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Validation of a Switching Operation in the External Grid of Gunfleet Sand Offshore Wind Farm by Means of EMT Simulations

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Validation of a Switching Operation in the External Grid of Gunfleet Sand Offshore Wind Farm by Means of EMT Simulations

I. Arana, J. Okholm, and J. Holboell

***Abstract*—This paper presents the voltage signals occurring during a switching operation recorded in the external grid of Gunfleet Sands Offshore Wind Farm recorded with an Elspec measurement system. The measurements are compared to electromagnetic (EMT) simulations for validation of the wind farm model using PSCAD/EMTDC. The simulation model then was modified to investigate the influence of a capacitor bank connection.**

It was found that for this kind of transients, the amount of wind turbines (wind turbine transformers, high frequency filters and wind turbine converter) included in the model makes a difference to the results; while the cable models (PI or distributed) and the type of model of the wind turbines converter (voltage source or open end), does not have a considerable influence on the transient response at the PCC or MV terminals of the park transformers

***Index Terms*— wind farm, capacitor bank, EMT simulations and transient overvoltages.**

I. Introduction

THIS paper presents the procedure to use the available as-build information from wind turbine and other equipment manufacturers and from transient voltage measurements to create and validate a model to represent a switching operation on the external grid of Gunfleet Sands Offshore Wind Farm (GFS). The measurements were extracted from the permanent Elspec measurement system at the Point of Common Coupling (PCC) and at the MV terminals of the park transformers. The simulations in PSCAD were performed using standard cable, capacitor and transformer models.

The investigations were made by DONG Energy in cooperation with the Technical University of Denmark and are part of ongoing efforts to improve the accuracy of electrical modeling of power system components.

II. Gunfleet Sands Offshore Wind Farm

The GFS project is located approximately 7km south-east off Clacton-on-Sea, Essex, see Fig. 1. The project consists of two phases, Gunfleet Sands 1 (GFS1) with 30 turbines and Gunfleet Sands 2 (GFS2) with 18 turbines (WTs). Total capacity of Gunfleet Sands Offshore Wind Farm is 172MW corresponding to the consumption of 125,000 British households.

The WTs are connected in "rows" by means of 36kV submarine cables. Pairs of rows are then connected to the platform by one "root" cable. Two park transformers (120MVA, YNd1, 132/33kV) are placed on an offshore platform in the centre of the wind farm. The radials of GFS1 are connected to one park transformer (TR1), and the radials of GFS2 are connected to the other park transformer (TR2). The grid connection of the park transformers is established via a single, three-phase HV submarine sea cable and a land cable to the grid connection point on land. The external grid where GFS is connected is owned by EDF Energy (EdF).

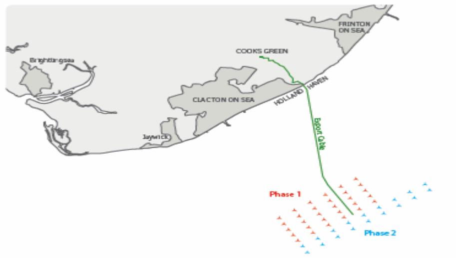

Fig. 1: Gunfleet Sands Offshore Wind Farm layout and location, approximately 7 km south-east off Clacton-on-Sea, Essex, UK.

III. Measurements

It is possible to extract current and voltage waveforms from different Elspec measurement equipment installed at GFS with the Elspec Investigator software. The embedded PQZip compression technology allows continuous recording of all electrical parameters for significant time duration. The voltage waveforms are sampled at 1024 samples per cycle and the currents at 256 samples per cycle; GFS is connected to a 50Hz system. The resulting digital waveform is compressed with FFT computation, resulting in 512 spectral components per cycle for voltages and 128 for currents. The resulting data are being further compressed using lossy compression algorithms. When the waveforms are required, the data are decompressed with full harmonic spectrum for each cycle along with the associated time stamps. The waveform displayed by the Elspec Investigator application is reconstructed based on the compressed spectral data of every cycle [1].

The voltage and current waveforms measured from the following locations have been extracted and are compared to the results from PSCAD simulations:

- at the onshore PCC at 132kV,
- at the MV terminal of the TR1 at 33kV and
- at the MV terminal of the TR2 at 33kV.

It is important to mention that only the maximum and minimum value from each time interval can be extracted from the Elspec Investigator; hence in some figures the averaged values for each time interval have been compared to the PSCAD results and in some other figures, also the

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minimum and maximum values for each time interval are shown.

In order to make an accurate comparison in all locations, the current and voltage waveforms in TR2 were shifted +0.62ms due to a GPS time error.

IV. SIMULATIONS

The model of GFS was created in PSCAD to replicate measurements recorded by the Elspec measurement system. It was decided to simulate this period of time due to the high transient overvoltages caused by the switching in operation of a 60MVAr capacitor bank in the EdF 132kV grid where GFS is connected.

The 60MVAr capacitor banks are located in the Bramford 132/400kV NGET Substation, on the public HV grid, but the exact state of the HV system where GFS is connected is unknown; however an approximate model of the export grid to which GFS is connected has been created based on the available information. In order to find the dependence of the results to different models and system states, different versions of the PSCAD model have been developed. All the different versions are shown in Table 1 including the main parameter variations. The influence of the different components and models was compared as:

- V1-V2: the influence of the MV cables when modeled as distributed or as PI elements,
- V2-V3: the influence of the wind turbines,
- V3-V4: the influence of the HV cables when modeled as distributed or as PI elements,
- V4-V5: the influence of the wind turbine converter modeled as ideal voltage source or as open circuit and
- V5-V6-V7: the influence of the HV capacitors connected prior to the switching event.

All the simulations in PSCAD were run over a period of 0.3s with a step time of 10µs, and the switching operation was performed at 0.201s. In that way it was ensured that the system was stable before the switching operation. In the figures presented below, the initial 0.13s were removed to simplify the comparison with the measurements.

A. *HV external grid*

The information about the HV external grid where GFS is connected is based on the forecasted load 2009-2010 from an EdF report [2]. The grid model includes 23 interconnections, 4 load centers and a super-grid of 400kV. The main problem with the construction of the external grid model is that the state of it at the exact moment of the incident is almost impossible to establish accurately. The influence of this unknown factor is investigated by sensitivity analyses of the results to changes in load, load location, and extension of the HV and MV network in the public grid. The HV and MV loads on the public grid model are located at Ipswich 132, Lawford 132, Clacton 33 and Cliff Quarry 33.

B. *Bramford 132kV busbar*

As mentioned before, the actual state of the public HV grid can only be guessed, so the ammount of capacitor banks connected at the Bramford 132kV busbar had to be investigated. Since the amount of capacitor bank connected prior to the switching operation is unknown, sensitivity analyses to this unknown factor were done by including the three possible configurations: in V5 one 60MVAr capacitor was connected, in V6 no capacitor was connected and finally in V7 two 60MVAr capacitors were connected.

C. *HV export grid*

Included in the models was the connection of the park transformer via a single three phase HV submarine cable (132kV/9.167km) and a land cable (132kV/3.622km) to the PCC on land. In some of the PSCAD models the cables were modeled as PI or as distributed cables.

The distributed cables were 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.

D. *MV collection grid*

The MV submarine cables connecting the WTs in the GFS1 rows are 550m long, while in GFS2 the rows are 950m long. Furthermore, the turbines connected at GFS1 and GFS2, both park transformers, as well as the row and root cables were included in the PSCAD model depending on the objective of the simulation.

The MV collection grid was simplified to different degrees depending on the version, but the main parameters like cable size and length were always kept. For example, for V1 the root and row cables were modeled as frequency dependant distributed models, but the row cables between the first and last turbine of the radial were simplified to one long cable instead of several short cables. On the other hand, for V2 the root and row cables were modeled as nominal PI sections but the row cables between the first and last turbine of the radial were simplified to one long cable instead of several short cables. In V3, V4, V5, V6, and V7 every root and row cables were modeled as nominal PI sections.

E. *Wind turbine and park transformers*

Both park transformers (TR1 and TR2), as well as the wind turbine transformers were included, based on the available information from the manufacturer and IEEE guidelines [4], by means of the standard transformer model in PSCAD. The capacitances between primary winding to ground, secondary winding to ground and primary to secondary windings were included as well as the saturation characteristic in the magnetic core.

F. *Wind turbines*

The wind turbine transformer (4 MVA, 33/0.69 kV) is connected to the radial via an MV Vacuum Circuit Breaker. On the LV side, between the transformer and the converter, a high-frequency filter and reactor were included. The wind turbine converter was modeled in some simulations as an ideal voltage source, and in others as an open circuit.

The super-grid of 400kV, capacitor bank at Bramford, high-frequency filters, reactors and circuit breakers were modeled based on the IEEE guidelines [5]

V. SIMULATIONS RESULTS

In general the results are divided in three subsections; model comparison, capacitor bank comparison and harmonic contents at the PCC comparison. Each of them will be explained below.

TABLE 1
SYSTEM STATE AND COMPONENT MODEL FOR EACH PSCAD VERSION

Versions	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**
EHV state	Normal	Normal	Normal	Strong	Strong	Strong	Strong
Initial C at 132kV	60MVAr	60MVAr	60MVAr	60MVAr	60MVAr	0MVAr	120MVAr
MV cables model	Distributed	PI	PI	PI	PI	PI	PI
Numer of WTs	12	12	48	48	48	48	48
Land and sea cable model	Distributed	Distributed	Distributed	PI	PI	PI	PI
WT model	Voltage source	Voltage source	Voltage source	Voltage source	Open	Open	Open

A. Model - measurements comparison

In this subsection, the averaged measurements were compared to the simulated phase A and B voltages from the PSCAD model versions V1, V2, V3, V4 and V5 at the PCC, TR1 and TR2. Only phase A and phase B at the MV side of the TR1 and TR2 are shown since in these phases the maximum overvoltages appeared. The results are shown in Fig. 2 to 4. Comparing the simulation results from these three figures, it is possible to see the peak transient voltage in all versions and locations is higher than the averaged measurements.

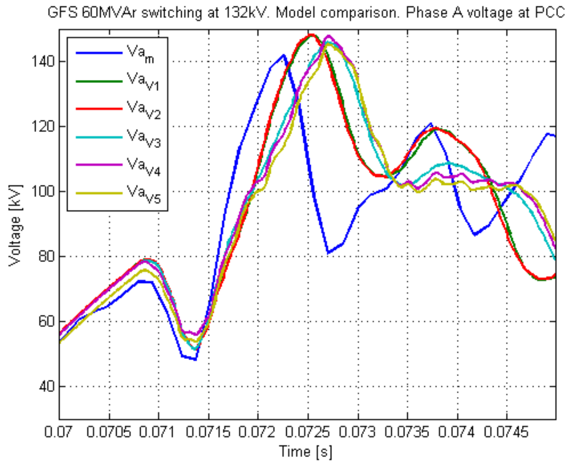

Fig. 2: Phase A voltage at the PCC from 70ms to 75ms for the averaged measurements (m) and PSCAD versions V1, V2, V3, V4 and V5.

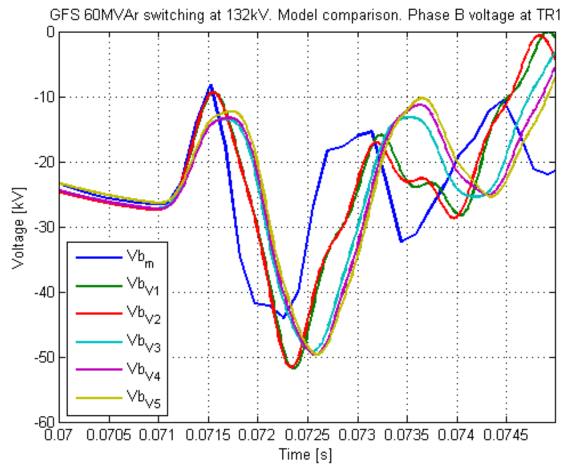

Fig. 3: Phase B voltage at the MV side of TR1 from 70ms to 75ms for the averaged measurements (m) and PSCAD versions V1, V2, V3, V4 and V5.

It is also possible to separate the results in two groups depending on the oscillation and magnitude of the overvoltage. In one group are V1 and V2 while V3, V4 and V5 are in a second group. It is possible to see from Table 1 that the main difference between these two groups is the amount of wind turbines connected in the wind farm collection grid. In the first group only 12 turbines are connected while 48 are connected in the second group.

There are small differences between V1 and V2 in the results at the PCC, TR1 and TR2 after 0.0725s. There are also small divergences between V3, V4 and V5 during the entire time, but especially after 0.0735s. These differences are due to the type of cable model used and also the wind turbine model (converter model). This would indicate that for this kind of switching operations the type of cable model (PI or distributed), wind turbine model and strength of the grid do not influence the results significantly.

It is also possible to see a clear difference between the measurements and results of the two park transformers. In practice however, the response to a transient on both locations should not be the same, since the equipment connected to the collection grid on both sides is different, specially the amount of cables.

From this series of plots it can be seen that in general, the results from the simulations in PSCAD are representative compared with the recordings from Elspec. However, some discrepancies have been found at the PCC after 0.072s and the following subsections will focus on the cause of this divergence.

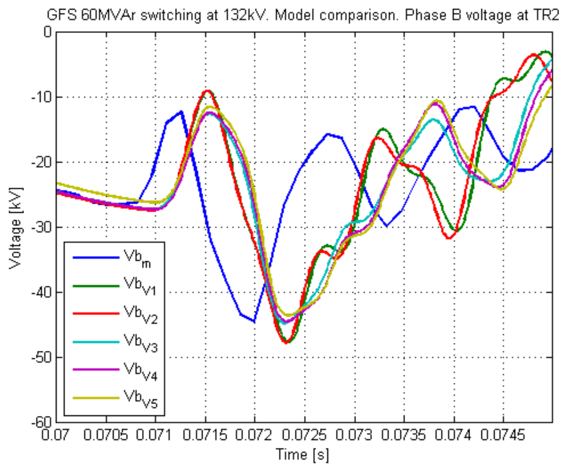

Fig. 4: Phase B voltage at the MV side of TR2 from 70ms to 75ms for the averaged measurements (m) and PSCAD versions V1, V2, V3, V4 and V5

B. Influence of capacitor banks

In this subsection the averaged, maximum and minimum measurements were compared to the simulated phase A voltage from the PSCAD versions V5, V6, and V7 at the PCC.

The results are shown in Fig. 5. Here it is possible to see that from 0.07s to 0.0718s the results from V6 seem closer to the actual measurements. The peak transient voltage in V5 and V6 is very close to the maximum measured voltage. V5, V6 and V7 start showing a complex behavior just before 0.072ms.

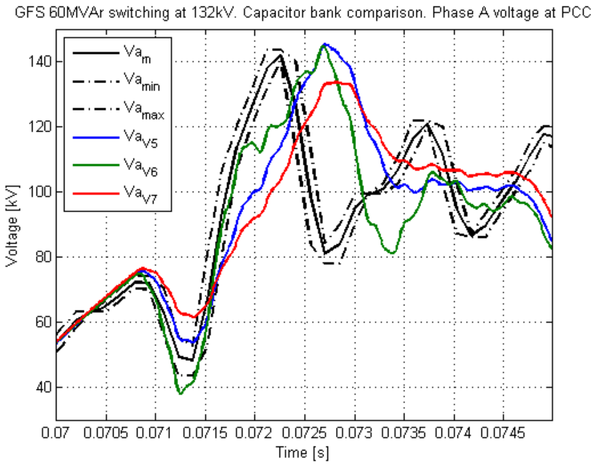

Fig. 5: Phase A voltage at the PCC from 70ms to 75ms for the averaged measurements (m), minimum measurements (min), maximum measurements (max), and PSCAD versions V5, V6, and V7.

From this figure it can be concluded that the number of capacitors of 60MVAr at 132kV previously connected to the switching operation cannot be found only by comparing the raw results from the PSCAD simulations. Further work has been done on the following subsection regarding this problem.

C. Harmonic contents at the PCC

In this subsection a frequency scan at the point of common coupling (PCC) is shown for different operating conditions, as well as FFT analysis of the phase A voltage at the PCC plus the harmonic contents of V5, V6 and V7.

First a frequency scan of the impedance at the PCC is shown for different operating conditions (Fig. 6). Here it can be seen that the parallel and series resonance frequencies decrease with the amount of capacitor banks connected to the grid; the parallel resonance for the system with no capacitor bank is 375Hz, for the system with one 60MVAr is 290 and 580Hz, for the system with 120MVAr is 250 and 540Hz; and finally for the system with 180MVAr is 210 and 520Hz. The system with 180MVAr represents the final state from V7.

In order to assess the effect of the loading and grid capacity from the external grid on the resonance frequencies at the PCC, the frequency scan for different version of the system with 120MVAr was calculated. Here the load in Ipswich 132, Lawford 132, Clacton 33 and Cliff Quarry 33 were increased. Also the grid short circuit capacity was increased several times. It was found that these variations do not change the resonance frequency of the system considerably, but only the magnitude of the impedance seen from the PCC. However, if additional loads at other locations in the 132kV grid are included, there is a small shift in the resonance frequencies. As mentioned before, no exact information of the state of the external grid was available, so no conclusions can be made based on this issue. Future work is expected to be done in this area.

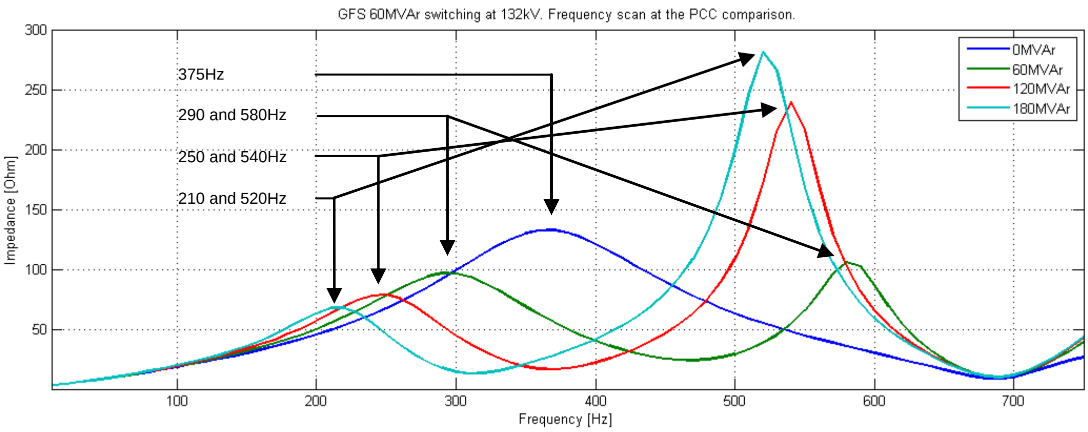

Fig. 6: Impedance sweep magnitude at the PCC from 0Hz to 1500Hz for the system with standard values of the 400kV super-grid and different amounts of capacitor banks connected at Bramford 132kV. The system with no capacitor banks (0MVAr), the system with one capacitor bank (60MVAr), the system with two capacitor banks (120MVAr) and the system with three capacitor banks (180MVAr).

TABLE 2
MAXIMUM HARMONIC CONTENTS [KV] OF PHASE A VOLTAGE FROM 0.07 TO 0.12S

Frequency [Hz]	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**Initial [MVAr]**	**Final [MVAr]**
Elspec	110	0.5	0,5	0,2	0,7	1	4	3	4	5	1,2	5	2	7	4		
V5	110	1	1	1,5	3	5	5	4	3	3	5	7	1,5	1,2	1,2	60	120
V6	110	1	1	1,5	2	4	6	5	4,5	4,5	5	6	5	1,2	1,2	0	60
V7	110	1	1	1,5	4	5	3	2	2	3	5	4	1,5	1,2	1,2	120	180

The magnitude of the harmonic contents on the phase A voltage at the PCC from the Elspec measurements and PSCAD versions V6, V5 and V7 is shown in the Table 2. In this table it is possible to see that:

- there are high harmonic contents around 400 and 700Hz when one capacitor bank is connected to the real system (Elspec);
- there are high harmonic contents around 300 and 600Hz when one capacitor bank is connected, while 60MVAr are connected previously (V5);
- there are high harmonic contents around 350 and 600Hz when one capacitor bank is connected, while no other capacitor is connected previously (V6);
- there are high harmonic contents around 300 and 550Hz when one capacitor bank is connected, while 120MVAr are connected previously (V7).

The simulated resonant frequencies from the PSCAD model versions are slightly higher compared to the ones found in the frequency scan.

On the other hand, if the harmonic contents from the PSCAD model versions are compared to the harmonic contents from Elspec, a clear shift can be seen of the two resonant frequencies to a higher value (around 400 and 700Hz).

Based on this comparison, in can be concluded, that the PSCAD model version closest to the real export system in GFS is V6. However, none of the versions is an exact representation of the external grid where GFS is connected; nonetheless all the available information has been used, so no further simulations were performed.

Finally the harmonic contents in time domain of the phase A voltages at the PCC for V6 is shown in Fig. 7. It can be seen in this figure that the discrepancies between the measurements and the simulations start before 0.072ms, just when the harmonic voltages start to appear in the system. The results from V5 were plotted because it was found that this model version shows the harmonic contents in best accordance to the Elspec measurements, taking into account a frequency shift to a lower level of the two main resonance frequencies.

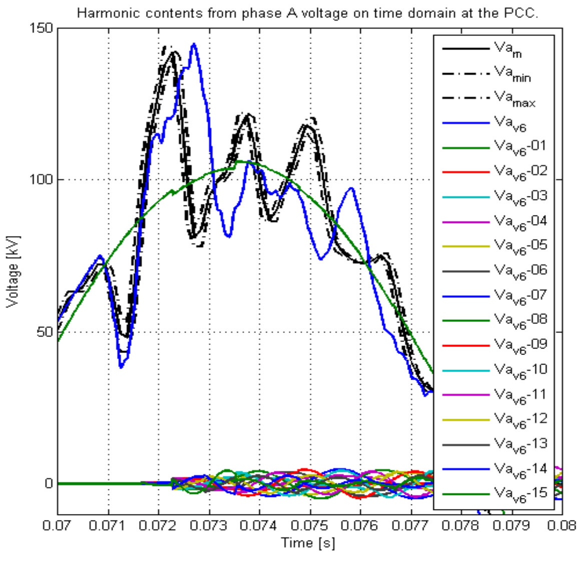

Fig. 7: Harmonic contents of phase A voltage at PCC from the 1st to the 15th harmonic from 0.7 to 0.8s of the PSCAD model version V6.

VI. Acknowledgment

The authors would like to acknowledge DONG Energy for proving access to the measurements and as-build information to carry out this study.

VII. Conclusions

This paper presents models to calculate transients in an offshore wind farm by means of EMT simulations. PSCAD was used to calculate overvoltages caused by a switching operation in the public grid to which GFS is connected. The results were compared to recordings made with an Elspec measurement system.

Several simulations were performed to find out which available standard models in PSCAD are most suitable, and to what extend the components in the export and collection grid of the offshore wind farm should be included in the simulations. First, it was found that the amount of wind turbines included in the model makes a difference to the results. It was also found that the cable models (PI or distributed) do not cause large deviations. It was found that for this kind of transients, the type of model of the wind turbines (voltage source or open circuit) does not have a considerable influence on the transient response at the PCC or MV terminals of the transformers.

Then by means of a frequency scan and analysis of harmonic components of the voltages at the PCC, it was found that the most likely capacitor bank switching operation in the public grid at GFS causing the most severe switching overvoltages was the connection of a 60MVAr capacitor bank, without any capacitor banks connected previously (V6).

It was also shown that an approximate public grid model could be used to estimate the magnitude of the overvoltages. In general, it can be concluded that the results from the simulations can be considered as being in good accordance with the recordings.

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