Power System Stability of Offshore Wind with an Energy Storage to Electrify O&G Platform

Abstract—**The CapEx of offshore floating wind turbine generation (WTG) and battery energy storage system (BESS) have declined over the years which increases the cost feasibility of replacing gas turbine power generation in offshore oil and gas (O&G) platforms. This paper presents a study of an integrated system consisting of an offshore floating wind turbine generation (WTG) and O&G production platforms with battery energy storage system (BESS) onboard to meet the load demand. It is shown in cost analysis that the integrated system consisting of BESS can lower overall cost in CapEx and OpEx, as compared with a typical system fueled by gas turbine generation. Moreover, transient stability in simulation has shown that the proposed system 2 has a significant reduction in both voltage and frequency transient deviations, with transient recovery time that could meet the IEC standards 61892-1 for O&G platforms.**

Keywords— Energy Storage, Microgrids, Oil Platforms, Power Quality, Renewable Energy

I. INTRODUCTION

Carbon emission reduction has always the focus of marine and offshore industry as International Maritime Organisation (IMO) has pledged to reduce carbon emission by 50% in 2050 [1], [2]. In the Paris Agreement, greenhouse gases (GHG) emission reduction is a factor for prevention of global rise in temperature. Reduction of GHG emissions from offshore O&G activities is critical as there has been a tremendous growth of O&G platforms till now with over 1300 operational rigs globally positioned mostly in Gulf of Mexico and North Sea [3]. As such, this has increased the need for offshore WTG to be considered in the electrification of O&G platforms in the North Sea [4].

In the North Sea, the water depth has been ideal geographical location for wind farm development. There has been a total of more than 10,000 MW offshore wind generation by end of 2016 [5]. Similarly, there has been abundant oil and natural gas reservoirs beneath North Sea and total of 184 O&G platforms in 2018 [6]. It is commonly seen that wind farms are mostly close in proximity to the O&G platforms and interconnections between these systems are beneficial in reducing operational cost and increasing reliability of output power to O&G platforms [7]. In recent years, a switch of fossil to renewable such as offshore wind to electrified offshore O&G platform has attracted researchers to focus on the feasibility study of such a business model. Intensive research has been focused on offshore wind farm with O&G platform for integration in a standalone micro-grid configuration to reduce carbon emission from traditional power generation of gas turbine [8 - 9]. This is further driven by the fact that capital expenditure (CapEx) of O&G platforms will be higher if subsea transmission cables are required to connect to the onshore power grid [10].

Battery energy storage system (BESS) has also been proposed to integrate with an offshore floating wind farm and O&G production platforms for load flow analysis without considering voltage and frequency deviation [11]. A subsequent study on transient stability analysis with ETAP on O&G platforms with WTG and 2MW of BESS has shown that the voltage and frequency deviations meet the IEC standards 61892-1 for oil and gas industry [12]. In that paper, the emergency essential generator has been removed but two 25-MW essential generators (EGs) are in operation with 2-MW of BESS, which results in one of the EG being on standby mode and emitting carbon emissions. In comparison, this paper will present both voltage and frequency with maximum / continuous transient stability studies on a standalone microgrid configuration consisting of WTG integrated with an O&G platform generator where one 25-MW EG has been physically replaced by a 2-MW BESS. The transient stability results will be compared against the tolerable ranges of voltage and frequency deviations in international IEC standards 61892-1, as shown in Table I [13], [14].

TABLE I. TOLERANCES VOLTAGE AND FREQUENCY FOR O&G PLATFORMS

Operation	Voltage Deviation	Frequency Deviation
Maximum Continuous Deviation	+/-6 / -10%	+/-5%
Maximum Cyclic Deviation	+/-2%	+/-0.5%
Maximum Transient Deviation	+/-20%	+/-10%
Maximum Transient Recovery Time	+/-1.5sec	+/-10sec

The outline of this paper is as follows. Section 2 presents the detailed configuration of two proposed systems with varying BESS. Four different test scenarios are presented in Section 3. Simulation results of conventional system will be shown in Section 4. Sections 5 and 6 presents the simulation results of the proposed systems 1 and 2 respectively. The discussion of simulation results will be described in Section 7. Lastly, conclusions are presented in Section 8.

II. SYSTEM CONFIGURATION WITH COST ANALYSIS

In this section, the details of proposed systems 1 and 2 are presented.

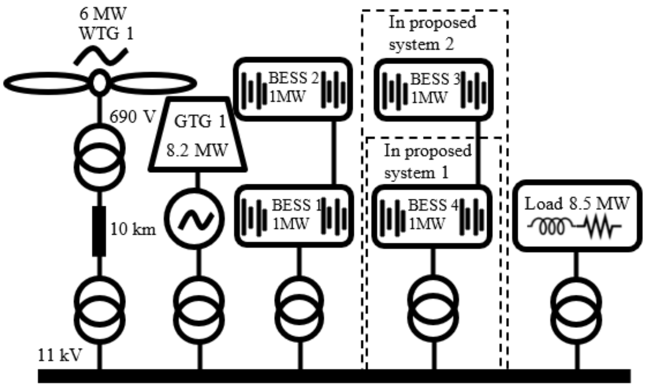

Fig. 1. Proposed offshore integrated system

As shown Fig. 1, the considered conventional system consists of 1 GTG, 1 WTG and 2 BESS. Proposed system 1 consists of an additional 1 BESS while proposed system 2 has an additional 2 BESS.

A. *Integrated system for Oil and gas platforms*

In the typical system, the O&G platforms are equipped with 2 x SCGTs (16.4-MW) and standby 1 x SCGTs (8.2-MW), where two SCGTs act as essential generators (EGs) and the other serves as an emergency essential generator (E.EG). The typical OG platforms have a fixed load of around 8.5-MW, as discussed in [11]. The conventional system consists of 1 x 6-MW Siemens (SWT6.0-154) Permanent Magnet Synchronous Generator (PMSG) floating WTGs connected in parallel, which mirrors the Hywind Park configuration in the North Sea [15]. WTG is situated 10km away with joint HVAC power transmission cable to the output on the power bus of the O&G platforms. In this paper, one of the EG has been removed in the typical system, resulting in the proposed systems 1 and 2 in Fig. 1, which allows for the physical replacement of a 2-MW battery energy storage system (BESS) onboard the O&G platform.

B. *Proposed system 1 and 2 for Oil and gas platforms*

With ongoing research and development (R&D) in battery technology, the BESS has declined in cost, which is attractive to integrate with renewable energy sources (RES) in micro grid configuration [16]. As such, the typical system has been replaced with the proposed systems 1 and 2 onboard. In this system, BESS 3 and 4, each with an energy capacity of 1- MWh, are installed onboard the platforms and connected to the 11-kV main switchboard on O&G platforms. The cost of proposed system 2 is based on the CapEx and OpEx from the cost analysis in [17]-[19]. Since GTG has the power factor of 0.8, the mathematical function of GTG. GT GC for CapEx (C/kW) onboard the O&G platform is written as follows:

$$GT\ GC = [(10000)(2)(GTG)] \quad (1)$$

where GTG is approximately \$1415/kW. Capital cost of WTG W T GC for CapEx (C/kW) onboard the platform can be calculated in the following equation:

$$W\ T\ GC = [(6000)(WTG)] \quad (2)$$

where WTG is approximately \$2870/kW. Initial BESS has the lifespan of 10 years and would require double times of the capital cost for lifespan of 20 years. Thus, CapEx of BESS BESSC for CapEx (C/kW) onboard the platform can be calculated in the following equation:

$$BESSC = [(1000)(1930)(2)(2)] \quad (3)$$

where BESS is approximately \$1937/kW.

Fig. 2 presents the CapEx and overall cost (CapEx and OpEx) in the lifespan of 20 years for the typical system, conventional system, proposed system 1 and 2. The typical system consists of 2 GTGs and 1 WTG onboard platforms has the highest cost as compared to conventional system which incorporated of 1 GTG, 2 BESS and a WTG that has overall CapEx of 15-% lesser. In comparison, the proposed system 2 has a 14-% lower CapEx and OpEx for 20 years as compared to the typical system.. It's CapEx and OpEx is slightly higher than proposed system 1 due to the additional BESS.

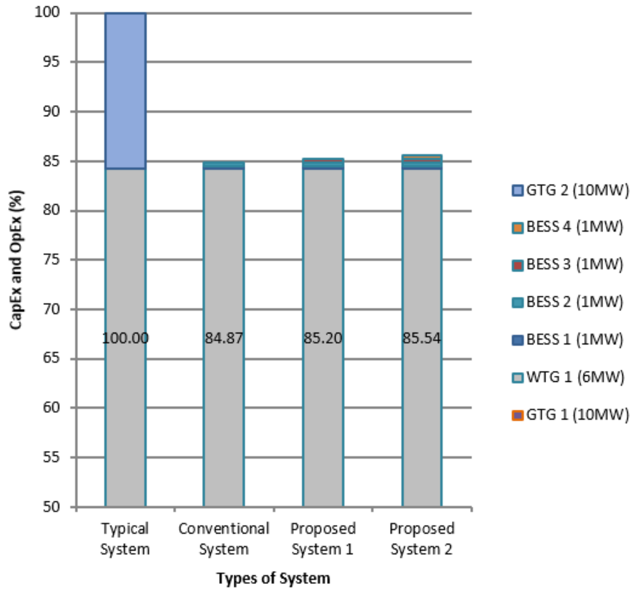

Fig. 2. Total cost for lifespan of 20 years of Capex and OpEx for system configuration of typical, conventional, proposed system 1 and 2.

III. TEST SCENARIOS

In this section, four test scenarios are described, as shown in Table II. These four scenarios are simulated in MATLAB and presented in Sections 4, 5 and 6.

TABLE II. FOUR SCENARIOS FOR SIMULATION

Scenario	Event
1	Continuous wind
2	Conventional system: WTG 1 is tripped and BESS 1 and 2 are turned on
3	Proposed system 1: WTG 1 is tripped and BESS 1, 2 and 3 are turned on
4	Proposed system 2: WTG 1 is tripped and BESS 1,2,3 and 4 are turned on

Through the four test scenarios, a constant rated wind speed is assumed. The simulation study is based on the ability of the power system, to maintain electrical power to load when subjected to transient fault of WTG. Usually, the duration of the trip event to study transient stability is at least 3 s and beyond for RES connected to BESS [20].

In Section 4, the simulation results are presented in Cases 1, 2 and 3 of conventional system. Simulation results of the proposed system 1 are shown in Cases 4, 5 and 6 in Section 5. Section 6 presents the simulation results of proposed system 2 in Case 7, 8, and 9. All simulation results are compared against the international IEC standards 61892-1 for maximum transient in voltage and frequency deviation, as shown in Table I. For a fair comparison, all systems are assumed to have a GTG together with a WTG running onboard, which are GTG 1 and WTG 1 respectively.

IV. CONVENTIONAL SYSTEM SIMULATION RESULTS

In this section, conventional system is started in Scenario 1 to Scenario 2. In Scenario 1 where there is continuous wind, GTG 1 and WTG 1 are supplying electrical power to OG platforms. In this simulation, BESS 1 and 2 are switched on when the WTG 1 is tripped while GTG 1 is running in operation.

A. Case 1

In this case study, it can be seen from Fig. 3 that there is a sharp surge in output power to the load of 1.18 and dip below 1 p.u. after the transient occurs. In this case, it is shown that the output load power profile has a surge of maximum transient deviation of 18-% from its initial load of 1 p.u..

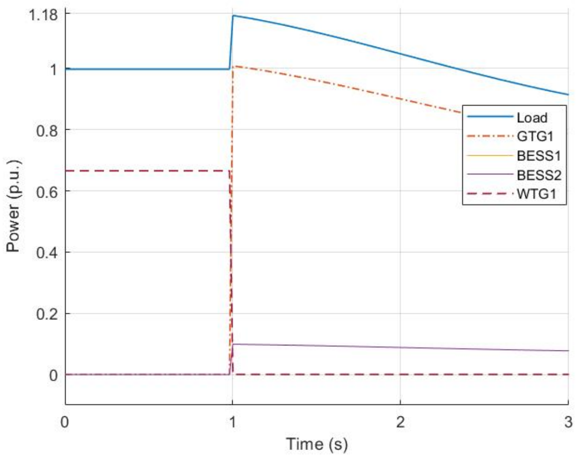

Fig. 3. Example Power flow in p.u. when WTG 1 is disconnected and BESS 1and 2 are turned on (Pbase =8.5-MW).

B. Case 2

In voltage deviation, it can be seen from Fig. 4 that there is a significant surge in output voltage to the load of 1.11 p.u., followed by drop in output voltage to the load below 1 p.u.. In this case, it is shown that the output load power profile has a maximum transient deviation of 11-% from its initial voltage of 1.02 p.u. This result shows that the conventional system can meet international IEC standards 61892-1 for maximum transient for voltage deviation.

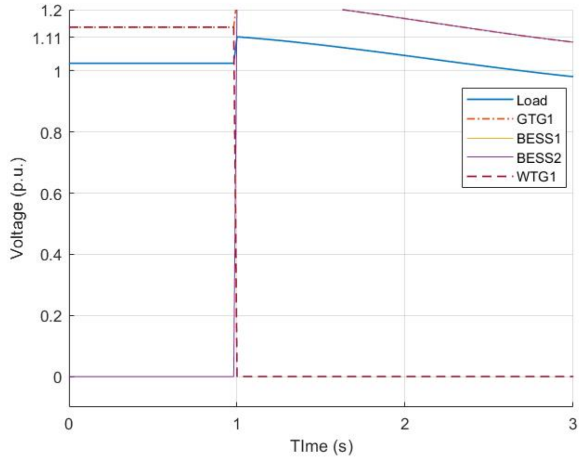

Fig. 4. Voltage in p.u. when WTG 1 is disconnected and BESS 1and 2 are turned on (Vbase =11-kV).

C. Case 3

In frequency deviation, it can be seen from Fig. 5 that there is a dip in output frequency to the load of 0.78 p.u. immediately after the transient period. In this case, it is shown that the output frequency has a maximum transient deviation of -22-% from its initial frequency of 1 p.u. This result shows that the conventional system does not meet international IEC standards 61892-1 for maximum transient frequency deviation.

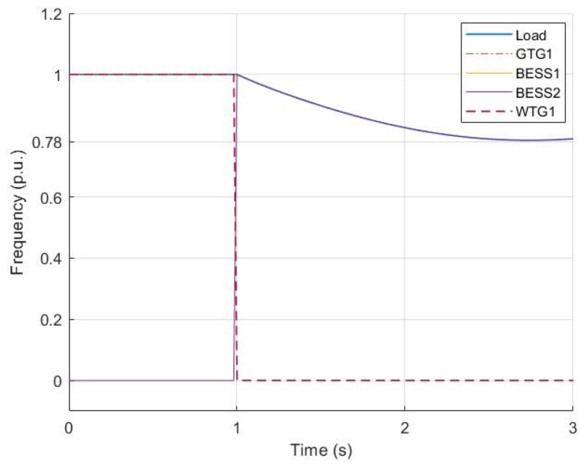

Fig. 5. Frequency in p.u. when WTG 1 is disconnected and BESS 1and 2 are turned on (fbase =50-Hz).

V. PROPOSED SYSTEM 1 SIMULATION RESULTS

In this section, a similar study is conducted on the proposed system 1. The perturbation is applied similarly to Cases 1, 2 and 3 in the previous section of conventional system. The proposed system 1 is started in Scenario 1 and switched to Scenario 3, where the WTG 1 is suddenly disconnected and BESS 1,2 and 3 are turned on with GTG 1 in operation mode.

A. Case 4

In this case study, it is observed that maximum transient deviation in load power is 10-%. This is a reduction of 8-% in the surge of output power, as compared to the conventional systems in Fig. 6. However, the output power drops below 1 p.u. after the transient period which could not be able to meet the load demand.

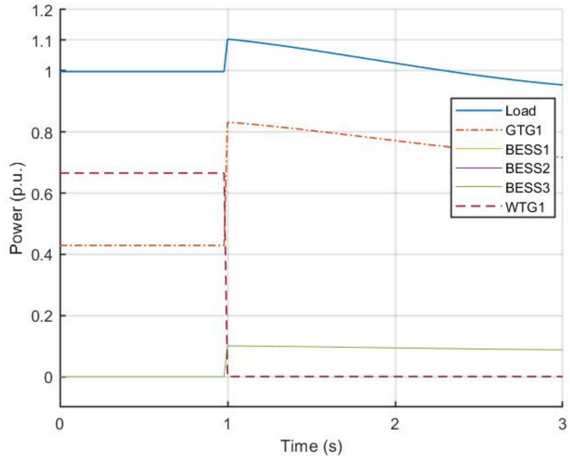

Fig. 6. Proposed system 1: Power flow in p.u. when WTG 1 is disconnected and BESS 1, 2 and 3 are turned on (Pbase =8.5-MW).

B. *Case 5*

In voltage deviation, it is observed that the maximum transient deviation in voltage is approximately 8-%. This is significantly lower with 3-% lesser as compared to the conventional system, as shown in Fig. 7. In addition, the output voltage drops below 1 p.u. after the transient period.

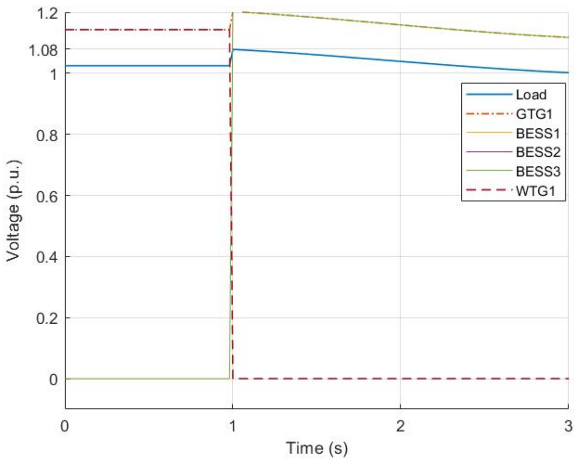

Fig. 7. Proposed system 1: Voltage in p.u. when WTG 1 is disconnected and BESS 1, 2 and 3 are turned on (Vbase =11-kV)

C. *Case 6*

In frequency deviation, it is observed that the transient deviation in frequency is approximately -11-% which is significantly lower with 11-% lesser as compared to the conventional system, as shown in Fig. 8. Similarly, this result shows that the conventional system does not meet international IEC standards 61892-1 for maximum transient frequency deviation.

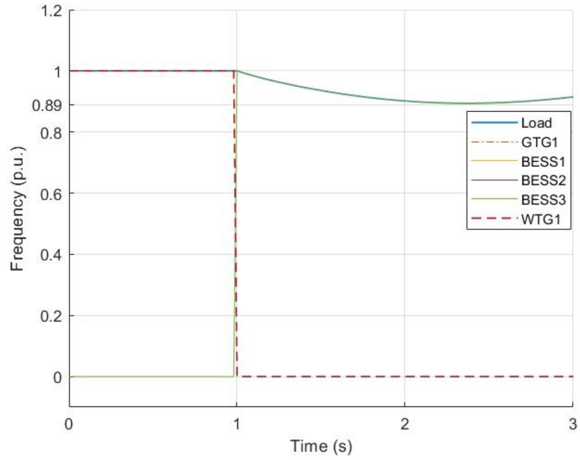

Fig. 8. Proposed system 1: Frequency in p.u. when WTG 1 is disconnected and BESS 1, 2 and 3 are turned on (fbase =50-Hz).

VI. PROPOSED SYSTEM 2 SIMULATION RESULTS

In this section, a similar study is conducted on the proposed system 2. The proposed system 2 is started in Scenario 1 and switched to Scenario 4, where the WTG 1 is suddenly disconnected and BESS 1,2,3 and 4 are turned on with GTG 1 in operation mode.

A. *Case 7*

In this case study, it is observed that maximum transient deviation in load power is 5-%. This is a further reduction in output power surge during transient period as compared to the both the conventional system and proposed system. In addition, the load power is maintained around 1 p.u. after the transient period

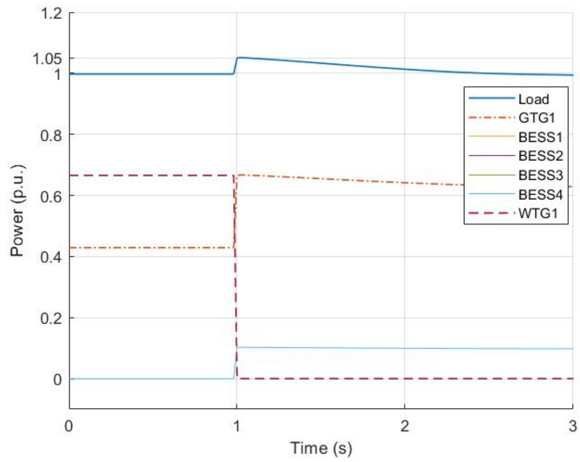

Fig. 9. Proposed system 2: Power flow in p.u. when WTG 1 is disconnected and BESS 1, 2, 3 and 4 are turned on (Pbase =8.5-MW).

B. *Case 8*

In voltage deviation, the output voltage has a surge of 1.05 p.u. as shown in Fig. 10, has concluded 5-% in maximum transient deviation. This is significantly lower by 3-% lesser as compared to the proposed system 1, as shown in Figure 7. In addition, there is a further reduction of 6-% lesser in maximum transient voltage deviation as compared to conventional system

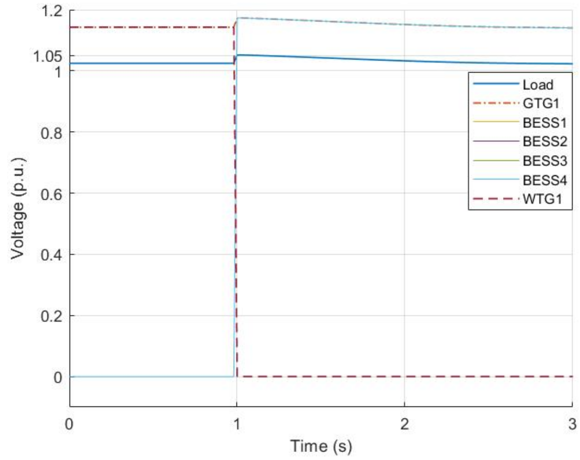

Fig. 10. Proposed system 2: Power flow in p.u. when WTG 1 is disconnected and BESS 1, 2, 3 and 4 are turned on (Pbase =8.5-MW).

C. Case 9

In frequency deviation, the output frequency has a surge of 0.96 p.u. as shown in Fig. 11, has concluded -4-% in maximum transient deviation. This is significantly lower by 7-% lesser as compared to the proposed system 1, as shown in Figure 8. where the transient deviation is -11- %. In addition, there is a further reduction of 18-% lesser in maximum transient frequency deviation as compared to conventional system. Overall, proposed system 2 can meet international IEC standards 61892-1 for maximum transient frequency deviation.

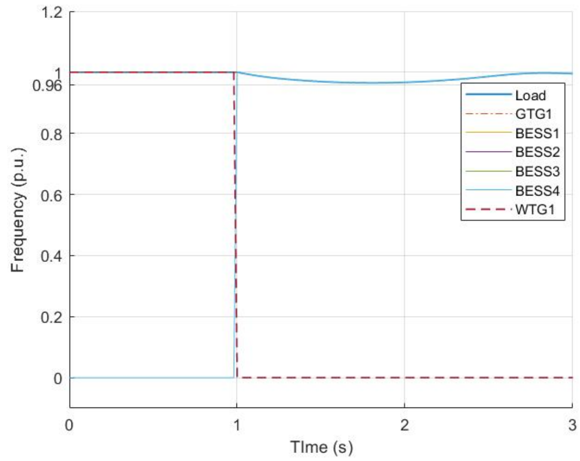

Fig. 11. Proposed 2: Frequency in p.u. when WTG 1 is disconnected and BESS 1, 2, 3 and 4 are turned on (fbase =50-Hz).

VII. DISCUSSION OF RESULTS

The simulation results of all cases of voltage deviation and frequency deviation are presented in Fig. 12. In the simulation on voltage deviation, increase in BESS from 2-MW to 4-MW led to a reduction of transient deviation from 11-% to 5-%. Whereas in simulation for frequency deviation, conventional system and proposed system 1 have not met maximum frequency deviation according to international IEC standards 61892-1, unlike proposed system 2 with BESS of 4-MW that is able to meet the standards. In order to enhance outout power quality and to meet international IEC standards 61892- 1 for frequency deviation, there is an increase in Capex and OpEx amount from conventional system with $ 0.475-M to proposed system 2 with $0.95-M for 20 years.

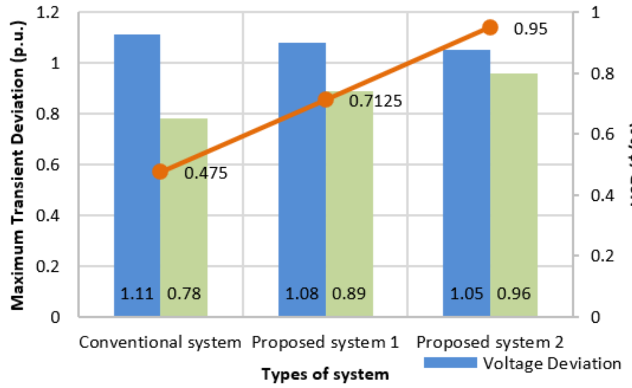

Fig. 12. Simulation results of voltage and frequency deviation with CapEx and OpEx for conventional system, proposed system 1 and 2.

VIII. CONCLUSION AND FUTURE WORK

In this paper, a conventional system consisting of 1 GTG, 1 WTG, 2 BESS is simulated and compared to proposed systems 1 and 2 with varying additional BESS capacity. It has been shown that proposed system 2 has a significant power quality improvement, as compared to the conventional system, and meets international IEC standards 61892-1. In addition, further optimization on the quality of energy enhancement has been demonstrated in proposed system 2. In load flow analysis, only proposed system 2 has maintained an output power of 1 p.u. that is able to meet the load demand. In addition, proposed system 2 has reduced the maximum voltage transient deviation of 8-% to 5-%, as compared to proposed system 1. Moreover, proposed system 2 has reduced the maximum frequency transient deviation from -22-% to -4-%. The transient stability study on variable loads is not considered in this paper, which could be studied in future work.

ACKNOWLEDGMENT

This research is funded under Economic Development Board (EDB) of Singapore and Sembcorp Marine Ltd. (SCM) under Industrial Postgraduate Programme (IPP).

REFERENCES

[1] B. Comer, C. Chen, and D. Rutherford, "Relating short-term measures to IMO's minimum 2050 emissions reduction target," unpublished, presented at the international council on clean transportation, Aug. 2018.

[2] R. .J. Dewey, "The NYISO Carbon Pricing Initiative: Helping New York Meet Its Clean Energy Goals," Natural Gas Electricity, Vol. 36, No. 8, pp.1-10. Mar. 2020.

[3] S.M. Watson, "Greenhouse gas emissions from offshore oil and gas activities—Relevance of the Paris Agreement, Law of the Sea, and Regional Seas Programmes. Ocean Coastal Management," 185, pp.104942, Mar. 2020.

[4] A.S. Tveiten, and B.T. Tanger ˚ as, "Hywind Tampen, project NPV ˚ calculation with and without subsidies," Master's thesis dissertation, Univ. of Stavanger, Norway, 2018.

[5] Offshore renewable energy developments - Offshore Wind, NorthSEE , 2017. [Online]. Available: https://northsearegion.eu/northsee/eenergy/offshore-renewable-energy-developments-offshore-wind/

[6] Number of offshore rigs worldwide as of January 2018 by region , statista,Nov.2020.[Online].Available:https://www.statista.com/statistics /279100/number-of-offshore-rigs- worldwide-by-region/

[7] T.M. Haileselassie, M. Molinas, and T. Undeland, "Multi-terminal VSC-HVDC system for integration of offshore wind farms and green electrification of platforms in the North Sea" In Nordic Workshop on Power and Industrial Electronics (NORPIE), Helsinki University of Technology, Espoo, Finland, Jun. 2008.

[8] F. Perera, A. Ashrafi, P. Kinney, and D. Mills, "Towards a fuller assessment of benefits to children's health of reducing air pollution and mitigating climate change due to fossil fuel combustion," Environmental research, vol. 172, pp. 55-72, May 2019.

[9] S. Sanchez, E. Tedeschi, J. Silva, M. Jafar, and A. Marichalar, “Smart load management of water injection systems in offshore oil and gas platforms integrating wind power,” IET Renewable Power Generation, vol. 11, no. 9, pp. 1153-1162, Jun. 2017.

[10] S. Hardy, K. Van Brusselen, S. Hendrix, D. Van Hertem, and H. Ergun , “Techno-Economic Analysis of HVAC, HVDC and OFAC Offshore Wind Power Connections,” IEEE Milan PowerTech, pp. 1-6, Jun. 2019.

[11] J.Z. Tee, K.H. Tan, L.H.l. Lim, K. Zhou, and O. Anaya-Lara, “Integration of Offshore Wind with OG Platforms with an Energy Storage System,” in Proc. 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 29 Sept – 2 Oct 2019. doi: 10.1109/ISGTEurope.2019.8905500

[12] J.Z. Tee, L.H.l. Lim, K. Zhou, and O. Anaya-Lara, “Transient Stability Analysis of Offshore Wind With O&G Platforms and an Energy Storage System” in Proc. 2020 IEEE PES General Meeting (PESGM), 3 – 6 August 2020.

[13] W. He, G. Jacobsen, T.Anderson, F.Olsen, T.D. Hanson, M. Korpas, ˚ T. Toftevaag, J. Eek, K. Uhlen, and E. Johansson, “The potential of integrating wind power with offshore oil and gas platforms. Wind Engineering, Vol. 34, No. 2, pp.125-137, Mar. 2010.

[14] J.I. Marvik, E.V. Øyslebø, and M. Korpas, “Electrification of offshore ˚ petroleum installations with offshore wind integration,” Renewable energy, vol.50, pp. 558-564, Feb 2013.

[15] Natural Gas Plants , National Renewable Energy Laboratory, 2018. [Online].Available:https://atb.nrel.gov/electricity/2018/index.html?t=cg

[16] K. Mongird, V.V. Viswanathan, P.J. Balducci, M.J.E. Alam, V. Fotedar, V.S. Koritarov, and B. Hadjerioua, “Energy Storage Technology and Cost Characterization Report (No. PNNL-28866). Pacific Northwest National Lab.(PNNL),” Richland, WA (United States), Jul. 2019.

[17] W.J. Cole, and A. Frazier, “Cost projections for utility-scale battery storage (No. NREL/TP-6A20-73222),” National Renewable Energy Lab.(NREL), Golden, CO (United States), Jun. 2019.

[18] T.J. Stehly, and P.C. Beiter, “2018 Cost of Wind Energy Review (No. NREL/TP-5000-74598),” National Renewable Energy Lab.(NREL), Golden, CO (United States), Jan. 2020.

[19] Fact Sheet: Energy Storage, Environmental and Energy Study Institute, Feb.2019.[Online].Available:https://www.eesi.org/papers/view/energystorage-2019.

[20] J.Z. Tee, E.Z.D. Chia, K.H. Tan, L.H.l. Lim, K. Zhou, and O. AnayaLara, “Techno-Economic Analysis and Battery Storage Placement in grid-connected Photovoltaic (PV) system,” in Proc. 36th European Photovoltaic Solar Energy Conference and Exhibition, 2019, pp. 1520- 1525, doi: 10.4229/EUPVSEC20192019-5CV.3.53.