such as valve closure)

    Possible causes: Excessive piston damage (e.g., advanced wear compression rings) leading to liner contact; contamination of or inadequate levels of lubricant oil; chemical reaction between combustion blowby water in the crankcase and a diester in the synthetic lube oil acid-neutralizing additives, causing the formation of hard deposits behind the piston rings

    Consequences: Reduced engine efficiency, EDG failure

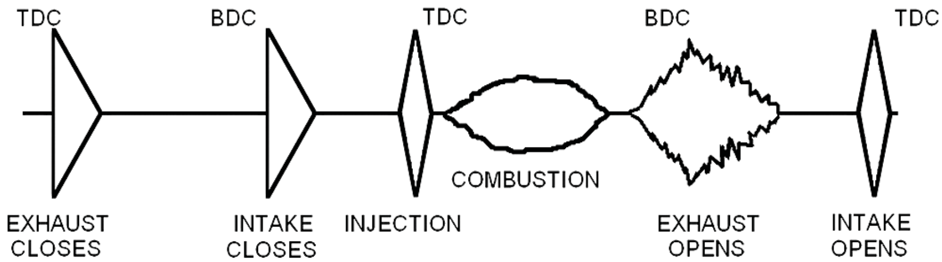

Figure 6. Typical vibration and acoustic emission patterns in four-stroke engines.

3.2 Generator Diagnosis

Two main EDG generator failure modes are stator winding insulation failure and rotor bar failure [Ramani 2008]. The most common faults are: rotor unbalance, broken rotor bar, cracked rotor end-rings, parts ripped off, thermal bend, gland impact and rubbing, rubbing of axis direction, bearing misalignment, cooling fluid pipeline break, insulation failure, open/short circuit in the stator windings, and overheating of the winding. Table 3 lists the commonly available monitoring parameters for EDG generators.

Table 3. Monitoring parameters for EDG system.

System	Component	Monitoring parameter
Generator	Stator windings	Pressure
		Exhaust temperature
		Vibration
	Lubricant oil	Chemical analysis
	Rotor bars	Stator current
		Axial leakage flux
	Bearings	Vibration
		Temperature

3.2.1 Technical Examinations

3.2.1.1 Insulation Fault Analysis

The survey of 1,199 hydrogenerators carried out by the CIGRE study committee SC11, EG11.02 provides useful information about the causes of generator failures [CIGRE 2003]. Among 69 generator failure incidents, 56% of the failed machines showed insulation damage; the root causes of the insulation damage were subdivided into seven different groups as shown in Figure 7. In many situations, measurements of insulation resistance (measured by means of a high voltage tester) and polarization index (1 minute reading/10 minute reading of resistance ratio) can serve as indicators of insulation condition. A low polarization index (below 1.5) suggests the windings are wet, dirty, or faulty [CIGRE 2003]. However, insulation resistance test data is useful only in evaluating the presence of some insulation problems such as contamination, absorbed moisture, or severe cracking. More detailed testing involving loss tangent, dielectric loss analysis, and partial discharge measurement, is undertaken at intervals in order to establish the extent of deterioration of insulation condition. Other tests such as high voltage withstand tests are particularly effective for investigative work in order to identify the onset of fault conditions.

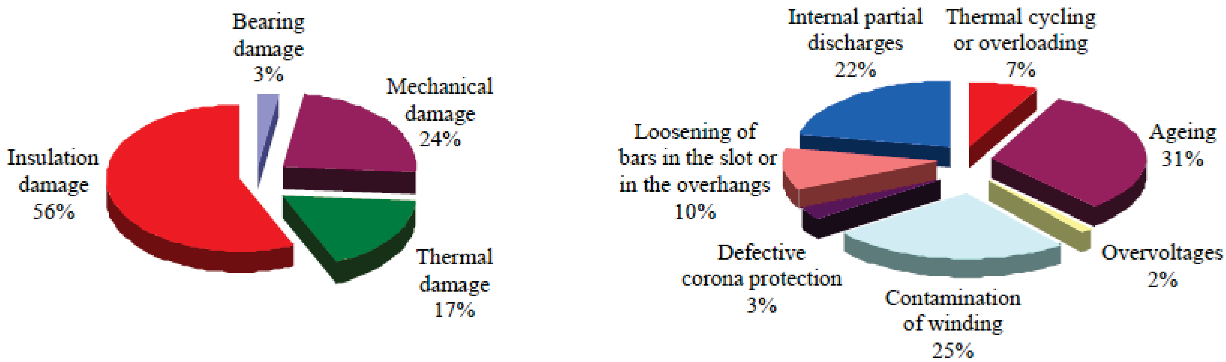

Figure 7. Damage of hydrogenerators (left) and root causes of insulation damage (right) [CIGRE 2003].

3.2.1.2 Rotor Bar Fault Analysis

There are several instruments available to measure parameters that can be used to detect broken rotor bars while the motor is running at normal speed and load; the relevant parameters include current, mechanical speed, frame vibration, air gap flux, and axial leakage flux. A broken rotor bar causes a rise of the higher order harmonic amplitudes in the stator current signal. A broken rotor bar also causes small asymmetries in both the material and geometry of a generator. This, in turn, produces a small axial leakage field that can be detected by an externally mounted coil. For a broken rotor bar, there are increased amplitudes in the fundamental frequency (50 Hz) as well as third (150 Hz) and fifth (250 Hz) components. This technique also can be used to detect a short-circuited stator winding when there is only large amplitude increase in the fundamental component.

3.2.2 Generator Fault Signatures

The following fault signatures were identified via a literature search. These fault signatures will further evaluated for inclusion in the FW-PHM software suite.

1. *Fault*: Open/short circuit in the stator windings

   Asset type: Stator windings

   Fault feature: Lower insulation resistance, higher vibration, and increased temperature

   Possible causes: Winding insulation breakdown (between turns within a phase coil, between turns of different phases, and between a turn and the stator core) because of thermal, electrical, mechanical, and chemical stresses as shown in Figure 8

   Consequences: Reduced generator efficiency, generator failure

2. *Fault*: Open/broken rotor bar [Welsh 1988]

   Asset type: Generator rotor bar

   Fault feature: Increased amplitudes in the fundamental frequency (50 Hz) as well as third (150 Hz) and fifth (250 Hz) components of the axial leakage flux; increased higher order harmonic amplitudes of the stator current

   Possible causes: Mechanical, thermal, or residual stresses

   Consequences: Generator efficiency, generator failure

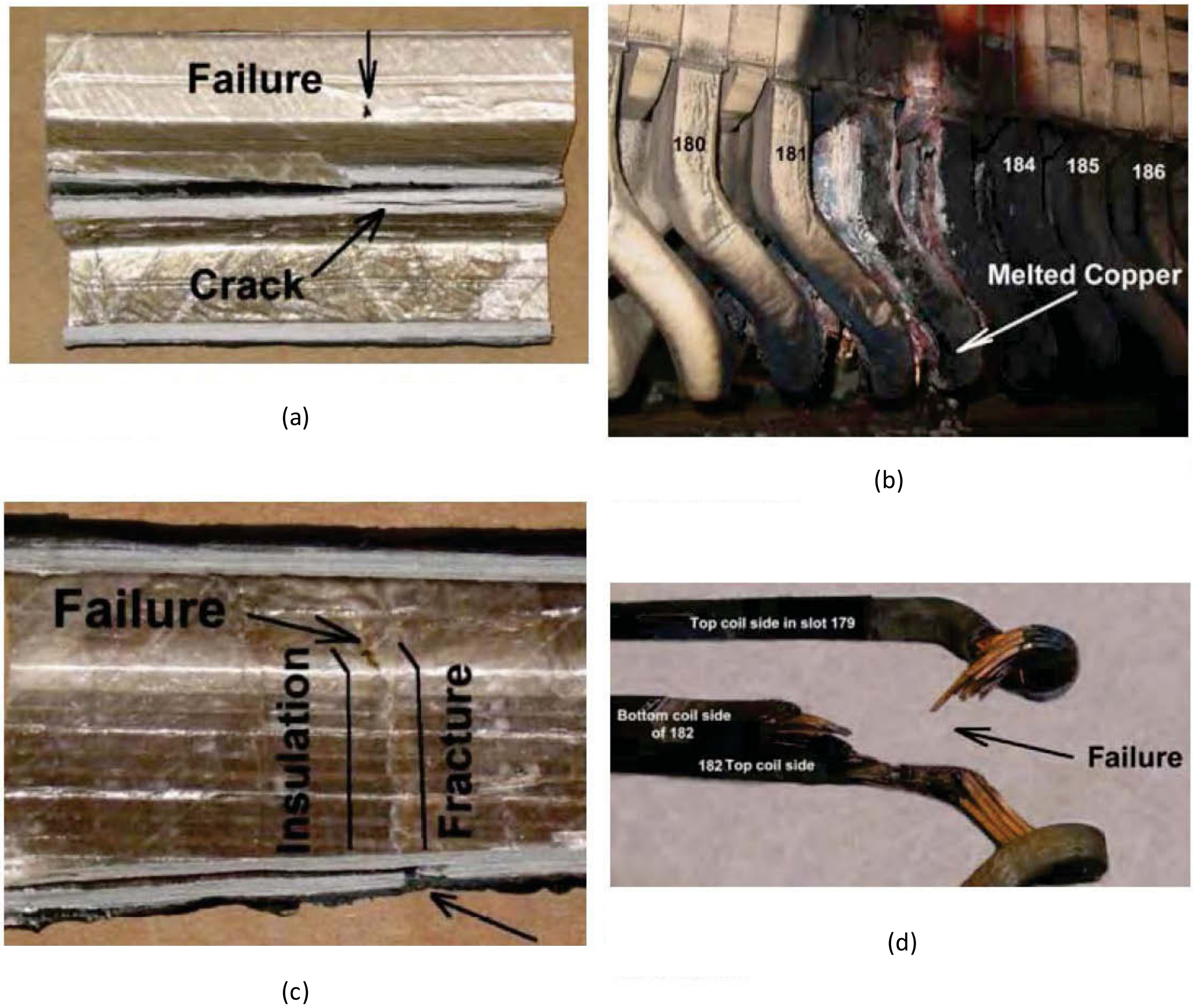

Figure 8. Examples of insulation failure leading to open/short circuit in the stator windings [CIGRE 2003]: (a) ground wall insulation was easily folded away from the conductor stack; (b) removal of the rotor revealed extensive stator winding damage; (c) the fracture completely encompasses the coil insulation; and (d) the center of the missing sphere of copper in the bottom coil is the point of origination of the failure.

3. *Fault*: Bearing fault

   Asset type: Generator rotor bearing

   Fault feature: Abnormal surface appearance; higher vibration and acoustic levels; high content of metal particles in the lubricant oil; existence of free metical particles larger than 1mm in diameter in the lubricant oil (indicates impending failure)

   Possible causes: Mechanical damage; wear; corrosion damage; electrical pitting; fatigue damage; thermal fatigue damage; inadequate lubrication

   Consequences: Reduced generator efficiency; generator failure; shaft journal, collar, or runner damage.

3.3 Prognostics

Greitzer and Ferryman [2001] suggested that to predict a failure and/or the RUL of a system such as EDG, three things typically must be known:

1. The system's current degree of fault as quantified by a figure of merit (FOM)
2. A theory about the progression of the fault, so as to postulate the system's degree of fault at a particular point in time in the future
3. The level of the fault, as quantified by the FOM, that will produce a system failure

Predictive analysis methods should consider: trade-off between false alarm rate and responsiveness to change; data may be exceedingly noisy and insufficient; unexpected changes in actual system; and high uncertainty in model extrapolation.

An example of an RUL model for an EDG engine is described here. Results from typical periodic technical examination results for an EDG engine can be used to establish a predictive RUL model for an EDG. Recall—the technical examinations discussed in Section 3.1—temperature analysis (T), pressure analysis (P), vibration analysis (V), and engine oil analysis (C) can be used to assess the condition of one or more components of EDG. In addition, trending of these parameters over time can be used to estimate RUL of a particular engine component or the whole engine, depending on measurement location. It is commonly accepted that larger measurement deviations from nominal values indicate higher levels of deterioration. This leads to the simplest linear function of FOM, representing the degree of fault for an EDG engine:

$$FOM = a_0 + a_1(T - T_N) + a_2(P - P_N) + a_3(V - V_N) + a_4(C - C_N) \qquad (1)$$

where a_i are weighted coefficients and subscript (*N)* stands for nominal value.

The coefficients a_i can be estimated such that FOM will monotonically increase when test results are further from normal conditions. The historical operational data are used to establish the maximum allowable FOM value (FOM_{max}), beyond which EDG's diesel engine is considered failed. Figure 9 depicts how the FOM model can be used to estimate the RUL of EDG's diesel engine basing on current measurements of periodic test of engine condition. A similar degradation function can be constructed as the RUL model for EDG generator.

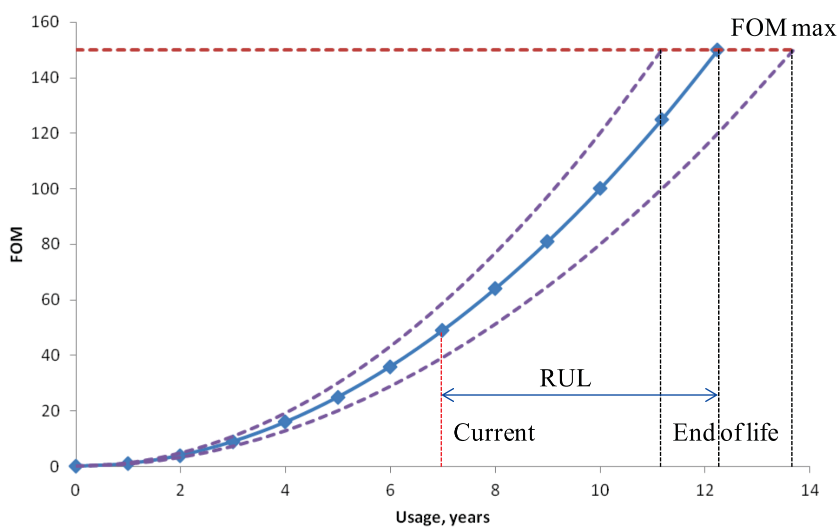

Figure 9. Example of RUL model with uncertainty bounds for an EDG engine.

4. SUMMARY AND FUTURE PLANS

This report presents the interim research activities associated with OLM of EDGs. The rigorous testing performed on EDGs, along with the sudden response required to a loss of offsite power or other design basis event, can impose significant aging damage to the EDGs. Inclusion of EDGs as part of a comprehensive OLM program will increase reliability and availability of this crucial system. EPRI and INL interacted with EDG experts from the Braidwood Generating Station to capture multiple fault signatures relevant to NPP EDGs. The fault signatures documented in this report are expected to streamline the diagnosis process by helping the expert focus his/her efforts on the most likely faults based on the behavior of the system.

In FY-13, INL will continue to work with the Braidwood Nuclear Generating Station to populate the asset fault signature database with EDG fault signatures. Different test scenarios will be developed and implemented to evaluate the ability of the Diagnostic Advisor in the FW-PHM Software Suite to identify the most relevant faults based on both complete and incomplete information entered manually or via a batch file. INL and EPRI will also assist the Braidwood Generating Station with software implementation, which will allow further testing of the Diagnostic Advisor based on online data sources. INL will initiate review of prognostic techniques to estimate the RUL of GSUs.

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Appendix A

EDG Fault Signatures

Appendix A
EDG Fault Signatures

Governor Not Responsive

Table A-1. Governor Not Responsive Fault Signature – General Specification.

Describe in detail the asset type for which this fault signature is applicable. Electronically controlled governor on diesel generator
Describe the sources of the information used to specify this fault signature. EDG Diagnostic Workshop at Braidwood NGS, Joliet, IL, September 2012.
Name or briefly describe the fault type for this fault signature. The governor does not control engine speed in response to changes in electrical load (speed of engine)
Describe the condition and/or mechanism of the fault and provide reference information. Failure to receive a needed input or to actuate the fuel rack as an output. Bad speed sensor, failure of governor circuit, failure of an input to the governor
Describe any limitations on the applicability or relevance of this fault signature. Mechanical governor controlling a fuel rack on a diesel engine that is driven by a generator load/speed demand
List the fault features indicating for the fault and attach a Fault Feature Specification for each. KW load: Unchanged when told to RPM or Frequency: Unchanged in response to a demand change Governor voltage Exhaust temperatures unchanged in response to demand change MPU Speed for governor unchanged in response to demand change
Describe other faults that can cause this fault to occur. Failure of speed sensor. Features include a signal that drops out, load decreases, trip on reverse power, trip on overspeed, fail over to mechanical control
Describe other faults that can be caused by this fault.
Describe the corrective actions that might remedy this fault. Determine contributing fault and correct
Provide contact information for the persons who prepared this fault signature. Richard Rusaw, EPRI Project Manager: RRusaw@epri.com

Table A-2. KW Load Unchanged in Response to Demand - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. KW Load should change on demand from the control switch during a test
Describe the asset location where the data for assessing the fault feature is acquired initially. Seen in output from DG electrical system on a kilowatt meter. Potential transformer on the generator.
Describe the technology used to acquire the data for assessing the fault feature. Potential Transformer (Power Analysis)
Describe the examination of the data that indicates whether or not the fault is present. Power in KW: online measurement of power output from the generator
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). Normal: power changed in response to demand No Change: power reading did not change
List in order of increasing confidence the outcomes of the examination that indicate for this fault. No Change indicates for
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Governor Troubleshooting written by NPR. Sharkey/EPRI on governor. Vendor manuals (Woodward) Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-3. Frequency Unchanged in Response to Demand - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. RPM or Frequency should change in response to request from control room switch during test
Describe the asset location where the data for assessing the fault feature is acquired initially. Frequency measured on generator output (potential transformer) RPM speed on the engine crankshaft
Describe the technology used to acquire the data for assessing the fault feature. Freq is Power analysis RPM are mag probes
Describe the examination of the data that indicates whether or not the fault is present. Frequency should be 60 Hz. Operator tries to bring it back to 60. RPM should be 600 (60 Hz). Operator tries to bring back to 600.
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). Normal/No change
List in order of increasing confidence the outcomes of the examination that indicate for this fault. No Change indicates for
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Governor Troubleshooting written by NPR. Sharkey/EPRI on governor. Vendor manuals (Woodward) Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-4: Governor Voltage Unchanged in Response to Demand - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. Governor voltage should change in response to request from control room to raise load
Describe the asset location where the data for assessing the fault feature is acquired initially. Voltage across the governor input leads
Describe the technology used to acquire the data for assessing the fault feature. Voltage measurement
Describe the examination of the data that indicates whether or not the fault is present. Voltage does not change
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). Normal/No change
List in order of increasing confidence the outcomes of the examination that indicate for this fault. No Change indicates for
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Governor Troubleshooting written by NPR. Sharkey/EPRI on governor. Vendor manuals (Woodward) Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Intermittent Control Signal to Governor

Table A-5. Intermittent Control Signal to Governor Fault Signature – General Specification.

Describe in detail the asset type for which this fault signature is applicable. Intermittent output signal from control system to EDG governor
Describe the sources of the information used to specify this fault signature. EDG Diagnostic Workshop at Braidwood NGS, Joliet, IL, September 2012.
Name or briefly describe the fault type for this fault signature. Intermittent control signal output to governor
Describe the condition and/or mechanism of the fault and provide reference information. Problems in the control system circuit or magnetic pickup unit speed sensor cause the control system to provide an intermittent signal to the engine governor.
Describe any limitations on the applicability or relevance of this fault signature. Generally applicable to EDGs of this type.
List the fault features indicating for the fault and attach a Fault Feature Specification for each. KW load: Fluctuating RPM or Frequency: Fluctuating Governor voltage: Fluctuates or oscillates or drops out or is unstable Excessive jitter in the governor fuel linkage (hunting)
Describe other faults that can cause this fault to occur. Bad internal circuits; Bad electrical connection on inputs; MPU faulty; Unreliable power supply
Describe other faults that can be caused by this fault. Governor wear or failure
Describe the corrective actions that might remedy this fault. Replace control unit or faulty components. Repair loose connections.
Provide contact information for the persons who prepared this fault signature. Richard Rusaw, EPRI Project Manager: RRusaw@epri.com

Table A-6. KW Load Fluctuation - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. KW load: Fluctuating
Describe the asset location where the data for assessing the fault feature is acquired initially. Generator output potential transformer
Describe the technology used to acquire the data for assessing the fault feature. Power analysis: potential transformer
Describe the examination of the data that indicates whether or not the fault is present. KW power output from the generator: oscillating or fluctuating. The meter does not move. Inspection of the meter in the control room or at the DG
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). "Normal" for stable KW power output; "Abnormal" for fluctuating power output;
List in order of increasing confidence the outcomes of the examination that indicate for this fault. An Abnormal result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-7. RPM or Frequency Fluctuation Fault - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. RPM and/or Frequency: Fluctuating
Describe the asset location where the data for assessing the fault feature is acquired initially. Generator output frequency meter (control room or DG room) or engine speed sensor (locally at DG or by computer point)
Describe the technology used to acquire the data for assessing the fault feature. Power analysis: potential transformer or speed
Describe the examination of the data that indicates whether or not the fault is present. Frequency output from the generator: Looking for oscillations. Expected to be constant Engine Speed: Vary more than expected. 1 RPM is a large change should be less than 0.25 RPM
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). "Normal" for stable frequency or speed output; "Abnormal" for fluctuating power output;
List in order of increasing confidence the outcomes of the examination that indicate for this fault. An Abnormal result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-8. Governor Voltage Fluctuates - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. Governor input voltage signal is fluctuating. This signal is the primary output of the control system.
Describe the asset location where the data for assessing the fault feature is acquired initially. Governor input signal leads
Describe the technology used to acquire the data for assessing the fault feature. Voltage: measurement by local meter or by computer point
Describe the examination of the data that indicates whether or not the fault is present. DC Voltage Value: Minor voltage variation (<0.1 volts) is the expected behavior. Any oscillations (most common), fluctuations or drop-outs are indicators.
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). "Normal" for stable voltage measurement; "Abnormal" for fluctuating voltage measurement;
List in order of increasing confidence the outcomes of the examination that indicate for this fault. An Abnormal result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. There will be a specification of normal in manufacturers' documents and in the local experience. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-9. Governor Fuel Linkage Hunting - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. The governor mechanical output is jittery or hunting to find the control.
Describe the asset location where the data for assessing the fault feature is acquired initially. Governor linkage to fuel rack
Describe the technology used to acquire the data for assessing the fault feature. Inspection
Describe the examination of the data that indicates whether or not the fault is present. Hunting: the fuel linkage is oscillating in response to the oscillating input
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). “Normal” for stable linkage position; “Abnormal” for oscillating linkage position;
List in order of increasing confidence the outcomes of the examination that indicate for this fault. An Abnormal result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Should be very stable. Experience helps. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Intermittent MPU Signal

Table A-10. Intermittent MPU Signal Fault Signature – General Specification.

Describe in detail the asset type for which this fault signature is applicable. Magnetic pickup unit sensor used to provide a speed signal to the control system providing diesel engine speed control using a governor
Describe the sources of the information used to specify this fault signature. EDG Diagnostic Workshop at Braidwood NGS, Joliet, IL, September 2012.
Name or briefly describe the fault type for this fault signature. Intermittent MPU sensor output signal because of connector or cabling defect
Describe the condition and/or mechanism of the fault and provide reference information. Longer description.
Describe any limitations on the applicability or relevance of this fault signature. Generally applicable to EDGs of this type.
List the fault features indicating for the fault and attach a Fault Feature Specification for each. All of the items for governor intermittent control signal (previous); MPU signal is intermittent or oscillating in coincidence with fuel linkage movements
Describe other faults that can cause this fault to occur.
Describe other faults that can be caused by this fault.
Describe the corrective actions that might remedy this fault.
Provide contact information for the persons who prepared this fault signature. Richard Rusaw, EPRI Project Manager: RRusaw@epri.com

Table A-11. Oscillating or Intermittent MPU Signal - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. Oscillating or intermittent MPU signal
Describe the asset location where the data for assessing the fault feature is acquired initially. MPU output leads (12-18 VAC) local meter or computer point
Describe the technology used to acquire the data for assessing the fault feature. Voltage: What general method will we use?
Describe the examination of the data that indicates whether or not the fault is present. VAC: Should be stable VAC value. <0.2-V variation
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). "Normal" for what set of observed results?; "Abnormal" for greater than 0.5 V variation (local experience dictates the threshold limit)
List in order of increasing confidence the outcomes of the examination that indicate for this fault. A Marginal result indicates for the fault; A High result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Improper Exhaust Valve Timing

Table A-12. Improper Exhaust Valve Timing Fault Signature – General Specification.

Describe in detail the asset type for which this fault signature is applicable. Exhaust valve for a single engine cylinder in a diesel engine
Describe the sources of the information used to specify this fault signature. EDG Diagnostic Workshop at Braidwood NGS, Joliet, IL, September 2012.
Name or briefly describe the fault type for this fault signature. Exhaust valve is not opening for the correct time period
Describe the condition and/or mechanism of the fault and provide reference information. The valve must open and close at the correct time in relation to the engine rotation position
Describe any limitations on the applicability or relevance of this fault signature. Generally applicable to EDGs of this type.
List the fault features indicating for the fault and attach a Fault Feature Specification for each. High exhaust temperature for this cylinder; High differential exhaust temperature between cylinders; High intake temperature at this cylinder or nearby Recent valve adjustment
Describe other faults that can cause this fault to occur. Numerous camshaft, pushrod, rocker arm, spring, guide, seat
Describe other faults that can be caused by this fault.
Describe the corrective actions that might remedy this fault. Inspect and repair
Provide contact information for the persons who prepared this fault signature. Richard Rusaw, EPRI Project Manager: RRusaw@epri.com

Table A-13. High Exhaust Temperature - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. High exhaust temperature for a particular cylinder
Describe the asset location where the data for assessing the fault feature is acquired initially. Engine cylinder exhaust neck before the manifold
Describe the technology used to acquire the data for assessing the fault feature. Temperature: Thermocouple
Describe the examination of the data that indicates whether or not the fault is present. Magnitude: Measured value compared to a local baseline
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). “Normal” can be 800 to 1100 F; “Abnormal” is greater than 1100 F
List in order of increasing confidence the outcomes o f the examination that indicate for this fault. A Marginal result indicates for the fault; A High result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-14. High differential Temperature Between Cylinders - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. High exhaust temperature differential between cylinder
Describe the asset location where the data for assessing the fault feature is acquired initially. Engine cylinder exhaust ports
Describe the technology used to acquire the data for assessing the fault feature. Temperature: Thermocouple
Describe the examination of the data that indicates whether or not the fault is present. Maximum Difference Value: Greatest difference between measured values for all ports compared to a local baseline
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). “Normal” for delta T less than 200 F “Abnormal” for delta T greater than 200 F
List in order of increasing confidence the outcomes of the examination that indicate for this fault. An Abnormal result indicates for the fault;
Describe the effectiveness of this fault feature for detecting the fault condition. ☒ Very High ☐ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Engine manual will provide the normal values. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-15. High Intake Air Temperature - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. High intake air temperature for this cylinder and possibly adjacent cylinder
Describe the asset location where the data for assessing the fault feature is acquired initially. Engine cylinder air intake
Describe the technology used to acquire the data for assessing the fault feature. Temperature: Infrared probe
Describe the examination of the data that indicates whether or not the fault is present. Maximum Value: Reading at the intake valve location at the manifold housing Compared to the normal 90-120 F value measured in manifold bulk, Abnormal is a hot location at 150-300 F
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). "Normal" for delta T less than 200 F "Abnormal" for delta T greater than 200 F
List in order of increasing confidence the outcomes of the examination that indicate for this fault. An Abnormal result indicates for the fault;
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Table A-16. Recent Valve Adjustment - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. Has a recent valve adjustment been performed
Describe the asset location where the data for assessing the fault feature is acquired initially. Maintenance history
Describe the technology used to acquire the data for assessing the fault feature. Maintenance Action:
Describe the examination of the data that indicates whether or not the fault is present. Valve Adjustment: Has a recent valve adjustment been performed?
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). "Normal" if no maintenance within last 6 months; "Recent" if within the last six months; "Very Recent" if within last month`
List in order of increasing confidence the outcomes of the examination that indicate for this fault. A Recent result indicates for the fault; A Very Recent result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.

Fuel Pump Degradation

Table A-17. Fuel Pump Degradation Fault Signature – General Specification.

Describe in detail the asset type for which this fault signature is applicable. Fuel injection components for EDG
Describe the sources of the information used to specify this fault signature. EDG Diagnostic Workshop at Braidwood NGS, Joliet, IL, September 2012.
Name or briefly describe the fault type for this fault signature. Low fuel supply to cylinder
Describe the condition and/or mechanism of the fault and provide reference information. A reduction in fuel pump performance or an increase in delta P across the injector causes low fuel supply to a cylinder
Describe any limitations on the applicability or relevance of this fault signature. Generally applicable to EDGs of this type.
List the fault features indicating for the fault and attach a Fault Feature Specification for each. Temperature: Magnitude Value (at engine cylinder exhaust port); Load changing response will be degraded, requested load changes will more slowly, may take more requests to achieve a desired result. Will have to compensate or readjust more often. Other cylinders will need more fuel to achieve same load. Inspection: Fuel metering rod is out of position (closed or off most likely)
Describe other faults that can cause this fault to occur. Fuel pump crosshead fails Internal failure of fuel pump Fuel injector is plugged, broken High pressure fuel line pump to injector is plugged or broken (double wall , leakage goes to floor)
Describe other faults that can be caused by this fault.
Describe the corrective actions that might remedy this fault.
Provide contact information for the persons who prepared this fault signature. Richard Rusaw, EPRI Project Manager: RRusaw@epri.com

Table A-18. Low Cylinder Exhaust Temperature - Fault Feature Specification.

Describe the application of the fault feature for detecting the fault condition. Low fuel flow to the cylinder decreases the amount of fuel burned in a cycle, leading to lower exhaust gas temperature
Describe the asset location where the data for assessing the fault feature is acquired initially. Engine cylinder exhaust port
Describe the technology used to acquire the data for assessing the fault feature. Temperature: Assessment of gas temperature, normally using a thermocouple
Describe the examination of the data that indicates whether or not the fault is present. Magnitude Value: The value of the gas temperature in the exhaust port is compared to a limit value
List all possible outcomes of the examination of the data (outcomes should be mutually exclusive). "Normal" for what set of observed results?; "Marginal" for what set of observed results?; "High" for what set of observed results?
List in order of increasing confidence the outcomes of the examination that indicate for this fault. A Marginal result indicates for the fault; A High result indicates for the fault with increased confidence.
Describe the effectiveness of this fault feature for detecting the fault condition. ☐ Very High ☒ High ☐ Medium ☐ Low ☐ Very Low
Provide reference information and examples for this fault feature. Values used for specific plant equipment applications should be determined in coordination with the equipment owner.