AC Cable solutions for Offshore Wind Energy

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Abstract

Different aspects of submarine AC cable systems for Offshore Wind Power will be presented. Advantages and disadvantages with 1-Core and 3-Core solutions will be discussed. For 1-Core solutions the possible rated power is significantly higher than for 3-Core solutions. One must however consider unbalance due to the un-transposed configuration and also make sure that galvanic corrosion will not be a significant aspect. A 3-Core solution will minimize the impact of these phenomena.

The cable design will also decide its electrical parameters. Wind farms must comply to grid codes defining for instance operating voltage range and power factor in the Point of Connection to the onshore transmission grid. The working regions for the complete cable system in active and reactive power must therefore be investigated in order to optimize cable design, transformer data and required steady state shunt compensation. The paper will illustrate one possible way of describing the cable operating range for active and reactive power transfer.

Reliability and exposure of the cable system is another aspect which is important to consider.

Energizing of a cable can cause switching transients and resonances. On such example causing resonance is transformer magnetizing currents. The paper will show a few examples of energizing parallel cables and transformers.

***Index Terms*—AC cables, 1-Core, 3-Core, installation, operating capability, reliability, energizing.**

I. Introduction

Planned offshore wind farms are growing in MW-size and in distance to an appropriate connection point to the grid. This requires higher ratings for cables. It is therefore necessary to investigate the different technical and practical limitations of long AC XLPE cables, connecting wind farms offshore. This paper will highlight both some practical aspects of cabling and also consider some electrical properties of such an installation.

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The experience of very long (~100 km) offshore cable connections are limited and the issue must be highlighted from several aspects to discover the full operating range of such an installation.

II. 1-Core and 3-Core cables

There are two different cable types considered here. The first one is when the three phases are separated. This is usually called 3x1-Core cables. The second one is 1x3-core cable where the three phases are bundled together in trefoil configuration and surrounded by a common shield and armoring, see Figure 1.

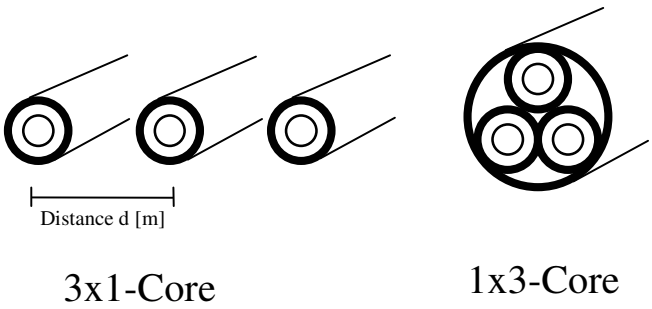

Figure 1 Two cable types 3x1-Core and 1x3-Core exists

A. Features of 1-Core cables

The benefits and features with a 1-Core cable solution can be described as follows:

Laying: 1-Core cables are laid offshore with a certain distance, d, between the phases. Normal laying distances have been some 10:s to hundreds of meters (10:s->100m). At some potential offshore wind farm locations now studied is the shore region exposed to many different interests. It has therefore been discussed to make the cable route as narrow as possible. It is possible to lay the individual phases 10 m apart with modern burying methods.

One must, however, consider the possibilities to repair a damaged phase cable. A repair requires a certain extra space to hold the added jointed piece because the cable will be a little bit longer after the repair. This extra length is dependent on the depth and must be placed on the sea bottom between the adjacent phases without violating maximum bending radius particularly for a repair on the middle phase. A failed cable is

sometimes raised to the surface with a special anchor. This anchor needs a certain phase distance in order to retrieve the cable phase safely.

A narrow laying distance d might also cause ground soil temperature rise around the cables. Another factor to consider for narrow laying distances is the increased risk of a common external fault causes. For example a fishing trawler turning a few meters too late can, with narrow phase distance, damage 2 phases instead of only 1 phase.

A cable is built up around a core with a number of layers with insulating and protecting properties. The watertight protecting layer is most often made of a metallic material. This means that the cable has several electrical circuits where currents are induced. Reference [1] indicates that at a cable distance, d, up to say 50 m in sea water we have to take the currents in the other phases into account. Since the phases are not transposed we will get a magnetic flux unbalance where the middle phase will have slightly different impedance than the other two phases. This will have an impact on the cable inductance and cause unbalance in the three phase system.

Above ~50 m we can treat the individual phases as "single core" ones with the same phase parameters.

The induced currents in the shield and armoring will cause a voltage drop along the cable. One does not want to have high voltages between these two layers or towards the surrounding due to the risk of a puncture of the electrical insulation. The cable armoring and shield must therefore be grounded at certain distances. The voltages along the cable become particularly high during transients and faults and hence decide the distance between the groundings [2], [3].

Another factor to consider is the variation in laying distance, d, between the phases. It can not increase or decrease more than a certain level to keep galvanic corrosion of the shield below a certain level, [4].

The presently available cable laying ships can carry say 6-7000 tons. Assuming a cable weight of 70 kg/m, there is a limitation in length of ~100 km before joints during installation must be made.

It is not uncommon to also lay a 4:th spare phase at the time of installation. This is then taken into operation if one of the other fails. This will improve availability of the transmission system.

Handling onshore: The three phases can be handled separately and allow for somewhat easier handling per cable.

Joints: Offshore repair cable joints for 170 kV have been demonstrated.

Rating: Higher rating is available than for the 3-Core cables at least up to around 500-600 MW. One particular issue for 1-Core solutions is that the armoring will carry roughly the same current as the conductor. This causes extra heating of the cable.

Magnetic coupling: The laying distance between the phases can introduce some magnetic coupling between adjacent parallel cables (and pipelines etc.) for distances lower than say 50 m.

Phase properties: A narrow laying can cause phase unbalance as discussed earlier. This will introduce negative and zero sequence currents in the system [6]. If the negative sequence currents become too high they will threaten induction generators used in many wind turbines due to overheating of the rotor. Synchronous machines usually manage 10% of negative sequence currents without any rating problem. The same unbalance on an induction motor with a starting-to-running-current ratio of 8 times requires a derating of the motor to 55% to avoid overheating [7]. This indicates that already quite small unbalance in the cable system can play a role for wind farms equipped with induction type generator as the Double Fed Induction Machines, DFIGs.

It is therefore advised to include an unbalance calculation of the transmission system in the pre-design if a 1-Core solution is chosen and match this to the induction generator characteristics. The power electronic controllers' behavior to the negative sequence current used in the DFIGs should also be included in such investigation. Measures to mitigate unbalance problems can be a Static Var Compensator, SVC or a Voltage Source STATCOM.

Shield protection: The polymeric sheath covering the metallic sheath of the cable must be protected against over voltages. This is done by grounding the metallic sheath at regular distances. There are basically three ways of connecting the submarine cable sheath to ground. It is grounded in one end for short cables (where sheaths in the other end are connected) and in both ends for medium to long cables. For very long lengths, conductive polymeric sheaths or intermediate grounding points are necessary.

The losses are higher for a 1-Core solution compared to a 3-Core solution due to the losses in the shield/amour. These currents may reach significant values since they "mirror" to the phase current. The shield and armoring must therefore be rated for this burden.

B. Features of 3-Core cables

The benefits or features with a 3-Core cable solution can be described as follows:

Laying: The cable is laid in only one instance and is therefore considerably cheaper to install compared to 1-Core cables. The handling is more difficult due to the heavier weight. Assuming a cable weight of 120 kg/m, there is a limitation in length of some 50 km. Another laying factor is the depth which is restricted due to the weight of the cable. Crossing deeper

channels in order to reach shallow banks may put restrictions on the cable size.

Furthermore it is possible to produce the cable with integrated fiber optical cables; hence there is no need for extra operations for laying a fiber optical cable.

Handling onshore: The 3-Core cable is heavier to handle onshore. If the distance to a suitable connection point is far one has either to change solution or find another point closer to the shore.

Joints: The joints are of course slightly more problematic for a 3-Core cable. Firstly must all three phases become jointed within a relatively short distance and then must armoring and watertight sealing of the cable become attached.

Rating: The highest rated cables presently delivered to offshore projects are around 200 MVA at 150 kV.

Magnetic coupling: Little or no coupling to neighboring or parallel cable systems. This also includes the metallic sheath and armoring of the cable itself which will carry rather low currents for this type of cable.

Phase properties: The solution will be symmetrical for phase impedances.

Shield protection: The shield must be grounded at regular intervals in order to avoid overvoltages particularly during fault conditions.

The 3-Core cable has a lower current capability per conductor but avoids several issues that 1-Core cables have: Laying, shield/armor losses, un-symmetry (to some extent) causing negative sequence currents and shield corrosion. It is most likely that the costs of a large 1-Core solution will increase from the 3-Core solution realized with parallel paths. For powers above say 250 MW multiple 3-Core cables should therefore be considered. This will also increase reliability of the wind farm.

III. Rating Considerations and Load Characteristics

The utilization of a wind farm compared to conventional thermal and hydro plants is rather low, seen from a yearly perspective. There will however be continuous periods of operation at rated power which can stretch up to a full week or more. For the longest part of the cable, the surrounding temperature and thermal time constant is rather high. The cooling conditions are probably not as good in the cable ends which may include a beach trench and the riser at the platform. The current along a cable is always highest in the cable ends due to the reactive power transfer so special care must be taken for the ampacity of the cables in that region. Reference [10] discusses the thermal loading of wind power cables.

IV. Operating Working Area for Active and Reactive Power

There are several papers on the capability of a cable in active and reactive power showing different aspects. Here only the basic circle diagram will be used for illustrating purposes.

A requirement for connection of a wind farm can be that the park shall be able to keep a certain power factor irrespective of voltage level. Several different operating points are interesting:

- High AC voltage level and low wind production
- Low AC voltage level

If the AC voltage is high and only a few machines are connected there is little reactive power consumption and the cable capacitance is generating more reactive power than for normal voltage level. The cable transmission working area for active and reactive power is therefore interesting to study. A graphical way of describing this is the power circle diagrams [5].

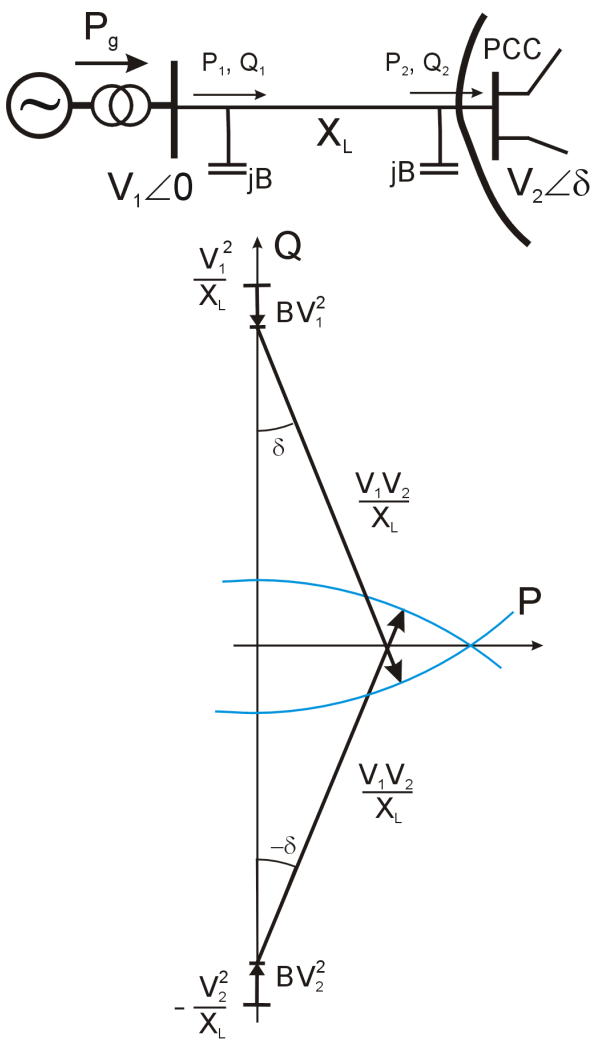

Figure 2 Power Circle diagram for a lossless cable transmission

The power flow for a lossless line is described by the equations

$$P_1 = \frac{V_1 V_2}{X} \sin\delta \tag{1}$$

$$Q_1 = -BV_1^2 + \frac{V_1^2}{X} - \frac{V_1 V_2}{X} \cos\delta \tag{2}$$

$$P_2 = \frac{V_1 V_2}{X} \sin\delta \tag{3}$$

$$Q_2 = BV_2^2 - \frac{V_2^2}{X} + \frac{V_1 V_2}{X} \cos\delta \tag{4}$$

These equations can be described in a xy-plane as described in [5], see Figure 2.

It is now possible to draw the required power factor in the Point of Coupling, PCC, and take into account lower and upper voltage limits respectively. The following figures will illustrate the procedures involved.

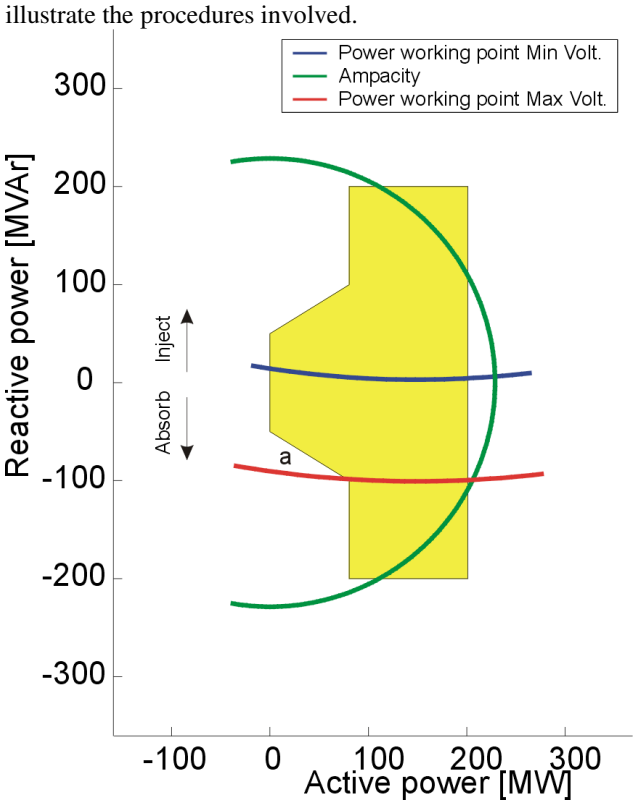

Figure 3 Sending end diagram 50 km, 132 kV, 3-Core cable, 1 kA rating

Figure 3 shows the sending end diagram for a 50 km, 132 kV cable with the rating of 1 kA An arbitrary capability diagram for the wind farm generators is shown as a shaded area in Figure 3. The analysis can take any type of capability curve for the wind turbines into account. We also see the cable ampacity as a green circle in the diagram.

If we study the sending end we also see that there is a small working area (assigned a) when we can not, for the high voltage limit, absorb enough reactive power in the wind generators.

The corresponding receiving end circle diagram is shown in Figure 4. Now we have an ampacity varying with voltage. We also see the two arcs representing the upper and lower voltage levels, in this case +-5% voltage. The figure also illustrates the required power factor as the area inside the black angle.

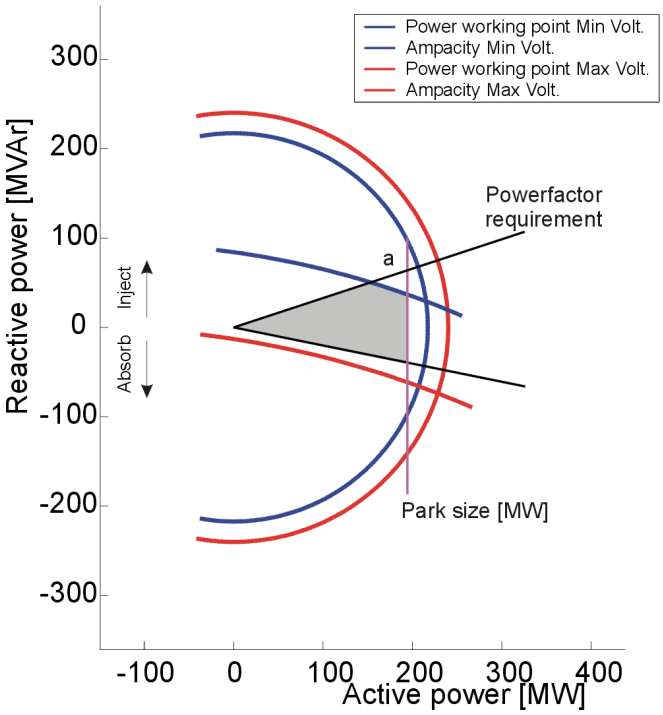

Figure 4 Receiving end diagram 50 km, 132 kV, 3-Core cable, 1 kA rating

The figures now indicate that we can work inside the required power factor in the PCC (receiving) end except for a small area a) when the cable transmission can not inject sufficient reactive power at low voltages. Reactive power compensation or tap changing operation increasing the voltage level on the cable in the sending end is two possible remedial actions.

The example point out the following issues:

- There can be working points for which the cable can not fulfill necessary power transfer capability.
- Wind mills can have different operating modes, for example two different speed regions where the reactive power capability is different.
- The number of operating wind mills can wary and hence also the size of the capability curve of reactive power for the farm which can shrink from the suggested one.
- It should be kept in mind that if no-load is regarded without operation of any wind generator; the whole amount of reactive power has to be supplied by compensation.
- Other measures to keep the cable operating area within grid requirements exist. Examples are switched

compensation of capacitors and reactors and tap changer control of the transformers. Also a coordinated secondary voltage control of the reactive power output of the wind generators can be used (when applicable).

The design of a long cable system shall take as much parameters as possible into account. The operating area of tap changer transformers, generator capabilities, grid strength and available shunt compensation will all influence the transmission capability of the cable. An optimum design includes also different fault and transient conditions on the cable system which will be discussed in the sequel.

Yet another issue is the fault ride through capability required in most grid locations. This is either handled via compensation at the connection point by for instance Static Var Compensators or in the wind generators themselves. In that case the cable system must be able to transfer the required currents to maintain operation after the fault. This will require further system studies of the setup.

V. Cable Reliability vz. Cable exposure

Cables may fail due to different reasons. Mechanical damages like dig-ins and anchoring are the most likely especially for submarine systems. There can also be mechanical difficulties going from the sea bed and up in the platform where waves, ice etc may cause damage.

Offshore cables are also exposed to damage by shipping. Little information is available of the actual likelihood of such damage especially for offshore wind farm locations. These are on one hand located on shallow waters avoiding some heavy traffic but are on the other hand located relatively near shore exposing them from small trawling vessel activities. The cable transmission system may cross deeper water and become more exposed than the cables within the park. The failure rate in 1981 for submarine cables is given in [8] as 1.3 faults per year per 100 km measured on 150 km length of offshore cables. Some cables are however located close to busy shipping lanes. The today's failure rate figure for a wind farm application will probably be a bit lower. CIGRE gives a global overall figure of 0.32 failures per year per 100 km [9]. Data is however from 1950-1980 and can be regarded as a little bit old especially since the introduction of new materials has changed the prerequisites. Another important figure is that 53% of the failures in service are due to mechanical damage from shipping activity.

There are several ways of affecting the redundancy and reliability of the transmission system. One is the number of parallel cables laid, two parallel systems or a 4-wire solution (one spare) for 1-Core solutions. The reliability is also important for the auxiliary power solution required out in the wind farm. Power is needed in order to keep batteries alive and maybe also to avoid freezing conditions in the towers.

The reliability is also affected by the spare parts of the cable system (joints). The weather conditions etc. may make the 'Time to Repair' or "Waiting for weather" rather long.

Modern XLPE cables have a very good reliability record. The fault rates used is therefore more dependent on the exposure to outer mechanical stress from fishing trawlers, anchors, ocean currents and other changes of the sea floor. One interesting aspect of offshore wind power is if the turbine foundations can enhance the biological life around the farm. It is well known that the creation of "artificial reefs" around decommissioned oil platforms and sunken ships will increase the habitat for large fish as one example. This may attract local fishermen which come into the area and cause an increased risk of external exposure on the cables.

VI. Grounding system

There are several ways of organizing the neutral grounding in a power system. For a cable system like this is the most common way to utilize directly grounded systems since these keep the overvoltages down on the healthy phases during unsymmetrical faults. The price to pay for this is a high fault current which the system has to be designed for. Also systems with the neutral isolated are used for offshore wind power farms. The fault current is then determined by the capacitance to ground. More about grounding is discussed for instance in [11] and [12].

Grid connection of several offshore wind farms to the same grid location implies several parallel cable systems. Different grounding conditions and different cable designs may then influence the current distribution in the respective shield/armoring during fault conditions. Figure 5 shows an example with two offshore platforms to the right and a grid connection point to the right. The onshore substation is assumed to have a very good grounding point and most of the fault current for the indicated position will go through that point. However, for a Single Line to Ground fault in the cable system the current distributions will become more cumbersome to establish since we then are dependent on all grounding impedances in the system.

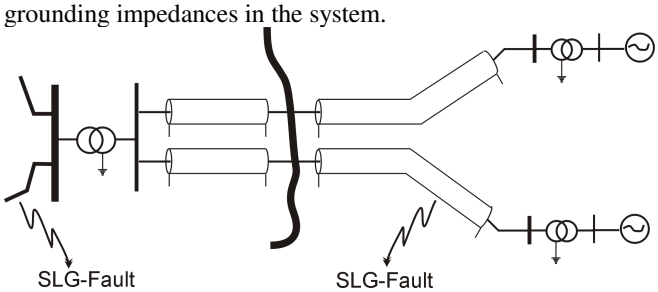

Figure 5 Where will currents flow during a SLG-fault?

VII. Cable energization

Energizing a cable is a transient event similar to energizing a capacitor. This causes transient voltages and transient inrush currents and an increased power frequency voltage.
An important difference between the capacitor and the cable is that the cable capacitance is distributed along the cable

influencing the damping of the transient voltages and currents during energizing.

There is a long experience regarding transient over voltages when energizing short cables in for instance industrial systems. The damping of high frequency transient over voltages would be improved with increasing length of the used cables reducing any problem transient over voltages. However, it could be possible that energizing long cables used in wind parks combined with the different system design could cause new phenomenon which have to be investigated.

Computer simulations of energizing cables for estimating the magnitude of the transient over voltages require very accurate high frequency computer models of cables covering the frequency dependent damping. This especially important for long cables, for which the damping of the transient over voltages has a large impact on the magnitude. A comparison between capacitor and cable energizing is performed as an introduction to cable energizing.

A. Capacitor energizing.

Capacitors are used for reactive power compensation of inductive loads and in harmonic filters. Energizing a capacitor is a well known transient event causing transient over voltages and inrush currents depending on the instant the circuit breaker is closed. In addition, the power frequency voltage is increased after the capacitor is connected.

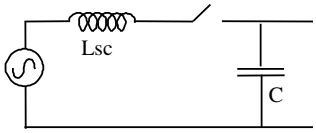

Figure 6 Energizing a capacitor.

The voltage to ground upstream the circuit breaker in Figure 6 is shown in Figure 7 - Figure 8 as an example of energizing a capacitor. The closing of the circuit breaker causes an oscillating transient over voltage followed by an increased steady state power frequency voltage. The capacitance of the capacitor and the short circuit power of the system give the frequency of the oscillating transient over voltage as well as the increase of the power frequency voltage.

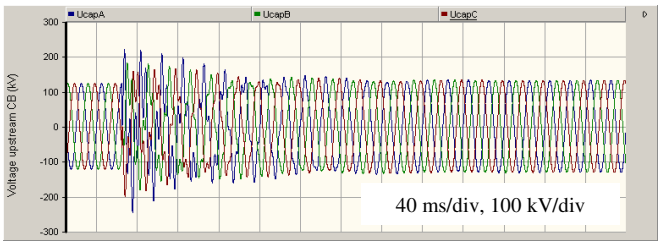

Figure 7 Voltage when energizing a capacitor.

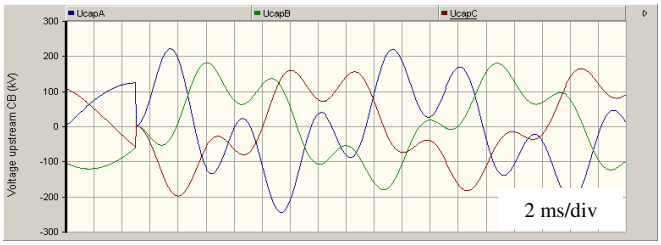

Figure 8 Time expansion of Figure 7. Voltage when energizing a capacitor.

In addition to the transient over voltage the energizing of a capacitor causes a transient inrush current followed by a steady state capacitive current. An example is shown in Figure 9-Figure 10. The resonance frequency of the in rush current is the same as for the transient over voltage

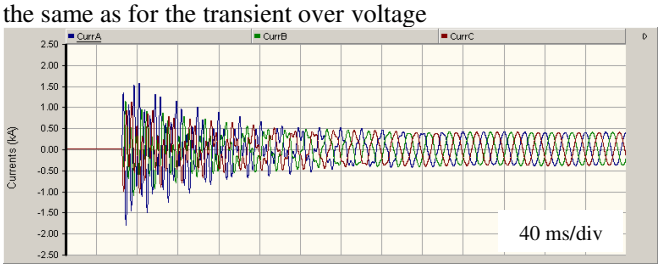

Figure 9. Current when energizing a capacitor.

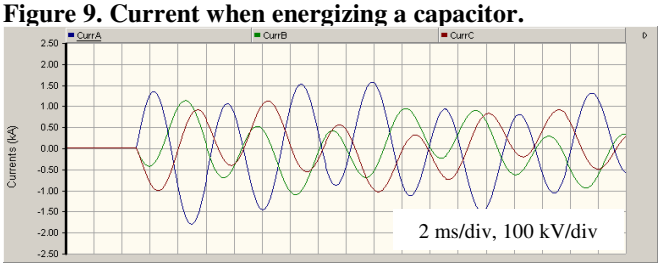

Figure 10 Time expansion of Figure 9. Current when energizing a capacitor.

1) Limitation of the transient inrush current.

The stress caused by the capacitor energizing could be limited when necessary by either a current limiting reactor in series with the capacitor, Figure 11, or by a synchronized closing of the circuit breaker.

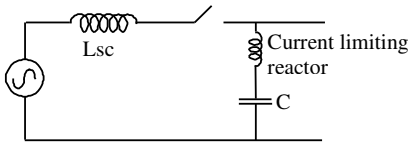

Figure 11 Current limiting reactor.

The limitation of the inrush current is particular important when energizing parallel capacitor banks one by one (Figure 12). Energizing the second capacitor when the first capacitor is already energized causes a much higher resonance frequency and amplitude of the in rush current compared to energizing the first capacitor. The reason is that the resonance frequency is not depending on the short circuit inductance of the system but by the inductance between the capacitor banks, which is much lower than the short circuit inductance of the system. The consequences are a high resonance frequency and a high in rush current.

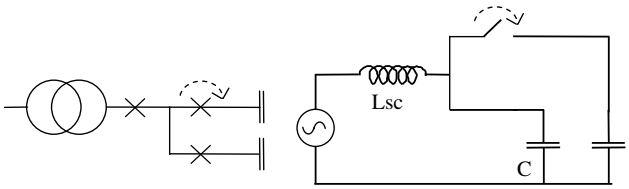

Figure 12 Energizing parallel capacitor banks.

B. Shunt compensation

Capacitors are used for reactive power compensation of inductive loads.

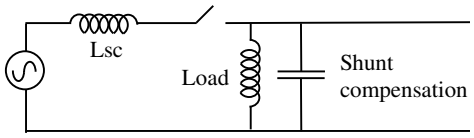

Figure 13 Shunt compensation.

For cables the situation is the opposite and shunt reactors are used to compensate the reactive power generated by the cables. The shunt reactors are used to mitigate the increase of voltage for idling cables and to reduce the reactive power transfer in the cables. If shunt reactors are required they should be connected before a cable is energized to prevent a voltage increase. There are different possible locations of the shunt reactors. They could be located at either ends of the cable or in between if the cable is split in two parts. Another alternative is to use shunt reactors at both cable ends.

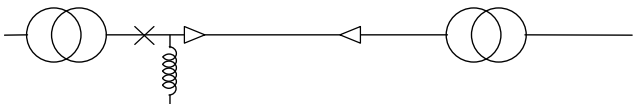

Figure 14 Shunt compensation of cable.

C. Cable energizing.

An idling cable could during steady state conditions be regarded as a capacitor generating reactive power. Energizing a cable is a transient event causing propagating waves and high frequency transient voltages and currents.

The simplest model of a cable representing the distributed capacitance and inductance of the cable as well as a constant resistance independent of the frequency is the pi-link. The model of the cable could be spilt into a number of sections, pi-links, depending on the required time resolution and the length of the cable, where each section is represented by the shunt capacitance and series inductance and resistance (Figure 15). Examples where this model has been used is shown in reference [13].

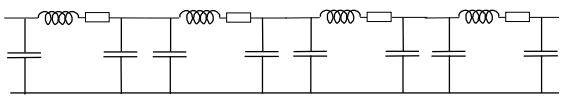

Figure 15 Single phase model of a cable represented by pi-links.

Computer simulations of three phase cable systems also require cable models taking into account the coupling between the phases.

The distributed transmission line model is an alternative to the pi-link model giving a more accurate result especially for computer simulations of transient events. The examples of cable energizing presented in the following sections are simulated using the PSCAD computer program as well as the PSCAD frequency dependent cable model taking into account the frequency dependence of the parameters.

D. Energizing a cable.

Energizing a cable connected to a transformer will charge the cable to the same voltage as the feeding system. The energizing is similar to energizing a capacitor. The cable is charged through the transformer and the transformer short circuit inductance is interacting with the cable capacitance.

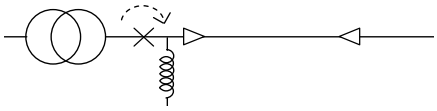

Figure 16 Energizing a three phase cable.

An example of energizing three single core 150 kV cables with a length of 50 km is simulated using the PSCAD program. The feeding power system is represented with ideal voltage sources in series with the short circuit inductance and resistance. The cable capacitance is compensated by shunt reactors downstream the circuit breaker.

The voltages phase to ground upstream the circuit breaker and at the end of the cable as well as the currents through the circuit breaker are presented in the figures below. Transient over voltages occur at both ends of the cable as well as inrush currents. The energizing of the cable is similar to the presented capacitor energizing except that the inrush current is faster damped and that the compensation of the cable mitigates the increase of the power frequency voltage and the steady state current.

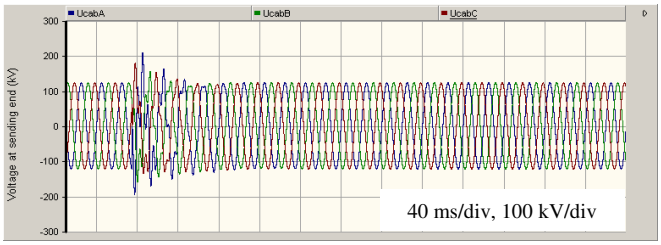

Figure 17 Voltage upstream circuit breaker.

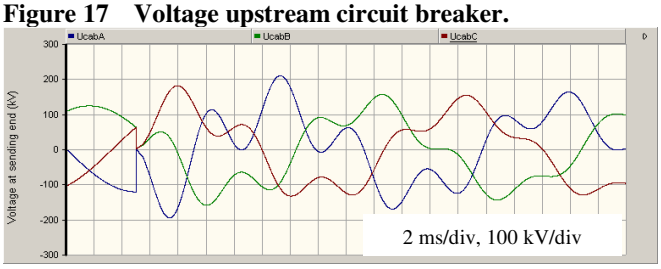

Figure 18 Time expansion of Figure 17. Voltage upstream circuit breaker.

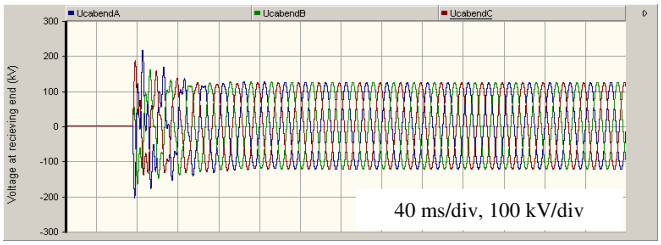

Figure 19 Voltage at cable end.

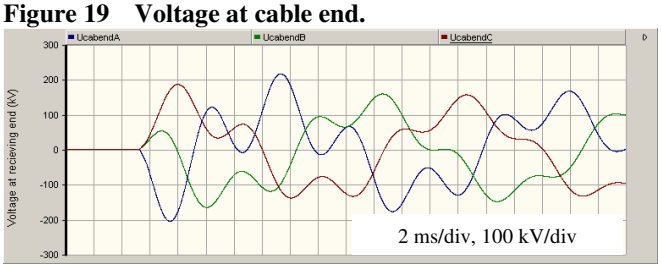

Figure 20 Time expansion of Figure 19. Voltage at cable end.

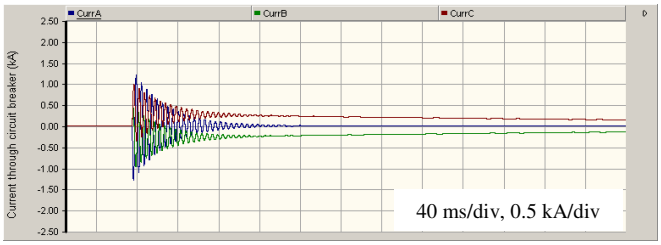

Figure 21 Current through circuit breaker.

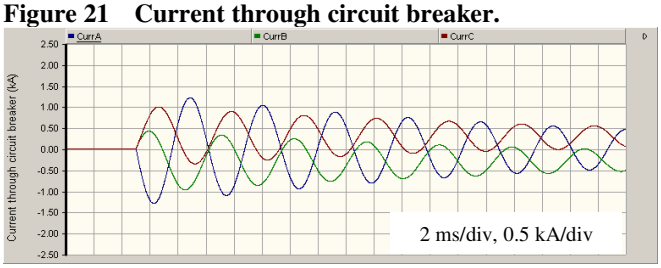

Figure 22 Time expansion of Figure 21. Current through circuit breaker.

E. Energizing a cable when another cable is already energized.

There is a difference when energizing a cable depending on if there is already one cable energized, similar to cases when one or two parallel capacitor banks are energized.

Energizing a cable when another cable already is connected could occur in the two examples in Figure 23. The first case could be a bus with two outgoing feeders and the second case could be a cable split in two sections.

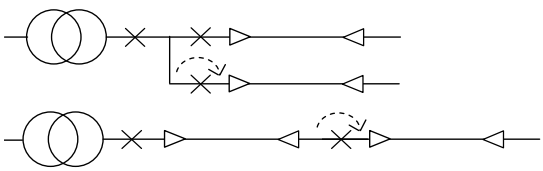

Figure 23 Examples of energizing a cable when another cable is already energized.

An example of energizing a second cable when one cable is already energized is shown in the following diagrams. The amplitudes of the transient over voltages are lower than when energizing the first cable, however the time derivative of the transient over voltages has increased due to reflecting waves, which can be better observed in the inrush currents. The reflecting waves are damped after a few reflections followed by transient oscillating voltages and currents before steady state conditions are reached.

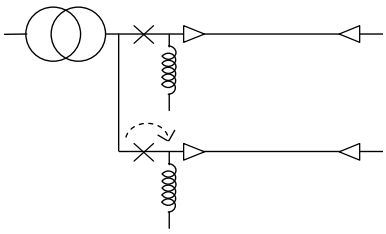

Figure 24 Simulated example of energizing two cables by one.

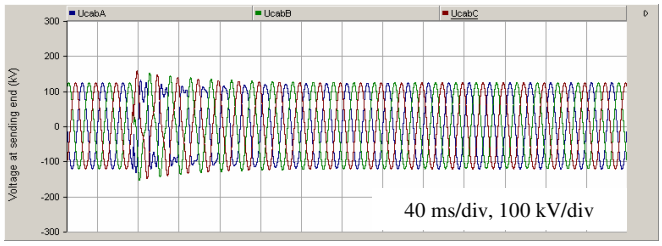

Figure 25 Voltage upstream circuit breaker.

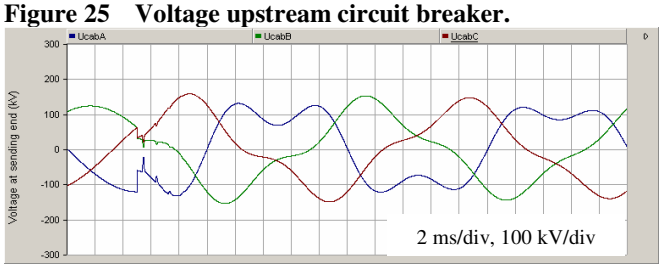

Figure 26 Time expansion of Figure 25. Voltage upstream circuit breaker.

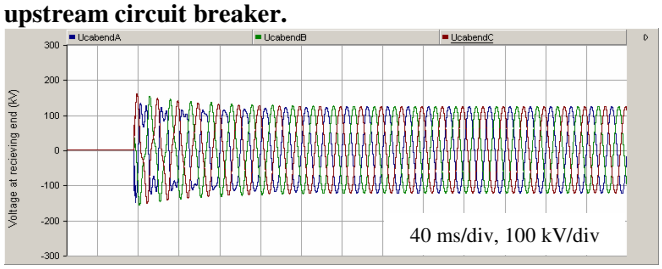

Figure 27 Voltage at cable end.

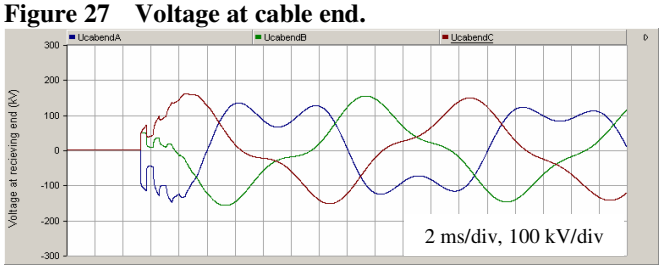

Figure 28 Time expansion of Figure 27. Voltage at cable end.

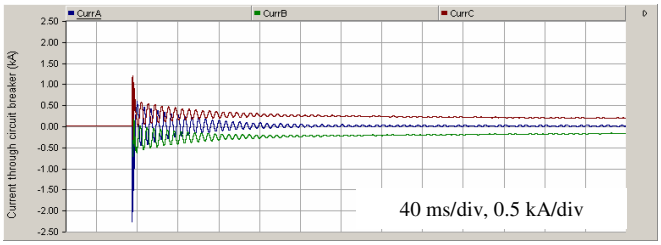

Figure 29 Current through circuit breaker.

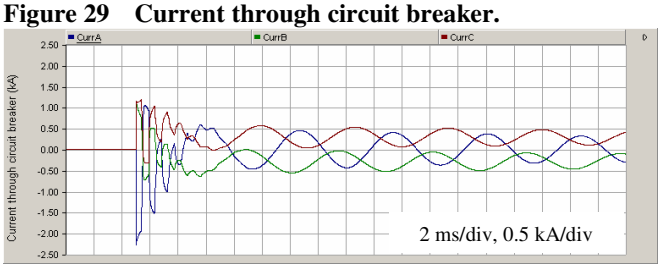

Figure 30 Time expansion of Figure 29. Current through circuit breaker.

F. Interaction between cable and transformer when energizing the transformer.

Two examples of cable energizing have been presented in the previous sections. The energizing of a cable is followed by energizing of the downstream transformer if existing. Energizing a transformer causes saturation of the transformer depending on the instant of energizing. Saturation and inrush currents will occur even if the transformer is energized through a stiff voltage source keeping the voltage at the rated value. The saturation and the magnitude of the inrush current depend on the instant of the energizing.

An example of energizing a transformer fed by a cable is simulated and presented below. A transformer model including saturation has been added to the computer model of the cable energizing case. The diagrams show that the same magnitudes of the over voltages and the inrush currents occur as when energizing the cable. The difference is that duration of the transformer energizing is much longer than for the cable energizing.

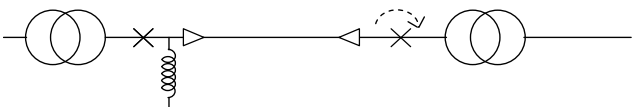

Figure 31 Energizing a transformer fed by a cable.

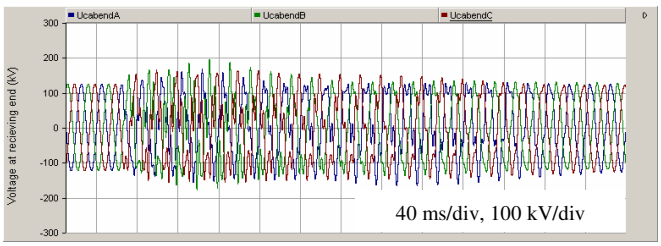

Figure 32 Energizing a transformer fed by a cable. Voltage at transformer.

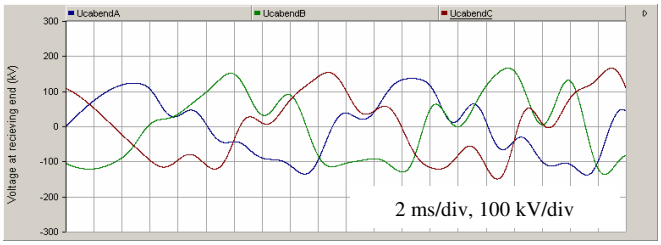

Figure 33 Time expansion of Figure 32. Voltage at transformer.

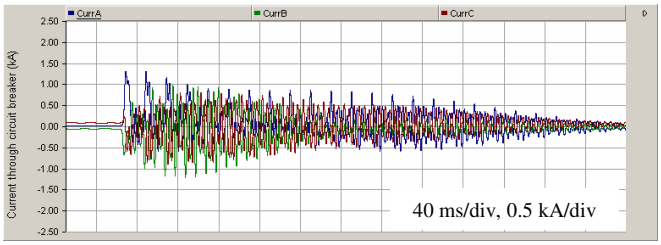

Figure 34 Current through circuit breaker.

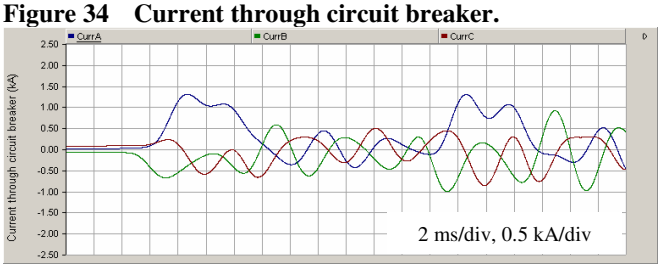

Figure 35 Time expansion of Figure 34. Current through circuit breaker.

G. Transient free energizing.

Synchronized energizing of capacitors and transformers are sometimes used to prevent high inrush currents or over voltages. Synchronized energizing could as well be implemented for energizing of cables when the normal random energizing could cause too high over voltages. It can also be used for minimizing the stress on the products in the system especially if the circuit breaker is frequently operated.

The benefit of synchronized switching is illustrated for the earlier presented case by first energizing the cable followed by energizing the transformer 0.5 s later.

The phase to ground voltages for non synchronized energizing of the cable and the transformer is shown in Figure 37. Transient over voltages are found as presented earlier.

The same case was simulated once again but synchronized energizing of both the cable and transformer were implemented. The cables were energized at the voltage zero crossings of each phase and the transformer were energized phase by phase at the peak voltages. The transient over voltages were eliminated according to Figure 38.

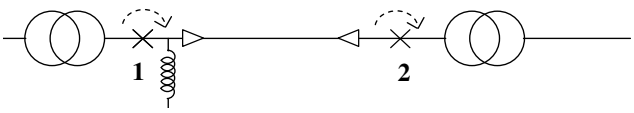

Figure 36 Energizing of the cable at 0.5 ms and the transformer at 1.0 ms.

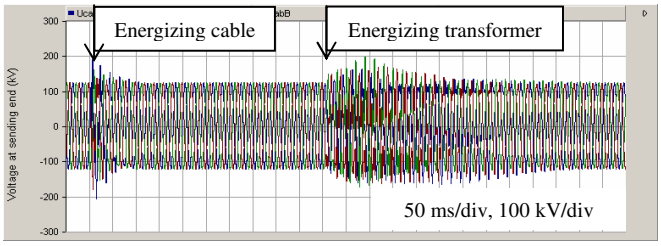

Figure 37 Random energizing of cable and transformer. Voltage upstream circuit breaker.

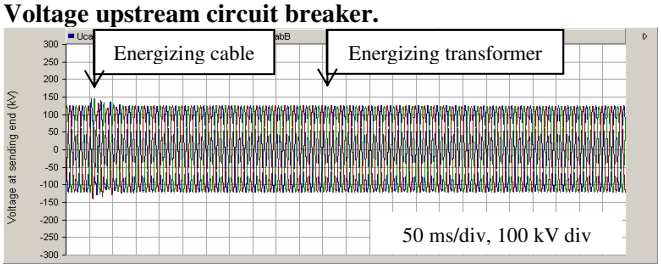

Figure 38 Synchronized energizing of cable and transformer. Voltage upstream circuit breaker.

H. Discussion

Transient overvoltages will occur during energizing of the cable. The system here has had a linear source impedance compared to reference [13] but similar effects occur when energizing the transformer from the cable. The simulations show the benefits with a synchronized operation of the breakers. They also highlight that when parallelizing cables we are creating traveling waves which increases the dV/dt stress on insulation in for instance transformers.

VIII. Load Rejection

Load rejection of a wind farm and a long cable must also be studied particularly for the case when the onshore grid isolates the wind farm. Two effects are important. The so called Ferranti-effect giving a voltage rise over the cable at no load and the frequency response of the wind farm should be considered. A transformer or reactor is sensitive to overvoltage in combination with under-frequency. This is called “Volts per Hertz” protection [7]. A transformer is normally sensitive to a ratio of the V/Hz to above 1.1 for which operation should be remedied. We now have an increase in voltage aggravated by the long AC cable and must make sure that the frequency increases to avoid a V/Hz restriction.

Reference [14] shows the condition for an induction generator farm where the frequency increases to roughly 53 Hz in 0.2 s and then decreases down to 51 Hz before it increases again to above 55 Hz and the park is tripped 0.8 s later. Similar measurements on a DFIG equipped park is not known to the authors but it is believed that the frequency changes will be much faster and deviations larger. One should check for resonances in the cable system for the extended frequency range and also equip apparatuses with appropriate protection devices.

IX. Conclusions

Designing a cable system for offshore wind farms does have many aspects. The choice of cable type and parameters will have impact on the electrical system and performance as well as the cable cost. It is therefore necessary to do careful investigations before a cable installation is commenced.

X. References

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