

FACTS and HVDC for grid connection of large offshore wind farms

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ABSTRACT: The connection of large wind farms to the electrical network is a challenge for transmission system operators and for wind farm developers. Main intention of the grid connection is that the wind farm and the electrical network operate in a safe and reliable manner during steady state as well as during fault conditions. Several issues have to be addressed whenever power-generating devices are connected to the grid. The paper describes how wind farms affect grid voltages and how faults in the connected transmission system impact on a wind farm. Two alternatives are offered for connecting offshore wind farms to the main grid: AC and DC.

It is shown that, when the network is weak, local dynamical reactive power support may prevent voltage collapse and make it possible for the wind farms to recover and remain in service after a short-circuit event. A dynamic voltage control scheme based on a combination of SVC and STATCOM is suggested.

1 INTRODUCTION

World-wide, more than 30 GW of wind power was in operation by the end of 2002, with a growth of 27% in 2002. It is expected that by the end of 2007, this figure will have increased to well over 80 GW. In Germany for example wind power was of marginal importance ten years ago. Today, with more than 17000 MW in operation, the country is Europe's most important user of wind power. In the UK, more than 1000 MW of wind generation was in operation by the end of 2005. In Denmark, more than 3000 MW of wind power is now contributing more than 15% of the country's electric energy balance.

Up to now most wind farms were installed onshore. Since nearly all locations of good wind conditions are used for wind generation, new ideas were born to install also wind farms offshore. So a lot of considerations were made to erect and plan new offshore wind farms.

The installed power of the offshore wind farms is intended to be rated up to 1000 MW. For the connection of the wind farm to the grid two technologies are available. First, a connection via three-phase high voltage ac (HVAC) cables, second, a connection via dc cables.

Even if HVAC cables are well-known including the experience of many years concerning maintenance, vulnerability, and reliability, there are still several technical problems to solve. Those technical problems are mostly related to the high demand on charging (reactive) power. This charging power reduces the transmission capability and might lead to critical voltage conditions. The reactive power balance of asynchronous generators can be improved to a certain extent by use of the recently introduced doubly-fed rotor concept. To keep this technology within reasonable cost margins, however, rotor converter ratings must be kept limited to steady-state requirements only.

Offshore wind installations are typically connected to the grid through long cables and a number of transformers, constituting considerable impedance between the generators and the grid connection point. It is in such

case unfavourable to control the reactive power at the grid connection point by using the generators or any other equipment installed at the generator side of the installation. Transmitting reactive power through a substantial impedance causes losses and might lead to voltage problems at the outermost part of the connection. During transient occurrences in the grid, the performance of doubly-fed induction generators (DFIG) may well prove inadequate to safeguard primarily voltage stability of the grid. Compensation devices such as shunt reactors or Static Var Compensators (SVC) have to be installed to achieve load flow conditions, which do not overload the electrical equipment.

2 GRID CODE REQUIREMENTS

Beneath overloading, additional requirements are given at the connection point to the public grid (Point of Common Coupling - PCC) in national grid codes, which are related to steady state and dynamic behavior during and after faults.

All National grid codes, even though several differences can be found, discuss the importance of grid support from all installed power generating devices. Many regulatory authorities require that the generators should be able to vary their reactive power output dependent on the grid voltage level. This requirement is a result of the desire to maintain voltage stability and limit dynamic voltage variations. Wind farms have often been excluded from these demands. They cannot, however, expect to enjoy this favoured treatment forever.

In the past wind power plants typically have had a small power rating, when compared to the strength of the connecting electrical network. The power system as such did not depend on the contribution from the renewable power sources. Under these circumstances the behaviour of the wind mills at faults in the network seemed to be non-critical and the manufacturers could design a simple control system that simply dropped out the wind mills whenever disturbed conditions did occur on the network.

Looking at the big wind farms presently being planned this design philosophy becomes questionable. When a fault occurs in a power system the faulty part will be disconnected from the system. Thus if the fault occurred on the feeder to which the windmill is connected it will be disconnected. But, if the windmill is connected to the non-faulted part of the system it is desirable that the windmill stays connected during the fault. As soon as the faulty feeder has been disconnected the wind generator shall return into operation in order not to cause consequential loss of generation in addition to generating units connected through the faulty feeder. If consequential loss of generation would occur it may lead to a system collapse.

Therefore the wind farm connection must be designed in a way that the wind farms is capable of continuous uninterrupted operation during events when the voltage is being depressed during the time required to disconnect a faulty feeder (“ride-through capability”). Typically the time required in a high-voltage system is in the range 100 - 200 ms.

Reactive power control is necessary to meet the criteria mentioned above. With synchronous generators, reactive power control is achieved by means of the exciter system. An active device such as SVC or HVDC Light positioned at the grid connection point acts as a central exciter system but with the advantage that reactive power can be controlled even when no power is generated.

The subtransmission, or even distribution, systems to which offshore wind farms will be connected are usually designed to distribute power from the main grid to remote customers. The system in most cases is very weak and a change in power flow direction will strongly affect the voltage level. Mechanically switched reactive power compensation, such as capacitor banks, MSC, in combination with transformers equipped with tap changers, are often used to deal with voltage level problems. However, power production, and thus reactive power consumption, in wind farms vary with wind speed. The resulting frequent switching of shunt devices and tap operations deteriorates power quality and decreases the lifetime of the equipment. An SVC, with continuously variable susceptance, is often a cost efficient alternative to several small reactors.

Several phenomena associated with power produced from wind introduce voltage flicker on the connecting node, i.e. generators' starts and stops, wind speed variations, and tower shadow effects. This flicker has a deteriorating effect upon other components connected to the grid, causing complaints from power consumers. By connecting an active device such as SVC or HVDC Light at the grid connection points, this flicker can be mitigated.

3 DC Solution by utilizing HVDC Light®

The following chapter describes how a DC transmission can help to fulfill the Grid Code for the connection of offshore wind farms to the public grid. One reason for choosing a High Voltage Direct Current (HVDC) transmission system for the connection of an offshore wind farm might be a long distance between the wind farm and the grid connection point, where HVAC cables can not be used due to their charging current, see Figure 4.

A new type of HVDC for the AC/DC conversion has been developed. ABB introduced its DC-transmission

system HVDC Light® in Hellsjön 1997. Since then the rating has increased 100 times to about 330 MW presently operating in the Cross Sound cable connection. A number of projects has now been commissioned and are showing good operating experience.

HVDC Light® is a DC transmission system based on voltage source converter (VSC) technology. In a VSC, the current in the valves can be switched on and off at any time - the converter is self-commutated. The advantages of voltage source converters especially for the grid connection of offshore wind farms is described in the following [3].

3.1 HVDC Light® technology

Voltage source converter (VSC) technology uses components that can not only switch on the current but also switch it off. Using high switching frequency components such as IGBTs, it becomes advantageous to use Pulse Width Modulation (PWM) technology. Switching very fast between two fixed voltages creates the AC voltage. The desired fundamental frequency voltage is created through low pass filtering of the high frequency pulse modulated voltage, see Figure 1 [2].

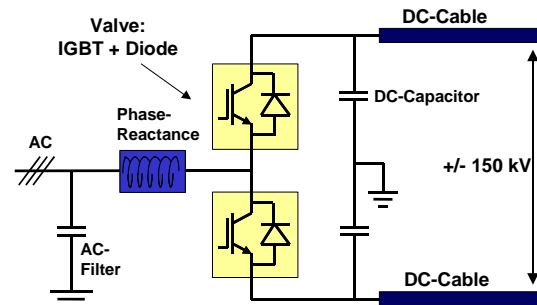


Figure 1 Voltage Source Converter

Using PWM, it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. With these two independent control variables, separate active and reactive power control loops can be used for regulation. No communication is needed between the two converter stations. This allows independent and very fast control of active and reactive power flows and permits the P-Q characteristics shown in Figure 2.

There are mainly three factors that determine the P-Q characteristics of a HVDC Light transmission. The first one is the maximum current through the IGBTs. This maximum current leads to a maximum MVA circle in the power plane where maximum current and actual AC voltage is multiplied. If the AC voltage decreases the MVA capability will also decrease.

The second limit is determined by the maximum DC voltage level. The reactive power is mainly dependent on the voltage difference between the AC voltage, which is generated by the VSC from the DC voltage and the grid AC voltage. If the grid AC voltage is high the difference between the maximum DC voltage and the AC voltage will be low. The reactive power capability is then moderate but increases with decreasing AC voltage. Since reactive power supply in a network is needed for low voltages, the moderate reactive power supply for

high AC voltages is not a limiting factor. The third limit is the maximum DC current through the cable.

A power capability curve of a HVDC Light® transmission is shown in Figure 2 [2]. For a decreasing AC voltage level the maximum DC voltage level will vanish and the P-Q characteristic is determined by the maximum current level. A small shift in direction of the Q-axis can be observed, which is due to the line reactor and the filter capacitance within the VSC transmission system. If the converter transformer is equipped with a tap changer, it will also influence the power capability curve.

Note the similarities of the described capability curve with a capability curve of a generator. Maximum DC voltage level corresponds to maximum field current in the rotor winding and maximum current corresponds to armature current.

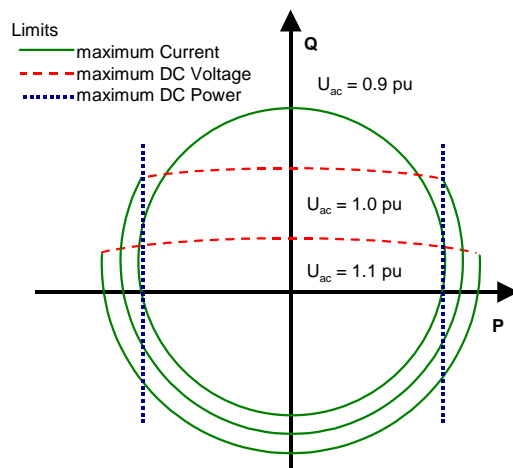


Figure 2 P-Q Characteristic of a VSC

3.2 Steady state operation

As a VSC transmission system can virtually instantly take any working point within the capability chart i.e. it can operate as rectifier or inverter at variable frequency and at the same time absorb or supply reactive power to the AC network. HVDC Light is a close to ideal component in the transmission network. From a system point of view, it acts as a zero-inertia motor or generator that can control active and reactive power almost instantaneously. No reactive power compensation equipment is needed at the converter stations, only an AC filter is installed. Reactive power generation and consumption of an HVDC Light converter can be used for compensating the needs of the connected network within the rating of a converter. As the rating of the converters is based on maximum currents and voltages, the reactive power capabilities of a converter can be traded against the active power capability.

In the wind farm the HVDC Light can supply an AC voltage to a dead net at start up as well as collect the wind power and at the same time supply reactive power to or take reactive power from the wind generators. It can also vary the frequency, getting the highest power economy from the wind farm.

The VSC situated in the isolated wind farm absorbs the active power that is produced by the wind generators and

sends it through the DC cable to the VSC situated in the receiving network. The DC voltage is controlled by the receiving VSC by injecting the received DC power into the public AC network. Onshore the HVDC Light reactive power controller can automatically control the AC voltage at the connection point or control to a determined power factor as defined in the Grid Code, without influencing the control of active power. Offshore the fast control of active and reactive power makes the VSC transmission an optimum instrument to control frequency and AC voltage of the wind farm [3].

Instant active power flow reversals are possible since the VSC transmission system changes DC current direction and not DC voltage polarity. The XLPE-based cable technology used will handle such current reversals without any problem. Any limitations in the maximum power changing rates of the connecting AC grids must naturally be taken into account.

Furthermore, the HVDC Light transmission is an asynchronous link, which can isolate the power system from the wind power fluctuations, especially because the inverter onshore can also give reactive power support to the receiving AC system.

3.3 Dynamic Properties

The VSC characteristic is suitable for connecting large amounts of wind power to networks, even at weak points in a network and without having to improve the short-circuit power at the connecting point of the network since no short circuit power is needed for commutation. The VSC can even operate against black networks. The VSC can be used to support the offshore wind farm and the grid, where the wind farm is connected to, with the best mixture of active and reactive power during stressed conditions. VSC transmission systems can therefore give added support to the grid.

By use of a DC link the wind farm is decoupled from the AC network, which gives the advantage that the voltage in the wind farm is not affected by changes of the voltage in the AC network, caused by switching actions or remote faults. Because of the short response time of the system for AC voltage control, the AC bus voltage can be kept constant during transients and other disturbances. Flicker is also mitigated to a high degree. For faults in the AC network with low remaining voltage the active power can not be injected into the AC network. The active power of the wind generators can then be stored temporarily in the wind generators by letting the rotor speed increase. After the fault in the AC network is cleared the energy in the wind generators can be injected into the AC network and the pre-fault rotor speed is resumed. The frequency control is not limited in the same way as a conventional power plant where boiler dynamics may limit the operation during a grid restoration. Therefore HVDC Light enables a fast voltage recovery after faults. It is thus possible to use the controllability of HVDC Light to stabilize the voltage in fault situations. A VSC Transmission system is also capable of influencing unsymmetrical grid conditions, power quality and harmonic problems.

If the wind generators trip, the HVDC Light will continue to operate with the converter on the platform working as a stiff voltage source allowing normal restart of the wind generators [3].

3.4 HVDC Light Offshore installation

Space and weight are expensive resources on offshore installations. Particularly with regard to these constraints, the HVDC Light concept offers important advantages: Since the converters and filters are small and synchronous condensers are not required, HVDC Light can be made compact and lightweight [2]. The compactness of HVDC Light is illustrated in Figure 3.

4 AC Solutions by utilizing SVC

4.1 Sea cables: a key issue

Comprehensive sea cable networks add another dimension, calling for additional elaborate reactive power control. The overall scope of reactive power control should encompass the wind farm just as well as the sea cables, to bring about a well regulated reactive power balance of the whole system, answering to the same demands on reactive power regulation as any other medium to large generator serving the grid.

Limits of transmission capacity of sea cables should be calculated with compensation, so half of the charging current flows to each end at maximum load. An example of transmission capacity for XLPE cables at four different voltage levels and as a function of cable length is shown in Figure 4 [1]. In the example, the cables all have a cross-section of 1.000 mm².

It is seen that the power transmission capability exceeds 350 MW at a distance of 100 km and a voltage of 220 kV. At a distance of 250 km, the power transmission capacity is still 175 MW.

A Static Var Compensator, SVC, can be provided as a reactive power source. This approach brings about some advantages:

- one device serves the whole wind farm
- the voltage in the connecting point is stabilised by a voltage controller
- Flicker due to tower shadow effect and variations in wind speed will be decreased

A typical system has been chosen and studied (Figure 5). The layout of this generic system is based on related cases and studies.

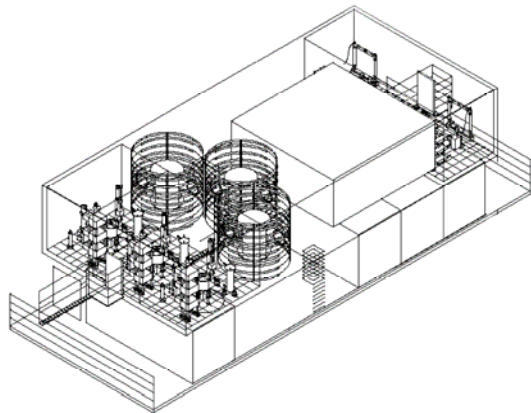


Figure 3 Sketch of a 250-300 MW HVDC Light offshore module requiring approximately (W x L x H) 30 x 40 x 20 m, including the transformer

4.2 Using SVC to improve voltage stability

Starting and stopping of generators is critical in many applications. Induction machines draw considerable reactive currents when the stator gets energised, even if the turbine is accelerated to synchronous speed before being connected to the grid. This results in a period of decreased voltage. In this paper, the phenomenon is simulated with a small example.

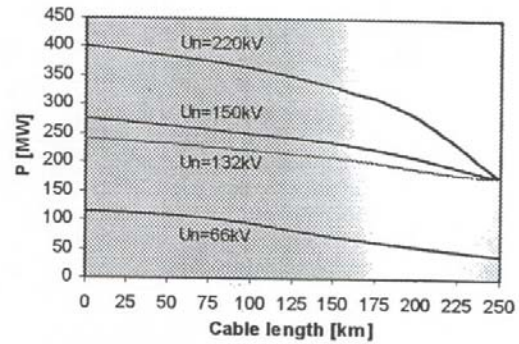


Figure 4 Limit of power flow as a function of length for compensated cables type 3x1x1.000 mm²

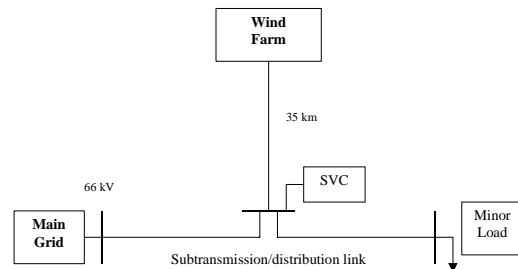


Figure 5 Set-up of generic study of grid connection of off-shore wind farms.

The total wind farm generation is 60 MW in this example and the switched generator produces 1.5 MW. A shunt capacitor producing 500 kvar is connected at the same time as the generator. The turbine is sped up to synchronous speed before being connected. Figure 6 and Figure 7 show that the SVC has a stabilising effect on the voltage variation.

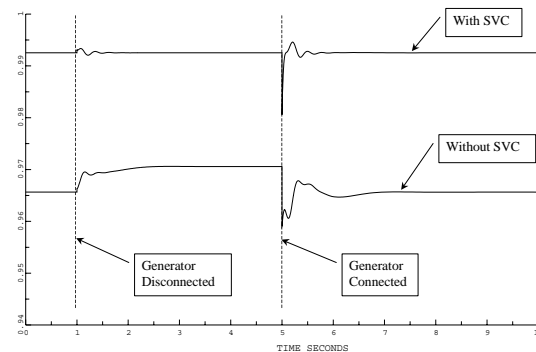


Figure 6 Voltage variations at the minor load associated with start and stop of one 1.5 MW wind generator.

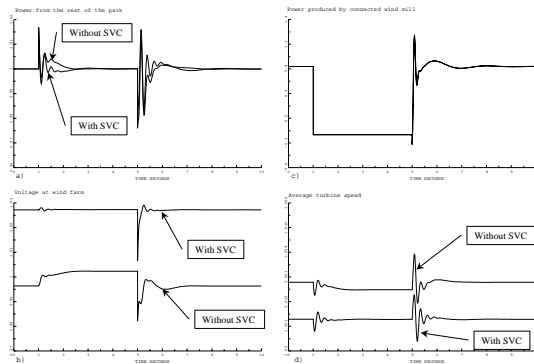


Figure 7 The same event as in Figure 6 but other data presented
 a) Power production from the rest of the wind farm – also affected by the voltage variation,
 b) Voltage at the wind farm,
 c) Power produced by the switched generator and
 d) Average turbine speed.

4.3 Using SVC to improve recovery from network faults
 It is crucial that induction generators are magnetized very rapidly, when the network voltage returns following a network fault. If this cannot be achieved sufficiently fast the generator will speed up and then the slip cannot be brought down close to zero by the electrical network. The speed reduction must then be achieved using the mechanical turbine blade angle control system. The time constants then become much larger than the typical short-circuit duration and the wind generator will require a restart in order to regain its pre-fault power generation operation. When the electrical network is weak the behavior of wind farms at network faults will be strongly improved by reactive power support at the connection point.

Figure 5 shows the set-up of a generic simulation of the recovery from a network fault. It is assumed that the network has a short-circuit strength of ten times the total rated power of the wind farm generators. Additional transformers are inserted between the subtransmission system and an intermediate voltage level (20-36 kV) and further from this intermediate voltage level down to the low-voltage internally used in the wind generator towers. It is assumed that the no-load reactive power consumption is compensated internally in the wind generators.

Figure 8 shows the simulation results when a 200 ms fault is applied at the high-voltage bus at the grid connection point and when the SVC is not in operation. It is assumed that the turbine power is constant.

The upper diagram shows the stator and rotor flux in the generators and the lower diagram shows the speeds of the wind generator turbines and the induction generators. The simulation indicates that the wind farm will possibly recover from this fault, but the network is very close to a voltage collapse situation.

Figure 9 shows the simulation result for the same event as in Figure 8 when an SVC connected to the intermediate voltage level and having the same rating in Mvar as the generators have in MVA is used.

The stability clearly has been improved a lot and the generators recover to the pre-fault generation within a second. The critical point occurs a few hundred ms after

the fault clearance and at that time it is determined whether the recovery will be successful or not. Although this simulation is very much simplified it gives a general indication that the conditions at fault recovery should be looked at if the (post-fault) network strength is lower than ten times the rating of the generators.

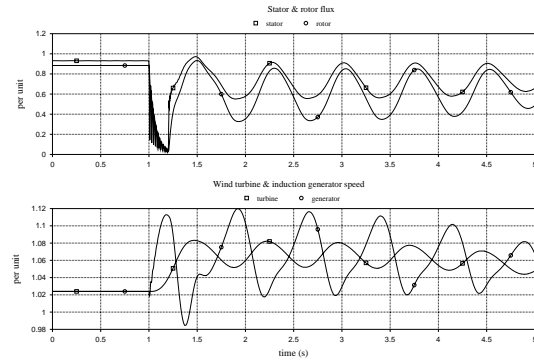


Figure 8 Simulation results without SVC

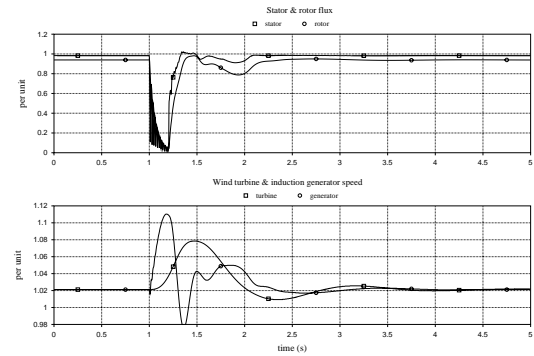


Figure 9 Simulation results with SVC

4.4 SVC implementation

The SVC today can be obtained in two different versions. The first SVC approach is based on conventional capacitor banks together with parallel thyristor controlled inductive branches, which consume the excess of reactive power generated by the capacitor bank. This type of equipment can be directly connected to the intermediate voltage bus, which interconnects the wind generators (up to 36 kV). It also is possible, but more expensive, to connect the SVC at the high-voltage network by a dedicated transformer.

The second alternative implementation of the SVC makes use of a power electronic voltage source (VSC). The converter utilizes semiconductors having turn-off capability. The converter can inject or consume reactive power to/from the bus where it is connected. This application of VSC technology is usually referred to as STATCOM (Static Compensator). This alternative has the benefits of a smaller footprint as the big air-cored inductors are not used. Another advantage stems from the fact that a smaller parallel capacitor bank can be used as the converter itself may contribute reactive power.

By combining the two types of schemes, a cost-effective dynamic compensator can be achieved, rated for a high dynamic yield during a short time and a lower yield for steady-state operation, Figure 10.

Thus, in Figure 10, in a current example, a VSC rated at ± 53 Mvar is combined with a Thyristor-Switched

Capacitor (TSC) rated at 94 Mvar and a 3 Mvar Harmonic Filter, giving a total output of $-50/+150$ Mvar. The purpose of the scheme is to yield dynamic var compensation of a large sea-based wind farm. The TSC will only operate in cases of potential voltage collapse until the wind farm can be tripped or until the fault has been cleared, i.e. only for a short while, and can therefore be rated in a very economical way.

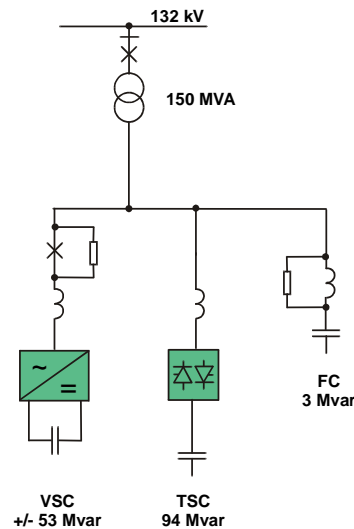


Figure 10 Combined VSC and TSC scheme

5 CONCLUSION

In this paper the technical requirements associated with an offshore wind farm being introduced in an existing power network have been discussed. The paper concludes that both technologies - AC and DC transmissions - are available and feasible for connection of large offshore wind power plants to a grid. A supplier with experiences from both technologies and having all components would be able to assist in the choice of transmission and connection system.

HVDC Light technology is suitable for connecting large amounts of wind power to networks, even at weak points in a network and without having to improve the short-circuit power at the connecting point of the network since no short circuit power is needed for commutation. The HVDC Light can be used to support the offshore wind farm and the grid, where the wind farm is connected to, with the best mixture of active and reactive power during stressed conditions. HVDC Light transmission systems can therefore give added support to the grid.

Even if HVAC cables are well-known including the experience of many years concerning maintenance, vulnerability, and reliability, there are still several technical challenges. Those technical challenges are mostly related to the high demand on charging (reactive) power. This charging power reduces the transmission capability and might lead to critical voltage conditions. Static Var Compensators (SVC) have to be installed to achieve load flow conditions, which do not overload the electrical equipment. Beneath overloading, additional requirements are given at the connection point to the public grid (Point of Common Coupling - PCC) in national grid codes, which are related to steady state and dynamic behavior during and after faults. Dynamical

reactive power support of SVC may prevent voltage collapse and make it possible for the wind farms to recover and remain in service after a short-circuit event.

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