An Overview of the Transient Studies Required for HVAC Connected Offshore Wind Farms

Kiran Munji, Jonathan Horne, Jose Ribecca

***Abstract*-- This paper discusses about the transient phenomenon in offshore wind farm and describes the methodology for modelling and simulation. Studies presented in this paper are based on a generic HVAC connected offshore windfarm rated higher than 700 MW and export cable length greater than 100km. The system is analysed for temporary, slow-front and very-fast-front overvoltages resulting from both planned and unplanned operations. This paper also addresses the challenges, appropriate selection of equipment insulation and technical considerations to be observed during the design and operation phase of offshore wind farm is discussed.**

***Keywords*: offshore wind farm, temporary overvoltages, slow-front overvoltages, very-fast-front overvoltages, insulation coordination.**

I. INTRODUCTION

The latest and largest offshore wind farms are often located at large distances (>100km or sometimes 200km) away from the shore, and more importantly, the onshore power grid. HVAC and HVDC options are often considered. One of the added challenges with export of power to the onshore grid through long export cables is the introduction of high overvoltages due to planned (e.g. switching) and unplanned (e.g. system faults) events. The insulation levels of equipment should be designed based on these overvoltages, or mitigation options must be introduced. This must work for different operating configurations of the system for continuous reliability of the network at reasonable cost.

This paper details the various studies which are typically performed, together with the modelling and methodology adopted for analysing the overvoltages in the windfarm. Note that fast front overvoltages (FFO) due to lightning on wind turbines, or on onshore substation equipment is not included in this paper due to the extent of these topics. Further reading on these topics can be found at [1]-[3].

II. SYSTEM DESCRIPTION

For the purposes of explanation in this paper, a generic offshore wind farm of 700MW with a connection in Great Britain to a National Grid 400kV substation has been used.

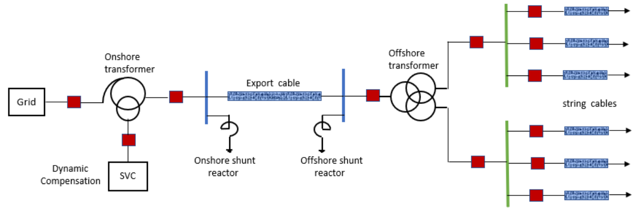

Fig. 1. Single line diagram of a typical offshore windfarm

The single line diagram of one of the feeders is shown in Fig. 1. Autotransformers connect the 400kV grid to a 220kV export cable network. At the tertiary winding of the autotransformers, a STATCOM unit is connected to meet onshore grid code requirements. A single 220kV export cable (>100km) connects the wind farm offshore substation to the onshore substation.

The reactive power generated by cable is compensated through onshore and offshore shunt reactors. The offshore transformer LV windings are connected to the array cables and thereafter connected to unit transformers and wind turbines.

III. MODELLING

The grid is modelled as a voltage source with positive and zero sequence impedance derived from 3-phase and 1-phase fault levels. Source equivalent models used for transient studies are connected in parallel with a surge impedance, for the purpose of avoiding unrealistic travelling wave reflections, that in practice will get transmitted to the rest of the external system and consequently attenuated. The surge impedance value is based on the transmission line configuration connected to grid [4].

Cables are modelled with the actual geometric parameters and validated with the guaranteed parameters at 20^0C provided by the manufacturer. At lower temperatures the resistance is lower and hence results in less damping of the transients [5].

The studies are initially analysed with Bergeron models and later with more detailed phase domain cable models for the system. Cable installation arrangement should be taken into consideration while deriving and validating model parameters for e.g. some sections of the cable are laid in flat configuration and other sections in trefoil configurations. Additionally, the cross-bonding of the cable from the design must be explicitly modelled.

Shunt reactors are modelled with non-linear saturation characteristics connected in series with a resistance derived from the load losses. Mutual coupling between the windings should be considered. Circuit breakers are usually modelled as ideal switches, however, for some of the studies like faults and TRV, where failures are observed, the analysis is repeated with the arc models to simulate a more realistic and less conservative approach [6]. Transformers are modelled with non-linear saturation characteristics obtained from no-load test data and a reasonable worst-case residual flux of 80% is

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considered for transformer energisation [7]. The stray capacitance between windings and between winding-to-ground are considered. Detailed explanation about modelling of components for transients are explained in CIGRE report [8].

IV. NETWORK STUDIES

The dielectric strength of the equipment is verified with respect to the overvoltages occurring in the system. The insulation should be designed to withstand these overvoltages without causing failures, or suitable mitigation measures introduced to manage these overvoltages. Table-I lists the types of overvoltages and the events causing them, the characteristics, like frequency and duration, are explained in IEC-60071-4 [9].

The following sections will explain the detailed methodology for analysing each event and recording maximum overvoltage at each busbar for an event.

TABLE I
TYPES OF OVERVOLTAGES AND EVENTS CAUSING THEM

Type of overvoltage	Event
Temporary overvoltages (TOV)	Transformer energisation, Ferroresonance, faults, load rejection
Slow-front overvoltages (SFO)	Transformer energisation, faults, cable energisation, shunt reactor and filter switching
Fast-front overvoltages (FFO)	Lightning on wind turbines
Very-fast-front overvoltages (VFTO)	Switching in GIS
Other studies	Zero-missing phenomenon, transient recovery voltages

A. *Energisation of transformers*

Energisation of transformers results in temporary overvoltages (TOV) and slow-front overvoltages (SFO). However, only TOV's are the driving factors for insulation coordination based on the location of transformer and fault level of the grid. For instance, the onshore transformer is located close to the grid and hence the TOV's and SFO's are not of high magnitudes because of the typically high fault level of the grid, although weak grid connections can also pose issues. Note that RMS voltage dips due to transformer energisation inrush current must also be assessed for the purpose of grid code compliance.

For energisation of offshore power transformers, the resonance point introduced by the export cable, together with the harmonics generated by the transformer on energisation, are of most interest. The following methodology is typically adopted (depending on available data):

- Impedance loci of the external grid are obtained. These cover all reasonable operating scenarios of the system and are usually given by the system operator.
- The 2^{nd}-order self-impedance loci is used, as this corresponds to the typical harmonic current spectrum produced by the energisation of transformer magnetic core.
- The points corresponding to the low resistance is considered as a worst-case. In order to reduce the size of problem four points (A, B, C & D) are considered in this region and further subdivided into multiple points as shown in Fig. 2.
    - AB1 (between A & B),
    - BC1, BC2, BC3, BC4, BC5, BC6, BC7, BC8 & BC9 (between B & C)
    - CD1 (between C & D)
- The grid impedance is tuned to above mentioned points for 2^{nd}-order resistance and reactance and a frequency sweep is performed at the 220kV terminals of offshore transformer. The worst case 2^{nd} harmonic impedance is obtained at point-A.
- Systematic switching over a complete cycle (20ms) in steps of 1ms is performed with residual flux of -80%, 80% and 0% in phase-A, B & C respectively. The maximum magnitude of TOV is recorded at all the busbars in windfarm during energisation.

The RMS voltage at interface point during transformer energisation is used for assessment against the grid code requirements CC.6.1.7 [10] which describe the maximum allowable voltage change with respect to time and are described by means of a parametric envelope curve. Fig. 3 show the maximum and minimum RMS voltage among phases A, B and C for each simulation step when energising. The RMS voltage with respect to time for transformer switched at 3ms and 11ms are compared with the envelope.

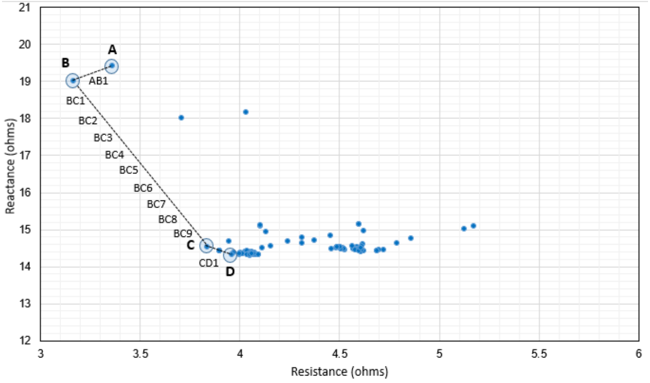

Fig. 2. Second harmonic order self-impedance at external grid

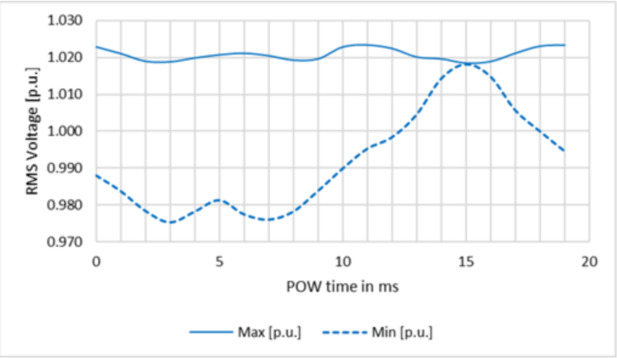

Fig. 3. Maximum and minimum RMS voltage during energisation of offshore power transformer.

B. Ferroresonance

Ferroresonance can be described as a highly non-linear and low frequency oscillation between a capacitive element and an iron core inductance, which can be driven into saturation, and then interact with the circuit capacitance. The Ferroresonance phenomenon is mainly characterised by high TOV, sustained for a long period of time, which could cause severe damage to equipment if no remedial action is taken. The overvoltages due to this phenomenon are not considered as a basis for selection of surge arresters voltage rating or for insulation design. However, the surge arrestor ratings may have to be adjusted so Ferroresonance does not cause surge arrestor failure due to thermal runaway [11]. The factors and typical network configurations influencing this phenomenon are listed in the CIGRE TB [12].

To determine the risk due to this phenomenon, typical network configurations causing the overvoltages should be selected and a sensitivity assessment should be adopted. The key parameters taken into consideration for analysis are the capacitance of the network, switching instant, system unbalance and saturation characteristics of voltage transformers, power transformers and shunt reactors.

The network configurations considered for analysis are listed below:

- Energisation of transformer in 2-phases
- Energisation of transformer in 1-phase
- Energisation of unloaded transformer via cable

An example of one of the cases where two phases close and one phase of circuit breaker fail to close as shown in Fig. 4 is considered here. For this case the breaker is switched over a complete cycle in step of 1ms with stray capacitance varied from 25% to 300%. This assessment gives an approximate idea about the risk of this phenomenon on insulation level of the equipment, and on the rating of surge arresters. There are various mitigation methods for Ferroresonance addressed in literature, such as suppression circuits, or simply avoiding that operating configuration. The surge arrester rated voltage must be always selected higher than the maximum TOV due to Ferroresonance to avoid failure should it occur.

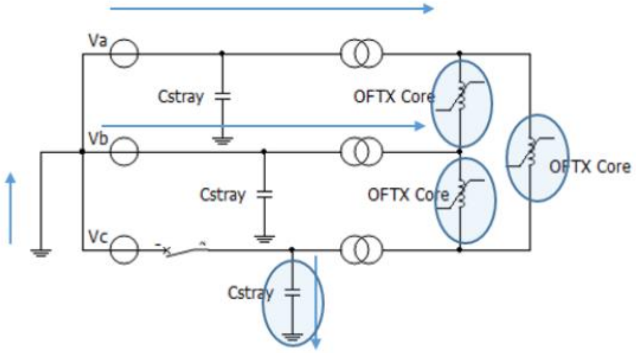

Fig. 4. Breaker failure for analysis of Ferroresonance overvoltages

C. Load rejection

TOV's due to load rejection can reach very high magnitudes when the complete wind farm is disconnected with generation in operation (without a system fault, but potentially due to breaker mal-operation or incorrect manual tripping without first shutting down turbines). Fig. 5 shows the case where breaker on the 400kV side of onshore transformer is tripped manually, disconnecting the complete wind farm. The voltages on the generation side (at HV of onshore transformer) reach the magnitude of around 2.5pu. The turbines trip after around 70ms and voltages decay quickly after disconnection. As the high magnitude of TOV is only for a very short duration, it should not exceed the thermal capability of surge arresters or insulation level of equipment.

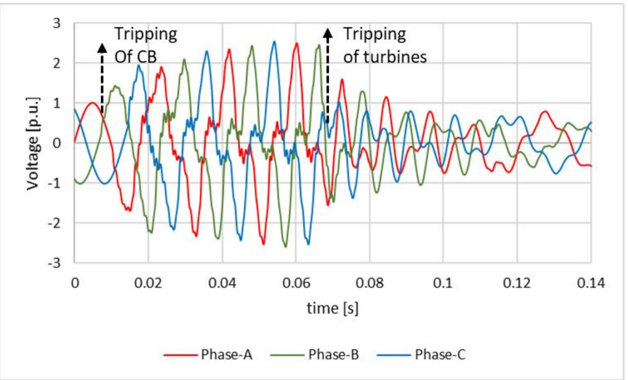

Fig. 5. Load rejection overvoltages due to disconnection of complete wind farm

If the duration of overvoltages remains for longer, then a cascaded tripping methodology should be implemented where CB4 in Fig. 7 is tripped first for manual tripping of any onshore breaker. The overvoltages due to load rejection should be verified for each circuit breaker in the windfarm in case of manual tripping or mal-operation.

D. Fault and circuit breaker tripping

System faults are the main source of slow front (SFO) and temporary (TOV) in the network. Faults are therefore studied at multiple locations across the windfarm, and for different operating scenarios of the windfarm network. The resulting overvoltages during and after clearing of the fault are recorded. Fig. 6 shows the voltage waveform for single-line to ground fault at an offshore array string end, where TOV's are observed during the fault and SFO's after clearing the fault. In some cases, the TOV's are observed after clearing the fault, where the decay of transient is slow and the evaluation of such wave shapes and their effect on insulation levels are described in the CIGRE paper in reference [13].

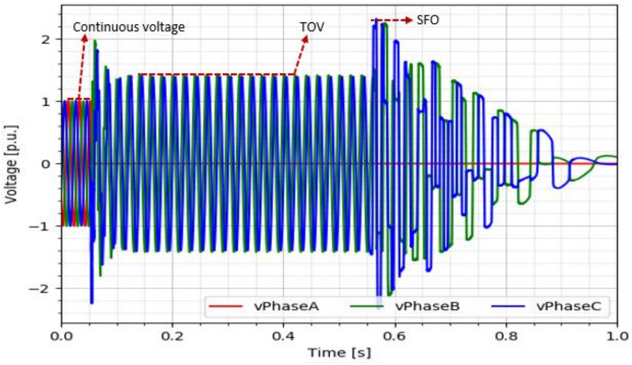

Fig. 6. Single line to ground fault at offshore array string end

One interesting case shown in Fig. 7, is for a fault at the onshore 220kV busbar. Circuit breaker CB2 and CB3 are tripped as per a typical protection methodology. However, in this case it was observed that the CB3 does not open due to a high DC component. Similar behaviour is observed for faults anywhere on the onshore network, where the breaker on the right side (as observed in Fig. 7) of the fault do not open.

The current flowing through CB3 includes an AC component due to the contribution from the wind turbines, and a DC component due to the energy stored in the shunt reactors. In some cases, the DC offset may exceed the AC component, preventing any zero-crossings in the current. CB3 may therefore be unable to interrupt this current. However, this should be analysed with frequency dependent models of the cables and dynamic models of the wind turbines.

CB2 can interrupt the fault current as it has to interrupt the current contribution from the grid only. The offshore end breaker CB4 does not experience this DC component phenomenon as the current it needs to interrupt is only due to the discharge of the offshore transformer and arrays.

In the above analysis breakers CB2 and CB3 are modelled as ideal breakers. To verify whether arc resistance will aid in damping of this DC component during interruption, the breakers have also modelled with arc characteristics. It can be observed from the summary of results in Table. II, that arc characteristics damp the DC component somewhat, but are not very helpful in decaying DC with long durations. In order to mitigate this problem, for a fault anywhere on the onshore substation, the offshore end circuit breaker CB4 is tripped.

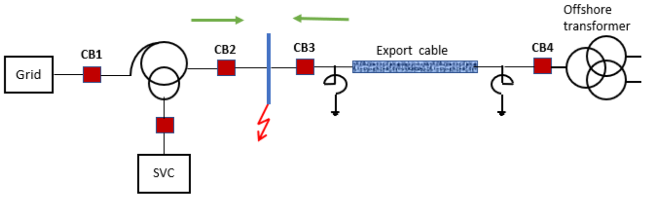

Fig. 7. Analysis of DC component due to fault on onshore substation

TABLE II

DURATION OF DC COMPONENT WITH IDEAL AND ARC MODEL OF BREAKER

Fault type	DC component duration [ms]	
	Ideal breaker	Arc model
Single line to ground fault	-	-
Double line fault	>1s	-
Double line to ground fault	-	-
Three phase fault	-	-
Three phase to ground fault	>1s	300ms

E. Energisation of cables

Energisation cables generate SFO. The closing times of the three phases of the circuit breaker have a great influence on the generated overvoltages, hence they are varied statistically. T_{random} is a value which statistically (uniform distribution) varies from 0 to 20ms (one complete cycle) and T_{scat_a}, T_{scat_b}, T_{scat_c} statistically (normal distribution) vary from 0 to 2.5ms.

$$T_a = T_{random} + T_{scat_a} \tag{1}$$

$$T_b = T_{random} + T_{scat\_b} \tag{2}$$

$$T_c = T_{random} + T_{scat\_c} \tag{3}$$

T_a, T_b, T_c are breaker switching time for phase-*A*, phase-*B* and Phase-*C* respectively [14].

For this example, energisation of export cables and string cables are analysed. The export cable is energised along with onshore and offshore shunt reactor and the magnitudes of TOV & SFO are recorded at all the busbars.

During energisation of offshore strings, it is possible that the RMS voltage can become temporarily too high if cables are energised without turbine transformers connected, or too low if all turbine transformers are energised (due to transformer inrush). If a problem is observed, then energising the strings with portion of the unit transformers connected often resolves the issue.

A special case of string cable energisation relates to the fault-finding strategy, where typically individual sections of the string are sequentially energised. In this case, it is important to verify the number of fault ride through events (FRT) per turbine is recorded and if it happens to exceed five then the turbine should shut down manually until fault finding is completed. The risk of FRT should be assessed during fault finding of the string cable sections and it is required to analyse whether the risk of FRT is with overvoltage or undervoltage. If the risk is due to undervoltage then the then the risk of FRT events can be reduced by switching the string under investigation without unit transformers.

F. De-energisation of cables

De-energisation of either export cables or string cables does not in itself generate any transient overvoltages. However, the analysis is helpful in determining the time required for trapped charge to dissipate completely, and wait times required for subsequent energisation. The export cable discharges through the shunt reactor and cable resistance. For the offshore transformer the MV side is usually delta connected and the hence the path for array cables is through magnetising path of voltage transformers, unit transformers and resistance of cables. The analysis should be carried out to verify the energy requirements of voltage transformers installed in the array. The earth switches can be operated at the end of discharge process for safety of personnel and equipment.

Fig. 8 show the discharge durations for array and string cables. When the array cables are de-energised with unit transformers connected, it discharges through the transformer core impedance hence the voltage resembles the decaying square waveform which has high decaying DC component superimposed with the fundamental. When the string cables are disconnected without the unit transformers, then the voltage will not contain any DC component, hence, there is no offset and decays faster to zero voltage. The export cable is discharged through onshore and offshore shunt reactor and therefore the only discharge path is the resistance of cable and reactors. Correspondingly it takes tens of seconds to completely discharge the export cable.

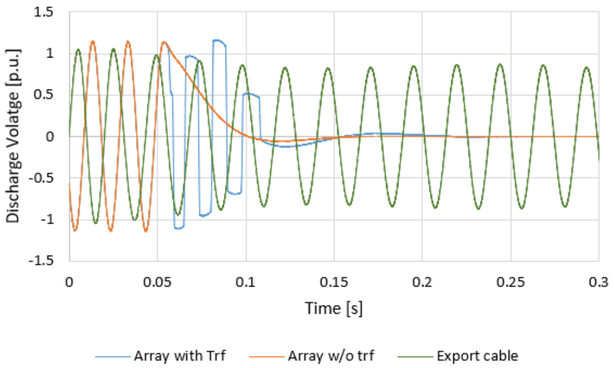

Fig. 8. Discharge duration for array and export cables

G. *Very fast transient overvoltages*

Very Fast Transient Overvoltage (VFTO) belongs to the highest frequency range of transients in power systems. The overvoltage is uni-directional with time to peak ranging between 3ns to 100 ns, and with superimposed oscillations at frequency 0.3MHz to 100MHz. As offshore wind farms typically employ gas insulated substations (GIS) – especially offshore – it is at this location where VFTO are of most concern.

Modelling of GIS components are performed as per CIGRE reference [15]. During the operation of a disconnector, sparking between its contacts is modelled as non-linear resistance (Rs). The arc resistance changes from 10^{12} Ω (R_0) to 0.5 Ω (R_f) during sparking, with a time constant of 1ns [16]. Due to this switching disconnector, a surge will be initiated, and will propagate further throughout the substation and other connected equipment. A section of modelled feeder network is shown in Fig. 9.

The highest magnitude of VFTO's are typically generated during disconnector operation with a magnitude depending on the voltage difference across the contacts just before striking, and the location in the GIS. A trapped charge of -1.0p.u. modelled as a capacitor on the load side of disconnector, and source voltage of 1.0p.u. on the source side of the disconnector results in 2p.u. voltage across the disconnector terminals. This considers the most unfavourable case for high speed disconnector operation.

A series of study cases for disconnector operation in GIS rated at 245kV and 72.5kV are analysed based on the above-mentioned methodology. The magnitudes, when compared to lightning impulse withstand voltage, have a large margin and hence VFTO's may not be a concern for GIS in windfarms rated less than 245 kV.

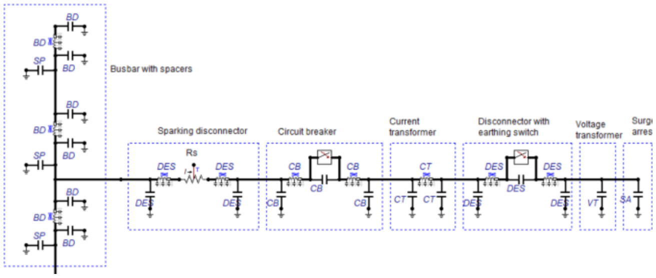

Fig. 9. Modelling of GIS components for VFTO studies

H. *Zero-miss studies*

Large generation of reactive power due to capacitance of the long export cable occurs in the offshore windfarms. To compensate, shunt reactors are usually installed. During energisation, the capacitive current of the export cable leads system voltage by 90^0, and the inductive current of the shunt reactor lags by 90^0. At voltage zero both the inductive and capacitive currents are in phase opposition to each other and cancel out, therefore leaving a DC current in the incoming breaker, otherwise known as a delayed zero crossing. During this moment it is not possible to re-open the circuit breaker (if a fault in the cable exists) because the circuit breaker must find the current zero for arc interruption. In a case such as this, it may take a long time (up to seconds) to attain, hence it is called the zero-missing phenomenon (ZMP).

There are various methods available for mitigation of ZMP and each has their own advantages and disadvantages. Table. III lists different mitigation methods and drawback of each method for implementation.

TABLE III

MITIGATION METHODS FOR ZMP

Mitigation	Method	Challenge
Point on wave switching	The closing instances of breaker contacts are controlled through a logic in such a way that, the contacts close when there is no ZMP observed by the breaker.	Operating temperatures, mechanical wear and deterioration of circuit breaker will cause a significant drift. Manufacturer cannot guarantee the suitable tolerance of closing time and ZMP can still exist. For these reasons it is not considered suitably robust
Pre-insertion resistor (PIR) [19, 20]	The resistance of PIR is designed in such a way that, it damps out the DC component completely during the pre-insertion time.	The energy dissipation of resistor stack, tolerance of resistance value with temperature, feasibility of PIR for GIS rated below 245kV. Generally, this is considered a robust solution, also reducing energisation transients
Tappable shunt reactor	The degree of compensation provided through the shunt reactor is brought below 50%. The system is energised with shunt reactor at minimum tap.	Cost of tappable shunt reactor at lower rating. Reactive power generated by the cable must be compensated with dynamic sources to avoid the reactive power spillage into the grid during this energisation time.
Sequential switching [17]	Circuit breaker poles are operated at different times depending on the type of fault. In this method the faulted phases of the main breaker are opened first, followed by the un-faulted phases of shunt reactor breaker, and finally the un-faulted phases of main breaker are opened.	This method requires a separate circuit breaker for the shunt reactor, and introduction of a complex protection system. These timings are entirely based on the duration of fault current and zero miss through the breaker contacts.

The suitability of a mitigation method depends on the system configuration and network parameters.

The duration of the DC component depends on many factors of the network like fault level of the grid, rating of shunt reactor, length of cable, degree of compensation, switching angle and fault type. A detailed explanation about effect of each factor on ZMP is mentioned in [17], [18].

I. *Insulation levels of equipment*

The insulation levels of equipment are selected such that they are higher than the maximum voltages occurring in the system. The maximum value of TOV, SFO, FFO and VFTO considering all the studies and for different operating configuration of the system are considered for determining the insulation level of the equipment. The maximum overvoltages occurring in the system are coordinated with the surge arrester ratings [21] to determine the final insulation withstand levels of equipment considering suitable safety factors [22].

V. CONCLUSIONS

This paper has reviewed the main transient studies and challenges observed for a typical HVAC connected offshore wind farm, with a focus on the issues which are crucial for the design process. Some of the main conclusions are as follows:

- In order to determine the worst case overvoltages for transformer energisation, the grid impedance has to be tuned to give the worst case impedance at 2nd -harmonic order, taking into account the export cable resonance. Additionally, the RMS voltage change at onshore connection point has to be verified.
- Overvoltages due to Ferroresonance can reach high levels, in order to verify it is not going to cause failure of the equipment, sensitivity analysis need to be performed and mitigation methods are needed which avoid destruction of surge arresters.
- For onshore faults, opening of the remote end export cable may be required due to zero miss in the onshore export cable circuit breaker
- Load rejection (due to manual circuit breaker operation, or mal-operation) can result in significant overvoltages. Opening of the remote end export cable circuit breaker can mitigate this issue.
- Based on the VFTO analysis for onshore and offshore GIS, the overvoltages when compared with the lightning impulse withstand voltages, are generally low and may not be a concern for GIS with voltage levels less than 245kV.
- A PIR is a very robust solution for mitigation of zero miss during export cable energisation. It has the added benefit of reducing switching transients and therefore reducing stress on equipment.

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