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APPLIED RESEARCH

Assessment of an Isolated Offshore Power Grid Based on the Power Hub Concept for Pre-Salt Oil and Gas Production

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ABSTRACT Towards a future with more renewable energy, oil and gas (O&G) will still play a major role in the energy and mobility sectors. Therefore, scientists must also investigate ways to mitigate carbon emissions in O&G production. In this sense, a power hub with local generation can be employed in offshore production sites to allow the adoption of more efficient power generation technologies without the weight and space constraints that exist in usual Floating Production, Storage and Offloading (FPSO) platforms. This power hub can be connected to the FPSOs forming an isolated offshore power grid that requires further study. This work investigates stability issues of such offshore power networks. Simulations of a system composed by the power hub and three identical FPSO units were performed in PSCAD, and the stability of the system was validated according to the IEC 61892-1 standard. Results demonstrate that it is possible to operate such system with a stable and secure supply. The main contributions of this work are the electrical modeling of the power hub and of the resulting isolated offshore electrical grid, and a detailed discussion of the rising challenges and the required models for dynamic electrical studies.

INDEX TERMS Offshore oil and gas, isolated power systems, offshore power systems.

I. INTRODUCTION

The energy demand is growing and it is expected to reach 365M barrels of oil equivalent per day (mboe/d) by 2040, with natural gas accounting for 25 % of the world's energy mix [1]. Moreover, oil still plays a major role in the mobility and energy sectors while the energy transition process plays out and new electric technologies are matured for the transport sector. However, the oil and gas (O&G) industry is one with high levels of energy intensity and, consequently, high levels of greenhouse gas (GHG) emissions. Alternatives should be proposed to mitigate the contribution of the O&G industry to the global warming, with special attention to the offshore assets that are responsible for nearly 30 % of the world's oil production [2].

Unlike onshore production sites, the weight and the footprint occupied by power generation units and by the process plant play an important role on offshore platforms. Thus, open cycle gas turbines (OCGTs) are typically used in offshore applications to make more room for the process plant. These turbines are designed to operate more efficiently around their rated power, but operate for most of their lifespan far from that [3], which contributes to the increase of GHG emissions in the O&G industry.

One of the most prominent alternatives for reducing GHG emissions from an offshore O&G platform is power from

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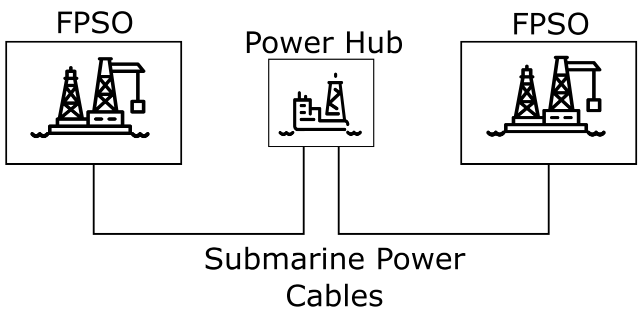

FIGURE 1. **Power generation and transmission from a power hub to FPSOs.**

shore (PFS), which was successfully applied to oil fields in Saudi Arabia [4] and Norway [5]. PFS connects offshore platforms with the onshore power grid, a strategy that may benefit of more efficient generation technologies and/or renewable energy generation. Another state of the art alternative proposed was the Utsira High Power Hub (UHPH), which consists of a combination of PFS and distribution network [6]. In this concept, an additional platform, called power hub, receives electrical power through PFS and distributes the power to other platforms located in the same field, acting as an offshore substation.

Brazil is the world's second largest offshore oil producer and the largest producer in ultra-deep waters [7]. The largest reserves are concentrated in the Campos and Santos basins, due to the oil located in the pre-salt layer. In the Brazilian case, the PFS concept would face many technical challenges to reach the pre-salt basin. These areas are located 200 km from the coast in water depths that can reach 2,000 m. As an alternative to reduce the GHG emissions from the offshore O&G ultra-deep waters activities, a power hub with local power generation can be employed. This concept was initially proposed [8] and further optimized for the Brazilian pre-salt basin case [9]. It consists of an additional offshore platform exclusively for power generation, without any productive processes on board.

The electrical interconnection of the power hub with the Floating Production Storage and Offloading (FPSO) units, responsible for production, would then form an isolated offshore power grid, as illustrated in Fig. 1. With an offshore platform exclusively for power generation, the trade-off between space requirements for more efficient power generation and the processing plant capacities for maximum economical output ceases to exist. This would enable the adoption of more efficient generation technologies such as Combined Cycle Gas Turbines (CCGTs) [10] and Carbon Capture and Storage (CCS) units [11]. Hence, the power generation could be displaced from the OCGTs aboard the FPSOs to the power hub for a more sustainable approach.

Concerning the possible adoption of the power hub, researchers have focused their attention to the exergy analysis [3] and emission studies [12]; optimization of the power generating module [9], [13]; its integration with CCS [11] and its economical evaluation [12], [14]. However, in the literature, there are only a few and not very up-to-date papers that investigate the electrical system stability of modern and isolated offshore power grids. Most recent studies focus mainly on the connection of offshore wind energy to the onshore grid, as in [15], [16], and [17] examples, and very few consider their integration with O&G platforms [18], [19], [20], [21], [22]. Anyhow, in both cases a connection with the onshore grid is considered.

A few studies regarding isolated O&G electrical systems are presented in [23], [24], and [25]. Nevertheless, these studies consider isolated offshore grids composed of a wind farm and a single O&G platform. Årdal *et al.* [23] performed a parametric sensitivity of voltage and frequency transients. The same system from [23] was again analyzed by Årdal *et al.* [24], where voltage and frequency support from the wind turbines was proposed. The electrical grid stability of a similar system was also studied by He *et al.* [25].

The operation of the power system of a single conventional FPSO is challenging by itself. Electrical equipment installed offshore needs to be protected from the rusty, moist and corrosive environment. Such precautions are not normally required onshore. In many cases, equipment must also be safe enough to operate in the vicinity of, or even inside, hazardous areas, where gases and vapors with high degree of flammability are often present. With the power hub concept, a number of additional operational challenges arise and are worthy of discussion. For example, a short-circuit at one FPSO unit might propagate to the others, because they are interconnected. This imposes a completely new scenario to the operation personnel, who will now have to investigate faults that occur on a meshed system, a network configuration far different from the well-known and traditional radial topology of conventional FPSOs.

The frequency dynamics is particularly affected since the interconnection of the power hub and the FPSO units allows for the sharing of inertia between otherwise isolated power systems. Changes can be observed in frequency excursions and in Rates of Change of Frequency (RoCoF) which might trigger protection equipment. Additionally, power reserves might be shared among all FPSOs. In this new scenario, the loss of a transmission line is now possible. Such an event should then be investigated to allow the comprehension on how it could propagate throughout the electrical system. In a worst-case scenario, the loss could be propagated throughout the system and cause the shutdown not only of the FPSO where the first event was triggered, but also of the whole system. A full blackout in such system could result in serious economic losses arising from the restart of the plant, that given thermal inertia, could take days to be reestablished.

Another challenge for the power concept concerns the direct online (DOL) starting of large compressor and pump motors [26]. This operation requires huge amounts of reactive power to be successfully completed. Since the transmission of reactive power is not a simple task, managing it locally frequently leads to better results. Therefore, bearing in mind that the FPSOs connected to the power hub have only one local generator, the DOL starting of these large motors might require a capacitor bank support.

The interconnection between the FPSO units and the power hub hints at the need of a central management of the otherwise independent island power systems. The power scheduling and management of the isolated offshore grid should take into account the local heat demand, large motors start forecasting and the availability of power generating units. This concept of grid is unique in the sense that is too big to be considered as a microgrid, but it also has a small number of elements to resemble a power system with similar ratings onshore. Another rising concern would be the communications for such power management. If they go down, a contingency plan should be in place to minimize the impacts of a communication loss.

This paper investigates stability issues in the electrical network composed of the interconnection between a power hub and a set of typical FPSOs of the Brazilian pre-salt basin region. This system under study is hypothetical, since there are no such isolated offshore O&G grids with a power hub in operation today. In view of the challenges regarding the operation of this electrical grid, with transmission between low inertia systems, low short-circuit ratio, and subject to large disturbances, such analysis is necessary to identify possible issues.

The main contributions of this work are the electrical modeling of the power hub and the resulting isolated offshore electrical system, including the discussions about the findings raising important issues related to the system operation under normal and abnormal conditions. A model of a system composed by the power hub supplying three identical FPSO units was developed in PSCAD, and simulations were performed comprising a set of four main studies: motor starting, fault clearance analysis, disconnection of a FPSO and disconnection of generators. The stability of the system was validated according to the IEC 61892-1 standard [27]. In addition, simulations were also carried out with a conventional FPSO, with the purpose to highlight the advantages and disadvantages of operating this system itself compared to the FPSO connected to the power hub.

This paper is structured as follows: the electrical system modeling is presented in section II; section III details the results of the simulations; and in section IV, the conclusions are provided.

II. SYSTEM MODELING

A. POWER GRID LAYOUT

The single line diagram of the isolated offshore power system resulting from the adoption of the power hub connected to three FPSO units is shown in Fig. 2. The power hub is a floating platform used exclusively for power generation, rather than also having productive processes. Hence, without the critical constraints of weight and equipment footprint, it is possible to adopt more efficient generation technologies, such as CCGTs and CCS systems, resulting in a more efficient and more sustainable power supply [28]. Each power hub CCGT is composed of a gas turbine (GT) and a heat recovery steam generator (HRSG) powering a steam turbine (ST).

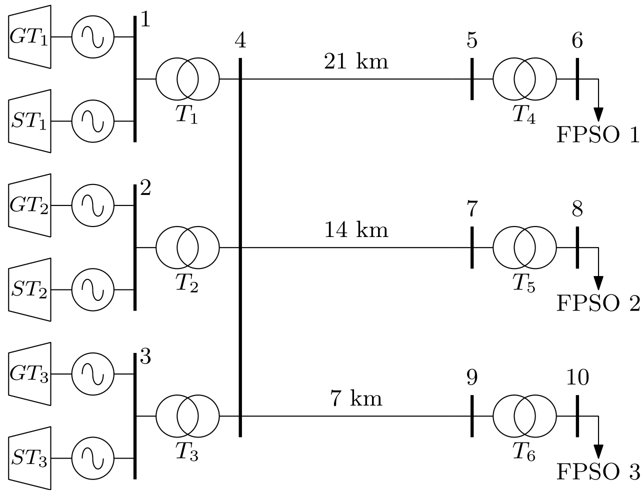

FIGURE 2. Single line diagram of the offshore O&G isolated power system with the power hub concept.

The power hub generation system is divided into three CCGTs, connected to buses 1, 2 and 3, as shown in Fig. 2, and rated 70 MVA each. Each CCGT is divided into a 52.5 MVA GT and a 17.5 MVA ST. The step-up transformers T_1, T_2 and T_3 connect the CCGTs to bus 4, which is the power hub point of common coupling (PCC) from where the submarine cables depart to supply the FPSOs. For the transmission lines, a classic π model was adopted for the submarine ac cables. The parameters of the power hub synchronous generators, and of the transformers and cables of the system in Fig. 2 are given in Appendix.

B. FPSO POWER SYSTEM

A single line diagram with the conventional power system of a pre-salt FPSO is shown in Fig. 3. It is composed of four OCGTs that supply the electrical power to the productive processes, eight direct connected induction motors that represent the main compressors of the platform, and a constant PQ load at the main busbar that aggregates the remaining loads, such as the living quarters and low voltage buses. Each OCGT is rated 31.25 MVA and 13.8 kV, the induction motors are rated 11 MW and the PQ load is equal to 37.38 MW and 8.04 MVAr. The parameters of the FPSO synchronous generators, induction motors in Fig. 3 are given in Appendix.

The main differences between the conventional FPSO power system in Fig. 3 and the one adopted in the power hub approach are the interconnection between all FPSOs in an oil field and the power hub, and the number of local generators. Since the power hub provides an external power source, the FPSOs can be modified in the sense of removing local generation. The core of this proposal is to displace the generation from less efficient point of operation aboard the FPSO to more efficient operation on the power hub. However, the OCGTs are not completely removed because the productive process has a need for heat and, as demonstrated by [29], the

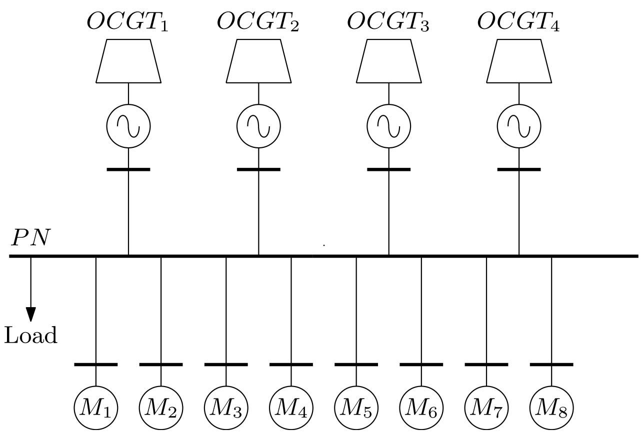

FIGURE 3. Single line diagram of a conventional pre-salt FPSO power system.

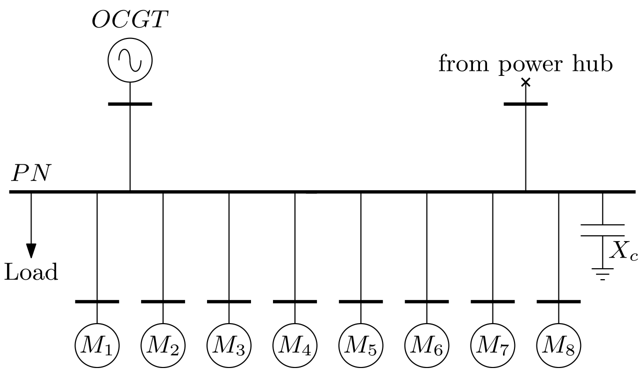

FIGURE 4. Single line diagram of a pre-salt FPSO power system adapted for the power hub concept.

exergy efficiency of the FPSO can be increased by profiting off the OGCT residual heat. In the absence of this heat source, local gas burners would have to be used, leading to a lower overall efficiency [3].

The resulting FPSO power system would contain a single OCGT and the receiving end of the transmission line as shown in the single line diagram in Fig. 4. In addition, a reactive power compensation of -22 MVAr was added to support the direct online start (DOL) of the compressors.

C. COMBINED CYCLE GAS TURBINE

Concerning the quantity of shafts and the ratio between the number of gas and steam turbines, many configurations can be adopted for modeling the CCGT [30]. The model of a CCGT is mainly divided between the gas turbine and the HRSG/steam turbine.

For gas turbines, the Rowen model [31] is one of the most accepted in the literature. It was further detailed in [32] to include the effects of valves, ambient temperature and air flow in obtaining the turbine speed. The model considered in this work was detailed by [33] and can be seen in Fig. 5. The functions F1, F2 and F3 comprise thermodynamic relations that affect the exhaust gases flow and the output torque.

For the HRSG/steam turbine there are also many possible models [30], [34], [35]. As shown in Fig. 6, they typically take input variables such as the exhaust gas flow (W_x) and temperature (T_x). These variables are initially used in a function, called HRSG, based on thermodynamic relations. They are then related through a function based on thermodynamics relations. The corresponding output is then processed by two first order transfer functions modeling the tube metal heat capacitance, T_m, (typically 5 s) and the boiler storage time constant, T_b, (typically in the range of 50–100 s) to obtain the mechanical power output of the steam turbine (P_{tv}) [33].

D. OPEN CYCLE GAS TURBINE

The modeling of the OCGT is one of the main tasks to perform an accurate study of the power system resulting from the adoption of the power hub concept for the electrification of the offshore O&G production. The model of the OCGT used in this work is shown in Fig. 7. A droop control strategy is adopted for regulating the speed of the turbine and a PI controller is responsible for generating the fuel in-feed. The generated fuel in-feed is the input of a gas turbine modeled by a transfer function obtained from test data made available to the authors by Petrobras. The transfer function represents the dynamics of the turbine and its valves.

III. RESULTS

The system shown in Fig. 2 was implemented in the PSCAD software to demonstrate the feasibility of an isolated offshore electric network resulting from the interconnection of three FPSO units and the power hub. The following studies were performed aiming at analyzing the stability of the offshore isolated power system: motor starting, fault clearance, load rejection and loss of generation. The stability of the system was validated according the operational requirements established in the IEC 61892-1 standard [27]. In all case studies, the set point for the power hub's CCGTs were set at 0.87 pu, and set point of the FPSO's OCGTs were set at 0.70 pu.

A. MOTOR STARTING

The motor starting study is conducted on FPSO 1, which is connected to the power hub by a 21 km length submarine cable, as was shown previously in Fig. 2. FPSO 1 is where the highest voltage drops are expected to occur, since it is connected to the power hub by the longest cable. The study considers the starting of motor M_7 when motors M_1-M_6 are already in steady-state and the capacitor bank is connected. Moreover, during the whole simulation, FPSOs 2 and 3 operate with motors M_1-M_7 in steady-state and also with their respective capacitor bank connected.

Fig. 8 shows the voltage behavior during the start up of M_7 in FPSO 1 and the tolerances given by the IEC 61892-1 [27]. At $t = 1$ s the motor is connected and begins its acceleration phase with no load. Then, at $t = 5$ s, the mechanical load is applied. As shown in Fig. 8, the voltage drop due to the high inrush current during the motor start-up did not violate any of the limits given by the IEC 61892-1 [27], in both FPSO 1 and power hub. The

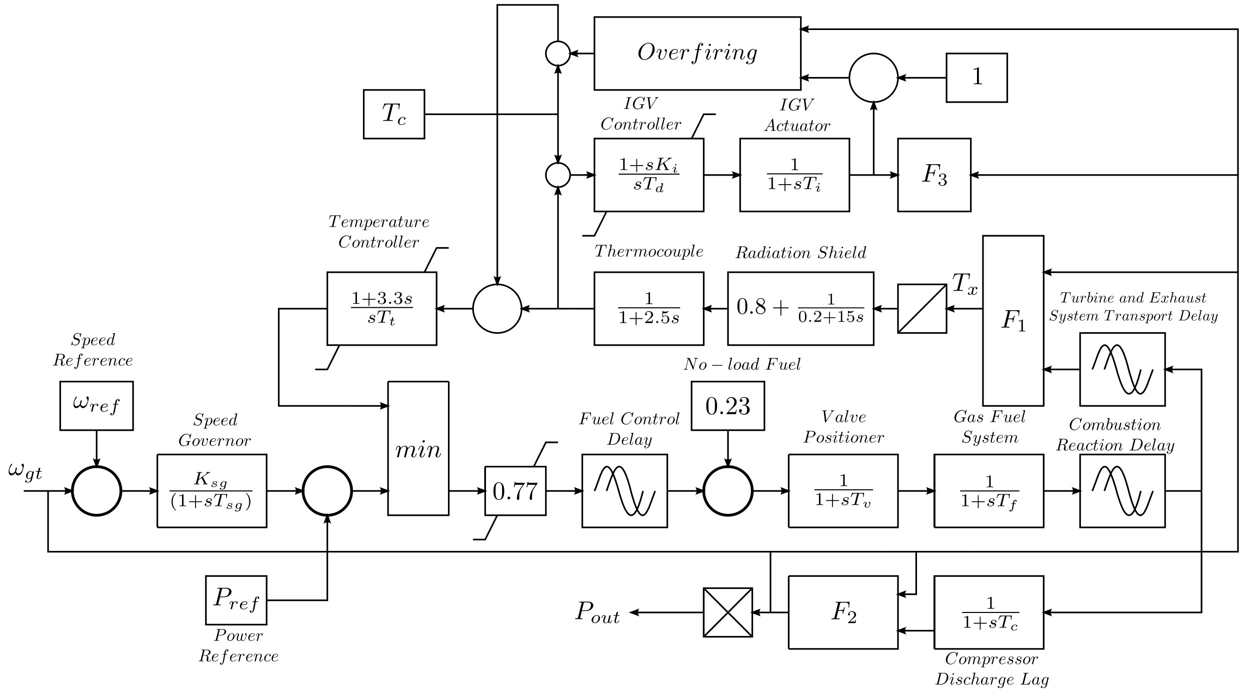

FIGURE 5. Rowen model used for the gas turbine in the CCGT.

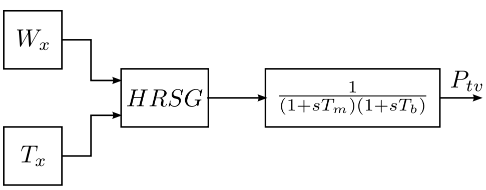

FIGURE 6. Steam turbine block diagram.

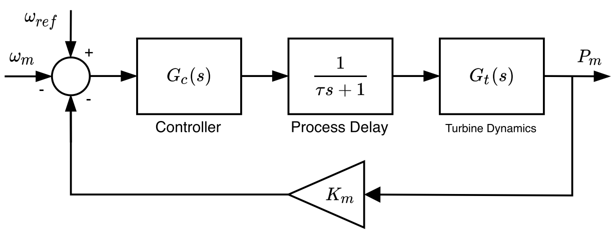

FIGURE 7. OCGT block diagram.

maximum voltage drops observed were 3% and 2.7% on the FPSO and the power hub, respectively.

Fig. 9 presents the frequency behavior during the start up of M_7 in FPSO 1 and the tolerances given by the IEC 61892-1 [27]. The maximum allowed frequency deviation is ±10% during transients. If the frequency is increased by 10%, there would be no impact in the induction motors. If the frequency decreases, there would be a risk of saturation in the iron cores of those motors, which can cause damage. However, this is not the case with these induction motors,

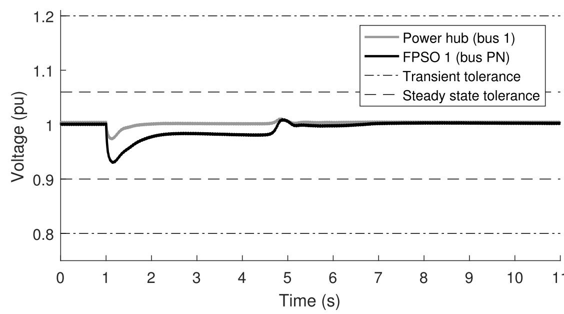

FIGURE 8. Voltage at bus PN of FPSO 1 during start-up of M_7 on FPSO 1.

which are built exclusively for direct online (DOL) start in FPSOs of the Brazilian pre-salt basin. Even without the power hub, these induction motors are already operating in the original FPSO with frequency margins of ±10 As shown in Fig. 9, the frequency of the offshore grid remains nearly unchanged during the start of M_7. This is thanks to the interconnection between three FPSO units and the power hub, which results in a system with a higher grid inertia than that found in a conventional single FPSO. The frequency drops in Fig. 9 were less than 0.2%.

B. FAULT CLEARANCE

The fault clearance study is conducted on FPSO 3, which is connected to the power hub by a 7 km length submarine cable, as was shown previously in Fig. 2. FPSO 3 is where the highest short-circuit currents are expected to arise, because

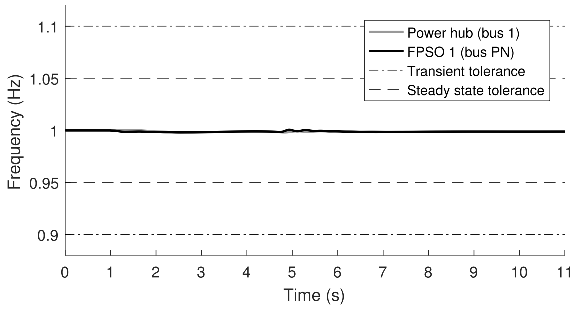

FIGURE 9. Frequency at bus PN of FPSO 1 during start-up of M_7 on FPSO 1.

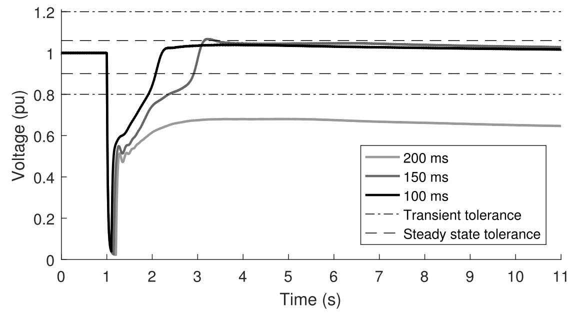

FIGURE 10. Voltage at bus PN of FPSO 3 during three-phase to ground short-circuit test at bus PN of FPSO 3 with fault clearance after 100, 150, 200 ms.

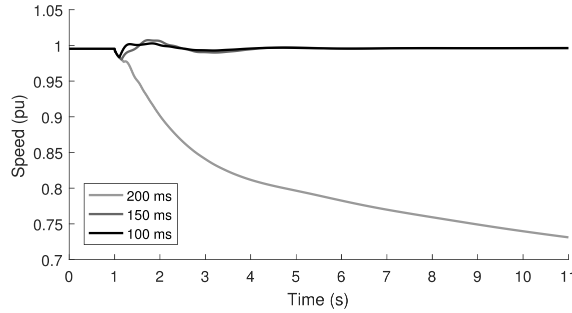

FIGURE 11. Speed of M_7 in FPSO 3 during three-phase to ground short-circuit test at bus PN of FPSO 3 with fault clearance after 100, 150, 200 ms.

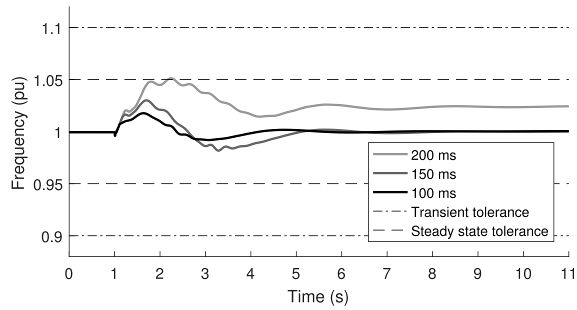

FIGURE 12. Frequency at bus PN of FPSO 3 during three-phase to ground short-circuit at bus PN of FPSO 3 test with fault clearance after 100, 150, 200 ms.

of the proximity to the power hub generation sourcees. The study considers a three-phase to ground short-circuit test at bus PN of FPSO 3 with fault clearance after 100, 150, 200 ms. The initial conditions consider motors M_1-M_7 in steady-state and the capacitor bank connected in all three FPSOs.

Fig. 10 shows the voltage at bus PN of FPSO 3 during three-phase to ground short-circuit tests at bus PN of FPSO 3. The fault occurs at t=1 s, and this figure depicts the voltage behavior with fault clearance after 100, 150, 200 ms. The tolerances given by the IEC 61892-1 [27] are also shown. With a clearing time of 100 ms, the voltage takes 1.08 s to return to the steady state tolerance range. With fault clearance after 150 ms this recovery time was 1.91 s, and with 200 ms the voltage collapses. Since the IEC 61892-1 establishes a maximum voltage transient recovery time of 1.5 s [27], it is recommended that three-phase faults in the vicinity of the PN buses of the FPSOs should be preferably cleared in a time not much greater than 100 ms.

As can be seen in Fig. 11, the voltage drop during the short-circuit fault decelerates the direct online induction motors, which can even stall depending on the fault clearance time. Consequently, the system voltage remains at a significantly reduced level after the fault has been cleared. This phenomenon is known as fault induced delayed voltage recovery (FIDVR) [36]. To prevent the system from going to short-term instability as shown in Fig. 10, an undervoltage protection is required to drop out the induction motors in case of sustained low voltages after the fault was cleared.

Fig. 12 shows the frequency in FPSO 3 during three-phase to ground short-circuit at bus PN of FPSO 3 test with fault clearance after 100, 150, 200 ms. It remained well within the limits specified by IEC 61892-1 [27] during the recovery from the fault. The maximum frequency deviations were 0.018 pu, 0.030 pu and 0.051 pu with fault clearance after 100, 150, 200 ms, respectively.

C. LOAD REJECTION

The load rejection studies were carried out considering two scenarios. In a first load rejection scenario, FPSO 1 is suddenly disconnected from the system following the loss of either a transformer or a cable. In the second scenario, all gas compressors that are operating (motors M_1-M_7) are sudden disconnected from FPSO 3. The initial conditions in both scenarios consider motors M_1-M_7 in steady-state and the capacitor bank connected in all three FPSOs.

Fig. 13 shows the voltages at bus 1 of the power hub and bus PN of FPSO 3 during sudden disconnection of FPSO 1. As can be concluded from the figure, the voltages which result from the simulation remain within the steady state and transient limits established by the IEC 61892-1 standard. The same holds to the system frequency, as shown in Fig. 14. The maximum frequency deviation was 0.021 pu, and the deviation in steady state due to unbalance between load and generation was 0.013 pu. Therefore, the sudden disconnection of an entire FPSO do not imply on operational risks to the system.

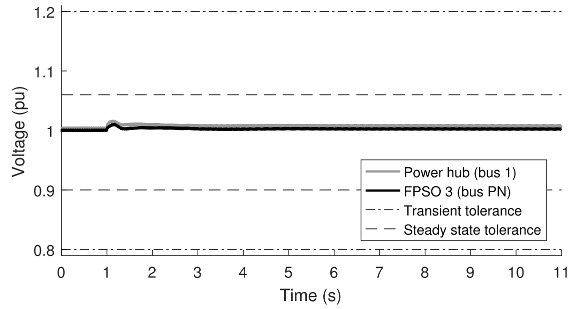

FIGURE 13. Voltages at bus 1 of the power hub and bus PN of FPSO 3 during sudden disconnection of FPSO 1.

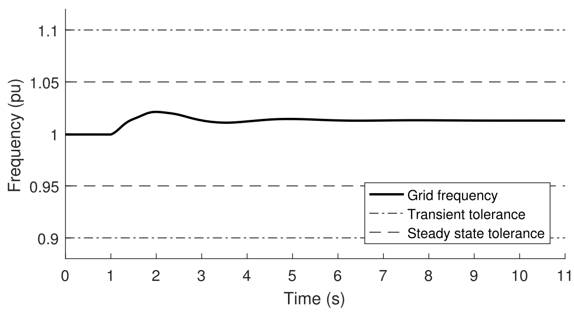

FIGURE 14. Grid frequency during sudden disconnection of FPSO 1.

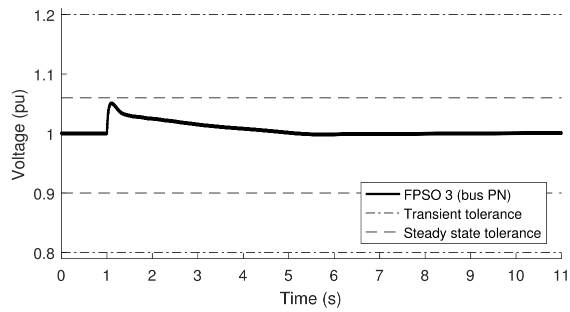

FIGURE 15. Voltage at bus PN of FPSO 3 during sudden loss of all gas compressors in FPSO 3.

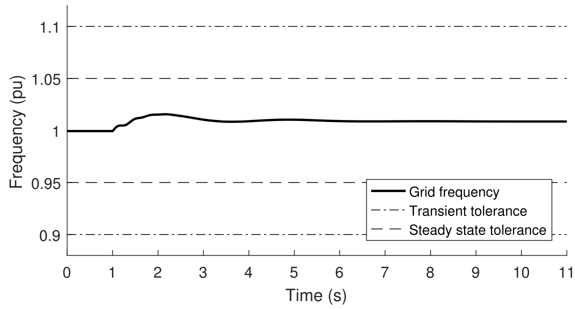

FIGURE 16. Grid frequency during sudden loss of all gas compressors in FPSO 3.

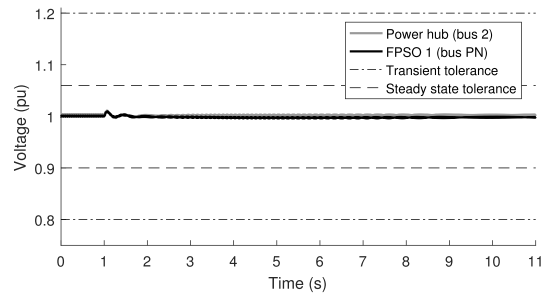

FIGURE 17. Voltages at bus 2 of the power hub and bus PN of FPSO 1 during the loss of generation without load rejection scenario.

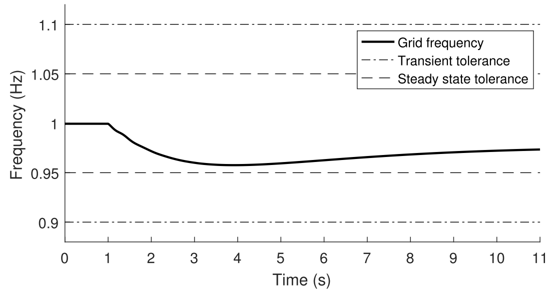

FIGURE 18. Grid frequency during the loss of generation without load rejection scenario.

Fig. 15 shows the voltage at bus PN of FPSO 3 during sudden loss of all gas compressors in FPSO 3. The maximum voltage deviation was 0.051 pu and, therefore, there was no violation of the IEC 61892-1 steady state and transient limits. Frequency is shown in Fig. 16. The maximum deviation was 0.016 pu and the deviation in steady state was 0.009 pu. Hence, the sudden disconnection of the gas compressors do not imply on operational risks to the system.

D. LOSS OF GENERATION

The loss of generation case study considers the sudden disconnection of a CCGT in the power hub. Such an event can be followed by a load shedding protection scheme, which consists of switching off two injection water pumps and two gas compressors 200 ms after the generation loss. Both scenarios, with and without this protection scheme, are analyzed.

Regarding the scenario with no control action after the generation loss, as shown in Fig. 17 and 18, results can be considered as acceptable where the system voltage and frequency are concerned, since both the quantities remain within the limits established in IEC 61892-1. However, as Fig. 19 shows, the OCGT generator of the FPSO 1 is overloaded, increasing their output from 20 MW to 33.8 MW during the simulation. This value is over the capacity of the generator. The other OCGTs from the other two FPSOs showed the same behavior in terms of active power increase. Therefore, this identifies the necessity for load shedding when it occurs the loss of a CCGT unit aboard the power hub.

The load shedding scheme is then implemented in accordance with the procedure defined previously. The three previous figures are replaced by Figs. 20, 21 and 22, which resulted from the new simulation. They show that the system voltage and frequency still remain within the standard limits, while the generator overload vanishes. The load shedding scheme

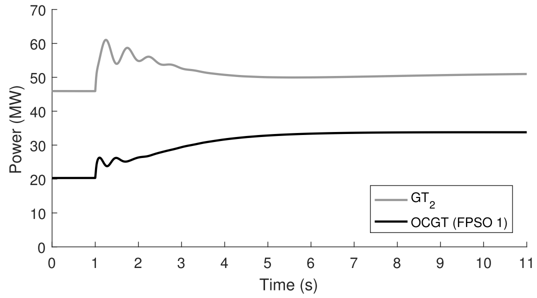

FIGURE 19. Generator loading during the loss of generation without load rejection scenario.

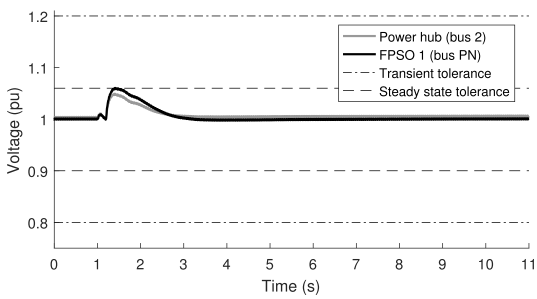

FIGURE 20. Voltages at bus 2 of the power hub and bus PN of FPSO 1 during the loss of generation with load rejection scenario.

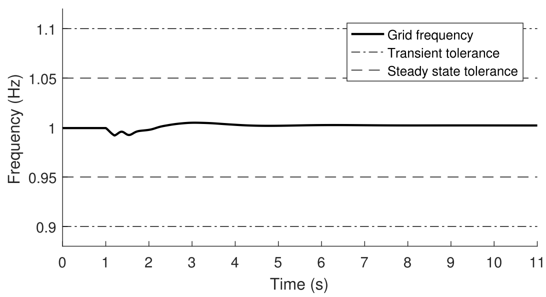

FIGURE 21. Grid frequency during the loss of generation with load rejection scenario.

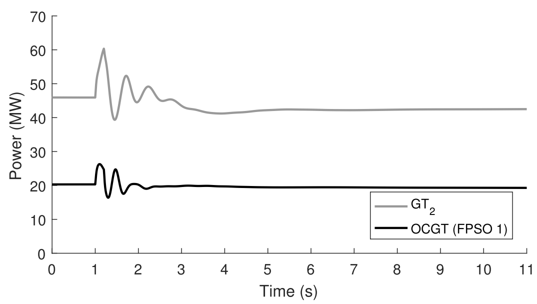

FIGURE 22. Generator loading during the loss of generation with load rejection scenario.

thus plays an essential role in avoiding the generator rated capacity to be exceeded.

IV. CONCLUSION

This paper presents an analysis of the isolated offshore electric grid that results from the deployment of the power hub concept, aiming at providing a more efficient power generation solution to the offshore O&G production in the Brazilian pre-salt basin. The paper details the models used to represent the FPSOs, the PH and the transmission system needed to interconnect them. In order to address the most challenging situations associated to the isolated grid operation, four types of studies are performed with the aid of PSCAD software tool: motor starting, short circuit analysis, loss of load and loss of generation that are identified as the main challenges in operating the grid. Simulations performed in PSCAD show that the adoption of the power hub is electrically feasible, complementing studies published in the literature concerning the improvement of efficiency in the generation that did not addressed the electrical grid. Moreover, these results are of interest of players in the offshore O&G industry in Brazil, that may become subject to carbon taxation in a near future, demonstrating that it is possible to operate an isolated power grid with a power hub feeding power to FPSOs in a determined oil field. Future research will focus on protection schemes to avoid the FIDVR phenomenon, also on the integration of renewable energy and the possible adoption of a HVDC transmission system between the power hub and the FPSO units.

APPENDIX
MODEL DATA
A. POWER HUB SYNCHRONOUS GENERATORS

GT rated power = 52.5 MVA, ST rated power = 17.5 MVA, $V = 13.8$ kV, $f = 60.0$ Hz, $H = 3.117$ s, $R_a = 0.0051716$ pu, $X_p = 0.163$ pu, $X_d = 1.014$ pu, $X'_d = 0.314$ pu, $T'_{do} = 6.55$ s, $X''_d = 0.28$ pu, $T''_{do} = 0.039$ s, $X_q = 0.77$ pu, $X'_q = 0.228$ pu, $T'_{qo} = 0.85$ s, $X''_q = 0.375$ pu, $T''_{qo} = 0.071$ s.

B. TRANSFORMERS

Rated power = 80.0 MVA, Rated voltages = 132.0 / 13.8 kV, $x = 0.063$ pu.

C. CABLES

$r = 0.0515$ Ω/km, $x = 0.1319$ Ω/km, $c = 250.0$ nF/km.

D. FPSO SYNCHRONOUS GENERATORS

Rated power = 31.25 MVA, $V = 13.8$ kV, $f = 60.0$ Hz, $H = 2.26$ s, $R_a = 0.002$ pu, $X_p = 0.138$ pu, $X_d = 1.74$ pu, $X'_d = 0.25$ pu, $T'_{do} = 3.52$ s, $X''_d = 0.2$ pu, $T''_{do} = 0.0423$ s, $X_q = 1.71$ pu, $X'_q = 0.25$ pu, $T'_{qo} = 1.7634$ s, $X''_q = 0.3$ pu, $T''_{qo} = 0.228$ s.

E. FPSO INDUCTION MOTORS

Rated power = 11.0 MW, $V = 13.8$ kV, $H = 1.0641$ s, $R_1 = 0.0045$ pu, $X_1 = 0.13155$ pu, $R_A = 0.00701$ pu, $X_A = 0.14112$ pu, $R_B = 0.13915$ pu, $X_B = 0.19506$ pu, $X_M = 3.9912$ pu, load curve $= 0.576(1 - s)^2$ pu.

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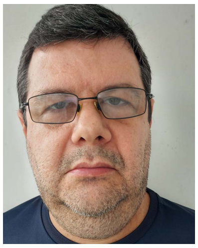

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