Comparison of Measured Transient Overvoltages in the Collection Grid of Nysted Offshore Wind Farm with EMT Simulations

I. Arana, J. Holbøll, T. Sørensen, A. H. Nielsen, P. Sørensen, O. Holmstrøm

***Abstract*-- This paper presents a comparison between GPS synchronized measurements of two switching operations in Nysted Offshore Wind Farm (NOWF) in Denmark, and results from electromagnetic transient (emt) simulations of these switching events using Power Factory/DIgSILENT and PSCAD/EMTDC.**

The collection grid of Nysted created in Power Factory and PSCAD was based on the information available from the wind farm as-built documentation. The cable model used in both programs was created based on the geometry and material properties of the cable. Circuit breakers and transformers were modelled by means of the comparable simple standard models in both tools.

The results from the simulations in Power Factory and PSCAD match the measured steep fronted first wave, when one radial is energized in the wind farm. However, differences were found in both simulation tools results compared with the measurements, in the more rounded fronted second waves.

***Keywords:* offshore wind farms, switching operations, transient overvoltages, modelling, cables, transformers, circuit breakers, PSCAD, Power Factory and model validation.**

I. INTRODUCTION

THE electrical conditions present in the collection grids for large offshore wind farms are not like any other industrial application. The number of generators, switchgears, transformers and cables is remarkable. This combination of components together with continuously changing load conditions creates an electrical environment never assembled before.

The best way for protection design and risk assessment, is the accurate prediction of possible occurrences by simulation studies. For this purpose, several simulation tools are available to calculate steady state, dynamic and transient conditions. With respect to transient overvoltages in the network commercial emt programs are available. However for studies with such tools to be useful, it is important to recognize the limitation and capabilities of these programs, since the system designer should know how reliable the simulation results are.

In collection grids of large offshore wind farms, switching operations are the main source of transient overvoltages, unlike the overhead systems up to 400 kV, where the lightning transients are the main concern. Previous work has been done to simulate switching transients in large offshore wind farms with PSCAD [1], Power Factory [4], PSCAD/Power Factory [5] and EMTP-RV [7].

In order to investigate switching transients in offshore wind farms, a field measurement campaign was conducted in Nysted Offshore Wind Farm (NOWF), where three GPS synchronized measuring systems were installed and used for simultaneous measurement at three different locations in the wind farm. The aim was to obtain accurate and synchronized records of the transient voltages at selected positions in the wind farm in order to study propagation and reflection effects that could be used for validation of the numerical simulations.

II. NYSTED OFFSHORE WIND FARM

The wind farm was installed in 2003 and is operated by DONG Energy who owns 80% of the farm, while E.ON owns 20%. It consists of 72 wind turbines (WTs) with a rated power of 2.3 MW each. The turbines are arranged in a parallelogram, formed by eight rows with nine WTs each (see Fig. 1). The WTs are delivered by former Bonus, now Siemens Wind Power.

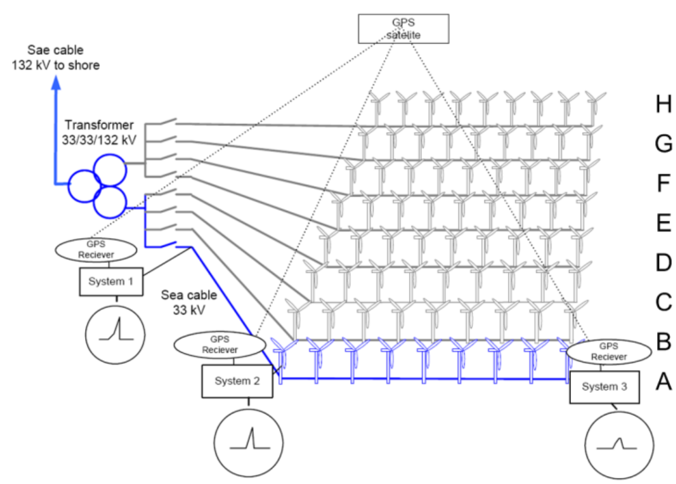

Fig. 1 Measurement locations in radial A of NOWF adopted from [2]. Three GPS synchronized high frequency transient recording systems to measure three phase voltages and three phase currents on the cable side of the vacuum circuit breaker, first turbine and last turbine.

The WTs are connected in "rows" by 36 kV submarine cables. Each row is then connected to the platform by one "root" cable. The park transformer (180/90/90 MVA,

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132/33/33 kV) is placed just north of the wind farm. Each root cable is connected to a MV bus bar via a vacuum circuit breaker (VCB). There are eight rows, from A to H, where A, B, C and D are connected to one MV winding, and E, F, G, and H to the other MV winding of the park transformer.

The submarine cables are connected to an air insulated bus bar in the bottom of each WT. The submarine cable armour and the phase conductor shields are grounded at both ends. The wind turbine transformer (2.5 MVA, 33/0.69 kV) is connected via a MV switch disconnector-fuse. On the LV side of each transformer only a capacitor bank for phase compensation of the induction generator and a small load were included.

The MV submarine cables connecting the WTs in the rows are 505 m long. The distance between the rows is 850 m, resulting in a corresponding difference in length of the root cables for the radial cables. Furthermore, included in the models was the connection of the park transformer via a single three phase HV sea cable (132 kV /10.5 km) and land cable (132 kV /18.3 km) to the grid connection point on land.

III. MEASUREMENT SYSTEM

A novel, GPS synchronized high frequency transient recording system was developed by DELTA for the measurements in NOWF [2]. Three phase voltages and three phase currents were simultaneously sampled at 2.5 MHz in three different locations in the MV collection grid and synchronized via GPS. The measuring points indicated in Fig. 1 were located at:

- The transformer platform on the cable side of the vacuum circuit breaker of radial A
- The wind turbine A01, the first turbine of radial A
- The wind turbine A09, the last turbine of radial A

The line-to-ground phase voltages are measured with capacitive voltage dividers, which are connected to the transient recorder through a high bandwidth amplifier developed by DELTA. The bandwidth (3 dB) of the total voltage measurement is 1 Hz to 10 MHz. From the measurements it was possible to estimate an accuracy of 20 V.

The line currents are measured with flexible current clamps with 600 A peak current and bandwidth (3 dB) from 0.55 Hz to 3 MHz.

Several switching transients were generated and recorded, but only switching operations closing the line breaker for radial A were investigated in this work.

IV. SYSTEM MODELLING

The collection grid of NOWF was created in Power Factory and PSCAD, based on the available manufacturer information of the cables, transformers and circuit breakers.

The switching operation investigated in this work is the closing of the line breaker for radial A. Here, 7 km of submarine cables connecting nine wind turbine transformers (WTT) were energized.

From this same switching operation two measurement cases were investigated. These two operations have been replicated in Power Factory and PSCAD as discussed in the next subsections. The two operations are basically the same, hence the models used were also same, except for the time (phase angle) at which the switching takes place.

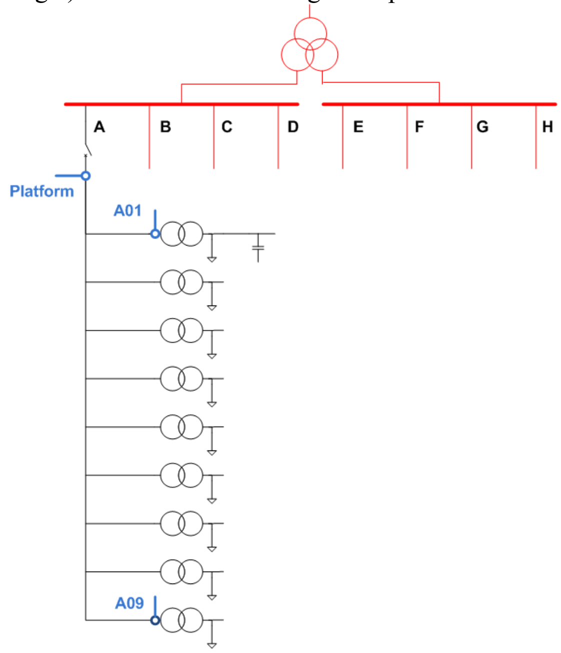

Fig. 2 Overview of switching operation closing the line breaker for radial A. The measurement equipment location is shown in the platform, WT A01 and WT A09. The equipments above the circuit breaker in the platform are the energized devices and the equipments below the circuit breaker are the non-energized devices prior to the switching event.

The network created in both simulation tools is shown in Fig. 2. Here it is possible to see the location of the measurement equipment at the platform, at WT number A01 and at WT number A09. At the LV side of each WT transformer a small load (0.37 kW) was connected. In WT number A01 a capacitor bank (180 kVAr) had to be included in the model as the measurements revealed that for unknown reasons this amount of capacitance remained connected during the measurements. The equipments above the circuit breaker in the platform are the energized devices, and the equipments below it are the non-energized devices prior to the switching event. Only row A is shown in detail, but the other rows B-H were in operation during the measurements.

The cable models were created in both simulation programs, based on the available information from the manufacturer and IEEE guidelines [3]. In PSCAD the cable model used was the Frequency Dependant (phase) model; while in Power Factory the Cable System was used with Single Core Cable Type in the Cable Definition.

It is important to mention that neither PSCAD nor Power Factory supports cable models where the armour surrounding the three single phase conductors with individual grounded sheaths could be included; hence the submarine cables in the collection grid were modelled as three single core cables placed relative to each other as defined by the physical constrains of the real cable. Additionally two important parameters were changed in Power Factory to improve the results: the separation between phases and the frequency for parameter approximation.

The geometrical cable parameter had to be edited in Power Factory, in order to improve the results. Here, some voltage coupling between the cables was found when the non simultaneous switching was simulated. This was solved by increasing the separation between single core cables horizontally to 50 cm.

It is important to mention that a frequency for parameter approximation of 1950 Hz was used in the distributed cable model in Power Factory [4]. This was found to be an important parameter regarding the transient and steady state behaviour of the voltage in Power Factory [5].

Since the Cable System in Power Factory is under development by DIgSILENT, limited information was available. According to DIgSILENT the frequency for parameter approximation is a fixed value representative of the range of frequency expected for the study, where a frequency of 1000 Hz may be used for switching transient studies.

Based on a series of simulations it was found that in the Cable System, an increase in frequency for parameter approximation would increase the wave velocity and the maximum transient overvoltage. It was found as well that the steady state reactance of the cable system was influenced proportionally to the frequency for parameter approximation.

The later adjustments to the cable model in Power Factory, might rise uncertainties about the limitations of the model, however the main aim of the current work is to compare simulation tools using standard models, in order to achieve results as close to the measurements as possible.

The vacuum circuit breakers (VCBs) were modelled as ideal switching devices, although pre-strikes were measured in both switching operations. It is important to mention that previous work has been done PSCAD to developed models where the random nature of arcing time, current chopping, dielectric strength and the quenching capability of the breaker has been incorporated [6]. However, further work is expected to be done with the creation of a validated model for the circuit breakers in future projects.

The nine WTT of the radial were included in both simulation tools, using standard transformer models. The capacitances between primary winding to ground, secondary winding to ground and primary to secondary windings were included based on manufacturer´s information. The saturation characteristic in the magnetic core was also included.

In both simulation tools, the collection grid of NOWF was created as close to reality as possible with the available information and the standard models in Power Factory and PSCAD. However, future projects will address the validation and further development of more accurate models for different MV components in the collection grid of large offshore wind farms.

V. Switching Operations

As mentioned before, two operations were investigated with 2 different switching times (i.e. phase angle at which the actual connection of the phases took place). The first 10 ms of the voltages recorded at the platform are shown in Fig. 3 for both switching operations.

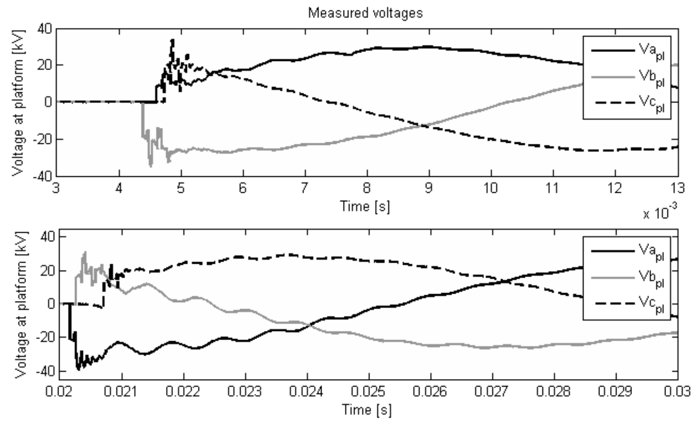

Fig. 3 First 10 ms from the measured voltages in the platform for both switching operations. Each voltage is plotted with one colour: phase A (Va) in solid black; phase B (Vb) in solid gray and phase C (Vc) in dashed black. **Upper plot:** first switching operation. **Lower plot:** second switching operation.

The upper plot in Fig. 3 is the voltage of the first switching operation measurement, where the plot in the bottom is the voltage of the second switching operation. It can be seen in the second switching operation, that the voltage reaches 40 kV and has higher oscillations after the switching occurred as compared to the first switching operation. In theory the system should be the same, only the point-in-wave has changed. In the first operation the switching occurred before the voltage of phase B (Vb_{pl}) reached a negative peak value. In the second operation the switching occurred after the voltage of phase A (Va_{pl}) reached a negative peak value.

If the zero crossing of phase A voltage is defined as zero degrees phase angle; the first switching operation occurred at 5 degrees phase angle; while the second switching operation occurred at 275 degrees phase angle. In the second switching operation the voltage of phase A (Va_{pl}) is closer to the peak voltage when the connection is made, than in the first switching operation.

This difference also had an influence on the inrush current presented in the transformers; however the current measurements and simulation results of that are not within the scope of this paper.

A. Switching operation at 5° phase angle

The voltage measured in the three locations (platform, A01, A09) for the first 10 ms are shown in Fig. 4. Here it can be seen that there are some transient overvoltages at the beginning of the waveform. These are caused by reflections in the cables that are attenuated during the first millisecond. It can be seen as well, that the transient due to the cable energizing and reflections is damped in less than 5 ms after the closing of the radial breaker.

The voltage wave travels from the platform to the last wind turbine (A09) in 45 µs where the reflection doubles the voltage and the wave then returns to the platform 45 µs later. Given that the cable between the platform and the last wind turbine is 7 km, and it takes 45 µs to the voltage wave to arrive at A09, the velocity of the wave would be 157 km/ms or 52% of the speed of light (300 km/ms) [4]. The same phenomena can be seen in phase A and phase C.

It is important to remember at this stage, that the sampling of the measurement system is 2.5 MHz, hence in 45 µs there are more than 100 samples of each signal; this shows that the recorded wave shapes are very accurate.

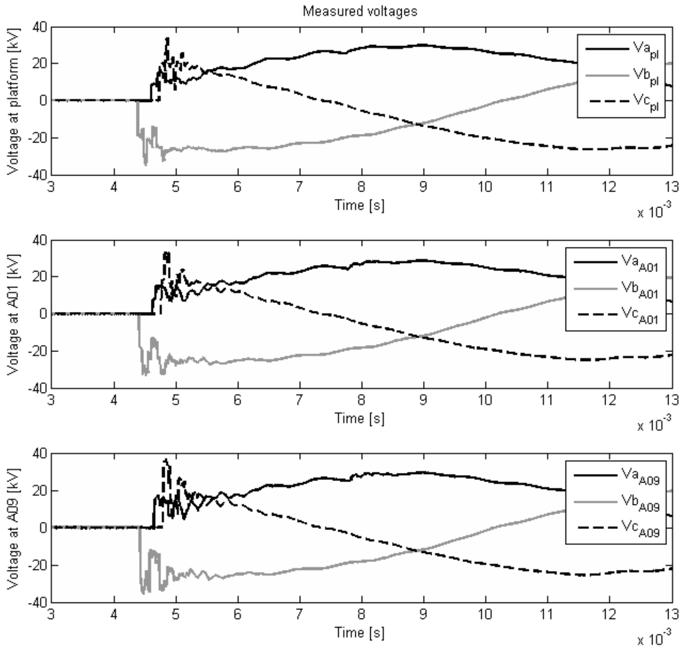

Fig. 4 First 10 ms from the measured voltages in the three different locations, for the switching operation at 5° phase angle. Each voltage is plotted with one colour: phase A (Va) in solid black; phase B (Vb) in solid gray and phase C (Vc) in dashed black. **Upper plot:** measured voltages at the platform. **Middle plot:** measured voltage at A01. **Lower plot:** measured voltage at A09.

Fig. 5 shows the first millisecond of the measurements of the first switching operation. Here, the voltage of phase B is presented for the three measurement locations. The voltage at the platform is shown in solid black, the voltage at A01 in solid gray and the voltage at A09 in dashed black. In the lower part of the figure, the colour and line nomenclature are the same, but the *y* axis shows the distance between measurement locations, and not the voltage as in the upper part.

The lower part of Fig. 5 presents the position of the voltage wave in thin black line. At T1 the phase B is energized at the platform. At T2 the voltage wave arrives to A01 and at T3 the voltage wave reaches A09.

It can be seen that the voltage wave is doubled at T3, since the cable ends at the transformer which would be seen as an open circuit for very high frequencies due to its inductance. Once the voltage wave has reached the end of the radial it bounces back towards the platform, arriving to A01 at T4 and to the platform at T5.

Three stepwise reductions of the platform voltage Vb_{pl} can be seen at D_{pl}, C_{pl}, and B_{pl} (indicated with black solid arrows), which are caused by the voltage drop at the platform bus bar due to the energization of the radial A cable. This voltage drop propagates as travelling waves into the three other radial cables connected to the same main transformer bus bar, and returns to the platform after being doubled in amplitude at the radial cable ends as the three steps separated in time corresponding to two times the difference in length of the root cables for the radial cables D, C and B. The three steps then propagate into radial A and can be seen in Vb_{A01} at WT A01. 21 µs later, they can be seen doubled once more in Vb_{A09} at WT A09 at D_{A09}, C_{A09}, and B_{A09} as indicated with black dashed arrows in Fig. 5.

At T5 the energization wave returns from radial A to the platform where it meets the 3 other radial cables B, C and D and the main transformer winding connected to the bus bar. This causes a negative reflection wave back into the radial A cable which can be seen as the sharp peak in Vb_{A01} at WT A01 at T6 and can be seen doubled in Vb_{A09} at WT A09 at T7.

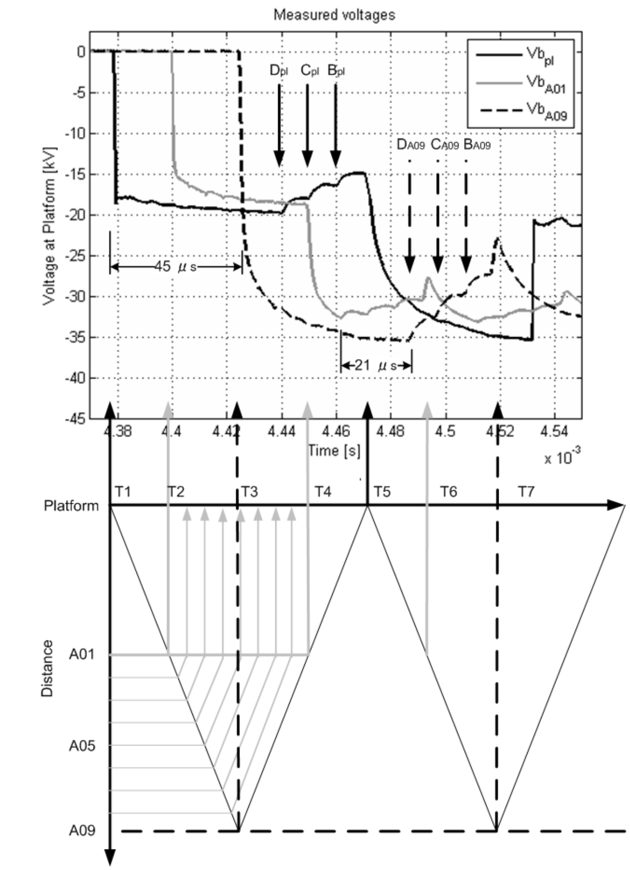

Fig. 5 **Upper plot:** measured phase B voltage, in the three different locations for the switching operation at 5° phase angle, from 4.3 ms to 4.6 ms. The voltage at each location is plotted with one colour: platform (Vb_{pl}) in solid black; WT A01 (Vb_{A01}) in solid gray and WT A09 (Vb_{A09}) in dashed black. **Lower plot**: position of the phase B voltage wave as seen from the platform. The same colour and line nomenclature were used: platform in solid black, A01 in solid gray and A09 in dashed black.

From Fig. 5 it is possible to notice seven small variations (less than 2%) of the voltage measured at A01 between T2 and T4. These are shown with thin gray lines representing the voltage waves reflected at bus bars in the each wind turbine where the wind turbine transformer is connected to the incoming and outgoing submarine cables. It can be seen that when the voltage wave reaches A02, a small amount of voltage was reflected backwards to A01, where it was measured as small variations in the voltage. From (1) the magnitude of the reflected voltage wave at a junction point can be calculated:

$$V_2 = \frac{Z_B - Z_A}{Z_B + Z_A} V_1 = \frac{48-50}{48+50} V_1 = -0.02 V_1 \quad (1)$$

with Z_A being the characteristic impedance of the cable and Z_B being the characteristic impedance on the refractive side with a value of 50 ‖ 1200 Ω = 48 Ω where 1200 Ω is the approximate characteristic impedance of the transformer.

The following figures and explanation account for the comparison between measurements and simulation results in Power Factory and PSCAD for the first switching operation. Throughout this subsection, the instantaneous value of the voltage for the measurements and results from Power Factory and PSCAD are plotted as "–m", "-pf" and "-ps" respectively.

The same colour and line nomenclature for instantaneous voltages for each phase were used as well in this subsection when possible.

Fig. 6 shows the first milliseconds of the three phases at the platform. It can be seen that the overvoltages due to voltage reflections in the row are not replicated accurately by the models created in both software tools. Furthermore, it is possible to notice a decrease on the voltage of phase C in PSCAD, before this phase is energized indicating that in PSCAD the models used has some coupling between phases This coupling was not replicated in Power Factory, because the separation between single core cables was increased in Power Factory to fit better the results to the measurements, as explained before.

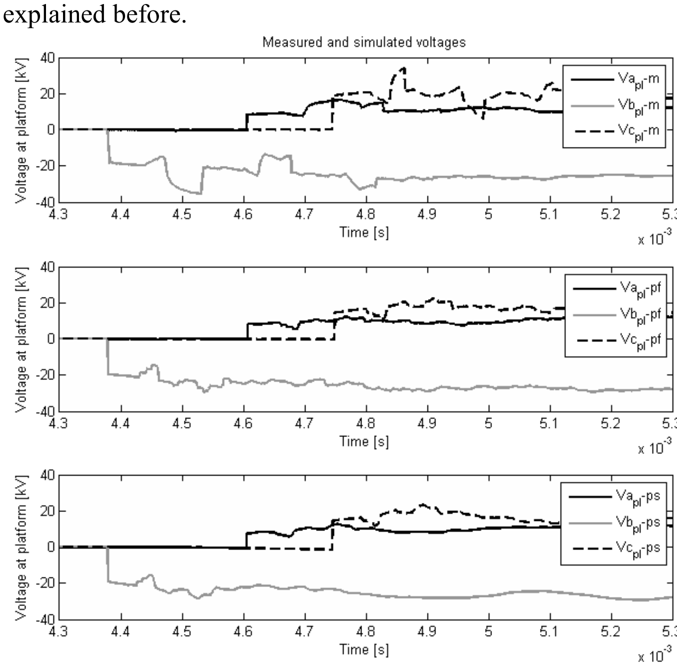

Fig. 6 Switching operation at 5° phase angle, measured and simulated voltages in the platform from 4.3 ms to 5.3 ms. Each phase voltage is plotted with one colour: phase A (Va) in solid black; phase B (Vb) in solid gray and phase C (Vc) in dashed black. The measurements and results from Power Factory and PSCAD are plotted as "–m", "-pf" and "-ps" respectively.

If only phase B (Fig. 7) is plotted and separated by location (Platform, A01 and A09), it is possible to see that the velocity of the wave in both simulation programs is higher than the measured velocity.

This difference was treated in [5] by increasing the relative permittivity of the cables on both simulation tools; however the wave velocity was higher in the results than the measurements. After the unsatisfactory results, another approach was taken to fit better the results to the measurements, where the length of the cables was slightly increased.

As mentioned at the beginning of this work, the distance between wind turbines is 505 m, where only the horizontal length of the cable was modelled. However, in reality the cables connecting the wind turbines at Nysted have also a vertical length because the foundation´s height from the seabed to each transformer is about 15 m, plus additional slack cable. Hence 35 m of cable was included in each side of each submarine cable on both simulation tools, with the original relative permittivity calculated on the cables; nevertheless there were still differences between the measurements and simulation results. Further work should be done to fully understand these differences between the models and the measurements.

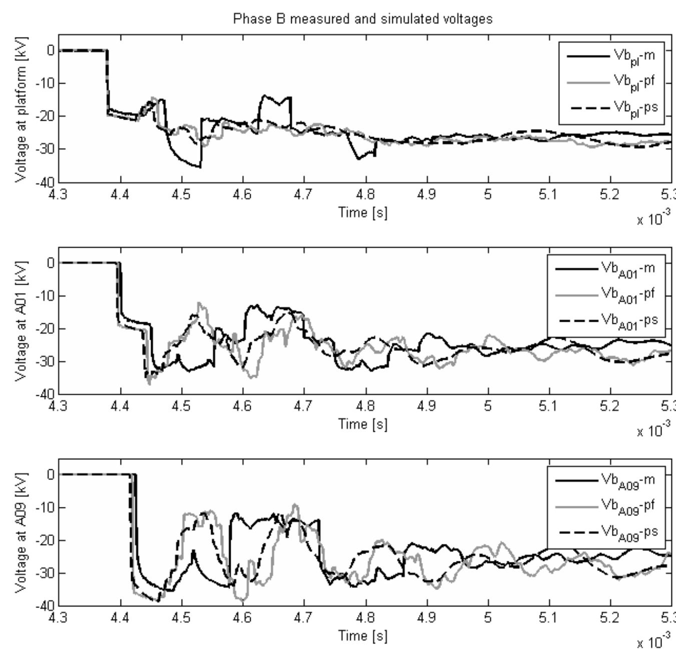

Fig. 7 Switching operation at 5° phase angle, measured and simulated voltage phase B in all locations from 4.3 ms to 5.5 ms. The measurements and results from Power Factory and PSCAD are plotted as "–m", "-pf" and "-ps" respectively. **Upper plot:** voltages at the platform. **Middle plot:** voltage at A01. **Lower plot:** voltage at A09.

In Fig. 7 the doubling effect of the voltage wave in phase B at A09, seems slightly higher in both simulations than in the measurements. Furthermore, the first voltage wave at A09 appears more damped in the real system and PSCAD than in Power Factory. This will be further presented in Fig. 10 for the second switching operation. However, this could be due to skin effect and dielectric losses in the cable.

The skin effect in AC conductors re-distributes the current density near the surface of the conductor due to the circulating eddy currents, in comparison with the core current density. The skin effect increases the conductor resistance depending on the content of higher frequencies of the current. For steep fronted pulses like the voltages measured in this study, it is important to acknowledge the limitations of the cable models to replicate the measurements.

The measured damping in the real system could be also explained by dielectric losses in the cable; however in both simulation tools the relative permittivity in the cable insulation was corrected and set to a constant value since none of the simulation tools can support the frequency dependence of this material property [3].

From the comparison of the voltages of the first switching operation, it can be seen that the systems created in both simulation tools shows similarities with the measurements in the steep fronted first wave, with explainable differences from the cable model simplifications. While the more rounded fronted second waves discrepancies, between the measurements and the simulations, will be treated next.

B. Switching operation at 275° phase angle

The voltages at three measurement locations are shown in Fig. 8 for the first millisecond after the closing of the radial breaker. It can be seen that the voltage at the platform and at the wind turbine A09 surpasses 40 kV several times. The reason for this large peak is that the closing of the breaker took place closer to the negative peak voltage of phase A. Then, when it reached the last wind turbine A09, the voltage was doubled as explained before.

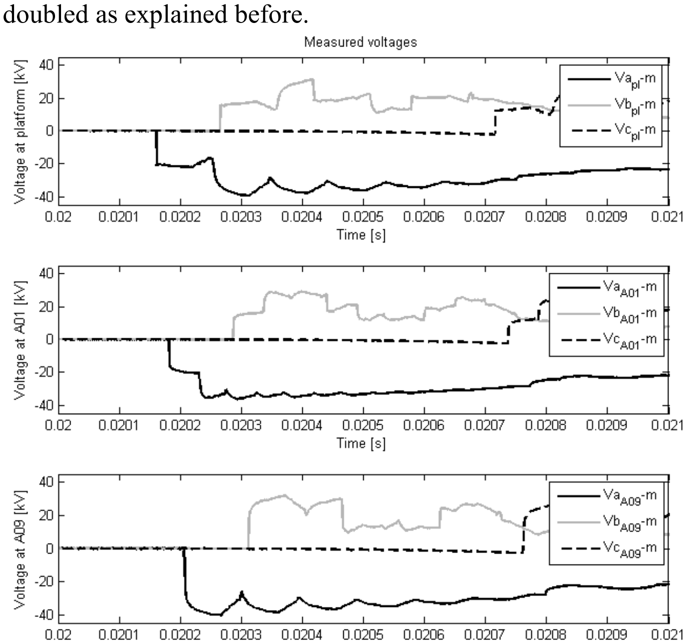

Fig. 8 Switching operation at 275° phase angle, measured voltages in the three different locations from 20 ms to 21 ms. Each voltage is plotted with one colour: phase A (Va) in solid black; phase B (Vb) in solid gray and phase C (Vc) in dashed black. **Upper plot:** measured voltages at the platform. **Middle plot:** measured voltage at A01. **Lower plot:** measured voltage at A09.

It's important to notice that in theory, the energization of an individual phase during a non simultaneous switching event, should not affect the voltage in the other phases. This is due to the grounded shield around each individual phase conductor within the cable. However, in reality there is some coupling between the phases due to the close geometrical arrangement of the cable. These capacitances are responsible for the small measured variations and decrease in voltage of phase C on the platform just before it gets energized, as can be seen in Fig. 9.

The following figures and explanation account for the comparison between measurements and simulation results in Power Factory and PSCAD for the second switching operation. The platform voltages from the measurements and both simulation programs are shown in Fig. 9. It is possible to see in the measurements for phase A (solid black) several overvoltages due to the reflection of the voltage wave. These overvoltages are also visible in phase B (solid gray) and phase C (dashed black), nonetheless these values are not as high in comparison with phase A. From this same figure it is possible to see, that these overvoltages are not present in the results from the created models in Power Factory and PSCAD.

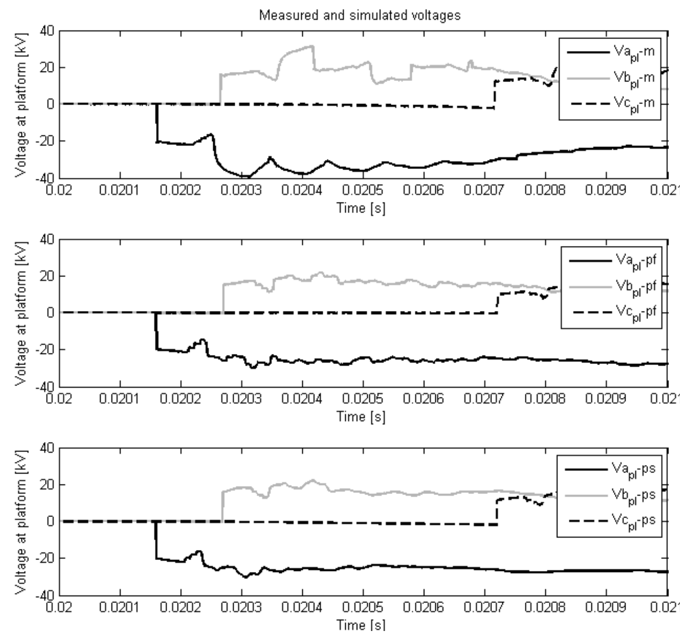

Fig. 9 Switching operation at 275° phase angle, measured and simulated voltages in the platform from 20 ms to 21 ms. Each phase voltage is plotted with one colour: phase A (Va) in solid black; phase B (Vb) in solid gray and phase C (Vc) in dashed black. The measurements and results from Power Factory and PSCAD are plotted as "–m", "-pf" and "-ps" respectively.

In order to simplify the visualization of the results, Fig. 10 shows the measured and simulated phase A voltages and currents from 20.1 ms to 20.4 ms. The voltages in the three locations are shown, while only the currents in the platform were included. From this figure it is possible to see that there is an agreement between measurements and simulations for the first 90 μs of the switching operation. However, after this time the simulated current and voltages differs from the measurements.

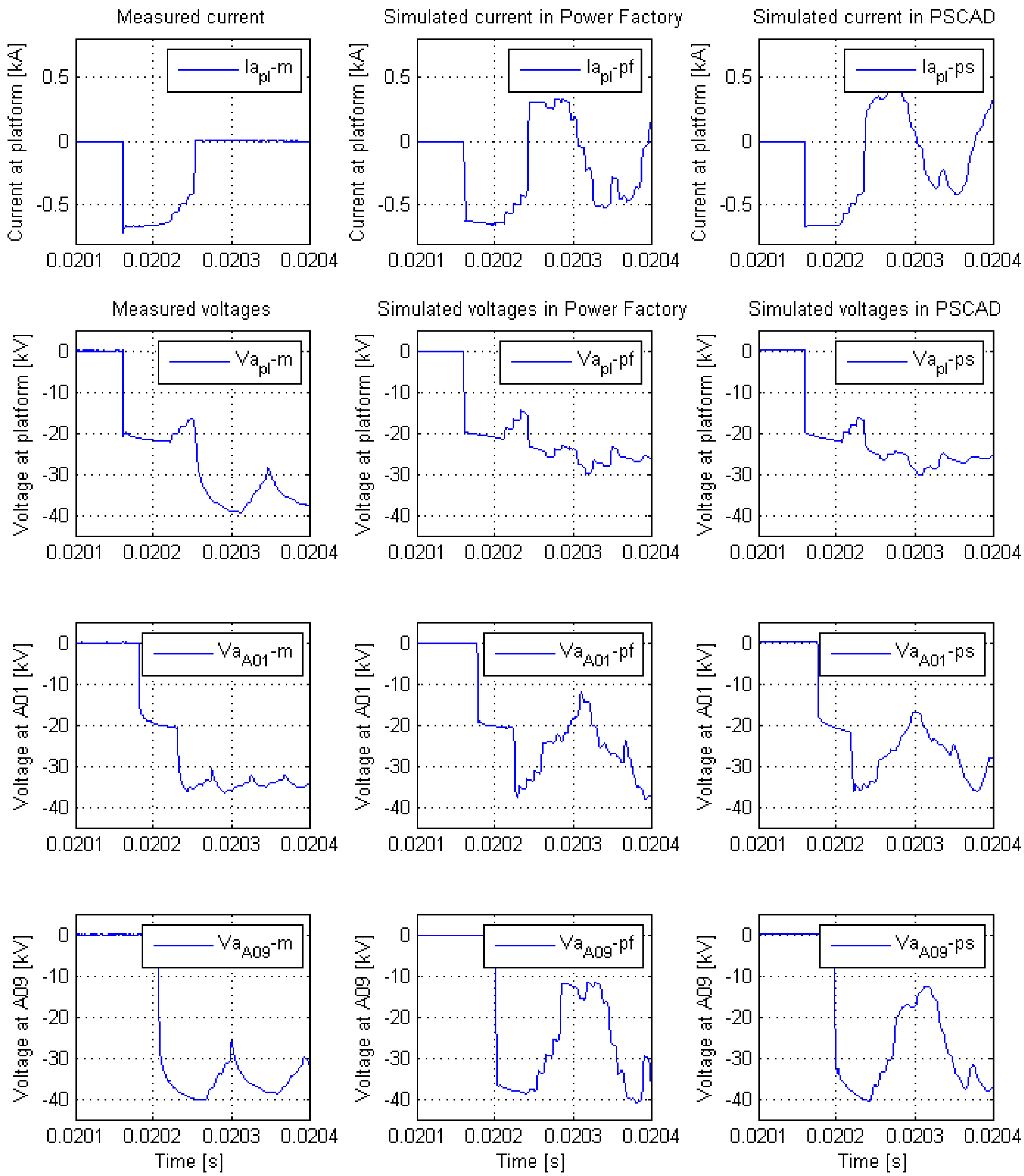

Fig. 10 Measured and simulated phase A voltages and currents, for switching operation at 275° phase angle, from 20.1 ms to 20.4 ms. The measured voltage and current are plotted in the left column, the simulated from Power Factory in central column, and simulated from PSCAD in right column. The measured and simulated currents are in the top row, while the lower three rows presents the measured and simulated voltages. The measured and simulated voltages for the different locations are divided in rows: second row) voltages at the platform, third row) voltages at A01 and forth row) voltages at A09.

The measured and simulated currents can be seen in the top row in Fig. 10. It is possible to see in this figure that at 20.25 ms the measured current stops flowing in the negative direction, while in both simulations the current oscillates to the opposite polarity, since the models used as the VCBs are ideal switches. As mentioned before these "half-wave" currents are typical from pre-strike phenomena in the VCB; hence the models used to represent this equipment in both simulation tools are insufficient to represent the measured switching operation.

It is important to mention that at 20,25 ms the measurements shows that the reflected voltage wave arrives to the platform and doubles again. However, this phenomenon in the instantaneous voltage is not clearly seen in the simulations as it coincides with an opposite polarity voltage wave appearing because the current through the breaker model oscillates to the opposite polarity i.e. not being interrupted. This difference between measurements and simulations is due to the simple VCB model used, which doesn't interrupt the current as the measurement show happens in the real breaker. The authors believe that the difference between measurements and simulation tools after 90 μs of the switching is not due to the voltage reflections inaccuracies, but to insufficient details in the breaker model. Further work is expected to be done in this area in further work.

From Fig. 10 it is possible to compare easily the velocity of the voltage wave, the rate of rise and maximum value of the transient overvoltage for the three different locations. From this figure several important conclusions can be made:

- The results from both simulation tools match well the measured steep fronted first wave in the three locations.
- The rounded fronted second waves measured in the three locations, due to the voltage reflections, were not visible in the simulations because of the simplified VCB model. In the breaker models the current oscillate to the opposite polarity and thereby causes an opposite polarity travelling voltage wave which incidentally appear at the same time as the voltage reflection, and therefore contradicts the reflected distorted wave.
- The round corners of the steep front of the voltage wave in A01 and A09 are only simulated in PSCAD. As explained before this is caused by the skin effect in the conductor.
- The three step-wise decrease in the voltage due to the waves caused by the initial voltage drop of the platform bus bar returning from radial cables D, C and B are less damped in Power Factory than in PSCAD, due to the missing frequency dependant damping.
- The behaviour of Power Factory and PSCAD after the first reflection period (90 µs) looks fairly similar in both simulation tools in all locations.
- The wave velocity from both simulation tools is higher than measured.

VI. Conclusions

Two measured switching operations when one radial is energized in the wind farm were modelled by means of two numerical simulations tools. For the steep fronted first wave the results showed good agreement between simulations and measurements. However, Power Factory presented insufficient frequency dependant damping. On the other hand, differences were found between simulations and measurements in the more rounded fronted second waves. These differences were found to be due to the insufficiently detailed modelling of the vacuum circuit breaker. This is important as is illustrated the limitations to be acknowledged when using standard models in these simulation programs while studying levels of transient overvoltages.

Further work will be done on the analysis of the measurements, since there are some other interesting switching events recorded. Validated models of different electrical components in the collection grid of large offshore wind farms will be made.

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