Excessive over-voltage in long cables of large offshore windfarms

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ABSTRACT
Large offshore windfarms are connected to onshore transmission grids through long high-voltage cables. When a large offshore windfarm goes into isolated operation with its high-voltage cable, for example by an action of the on-shore main-circuit breaker, there is a risk of significant over-voltage in the cable and the windfarm transformer. This paper analyses such a situation for both an existing and a planned large offshore windfarm in Denmark.

1. INTRODUCTION
At present, there are two large offshore windfarms in Denmark connected directly to the transmission grid, at voltages above 100 kV. These are Horns Rev A (160 MW), in the North Sea, and Rødsand 1 / Nysted (165 MW), located south to the Danish island of Lolland. Both windfarms are grid-connected through long high-voltage cables from respective offshore transformer platforms to on-land connection points. Two new large offshore windfarms, Horns Rev B and Rødsand 2, each with planned power ratings of 215 MW, will be commissioned by 2009 and 2010, respectively, and also grid-connected through long high-voltage cables to the on-land connection points.

For the Horns Rev A and two planned offshore windfarms, the offshore windfarm transformers, including the circuit breakers at the 36 kV secondary side of these transformers, the high-voltage cables providing the grid-connection and the on-shore connection point belong to the Danish Transmission System Operator (TSO), Energinet.dk, see Figure 1. The long high-voltage cables are compensated by reactors, i.e. 'shunt inductors', absorbing a surplus of the reactive power generated in the cables.

There may still be a risk of significant (transient) over-voltage in the long high-voltage cables and windfarm transformers when the main-circuit breaker at the on-land connection point disconnects the cable from the entire transmission grid and the large offshore windfarm, together with the cable, goes into isolated operation. The duration of such over-voltage may be of seconds and so affect the cable itself, the windfarm transformer and the reactive compensation equipment. Such events are rare, but do occur. This paper summarises the experience of the Danish TSO for such events.

2. EXPERIENCE FROM AN EXISTING WINDFARM
The Horns Rev A windfarm is grid-connected at the Danish sub-station Karlsgårde through a 150 kV sea/underground cable with the total length of 55 km, see Figure 1.

On March 14 2005, the main-circuit breaker of the windfarm cable at the sub-station Karlsgårde opened. Hence, the Horns Rev A windfarm and the 150 kV cable were tripped from the Danish transmission grid.

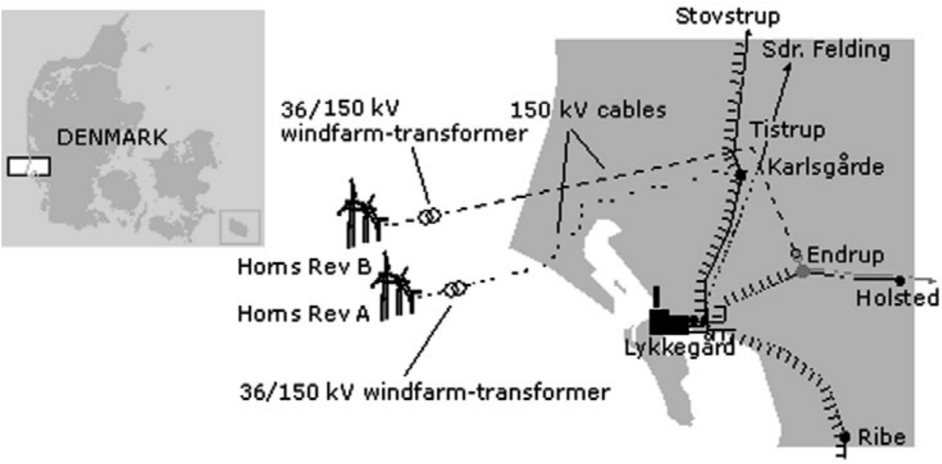

Figure 1. The windfarms at Horns Rev connected to the 150 kV transmission grid of Denmark.

The voltage measuring equipment at the 150 kV sub-station Karlsgårde recorded the transient voltage and current behaviour just prior to, and during, the isolated operation, see Figures 2 and 3. However, the voltage magnitude was so excessive that it exceeded the measuring equipment range. By a simple analysis, the voltage magnitude was estimated to be in a range of 2 p.u., with 1 p.u. corresponding to the rated voltage of the windfarm cable.

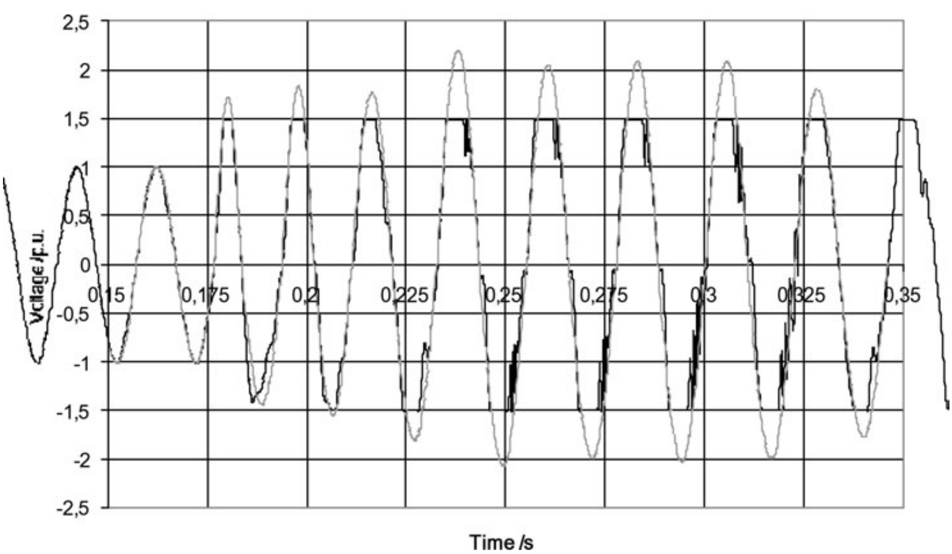

Figure 2. A single phase voltage in the windfarm cable at the on-land connection point at the isolation moment. The traces are (1) black - as measured, (2) grey - as estimated using the fundamental-frequency sine function. Similar voltage behaviour is also observed in the two other phases.

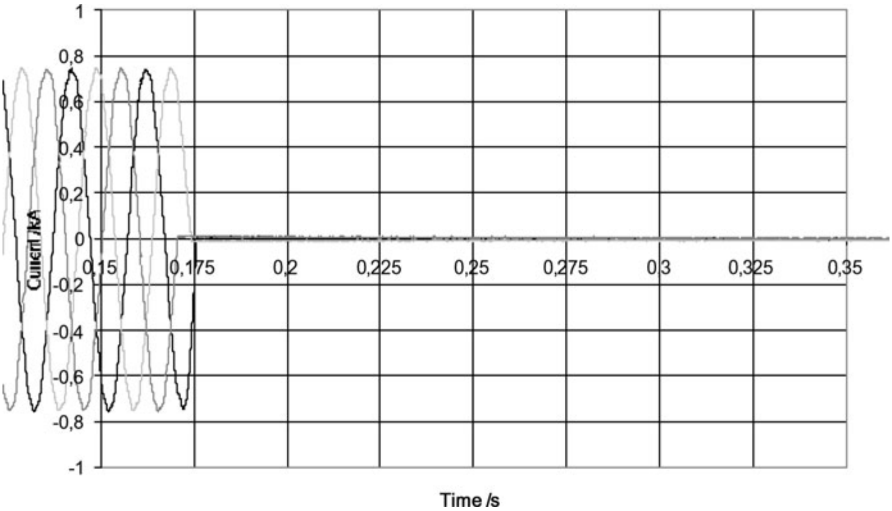

Figure 3. Phase current in the windfarm cable at the on-land connection point at the isolation moment.

Immediately after the break, and while the offshore wind turbines were still in operation (connected to the windfarm internal grid), the voltage magnitude and the electric frequency of this isolated grid rapidly increased from the normal 50 Hz. Before the offshore turbines were disconnected from the windfarm internal grid, the electric frequency reached 60 Hz.

After the offshore wind turbines were disconnected by their protective systems, the voltage magnitude decayed and the electric frequency was recorded as equal to the 'natural' frequency, f_N. , of the second-order system; this has the windfarm cable as the capacitance, C =12.2 μF, and the compensation reactor as the inductor, L =1.15 H.

$$f_N = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{1}$$

The natural frequency of the second-order system, f_N, was approximately 42.5 Hz.

2.1. Simulations

The Danish TSO, Energinet.dk, performed an investigation of this event, applying the Electro-Magnetic Transient (EMT) module of the simulation tool Powerfactory (DigSilent). Figure 4 shows the windfarm grid-connection model set-up for this investigation. Relevant circuit breakers are also marked in Figure 4.

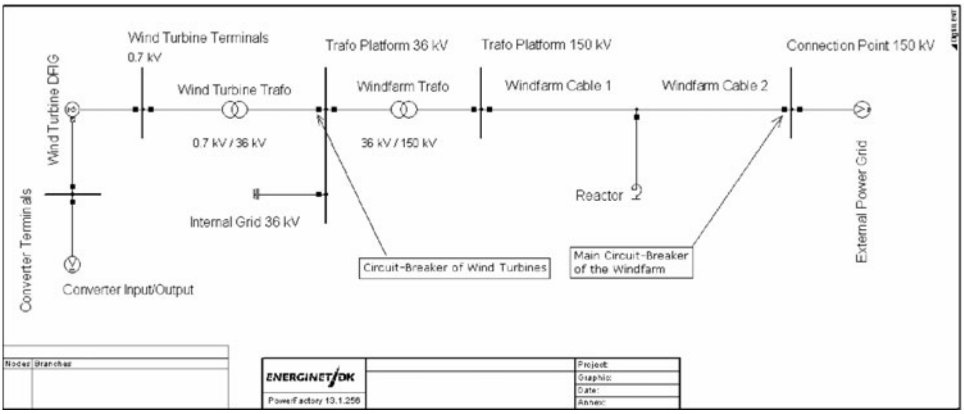

Figure 4. Windfarm grid-connection model set-up applied for investigation of transient voltage at isolated operation.

In this investigation, the windfarm is represented by a single-machine equivalent of power rating 160 MW. The rated terminal voltage of the wind turbines is 0.7 kV. Through the 36/0.7 kV transformer, the windfarm is connected to the internal grid, consisting of 36 kV sea cables and represented by a capacitor with the reactive power rating of 4 MVAr, which corresponds to reactive power generation in these cables. The windfarm is connected to the on-land connection point through the 150/36 kV transformer and the 150 kV cable. The entire transmission grid is modelled by a 3-phase AC voltage source, as the transmission grid operation after the break is irrelevant for this investigation.

In simulations, the main circuit-breaker of the windfarm opens at time 0.1 sec. and the wind turbines trip at time 0.14 sec. (i.e. the circuit breaker of the wind turbines opens).

The simulated phase voltage and current for all 3 phases at both ends of the 150 kV cable are shown in Figure 5, which is in agreement with the measurements.

2.2. The voltage rise phenomenon

The voltage rise phenomenon in such long high-voltage cables at given operational conditions has a transient nature. However, the main interest of the investigation of the Danish TSO is excessive over-voltage having durations of seconds (or longer), i.e. pure transient phenomena are disregarded.

The investigation has shown that such excessive over-voltage is present as the offshore windfarm (the active current source, I_P, of the wind turbine generators) charges the long, high-voltage cable in no-load operation because of its capacitance, C. This implies that shorter cables are charged faster than longer ones, which has been confirmed by simulations using the EMT module of the simulation tool Powerfactory.

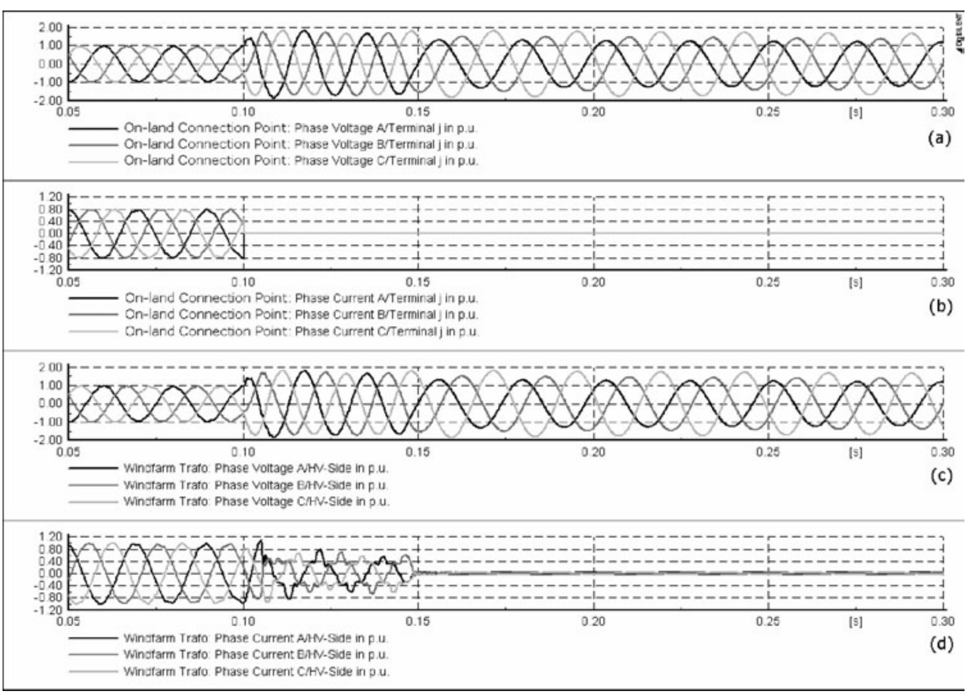

Figure 5. Simulated behaviour in the windfarm cable at the cable ends: (a) - voltage and (b) - current at the on-land connection point (the sub-station Karlsgårde), (c) - voltage and (d) - current at the high-voltage side of the windfarm transformer.

The voltage rate in such long high-voltage cables is, however, influenced by several parameters. The investigation of the Danish TSO has shown that:

1. The active current of the wind turbines, I_P, charges the cable capacitance. Then, the voltage rate is larger when the active power generation, i.e. I_p, in the windfarm is larger. For example, when the windfarm is in no-load operation, which means that the wind turbines are grid-connected, but their active power is zero, the disconnected windfarm cable does not charge to such excessive over-voltage.
2. When the wind turbines are fully-compensated or supply the reactive power to the isolated grid, the voltage rate will also be larger. This is because the voltage magnitude of this 3-phase system increases when the reactive power is supplied to the system and reduces when the reactive power is absorbed from the system.
3. The reactor absorbs an amount of reactive power from the isolated grid and reduces the voltage increase rate.
4. Saturation in the wind turbine transformers and the windfarm transformer may limit the voltage magnitude.

Power electronics converters or other reactive-power compensating equipment of the wind turbines may trip by such excessive over-voltage. In such situations, the wind turbine generators must then be excited from the internal cable network, start absorbing reactive power and reduce the voltage increase

4. PLANNED WINDFARMS

The grid-connection of the Horns Rev B windfarm to the Danish transmission grid can be arranged as shown in Figures 1 and 4.(schematically for the model set-up) Through a long 150 kV sea/underground cable and a 400/150 kV transformer, this large offshore windfarm is, in this analysis, connected at the 400 kV Endrup sub-station . The Horns Rev B windfarm will then have a longer high-voltage cable than that of the existing Horns Rev A windfarm. A reactor with the rating of (presumably) 180 MVAr will be established to provide reactive compensation for this long high-voltage cable. The issue of excessive over-voltage in, and design and protection of, the high-voltage cable and the windfarm transformer becomes very relevant.

The Danish TSO, Energinet.dk, has performed an investigation for such excessive over-voltage for this 150 kV grid-connection of the Horns Rev B windfarm. This investigation has clarified how different wind turbine concepts may influence the over-voltage magnitude and duration. The wind turbine concepts of the investigation are:

1. Fixed-speed wind turbines equipped with induction generators with short-circuited rotor circuits and thyristor-switched capacitors (IG and TSC).
2. Variable-speed wind turbines equipped with doubly-fed induction generators and partial-load frequency converters (DFIG) [1].
3. Variable-speed wind turbines equipped with induction generators and full-rating frequency converters (IGFRFC). In this concept, the generator is grid-connected through the full-rating converter [2].

Figure 6 presents the simulated magnitude of the 3-phase voltage in the 150 kV cable at the Endrup sub-station (the 150 kV side of the 400/150 kV transformer). The simulated behaviour is explained in the following sections for each investigated wind turbine concept. The voltage magnitude does not increase so much as observed in the existing Horns Rev A windfarm, because the Horns Rev B windfarm will use a longer cable for its grid-connection. The voltagelimiting effect of saturation in the transformers and fast interruption of the active current injection from the wind turbine generators contributed also to reducing the magnitude of excessive over-voltage.

4.1. Induction generators with TSC

The circuit outlines for the windfarm and a single wind turbine are shown in Figures 4 and 7. When the main-circuit breaker of the windfarm cable at the on-land connection point opens and the voltage magnitude in the isolated windfarm grid starts increasing, the TSC disconnects. The induction generators are now excited from the windfarm grid and start absorption of the reactive power. This leads to some reduction of the voltage magnitude. However, the voltage magnitude may continue increasing due to the active current injection from the wind turbine generators into the windfarm cables.

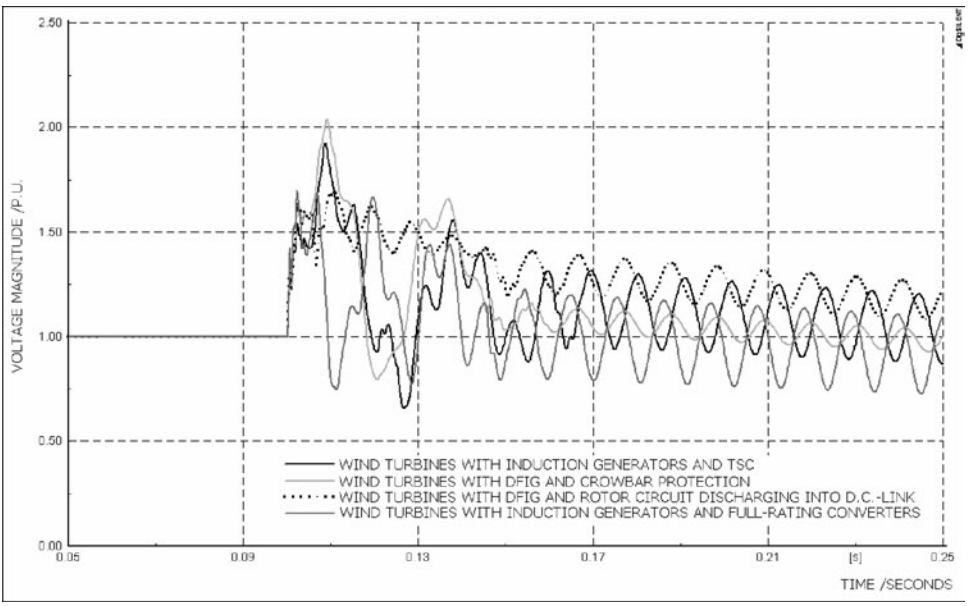

Figure 6. Simulated voltage magnitude in the 150 kV cable at the Endrup sub-station for different wind turbine concepts in the planned Horns Rev B windfarm.

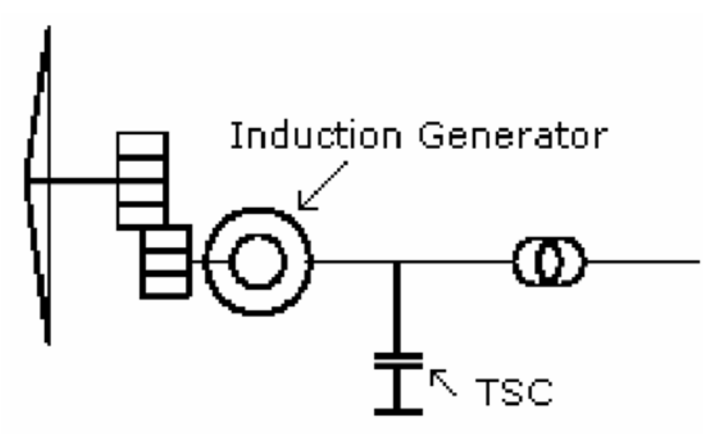

Figure 7. The concept of wind turbines with induction generators and TSC.

The induction generators may trip tens of milliseconds after the main-circuit breaker has opened. The voltage magnitude starts then decaying.

4.2. Doubly-fed induction generators

The circuit outlines for the windfarm and a single wind turbine are shown in Figures 4 and 8. A few milliseconds after the main-circuit breaker has opened, the rotor converter of the DFIG blocks due to excessive current transients in the generator rotor circuit. In this case, the rotor converter may block in two different ways [1].

1. The rotor converter trips and the rotor circuit is closed through a crowbar with a small electric resistance.
2. The IGBT-switches off; the rotor converter stops operating and opens. The rotor circuit is discharged into the d.c.-link capacitor through the diode-bridge of the blocked rotor converter.

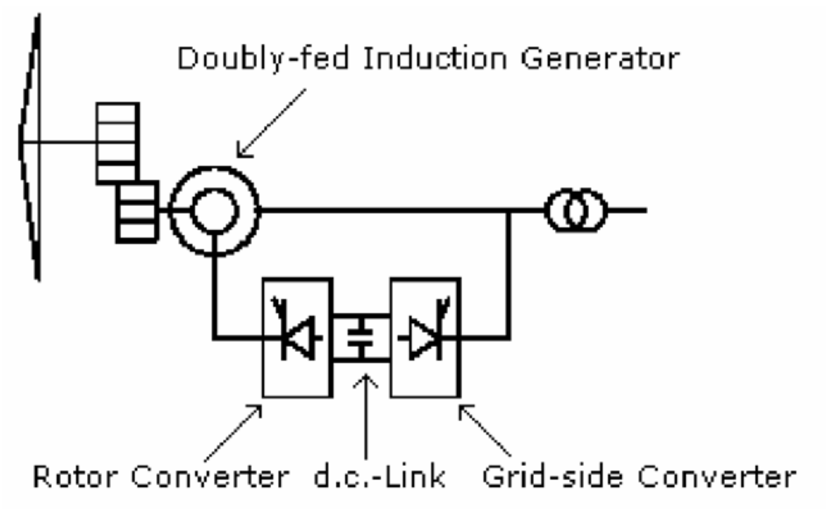

Figure 8. The concept of wind turbines with DFIG and partial-load converters.

The first blocking sequence, (1), resembles that of the fixed-speed wind turbines equipped with induction generators and TSC, because the DFIG with activated crowbar protection operates as an induction generator with a short-circuited rotor circuit [1]. When the rotor converter has blocked, the reactive power control of the generator is disabled. The generator absorbs reactive power from the isolated grid for maintaining its excitation and reduces over-voltage.

With the second blocking sequence, (2), the generator has lost excitation during the rotor circuit discharging into the d.c.-link. This results also in some reduction of over-voltage in the isolated windfarm grid.

4.3. Full-rating converters

The circuit outlines are shown in Figures 4 and 9. Due to the presence of the full-rated frequency converter and the decoupling the generator from the grid, this wind turbine configuration may give better control and less risk of excessive over-voltage in the isolated windfarm grid. This requires, however, that:

1. The grid-side converter of the wind turbine has a sufficient current rating and
2. Its reactive power control is designed to ride-through likely over-voltage in the grid.

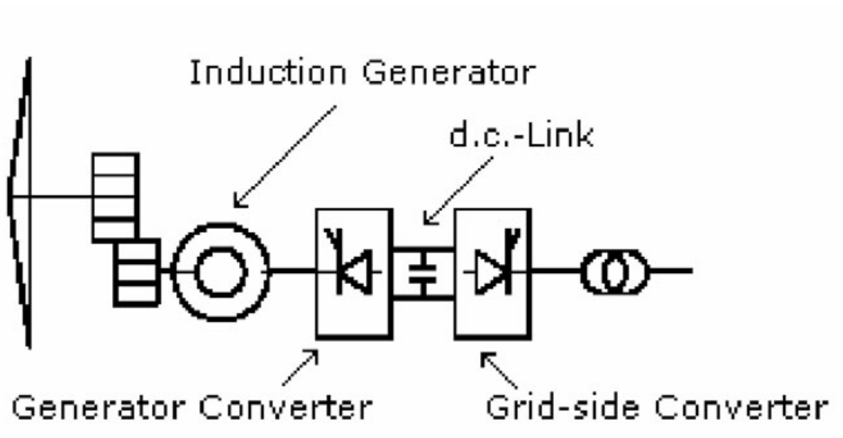

Figure 9. The concept of wind turbines with induction generators and full-rating converters.

In this investigation, it is assumed that the grid-side converter control is arranged as a cascade control with independent control of the d.c.-link voltage and reactive current, and with an additional loop accessing the reactive current reference and providing the voltage/reactive-power control [2]. The rated terminal voltage is 0.7 kV, the rated d.c.-link voltage is 1.5 kV. The size of the d.c.-link capacitor is chosen to keep the 2 kHz contribution from the converter switches within ±1% of the rated d.c.-link voltage.

When the main-circuit breaker of the windfarm cable at the on-land connection point opens, the voltage magnitude at the grid-side converter terminals rapidly increases. This activates the blocking of the generator converter and interrupts the active current injection to the isolated grid.

The grid-side converter maintains uninterrupted operation. Seen from the grid, the wind turbine operates as a Statcom and is set to control the voltage in the isolated grid. So long as the d.c.-link voltage, the converter current, the a.c. grid voltage, the electric frequency are within their respective operation ranges, the grid-side converter absorbs the reactive power surplus and keep the grid voltage within an acceptable range, see Figure 10.

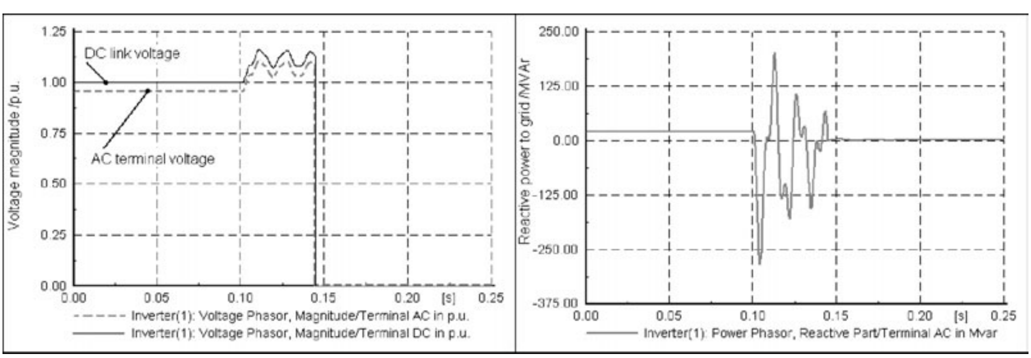

Figure 10. A simulated behaviour of a.c. voltage at the grid-side converter terminals, d.c.-link voltage and reactive power supplied from the converter to the isolated grid.

Nevertheless, in this investigation, it was considered that the wind turbines would trip tens of milliseconds after isolating the large offshore windfarm.

5. CONCLUSION

Long high-voltage cables, windfarm transformers and other equipment applied for connection of large offshore windfarms to the transmission grid can be subject to significant over-voltage. Such over-voltage with the voltage magnitude up to 2 p.u. was observed in a Danish offshore windfarm when the main-circuit breaker tripped the windfarm cable at the on-land connection point and the windfarm was in isolated operation with the cable and the windfarm transformer. Although such events are rare, this may introduce a risk of the equipment damage.

The Danish TSO, Energinet.dk, performed investigations of such over-voltage in connection with commissioning of a new offshore windfarm at Horns Rev. The investigations have shown that the voltage increase rate is influenced by many parameters, including (a) operational characteristics of the wind turbines prior to the isolation, (b) protection and control and the electric parameters of the cable and the transformers.

In particular, this investigation has shown that the active power supply from the wind turbines to the isolated grid of the windfarm must be interrupted as fast as possible, because the active current magnitude is proportional to the voltage increase rate. The reactive compensation of the wind turbine generators must be switched off or set to prevent excessive over-voltage.

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