HVDC Connection of Offshore Wind Parks: VSC vs LCC with STATCOM

João Jesus, Rui Castro and J.M. Ferreira de Jesus

Abstract — **It is now clear that the installation of offshore wind parks is the next step towards an even more widespread use of wind power. In what concerns the interconnection of remote offshore wind parks to the existing onshore grid, for distances over 50 km and/or installed capacities above 100 MW, High Voltage Direct Current (HVDC) technology seems to be more adequate than High Voltage Alternating Current (HVAC). This paper addresses only the interconnection of offshore systems with the onshore grid through the HVDC technology. Two HVDC technologies are compared: HVDC using Line Commutated Converters (HVDC-LCC) and HVDC using Voltage Source Converters (HVDC-VSC). As it is known that LCC technology is unable to offer reactive power support in fault conditions, the association with a STATCOM is considered. Specific studies are performed in both steady-state and transient conditions of the grid in order to evaluate the pros and cons of each HVDC technology. The impact of the HVDC technologies in the compliance of existing grid code requirements is also assessed.**

***Keywords*: Offshore wind power, HVDC, Line commutated converters, Voltage source converters, STATCOM.**

I. Introduction

In the last decade the interconnection of wind turbine generation, WTG, systems to the existing transmission and distribution grids has grown consistently without noticeable adverse impacts in the operation of these systems.

The experience gained so forth with the integration of wind generators in the existing power transmission systems justifies the tendency for the increase of the installed capacity of WTG systems in the generation mix.

Recently, the case for offshore WTG systems has been stated with the aim of increasing the installed capacity of WTG systems. The rationale for offshore wind energy lies in the lack of land availability for the installation of new turbines in places where the wind resource is interesting, the planning restrictions posed for the installation of new onshore WTG systems and the low turbulence intensity and wind shear that is registered in the relative smooth surface of the oceans, which, generally, favours offshore wind conditions in relation to onshore.

Although the offshore environment has some advantages in what relates to wind turbulence, it also bears some constraints in what regards wind turbine and foundation designs [1].

One of the issues that arise when considering the installation of offshore WTG systems is the type of interconnection between the offshore WTGS and the onshore grid. Currently, two alternative connection technologies are available for the interconnection of remote WTGS to the grid: High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC). For distances over 50 km and/or installed capacities above 100 MW, HVDC technology seems to be more adequate [4].

This paper addresses only the interconnection of offshore WTG systems with onshore grids through the HVDC technology. Two HVDC technologies are compared: HVDC using Line Commutated Converters (HVDC-LCC) and HVDC using Voltage Source Converters (HVDC-VSC). Due to the known limitations of LCC technology in providing reactive power support during disturbances, the association with a STATCOM is also evaluated.

Specific studies are performed in both steady-state and transient conditions of the grid in order to evaluate the pros and cons of each HVDC technology. Furthermore, the impact of the HVDC technologies in the compliance of existing grid code requirements is assessed.

II. Technology Overview

The connection between offshore wind farms and the onshore electrical grid can be made with HVAC or HVDC technologies.

Alternating current systems are the most common mode of electric energy transmission since the beginning of the XX century and are widely used all over the world. Among their advantages, one can highlight that it is the cheapest technology, has low losses over relatively small distances and does not need auxiliary power sets. Due to these advantages, today, HVAC is the most common used technology to connect offshore wind farms to the onshore grid. On the other hand, it has also some disadvantages that we should mention. From a technical point of view, perhaps the most relevant one is that the submarine cables generate large quantities of reactive power, which has to be consumed. This explains why HVAC transmission cannot be used over long distances. As a consequence, engineers elected HVDC transmission as an alternative to overcome the limitations of HVAC transmission.

Basically, there are two ways of making the connection using HVDC transmission: HVDC-LCC and HVDC-VSC. Each technology has advantages and disadvantages and possesses different operation modes.

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A. HVDC-LCC

HVDC-LCC, or classical HVDC system, is based on LCC using thyristors as the switching element. The origin of the name of the converter is the need of an existing AC network, in order to achieve proper commutation.

It is a mature technology used to either transmit large quantities of power over long distances or to submarine cable connection or to ensure interconnection between systems with different frequencies.

Until now, application of HVDC-LCC transmission was only used for the interconnection of high voltage grids and there is no single HVDC-LCC system for the connection of offshore wind farms, gas or oil extracting platforms. Examples of projects using this technology are Cahora Bassa in Mozambique (2000 MW), Itaipu in Brazil (6000 MW), the Cross Channel Link (2000 MW) and Three Throats in China (18200 MW).

In order to get a high DC voltage value, the system uses two 6-pulses *Graetz* bridges connected in series making a 12-pulse converter. It is important to mention that the bridges are connected in series on the DC current side, but in parallel on the AC current side.

Feeding each bridge, there are two transformers connected in star/star and star/delta, in order to get a 30º angle difference between the two voltages from the transformers. The neutrals are connected to the ground on the primary side and isolated on the secondary side.

Several advantages of HVDC-LCC technology may be listed [2], [3]:

- Asynchronous connection, so the frequency can be different in either end, which allows more advanced control schemes of the wind turbines.
- Losses do not limit the transmission distance.
- Active power control can be used to regulate frequency in the grid.
- HVDC does not increase the short-circuit power in the point of connection, which implies that it will not be necessary to change the equipment installed in the existing network.
- Short circuit currents are not transferred in HVDC-LCC link because the converters block them.
- DC cables have a longer life than AC cables.
- DC cables can carry more power for a given size of conductor, when compared to AC cables.
- The power electronic devices allow instantaneous power control.
- It is possible to control the direction and magnitude of the power.

On the other hand, it has also some disadvantages, such as [2]:

- The control of active and reactive power is not independent.
- Large amounts of harmonics are produced which makes the use of big filters necessary.
- A black start-up is not allowed, so it needs an auxiliary start-up system in the offshore farm.
- There is no experience in installing this converter in these conditions.

B. HVDC-VSC

A HVDC-VSC system uses Insulated-Gate Bipolar Transistors (IGBT) as the switching element, instead of the thyristors used on HVDC-LCC. These electronic components were only available for commercial applications in the last few years and they opened a large number of opportunities for HVDC transmission.

Today, two manufacturers make available HVDC-VSC systems: *Siemens*, with the name of *HVDC PLUS*, and *ABB*, with the name of *HVDC Light*. Commercial systems are available with nominal power between 50 MW and 1100 MW and with voltages up to ±300 kV. The voltages available in commercial systems are ±80 kV, ±150 kV and ±300 kV.

In recent years, this technology started to be used in projects such as Cross Sound in USA (330MW,±150kV), Direct Link (180MW,±80kV) and Murray Link (220MW,±150kV) in Australia and, more recently, in the BorWin 2 wind farm in Germany (800MW,±150kV), the so far unique offshore wind farm using HVDC-VSC technology, which is expected to start operation in 2013.

HVDC-VSC uses Pulse Width Modulation (PWM) control to give the desired fundamental frequency voltage. Using very high switching frequencies, between 1300 Hz and 2000 Hz, this method reduces the number and amplitude of the harmonics produced and thus the size of the filters.

In addition to the advantages mentioned about HVDC-LCC technology, HVDC-VSC technology adds the following advantages [4], [5], [6]:

- With the use of PWM, the HVDC-VSC can control both active and reactive power independently without extra compensating equipment.
- While the transmitted active power is kept constant the AC voltage controller can control the voltage in the AC network and contribute to an enhanced of power quality.
- Reactive power generation and consumption of a HVDC-VSC converter can be used for voltage control within the ratings of the converter. This is very important if the wind farm is connected to a weak grid and could be vital with the increase of wind farm capacity.
- It does not need an independent reactive power compensation system to supply the grid with reactive power.
- It can operate at a very low power, even at zero power, just transmitting reactive power.
- As the HVDC-VSC uses self-commutating semiconductors devices that no longer need a sufficiently high AC voltage to commutate, it significantly reduces the risk of commutation failures.
- It needs fewer filters than HVDC-LCC because it has switching frequencies of 1–2 kHz instead of 50–60 Hz on HVDC-LCC. Higher frequencies in HVDC-VSC would reduce the filter size but switching power losses could be excessive.

- HVDC-VSC converter stations are more compact than HVDC-LCC and the offshore platform size can be smaller and less expensive.
- As the control systems on the rectifier and the inverter sides operate independently, they do not depend on a telecommunication connection, which improves the speed and the reliability of the controller.
- As the polarity of the DC side is equal in rectifier and inverter modes of operation and as there is little need for coordination between HVDC-VSC converters, it is suitable for creating a multi-terminal DC grid with a large number of converters.
- This converter is able to create its own AC voltage at any predetermined frequency without the presence of rotating machines, so it is suitable for isolated operation.

A couple of disadvantages are to be mentioned [4], [5], [6]:

- Nowadays, IGBTs are much more expensive components that thyristors.
- The higher frequency of PWM originates bigger losses (4–5%) than in HVDC-LCC technology (1–2%).

III. Problem Formulation

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. The key-idea is that the wind farms remain connected to the grid providing reactive power support during the fault and are able to deliver active power following fault clearance, thus contributing to a stable operation of the grid.

As it was outlined in the previous section, HVDC-VSC converters are self-commutating, not requiring an external voltage source for its operation. Therefore, the reactive power flow can be independently controlled at each AC network and is independent of active power control [7], [8], [9]. This means that this technology allows for the continuous variable reactive power absorption or supply, up to its nominal power, depending on the grid needs.

HVDC-LCC scheme is much less versatile, since it cannot offer reactive power support to the grid during a fault; furthermore, for this system to work properly, it is necessary to supply reactive power to the valves even in steady-state conditions. This can be easily achieved through capacitor banks, which is a proven solution, as far as steady-state is concerned. However, capacitor banks are unable to provide reactive power support during grid disturbances, because the reactive power they deliver is voltage dependent.

A promising alternative is the association of HVDC-LCC with an electronically controlled voltage regulator, namely the STATCOM (Static Synchronous Compensator), a member of the FACTS (Flexible AC Transmission Systems) family. STATCOM use the VSC technology and therefore have a huge advantage when compared to the capacitor banks: since it can generate or consume reactive power, it can assist in the bus voltage control over a wider range and, furthermore, it can also supply the grid with reactive power during the short circuits, helping in the reduction of the associated voltage dips [10], [11], [12].

As far as reactive power support during grid disturbances to reduce voltage dips is concerned, this is one way of setting the basis for a fair comparison between the two technologies, as it is expected that both solutions present a somehow similar behaviour. Under these circumstances, it would be interesting to compare the dynamic performance of both HVDC-VSC and HVDC-LCC+STATCOM schemes, following a disturbance in the grid, namely if they are able to avoid the wind farm disconnection following a fault in the grid. A case study allows the comparison between these two solutions.

IV. Case-Study Definition

The case-study is based on a test grid composed by an offshore wind farm connected to an onshore existing grid (see Fig. 1).

The software chosen to perform the simulations was the PSS/E (Power System Simulator / Engineering), from *Siemens/PTI*. This software was selected because it allows running power flow analysis, dynamic simulations and stability studies, among other features, and has an extensive list of power devices steady-state and transient models. Furthermore, this is the software used in most power system utility companies in Europe and USA.

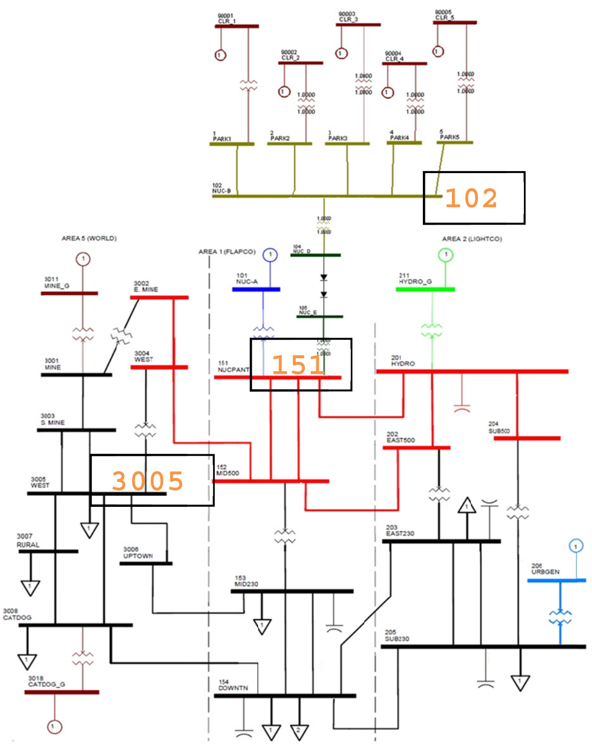

Fig. 1. Case-study test grid; bus 102 – offshore connection bus; bus 151 – onshore connection bus; bus 3005 – bus where the fault is applied

A. Grid Composition

A realistic test grid was built composed by 33 buses with two voltage levels: 400 and 220 kV. It comprises:

- Five conventional generators (four thermal plus one hydro) and five aggregates of wind turbines representing a 110 MW nominal power wind farm. The total generating power is 2726,66 MW and 910,75 Mvar.
- Five shunt compensators that generate 1150 Mvar.
- Eight loads all of them located in the 220 kV voltage level. The loads have a total consumption of 2700 MW and 1875 Mvar.

It was assumed that the distance between the offshore wind farm and the onshore grid is 100 km and that the interconnection to the onshore grid is ensured by a DC isolated cable transmitting 110 MW, at a voltage of 150 kV. The length of 100 km was chosen, because it is for values of this magnitude that the DC link can compete with the AC link. In this situation, the compensation of the reactive power generated by the AC cable is very expensive which renders the DC link solution competitive.

The parameters of the studied system can be found in [13].

B. System Modelling

1) Onshore grid

Standard PSS/E library models were used to model the main components of the onshore grid. The thermal generators were represented by a round rotor generator model (quadratic saturation), the hydro generator being modelled as a salient pole generator (quadratic saturation on d-axis). The appropriate excitation systems, steam turbine and hydro turbine governor models were also considered.

2) Wind farm and offshore grid

GE 1,5 MW wind turbine generators model available in the PSS/E Wind library was used. This package includes models for the wind turbine generator converter and electrical control, two mass shaft and wind turbine aerodynamics. Furthermore, modules for under / over voltage and frequency generator bus disconnection relay were also used.

A 33 kV wind farm offshore internal grid connects the five wind turbine aggregates to a common offshore bus.

3) HVDC-LCC

The HVDC-LCC link consists of one AC/DC converter on the offshore connection bus, one DC/AC converter on the onshore connection bus and a DC cable to interconnect the buses.

The steady-state configuration of the HVDC-LCC PSS/E model was made bearing in mind the proposed objective of transmitting 110 MW, from the offshore wind farm, located at a 100 km distance, to the onshore grid.

The transient model used in the dynamic simulations was the "CDC4T" PSS/E library model. The voltage-dependent current characteristic, i.e., the maximum allowed current as a function of the inverter DC voltage, was configured accordingly to the manufacturers supplied data.

4) STATCOM

The parameters of the STATCOM were chosen in order to keep the steady-state voltage on the onshore connection bus at 1,02 pu. The STATCOM nominal power was set to 64 Mvar. Until its nominal power is reached, the STACOM controls the onshore connection bus voltage at the desired value. From this point on, the STATCOM keeps injecting or consuming the maximum reactive power but no longer keeps the voltage under control.

"CSTCNT" PSS/E library model was selected to represent the STATCOM in the dynamic simulations. The value of the integrator gain of the STATCOM control system was calculated following the data supplied by the manufacturer.

5) HVDC-VSC

The HVDC-VSC PSS/E model includes two converters. The one located in the offshore wind farm controls the DC-link voltage, whereas the one located onshore controls the active power. In steady state, the user can control also the AC side voltage of the converters. It was chosen to control the voltage at the offshore connection bus to 1,0 pu and the voltage at the onshore connection bus to 1,02 pu.

The transient model used in the dynamic mode was the "VSCDCT" PSS/E library model. This model is a current injection model, composed by the integration of three models: two voltage source converter modules for the VSC, one at each DC line terminal, which controls the converter's behaviour during a fault, and one DC transmission line module, that coordinates the power flow in the DC line between the pair of VSC.

Once again, the model parameters were configured accordingly to the data supplied by the manufacturer.

C. Simulation Conditions

To perform the simulations, a load flow analysis was firstly performed, in order to calibrate the grid and assure that the voltage profile was within acceptable conditions and no overloads were detected. Then, all generators and loads were converted as Norton equivalents. Finally, the dynamic simulations were performed, starting from the initial conditions as given by the load flow results.

Three HVDC connection schemes were assessed, which were denoted by HVDC-LCC, HVDC-LCC+STATCOM and HVDC-VSC.

A symmetrical three-phase short-circuit was simulated to occur at t = 0,5 s with a duration of 100 ms. The considered fault is located far from the DC-link, in bus 3005 located in the 220 kV grid, as indicated in .

Two fault conditions were considered: a high severe fault (fault internal susceptance $B = -0{,}2\times10^{10}$ pu) and a medium severe fault (fault internal susceptance $B = -0{,}2\times10^{4}$ pu).

In all the simulations, it was assumed that the wind farm was operating at its nominal power, 110 MW. No wind variations were considered within the time frame of the dynamic simulations.

V. Simulation Results and Discussion

A. High Severe Fault at Bus 3005

In this situation, the wind farm is disconnected from the onshore grid for all the three HVDC connection schemes studied. When this high severe fault occurs, the active power transmitted by the DC-Link is limited by the maximum current permitted and the wind generators lose their load totally. Therefore, the frequency increases rapidly and the over frequency protections are activated, disconnecting the wind farm.

However, it is interesting to observe the variation of the voltage in the onshore bus 151, which is represented in Fig. 2.

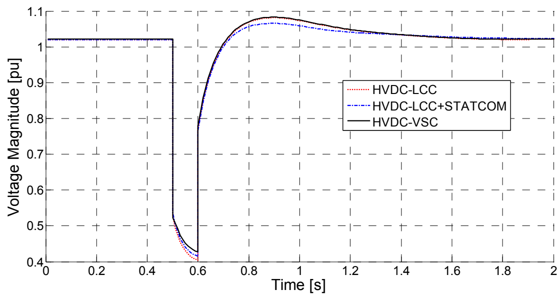

Fig. 2. Onshore connection bus 151 voltage; high severe fault at bus 3005; HVDC-LCC, HVDC-LCC+STATCOM and HVDC-VSC connection schemes

For the HVDC-LCC connection, the maximum voltage dip is 0,40 pu, whereas with the STATCOM, this value is slightly higher, 0,42 pu. This is explained due to the fact that the STATCOM injects around 28 Mvar of reactive power in the grid, during the fault, therefore, limiting the voltage dip excursion. When the fault is cleared and the voltage recovers, the STATCOM absorbs a maximum value of about 55 Mvar, in order to prevent the overvoltage, as can be seen in Fig. 3.

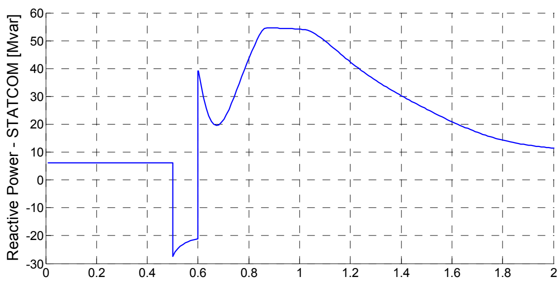

Fig. 3. STATCOM reactive power; high severe fault at bus 3005; HVDC-LCC+STATCOM connection scheme

As far as the HVDC-VSC connection is concerned, the voltage dip reaches 0,43 pu. This slight improvement is caused by the injection of 93 Mvar in the grid, during the fault; after fault clearance, no contribution is given to the voltage control, because the DC-link has been disconnected, as reported in Fig. 4.

These results are quite interesting as they show that the contribution to the voltage dips mitigation provided by the electronic regulators exists and is welcomed, but is limited to the device nominal power.

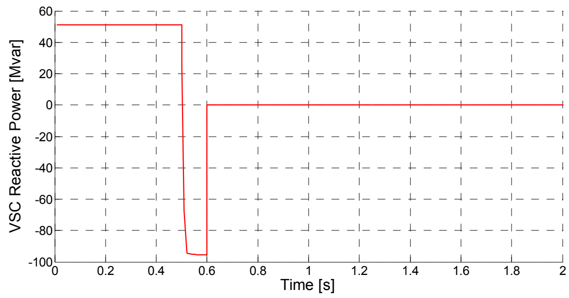

Fig. 4. HVDC-VSC reactive power; high severe fault at bus 3005

B. Medium Severe Fault at Bus 3005

This is a less severe fault, that brings the voltage at the onshore bus 151, down to around 0,80 pu (see Fig. 5).

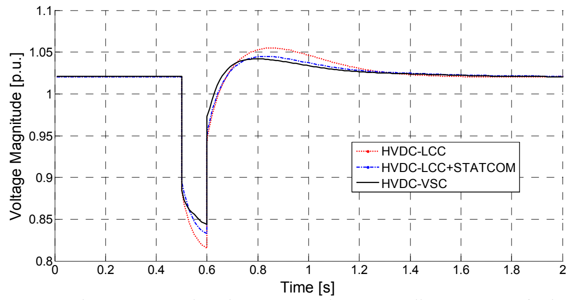

Fig. 5. Onshore connection bus 151 voltage; medium severe fault at bus 3005; HVDC-LCC, HVDC-LCC+STATCOM and HVDC-VSC connection schemes

Both the HVDC-LCC and HVDC-LCC+STATCOM connection schemes fail to keep the wind farm connected and it is isolated following the fault clearance, at t = 0,6 s. Despite the positive contribution given by the STATCOM to voltage dip mitigation, as seen in Fig. 6, it was not enough to avoid the activation of the voltage-dependent current characteristic and so the wind farm was disconnected by the over frequency protection.

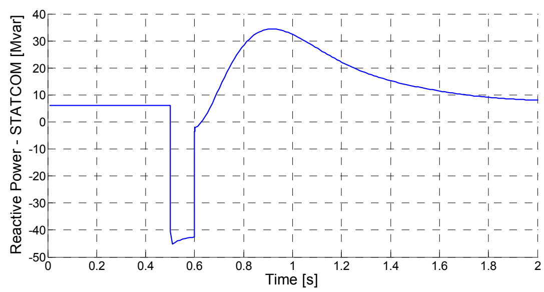

Fig. 6. STATCOM reactive power; medium severe fault at bus 3005; HVDC-LCC+STATCOM connection scheme

However, as far as the HVDC-VSC DC-link is considered, the simulation results show that the wind farm is not disconnected, as the voltage variation is kept under the regulation margins of the VSC. In this situation, the VSC was able to control the active power flow in the link to the reference value, as the maximum AC current allowed in the converters was not reached.

We highlight the positive contribution given by the VSC both during the fault (injecting reactive power, to control up the voltage) and after the fault clearance (absorbing reactive power, to control down the voltage). The reactive power at the VSC is depicted in Fig. 7.

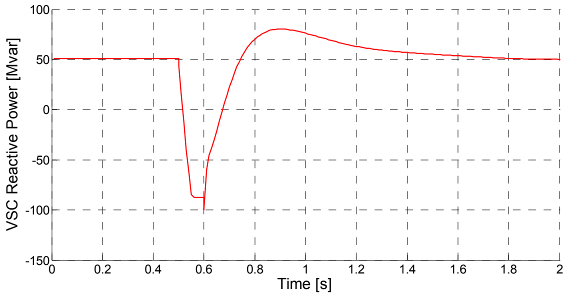

Fig. 7. HVDC-VSC reactive power; medium severe fault at bus 3005

VI. Conclusions

In this paper, different HVDC solutions for the interconnection of offshore wind farms to the onshore existing grids were considered. The main objective of the study performed was to assess the behaviour of the different HVDC solutions with regard to the rule set in the utility's grid codes that relates to the behaviour of wind farm during and after the occurrence of faults in the transmission system. This point is of particular importance as it is foreseen that the installed capacity of offshore wind farms will be an important share of the installed capacity of the onshore grids to which they are connected. The loss of an appreciable amount of active power after the occurrence of a fault and the lack of reactive power support during the fault occurrence may contribute to an unstable behaviour of the electrical transmission systems, which is clearly an unacceptable situation for the utilities.

The studies performed showed that, irrespective of the HVDC solution used, there are faults that lead to the disconnection of the WTG systems, a situation which is clearly undesirable and not accepted by existing grid codes. A possible way of overcoming this situation is to have a system that adapts the active power produced by the WTG systems to the active power that the DC transmission links allow to be transferred during the fault occurrence. A fast reduction in the DC link transmitted power should be followed either by a reduction of the output power of each individual WTG system or by a solution of dissipation and/or storage of the excess output power.

The studies performed also showed that the HVDC transmission technology based upon VSC seems to be more effective than HVDC-LCC and HVDC-LCC+STATCOM technologies.

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