Renewable Offshore Power for Islanded Oil & Gas Platforms Theoretical case study from Modeling, Simulation to Operations

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Abstract - Offshore oil & gas drilling platforms are typically isolated systems with onsite generation primarily consisting of gas turbines. These turbines have an energy conversion efficiency comparable to renewable energy (wind and solar) conversion technology, around 30%, versus onshore gas turbines with efficiency greater than 50%. Climate change is the key driver to revisit CO_2 and NO_X emissions from these gas turbines near pristine ocean waters and replace them with clean energy as the primary generation source. Potential benefits of supplementing fossil fuel based power generation with renewable energy is explored in this theoretical case study where a power generation controller algorithm is developed such that renewable energy is given higher priority and energy 'gaps/dips' are filled in by fossil fuel. Further optimization of energy usage and higher wind energy penetration is analyzed with the use of energy storage device.

Index Terms — Wind energy, offshore electrical systems, time domain simulation, load shedding, time series analysis, solar energy, wave energy, DC power distribution, photovoltaic renewable energy, generation management, microgrid control, minigrid control, energy storage.

I. INTRODUCTION

Industry forces and digital innovations are reshaping the oil and gas industry. Several powerful supply and demand forces including greater penetration of renewables, environmental regulations and emergence of smart grid systems are affecting the broader value chain especially upstream oil and gas exploration. Connecting offshore wind and solar plants with oil and gas installations is a logical progression with two possible approaches. (1) Platforms closer to onshore renewable energy interconnected via HVDC technology has a potential to cut 600,000t of CO_2 emissions and 2,500t of NO_x per year as in the case of Troll C and Sleipner field centre (2) Deep water platforms can be interconnected with dedicated offshore renewable energy production that may or may not be grid connected. Regardless of the connection approach, there are a number of advantages and challenges of including renewable energy mix in the generation portfolio and will be discussed in subsequent sections.

While early examples of offshore wind turbines were anchored to fixed foundations, which limited their use to relatively shallow water, most offshore oil fields are found in deeper water. The first operational deep water large-capacity floating wind turbine, the 2.3 MW HyWind, only became operational in the North Sea off Norway in late 2009. In 2017, Statoil commissioned Hywind Scotland, a 30 MW floating wind farm 18 miles (29 km) off Peterhead using 5 Hywind turbines. This wind farm includes a 1 MWh lithium-ion battery system (called Batwind) located in a substation onshore. [1]

The next logical progression a number of offshore oil and gas exploration facilities interconnected and their resources pooled to form a mini-grid environment (decentralized system in the order of MW of power generation or consumption). Eliminating onshore grid connection will reduce transmission costs and availability of renewable energy will reduce emissions from traditional gas turbine generators installed on the platforms. Sustainability and operational reliability strategies need to be assessed and appropriately deployed for inadvertent conditions such loss of generation, generation optimization, load shedding, etc.

This is the motivation for the current study, which investigates various issues related to the platform/renewable/storage alternatives through a case study analysis. The goal of the study is to address control and stability issues in broad terms.

II. CHALLENGES OF RENEWABLE INTEGRATION

Integration concepts offer significant advantages but present also critical technical challenges.

1. An offshore facility cannot entirely rely on renewable energy especially wind as the wind power generation is intermittent by nature. This implies that backup generation and/or some flexibility on load shedding of noncritical loads are essential.
2. If offshore fields and renewable energy power plants are planned to be interconnected, coordination has to be initiated in an early stage of the development process. For example, control issues and solutions for fast power balancing must be resolved as it will play a major role in stability of the system.
3. The wind power plant must not affect negatively operation of the offshore field and vice versa. This has particular importance concerning stability issues, design of control and protection systems.
4. Regulatory frameworks of such interconnected offshore mini-grids are not in place yet.

Isolated power systems in offshore installations are generally sensitive to disturbances, as they cannot rely on the onshore grid for maintaining the power, voltage and frequency balances. Comprehensive stationary, dynamic and transient analyses are crucial in order to identify possible issues that may harm or interrupt system operation. Furthermore, adding renewable power to the system introduces additional complexity to the system and increases the importance of detailed power system studies. [2]

III. POWER SYSTEM MODELING

Frequency support has been studied extensively for renewable power plants connected to the onshore grid, and very few references consider or investigate detailed simulation and operations of isolated or islanded systems. The following section presents case study setup that describes the power system modeling required to setup various simulation cases. Dynamic stability simulations shall be carried out to investigate the system response and to quantify the potential benefits of utilizing state-of-the-art controller that will be tested in simulation environment and the process of deploying it into real-time operations.

The offshore facility under investigation should be able to withstand rejection of large loads or loss of generation without affecting the operation of critical loads and other generating units in the system. The following sub-sections describe the input data utilized for this case study.

A. Electrical System Topology

There are many configurations for connecting the collector system and the collector system to the platform load. The basic consideration involves striking the optimum balance between reliability and the cost for the collector network and platform connection. A general overview of these configurations is shown in Fig. 1. The two most popular configurations are off course Star or Ring systems.

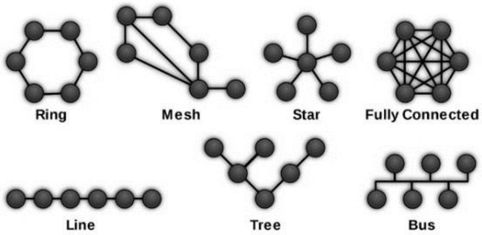

Fig. 1 – Power system network topologies for collector and offshore load [4]

1) *Radial or Star Topology*: The simplest arrangement for the collector system and the platform is the radial design in which a group of turbines or platforms are connected to a lateral feeder string. This arrangement enables the use of a simple protection concept, easier control possibility, and the shortest possible cable run. [3]

2) *Ring or Loop Topology*: In the ring bus configuration, circuit breakers are connected to form a ring, with isolators on both sides of each breaker. Circuits terminate between the breakers and each circuit is fed from both sides. Any of the circuit breakers can be opened and isolated for maintenance without interruption of service. The main disadvantage of the ring bus system is that if a fault was to occur, the ring is split which could result into two isolated sections. Each of these two sections may not have the proper combination of source and load circuits. This can be somewhat avoided by connecting the source and load circuits side by side. Ring bus schemes can be expanded to accommodate additional circuits, but it's generally not suited for more than six.

B. AC & DC Electrical System

Since five platforms were planned and renewable generation sized accordingly, the electrical system model chosen, is a ring bus system for operational reliability as shown in Fig. 2. The power system model consists of offshore wind, solar connected to a common collector bus. Platform A is represented with the full model of the platform power system network with two 8 MW gas turbines that are operating primarily as spinning reserve with less than 1 MW output. The other platforms are represented with an equivalent power system model with only the large motors modeled explicitly and all other motor loads presented as lumped motors.

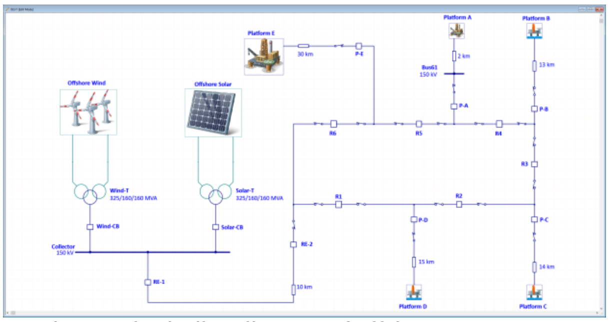

Fig. 2 - Single-line diagram of offshore system

The decision on whether to opt for AC or DC supply from shore is often dictated by distance. AC cables have a certain capacitance per unit of length. The applied voltage generates so called reactive current due to the capacitance. If the cable is very long, eventually the generated reactive current will equal the rated current of the cable, and at that point no rating is left for useful active current.

Logically, the cable length must be kept significantly shorter than that limit. However, by skillful use of reactive compensation and/or reduced operating cable voltage against nominal voltage, one can achieve longer AC cable distances. With DC voltage the reactive current phenomena does not apply. DC distribution system reduces fuel consumption and the weight of the electrical system. This is mainly because the DC grid allows the diesel engines to run at variable speed for top fuel efficiency at each load level. Fuel consumption is expected to be cut up to 20% and 30% less space required for electric –power equipment. Big and expensive components like transformers are not needed. DC system is able to host cheaper conductors or reduced losses since the current a given conductor can carry is 1.22 times larger for DC than AC. The main advantage is its possible to easily integrate modern large scale battery systems. The batteries can act as sole energy source for the low load conditions, handle peak loads without starting standby generators and act as energy buffer for optimized energy production. A disadvantage of the DC grid is the large currents during fault. In an AC grid, the circuit can much easier be disconnected because of the currents zero-crossing.

C. Gas Turbine Model

The gas turbine modeled is a single shaft turbine. A speed governor is the main means of control on the gas turbine. Fig. 3 represents a simplified dynamic governor model for the offshore oil platform operating in droop mode.

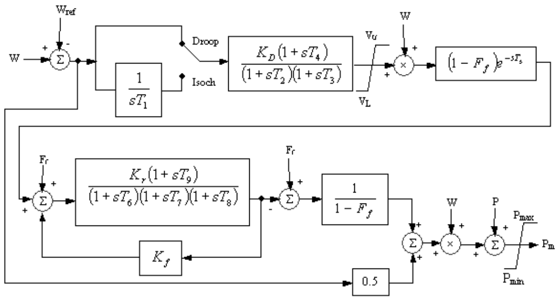

Fig. 3 – Governor model for gas turbine

D. *Wind Energy Conversion System (WECS)*

A pitch regulated variable speed directly-driven PMSG wind turbine generation system offers key maintenance and reliability incentives in the context of offshore wind power. Neither a gear box nor slip-rings are required, both of which require regular maintenance and are probable causes of mechanical failure. Besides reducing the likelihood of failure, it also implies that fewer spare parts are needed over the lifetime of the wind turbine. The basic construction of the wind turbine is shown in Fig. 4.

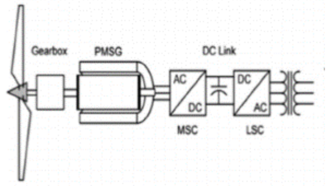

Fig. 4 – WECS PMSG technology

E. *Solar Energy Conversion System (SECS)*

The solar energy conversion system is modeled using the P-V and I-V characteristics as shown in Fig. 5. Photovoltaic (PV) characteristics including P-V and I-V curves are available directly from the manufacturer or can be estimated by specifying the maximum peak power voltage (V_{mpp}), maximum peak power current (I_{mpp}), open circuit voltage (V_{oc}) and short circuit current (I_{sc}).

When modeling the solar planes, it is important to consider the effect of performance coefficients (α, β, γ) that define ranges in irradiance and cell temperature to automatically calculate the expected power output from the photovoltaic array.

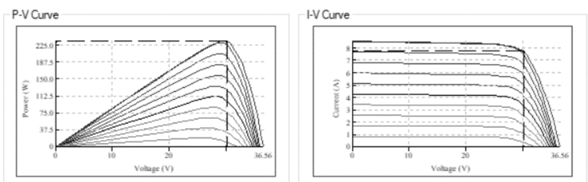

Fig. 5 – Photovoltaic modeling using P-V and I-V curve

In the PV system, we assume that a maximum power point tracker will be used. The PV converter dynamic model was considered as shown in Fig. 6. The inverter includes terminal bus voltage and base power setpoint to determine the required real and reactive power control.

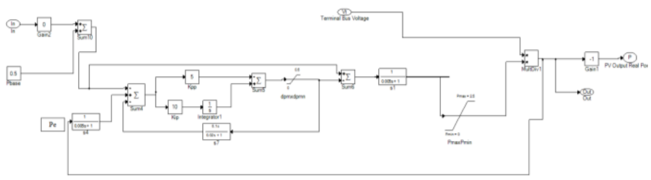

Fig. 6 – Full converter PV inverter (real power only)

F. *Energy Storage System (ESS)*

In recent years, several forms of energy storage are studied intensely. These include electrochemical battery, supercapacitor, compressed air energy storage, superconducting magnetic energy storage, and flywheel energy storage. Lithium ion (Li-ion) batteries are chosen in this paper. The battery or energy storage system is modeled using the frequency versus power characteristics as shown in a simplified energy storage control system (Fig. 7). The ESS is modeled using frequency and state of charge (SOC) as input points to determine the required power input or output to balance frequency in the system.

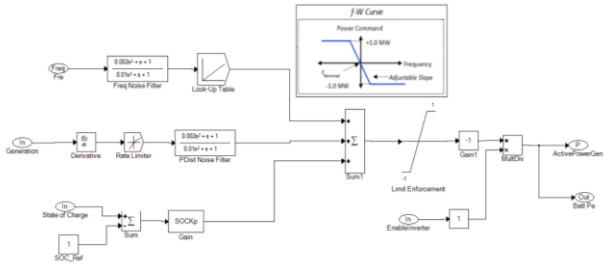

Fig. 7 – Energy storage system control system

The charge and discharge equations are shown in (1). $P_t^{E,d}$ is the power discharged by the ESS during a given time period *t*. $P_t^{E,c}$ is the ESS charging power. $C(t)$ is the energy stored in the ESS at time *t*. The duration of time is given as Δt. η_d and η_c are charge and discharge efficiency.

The cost of ESS includes the one-time ESS cost and the annual maintenance cost. The maintenance cost per year is also a variable cost proportional to the size of BESS. If BESS's life time is *n* years and the maintenance cost is MC €/kWh per year, then the total cost of BESS is $CE(FC + n * MC)$ where CE is the size of BESS.

The ESS will play a crucial role in the simulation for frequency support and low voltage ride through in cases of renewable intermittence and/or any other sudden, large change such as loss of generation or load.

IV. SIMULATION & ANALYSIS

A. *Unified AC & DC Time Series Power Flow Simulation*

Commercial circuit analysis tools have historically provided the capability to analyze the power system at specific snapshots in time. More recently, simulation platforms have the capability to perform time series or quasi-static time series simulations. Due to the renewable energy output being highly variable and the potential interaction with control systems, using snapshot based analysis may not be adequately analyzed. Further due to the possibility of including AC and DC mixed system the steady-state or quasi-static time series analysis should be able to solve AC and DC network simultaneously as opposed to iteratively.

In upstream E&P facilities, operators can create DC microgrids, with solid-state generators and solar panels, to power an entire facility. For AC motors, they can use DC-to-AC converters or replace them with DC ones as shown in Fig. 8.

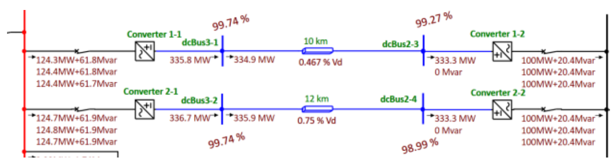

Fig. 8 – AC & DC unified load flow interconnected system

A DC microgrid can eliminate wasteful AC-to-DC conversions that would otherwise be required for use in most automation applications. These applications typically use solid-state digital components like programmable logic controllers (PLCs) that run on 24V DC power. DC distribution system also gives flexibility of placement of the electrical equipment allowing for significantly more cargo space and a more functional vessel layout.

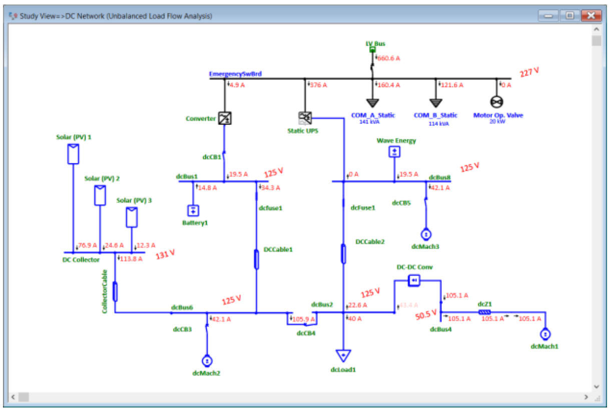

Fig. 9 – Unified AC & DC load flow for a DC Microgrid

Being a theoretical case study, synthetic data was generated to show variability of renewable energy including wind and solar energy. This variability was added to respective elements in order to solve power flow as function of time in one-second resolution for 24 hour period. The wind power data utilized for all turbines was assumed to be the same and shown in Fig. 10.

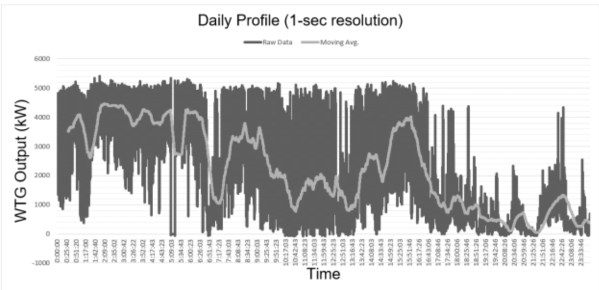

Fig. 10 – Wind turbine generator variability

The solar output was generated based on the P-V characteristics and solar irradiance (W/m^2). The solar out from each set of PV arrays was also varied over the same 24 hour time period. A PV array is a set of PV panels connected in series and parallel such that the required rated voltage and power is available when connected to rated load.

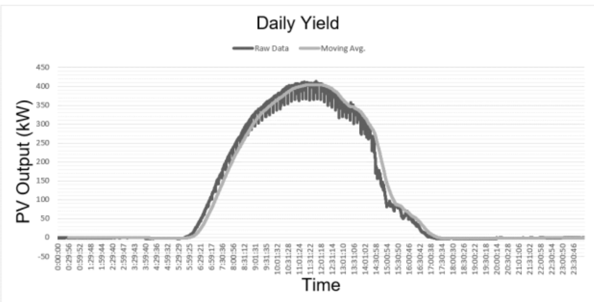

Fig. 11 – Solar output variability

The load is kept constant during this time period in order to eliminate one of the variables from the system simulation and maintain focus to the effect of renewable energy variability on system voltage and frequency. A snapshot load flow considering AC and DC mixed simulation using rated conditions is shown in Fig. 12.

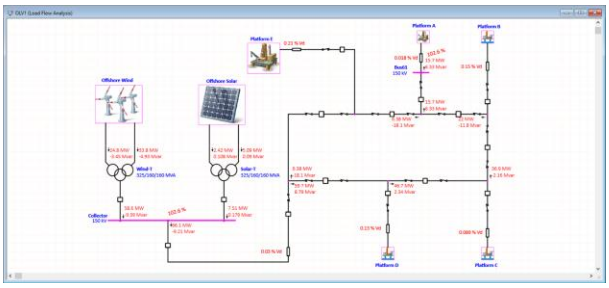

Fig. 12 – Steady-state load flow at rated condition

Time series load flow simulations are carried out using the generation profiles specified in Fig. 10 and Fig. 11 and the gas turbine generator governor is assumed to be in isochronous mode. Based on this simulation it is observed that the generator in isochronous mode is able to compensate for the change in wind and solar variability by providing filling in the gaps of real and reactive power and the energy production from the gas turbines.

Considering the same system, the generators are now switched to droop mode and the generators are treated as spinning reserve by changing the power setpoint to 15% of rated MW value such as to not trip the under-power relay. Based on the simulation it is observed that the system voltage and real power demands are not able to be supplied by the renewable energy sources alone due to their variability. It is noted in order to minimize cost of the gas turbine generators and operating them in a spinning reserve mode will require introduction of energy storage device to provide the energy damping or inertia in the system. The ESS will charge or discharge based on ESS control in order to meet the power system demand.

With the introduction of the ESS it is noted that the system voltage and power requirement variations are damped and the ESS is able to fill in the power and voltage gaps. Note that the slope of the power vs frequency curve for the ESS must be calculated and tuned for each system such that there is sufficient inertia and damping. Too little inertia due to fast adjustment or compensation from the ESS can result in large number of oscillations, which is not ideal for other rotating equipment in the system. Excessive damping or inertia can result in the compensation being slow acting and unable to correct quick variations in the system with possible loss of system stability.

For a smart power system, renewable energy resources are supposed to supply electric power to the grid as much as they could. This means that renewable energy resources are kept on all the time if conditions permit. When the power supplied by renewable energy resources is more than the load in the system, it will be used to charge up the BESS. Then the minimum energy charged to BESS is defined as

$$E_{charge}^{min} = \int_0^T \left(P_{sys}^{t,min} - P_{load}^{t}\right)\delta t$$

where $P_{sys}^{t,min}$ represents the minimum power supplied by the renewable energy sources in the power system. The minimum value of ESS rating can be obtained in

$$E_{ESS}^{min} = \max\left(\frac{E_{dis}^{min}}{\eta_d}, \eta_c E_{charge}^{min}\right)$$

where η_d and η_c are the discharge efficiency and charge efficiency respectively. E_{dis}^{min} and E_{charge}^{min} are the minimum discharge energy and charge energy of the battery bank.

B. Dynamic Stability Simulation

Though time series power flow can be used to determine the economics and size components based on steady-state daily operation, it is not the optimal simulation analysis for simulating transient behavior of the system. Power system dynamics and controls are taken into account when performing dynamic studies though the timeframe for these studies is not for the entire daily period. For the system under consideration the following scenarios are consider:

1) Loss of 1x 1.5 MW of PV system
2) Loss of 2x 1.5 MW of PV system
3) Loss of 1x 6 MW wind turbine
4) Loss of 2x 6 MW wind turbine

In all cases it was observed that though the frequency and voltage are stabilized by the remaining energy sources, ESS and gas turbines, the new setpoint of the gas turbine generators is not minimum MW value. Therefore, a secondary or microgrid controller is investigated that utilizes load and generation input to determine the optimal dispatch of generation post contingency and can also improve on steady-state operations.

V. SECONDARY CONTROL SYSTEM

A secondary control system also known as a microgrid controller is designed around a hybrid centralized autonomous topology. The control system is constructed using logical transfer functions and scripted logic combined with the electrical model of the power system network.

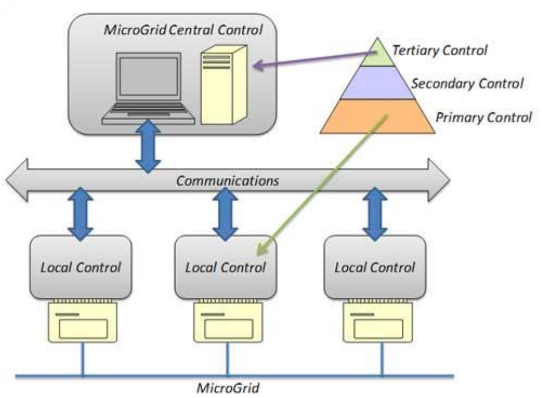

Fig. 13 – Microgrid controller hierarchical controls

The microgrid control coordinates the power system assets for optimal and stable operation in autonomous islanded mode of operation. The control system is designed with hierarchical levels of control as shown in Fig. 13.

(1) Primary control - Based exclusively on local measurements, output control, and power sharing (and balance control) traditionally done using local generator controls or substation relaying. Microgrid control system does not directly affect primary control but adjusts the dispatch for primary control.
(2) Secondary control – The controller dispatches assets for islanded operation, reliability economy and stability.
(3) Tertiary control - Sets long-term and “optimal” set points depending on the host grid’s requirements.

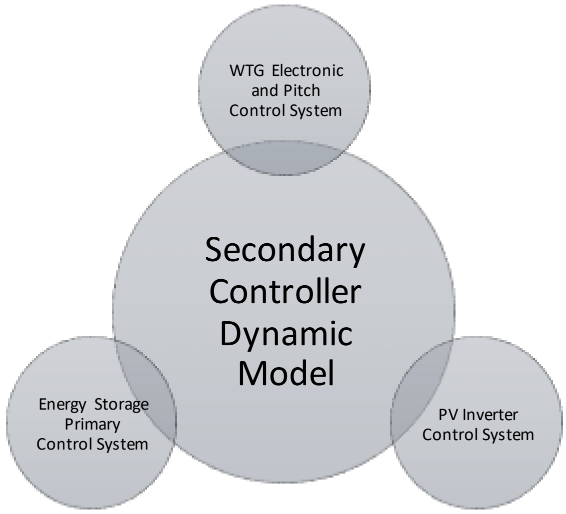

Fig. 14 – Microgrid controller interaction with primary control systems

The control system in offline mode or simulation mode performs the following key functions based on the time horizons of hierarchical levels of control:

1) Communicates and coordinates resources via generation controllers, storage controllers, load controllers and breaker controllers as shown in Fig. 14.
2) Executes systems analysis to determine optimal and stable control settings
3) Accepts real-time data for display and analysis

The secondary control functions of the microgrid control for simulation include:

1. Automatic Generation Control
2. Economic Dispatch
3. Spinning Reserve Management
4. Unit Commitment
5. Fast Load Shedding
6. Demand Management (optional weather forecast input)

A sample secondary controller frequency control logic or automatic generation control for more than one type of distributed generation is shown in Fig. 15.

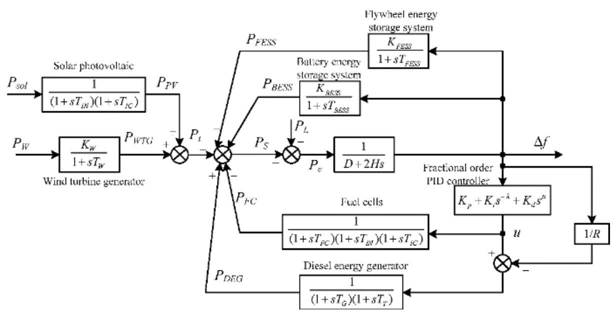

Fig. 15 – Sample frequency control logic

The microgrid control logic is incorporated into the system for PV, ESS and wind turbine sources and the time series and dynamic stability cases are rerun again. The dynamic stability simulation results with the microgrid controller showed stable response with wind gust and solar irradiance variations with a number of trial and errors made to tune the microgrid controller dynamic response.

VI. OPERATION CONTROL

A. Generation Management

Upon verification, validation and tuning of the response the microgrid secondary control logic can be downloaded into a Windows or LINUX based hardware controller. The hardware controller with the tested logic is then connected to the field measurements directly using ModBus, IEC 104 or IEC 61850 protocols. The electrical design model in the engineering workstation also communicates with the hardware controller and has connectivity to real-time data. The real-time power system digital or virtual model including topology processing and engineering properties is then used to continually determine optimal system settings based on real-time system measurements as shown in the Fig. 16.

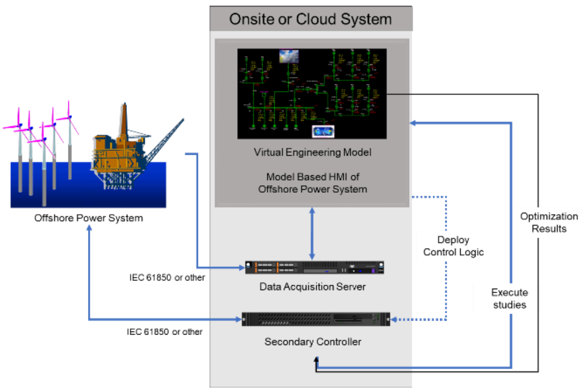

Fig. 16 – Microgrid controller setup for unmanned operation

The microgrid controller continuously utilizes local logic for secondary control of frequency, power and voltage based on a 5 to 10 sec. calculation cycle and makes decisions for generation dispatch based on system security and reliability requirements. Every 10 to 15 minutes, the controller communicates with the virtual model based onsite in the data acquisition (DA) server and commands the DA server to provide optimal settings from economic dispatch such that generation dispatch is based on economy while maintaining security constraints.

B. Load Shedding

A state-of-the-art load shedding system uses real-time system-wide data acquisition that continually updates a computer based real-time system model. This system produces the optimum solution for system preservation by shedding only the necessary amount of load and is called Intelligent Load Shedding (ILS). The microgrid controller hosts the load shedding knowledge base and computation engine. The load shedding module interfaces with the virtual model based real-time power system monitoring and simulation system that continuously acquires real-time system data. Based on ILS calculations, the microgrid controller dynamically updates the load shedding tables and as needed propagate the information to the distributed PLCs. Upon detection of any disturbance by the local relays or PLCs, load shedding is initiated. The load circuit breakers will be tripped based on the pre-generated optimal load shedding tables.

VII. CONCLUSIONS

This paper describes the typical process of modeling offshore facilities with renewable energy connections. Simulations for 24 hour period were carried out using time varying generation of various renewable sources followed by contingency based dynamic analysis. Though the system returns to stable condition in some cases, there is a need for a secondary control to harvest the maximum possible power while maintaining system security and minimizing gas turbine operation. Minimizing gas turbine operation will not only assist in lower economy of operation but also reduce the overall carbon footprint of the facility.

Next, a microgrid control logic was developed and utilized in the simulations to demonstrate frequency and voltage support. Advanced optimize settings are obtained from the virtual model used for offline design and simulation. Finally, the microgrid control logic that has been validated using simulations can be downloaded to industrial controllers and deployed onsite for unmanned operations with optional link to onshore engineering office using cloud based communications.

Therefore, a unified and integrated model approach from design to operation gives the flexibility from designing, analyzing, implementing, operating and maintaining the electrical system in a common environment. Any change made to the virtual model or logic can be tested in the offline or development environment and downloaded and deployed into the production system. This process though demonstrated for deep water offshore facility can be used with grid connected facilities and will be covered in a follow-up paper.

VIII. REFERENCES

Examples are given for pamphlets [1], transaction papers [2], standards [3], conference records [4], books [5], and National Electrical Code [6].

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IX. VITA

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