UTILIZING IEC 61850 FOR A POWER MANAGEMENT SYSTEM OF AN OFFSHORE PLATFORM

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Abstract – Second only to safety, the most critical aspect related to electrical power on an offshore platform is reliability. Reliability can be broken down into three subcategories; availability, stability, and quality. Availability mainly pertains to the status of the primary equipment. Stability is achieved by having an effective Power Management System (PMS) to regulate voltage and frequency even during abnormal conditions (e.g. the sudden trip of a generator). Quality is a diverse topic, but the fundamental point is that the power delivered must be suitable for the loads and continuously monitored. By optimizing each of these subcategories, the reliability of the electrical power is maximized. This paper will cover technical details related to design and testing of an offshore platform PMS which uses many of the benefits of the IEC 61850 Standard, including Generic Object Oriented Substation Event (GOOSE) messaging between Intelligent Electronic Devices (IEDs) and controllers to achieve fast power-based load shedding and load inhibition in a real application.

Index Terms — IEC61850, Power Management System, GOOSE, MMS, Load Shedding, Offshore, FPS, Electrical.

I. INTRODUCTION

A semi-submersible Floating Production System (FPS) Platform nearly 80 miles out to sea with no connection to a local electrical utility. The power grid of such a vessel is an actual electrical island, and as such, a proper voltage and frequency must be maintained within certain tolerances to keep critical equipment operational. A common power grid for an FPS Platform is comprised mainly of generators, transformers, switchgear, motors as well as the bus bar and cables that connect the equipment. Because electrical power is essential to so many operational aspects of the FPS Platform, there is typically multiple generator sets included so that a failure of one, or possibly more than one generation unit, would not result in a blackout. This is not to say that a loss of one or more generators would not compromise the normal reliability factor of the overall power network. The FPS Platform, following the loss of a primary energy source, would be more susceptible to an even more critical condition with a potential subsequent issue with another generator. Also, the facility electrical load that was previously being supplied by the generating unit that was taken offline would immediately need to be supplied from the remaining generator(s). The goal, in order to best maintain a stable frequency during a contingency event such as a sudden loss of generation, is to quickly and selectively shed load by opening the circuit breakers or motor contactors of the lower priority circuits and to maintain power to critical loads that must continue to operate to safely maintain the process and operation of the platform. Fig. 1 below shows a simplified offshore power one line.

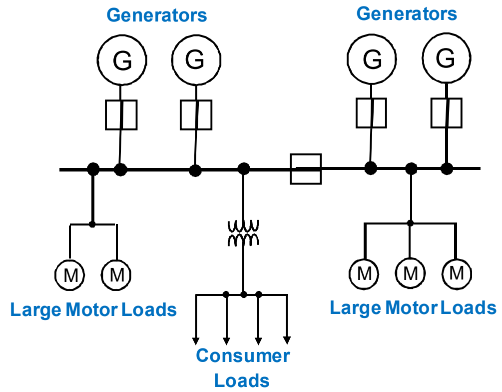

Fig. 1 Simplified Offshore One Line

The balance between consumed and generated power must be maintained even during a contingency event. In the case of a loss of a primary power source, typically a shedding of lower priority electrical loads must occur quickly to ensure the remaining generators do not become overloaded and then also trip causing a cascading event leading to a blackout. It is the task of the Power Management System to automatically direct the operation of the electrical equipment under normal and abnormal conditions. The goal is to ensure that the generation and load stay balanced thus maintaining a stable frequency. Fig. 2 illustrates the balance that must be kept to achieve a nominal frequency.

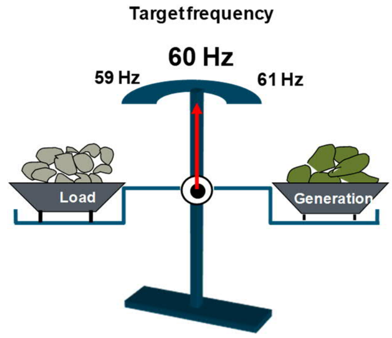

Fig. 2 Balanced Load and Generation

Under normal conditions, monitoring of the live electrical grid is being done constantly as well as standard operational control sequences being carried out. Under abnormal conditions, such as the unexpected trip of a primary generating unit, the system must act almost instantly to recognize what is happening and immediately issue load shedding commands accordingly before the system frequency decays. Fig. 3 illustrates the lower frequency that would result from a loss of generation if load remained the same.

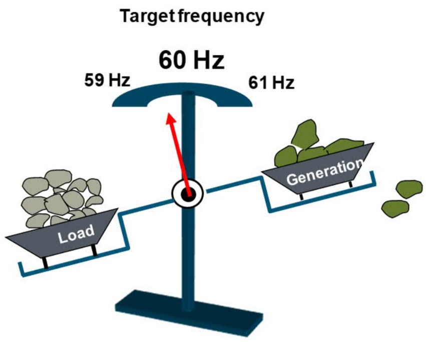

Fig. 3 Under-frequency following loss of generation

The challenge then is shedding enough loads to prevent overloading of remaining generators but also being selective enough to not shed too many loads thereby turning off equipment when it wasn't necessary. Or, possibly worse yet, causing the frequency to rise due to a surplus of generation. Fig. 4 illustrates the higher frequency that would result from shedding too much load.

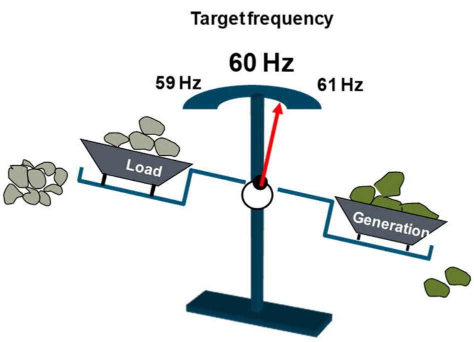

Fig. 4 Over-frequency due to too much load shed

Load shedding commands open circuit breakers or motor contactors. These commands are delivered over a redundant Ethernet-based communications network in the form of GOOSE messages between IEDs and also PMS Controllers. GOOSE is one of the communications protocols of the IEC 61850 Standard and is applied when fast, supervised and sequenced peer-to-peer messages that share either digital or analog values are needed. The main reason that GOOSE messages can achieve such fast transmission times and also be more secure is that only the bottom two layers of the Open System Interconnection (OSI) Model are used. These are the Data Link (Layer 2) and Physical (Layer 1) layers. A depiction of the International Standards Organization (ISO) OSI Model is shown in Fig. 5.

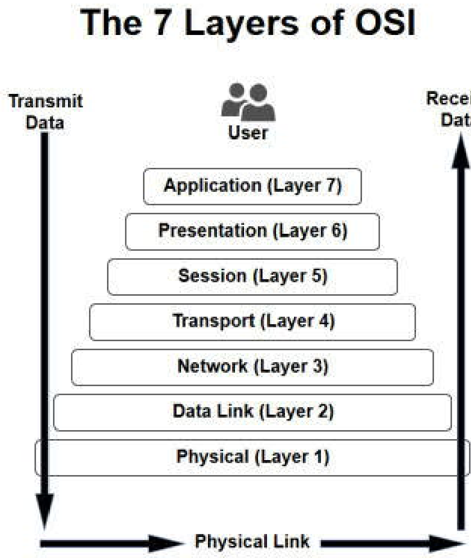

Fig. 5 ISO/OSI Model (Webopedia.com) [1]

This extremely fast transmission time of supervised messages allows for fast load shedding and is at the heart of this PMS application. By using fast and prioritized GOOSE messaging, the total cycle time from the recognition of the contingency event to the command issuance to disconnect the load was recorded to be less than 10ms. By achieving such fast speeds of data transmission and utilizing the capabilities of the devices, stability can be maintained even in the event of a loss of a primary generating unit by quickly and selectively shedding enough loads.

The communications network links IEDs, such as meters and protection and control devices located near the primary equipment to the PMS Controllers and Human Machine Interface (HMI) Servers. Ethernet Switches are the primary network devices between the IEDs and the PMS Controllers and when connected in a redundant fashion allow the system to continue to maintain full communications in the case of a single failure such as a broken fiber optic cable or a port failure of a device.

Redundancy is necessary to ensure a higher degree of reliability of the system since the issuance of commands such as those for load shedding and load inhibition are delivered over a fiber optic communications network. Simple Network Management Protocol (SNMP) at the system level monitors the health of the communications network, to verify proper data flow. At the device level, IEDs and Network Devices are also monitoring their communications ports and connection to the network. At the time a failure is detected, an alarm is quickly presented at the PMS HMI with a distinct location of where the problem has occurred so facility maintenance personnel can address the problem.

A PMS that provides a Fast Power-based Load Shedding System is continuously monitoring and evaluating the power profile of the electrical network. Cyclically, the PMS controllers are processing the amount of power generated (combined and individual), the consumed load by different feeder circuits and the spinning reserve (excess capacity) of the online generating units. Using this information, the controllers can issue status commands to the relays approximately every half second, and these status commands will direct whether a particular relay will trip its associated load in the event of contingency X (with X representing multiple possible contingencies). The goal of fast power based load shedding is to initiate tripping without waiting for the measured frequency to decay considering that the frequency will decay following the trip of Generator X if load is not removed.

II. OPERATIONAL CHALLENGES AND REQUIREMENTS FOR THE PMS FROM THE OWNER'S PERSPECTIVE

Without electrical power, the processes on the platform cannot run. Without the processes, there is no production and thus the critical importance of the electrical energy supply. Even more significant is the fact that the electrical power is also essential to the safety of the personnel on the platform.

The main challenges that are faced in keeping the power system stable and up and running on a semi-submersible FPS mainly relate to the fact that the electrical network on the platform is an electrical island with no utility grid connection and therefore the supply of the electricity is fully dependent on the generation units on the platform. Because the electrical network is an island, it can be much more susceptible to losing overall stability when sudden generation changes and load changes occur unless automated controls are in place to quickly and correctly react to those changes. One key purpose of the PMS is to provide these automated controls, including load shedding and load inhibition to help maintain stability and avoid the dangerous and undesirable condition which is a total blackout aboard the platform.

Safety is a primary benefit of the PMS. In addition to helping to improve the stability of the electrical network, the PMS offers functionalities that tie directly to the operational safety of the personnel working on the platform. Specifically, the PMS allows the remote control of switchgear and remote racking of the switchgear. Both of these operations can introduce a real danger to personnel if he has to carry out the operation in front of the live switchgear. By having local PMS control cabinets in the various areas on the platform, these operations can be carried out from the local building where the gear is located, but from a safe distance as to not endanger personnel. Having these local operating stations rather than a centrally located panel prevents the need for workers to traverse across different areas to access information, in particular on a platform of this size.

Two of the most important aspects of the PMS are that it needs to be up and running and also user-friendly for the operators. Many times the operators need to make quick decisions based on information that is displayed on the PMS HMI screens and execute controls, so the system must be easy to use. Also, because the PMS supports important operations like load shedding and load inhibition, which are functions that need to happen without operator interaction, the up-time of the system is critical and therefore multiple layers of redundancy are built into the design.

Other aspects of the PMS which are of the utmost importance are speed, selectivity, and flexibility. Speed is needed to execute load shedding commands quickly before the frequency decays to a tripping level. Selectivity ensures that only the minimum number of circuits is shed to keep as much equipment up and running as possible. Finally, flexibility is important for the operators to ensure that they can set load shedding priorities according to the changing day to day operations.

III. ELECTRICAL DESIGN OF FPS PLATFORM

One of the primary goals when designing the power supply of an FPS Platform is to ensure that one failure, even significant, will not bring down the entire operation. For example, critical pumps and other motors have the ability to be fed from different switchgear buses and that approach is followed from the main medium voltage bus down to the lower voltage levels where practical. Generation is sized so that nominal load can be supplied by remaining generators even if one unit is down for maintenance.

This FPS Platform will be owner's first offshore vessel with combined cycle power generation. In addition to the Gas Turbine Generators (GTG), there is an additional Steam Turbine Generator (STG) that supplies electrical energy using steam from process and heat output of the GTGs. With a combined cycle power plant, there is an added degree of complexity to the control of electricity and steam, but takes advantage of energy available to produce electrical power. Additionally, two of the GTGs can use dual fuel supplies of either natural gas or diesel, providing flexibility, but also the ability to black-start the system since the natural gas is provided by the production through fuel skids on the platform.

Another benefit of the PMS that relates to operational flexibility is the ability to re-prioritize loads in the load shedding scheme depending on the importance of certain equipment under certain conditions. For instance, at one point in time the water flood pump may be of higher critical importance than the main compressor, but on other occasions, the priority could be reversed. The operators need this flexibility at the HMI screens to change priorities based on current conditions.

IV. PMS DESIGN BASIS

A. System Overview

The purpose of the electrical power management system is to provide the user a comprehensive view and control of the vessel's electrical equipment. Fast power based load shedding and load inhibition are primary, automated functions of the PMS. The PMS provides a top-down view of the substation components, giving the operator a high-level overview of the substation's state as well as the ability to drill down into more detail in the case of electrical system anomalies, or when seeking more detailed information related to a particular piece of equipment.

The PMS for this project was intended to provide the following five main primary functions:

- Mimic displays at identified workstations for monitoring/control of switchgear and motor starters
- Distribution Control - ability to open or close switchgear breakers and medium voltage motor starters
- Ability to remotely rack medium switchgear breakers
- Load shedding of prioritized medium voltage motors
- Start inhibit of medium voltage motors to prevent generation overload

Each PMS controller interfaces with electrical power equipment within the substation concentrates data, executes logic for interlocking and load shedding, oversees control authority, and handles alarm processing. It works as a gateway between the different process elements, including IEDs, Controllers and I/O Modules and the supervisory systems, including HMI System and Distributed Control System (DCS). The PMS works with redundant hardware that logically behaves as a single unit. It is also a multiple-protocol system.

Communications protocols used in this project are as follows:

- IEC61850 Client
- Modbus Master
- Modbus Slave
- SNMP Client (Network Monitoring)
- SNTP Server (Time Synchronization)

The HMI System of the PMS is designed to be able to monitor and control the complete system in a safe manner, considering the availability of the functionalities and the location of each HMI. The system has two levels described below, (Level 2 and Level 3):

- Level 2 control stations have control only over the equipment within its station location/building, but can monitor the status of the entire power distribution system;
- Level 3 control stations have full functional control and monitoring of the whole system.

B. Overall Security Standards

Various cyber security aspects are being addressed and supported by the PMS. First and foremost, the system provides the necessary tools and configuration capabilities to adhere to the owner's strict IT Security requirements. Below are some examples of cyber security aspects of the PMS.

- The defined electronic security perimeter is maintained by segregating the PMS network from any other external network
- Restricting user level access to the HMI based on user credentials, specifically the following three (3) levels – View only, Control, Configuration Changes
- After an elapsed time, the HMI returns to the so-called "kiosk" mode, which shows the simplified single-line screen in "view only" mode. This prevents unauthorized access if the operator steps away for an extended period.
- Logging of system activities, i.e. event list with actions logged in.

The overall PMS communications network is segregated into multiple VLANs for various purposes, including maintenance and process. There is an additional VLAN which is not accessible for security reasons. All ports which are unused are shut down and are assigned to this security VLAN. The VLAN for maintenance is used by corporate IT to deploy patches, update antivirus software and retrieve the back-up of the computer images. The process VLAN is used for PMS operations.

C. System Redundancy

In complex systems such as a PMS, the failure of individual devices can cause unpredictable problems in operating processes. The term *redundancy* designates the existence of functionally identical resources. Depending on the protocol, hot standby is supported for redundancy. If a device works in hot-standby mode, the interface which controls the process has a complete process image of the device and can immediately take over the control of the device concerned. With all other protocols, a general interrogation must be performed first to ensure that the interface has a process image.

D. Overview of IEC61850

"IEC 61850 is one central communication standard of the Power Utility control system reference architecture of IEC technical committee 57 (IEC 62357). The objective of Power Utility Automation Systems standardization is to develop a communication standard that will meet functional and performance requirements while supporting future technological developments. To be truly beneficial, a consensus must be found between IED manufacturers and users on the way such devices can freely exchange information. IEC 61850 is fully complementary to the Common Information Model (CIM) Standard (CIM – IEC 61970 – IEC 61968). The approach of the IEC 61850 series is to blend the strengths of the following three methods:

- Functional decomposition
- Data flow modeling
- Information modeling

"IEC 61850 standardizes the set of abstract communication services (Abstract Communication Service Interface services – ACSI, part 7-2) allowing for compatible exchange of information among components of a Power Utility Automation System.

"IEC 61850 offers three types of communication models:

- Client/Server type communication services model
- Fast and reliable system-wide distribution of data, based on a publisher-subscriber model (GSE Management). Two control classes are defined for that purpose.
    - GOOSE – analog and digital multicast
    - GSSE – digital data exchange over multicasts (deprecated)
- Sample Measured Values (SMV) model for multicast measurement values

"To be able to exchange the device descriptions and system parameters between tools of different manufacturers in a compatible way, IEC 61850-6 defines a System Configuration Language (SCL)." [2]

E. Communications Network Design

The network design of the PMS includes redundancy at the bay level and the station level. First, at the bay level, the network topology chosen for the IED networks was Rapid Spanning Tree Protocol (RSTP). RSTP is essentially a ring topology whereby the IEDs connect with each other and redundant Ethernet Switches. Fig. 6 shows the simplified connection.

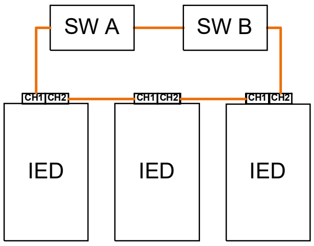

Fig. 6 Simplified RSTP connection

To prevent endless cycling of information around the physically closed ring, RSTP applies a virtual gap in the ring. In the event of a fault in the fiber network, either at a device port or a cable, the virtual gap will move to the location of the now physical gap. After a very fast switchover time, communications between all devices is regained. For this project, the rings were limited to two or three IEDs because of the customer's maintenance procedures. The rings could have contained more than three relays, thus reducing the number of switch ports required. But in doing that, based on maintenance procedures, it would have been possible that if multiple switchgear sections were taken out of service, communications to the relays in between would be lost as these relays would be isolated from the main PMS network. At the station level, the redundant Ethernet switches located in each area connect with the master switches in a ring topology.

F. GOOSE Messages

As previously mentioned, GOOSE messages are at the heart of this PMS application. Since these GOOSE messages carry important status indications and commands, there must be a priority over normal telegrams. Fig. 7 illustrates this priority.

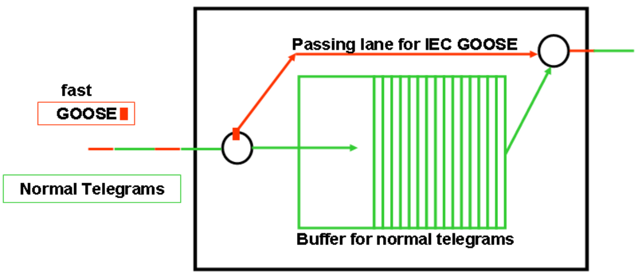

Fig. 7 Prioritizing of GOOSE on Network

The following items compromise GOOSE Telegram Structure:

- 4 Tag bytes define the tag control information
- Up to 1500 data bytes are available per message

The GOOSE message frame uses a layer 2 frame extension as defined by IEEE called 802.1Q. This makes the IEC 61850 GOOSE different from most other protocols which do not use this Ethernet feature. This frame has an extra parameter that defines priorities for switches. The IEC 61850 standard allows for the prioritization of GOOSE messages, thus allowing them to bypass the Ethernet data buffer. This requires Ethernet switches that support this feature. Dependent on the priority set, the switch will bypass the buffer of non-prioritized telegrams and handle GOOSE messages based on their priority.

The transmission of GOOSE messages can be both cyclic and spontaneous. For the example of a circuit breaker, at a set interval, as long as no change of state has taken place, a new message will be sent repeating the current position of the breaker (e.g. closed). At the moment a trip happens and the breaker position changes from closed to open, the sending of the GOOSE message indicating the position of the breaker suddenly becomes spontaneous and begins a rapid firing of messages between which the interval (starts at Tmin) doubles until it reaches the set value for cyclic intervals (Tmax). The following are descriptions of various settings for GOOSE messages.

TimeMin=Tmin. When a substation event occurs the transmission rate of the new GOOSE messages increases to statistically assure that the message is delivered. This rapid fire mode called Tmin has a range of 1 to 20ms.

TimeMax=TMax. Under normal conditions, all GOOSE messages are cyclically retransmitted with a predefined time called Tmax. The normal range for Tmax is 100-2000 ms.

TimeTAL=TTime Allowed to Live. If a non-sequential message character is received, the GOOSE message receiver or subscriber will wait a predefined time before it invalidates the signal. This waiting time is commonly defined as 1.5 times Tmax.

GOOSE Status Number. The numerical value that increases by one each time a trigger event occurs.

GOOSE Sequence Number. The numerical value that increases by one each time there is a GOOSE message.

In summary, the functionality that GOOSE messages were designed to cover includes high-speed transmission of essential data to and from devices as multicast and not just as point-to-point messages. Multiple devices will be subscribing to GOOSE messages from multiple generator IEDs, as an example. Therefore, it is imperative that these messages are fast, supervised, and given redundant communications paths.

G. PMS Controllers

The PMS Controller is an open, modularly-designed numerical system for energy automation. The specific functions are combined with those of a programmable logic controller system and include the communication possibilities of today's IT-world. The controller has been designed specifically for the requirements of energy and power automation systems and is easily scalable due to its distributed architecture. It provides a system solution for an efficient execution of all tasks required in a substation and can also be used as a communication gateway.

The PMS Controller is designed to perform the following functions:

- Telecommunications
- Monitoring
- Automation
- Local and remote control
- Control of switchgear interlocking and switching sequences
- Connection of IEDs
- Editing and displaying of process information in the station using the HMI Monitors

- Sending archiving and logging of operation and disturbance data (fault records) to HMI Servers

H. Power Based Load Shedding

As previously mentioned, one of the major functionalities of the PMS is the power based load shedding. This is a predictive function that will shed some pre-defined loads in case of generation loss, to avoid the overloading of the remaining generation. The functionality is divided between the PMS Controllers and the Protection and Control IEDs. In this solution, a fast reaction and subsequent commands to shed the correct amount of load can be achieved. Fig. 8 provides an illustration of the connection between the IEDs and PMS Controllers and associated signals.

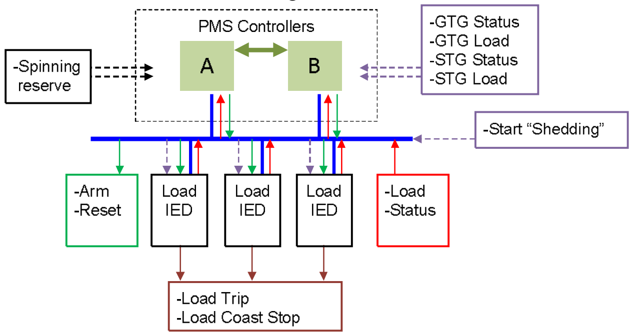

Fig. 8 Components for Load Shedding

The PMS Controller receives all data from the load relays and the turbine generators controllers and relays and calculates in a cyclic processing the worst case scenarios of generation loss. After that, it arms the necessary amount of loads to be shed. This information is sent to the relays according to a predefined load priority table. The relays are ready to shed in case of a disturbance. This function is only active if more than one generator is online. Note that the disturbance could be a generator trip or shutdown, or any other condition that is considered harmful for the generator.

The protection and control device associated with each generator is responsible for sending the GOOSE message indicating the generator is being tripped or shut down. This is a multicast message that is received by all the protection and control devices subscribing to that message. Once the load relay receives the GOOSE message from a generator relay that a trip or shutdown is imminent, it initiates an internal processing of the message to determine if it will trip its respective load using the fastest processing level of its internal PLC. This determination is based on which contingency message was received and whether the load is armed for that contingency. If yes, then the relay closes its output contact to trip the associated circuit breaker or motor control contactor.

I. Start Inhibit

Another important primary, automated function of the PMS which utilizes IEC 61850 GOOSE messages is the start inhibit of medium voltage motors. This function will prevent some pre-defined motors to start, to avoid the overloading of the remaining generation. The PMS Controller will be continuously monitoring the spinning reserve of the online generation; also a predefined list of loads will be programmed in the system, with the individual rating. This calculation is considering that only one motor will be started at the time, and it will compare the remaining generation capacity of the system to the offline equipment rating, one by one. In case that the motor rating is bigger than the total spinning reserve the binary output contact will close for the specific motor(s) to inhibit starting.

J. Connection to Distributed Control System (DCS)

There is a communications connection between the PMS and DCS using Modbus TCP protocol. This communication link will be used to share data between the systems. For security, router/firewalls will be installed between the systems. There will also be hardwired indications used between DCS and PMS systems instead of communications for the start inhibit functionality.

K. Intelligent Electronic Devices (IED)

The interface with the medium voltage switchgear and MCCs (13.8kV and 4.16kV) along with the 480V switchgear is through IEDs that support IEC 61850 MMS and GOOSE. Those devices will be responsible for providing the PMS with information, including position, status, alarms, measurements, etc. and receive commands, including open, close, rack connect, test, disconnect, arm, shed, etc.

Each switchgear lineup has a pair of switches that will be integrated into the overall PMS network through a ring topology. This network is designed to run the RSTP protocol and the connections between those backbone switches to be on 1Gbps fiber optic channels. Small sub-rings are implemented to speed up the reconfiguration time in case of a backbone switch failure. This interface with the relays will run the MMS and GOOSE messages, and that requires a safe and reliable network structure.

V. PMS TESTING

Considering the complexity of the PMS and all of the functionality it delivers, extensive testing is needed to prove the systems is functioning as designed. During the configuration phase of the project, tests are being done to ensure various modules are operating as desired. The main testing starts following configuration of the system and IEDs. A primary project goal is to test as much as possible in the factory thus minimizing testing that needs to be done during onshore and offshore commissioning. Being able to carry out extensive testing in the factory was advantageous to the project.

The system testing procedure is divided into four groups: the system startup behavior; the operation functional test; the redundancy test; and testing of the system functionality.

The System Startup Behavior was tested for the complete PMS system, including the PMS Controllers, HMI Servers and typical IEDs. All systems run on PC platforms and have been setup to start certain applications on system startup. These were verified for correct functionality.

The Operation Functional Test covered the specific functionality of the configured HMI screens. It took a comprehensive systematic approach for testing the system from an operator's standpoint. HMI screens were tested for correct functionality, look and feel, representation, control rights, network security, and other linked services.

The Redundancy Test evaluated different levels of redundancy across the PMS system. This testing involved a hierarchical approach analyzing redundancy concepts starting from the process level up to the HMI level.

The System Functionality Test covered different system features, devices and communication interfaces across the PMS system, as well as checked the automated logic for the load shedding and start inhibit. For this test, the actual switchgear was available and included the IEDs associated with loads and generators. Part of this factory testing included several automated tests using the actual devices, switchgear, and test sets to provide secondary injections of Current Transformer (CT) and Voltage Transformer (VT) values. First, modeling software was used to derive the different values of voltage and current that would need to be simulated for the various contingencies to prove all contingencies related to load shedding. In addition to the automated load shedding tests, testing of routine operations such as opening and closing of breakers and remote racking were also tested for the entire switchgear line-up. Load inhibit functionality was also tested at this time.

VI. CONCLUSIONS

The PMS for this FPS Platform is an integrated system and utilizes many of the features and benefits of applying the IEC 61850 Standard in a power automation application. Because the reliability of the electrical power is of the utmost importance to safely operate the platform, measures have to be considered in the design to maximize this reliability. These measures include redundancy, speed, selectivity, and security. *Redundancy* is employed to ensure that no one failure can compromise the system operation. Fast *Speeds* are needed to achieve fast power based load shedding to quickly react to a sudden trip of a generating unit by initiating commands to shut off lower priority loads to maintain the stability of the electrical grid during an abnormal condition. *Selectivity* ensures that only the maximum amount of load is shed considering the current power profile and spinning reserve of the remaining online generating units. Finally, *Security* of the system is crucial as the PMS has control over the electrical system and measures have to be in place to ensure cyber security requirements are met and that the system can be operated safely.

VII. REFERENCES

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VIII. VITAE

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