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Simulated Switching Transients in the External Grid of Walney Offshore Wind Farm

I. Arana, D. T. Johnsen, T. Soerensen and J. Holboell

Abstract—**This paper presents the results of several simulations to assess the highest possible line-to-line overvoltage at the terminals of wind turbine converters after the switching operation of a cable or capacitor bank in the external grid of Walney 1, one of two phases of Walney Offshore Wind Farm. These switching operations were simulated using the EMT software PSCAD/EMTDC A number of parameters were varied in order to determine the most critical transients.**

Based on the results, it was concluded that the worst line-to-line transient overvoltage occurred in the DC05 and EF06 turbines, when a 25km cable is connected at 152ms and when the wind turbines are producing 100% of maximum apparent power. The magnitude of the worts transient would not reach 1.2kV.

Index Terms— **Wind Farm, switching overvoltages, capacitor bank, cable energization, EMT simulations**

I. INTRODUCTION

This paper presents the procedure to predict the highest possible line-to-line overvoltage at the terminals of the wind turbines (WTs) after a switching operation which connects a capacitor, cable or capacitor bank to the external grid of an offshore wind farm. All the available as-build information was used to create model to represent a switching operation on the external grid of Walney 1, one of two phases of Walney Offshore Wind Farm (WOW). The simulations in PSCAD were performed using standard cable, capacitor and transformer models. This paper is the continuation of a similar study performed for Gunfleet Sands Offshore Wind Farm [1].

The work is made by DONG Energy in cooperation with the Technical University of Denmark, is part of ongoing efforts to improve the accuracy of electrical modelling of power system components.

II. WALNEY OFFSHORE WIND FARM

THE WOW project is located approximately 15km west of Barrow-in-Furness in Cumbria at the East Irish Sea. The project consists of Walney 1 (WOW1) and Walney 2 (WOW2) each with 51 3.6MW wind turbines, giving a total capacity of the Walney project of 367.2MW.

WOW1 consists of two parts, WOW1.1 with 21 wind turbines and WOW1.2 with 30 turbines, each with a rated power of 3.6MW.

The WTs are connected in "rows" by 36kV submarine cables. Pairs of rows are connected to the platform by one "root" cable, thereby forming a radial to be connected to the platform. Two park transformers (120MVA YNd1 132/33kV) are placed on an offshore platform in the centre of each wind farm. The radials of WOW1.1 are connected to one park transformer (TR1), and the radials of WOW1.2 are connected to the other park transformer (TR2). The connection of the park transformers is via a single three-phase HV submarine sea cable and land cable to the grid connection point on land.

III. DIFFERENT SIMULATIONS

The model of the WOW1 was created in PSCAD to predict the highest possible line-to-line overvoltage at the LV terminals of the wind turbines after the switching operation in the external grid where WOW1 is connected. In order to do so, several simulations were performed. First of all, a simulation was performed to find the wind turbine that would experience the highest overvoltage within the collection grid; here a 12μF capacitor was connected. Then a comparison was made between the overvoltages caused by the connection of a capacitor bank, a cable simulated as PI equivalent and a cable simulated with distributed parameters. Afterwards the PI cable length was varied seven times to find the effect of the length on the overvoltage. Subsequently, the switching time at which the cable is connected was varied eight times to find the worst possible switching instant. Finally, the apparent power generation from the WTs was increased to see the effect of the power generation on the line-to-line overvoltage. All the different versions created in PSCAD are shown in Table 1 together with the main parameter variations.

It was decided for the present study that only cables and capacitor banks´ connecting operations would be investigated. This is based on previous experience on switching operations in the external grid of offshore wind farms [1]. All the components were modelled according to the available information and IEEE guidelines [2], [3] and [4].

TABLE 1
INFORMATION ABOUT THE SYSTEM FOR EACH PSCAD MODELS

Aim	Model	Switching component	Cable length	Switching time	Apparent power generation
Grid	12μF	2μF capacitor		0.15s	0%
Component	60MVAr	Capacitor bank		0.15s	0%
	10km-PI	PI cable	10km	0.15s	0%
	15km-PI	PI cable	15km	0.15s	0%
	15km-	Distribu-	15km	0.15s	0%

	Cable	ted cable			
Cable length	10km-PI	PI cable	10km	0.15s	0%
	15km-PI	PI cable	15km	0.15s	0%
	20km-PI	PI cable	20km	0.15s	0%
	25km-PI	PI cable	25km	0.15s	0%
	30km-PI	PI cable	30km	0.15s	0%
	35km-PI	PI cable	35km	0.15s	0%
	40km-PI	PI cable	40km	0.15s	0%
Time	150ms	PI cable	25km	0.15s	0%
	151ms	PI cable	25km	0.151s	0%
	152ms	PI cable	25km	0.152s	0%
	153ms	PI cable	25km	0.153s	0%
	154ms	PI cable	25km	0.154s	0%
	155ms	PI cable	25km	0.155s	0%
	156ms	PI cable	25km	0.156s	0%
	157ms	PI cable	25km	0.157s	0%
Generation	0S	PI cable	25km	0.152s	0%
	10S	PI cable	25km	0.152s	10%
	25S	PI cable	25km	0.152s	25%
	50S	PI cable	25km	0.152s	50%
	75S	PI cable	25km	0.152s	75%
	100S	PI cable	25km	0.152s	100%

A. HV 132kV network

In all the simulations, the external 132kV Heysham substation is represented as an equivalent network (Thevenin: voltage source behind impedance). Two 1km cable sections simulated as PI were included between the substation and the Point of Common Coupling (PCC).

In subsection IV-B different components were switched in at the Heysham substation. In the PSCAD model 15km-Cable, a 15km distributed cable was created based on the available information from the manufacturer and IEEE guidelines [3]. In PSCAD the cable model used was the Frequency Dependant (phase) model.

B. HV export grid

Included in the models was the connection of the park transformer via a single three phase HV submarine cable (132kV /45km) and land cable (132kV /3km) to the PCC on land. In all of the PSCAD models the cables were modelled as PI cables.

C. MV collection grid

The length of the MV submarine cables connecting the WTs in the WOW1 varies between 0.6km and 2.3km long. Furthermore, the turbines connected at WOW1.1 and WOW1.2, both park transformers, as well as the row and root cables were included in all the PSCAD models.

D. Wind turbines

The wind turbine transformer (4MVA, 33/0.69kV) is connected to the collection grid via a vacuum circuit breaker. On the LV side of each transformer a high-frequency filter and reactor were included between the wind turbine transformer and the wind turbine converter. The wind turbine converter and the generator behind were modelled in all simulations as an ideal voltage source.

IV. SIMULATIONS RESULTS

In general the results are divided in three subsections; overvoltage level within the collection grid, switching component, cable length variation, switching time variation and generation variation. Each of them will be explained below.

A. Overvoltage level within the collection grid

In this subsection the procedure to find the maximum overvoltage within the collection grid is explained. First a 12µF capacitor is switched in at the Heysham substation. It was decided to try first by connecting a 12µF capacitor at 150ms; this would represent the total capacitance of a 50km 132kV cable with a capacitance per length of 0.24µF/km. The switching time was decided to be at the peak line-to-line voltage, seen from the LV side of the wind turbines. The results of the voltages at the LV side of several WTs are shown in Fig. 1. The small plot in Fig. 1 shows a zoom of the highlighted zone where the highest voltage appears.
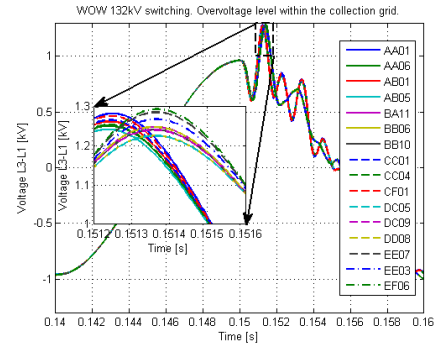

Fig. 1 Phase L3 to phase L1 voltage at the LV side of the WT at different wind turbines from 140ms to 160ms from the PSCAD model 12µF. In the small plot the same results are shown from 151.2ms to 151.6ms.

It is possible to see from Fig. 1 that the switching in operation of a capacitor at the Heysham substation would cause a serious overvoltage at the LV side of the WT terminals.

In Fig. 2 it is possible to see that the maximum overvoltage is slightly different from turbine to turbine; the maximum value appears at the EF06 turbine and the minimum value at the DC05. If the maximum voltages at each location are separated in groups depending on the value, then given colours where the highest value are red and the lowest green, and finally this colours used in a diagram of WOW1; it is possible to see that the WTs connected through the longest cable to the offshore substation experience the highest overvoltage. This is shown in Fig. 2.
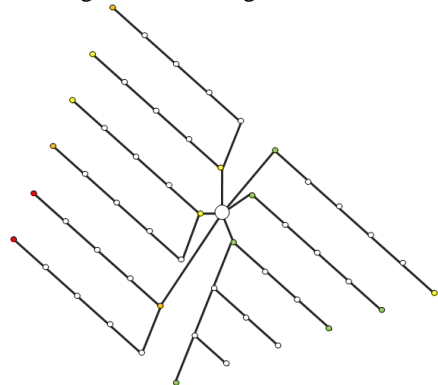

Fig. 2 Collection grid with colour nomenclature based on the maximum transient overvoltage from the PSCAD model 12µF.

B. Switching component

In this subsection the line-to-line overvoltage in the WT EF06 and DC05, caused by the connection of a capacitive element in the Heysham substation has been analyzed. Here the switching element has been modified from a capacitor, capacitor bank and cables. The results are shown in Fig. 3. Here it is possible to see that the connection of a 12µF capacitor causes the highest overvoltage, followed by the 60MVAr and finally the 10km and 15km PI and distributed cable model. The connection of a bare capacitance with an added value of a 50km 132kV cable seems to be unrealistic and conservative.
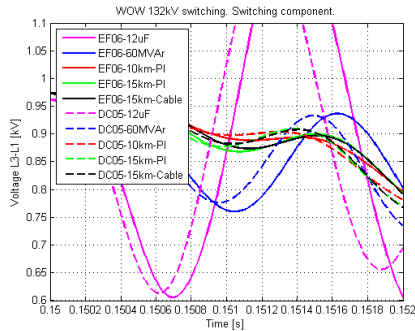

Fig. 3 Phase L3 to phase L1 voltage at the WTs DC05 and EF06 converter terminals from 150ms to 152ms for different PSCAD models.

The response between the WT EF06 and DC05 is very similar, however the overvoltage oscillation is not the same, since the impedance seen from each turbine is different due to the amount of cables of the collection grid that each turbine is connected though.

In general there is no large difference between the type of cable. It was concluded, based on the results, that for this kind of switching operations the type of cable model (PI or distributed) does not influence the results. While the effect of the cable length on the switching overvoltage will be investigated in the next subsection.

C. Cable length variation

As shown before, the length of the cable connecting in the Heysham substation, has an influence on the overvoltage at the converter terminals of the WTs. In order to analyze this, seven simulations have been done where the cable length was varied from 10 to 40km, in 5km steps. The results are shown in Fig. 4 and Fig. 5.
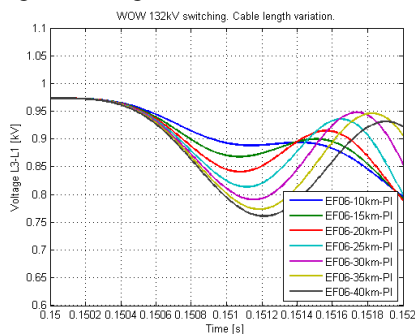

Fig. 4 Phase L3 to phase L1 voltage at the WT EF06 converter terminals from 150ms to 152ms for different PSCAD models with different PI cable lengths.

It is possible to see from this two figures that the longer the cable, the higher the amplitude of the voltage disturbance. However the second oscillation peak has different amplitude depending on the cable length and WT location. The lowest value of the first oscillation is present in the EF06 WT, in comparison to DC05.

As mentioned before, this difference is due to the impedance seen from each turbine. Based on experience from the operation of other wind farms, it is decided that the 25km cable is the most likely cable length to be energized without point-on-wave switching devices, so this cable length will be used for the following simulations.
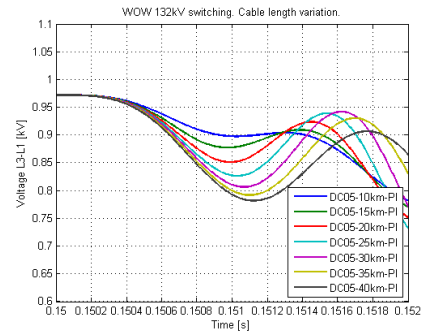

Fig. 5 Phase L3 to phase L1 voltage at the WT DC05 converter terminals from 150ms to 152ms for different PSCAD models with different PI cable lengths.

D. Switching time variation

In this subsection the switching time at which the 25km cable is connected has been varied from 150 to 157ms, with 1ms step size. 150ms correspond to the time when the phase L3 to phase L1 has peak value. This is achieved by point-in-time trigger of the switching device connecting the cable, taking into account the three-phase symmetry of the system i.e. repeating results every 1/3rd of a cycle. The results are shown in Fig. 6 and Fig. 7. The time and amplitude frame selected in Fig. 6 is further shown in Fig. 7 for both wind turbines.
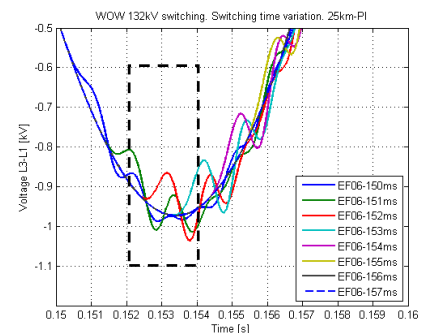

Fig. 6 Phase L3 to phase L1 voltage at the WT EF06 converter terminals from 150ms to 160ms for different PSCAD models with different switching times of a 25km cable.
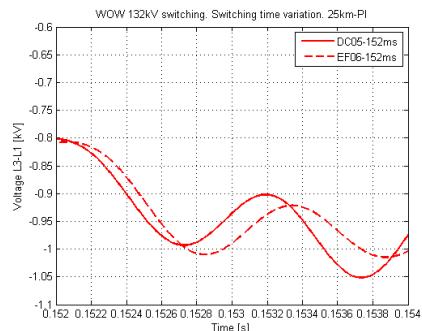

Fig. 7 Phase L3 to phase L1 voltage at the WTs DC05 and EF06 converter terminals from 152ms to 154ms for the PSCAD model with a 25km cable switching at 152ms.

In Fig. 6 the line-to-line voltage at the EF06 WT is shown for all switching time variations. It is possible to see here that the highest voltage appears when the switching operation happens at 152ms. If now the transient overvoltage at the WTs EF06 and DC05 are plotted (Fig. 7) it is possible to see different oscillations at both locations.

The highest value appears at the DC05 WT during the second high frequency oscillation; in contrast to the maximum value on the EF06 WT during the first high frequency oscillation. This shows the importance of EMT simulation to assess the highest possible voltage within the collection grid.

E. Generation variation

As a final parameter to be varied, in this subsection the apparent power of the WTs has been increased from 0% to 100%, in order to see the effect of the current though the reactor and high-frequency filter between the wind turbine transformer and the wind turbine converter. The results are shown in Fig. 8 and Fig. 9. The time and amplitude frame selected in Fig. 8 is further shown in Fig. 9 for both wind turbines.
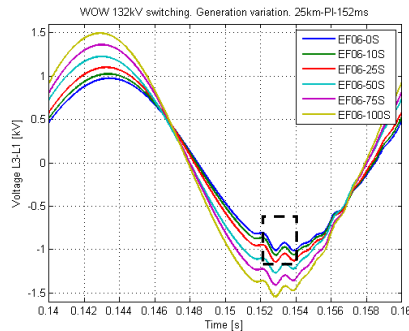

Fig. 8 Phase L3 to phase L1 voltage at the WT EF06 converter terminals from 140ms to 160ms for the PSCAD models with a 25km cable switching at 152ms under different generation levels.
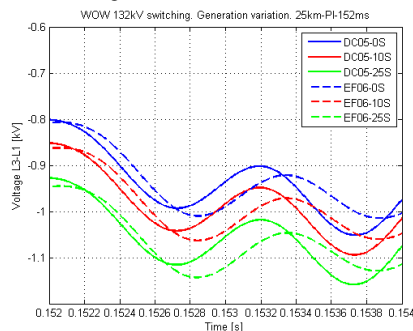

Fig. 9 Phase L3 to phase L1 voltage at the WTs DC05 and EF06 converter terminals from 152ms to 154ms for the PSCAD models with a 25km cable switching at 152ms under different generation levels.

The line-to-line voltage at EF06, from the six simulations is shown in Fig. 8. It is possible to see the direct proportionality between the apparent power generated from the WT and the magnitude of the transient overvoltage.

Based on the construction of the WT, it has been decided that the maximum apparent power of the converter is one quarter of the maximum WT power, since there are several modules connected in parallel on each WT. Based on this assumption, the results from the WTs EF06 and DC05 are shown in Fig. 9. The maximum value on DC05 of 1.16kV

appears during 25% generation during the second high frequency oscillation peak; while the maximum value on EF06 of 1.14kV appears during the first high frequency oscillation peak.

It is important to mention that there are no available standard models of wind turbines for EMT simulations, so the real behaviour of the wind turbine is unknown.

V. CONCLUSIONS

This paper describes a procedure to assess the highest possible line-to-line overvoltage at the terminals of wind turbine converters after the switching operation of a bare capacitor, capacitor bank or cable in the public grid to which WOW1 is connected. The results are based on numerical time domain simulations in PSCAD.

Several simulations were performed to find out which WT in the collection grid experiences the highest transient overvoltage, which available standard models in PSCAD should be used, and to what extend the cable length, switching time and generation level are important. First, it was found that the switching component is very important, and the response is highly dependent on which device is connected. It was also found that the cable models (PI or distributed) does not cause large deviations.

It was found that for this kind of transients, the cable length and switching time of the 132kV cable are important. Then, based on operational experience it was decided to narrow the simulations to cables of certain length range.

Based on the simulation results, the highest transient overvoltage is dependent on the location; during the first high frequency oscillation it appears on the EF06 WT, and during the second high frequency oscillation the maximum value appears on DC05.

Finally the generation level of the wind turbines was varied and a direct proportionality was found between the apparent power generated from the WT and the magnitude of the transient overvoltage.

It can be concluded that the worst line-to-line transient overvoltage occurs in the DC05 and EF06 WTs, when a 25km cable is switched in at 152ms and the wind turbines are producing 100% of apparent power. The magnitude of this transient would not reach 1.2kV

VI. REFERENCES

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