Electrification of offshore petroleum installations with offshore wind integration

E.Øyslebø/M.Korpås
SINTEF Energy Research, N-7465 Trondheim
eirik.veirod.oyslebo@sintef.no, Tlf: +47 73597191

***Summary* – This paper discusses transient stability issues related to combining offshore wind power with electrification of offshore petroleum installations. The study is based on a model that connects a petroleum installation cluster in the Norwegian part of the North Sea to the Norwegian power grid by using a VSC HVDC connection. Offshore wind power generation close to this petroleum cluster is investigated in the study. All parts of the modelled system are described in the paper, and several system topologies are discussed for use in the simulations part of the project. These simulations are mainly regarding transient stability of the offshore AC system, with focus on the quality of supply to the petroleum installations. Simulations show that faults on the offshore converter platform can be critical due to the dependency of the reactive power delivered by the HVDC-link to the offshore AC-system. However, it is shown that local wind power production matching the offshore power demand will improve both voltage and frequency stability. Further on, it is indicated that offshore reactive power injections or alternative wind farm control topologies could improve voltage stability offshore. The simulation work is done in the power system simulation software Simpow 11, developed by STRI AB.**

1. Introduction

Electricity to petroleum activities in the Norwegian part of the North Sea are mainly supplied by gas turbines located on the platforms. These turbines have a low efficiency ratio, and emit considerable amounts of CO_2 and nitrous oxides. An increased focus on climate change and emission reductions has made it interesting to address solutions for lowering these emissions from the Norwegian petroleum sector.

One way to reduce the need for these turbines is to connect the petroleum installations to the Norwegian power grid. This paper will discuss issues regarding a petroleum installation cluster in the southern part of the North Sea with long life expectancy and high CO_2 and NO_X emissions. The cluster is located 280 kilometers southwest of Norway, which means that it is well within the possible range of a VSC HVDC connection.

This solution will however reduce, but not eliminate the CO_2 emissions from the petroleum sector. The reason for this is that Norwegian power production has a relatively high dependence of hydrologic conditions. In dry years there are high imports from fossil fueled power sources which increases the CO_2 emissions of the electricity production mix.

An alternative for further emission reductions is to expand the system with offshore wind power production close to the oil and gas activities. The ocean depth and the wind conditions in this area could make such a wind farm both possible and favorable, both in terms of economy and emissions. This is the motivation for the current study, which investigates transient stability related to offshore wind and VSC HVDC in a situation where security of supply to the petroleum installations is highly valued.

2. Model data

2.1 Case study

Today, the area in question consists of nine petroleum fields, which again include several installations. Five of these are not candidates for electrification due to low electricity demand and/or short remaining life expectancy of the activity on the field. The four remaining installations are suitable for further investigations. The total power demand is estimated to be

142 MW, which is assumed to be constant in the simulations, see Figure 1. The total load is what is required of the gas turbines that produce electricity on the petroleum installations today. It is considered too difficult and expensive to replace gas turbines that directly feeds large loads by electrification via cable. Thus, replacement of direct-driven gas turbines is not is not treated in this study.

This area is already a hub for the North Sea grid of petroleum pipelines between the Norwegian sector and UK and Continental Europe. This could also be the case for a future offshore grid, but the wind farms and HVDC-links would be considerably larger than the ones that are investigated in this project. However, a larger system will be considered in further work. The area is also considered by a group of government directorates as one of the most suitable sites for offshore wind in the Norwegian sector [1].

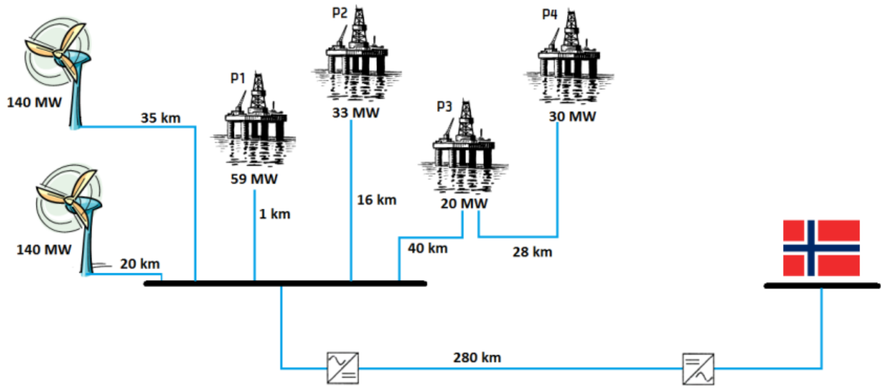

Figure 1 – Model overview

The VSC HVDC connection is designed to handle up to 200 MVA of power, in order to both be the balancing provider in terms of active power, but also the main provider of reactive power in the offshore power system. Therefore, the offshore converter unit is regarded as the balancing unit of the offshore AC-system, as the wind production units have a low degree of regulating capability. Three scenarios are investigated in the study:

1. 0 MW wind, 140 MW load
2. 140 MW wind, 140 MW load
3. 280 MW wind, 140 MW load

Scenario 1 represents electrification without wind power. Scenario 2 represents a system where the wind farm balances the offshore load when all wind turbines produces at full power simultaneously. Consequently, the cable is only used for import to the offshore system in Scenario 1 and 2. In Scenario 3, there is full export to shore when the wind turbines produces at full power simultaneously.

2.2 Simulation model

The simulation model is built in the power system simulation software Simpow 11, developed by STRI AB [2]. The simulation model consists of two AC grids connected with a VSC HVDC system. The AC system offshore is designed as a radial system with cables that connects the petroleum installations and the wind farms to the offshore HVDC-converter platform, which could be considered as the hub of the system, as shown in Figure 1. This converter will probably be located on a dedicated platform that will not be used for petroleum purposes due to footprint considerations [3]. In addition to the converter itself, there will be implemented filters on both sides of the converter, a transformer and eventually some reactive compensation equipment if needed.

A real life electrification of the electricity demand on a petroleum installation has to cover all loads except those that are directly driven by gas turbines. All four petroleum installation models have large motors representing pumps for oil and gas extraction (with a rating at about 6-8 MVA), but also smaller motors that for example generate electricity to lighting and housing of personnel. The gas turbines that are used to generate electricity on the platforms today, is assumed disassembled due to the footprint of the electrification equipment. It could be discussed that implementation of a system like this will not give an acceptable reliability of the supply to the petroleum loads, with no gas turbine backup. But this setup with replacing gas turbines with an electrical connection to shore is already chosen for several petroleum installations in the Norwegian sector, where the operational responsible parties see other increased values which makes such a system beneficial, as for example remote operation and lower need for labor [4].

For all of the scenarios with petroleum loads, the total power demand is given as shown in Table 1.

	P1	*P2*	*P3*	*P4*	***Total***
P (MW)	59.85	31.92	20.36	30.51	**142.64**
Q (MVAr)	32.79	19.59	11.48	16.73	**80.59**

Table 1 – Petroleum loads

The wind power plants consist of identical power generation unit models, which are called Full Power Converter Wind Turbines (FPCWT) in the Simpow library [2]. The implementation of a back to back converter, as shown in Figure 2, will give a high degree of control within the turbine model. The control system of the rectifier in the back to back converter will together with pitch control of the blades control the rotating part of the turbine to keep a constant rotational speed at low wind speeds, and a constant power output at higher wind speeds. The inverter will change its reactive power production or demand in order to keep the voltage on the grid side of the turbine at a certain level, i.e. voltage control.

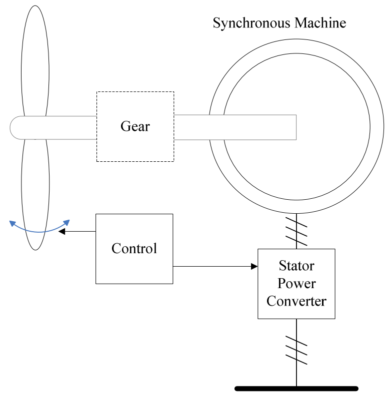

Figure 2 – Full power converter wind turbine

The voltage level of the offshore AC-system was set to 52 kV with cable parameters from ABB literature [5][6]. A voltage level of 52 kV is also used in earlier electrification considerations of this particular area [7], and will give an acceptable voltage level at the farthest points in the grid during normal operational conditions. Lower voltage levels will increase the need for reactive compensation, while a higher voltage level will increase costs without a substantial increase of the grid performance.

A voltage source converter based HVDC-system will connect this AC-system offshore to the Norwegian power grid that is located 280 kilometers to the northwest of the petroleum cluster. A 150 kV DC-installation with a total rating of 200 MVA is proposed. This topology has capacity to handle all four scenarios in this study during normal operation, but will also have margins for transient behavior. Control of the VSC HVDC system is based on results from another study, where the offshore converter station controls the offshore AC voltage and frequency, while the voltage and flow on the DC-cable is controlled by the onshore converter station [8]. This converter control topology makes the HVDC-link the most important component in the offshore AC-system when it comes to balancing issues and stability.

The other AC system in this simulation model is a simplified description of the Nordic synchronous system. This model was included to look at how transients in the offshore AC system could affect the onshore AC system, and vice versa. None of the simulations gave results interesting enough to be included in this paper, as the HVDC-system is too small to give a critical impact on the Norwegian power system. Also, the onshore faults that were investigated did not make critical transients on the offshore system. However, further work includes larger wind farms, and therefore a larger potential for implications in the onshore power grid due to offshore events.

Reactive compensation is considered as an instrument to improve the voltage in the areas offshore farthest from the converter, to improve voltage stability during fault events. A 30 MVAr Static Var Compensator (SVC) is inserted at P4 in some simulations to see the effect on the system voltage stability.

3. Simulation

3.1 Power flow

Static power flow analysis has been performed to assess power losses and voltage drops throughout the different system topologies. Table 2 gives the flow on the HVDC-link. Positive numbers means import from the Norwegian power grid to the offshore AC-system.

	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 4*
Active power (MW)	147.91	17.79	-109.94	-129.44
Reactive power (MVAr)	76.21	90.47	117.49	33.58
Apparent power (MVA)	166.39	92.20	160.91	133.72

Table 2 – HVDC power flow

When investigating the total system losses, there is a clear relation between HVDC-cable loading in Table 2 and HVDC-system losses in Table 3. The losses in the HVDC-cable range from 2% when the power flow on the HVDC-link is relatively small in the second scenario, up to 5-7% losses when the HVDC-system is fully, or close to fully loaded. Table 3 shows clearly that introduction of wind power generation in the offshore system will improve the system in terms of total losses, since the production of power is located closer to the consumption.

	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 4*
Total Losses (MW)	17.35	9.97	19.12	9.13
Total Losses (%)	10.84	6.53	7.23	6.91
HVDC-system Losses (MW)	10.15	0.41	5.50	6.77
HVDC-system Losses (%)	6.34	2.00	5.10	5.22

Table 3 – Steady state power losses

3.2 Power system stability

Power system stability studies in this paper are focusing on voltage and frequency stability in order to keep the quality of the power supply to the petroleum installations at an acceptable level.

	Voltage (ΔU)	*Frequency (Δf)*
Constant	+6 / -10 %	±5 %
Transient	±20 %	±5 %
Cyclic	±2 %	±0.5 %
Recovery time	1.5 sec	5 sec

Table 4 – Transient requirements for offshore installations

The simulations are investigated with reference to existing requirements regarding voltage and frequency. Table 4 shows threshold values from the NORSOK E-001 standard [9] developed by the Norwegian petroleum industry, which is based on international standard IEC 61892-1 for mobile and fixed offshore units [10].

Figure 3 shows the locations on the faults that are investigated. Cases 1 and 2 will isolate wind production and petroleum load from the Norwegian power system and the HVDC-link, and are expected to be the most critical situations. A short circuit fault on one of the wind power plants, as depicted in case 3, is also interesting due to the immediate power imbalance that is caused by this event. All simulations are run for a 20 seconds period, where the fault occurs after 2 seconds, with a succeeding reconnection after 2.1 seconds. The following figures are cut to show the period from t=1 second to t=5 seconds, as this is the transient period of time for all simulations given in this paper.

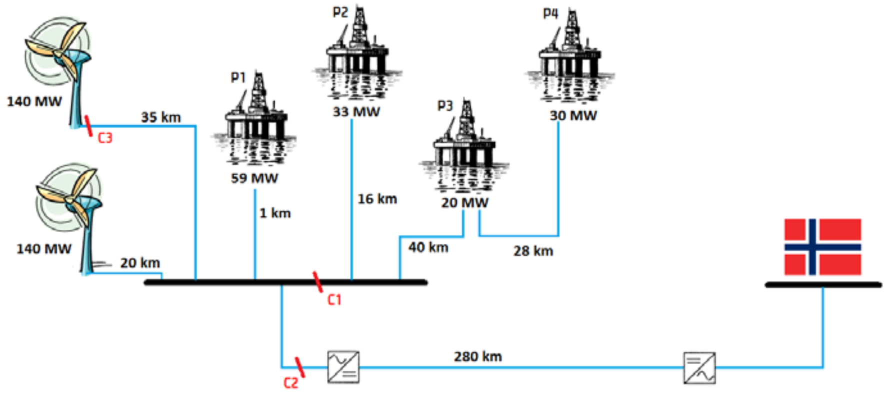

Figure 3 – Fault locations

3.3 Case 1

The first dynamic event to be investigated for the three scenarios is a short circuit fault on the main busbar of the converter platform, that isolates every radial, as shown in Figure 3. This means that the complete system is split into several islanded systems during the fault, where the number of islanded systems depends on which scenario is investigated (i.e. for scenario 1, there are four subsystems during the fault: P1, P2, P3&P4 and the onshore grid). The system is re-connected after 100 milliseconds.

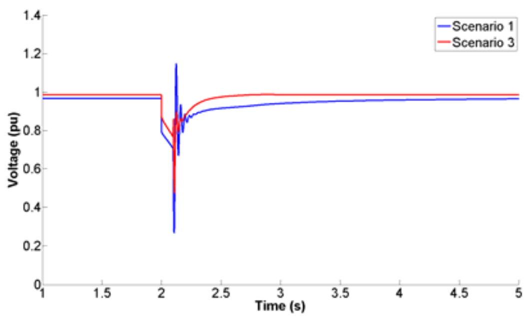

Figure 4 – Voltage on platform P1 in case 1 for scenarios 1 & 3

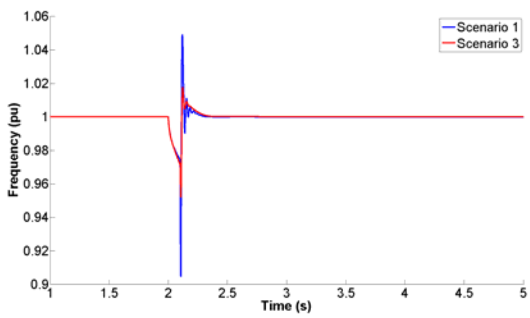

Figure 5 – Frequency deviation in case 1 for scenarios 1 & 3

Figure 4 show that oscillations are reduced when introducing wind power to the offshore system. The figure show the cases with 0 MW and 280 MW wind power generation (in blue and red graphs respectively), and it is clear that both the amplitude of the largest dips and the recovery time of the voltage is improved in the 280 MW wind case. Scenario 2 with 140 MW wind is not shown in the graphs, as it is neither worst case, nor best case when it comes to voltage stability. This is also the case for the frequency deviations, which is shown for scenarios 1 and 3 in Figure 5.

The reason for the improved stability, which is experienced in the case with the highest wind penetration, is that the wind turbines will use some milliseconds to get back to pre fault production levels, and will therefore reduce the demand for reactive power from the HVDC-interconnection immediately after re-connection of the whole system.

The system shows improved stability with wind power integration. In both scenarios, the voltage dip amplitude exceeds given requirements, but less for the case with wind power. The frequency plots in Figure 5 shows the same improvement as for voltage.

3.4 Case 2

The next dynamic event is a short circuit on the converter platform that isolates the AC system from the HVDC-interconnection and the Norwegian power grid. The biggest difference between cases 1 and 2 is that in case 2, the fault is closer to the converter, which makes it possible to continue running the offshore AC-system as one complete islanded system. The system is re-connected to the HVDC-link after 100 milliseconds.

Figure 6 show the voltage and Figure 7 the frequency for scenarios 1 and 2. Scenario 3 gives unstable conditions for this case. This is because of the large dependency of reactive power from the HVDC-connection which induces a voltage collapse in the time period between fault and re-connection. Additional simulations indicates that reactive compensation on the converter platform could improve system stability and prevent voltage collapse, but the compensation unit would be quite large in order to keep the system stable, so alternative solutions on how to prevent collapse will be interesting in future work.

One option for reducing the reactive power demand in the offshore grid would be to change the control of the wind turbines. As it is implemented in the current model, the voltage control of the wind turbine inverter makes the converter consume reactive power from the grid in order to keep the voltage at a given level. A change from voltage control to power factor control could be interesting, because of the increased flexibility when it comes to reactive power. However, it is important to still keep the AC-system voltage at reasonable levels, which is crucial to have in mind when investigating this subject in further work.

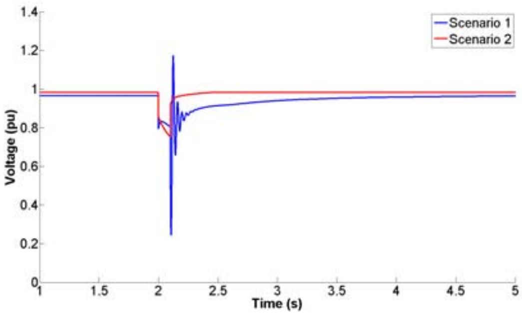

Figure 6 – Voltage on platform P1 in case 2 for scenarios 1 & 2

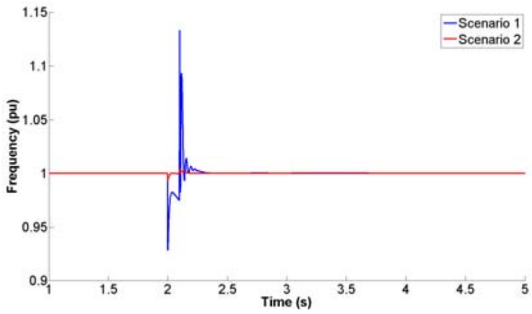

Figure 7 – Frequency deviation in case 2 for scenarios 1 & 2

As Figures 6 and 7 shows, the amplitude of the oscillations are utside given limits for scenario 1. For scenario 2 however, both the frequency and the voltage behavior is better, and shows that the system could run without the offshore voltage controller (which is the offshore HVDC-converter) for a small period of time. The frequency is almost constant because of the low dependency for the HVDC-link when it comes to active power flow (wind power generation matches the load), but there is still need for the HVDC-link for delivery of reactive power, which is the reason for the voltage transient that is given in Figure 6.

3.5 Case 2 with SVC

In addition to the reactive power issues for the complete system when experiencing a short circuit, as discussed in the previous subsection, there are other issues regarding voltage stability in this model. The voltage on P4 is the one that is most vulnerable to faults and transients as shown by the blue graph in Figure 8. The blue graph in Figure 9 could be used as reference, as this shows the voltage on platform P2 in the same case. When comparing these graphs, it is obvious that the voltage on P2 has a better transient behavior during faults than the voltage on P4.

An SVC unit with a 30 MVA rating was introduced on platform P4 to increase voltage stability for platforms 3 and 4, which are located far away from the nearest source of reactive power. As the red graph in Figure 8 indicates, both transient and steady state voltage on P4 improves when introducing this SVC unit. For the behavior of P2, there is not a big difference when introducing this unit, but there is a small improvement in the oscillation amplitudes.

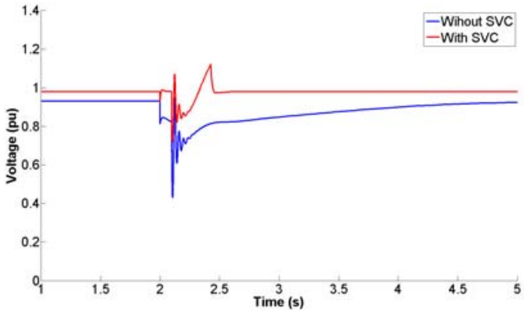

Figure 8 – Voltage on a platform close to the SVC-unit (P4)

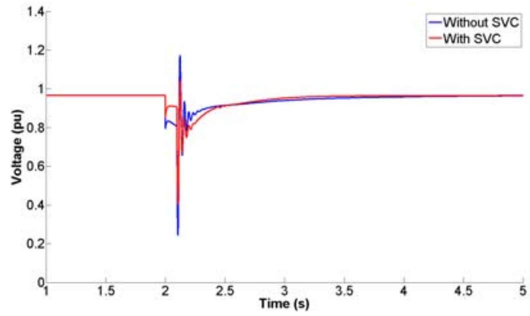

Figure 9 – Voltage on a platform far from the SVC-unit (P2)

An SVC unit of this size will cover all reactive power demand for the platforms P3 and P4 and will thus ensure local reactive power production to these platforms. This is considered as one of several solutions to the problem. Other solutions could include leaving a gas turbine on platform P3 or P4, increasing the voltage level offshore or increasing the size of the cable between the offshore converter and P4 in order to reduce losses. These are all interesting alternatives that are possible from a technical point of view, and should be addressed further also with respect to cost and reliability.

3.6 Case 3

The last dynamic event that is investigated in this paper is the event of a short circuit in a wind farm that temporarily isolates the wind turbines in that particular wind farm from the petroleum loads and the HVDC-interconnection. This happens for all cases that include one or more wind farms, which is scenario 2, 3. For scenario 3 it is important to notice that there is only a short circuit on one of the wind farms. The system is reconnected to its pre fault situation after 100 milliseconds.

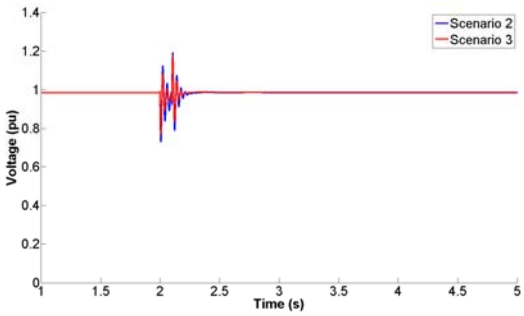

Figure 10 – Voltage on platform P1 in case 3 for scenarios 2 & 3

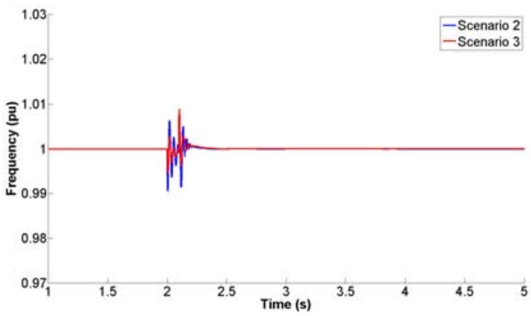

Figure 11 – Frequency deviation in case 3 for scenarios 2 & 3

For scenarios 2 and 3, frequency and voltage behavior during and after fault is almost similar, as shown in Figures 10 and 11. The reason for the similarity of the results is the invariable nature of the petroleum loads and the remaining wind power, which makes the HVDC-interconnection the main balancing provider in this case. The event will cause some transients to emerge, due to the sudden imbalance of both active and reactive power.

4. Conclusion

Integration of wind power production in electrification projects for offshore petroleum installations is shown to improve system stability regarding voltage and frequency during and after short circuit faults. This is shown when investigating two of the most severe short circuit events that the offshore grid could experience, for a case where the offshore wind farm is dimensioned to balance the offshore power demand at full wind power generation.

It is also shown that faults which isolates the offshore AC-system from the HVDC-cable makes unacceptable voltage deviations due to the lack of reactive power in the offshore system. For a case with a wind farm capacity twice the size of the offshore power demand, such faults may lead to unstable conditions. This could be improved by inserting reactive compensation. Power factor regulation instead of voltage regulation of the wind turbines could also be desirable, as it will increase local production of reactive power, and will make the offshore AC-system less dependent of the HVDC-system for acceptable system stability during transient events.

Further work includes an increased system size, where the HVDC-link will be dimensioned by a larger offshore wind farm, and not by the petroleum load size, as was the case in this study. Further focus will also be on the reactive power challenges that were identified in this study, with investigating alternative control structures for the wind turbines.

5. References

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