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DC protection for a multi-terminal HVDC network including offshore wind power, featuring a reduced DC circuit breaker count

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Abstract: Large offshore wind farms located far from shore, as are being planned or built in the North Sea, will require high-voltage DC (HVDC) transmission to shore, and multi-terminal HVDC could offer further benefits. Currently proposed methods to protect against faults in the DC network are based on extremely fast-acting DC circuit breakers located on all cable ends, leading to high cost. A method is proposed based around discharging the DC network to isolate the fault, which drastically reduces the circuit breaker requirement, while making use of the inherent current-limiting behaviour of the wind turbines. The validity of this approach is demonstrated in simulation.

1 Introduction

Offshore wind energy is set to become an increasingly important part of the generation mix in Europe, due to falling costs, more consistent wind resource and a lack of space for onshore wind farms. By nature, these wind farms will be located away from the major load centres. At the same time, the intermittent nature of renewable energies such as wind and solar power could result in much greater cross-border power flows in order to balance the power from different sources. It has been recognised that a business as usual approach will not achieve the required transmission capacity at reasonable cost [1, 2].

Many planned offshore wind farms will be located at a significant distance from shore, making high-voltage DC (HVDC) transmission to shore the most economical option. HVDC is also used for interconnection of unsynchronised grids, for instance between the UK and European grids, and is necessary for longer undersea interconnections. For most of these situations, the newer voltage-source converter (VSC) HVDC will be used, which allows a converter that is small enough to be located on an offshore platform and which is able to provide an islanded grid reference for the offshore turbines [3, 4].

The few operational HVDC-connected wind farms, and most of those in planning, use point-to-point links, in which a single offshore platform is connected to a single onshore terminal. Multi-terminal links, in which multiple offshore platforms and onshore terminals can be used with a network of cables, could offer many benefits [5]. For instance, several closely located wind farms could be connected together on the DC side, which would allow much greater resilience to faults in either the interconnector cables or onshore converter stations. Furthermore, if the wind farms were connected to different countries then the HVDC network could allow power transfer between these countries when the level of wind power was low.

A significant issue with the use of HVDC for offshore wind, and multi-terminal HVDC in particular, has been a lack of experience within the industry with VSC-HVDC. Problems have also been reported with the German BorWin1 HVDC link, including harmonic problems in the offshore grid and frequent outages, which are potentially related to interactions between the wind turbines and HVDC system [6, 7]. Furthermore, protection from faults in the DC cables can be difficult for multi-terminal HVDC networks and has not been demonstrated commercially. These issues have led to a reluctance on the part of wind developers to implement HVDC technologies.

To address these issues, the Demo 1 partners of the EU-funded BEST-PATHS project have developed an open-access MATLAB/Simulink toolbox for the study of integration of offshore wind farms using MTDC grids. This toolbox includes generic models of HVDC converter stations and controllers based on modular multilevel converters (MMCs), frequency-dependent DC cable models, and a manufacturer-supplied aggregated wind farm model based on a turbine using a fully rated converter [8].

As part of the BEST-PATHS activities, a system consisting of three GW-scale wind farms connected to shore via a multi-terminal network was simulated. This topology was under consideration by a UK developer for a major offshore wind farm. A protection strategy for faults in the DC network was developed based on the use of fast-acting hybrid DC circuit breakers and is able to isolate faulted cable sections without affecting the operation of the wind farms or the remaining HVDC network [9]. Unfortunately, this approach relies on using large numbers of costly DC circuit breakers, particularly on the offshore platforms which are also subject to space constraints. The purpose of this study is to demonstrate an alternative protection strategy which greatly reduces the required number of circuit breakers and eliminates them from the offshore platforms.

2 Network design and protection strategy

The originally proposed network layout and protection strategy is shown in Fig. 1*a*. Each of the three offshore terminals is connected to several collection platforms via a 220 kV AC link, with the collection platforms connected to multiple wind turbines at 33 kV. In the model, these are represented by a single aggregated 1 GW wind farm, transformer, and 220 kV link. The 33 kV network is represented as a lumped capacitance, while the 220 kV cable uses a pi-section model. Each offshore platform is connected to shore with a 100 km cable, using a frequency-dependent travelling wave model. The 5 km cables connect the offshore platforms, represented using a pi-section model due to problems using the travelling wave model with shorter cable lengths.

DC protection is based on using hybrid circuit breakers on each cable end, as proposed by several vendors [10, 11], which can break the circuit within 5 ms. In addition, inductance must be added to each DC cable in order to limit the rate of rise of the fault current. This is so that the fault current does not exceed the breaking capacity of the DC circuit breakers (around 10 kA). The inductors also aid in fault discrimination without the need for communication [12], and limit the amount of voltage collapse

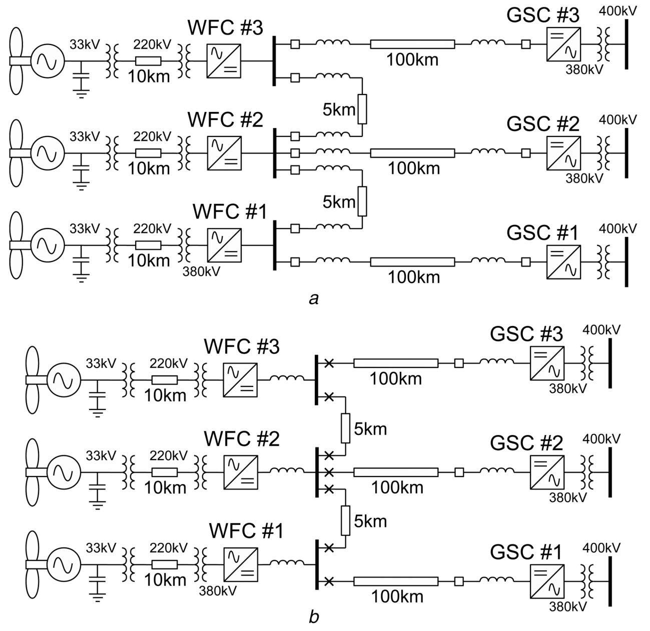

Fig. 1 *Network topology,*

(a) Conventional protection design, ***(b)*** Reduced-cost protection design

Table 1 Additional network and converter parameters

rated HVDC voltage	±320 kV
rated converter DC current	1875 A
rated wind farm power	1 GW
capacitance of 33 kV network	62 μF
transformer leakage reactances	0.1 p.u.
offshore grid frequency	50 Hz
onshore grid short circuit ratio	15
converter arm inductance	56 mH (0.15 p.u.)
additional current-limiting inductance	100 mH
circuit breaker and isolator switching time	5 ms
sampling rate for measurements	10 kHz

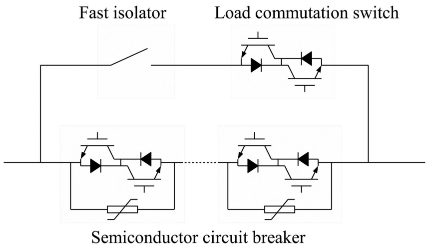

Fig. 2 *DC circuit breaker design*

around the network. This method has been shown to rapidly isolate cable faults without causing the wind farms to trip. However, it features a large number of DC circuit breakers, particularly on the offshore platforms.

An alternative system is to use AC-side circuit breakers to disconnect the converter stations and to allow the DC network voltage to collapse. Fast disconnectors can then be used to isolate the faulted cable, these do not have to interrupt the DC current and are relatively compact and the network re-energised [13, 14]. A problem with this method is that the AC circuit breakers are slow to operate, both to open and close, and the DC fault current in the inductors is slow to decay. Alternatively, full-bridge MMCs can be used for the converter stations, which can block the fault current, removing the need for the AC circuit breakers [15]. However, these are more expensive and with higher losses than the conventional half-bridge MMCs.

The proposed network topology is based around de-energising the DC network and using fast disconnectors to isolate the fault, but with improved isolation speed, and is shown in Fig. 1*b*. The main principal is that DC circuit breakers are used onshore, where there is more space to house them, to isolate the network from the onshore grid. On the offshore terminals, the offshore AC network voltage demand is reduced to zero, meaning that the AC current from the wind farms circulate through the offshore converters without entering the DC network. In this case, AC current is limited by the current-limiting functionality of the fully rated converters on the wind turbines. DC inductors are used at the converter terminals in order to limit the rate of current rise, but not on the cable ends in order to allow the DC voltage to quickly collapse.

Once the energisation sources are disconnected from the DC network, current will continue to flow through the fault, sustained by the stored energy in the cable, converter, and current-limiting inductances. To dissipate this energy, a small semiconductor-based DC circuit breaker is used in series with each terminal, having a breaking capacity of around 10 kV. This will not have a significant impact on overall losses, and as an alternative, a small number of the half-bridge cells in each converter could be replaced with full-bridge cells, which can supply the required negative voltage.

A critical aspect of the proposed method is the speed with which the offshore grid voltage can be restored, as it has been shown that the wind turbines will trip if their offshore grid reference is absent for more than around 160 ms [9].

3 Network and converter modelling

In addition to the parameters shown in Fig. 1, further parameters for the converters and network are given in Table 1.

MMC, wind farm, and cable models are described in detail in the documentation accompanying the models [16], but a brief description of the control scheme for the control scheme of the HVDC terminals will be given here as it impacts on the behaviour during and after the fault. The MMC is modelled using a switching function-type model, based on a voltage source for each arm, and a single representative cell voltage per arm is used. Additional components are also used to represent the blocked operation of the converter [17].

All the terminals use a controller based on the principle of de-coupling the AC- and DC-side currents in the converter and controlling them separately [18]. In the grid terminals, this only regulates the internal circulating currents, with the converters presenting the sum of the capacitor voltages to the DC grid. In these terminals, a conventional DQ current controller is used on the AC side, with the *D*-axis demand used to regulate the overall cell capacitor voltage and the *Q*-axis demand to regulate the reactive power. The cell capacitor voltage demand is set using a droop controller based on the power flow, which determines power sharing between the three onshore terminals. On the offshore terminals, the AC side provides an AC voltage of fixed magnitude and frequency. The DC current demand is used to regulate the overall cell capacitor voltage.

For the DC circuit breaker, a hybrid design as proposed by ABB is used [10], which is shown in Fig. 2. In operation, the load commutation switch first turns off, transferring the current through the semiconductor circuit breaker path. The fast isolator opens at zero current, and when it is open, the semiconductor circuit breaker opens, with the current being commutated in the parallel varistors.

The circuit breaker is modelled as a voltage source, with the voltage set at zero during normal operation. Following a signal to disconnect, a delay of 5 ms is applied, to represent the operation of the load commutation and fast isolator, then a voltage is applied based on the current, according to the transfer characteristics of the varistors. Finally, when the current is close to zero, a series ideal switch is used to disconnect the circuit fully. This is necessary as the simulation method causes the varistor voltage to oscillate when the current is zero amps. The circulating current-suppressing breakers use a similar methodology, using only the semiconductor circuit breaker and with a significantly lower varistor voltage. It is assumed that both circuit breakers will close instantaneously, conducting through the semiconductor section. The fast disconnectors are represented using ideal switches, and an operation delay of 5 ms is used.

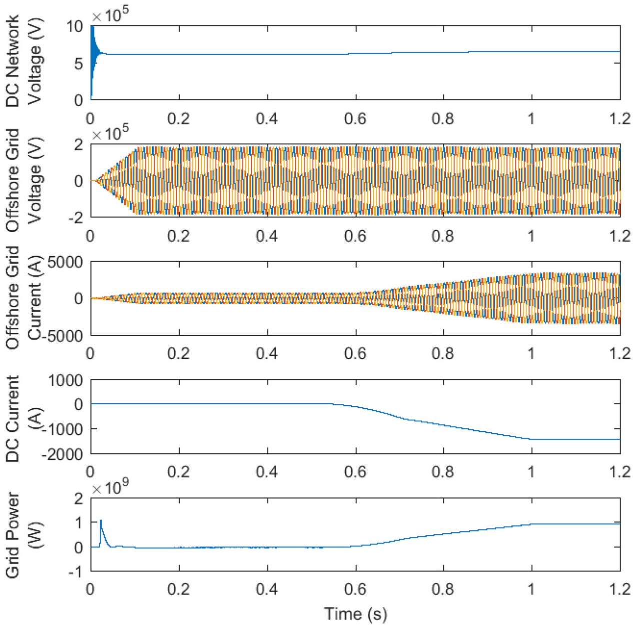

Fig. 3 *Network and wind farm initialisation*

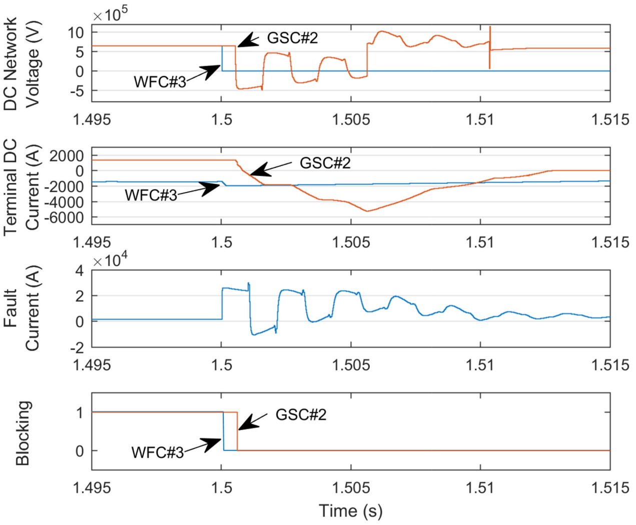

Fig. 4 *Initial fault response*

4 Protection stages

The steps for detection and isolation of a DC fault are as follows:

Fault Detection: Occurrence of a DC fault will cause a rapid collapse in the DC network voltage, and the fault is detected based on the rate of change of DC voltage. A threshold of -1×10^9 V/s was used. Several control actions are triggered:

- Blocking of the grid-side converter stations in order to protect the switching devices from the high fault currents.
- Triggering of the DC circuit breakers on the grid side.
- Reduction of the offshore AC voltage references to zero. The DC current controllers in the offshore converter stations can act to limit the DC current.

Fault Current Suppression: Depending on the fault location and resistance, the DC network voltage will either collapse completely as soon as the converters are blocked, or when the grid-side DC circuit breakers open after 5 ms. The small semiconductor DC circuit breakers on the offshore platforms are activated when the DC network voltage drops below 10 kV, and the negative voltage provided causes the fault current to decay.

Fault Location and Isolation: Although methods exist to locate the fault without communication networks [14], for simplicity a communication-based differential protection scheme is used. This locates the fault based on the current directions at either ends of each cable, and a communication and processing delay time of 5 ms is assumed. This is a pessimistic assumption based on the likely propagation delays and processing time, but is considerably shorter than the current decay time, which is the main limit to the fault clearance time. With the fault location determined, the isolators are opened once the DC current is fully suppressed.

Re-Energisation: As the onshore terminals remain connected to the AC grid, they cannot be used to re-energise the DC network without switching in pre-charge resistors using mechanical switches, which would take additional time. For this reason, re-energisation is achieved using the offshore terminals, which have remained connected to the DC network, using the stored energy in the MMC cell capacitors. Once the isolation switches have opened, the terminals on which the isolations switches are located will attempt to re-energise the DC network. This is achieved by the use of a proportional controller driving the DC current demand through a limiter, and the terminal attempts to charge the DC network to a value below the nominal value, in this study 600 kV is used. The onshore terminals detect the recovery in voltage and reconnect to resume DC voltage regulation and bring the DC voltage up to 620 kV. The remaining offshore terminals detect the recovery to the full DC voltage and attempt to resume normal operation.

Resumption of Power Transfer: Upon recovery of the DC voltage, the offshore terminals ramp up the offshore AC grid voltage at a pre-set rate, and the wind farms can re-synchronise and resume power transfer.

5 Simulation results

The model was simulated using MATLAB/Simulink and SimPowerSystems, using a discrete solver for the power system component, and a fixed time step of 20 µs.

5.1 Model initialisation

The model was first initialised and the wind farms run up to full power. The MMC cell capacitors begin fully charged, and the DC network is charged using a fixed voltage source which is disconnected after a set time. The offshore grid voltage is ramped up over a period of 100 ms. The so-called impedance multiplication effect means that the full aggregated wind farm will not connect to the grid at once, as the combined wind farm will see a much weaker grid than the individual wind turbines are expecting [19]. For this reason, the number of wind turbines in the farm is set as a variable and is kept at one turbine until 0.5 s, at which point it is ramped up to the full number over 0.2 s. Meanwhile, the wind turbine output power is ramped up over 0.5 s, starting at 0.5 s. This occurs simultaneously for all three wind farms.

This process is shown in Fig. 3. A significant initial oscillation in the DC voltage can be seen, due to excitation of cable resonances. During this time, the protection system is disabled to prevent spurious activation.

5.2 Initial fault response

At 1.5 s, a pole-pole fault with a resistance of 0.001 Ω is applied to the top 100 km cable, at the end closest to WFC#3. The response is shown in Fig. 4, for WFC#3 and GSC#2, the other terminals showing a similar response. All converters rapidly detect the fault, and the onshore terminals block to protect the MMC transistors from the fault current. The offshore terminals reduce the offshore grid voltage to zero, and the fault current, flowing through the MMC transistors, is minimal. A significant fault current flows, fed mostly by the onshore terminals and the cable resonances. Just after 5 ms following the fault, the onshore DC circuit breakers operate, reducing the current to zero over around 7 ms and recovering the DC terminal voltage of the converters.

5.3 Discharge, isolation, re-energisation

Overall response to the fault, including dissipation of the fault current, isolation of the fault and re-energisation of the link are shown in Fig. 5. Due to the rapid collapse in the offshore DC

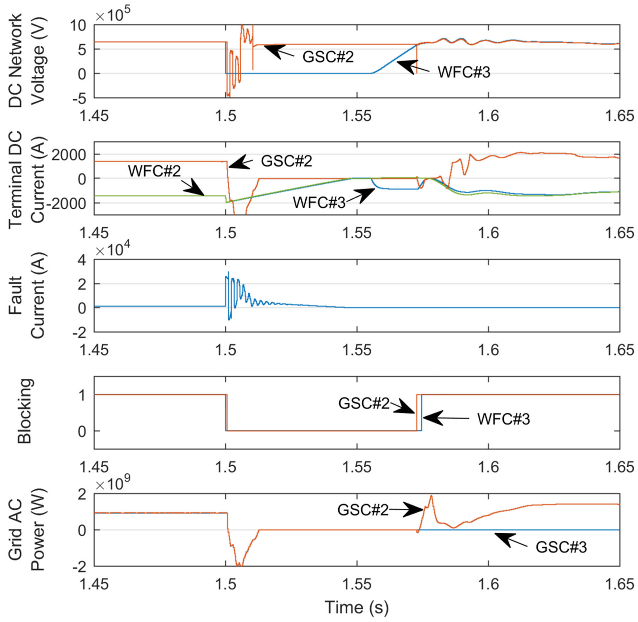

Fig. 5 *Overall fault response*

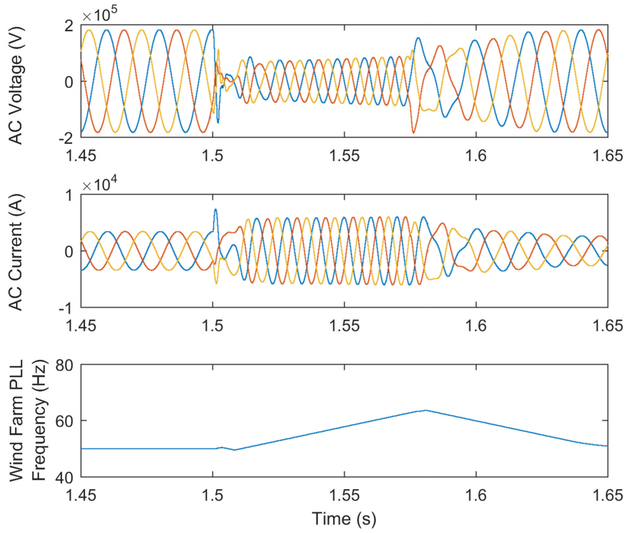

Fig. 6 *Wind farm and offshore network response*

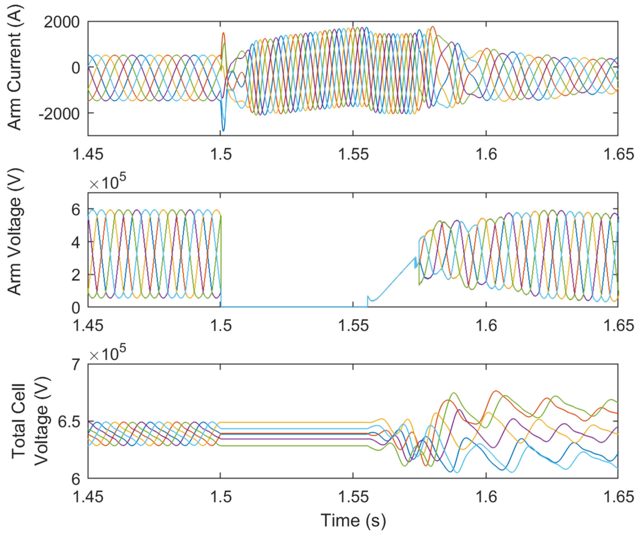

Fig. 7 *Offshore converter response*

voltage, the current dissipation circuit breakers operate immediately. The fault current contribution from the offshore terminals is slow to dissipate, due to the low blocking voltage of these circuit breakers compared with the onshore breakers, and the overall fault current reaches zero at 50 ms after the fault. During this time, the fault is located using the differential protection algorithm, and the isolators are opened as soon as the current reaches zero.

Following the operation of the isolators, terminal WFC#3 begins to re-energise the DC bus, and at around 1.57 s, it reaches the level at which the onshore terminals de-block and begin to regulate the DC bus voltage. At this point, the offshore terminals return to normal operation and re-establish the offshore AC network voltage. This causes power flow from the wind farms to resume, reaching a steady value at 1.62 s.

5.4 Effect on the offshore network

The response of the wind farm and offshore 220 kV network connected to WFC#3 is shown in Fig. 6. Following an initial transient, the wind farm detects what it thinks is a grid fault, and increases the reactive power output to the maximum, helping to sustain the offshore grid voltage. At the same time, the inability to export real power and the absence of a reference grid voltage cause the wind turbine PLL to rapidly increase in frequency. This frequency rise is reversed when the grid voltage reference from the offshore converter is restored. In this case, the offshore voltage is immediately re-applied at 50% of the nominal, and increased to the value rated over 50 ms.

While this particular wind turbine is able to ride through the loss of grid, others may not necessarily behave in the same way. In general, the national grid codes require the turbines to continue to operate under moderate frequency excursions, and to trip only after a delay of several hundred ms [20]. However, the level of frequency excursion in this case is extreme and could trigger other protection mechanisms, and it is uncertain whether the turbines in the wind farm would remain synchronised to each other during the fault. As of this, a control system in which the turbines can remain synchronised to each other and are capable of regulating the offshore frequency during the fault would be preferred, and similar systems have been proposed [21].

5.5 Effect on the offshore converter

The response of the MMC at converter terminal WFC#3 is shown in Fig. 7. Upon fault detection, the arm voltages are almost immediately reduced to zero, and a large transient arm current occurs. During the fault, the AC component of the arm current is higher than normal, but the DC component reduces rapidly. As the DC network is re-energised, the DC component of the arm voltage rises slowly to regulate the current, before the AC component recovers upon re-activation of the converter. Cell voltage only reduces slightly during re-energising of the network, but the transient effects during offshore voltage recovery and re-synchronisation of the wind farm lead to a significant imbalance between cell voltages in each arm.

6 Conclusion

A protection system for a multi-terminal HVDC network featuring offshore wind turbines has been developed, based on the concept of discharging the DC network to isolate the fault, then re-charging. Compared with the conventional design, which uses 10 pairs of hybrid DC circuit breakers, most of them located offshore where space is constrained, this design uses only three pairs, and makes use of the current-limiting capability of the wind turbines. This method is most relevant to networks which connect multiple large offshore wind farms together on the offshore DC platforms, which will allow tolerance to cable faults.

The time to isolate a DC fault and resume normal operation was found to be around 120 ms – this is mainly limited by the speed with which the inductive energy of the fault current can be dissipated, which is achieved using semiconductor DC circuit breakers with a low blocking voltage of 10 kV. Increasing the blocking voltage will decrease the fault clearance time, but increase the capital cost and the losses during normal operation.

The effects on the onshore grid of cutting off and restoring several GW of power in this time frame will need further study.

The manufacturer-supplied wind farm model is able to ride through the fault, and the increased current in the offshore converters is not excessive. However, this operating mode is largely undefined by the national grid codes, and other wind turbines may behave differently. A turbine operating mode which can recognise the loss of the offshore grid reference, and maintain the frequency until the grid is restored, would be beneficial. The modelling was also carried out using linear transformer models – simulating saturation as in a real transformer would require additional control functionality to limit the inrush current during re-energisation of the offshore AC grid. This may also have an impact on the fault recovery time.

7 Acknowledgments

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