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Energy Management Strategy Designed for Offshore Oil Rig with Offshore Wind

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Abstract—Dynamic load demand affects output power to load, which may fail to meet IEC standards 61892-1 for offshore oil and gas installation. High power consumption in offshore oil rig requires both large gas and wind turbine generation that are unable to react quickly to enhance transient stability. Hence, an energy management system (EMS) is designed with a battery energy storage system (BESS) to replace partial output power from the gas turbine onboard the oil rig for optimal transient response. Our designed EMS differs from the current state of art by not using a low-pass filter so as to improve rapid response from BESS, while enhancing output power quality to load. Our EMS is validated with maximum transient voltage and frequency deviations in simulation to illustrate improved transient stability results.

Index Terms—battery energy storage system, offshore renewable energy system, oil and gas platforms, transient stability

I. INTRODUCTION

Offshore oil rig (OOR) requires heavy power consumption, which reaches as high as hundreds of Megawatts in power demand, contributing to high carbon emission [1]. Over the years, OOR installation has been increasing gradually [2] due to new discovery of oil and gas reservoirs, resulting in more carbon emission in the offshore industry. Hence, carbon emission reduction has always been the focus in the marine and offshore industry ever since global temperature has risen, which results in extreme weather conditions to mankind. However, even though there have been international policy and regulations in place for carbon emission reduction, more carbon emission has been generated due to the increasing installation of OOR to meet global energy demand.

In the developments of offshore oil and gas platforms, the adoption of IEC standards 61892-1 is used to ensure that voltage and frequency deviation are within ranges for power stability during oil and gas production [3]. Dynamic load demand and stochastic wind affect output power to load and the transient stability of the system. These conditions commonly lead to large deviations in voltage and frequency, which fail to meet IEC standards 61892-1.

In the last decade, the development of high-voltage direct current (HVDC) transmission technology has been deployed to electrify OOR that could potentially reduce carbon emission from localisation onboard open-cycled gas turbine generation [4]. However, new oil and gas reservoirs are being discovered far away from the coast, the installation of HVDC transmission would be unfavourable due long subsea cabling required high Capital Expenditure (Capex). Conversely, the decline in the Capex on offshore floating wind turbines has led to great interest to integrate with OOR for green electrification. Since intermittency of wind power due to stochastic wind speed affects output wind power quality, wind turbine generation (WTG) is considered as a secondary power generation. This complements the gas turbine generation (GTG) on the OOR as the primary power generation. As such, the integration of OOR with offshore WTG will provide continuous carbon emission reduction during operation.

Dynamic load condition in OOR usually occurs either due to unbalanced load in living quarter [5] or in the event when flexible load requires more oil and gas production output by turning on additional water injection pumps system [6]. This affects transient stability in an islanded mode given that the main power generation onboard GTGs contribute to the total output power to the load. Notwithstanding twin GTGs that are sharing the load in OOR which can control frequency response due to dynamic load condition, there are time delays for GTGs to react in synchronisation mode [7].

In addition, the integration of OOR with a standalone offshore WTG introduces challenges in frequency response for dynamic load condition due to the intermittency of wind. This poses a technical challenge to address frequency stability in an islanded mode. Although there is a control strategy embedded in WTG to improve transient frequency response to mitigate large power oscillation due to dynamic load [8], the larger inertia in GTG and WTG hinder in power stability. In addition, the scenario of the WTG switching off in extreme wind conditions would result in a sudden power loss, which is inevitable and could trigger large output power oscillations to load and affect transient stability. Hence, a thorough investigation is vital to have an energy management strategy for fast response to meet maximum transient voltage and frequency deviations besides meeting international IEC standards 61892-1 in [3].

The technology of battery energy storage system (BESS) has been decreasing in cost swiftly over the years due to high demand in improving power stability [9]. This is a critical element in transient stability improvement, which has always been the main research focus in the integration of OOR and...
WTG that is introduced in [10], [11]. Since then, a similar application has been presented in [12]. With an increase in capacity of BESS, the system can perform significantly better in transient stability. However, this method does not work on OOR since there is space constraint to limit the sizing of BESS. The latest research study on a fixed BESS capacity embedded with energy management system (EMS) to improve transient stability on output power quality to load is carried out in [13]. This lays the foundation for our motivation to design a proposed EMS that has the ability to optimally improve transient stability due to dynamic load condition.

In this paper, an investigation will be carried out on the implementation of EMS for optimal transient stability in the event of dynamic load with realistic wind profile from the OOR. The dynamic load demand is a crucial issue that need to be addressed as it could potentially cause poor power quality, which results in higher oscillation in the transient stability of the system. Due to poor power quality, the system may fail the IEC standards 61892-1 as the voltage and frequency deviation may consist of higher surge and dip behaviours. Hence, there is a need to enhance the power quality based on the implementation of energy management strategy into the system. The transient stability test will be demonstrated using our proposed system embedded with EMS to compare with conventional system.

This paper is organised as follows. Section 2 will present the system overview in actual load sizing and describes the methodology on how our EMS works. Section 3 presents three test scenarios. Section 4 includes simulation results with discussion for all test scenarios. Lastly, Section 5 shows conclusions and future work.

II. SYSTEM OVERVIEW

A. System Architecture

In the system overview of both proposed and conventional system, each of power generation profile is shown in Table I. Following this, the detailed configuration of the conventional system and proposed system are shown in Fig. 1. GTG has a apparent power of 10 MW active power to 3-phase power grid in 11 kV voltage rating. The circuit breaker (CB) 3 is placed in between the GTG and the point of common coupling (PCC), which has a voltage rating of 11 kV. Lithium-ion BESS consists of battery bank, which has bi-directional power flowing through voltage source converter (VSC) as either a rectifier or inverter, and directly links to the step-up transformers before connecting to PCC. The CB 2 is placed in between the PCC and BESS while CB 1 is placed in between the PCC and WTG. The model of WTG is based on a floating 6 MW Siemens SWT-6.0-154 permanent magnet synchronous generator, which is connected to a step-up transformer. As the second GTG is replaced by a BESS which is installed onboard OOR, the WTG and the first set of GTG will share the load equally. Taking into consideration that offshore WTG is deployed at a hundred metres away from OOR, the loss of output power from the power transmission line can be neglected in this simulation study.

<table>
<thead>
<tr>
<th>No.</th>
<th>Power Generation</th>
<th>Power rating (kW)</th>
<th>Demand Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GTG</td>
<td>8000</td>
<td>Primary</td>
</tr>
<tr>
<td>2</td>
<td>WTG</td>
<td>6000</td>
<td>Secondary</td>
</tr>
<tr>
<td>3</td>
<td>BESS</td>
<td>2000</td>
<td>Secondary</td>
</tr>
</tbody>
</table>

Subsequently, the proposed system has an additional EMS designed in BESS with all other components, similar to the conventional system. In the proposed system, EMS will be connected to VSC, which is capable of controlling the amount of active and reactive power to inject into PCC. This control algorithm aims to achieve optimal output power quality either by discharging to PCC or by charging into BESS. This is demonstrated based on droop setting in BESS that is synchronising with the power generation of both GTG and WTG.

![Fig. 1. System architecture of proposed system.](image)

B. Lithium-ion Battery Energy Storage System

While energy density of energy storage is vital to system integration in OOR due to limited space available onboard, specific energy is worthwhile to be considered due to weight limitation in the building of structures for OOR. Considering the above, lithium-ion is selected as the energy storage device in our application and will be modelled.

In the BESS, there are electrical equipment that comprise of 2 MW of Lithium-ion batteries pack with 2 MW of bi-directional converter, which is connected to 2 kVA transformer for discharging/charging electrical power in the micro grid, as shown in Figure 2. BESS is designed in 40 ft container with built-in heating, ventilation, and air Conditioning (HVAC), similar to the industrial make [14]. While this figure depicts the schematic diagram, which represents electrical equipment in the simulation model, the electronic devices of BESS’s controllers that control the depth of discharge/charge to keep batteries pack in healthy state and improve its lifespan is being modelled for simulation.

C. Design of Energy Management System

Since BESS with EMS is designed to discharge and charge energy from and to the battery bank to improve output power quality at PCC, the schematic of EMS model is developed and designed in BESS as shown in Fig. 3. EMS is not necessary to develop in GTG and WTG as GTG has primary
frequency control to load and WTG must deliver output power fully to reduce optimal carbon footprint. BESS has its key advantage of battery bank which is assembled with Lithium-ion technology potentially improve cycle lifetime, performance and reduced overall cost and it fits in operation during transient period to provide short and fast response time [15]. The charge controller in BESS supports to maintain the state of charge (SOC) safely in the system by discharge/charge electric current from battery bank. PWM converter is identical to AC-DC converter which is a bi-directional type, act either as an inverter to regulate output power to PCC or as a rectifier to regulate excess output power to BESS.

On the other hand, there is an advantage of forecasting wind power to charge BESS effectively to improve its life cycle since the weather forecast monitoring system tailored in WTG has the functionality of hourly wind speed forecast stated in [16], to provide for the load variation in demand. This is comparable in [13] to have a feedforward dynamic control limit. Conversely, our EMS is a standalone system which does not depend on weather forecast to forecast load demand to schedule for BESS charge/discharge. Our proposed system also differs to the current state of art as it does not make use of a low-pass filter, which introduces delay, potentially affecting the quick response required.

The detailed block diagram of the current controller is shown in Fig. 4 where $I_q^{\text{ref}}$ and $I_q^{\text{Dev}}$ are generated from the frequency and voltage controllers. There is similarity in term of the design concept to integrate BESS to the droop control in micro grid which can be found in [12]. The other $I_d^{\text{ref}}$ and $I_q^{\text{ref}}$ are the signals of nominal power from PCC, which are added into current controller to assist in regulating

![Fig. 2. Schematic diagram of BESS modelled in simulation.](image)

![Fig. 3. Schematic of EMS.](image)
optimal output power quality control to meet load demand. The current controller compares all of the signals to offset the feedback of the measured current $I_{d-BESS}$ and $I_{q-BESS}$ from the 3-phase distribution lines that is closest to the BESS. Next, the output signals from current controller has an anti-windup limiter to prevent a wind-up condition. This sequence generates $P_d$ and $P_q$ as the optimal output power, which is required on PCC. As such, the resulting controller output is used to regulate the BESS active and reactive current and power, which supports the frequency and voltage at PCC.

![Current controller model](image)

Fig. 4. Current controller model.

In the frequency/voltage controller, the functionality of a PI controller has an identical model described in [17] with anti-windup to prevent undesirable oscillation in a given nonlinear system with BESS that contributes to stability with droop setting in GTG. The equations of the control signals $I_{d-Dev}$ and $I_{q-Dev}$ in frequency/voltage controller are shown as follows:

$$I_{d-Dev} = K_p(f_{ref} - f_{PCC}) + K_i/T_i \int_0^t (f_{ref} - f_{PCC}) dx Y_{max},$$  

(1)

$$I_{q-Dev} = K_p(U_{ref} - U_{PCC}) + K_i/T_i \int_0^t (U_{ref} - U_{PCC}) dx Y_{max},$$  

(2)

where $K_p$ is proportional gain in PI controller, $f_{ref}$ is the reference frequency value [p.u.] at PCC, $f_{PCC}$ is the measured frequency deviation value at PCC, $U_{ref}$ is the reference voltage value at PCC, $U_{PCC}$ is the measured voltage deviation value at PCC, $K_i/T_i$ is integral gain in PI controller and $Y_{max}$ and $Y_{min}$ are the maximum and minimum values in the anti-windup limiter. As shown in Fig. 4, $I_{d-Dev}$ and $I_{q-Dev}$ are generated and passed through current controller. The equations of feed forward controls in term of frequency, $f_{ff}$ and voltage, $U_{ff}$ in current controller can be defined as:

$$f_{ff} = K_p(I_{d-ref} + I_{d-Dev}) + K_i/T_i \int_0^t ([I_{d-ref} + I_{d-Dev}] dx Y_{max}),$$  

(3)

$$U_{ff} = K_p(I_{q-ref} + I_{q-Dev}) + K_i/T_i \int_0^t ([I_{q-ref} + I_{q-Dev}] dx Y_{max}),$$  

(4)

where $I_{d-ref}$ and $I_{q-ref}$ are the reference current control signals from PCC.

Since EMS comprises of voltage and frequency deviation from PCC to generate control signals, $I_{d-Dev}$ and $I_{q-Dev}$, to pass through current controller either to discharge or to charge power from BESS, the transfer function of the designed EMS embedded in BESS is presented as follows.

$$I_{d}(s) = \Delta F(s)[K_p(s) + K_i/s]$$  

(5)

$$I_{q}(s) = \Delta U(s)[K_p(s) + K_i/s]$$  

(6)

where $I_{d}(s)$ and $I_{q}(s)$ are the output current of d-axis (p.u) and q-axis (p.u) within inner loop of VSC, $\Delta F$ is the output transient voltage deviation (p.u), $\Delta U$ is the transient voltage deviation (p.u), $K_p$ is the proportional gain and $K_i$ is the integral gain (p.u) in the PI controller.

III. Test Scenario

The simulation in the next section will investigate the transient stability of both the proposed and conventional system that is based on three test scenarios, as shown in Table II. Event 1 is in the normal condition when both GTG and WTG are turned on with a fixed load. Subsequently, Event 2 describes a dynamic load situation with flexible load and BESS turned on. Event 3 considers the scenario when the flexible loads are removed and the BESS is still connected. While the power rating of individual power generation profile is the same for both proposed system and conventional system, fixed load and flexible load each will consume output power in 0.6 p.u. and 1 p.u. respectively.

Recent article in [13] creates test scenarios using system architecture comprising of EMS integrated with BESS, offshore WTG and OOR to enhance transient stability. This is the current state of art to show that EMS can improve the output power in the event of dynamic load situation. Based on this example, similar test scenarios have been created with a dynamic load condition to test our designed EMS and study the transient stability improvement in the system. While duplicate test scenarios are in place, the load demand is sized accordingly to recent article in [13]. For a fair comparison between our designed EMS and the current state of art on the output power quality to load, the results will be based on both maximum transient voltage and frequency deviation as shown in Table III in Section 4.

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
<th>Load Test</th>
<th>Time Starts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Disconnected BESS</td>
<td>Fixed</td>
<td>0 s</td>
</tr>
<tr>
<td>2</td>
<td>BESS is turned on</td>
<td>Fixed &amp; Flexible</td>
<td>10 s</td>
</tr>
<tr>
<td>3</td>
<td>BESS On, Lower wind speed</td>
<td>Fixed</td>
<td>15 s</td>
</tr>
</tbody>
</table>
IV. TRANSIENT STABILITY TEST

A. Event 1 Is Switched To Event 2 And Event 3

Since the proposed system has the ability to improve transient stability as compared with conventional system, both systems are shown in Fig. 5 with simulation result of load consumption. At Event 1, fixed load consumes 0.6 p.u. in constant for both conventional system and proposed system. Once Event 1 is switched to Event 2 at 10 s, the conventional system without EMS has a surge of 1.1 p.u. followed by a dip of about 0.85 p.u. before rippling at 0.95 p.u. at 12 s followed by settling down to 0.9 p.u. at 14.5 s. In comparison, the proposed system with EMS has a similar surge at 1.1 p.u. followed by a dip of 0.9 p.u. before settling down to 0.95 p.u. at 12 s. In term of load flow analysis, the result has shown that the conventional system has a lesser load consumption of 0.9 p.u. which can be improved to 0.95 p.u. in the proposed system. Furthermore, the simulation result has concluded that BESS from conventional system is supplying output power of approximately 0.14 p.u. without reaching its maximum capacity unlike proposed system which is maintaining output power at 0.2 p.u.

During a switch from flexible load to fixed load at 15 s when Event 2 is switched to Event 3, conventional system shows its load consumption react with an oscillation with a dip of 0.5 p.u. at 16.4 s before reaching a steady state at 18 s. Proposed system reacts with a faster response during the transient period has a dip of 0.52 p.u. at 16.1 s before settling down at 18 s.

![Fig. 5. Load consumption from both conventional and proposed systems when Event 1 is switched to Event 2 and $3(P_{\text{base}} = 10 \text{ MW})$.](image)

In term of voltage deviation in Fig. 6 at 10 s when Event 1 is switched to Event 2, both conventional and proposed systems have an immediate surge of 1.05 p.u. in voltage flow followed by a dip which range between 0.92 p.u. and 0.94 p.u. before settling down to reach steady state at 12 s. This results in a 5/-8 % in maximum voltage deviation for conventional system and 5/-6 % in maximum voltage deviation for proposed system. Subsequently, the proposed system, which is maintaining an output voltage at 0.97 p.u., has introduced -3 % in continuous voltage deviation. On the other hand, the conventional system oscillating in the output voltage and settling down at approximately 0.93 p.u., has introduced -7 % in continuous voltage deviation.

Once Event 2 is switched to Event 3 when flexible load is switched to fixed load at 15 s, conventional system has a surge of 1.08 p.u. followed by a dip at 0.91 p.u. while proposed system surge at 1.055 p.u. followed by a dip at 0.925 p.u. As such, conventional system has the maximum voltage deviation of 8/-9 % while proposed system has a maximum voltage deviation of 5.5/-7.5 %. Hence, proposed system has the lower maximum voltage deviation. Pertaining to continuous voltage deviation, conventional system has voltage oscillation at 1.03 p.u. and sustaining at -3 % in 18 s. while proposed system sustains at -3 % with voltage flow at 1.03 p.u. at 17.2 s.

![Fig. 6. Output voltage (p.u.) from both conventional and proposed systems when Event 1 is switched to Event 2 and 3($V_{\text{base}} = 11 \text{ kV}$).](image)

The simulation results of frequency deviation from both conventional and proposed systems are presented in Fig. 7. During the transient period at 10 s when Event 1 is switched to Event 2, conventional system reflects 0.1/-1% in maximum frequency deviation and 0.1 % in continuous frequency deviation. On the other hand, proposed system reflects 0.1/-0.95 % in maximum frequency deviation with 0 % in continuous frequency deviation.

While Event 2 is switched to Event 3 when flexible load is switched to fixed load at 15 s, both conventional and proposed systems surge with lower dip in frequency response. Hence, conventional system reflects 1/-0.25 % in maximum frequency deviation and proposed system reflects 0.95/-0.15 % in maximum frequency deviation.

B. Summary of Simulation Results

In summary, both voltage deviation and frequency deviation from all simulation results are shown in Table III. In terms of maximum transient voltage deviation when either fixed load or flexible load is switched over one another, there is an improvement in proposed system, as compared with conventional system by having results from 5/-8 % and 8/-9 % reduced significantly to 5/-6 % and 5.5/-7.5 %. The outcome is similar to proposed system that has maximum transient frequency deviation of 0.1/-0.95 % and 0.95/-0.15 %, which are improved, compared to the conventional system in maximum transient frequency deviation of 0.1/-1 % and
Fig. 7. Output frequency ($p.u.$) from both conventional and proposed systems when Event 1 is switched to Event 2 and $3f_{bus}=60\text{ Hz}$).

1/-0.25 %. In the table, current state of the art is abbreviated as SOA which has maximum transient deviation that does not perform better than our proposed system. Both conventional and proposed system are abbreviated as Conv. and Prop., respectively.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maximum Transient Deviation Voltage (%)</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv.</td>
<td>Prop.</td>
<td>SOA</td>
</tr>
<tr>
<td>Fixed load is switched to flexible load</td>
<td>5/-8</td>
<td>0.1/-0.15</td>
</tr>
<tr>
<td>Flexible load is switched to fixed load</td>
<td>8/-9</td>
<td>5.5/-7.5</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS AND FUTURE WORK

In this paper, an investigation has been carried out on a proposed system with EMS on the improvement of transient stability in OOR, without increasing the capacity of a BESS. The proposed system entails an EMS designed in BESS, which is integrated with GTG and WTG for mitigating maximum transient deviation so as to improve output power quality to load variation. In the event of dynamic load conditions, it has been demonstrated that the conventional system without EMS has a maximum transient voltage deviation of 8/-9 %, which is higher than the proposed system with EMS that has a maximum transient voltage deviation of 5.5/-8 %. Likewise, the proposed system has a lower maximum transient voltage deviation, compared to that of the current state of the art. In the simulation result on maximum transient frequency deviation, proposed system has also shown improved results, compared to the conventional system. Hence, the proposed system has achieved an improved output power quality, as compared to the other systems in this paper. In addition, the maximum transient deviation meets the international NORSOK and IEC standards 61892-1. While much attention has been focussed on the transient stability enhancement from proposed system in the event of dynamic load condition, the ability to implement the proposed system will also rely on the economic analysis, which is crucial to be evaluated for future work.

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