Steady State Analysis of the Interconnection of Offshore Energy Parks

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Abstract - Among the renewable energy sources, wind energy has gained relevance, becoming a viable alternative to conventional sources. High wind speeds and wide available area at sea have recently increased the global interest on offshore wind farms. As offshore wind farms become larger and are placed further from the shore, the power transmission to the onshore grid becomes a key feature. The available options are HVAC, HVDC-LCC and HVDC-VSC. The objective of this work is to compare the performance in steady-state and the transient behaviour of two alternative transmission systems: HVAC and HVDC-LCC. Compensation schemes for excessive reactive power for HVAC are also evaluated, as well as the benefits of the STATCOM for both technologies. The PSS/E software is used for simulation of all cases. The results obtained show some important differences for the technologies. In steady-state, the behaviour of HVDC-LCC and HVAC with compensation both onshore and offshore hold some similarities, namely in the power factor and the power losses. In transient regime, the response of the HVAC link to a fault in the grid is very different to the response of HVDC-LCC link. The HVAC link allows the “fault ride through” of the offshore wind farm while the HVDC link is blocked, interrupting the power transmission during the fault.

Keywords: Offshore Wind Farms, HVAC, HVDC-LCC, STATCOM, PSS/E.

I. Introduction

The energy crisis that affected the world in the 1970s and 1980s led to major changes in the hitherto energy paradigm. Reducing the world’s dependency of fossil fuels became a priority, as the finiteness of these resources was found to be truly concerning. The need to guarantee diversity and reliability of energy sources, together with the fast growing concern for environmental issues also contributed to a greater interest in alternative energy sources.

In fact, renewable energy sources such as wind, solar photovoltaic and hydro power, to name a few, have suffered significant increases in recent years. The installed power over the last ten years has increased in such way that renewables account for more than 50% of new installations in the EU [1]. Among the available renewable sources, wind power clearly stands out as one that experienced the largest increase in installed power: wind power’s share of total installed capacity has increased from 2% in 2000 to 9% in 2009 [1].

More recently, placing wind turbines at sea became a possibility, as many of the windiest locations onshore are already occupied. Higher wind speeds at marine locations and wider installation areas, together with the possibility of moving wind turbines away from population – to which wind turbines may cause some discomfort – were the main reasons driving the investment on offshore wind energy. The Vindeby wind farm in the Baltic Sea, off the coast of Denmark, was the first offshore wind farm in the world.

The technology used for the interconnection of offshore wind farms influences in a very significant manner the whole operation of the system. As so, the main characteristics of operation for each transmission system have to be assessed and thoroughly studied, including steady-state analysis and dynamic behaviour analysis of the link (when disturbances occur), making this an important field of investigation in the near future.

II. Wind Energy Offshore

1. The Wind Resource

The nature of the surface influences the wind profile at a given region. Offshore, the smoothness of the surface of the ocean results in a low surface roughness (a parameter referred to as \( Z_0 \)). Offshore locations are in fact windier and the winds are more persistent than those at an onshore location. These effects increase with distance from shore in the downwind direction, making it more appealing to locate offshore wind farms further from land [2].

As the power that can be extracted by a wind turbine is proportional to the cube of the wind speed (as given by
Equation (1)), the extracted power is highly dependent on the wind speed [3].

\[ P = \frac{1}{2} \rho A u^3 \]  

(1)

Therefore, and given the fact that wind speed offshore is potentially higher than onshore, a 10% increase in wind speed results in an approximate 30% increase in power production, making wind power offshore a very interesting option.

2. Offshore Wind Farms

The fact that offshore wind farms are located at sea offers several advantages but also poses major challenges for potential investors. Some relevant constraints associated with the offshore wind farms that need to be considered are the following:

- Installation and maintenance of a large structure located far from shore is a complex procedure, given the distance and the need for special ships;
- Accessibility of turbines may prove difficult, as harsh weather conditions and extreme waves are likely to exist at sea;
- As a consequence, materials used for wind turbines and additional equipment need to be resistant to physical impact as well as to salt corrosion (when the wind farm is placed in salt water);
- Overall, at present time, the construction and maintenance of offshore wind energy is more expensive than on shore, given the higher costs of foundation, installation and electrical connection of wind farms [4].

However, as the number and size of offshore wind farms increase, technology is likely to advance to deal with these problems and reduce transportation and installation costs. The advantages will outweigh the disadvantages making offshore wind farms a reliable investment [4].

Advantages of offshore wind power are as follows:

- Wind speeds are higher offshore than onshore, which means that a large potential for power production lies offshore. In fact, the annual average full-load hours offshore is between 3500-4000 hours, while for onshore this figure is between 1500 and 3000 (the average being around 2000 hours) [5];
- Winds at marine locations are more persistent and less turbulent than those on land;
- Due to the proliferation of wind parks onshore, some countries are running out of suitable onshore locations, as the windier sites are already occupied;
- A wider area for installation of wind turbines is also likely to be available at sea, compared to land;
- Wind turbines that might be intrusive and cause visual and noise impact on land might be acceptable if sited away from shore, far from population.

3. Transmission Technologies Overview

Currently available technologies for transmission system to shore are high voltage alternating current (HVAC) and high voltage direct current (HVDC). For HVDC connections, there are two technical options: line commutated converter based HVDC (known as HVDC-LCC) and voltage source converter based HVDC (HVDC-VSC). The AC connection has been used in all offshore wind farms. The HVAC solution is indeed the most straightforward technical approach as it features some interesting advantages such as ease of interconnection, installation and maintenance; operational reliability and cost effectiveness. Some disadvantages include the limits for transmitted power, associated to the charging current on AC cables, which will limit the maximum distance of transmission. Some scheme of reactive power compensation must then be used in AC cable systems. HVDC solutions might prove a reliable option for large wind farms further from shore as this technology has some very promising characteristics. One of the most important is the ability to transmit large amounts of power over long distances with lower losses than HVAC. Since the transmission is done using DC cables, the transmission distance is not affected by cable charging current. Main disadvantages include the complexity and associated cost of installation and maintenance of the HVDC system, which may well be overcome in the future, due to economies of scale.

4. Grid Connection Requirements

Until some years ago wind farms were allowed, or even required, to disconnect from the grid during a disturbance in the grid [6]. This has changed significantly, specially due to the proliferation of large amounts of installed wind power capacity and, predictably in a near future, installed capacity offshore. The disconnection of a large offshore wind farm would result in a significant loss of generation that could cause some stability problems to the network. Transmission system operators require nowadays for offshore wind farms to stay connected under certain disturbances in the grid. These requirements are known as the fault ride through capability of the wind farm and are generally regulated in grid codes. As established in most grid codes, only under certain circumstances shall wind farms be disconnected from the grid following a grid fault, remaining otherwise connected in order to assist in the stabilization of the grid frequency or the voltage during fault, providing voltage back-up.

Apart from the fault ride through capability, other technical requirements must be fulfilled by the wind
farm, since the increasing size of offshore wind farms means that the rating of such installations will be comparable to that of traditional generating plants on the grid. These requirements include: control of active and reactive power (operation under a specified range for power factor); frequency range (with time durations for extreme conditions, permissible reduction at frequency extremes, if any); contribution to network stability and AC voltage control capability [7] [8].

As the proliferation of offshore wind power increases, wind farms will be bound to meet these demands, which may prove difficult depending, to great extent, on the transmission system used between the wind farm and shore.

### III. Transmission Technologies

There are currently three different transmission technologies available:

- HVAC – High Voltage Alternate Current;
- HVDC-LCC – High Voltage Direct Current with Line Commutated Converters;
- HVDC-VSC – High Voltage Direct Current with Voltage Source Converters;

#### 1. HVAC Transmission

Connecting the wind farm to the grid by an AC cable is the most straightforward technical solution, as both the power generated by the wind farm and the onshore transmission grid are AC. In fact, all the operational offshore wind farms use HVAC for the connection link to shore. The HVAC transmission offers some advantages over the DC solutions such as [7] [9]:

- Proven and low-cost technology;
- Easy to integrate in existing power systems;
- Low losses over small distances.

On the other hand there are some constraints of the HVAC system that limit significantly the use of this technology, namely [7] [9]:

- There is an excessive amount of reactive power produced in the AC submarines cables;
- Increase in the cable length means increase in its capacitance which results in a reactive power increase, resulting in a transmission distance limit for AC systems;
- Necessary use of compensation systems (shunt reactors, STATCOMS, SVC, etc) at the ends of the cable;
- Load losses are significantly higher for longer distances;
- For large wind farms several cables may be necessary, increasing line losses.

#### 1.1. AC Submarine Cable

The submarine cable used in the transmission system is one of the most important components of the system, as the cost of the cable represents a large fraction of the total cost of the offshore wind farm investment. A submarine cable has typically the following structure [9]:

- Conductor core, typically copper or aluminium;
- Electrical Insulation, either solid dielectric (XLPE cables) or oil impregnated paper (OIP);
- Shielding, a conductor layer of paper or polymer;
- Sheathing, metallic layer used to ground the cable and also protect it from water;
- Armour, an outer metallic armature, to increase mechanical resistance;
- Optic Fibre, for communications;

The link can be achieved with either three single-core cables or one three-core cable (more than one may be used, depending on the transmitted power). The latter is the most common type, as it represents lower cable and installation costs and lower electromagnetic fields and induced current loss, compared with separate cables.

The main types of AC cables differ in the electrical insulation used in the cable. Historically, cables used lapped paper insulation impregnated with insulating oil. These cables are:

- High-pressure pipe-type, either fluid-filled (HPFF) or gas filled (HPGF);
- Low-pressure oil-filled (LPOF).

Cross-linked polyethylene cable (XLPE) cables are currently the most cost-effective and modern alternative. The insulation is made of solid dielectric (also called extruded dielectric or polymeric insulated) and it presents several advantages over the fluid-filled options: higher mechanical resistance, lower weight and, consequently, easier installation process [9]. Furthermore, XLPE cables have lower capacitance and lower dielectric losses than the fluid-filled cables.

One three-core XLPE cable is shown in Figure 1, where the structure described above can be seen.
The major problem concerning the connection of wind farms with AC submarine cables is the fact that cables generate significant amounts of reactive power. This reactive power is produced by the high shunt capacitance of cables (significantly higher than overhead lines). In the AC system, the cable must carry the load current and the reactive current generated by the cable capacitance, which reduces the power rating of the cable.

Considering the cable is modelled by an equivalent π-model, the submarine cable can be represented by the scheme shown in Figure 2. The charging current at each end are represented by $I_{c_1}$ and $I_{c_2}$.

Neglecting the voltage drop across the resistance and the reactance of the cable, one can consider that $V_1 = V_2 = V$. As so, the total charging current affecting the cable is the sum of $I_{c_1}$ and $I_{c_2}$ (as represented in Figure 2) and is represented by $I_c$, which is given by Equation (2):

$$I_c = \omega \cdot C \cdot V$$

(2)

In the equation,
- $\omega$ is the angular frequency (rad/s),
- $C$ is the capacitance (F)
- $V$ is the terminal voltage (V).

From Equation (2) it is clear that, as the cable system voltage is increased to minimize losses, the charging currents also increase, worsening the situation.

The reactive power generated by the shunt capacitance is then given by Equation (3):

$$Q_c = -\omega \cdot C \cdot V^2$$

(3)

Note that the negative signal means the capacitance supplies reactive power to the grid. From Equation (3) it can be seen that the reactive power generated by the cable is a function of the capacitance and the voltage, being particularly dependent on the voltage (since it is squared).

Since the cable capacitance is distributed along the entire length of the cable, the longer the cable the higher the capacitance and the resulting generated reactive power. As a consequence, the load carrying capability of the cable is reduced, which means that a cable can only transmit a certain amount of power for a given distance. This results in an obvious limitation for the length of AC links.

1.2. Reactive Power Compensation

The solution for the large amounts of reactive power at the cable is to compensate the reactive power produced by absorbing reactive power, thus reducing the additional losses and increasing the maximum transmitting distance. The compensation is usually realized by fixed or electronically controlled shunt reactors. The fixed shunt reactor is the simplest device but the progress in FACTS (Flexible AC transmission system) devices, such as SVC (Static VAr compensator) or STATCOM (Static Synchronous Compensator), considerably extends the reactive power and voltage control possibilities offered by the switched shunt reactors.

Shunt reactors are the most commonly used devices as they represent simple and robust solutions with low installation costs. They also have the advantage of requiring no transformer for the connection, thus having no additional power losses. One of the disadvantages is that the reactors are designed for a single operational mode, usually to compensate the cable at full load. Another disadvantage is the fact that the reactive power absorbed by the shunt reactor is proportional to the square of the terminal voltage.

The STATCOM device uses a power electronic voltage source (VSC). The converter uses semiconductors with turn-off capability, such as Insulated Gate Bipolar Transistors (IGBTs). The benefits of the STATCOM (commercially known as “SVC Light” by ABB or “SVC Plus” by Siemens), compared with the SVC, are the fact that the capacitor banks used are smaller and also there is no need for big air-cored inductors. Further advantages of the STATCOM are also found in the dynamic behaviour (such as faster transient response).

The SVC (“SVC Classic” for some manufacturers) is based on conventional capacitor banks together with parallel thyristor controlled inductive branches. These inductive branches can either be TCR (Thyristor Controlled Reactor), used for linear injection of reactive power or TSC (Thyristor Switched Capacitor), used for stepwise injection of reactive power.

The SVC and the STATCOM are part of the FACTS device family, used for voltage regulation and power
system stabilization, based on power electronics. These devices are capable of both generating and absorbing reactive power. The flexibility of use is, therefore, the main advantage of these equipments, since they allow the continuous variable reactive power absorption (or supply). The reactive power is not proportional to the voltage at the bus, also another advantage of these equipments. The FACTS devices can also contribute in the improvement of the voltage stability and the recovery from network faults.

The distribution of the reactive power compensation devices is also an important matter. The best solution is to install distributed compensation along the cable, since the charging current generated would flow towards the reactor, not increasing the rating of the cable so significantly. It is however important to notice that the placement of reactive power compensators in the middle of the cable is likely to not be possible, as the installation of these interstitial reactive power compensators would present an added technological and economic challenge.

2. HVDC-LCC Transmission
The main advantage of HVDC-LCC over the HVDC-VSC is its proven track record, since there is an accumulated experience of decades for this technology. The first commercial HVDC-LCC connection was installed in 1954 and since then many other conventional HVDC links were installed all over the world.

Some of the most important advantages that HVDC-LCC transmission offers over AC are [11] [12]:
- Asynchronous connection, since sending and receiving end frequencies can differ;
- Transmission distance using DC is not limited by cable charging current;
- Low cable power losses;
- Higher power transmission capability per cable;
- Power flow is fully defined and controlled;
- HVDC does not transfer short circuit current.

Some of the constraints of HVDC-LCC transmission are the following [11] [12]:
- No experience in connecting offshore wind farms;
- Production of harmonics in the converter, making the use of filters necessary;
- The converters at each end consume reactive power.

The LCC power converters (onshore and offshore) are the most important elements in the system, as they perform the AC/DC conversion offshore and the DC/AC conversion onshore.

In the LCC converter the current is always lagging the voltage due to the control angle of the thyristors; hence these converters consume reactive power. For this reason, reactive power compensation is necessary at both ends to provide reactive power to the system. Capacitor banks or STATCOM devices are considered for this effect.

2.1. DC Submarine Cable
The elements comprising a DC cable are the same as the ones in an AC cables. As so, like the HVAC cables, the HVDC cable main technologies available differ in the electrical insulation used:
- Oil Filled (OF) cables;
- Mass Impregnated (MI) cables;
- Cross-linked Polyethylene (XLPE) cables.

In Oil Filled cables (also known as SCFF – Self Contained Fluid Filled) the insulation consists of paper impregnated with low-viscosity oil. The danger of oil spill and the need for cable protection are also obvious disadvantages of the Oil Filled cable technology.

Mass Impregnated cables have similar construction but the paper insulation is impregnated in resin and high viscosity oil and no oil circulation system is required. It is the most used cable technology in existing HVDC systems and so the track record and high reliability are some of the advantages of the MI cable.

In XLPE cables the insulating material is made of solid dielectric, also known as extruded dielectric. It is a relatively new technology, developed to overcome some of the limitations of the previously referred technologies.

2.2. Converter Technology
The 12-pulse converter is a series-connection of two 6-pulse converter bridges and it requires two 3-phase transformers, one with a star-star and the other with star-delta (i.e. with 30º phase shift between them).

This arrangement has some advantages when compared to the 6-pulse bridge converter, namely the fact that the converter injects harmonic currents of orders n=12k±1 into the AC system, and so no filtering of lower order harmonics, like the 5th and 7th is necessary (like in the 6-pulse converter) [13]. The alternate voltage supplied by the AC network is also more sinusoidal, meaning it has lower harmonic content, requiring less filtering. The voltage on the DC side repeats itself 12 times during the cycle, making it closer to the ideal continuous voltage. In the 6-pulse converter the voltage repeats itself six times during a period at AC grid frequency.
2.3. HVDC-LCC + STATCOM

The STATCOM provides the necessary commutation voltage to the HVDC converter, continuous AC voltage control, fast reactive power compensation to the network under transient conditions and removal of possible non-characteristic harmonic interactions [14]. The STATCOM can also provide limited active power support to the network during transient conditions, such as active power changes of the wind farm output. However, the ability to provide active power support depends on the energy storage on the DC side, which in the case of a conventional DC capacitor will be very limited. Larger energy storage could be provided by means of batteries or SMES (Superconductive Magnetic Energy Storage).

The HVDC-LCC transmission system may benefit significantly from the STATCOM technology since it can, in steady state, provide the reactive power consumed by the converter. In a LCC transmission systems both converters absorb reactive power, as in the converters the current always lags the line voltage due to the requirements for a positive commutation voltage at the firing of the thyristors. Thus, this type of converter needs reactive power for operation, which has to be provided by reactive power devices connected to the AC network. As these converters depend on the line voltage for commutation, a minor disturbance in the AC voltage might also result in commutation failures in the converters.

3. HVDC-VSC Transmission

HVDC with voltage source converters is a fairly recent technology (first installed in 1999) and it is known commercially as “HVDC Light”, for ABB and “HVDC Plus”, for Siemens. VSC converters are self-commutating, not requiring an external voltage source for its operation. Also, the reactive power flow can be independently controlled at each AC network and the reactive power control is independent of active power control. These features make VSC transmission an interesting option for connection of offshore wind farms. In addition to the referred HVDC advantages, the VSC technology also offers the following main benefits [7] [9]:

- Total control of active and reactive power;
- Minimum risk of commutation failures;
- Smaller size of converters and filters than HVDC-LCC;
- Possibility of the converters starting with a dead grid, not needing any start-up mechanism (“Black-start” capability).

However, there are some constraints to the use of VSC technology. The main constraint is the considerably lower experience in HVDC transmission, compared with the LCC option. HVDC-LCC has more than 30 years of service experience, with high availability rates.

IV. PSS/E Modelling

In order to simulate the behaviour of an offshore wind farm and of the required transmission system, appropriate models of the wind farm, the transmission system (either HVAC or HVDC) and the electrical grid have to be constructed. Only then is it possible to analyse the steady-state and the transient behaviour of the power system. The software used to model the system and perform the simulations in the work of this thesis is the PSS/E software. PSS/E stands for Power System Simulator/Engineering and it is a software tool provided by Siemens Power Technologies International (PTI). It is used by most utilities in the world to perform power system simulations, as it allows the performance of power flow analysis, dynamic simulations and stability studies, among other features.

The electrical grid that will be used for steady-state and transient analysis – and in which the offshore wind farm will be integrated – is the “savnw” network, provided by PSS/E as an example of a relatively large grid, as it has 23 buses, 6 generators and 7 loads. In order to properly use this grid, a few changes were made, namely to the operating frequency and voltage levels. These changes were made taking into account values used in the European electrical grid.

The offshore wind farm and the HVAC and HVDC-LCC transmission systems were modelled accordingly.

V. Power Flow Results

1. HVAC Power Flow

For the HVAC transmission system the power flow analysis focuses on the reactive power flow in the submarine 100 km cable. Therefore, with the objective of compensating the reactive power generated in the cable, some reactive power compensation options are studied. The alternatives considered are reviewed in Table 1.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Onshore (Mvar)</th>
<th>Offshore (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore shunt reactor</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Onshore shunt reactor</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>Onshore and offshore shunt reactors</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Offshore STATCOM</td>
<td>0</td>
<td>64</td>
</tr>
</tbody>
</table>

The main criteria for the choice of the value of the shunt reactors (defined in terms of reactive power injected, in Mvar) is the power factor at the PCC, which
is chosen to be approximately of 0.9, a typical value in grid integration of wind farms [7]. As so, the shunt reactor chosen for offshore compensation only absorbs 60 Mvar, as the 0.9 power factor at the PCC is guaranteed with this value.

Table 2 shows the results obtained for the power factor at the PCC, the voltages at each end of the cable and the active and reactive power at each end of the cable for the four configurations studied. The values are taken from the power results presented above.

Table 2: HVAC selected results for different compensation alternatives.

<table>
<thead>
<tr>
<th></th>
<th>Power Factor at the PCC</th>
<th>V onshore bus (p.u.)</th>
<th>V offshore bus (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore</td>
<td>0.88</td>
<td>1.023</td>
<td>1.038</td>
</tr>
<tr>
<td>Onshore</td>
<td>0.93</td>
<td>1.021</td>
<td>1.070</td>
</tr>
<tr>
<td>Offshore and Onshore</td>
<td>0.94</td>
<td>1.020</td>
<td>1.046</td>
</tr>
<tr>
<td>STATCOM offshore</td>
<td>0.88</td>
<td>1.023</td>
<td>1.037</td>
</tr>
</tbody>
</table>

From the results obtained it is obvious that the compensation alternatives studied bare some similarities but also important differences between them.

Compensating onshore only is the option that leads to less favourable results. The influence of the bus voltage amplitude on the transmission of reactive power is thus demonstrated by the results. Another important issue to consider is the power rating of the AC cable. In the onshore compensation scheme the power transmitted by the cable reaches its peak near the onshore bus. This may lead to the overloading of the cable, a direct consequence of the significantly high amount of reactive power transmitted through the cable.

The other compensation alternatives present more satisfactory results. As far as the power rating of the cable is concerned, compensating at both ends of the cable leads to a more evenly distributed loading of the cable as similar amounts of reactive power flow to each end of the cable. The bus voltages at each end of the cable (bus offshore and bus onshore) are below 1.05 p.u. (as can be seen in Table 2) so no overvoltage exists, since the excess of reactive power at the offshore bus no longer exists. Therefore, compensation offshore is proven to be necessary, in order to maintain the stability of the bus voltages. It is, however, important to notice that the installation of compensators offshore is likely to be more expensive and technically challenging than the placement of such devices at the onshore substation.

The STATCOM compensation presents very similar results to the compensation offshore using a shunt reactor. This option was introduced since the STATCOM device may offer benefits for the system in its dynamic behaviour.

In Table 2, it is obvious that for any of the cases studied the power factor achieved is close to the 0,9 power factor, set as an objective of the compensation. Without compensation of any sort, the reactive power injected in the grid would be very high, leading to a much deteriorated power factor at the PCC. The bus voltages would also be above 1,05 p.u., due to the excess of reactive power.

The solution considered to be the most effective and cost-efficient, given the smaller size of the compensators is the offshore and onshore compensation.

2. HVDC Power Flow

Comparing with the HVAC transmission, the HVDC configuration holds no reactive power issues, since these issues yield from the shunt capacitance of the AC cable, inexistent in HVDC.

Table 3 presents some results for the two HVDC configurations studied, including power factor at the PCC, voltage magnitudes on both ends of the transmission scheme and active and reactive powers circulating on both ends of the submarine cable.

Table 3: HVDC-LCC and HVDC-LCC+STATCOM selected results.

<table>
<thead>
<tr>
<th></th>
<th>Power Factor at the PCC</th>
<th>V onshore bus (p.u.)</th>
<th>V offshore bus (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVDC-LCC</td>
<td>0.89</td>
<td>1.012</td>
<td>0.978</td>
</tr>
<tr>
<td>HVDC-LCC+STATCOM</td>
<td>0.89</td>
<td>1.016</td>
<td>0.978</td>
</tr>
</tbody>
</table>

From Table 3 it can be noted that the two configurations bare similarities. Offshore, as the wind farm is the same, the voltage magnitude and the active and reactive powers transmitted in the cable are equal. Onshore, the influence of the STATCOM – although slight – can be noted, as the voltage is higher, due to the injection of reactive power by the STATCOM.

The use of a STATCOM is justified in steady-state for the injection of reactive power in the onshore bus, in order to compensate the reactive power absorbed by the inverter. So, in the power flow analysis, the STATCOM is working as a capacitor bank, injecting 65 Mvar – its maximum value for the bus voltage at the onshore bus. In this case, the use of the STATCOM changes the reactive power that flows to and from the lines connected to the onshore bus, because of the behaviour of the LCC converter (consuming reactive power). For the purpose of this study, in steady-state, capacitor banks could have also been used but the STATCOM is chosen as to also provide support to the grid in transient situations.

VI. Dynamic Results
The behaviour of some parameters of the grid, namely the voltage and the frequency in each bus, during and immediately following the disturbance are analysed for the two transmission systems under analysis: HVAC and HVDC-LCC.

The analysis is carried out for the two transmission alternatives and for different fault types, with the objective of assessing the fault ride through capability of the offshore wind farm, i.e. the requirement for the wind farm to stay connected to the grid during the disturbance, thus contributing to the reestablishment of the normal operation.

1. HVAC Dynamic Behaviour

In order to evaluate the behaviour of the offshore wind farm connected to the onshore by an HVAC link, different dynamic cases are analysed, as presented in Table 4.

<table>
<thead>
<tr>
<th>Case</th>
<th>Fault Duration (ms)</th>
<th>Fault Severity</th>
<th>Reactive Compensation Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>100</td>
<td>Moderate</td>
<td>Shunt reactors at both ends</td>
</tr>
<tr>
<td>Case 2</td>
<td>300</td>
<td>Moderate</td>
<td>Shunt reactors at both ends</td>
</tr>
<tr>
<td>Case 3</td>
<td>100</td>
<td>Severe</td>
<td>Shunt reactors at both ends</td>
</tr>
<tr>
<td>Case 4</td>
<td>100</td>
<td>Severe</td>
<td>STATCOM offshore</td>
</tr>
</tbody>
</table>

When the fault occurs, the electromagnetic torque drops, caused by the terminal voltage drop of the generators. This causes the machine to accelerate, a behaviour noticed in all cases under analysis. When the fault is cleared (either 100ms or 300ms after the application), the machine speed decreases until it reaches a stable value close to the initial.

The speed variation of the machines in the onshore grid is very similar for all four cases: the machines accelerate during the fault and then decelerate following the disturbance (as depicted in Figure 3).

The electrical frequency in the offshore buses also increases, followed by the stabilization to the initial 50 Hz. Similar results are found for onshore buses, for all the cases studied (an example, for Case 1, is shown in Figure 4).

The voltage dips in offshore and onshore buses present some differences in the cases. Cases 1 and 2 present voltage dips less profound than the ones in Cases 3 and 4, due to the difference in the short-circuit severity. In Cases 1 and 2 the voltage at the offshore buses reach approximately 0.9 p.u. (Figure 5). In Case 3, the voltage at the offshore wind farm buses reach about 0.6 p.u. In Case 4 the voltage decreases to approximately 0.65 p.u.

The STATCOM provides the voltage support it was supposed to. The voltage dip in the offshore buses is less severe (approximately 0.65 p.u.) than the voltage dip in case 3 (0.6 p.u.). The wind turbine speed increases slightly less than in case 3. The effect of the STATCOM in the onshore buses is not significant, derived from the fact that the STATCOM is placed offshore. During the fault, the STATCOM injects reactive power, thus contributing to the rise of voltage in all offshore buses, making the dips less profound. Following the clearance of the fault, the STATCOM slowly tends to consume reactive power, as in steady-state.

In all four cases, the recovery of the voltage magnitudes, the machine frequencies and the machine speeds indicate that stability is reached in all four cases, regardless of the
differences in the behaviour of the cases. This means that the faults to which the grid is subjected allow the fault ride through of the wind farm, as these faults are not severe enough to allow the disconnection of the machines by the under/over voltage relays. If more severe faults and/or with a larger fault duration were to be applied to the grid, the disconnection of the machines would occur, thus having the wind farm disconnected from the grid. This case was not, however, studied in this work.

2. HVDC-LCC Dynamic Behaviour

From the results for HVDC and HVDC+STATCOM transmission options, the most relevant conclusion is that the offshore wind farm connected in such ways does not possess fault ride through capability, i.e., the wind farm does not remain connected to the grid during the disturbance. Rather, the voltage drop causes commutation failure in the inverter, which means that the current does not transfer from one semiconductor switch to another. The consequence of the commutation failure is the bypassing of the inverter by short-circuiting its input and opening its output. The bypassing occurs at time 0.502 s – Figure 6 depicts this behaviour.

![Figure 6 - Active Power in the converters, for the HVDC-LCC transmission.](image)

During the disturbance, with the inverter bypassed, the rectifier continues to circulate a lower level of direct current through the shorted inverter, resulting in a lower active power drawn by the converters as a consequence of the voltage dip. Active and reactive power at the rectifier and the inverter continue to flow during the fault until the AC voltage at the rectifier finally goes to zero, at which time the DC link is blocked, at 0.602 s. The active and reactive power circulated through the converters become equal to zero.

From the point of view of the onshore grid, the disconnection of the offshore wind farm is a loss of a 110 MW generator. As so, the frequency of the onshore buses increases but it does not reach the value it had before the disturbance, 50 Hz. This is caused by the fact that the governors of the onshore generators have first order control and so the reference level of power is the same before and after the fault, even though the amount of active power has changed. This means that the frequency establishes in a lower value, approximately 49.85 Hz. Similar reasoning is applied to the speed of the onshore machines. The voltage drops at the onshore buses are, much like all the other results here analysed, identical for both transmission alternatives.

The conclusion is that the use of the STATCOM does not improve the performance of the transmission system. The objective was that this device would inject reactive power in the onshore bus during and immediately after the grid disturbance and thus contributing to a less severe voltage dip in the bus at which it is connected. However, as can be verified in Figure 7, the STATCOM is already injecting the maximum reactive power it can supply before the fault and so its action is very limited, as it does not have the ability of injecting more than 70 Mvar. As such, the benefits of the STATCOM to the dynamic behaviour of an HVDC-LCC are not significant enough to consider the HVDC+STATCOM a viable alternative to the HVDC transmission. The utilization of a larger STATCOM could, in theory, solve this limitation.

![Figure 7 - Reactive Power injected/absorbed by the STATCOM on the onshore bus.](image)

The disconnection of the wind farm during the fault becomes the only viable solution due to the operating problems of the LCC converters. Limited improvements are available: increasing the minimum extinction angle of the inverter is possible although it represents an increased reactive power consumption of the converter.

VII. Conclusions

For HVAC the main issue is the large amount of reactive power produced at the submarine cable. As such, some compensation schemes were studied, in order to absorb the surplus reactive power. The application of a compensator device of some sort (a reactor or a STATCOM) located offshore was found to be necessary. The scenario of onshore compensation only (no offshore device) led to an unacceptable voltage rise on the offshore bus voltage, as a result of the excessive amount of reactive power. The performance of the remaining compensation schemes was similar: the compensation at
both ends of the cable, the compensation offshore only (by a shunt reactor) and the STATCOM offshore compensation all lead to a high power factor at the point of connection of the wind farm to the remaining grid (around 0.9, injecting reactive power in the grid). The application of a STATCOM offshore leads to almost the same results as the shunt reactor offshore. The offshore and onshore compensation alternative led to the most favourable results: lowest reactive power injected in the onshore grid and an even distribution of the cable loading (low power rating of the cable). The need of smaller shunt reactors (40 Mvar) are also an advantage of this alternative.

The HVDC link allows the transmission of the power generated at the wind farm with low power losses (around 2%) and no reactive power problems are originated by this technology. However, both line-commutated converters (rectifier and inverter) always consume reactive power, which can be compensated. The use of a STATCOM (as part of the HVDC+STATCOM alternative considered) provides that compensation, supplying reactive power to the onshore grid.

The dynamic behaviour of the offshore wind farm and the onshore grid was studied for the response of this power system to an AC grid fault. In this case, the results differ very much according to the transmission system. The offshore wind farm connected to the grid by HVAC presents favourable results, as the wind farm is able to stay connected to the grid during the disturbance. This fact is valid for all three bus faults applied (differing in duration and severity) which means this wind farm is able to “ride through” the fault. The performance is improved by the application of the STATCOM, as this device injects reactive power during the fault, reducing the voltage dips and also reducing the frequency rise and offshore wind turbines speed increase.

The HVDC transmission, however, gives totally different results. The AC onshore grid fault causes commutating failure of the inverter, which is bypassed instantly after the disturbance. The tripping of the machines leads to the blocking of the DC link. The offshore buses are disconnected from the grid and the power generation is lost. This means that the converter technology governs the behaviour of the wind farm, since the limitations of the LCC converters cause the wind farm to be disconnected. The disconnection during the fault and the subsequent reconnection after the fault is the solution for operating one such system, although the reconnection is not analysed in the course of the thesis. The STATCOM does not improve the performance of the transmission, since it is already, in steady-state, supplying reactive power to the grid, not having, therefore, the capability of injecting further amounts of reactive power (since it is already injecting initially the maximum reactive power it can).

In conclusion, one can state that if HVAC is used to implement the grid connection, the response of the wind farm to disturbances is determined by the wind turbines, since the connections themselves are passive elements. With the DC link, the wind turbines are electrically decoupled from the analysed system. As so, the response of the wind farm is governed by the technology in the LCC converter.

VIII. References