Switching transients in offshore wind farms – impact on the offshore and onshore networks

R. King, F. Moore, N. Jenkins, A. Haddad, H. Griffiths, M. Osborne

***Abstract*—The types of switching transients which may be experienced in both the onshore and offshore networks due to the particular configurations of offshore wind farms are investigated. These range from temporary overvoltages and the zero-missing phenomenon during energisation of long export cables to very fast transients within the MV offshore network due to the combination of array cables and transformers. Some of the switching transients highlighted in the review are then studied in an example offshore wind farm. High overvoltages are shown to occur when a radial is disconnected with the wind turbines still generating.**

***Keywords*: offshore wind, switching transient**

I. INTRODUCTION

There is currently over 30GW of offshore wind generation projects at various stages of development in the UK [1], resulting from government targets and incentives for renewable energy. As a result, several large offshore wind generation projects are being connected to the GB Transmission system [2, 3].

The location of these wind farms out at sea means that long submarine cables are required to connect the wind farms to the onshore transmission network, whereas onshore networks are principally constructed using overhead lines to cover longer distances. These long lengths of cable are significantly more capacitive than overhead lines, and as a result have different electromagnetic properties.

Understanding the transient overvoltage levels allows plant to be correctly specified, and protected from transient overvoltages. Overvoltages can potentially be mitigated by using particular switching sequences, installing surge arresters, or pre-insertion resistors.

II. REVIEW OF OVERVOLTAGES IN WINDFARMS

The main source of Transient Overvoltages in overhead power lines is lightning, whereas in cable systems overvoltages are mainly caused by circuit breaker operations [4].

Overvoltages can be classified into five groups according to IEC 60071-1. These are Continuous Operating Voltage, Temporary Overvoltages, Slow Front (switching), Fast Front (lightning) and Very Fast Front.

A. Temporary Overvoltages

Temporary overvoltages can last for over a hundred cycles and have a slowly decaying amplitude. They can originate from transformer energisation, fault overvoltages, overvoltages due to load rejection and resonance.

Temporary overvoltages may arise when a large offshore wind farm with a long high voltage cable to shore goes into islanded operation due to the operation of the onshore main circuit breaker [5, 6]. Such an overvoltage was experienced by the Danish Transmission System Operator at Horns Rev A 160MW offshore wind farm in 2005. This situation at Horns Rev A was analyzed in [5] along with a planned large offshore wind farm in Denmark. It was shown that the active power supply from the wind turbines to the isolated wind farm network must be interrupted as fast as possible because the rate of voltage rise is proportional to the active current magnitude. In [7], it was shown that converter-controlled wind turbines cannot be represented by a synchronous generator model when in isolated operation with long HVAC cables as the overvoltages initiated by the synchronous generator model were not as severe as when the wind turbines were represented by a controlled current source.

Temporary overvoltages could occur if the harmonic content of the transformer inrush current excites the power system resonant frequency (known as resonant overvoltages). This has been identified as an issue in systems with transformers and significant lengths of HV cables [8] and also in industrial distribution systems where power factor correction capacitors have been applied [9]. In all cases involving transformer inrush current, the power system has a relatively low resonant frequency. Resonant overvoltages can have magnitudes greater than 3 per unit [10]. This issue was discussed in [11] and caused operational problems on a number of offshore installations during commissioning.

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B. Slow Front Transients

Slow front transients are mainly due to switching operations, including cable discharge, reactive compensation operation and transformer energisation. They could occur during energisation and disconnection in normal operation or during a fault. Ground faults also produce slow front transients.

During closing of the circuit breaker (energisation), large inrush currents can flow associated with the charging of the cable against the inductance of the system. This inrush current is limited by the surge impedance of the cable so is usually smaller than that associated with capacitor banks [12]. High overvoltages could occur if the cable is energized with trapped charge [13] (the cable was pre-charged as a result of a preceding breaker operation); this could occur if there is no discharge path (i.e. the cable is not connected to the offshore transformer) or if the cable is re-closed after only a short interval.

Multiple zero crossings on the onshore network following energisation of the wind farm could also occur. This was an issue in [14] which resulted in the offshore wind farm being limited to energisation during light load periods only.

C. Fast Front Transients

Fast front transients are usually associated with lightning. Direct lightning strikes onto the network are not likely due to the cable systems in offshore wind farms. The indirect effects of lightning hitting the wind turbine towers or blades could cause fast front transients on the network, however it is not studied here as the focus of this paper is on switching transients.

D. Very Fast Front Transients

Very fast transients can occur in a number of situations, however they are not covered by standards at present. They have been extensively studied in Gas Insulated Switchgear (GIS) systems, where the geometry of the system supports the generation and propagation of very fast transients [15, 16]. In the case of dielectric breakdown across the contacts of a switch or to ground, the voltage collapse can occur in 3 to 5ns which can excite resonances within the GIS at frequencies up to 100MHz [13]. Studies have also been carried out on very fast transients in distribution networks, particularly on their impact on transformer and motor insulation [17]. The majority of very fast transient studies in medium voltage networks have focused on mining and other industrial systems, where the economic impact of failure is high [18].

Vacuum Circuit Breakers (VCBs) are widely used in medium voltage networks because they have outstanding breaking properties along with low maintenance requirements [19, 20]. It has long been recognised that the combination of VCBs and cable networks in industrial systems can cause problems with very fast front transients if the system is not designed properly [21 - 24]. Multiple restrikes in VCBs generally have frequencies in the range of 10kHz to 1MHz [13].

Switching transients in a 160MW offshore wind farm were studied in PSCAD/EMTDC in [20]. It was shown that the electrical stress on transformers during transients depended on the wave propagation in the cable system and on their location in the system. In order to analyse this fast phenomenon, a cable model which included both wave propagation and frequency dependence was used.

Two cases of energizing a wind farm are shown in [20], the first when a feeder is first to connect and the second when the feeder is the last to connect. The cables are energized with the transformer during no load, and saturation is included in the transformer model. The rate of rise of voltage at the first transformer with no other feeders connected was around 0.2kV/μs whereas the rate of rise of voltage for the same transformer but when all other feeders were connected was around 25kV/μs. The rise time was increased by over two orders of magnitude when all feeders were connected.

A single line to ground fault (SLGF) was simulated in [20] along with the clearing of the fault by the feeder VCB. The wind turbine generators were not connected. The SLGF was placed at the base of the first wind turbine (at the end of an 80m cable which connects to the transformer located in the nacelle) at one of the feeders. Although the fault caused a step voltage in the system with travelling waves similar to feeder energizing, an expanded timescale showed that the faulted phase is exposed to very high frequency reflecting voltage waves (625kHz) with very fast fronts. The reason for the high repetition frequency is the short distance (80m) between the fault and the transformer causing very short travelling times for the propagating waves. The short cable also has negligible damping effects which cause the very fast front. When the fault is cleared by the feeder VCB, three reignitions occurred. The voltages at the transformers were similar to those during energisation except that the reignitions caused much higher voltages.

Every transformer has particular internal natural frequencies which may be excited by a transient applied at its terminal, causing dielectric stresses [25, 26]. Two distinct types of excitation are described in [26]; a once-only surge and regularly repeated surge voltages. The once-only surge has a damped oscillatory response with a frequency which is mainly dependent on the configuration of the system. The second type of excitation could be generated by multiple restriking of a circuit breaker. In [27], it was suggested that the internal transformer insulation may be overstressed when certain wave shapes such as a fast front long tail switching surge and in particular oscillating overvoltages are applied at the terminals of the transformer, even if the voltage magnitude is below the surge arrester protective level.

There are relatively few large offshore wind farms in operation at present; however there has been a high rate of failures of transformers. A fault in an offshore transformer would be more severe in terms of both repair costs and lost revenue than for an onshore transformer due to its location. In one particular offshore wind farm all 80 of its wind turbine nacelles were brought ashore to correct a number of issues, one of which being the replacement of the transformers, since within only a few months operation over 20% of them had failed [28]. Eighty percent of the transformers at Middelgrunden offshore wind farm have also been replaced, with the first transformers breaking down shortly after production started in 2001. In [29], methods to optimize the cost spent on the replacement of defective transformers at Middelgrunden were described. The average value of the energy production loss was calculated to be 40,000 Euros per turbine, which is close to the total cost of installation for the replacement transformer, showing that the length of the exchange process is important. The overall cost of an optimized exchange of transformer (in 2007) was 115,000 Euros. In another offshore wind farm, a failure of the main offshore transformer led to a 4.5 month outage of the entire 166MW wind farm [30]. Although the various manufacturers and designers involved disputed the causes of these problems, such as adverse weather conditions, the root cause was the breakdown of insulation which eventually caused electrical short circuits. It is possible that high frequency, high voltage switching transients made a major contribution to the insulation failure. All the examples mentioned here relate to transformer failures which originated in the early years (2000 – 2003) of offshore wind farm development and therefore represent the early stages on the learning curve. This clearly illustrates to the offshore wind industry that care has to be taken when designing the MV systems for offshore wind farms.

E. Other matters related to transients

With respect to the Continuous Operating Voltage, the remote ends of radials may operate at a high voltage when the grid voltage is high and the wind power output is high. The selection of the surge arrester Continuous Operating Voltage (COV) may be affected by this high operating voltage and also by harmonics which could increase the system peak voltage.

Often the Lightning Impulse Withstand Voltage (LIWV, also known as BIL) and Switching Impulse Withstand Voltage (SIWV, also known as SIL or BSL) are already given for equipment, and verification of the standard insulation levels is required rather than the selection of them. This is usually the case for offshore wind farms, where the equipment may have been ordered well in advance. In this situation, an inverse approach to the insulation coordination procedure given by the IEC may be required. The usual insulation coordination process for wind farms is to select the insulation level of the transformers, select the surge arresters required to protect that insulation level, and then determine the level of transient overvoltage which can be withstood [31].

Transient Recovery Voltage (TRV) assessments are required not only on the circuit breakers within an offshore wind farm but also on the existing circuit breakers to which the offshore wind farm is connecting to. A TRV assessment for 138kV circuit breakers with the addition of an onshore wind farm was made in [32]. It was shown that the TRVs with the addition of the new wind farm did not exceed the existing breaker capabilities. The fault current level at the substation increased by 1%, due to the 43km transmission line from the wind farm to the substation which limited the fault current. TRV investigations in [33] indicated that three phase ungrounded faults produced the worst case TRVs and that the TRVs marginally exceeded limits in some cases. The TRVs for the 33kV offshore circuit breakers were shown to be within the Rate of Rise of Recovery Voltage (RRRV) limits specified in [34], however the TRV amplitude exceeded 66kV for the T30 duty. In [35], it was shown that the RRRV was exceeded in some cases for the 33kV offshore circuit breakers. Significant overvoltages were shown to occur if a single phase fault occurs at the base of a wind turbine and the circuit breaker connecting that radial then opens to clear the fault whilst the wind turbines are still generating. These overvoltages were limited if grounding transformers were added to the radial side of the circuit breaker or if the wind turbines stopped generating before the circuit breaker opened to clear the fault [35].

The zero-missing phenomenon is defined as the ac current not passing through zero for several power frequency cycles. If there is no current zero, it is not possible for the circuit breaker to interrupt the current without the risk of damage, except if the circuit breaker is designed to interrupt dc current. Zero-missing can occur when energizing a long HVAC cable which is connected to reactive compensation [36]. In an unloaded cable system, the shunt reactor current is almost in phase opposition to the current in the cable which reduces the amplitude of the ac component through the circuit breaker. The shunt reactor current will have a transient dc component. This may result in the current through the circuit breaker having a dc component which is larger than the ac component, resulting in the zero-missing phenomenon.

F. Techniques to reduce switching transients

Point-on-wave switching is a way to reduce transients by controlling each of the three poles in the circuit breaker individually, closing each pole with a certain time delay. Different time delays are used depending on whether the load is capacitive or inductive. In [14], it was shown that it is difficult to derive suitable synchronization parameters in cases where there is both capacitive (the HV cable) and inductive (the offshore transformer) loads. There is also the risk that overvoltages maybe exacerbated if the point-on-wave switching mal operates.

Pre-insertion resistors can be used to reduce the overvoltage and frequency of transient recovery voltages. This technique requires two circuit breakers in parallel, one of which is in series with a resistor. The circuit breaker in series with the resistor is closed first (the inrush current is then limited by the resistor), then the second circuit breaker is closed after a few power frequency cycles. The transients in an offshore wind farm could be reduced significantly by using pre-insertion resistors [14]. There is currently very limited availability of these for ratings of below 145kV; they will require new larger designs of CB which will be more expensive, less reliable and require more maintenance which is not desirable for offshore platforms

In [37 - 40], surges which exceeded the BIL of dry-type transformers were recorded during both the simulations and measurements, even when surge arresters were used. A number of mitigation methods were tested in [39], with the combination of surge capacitor protection with surge arresters performing best.

III. STUDIES IN AN EXAMPLE OFFSHORE WIND FARM

A. Transients in the offshore network

In order to study the type of switching transients which may be experienced within an offshore wind farm, an example network is modeled in EMTP-RV as shown in Fig. 1.

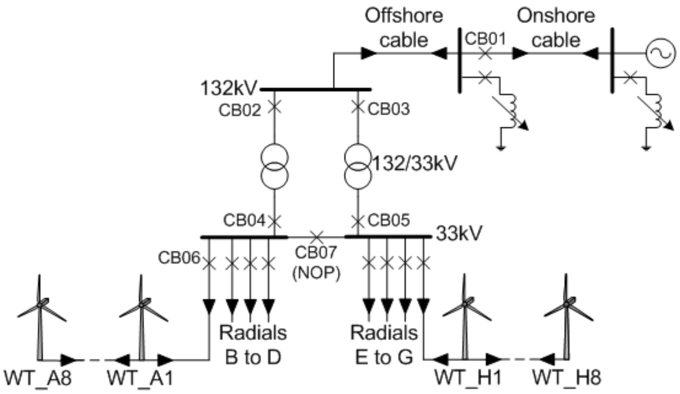

Fig. 1. Typical wind farm configuration

There are 8 radial array cables A to H, each connecting 8 3MW wind turbines to an offshore substation. Under normal conditions, four of the radials each connect to one of the two 33/132kV step-up transformers on the offshore substation which then connect to a three phase submarine export cable. The submarine cable is connected to a land cable at the shore. Reactive compensation is located at the shore connection point and also at the onshore substation which connects to the grid. If one of the offshore transformers is taken out of service for some reason, the circuit breaker connecting the two 33kV busbars can close, so that all 8 radials connect to one transformer. In this case, the wind turbines would be required to operate at a reduced output.

The wind turbine generators and grid are represented by a 'voltage behind a reactance' model. The value of reactance is calculated based on the fault level contribution of the wind turbine. These fault levels are 6pu and 1pu for the squirrel cage induction generator and full power converter wind turbines respectively, based on a base (rated output) of 3MVA. The fault level of the grid is set to 1500MVA, with an X/R ratio of 10. The wind turbine transformer and 33/132kV transformer models include the magnetizing characteristic and winding capacitances. All cables were modeled using a frequency dependent (phase domain) distributed parameter model. There is a 10m length of connection between the 33/132kV step-up transformers and the 132kV circuit breakers which is represented by a PI equivalent. Stray capacitances are included to represent busbars and other equipment such as CVTs and are chosen following [41]. The capacitance of equipment between CB04 and the transformer terminals is 1nF, the stray capacitance of each 33kV busbar is 1.8nF (assuming 60pF/m x 30m busbar). The capacitance of a closed 33kV and 132kV circuit breaker is 0.1nF and 0.3nF respectively. A circuit breaker model similar to that described in [42] which includes pre-strike and re-strike characteristics is used to represent the vacuum circuit breakers in the 33kV offshore network.

1) Energisation transients

Energisation of radial A is simulated for the case when the first pre-strike of the circuit breaker occurs at the peak voltage of one of the phases, which produces the worst case in terms of the magnitude of overvoltage. The wind turbines are not generating during energization. The three phase voltages at the 33kV busbar which connects radial A to D and at WT_A1 are shown in Fig. 2 for a case when radial A is first to connect and three other cases when other radials are already connected.

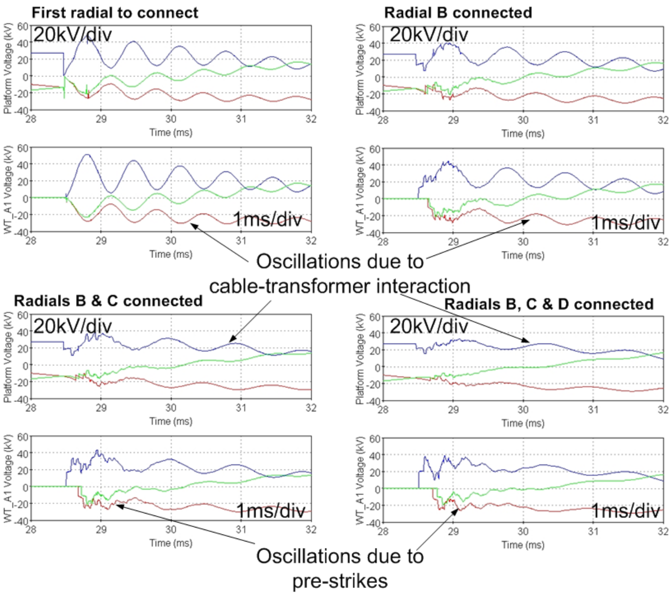

Fig. 2. Three phase voltages at the 33kV offshore platform and WT_A1 during energization of radial A.

The results in Fig. 2 show that the highest overvoltage (2pu at WT_A1) occurs when radial A is first to connect with a corresponding rate of change of voltage is 0.2kV/us. For the cases when other radials are already connected, the overvoltage is lower (1.43pu at WT_A1), however the rate of change of voltage at the wind turbine is significantly increased to 21kV/us and a number of voltage steps or 'oscillations' occur due to the pre-strikes. The initial voltage step at the wind turbine increases with an increase in radials already connected. Oscillations due to cable-transformer interaction occur in all cases and the corresponding frequency is higher when radial A is first to connect than when other radials are already connected.

The cable length between the platform and WT_A1 was varied for the case when radial A is the first to connect. The maximum voltage at the platform, WT_A1 and the corresponding frequency of oscillations are shown in Fig. 3. The maximum voltage at the platform is highest (2.02pu) when the cable length is 1km and reduces to 1.8pu when the cable length is 10km. The maximum voltage at WT_A1 is higher than the maximum voltage at the platform and has a fairly steady value for all cable lengths, having a value of around 2.08pu. The frequency of oscillations is nearly 2kHz when the cable length is 1km and decreases to just under 1.2kHz when the cable length is 10km.

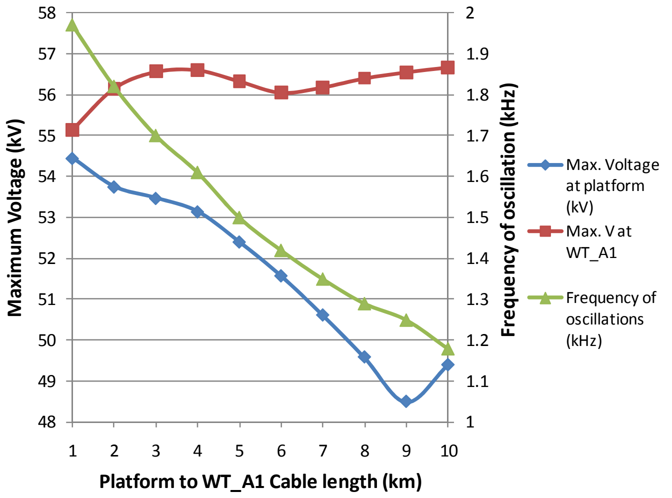

Fig. 3. Maximum voltage at the platform and WT_A1 during energization of radial A (closing of CB06) and the corresponding oscillation frequencies for cable lengths between the platform and WT_A1 of 1km to 10km.

2) *Disconnection transients*

Disconnection studies in the 33kV network were carried out for both normal operation and for a single phase fault. Each wind turbine was set to generate 3MW and stop generating at 120ms. The results are shown in Fig. 4.

If the radial circuit breaker (CB06 in Fig. 1) opens while the wind turbines are generating in normal operation, high overvoltages occur. Two examples of this are shown in A) and C) of Fig. 4. The overvoltage reaches 134kV (4.97pu) when no other radials are connected and 95kV (3.53pu) when radials B to D are connected and generating. There are multiple re-strikes in each case which causes voltage escalation.

The clearing of a single phase fault (with an ideal circuit breaker) at the base of WT_A1 was shown to cause very high overvoltages in [35]. Here, a VCB model was used. Two examples are shown in B) and D) of Fig. 4. The overvoltage reaches 185kV (6.87pu) with a corresponding rate of change of voltage of just under 1kV/us when no other radials are connected. When radials B to D are connected and generating, the overvoltage is lower 167kV (6.20pu), however the rate of change of voltage is higher at 85kV/us.

Grounding transformers will limit the overvoltage that occurs, but only if they are located on each radial. It is more likely that the grounding transformer will be on the 33kV side of the main offshore transformer. When a grounding transformer was included in the simulation and located in that position, the overvoltage was not limited. If the wind turbines stop generating before the circuit breaker opens to clear the fault, the overvoltages are lower (reaching 80kV) and are not sustained as they are when the wind turbines continue generating. If surge arresters are installed, they will limit the overvoltage. As the overvoltages studied here are sustained for around 100ms the surge arrester temporary overvoltage capability is likely to be exceeded, particularly if the wind turbines continue to generate for a significant length of time. It is therefore desirable that the wind turbines stop generating before the circuit breaker is opened.

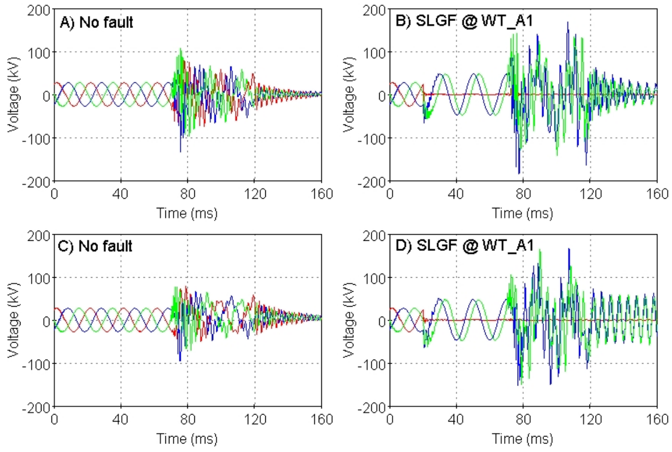

Fig. 4. Three phase voltage at the radial side of CB06. The single-line-to-ground-fault (SLGF) is applied to the base of WT_A1 at 20ms. CB06 opens at 70ms.Case A) and B) are when no other radials are connected and cases C) and D) are when radials B to D are connected and generating.

B. *Transients at the onshore connection site: onshore transmission network and long cable interconnection*

Fig. 5 shows a model in ATPDraw, for the interface between offshore and onshore transmission networks. The model described here was created to explore the level of overvoltages seen when energizing the long cable circuits connecting to the offshore platform substation. The energisation of a 45km three core 630mm2 subsea cable connecting the offshore platform substation is simulated.

The onshore transmission system was represented as a voltage source at each end of the overhead line. Each voltage source sits behind an impedance; an inductance representing the network fault level in parallel with a resistance representing the network surge impedance. It was assumed that the fault level contribution is shared equally between the two equivalent sources. Two separate onshore connection voltages were considered; 400kV and 132kV. Simulations were carried out using representative high and low fault levels; 35GVA and 4GVA at 400kV; 7.2GVA and 1.1GVA at 132kV.

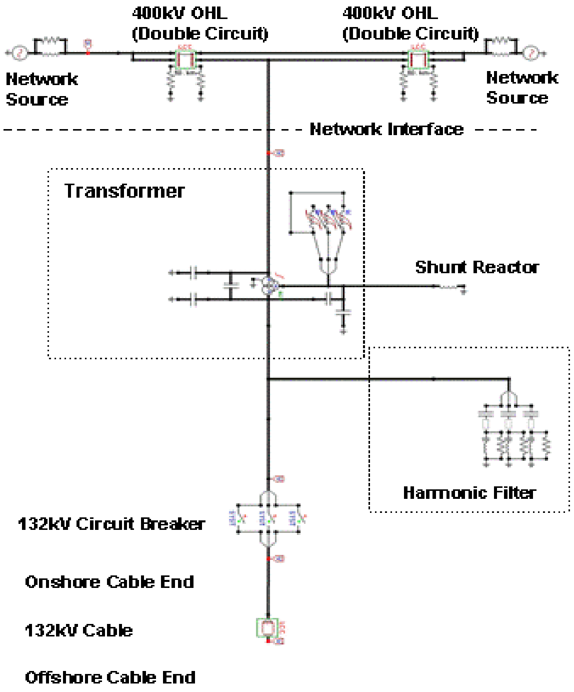

Fig. 5.Simplified Offshore Connection Model in ATPDraw for 400kV Onshore Network

The offshore wind farm is connected to the transmission system by turning in one circuit of a double circuit overhead line to provide two connection circuits. The length of the overhead line is 60km each side of the connection to the offshore network, was selected to have comparable travel time to the offshore cable. This was to keep the onshore representation relatively simple and free of multiple traveling reflections and site specific qualities.

The 400kV onshore network has a 240MVA, 400/132/13kV transformer represented using the BCTRAN component with saturation represented using nonlinear inductors connected to the tertiary winding. The 132kV network was modeled similarly using the same overhead line model, but with a direct connection from the overhead line to the 132kV circuit breaker in place of the 400/132/13kV transformer, and 132kV as a source voltage.

A harmonic filter (C-type, 3rd harmonic, 20MVAR, QF=1) is connected on the source side of the 132kV circuit breaker in both 132kV and 400kV models.

Cables and transmission lines were represented using the JMarti frequency dependant model, with the modal transformation matrices calculated at 10kHz. No forms of overvoltage protection other than the harmonic filter were included in the model. The 132kV circuit breaker was represented as an ideal switch.

The capacitance of the cable and filter was 100% compensated for using air core shunt reactors (linear behavior) onshore; connected to the transformer tertiary winding in the 400kV onshore model, and with direct connection at 132kV on the source side of the circuit breaker for the 132kV onshore model.

The offshore wind farm network and offshore transformers were not included in the simulation as this study focuses on the energisation of the offshore cable only.

1) *Systematic Switching*

Energisation of the 132kV cable was examined using systematic switching on the 132kV circuit breaker to look at the range of possible overvoltages at different nodes. A window of 120 degrees was divided into 11 steps per phase, giving 1331 switching operations with different pole closing times. When each operation was simulated, the maximum voltage of each phase was recorded at each node, giving 3993 recorded voltages per node. This approach does result in some extreme and potentially unrealistic pole spreads, but assuming symmetry between phases; the 120 degree window allows pole closing times across the full wave to be explored simply.

Fig. 6 shows the range of overvoltages that resulted from systematic closing of the 132kV circuit breaker onto the 132kV offshore cable for both 400kV and 132kV onshore voltages. The lower fault levels are illustrated because they resulted in higher overvoltages on the onshore network.

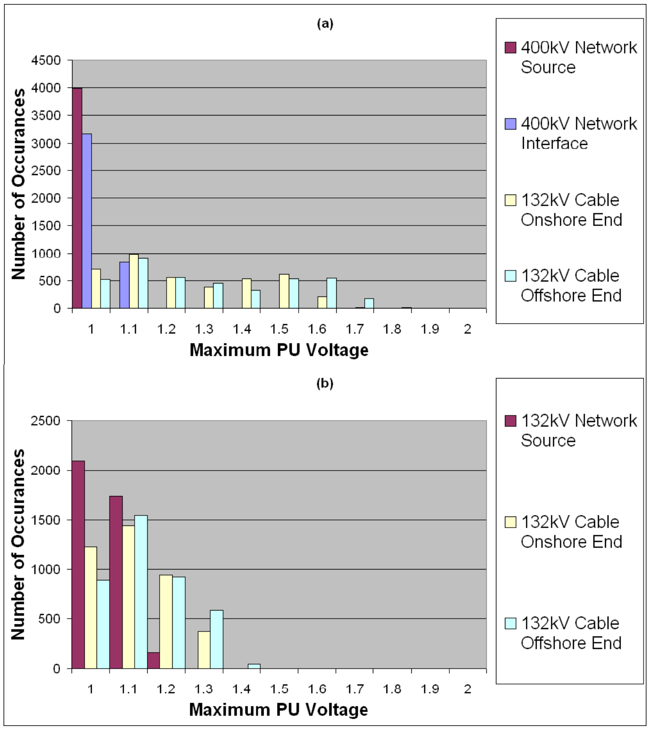

Fig. 6. Range of overvoltages at different nodes during 1331 systematic CB closing operations for two different transmission network models –a) 400kV network with 4GVA fault level and b) 132kV network with 1.14 GVA

The results in Fig. 6 (a) show that slight overvoltages up to 1.1pu were seen on the 400kV network, whilst overvoltages up to 1.8pu were seen on the offshore end of the 132kV offshore cable. Fig. 6 (b) shows that slightly higher overvoltages were seen on the onshore 132kV network, whilst energizing the offshore cable from this weak network produced lower overvoltages on the offshore cable.

2) *Voltage Waveforms*

Fig. 7 shows a set of simulated voltage waveforms from different nodes with the 400kV onshore network model. The circuit breaker pole closing times were taken from the results of the systematic study, and correspond to the highest overvoltage found on the offshore cable.

The maximum phase voltage on the offshore cable appeared to occur due to series resonance between transformer inductance and the cable capacitance, with the resonance damped by the harmonic filter. On the 400kV side of the transformer, the 50Hz waveform is only slightly distorted.

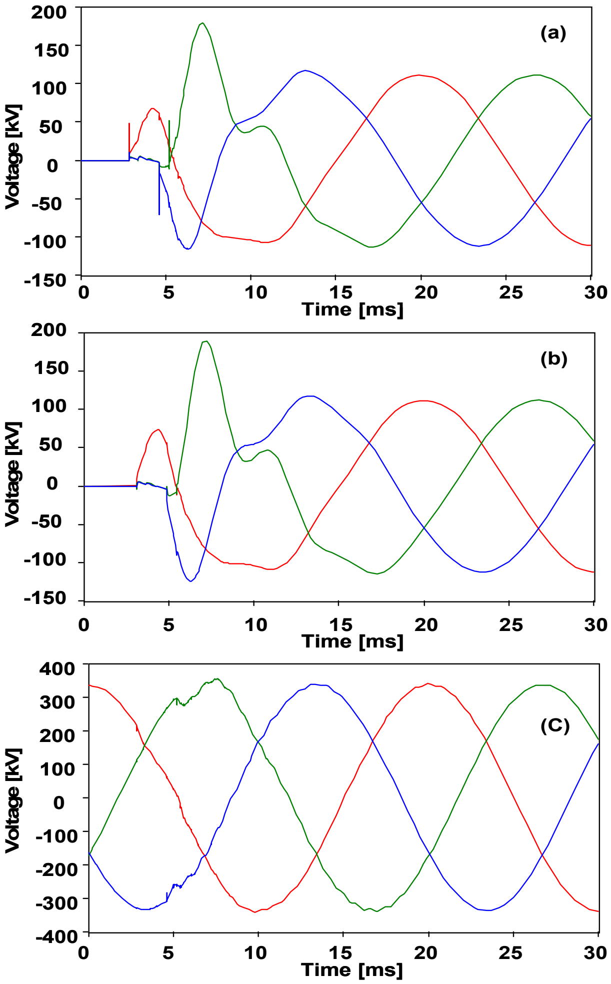

Fig. 7. Simulated three-phase voltage waveforms when energizing the export cable for the 400kV, 4GVA Onshore Network at: a) The Onshore end of 132kV cable, b) The Offshore end of the 132kV cable, and C) At the 400kV terminals of the Transformer (with CB poles closing at 2.8ms, 4.6ms, and 5.2ms).

The simulation results show that the overvoltages are more severe on the offshore network than on the onshore network. Further work is needed to look at more complex connection arrangements. These could include transformer feeder arrangements with the offshore platform transformers connected to the offshore cable, or more complex onshore networks.

IV. CONCLUSIONS

A variety of overvoltages could occur in an offshore wind farm ranging from temporary overvoltages to very fast front transients.

The overvoltages experienced in the onshore network are generally lower than those in the offshore network. Energizing cables and transformers together can result in resonant overvoltages.

Energization transients were studied in the offshore network. When a radial is first to connect, the overvoltages reach just over 2pu. Although the overvoltage is lower when a radial is energized with all other radials already connected, the rate of rise of voltage at WT_A1 is two orders of magnitude higher at 21kV/us.

Disconnection transients can produce higher overvoltages than energization transients. The studies showed that if a circuit breaker disconnects a radial whilst the wind turbines are still generating in normal operation, the overvoltage is almost 5pu. If the radial circuit breaker clears a single phase to ground fault whilst the wind turbines are generating, the overvoltages reach almost 7pu. The rate of change of voltage at WT_A1 is 85kV/us for the case when other radials are connected.

Grounding transformers do not reduce these overvoltages unless they are connected on the radial side of the circuit breaker. There are no significant overvoltages if the wind turbines stop generating before the circuit breaker disconnects the radial. It would therefore be desirable that the wind turbines have stopped generating before a radial is disconnected.

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