1. INTRODUCTION

Large wind turbine-/ wind park Installations are developing to an important alternative of renewable energy resources. Wind park installations with a rated capacity of several hundred Megawatts up to more than 1000 MW installations for future offshore applications are under investigation in different countries. This paper will give an overview on planning and applications studying such large applications. Both the transmission technologies and the Grid Code requirements are in discussion with the Power Grid Utilities to find the most economical and reliable technical solutions. Long distance underground and sea cable transmission may be used either in HVDC or HVAC technology for some of these applications: Also Power Quality and Reactive Power Compensation / FACTS devices may be used to improve transmission capacity and dynamic stability of such transmission systems. The presentation will provide a summary on the present technologies available and the necessary planning/design steps. The advantages of using both AC- and/or HVDC transmission will be compared from technical and economical aspects. The presentation will include some examples to demonstrate some specific design principles, the basic arrangements of different technical solutions, which can be used to interconnect and transport the electrical energy from far remote located wind parks to the local consumer’s at large industrial or residential areas.

The adoption of proven power electronics and switchgear up to the highest ratings of several thousand MW transmission capacity over long distances provides highest flexibility and safe and stable dynamic performance up to the limits of state of the art semiconductor ratings available in industry. Physical limitations in submarine cable dimensions and ratings need to be discussed and their impact on the structure and topology of such collector systems has to be demonstrated. Stable operation of bulk power wind park installations during / after grid disturbances need to be demonstrated in order to fulfill the grid owner’s operational requirements. The installation of offshore HVDC converter stations will be very complex due to limited space and weakness of a wind turbine offshore grid. There are projects with more than 150 km far offshore installation under planning over areas of approx. 20km x 20km with up more than 80 -300 Wind Turbines collecting the electrical power by a 33 kV cable collector system.

![Offshore Collector System for Wind parks](image1)

Figure 1: Offshore Collector System for Wind parks

In comparison with a conventional power station, large scale wind farm power as per Figure 1 is generated by a large number of relatively small generating units. Apart from power stations for supply to local consumers (e.g. industrial power stations), the unit sizes of conventional stations are in the range from 50 MW to 1000 MW. In this respect, even WTGs with larger unit ratings of approx. 5 MW can be deemed small. If wind power plants with topologies of a wind farm as given in Figure 2 are formed out of these small units, the individual generators must be suitably interconnected.

![Typical 33 kV Cable Distribution Network Arrangement for a 600 MW Windpark Installation](image2)

Figure 2: Typical 33 kV Cable Distribution Network Arrangement for a 600 MW Windpark Installation
The following criteria are important for planning the MV Medium Voltage collector grid. WTGs are usually arranged in a grid at distances of between 500 m and 1000 m. The individual generators must be connected to their neighbours by cables. The power produced by the generators must be collected by one or more central medium-voltage switchgear assemblies/cables and further transformed to the high-voltage network. At the same time, the typical parameters of medium-voltage switchgear must be taken into consideration. For large power ratings > 100 MW likely the highest voltage class of 36 kV distribution systems will be used to minimize the internal distribution losses in the interturbine connectors. Particularly for submarine cables, the investment costs are very high and must therefore be compared against the economic advantages of higher availability and lower losses of the selected network structure (ring or radial scheme). Both possible network topologies for power infeed of the individual WTGs are always in discussion:

- Infeed in groups via radial feeders comprising with up to approx. 10 WTGs
- Infeed in groups via open/closed cable rings with up to approx. 10 WTGs

2. THE POWER TRANSMISSION SYSTEM

In AC transmission due to capacitive current in the cable, the transmission capacity of the cable is reduced and limited in transmission length. How much the transmission capacity is reduced depends on the cable design, length, required voltage quality, the compensation scheme and the relevant reactive power requirements at the onshore grid connection point. Compensation may vary from zero to approximately 100 % of the total reactive consumption of the cable on any of the ends, but the most effective scheme is to compensate from both ends of the cable equally.

The nature of AC transmission by cables is that a long cylindrical condensator, is charged and discharged twice during each cycle. The external circuit must supply this charging current and it must be carried by the cable conductor in addition to the required load current. Fortunately the charging current is capacitive and it is displaced 90° ahead of the load current, so it is the vector sum of the load current and the charging current that determines the required design transmission capacity. The charging current generation is distributed evenly over the whole length of the cable. If no effort is done to control from which cable end the charging current is supplied, i.e. there is no compensation scheme at the cable ends, the operational grid impedances at the two ends determines how large part of the charging current goes to which end. For example - if the load at one end is used for ohmic heating, i.e. angle 0°, that end gives no compensation to the charging current, so it all has to be supplied from the other end. If the load is a large generator/motor drive with approx. \( \cos \varphi = 0.90 \), the impedance is inductive and it may supply part or all of the charging current.

So there are two extreme situations with regard to the charging current, one is that all charging current is supplied from one end, while the other is that the charging current is supplied equally from both ends. There may be any type of mixed compensation scheme in between the extremes. The longest transmission lengths, lowest over all losses and lowest overall cable cost is reached when the cable is compensated equally from both ends.

All in all the design current is no longer constant along the whole length of the cable, so the conductor cross sections and to some degree the insulation thickness has to be designed to take care of the changing situation in an optimal way. The limitations of the AC transmission length with cable, in addition to the compensation scheme is dependent on the required quality of voltage at the far end, on the voltage level and on the design and laying configuration of the cables. The voltage changes from no-load to full-load and has to be calculated on a model based on the distributed parameters of the cable i.e. by the “Telegraph equations.” Usually the maximum allowed voltage swing is ±10%. This is an important design criterion for long cables.

The system voltage in itself is a limitation, because the relative insulation thickness decreases as voltage level increases and this leads to an increased capacity with increasing voltage. It can be to some degree offset by increasing the insulation thickness somewhat, but such increase leads to higher weight, volume and price. The major contribution is due to the dielectric constant of the insulation together with the insulation thickness.

The lowest dielectric constant gives the longest transmission length under otherwise like circumstances. Because of this the XLIPE insulation with a low, 2.5, relative dielectric constant is uniquely suited for long length transmission. The design must find the optimum insulation thickness with regard to the transmission capacity, the conductor cross-section and the necessary compensation to minimise the total cost of the transmission system. The three-core cable design is uniquely suited for long length transmission as, by careful design, the charging currents from the three phases short circuited, so there are no losses caused by return currents in the outer metallic parts and in submarine cables the armour losses are low with this design.

The laying configuration refers to how single core cables may be laid to maximise the transmission
length. The best alternative is laying the cables in three-foil formation with the outer metallic layers either continuously or at discrete points bonded together to reduce additional losses from the charging current. If it is necessary to lay the single core cables apart in flat formation as in submarine application the transmission lengths will be reduced even if the armour material is copper.

Fig. 3 & 4 depicts such a typical application for an AC transmission solution with sea cables with a rated voltage between 36 kV to 110 kV and 170 kV AC. In some cases it can be beneficial to provide additional AC shunt compensation equipment along the transmission cable route. These components can be either allocated on a main land based substation or a remote offshore platform tapping substation with equipment for offshore made of compact gas insulated type. Typically XLPE type AC cables up to 240 MW and 170 kV (or 245 kV) can be supplied either as three-core or single-core cables depending on environmental aspects and limitations in transportation capacities of the cable laying vessels. In case higher voltages are under discussion also single core XLPE or oil cables may be used.

Typical three-core Medium Voltage MV Submarine Cables can be manufactured up to 36 kV rated voltage for 20-40 MVA , with cross sections between 95 sqmm up to 800 sqmm (copper conductor). Typical weights per km are 15 – 80 kg/m depending on cross section and type of lead sheet/armour. Typical three phase losses for such cables are expected in the range between 20 – 60 W/m.

Typical three-core High Voltage HV Submarine Cables can be manufactured with cross sections between approx. 300 sqmm up to 1200 sqmm (copper conductor). Typical weights per km are 30 – 110 kg/m depending on cross section, insulation and type of lead sheet / armour. Typical three-phase losses for such cables are expected in the range of 50 – 110 W/m.

Figure 5 shows an example arrangement for a 200 MW wind park Installation with AC cables over a distance of approx. 60km – 90 km away from shore.

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CONTROLLED DYNAMIC REACTIVE POWER COMPENSATION SVC / FACTS

There are two types of compensation devices, the passive and active types. The passive types are usually not variable reactors in tanks or in air. They are very robust and long life components requiring almost no maintenance. They are well suited to offshore application as they have as small footprint, as a transformer. The disadvantage is that they are designed for a single operational mode, usually to compensate the cable at full load. Also they are unable to assist the grid at rapid load variations. The active Static VAr Compensators use fast thyristor switched reactors and/or capacitors. They may help the flicker and voltage variations caused by the statistical nature of the wind power. By monitoring the voltage on the platforms the SVC may ensure the optimal transmission properties at all operational conditions. Reactive compensation and Grid Code Compliance need to be fulfilled at the power transmission and distribution terminals to ensure power quality for both steady state and transient operating conditions. Reactive power requirements are local and dependent on the actual load flow and voltage profiles in the meshed distribution systems. In most of the cases when the AC cables are operating on their thermal current limits it is desirable not to transport the additional VAr’s needed from the system through the cables. Also transient and switching surge type overvoltages / undervoltages need to be limited by dynamic compensation and avoiding transformer saturation phenomena during fault recovery of severe AC-system faults. Figure 8 depicts some combinations and possibilities to overcome / limit such critical operating conditions. The grid code requirements have to be fulfilled at the grid entry PCC (point of common coupling) at the High Voltage terminals. To reduce the cable ratings (reactive current) and the transmission losses it is recommended to provide the compensation equipment not at the turbine generators side.

4. LONG DISTANCE HVDC TRANSMISSION FROM WINDPARK INSTALLATIONS

The DC converters require a large amount of space in addition to the AC substation equipment, so the offshore converter platforms become large / costly. The converter contains electronic components with lower MTBF that requires an appreciably higher maintenance level than an AC substation. These characteristics make the use of converters expensive offshore. When the cable transmission parameters prohibit the use of AC transmission system, the DC system should be employed. This is the case if the distance to shore is > ~150 km and the power is >~300 MW for a three core cable or the power to be transferred on a single circuit is more than 1000 MW and the distance is >~100 km. However, reactive power compensation becomes technically and economically a challenging requirement. As earlier touched two main types of DC converters can be used over extremely long distances, the LCC and the VSC types Figure 9. Typical HVDC Cable Losses are 10-25 W/m for each cable conductor.

The majority of HVDC transmission systems are between strong grids, that allows the LCC thyristor based converters to function. A strong grid contains many large rotating machines with large moment of inertia near the feed in point of large capacity transmission lines between the machines and the converter. In the offshore windmill parks the machines are small and each transmission line is weak in this context, so an appreciable rotating unit, for example a rotating synchronous condensers needs to be installed on the offshore platform to facilitate the start up.

The VSC based converter can be started into a dead load, with no rotating machines present. Also as the type has a much smaller footprint this type is better suited for offshore use. In the following the
converters for DC transmission system are discussed (LCC and VSC type).

Line commutated converters LCC HVDC transmission can be used up to more than +/- 500 kV DC and to approx. 1300 – 1500 A DC single core DC cable current capability as shown in Figure 11. This results into a power transfer capability up to approx. 1300 – 1500 MW. Thyristor converters are capable to supply up to 3000 A DC current, e.g. the limitation of the power transfer capacity is a result of viability and economics to design and manufacture the appropriate HVDC cables with high current capabilities (parallel connection of cables). In case of extremely high DC currents also the possibility of laying more than two parallel cables for both the positive and negative converter pole can be discussed. The discussion of use of VSC (Voltage Sourced Converters) is an upcoming new interesting transmission principle, however some physical constraints in developing converters for DC voltages higher than +/- 300 kV and limitations in the current capabilities (steady state thermal / transient fault currents) will limit the maximum block and cable ratings of such transmission systems in the range between 250 to 600 MW. Technical and economical advantages and disadvantages on transmission distance of such systems will be discussed below. Fig. 9 depicts the principle arrangement for an HVDC long distance transmission. HVDC transmission systems exist of two typical cases, the bipolar system and the monopolar system.

5. BIPOLAR SYSTEM

The bipolar system contains two converter groups and two cables each carrying half of the power one is with a positive polarity voltage the other with a negative polarity voltage with respect to the ground. If one of the groups is out of service the system reverts to the monopolar mode and may carry half of the nominal power. However, in this case the converters and the electrode system must be designed to carry the full load current. Also the environmental aspects such as the ground return electrode currents must be investigated and certified by the authorities.

6. MONOPOLAR SYSTEM

The monopolar system has one high voltage cable with one polarity with respect to the ground and a return path at ground potential (electrode), to complete the circuit.

7. EARTH RETURN

While this is the cheapest mode with usually the lowest losses, it feeds large DC currents into the earth / earth electrodes. The requirements to the sea electrodes have become rather extensive, so for short lengths, ≤ 100km, the costs of electrodes may exceed the cost of a metallic return cable.

8. METALLIC RETURN

The metallic return cable is usually a conductor with XLPE insulation to the 24 kV level. In this case the system is earthed at a single position, usually at one of the converters. This requires laying and protection of two cables.

9. INTEGRATED RETURN CONDUCTOR

To eliminate the need for two cables in a monopolar system the cable with IRC was developed. 126 km length of this cable type has been in operation in the 2x 250 MW, 1000 A DC Northern Ireland – Scotland interconnection, Moyle. In comparison to single core cables it does not have an outer magnetic field. (see Fig. 10)

Figure 9: Principle Arrangement of Wind Power Transmission with HVDC Technology

Figure 10: 250 kV Moyle HVDC Converter Valves and Cable with Integrated Return Conductor

Fig. 10 : 250 kV Moyle HVDC Converter Valves and Cable with Integrated Return Conductor

Fig. 11 : Tasmania – Australia Basslink HVDC Cable 500 MW, 400 kV DC, 1250 A DC
10. PHYSICAL LIMITATIONS

10.1 LIMITATIONS OF POWER CAPACITY BY CABLE LENGTH / THERMAL CURRENT

Limitations of cable length are mainly determined by the electrical characteristics which apply for AC- and for DC- transmission principles. Some of the electrical limits (rated current of the cable) are related to transmission losses/heat dissipation from the cables – this has of course to consider the environmental aspects:

- maximum ambient temperature in sea bed
- thermal resistivity of sea bed/soil
- burial depth of cable in sea bed/soil

Different electrical criteria are discussed below. They are compared on the same assumptions of the ambient conditions as listed above. Comparison between AC- and DC- transmission here shall only provide principal information therefore. Real limits need to be adopted case by case based on the relevant real ambient conditions:

There are basically two different mechanisms to be considered for AC long distance cables depending on the length:

- thermal capacity due to active and capacitive current
- resistive voltage drop within limits of AC systems (typically 5%-7% \( U_n \))

Technical limits will be reached when the capacitive current exceeds between 40 and 55 % of the thermal current capacity of the cable. Reasonable voltage drop between the sending and receiving end shall not exceed 10 % -15 % of maximum line to ground voltage at the sending end.

For HVDC the corresponding criteria are different since no capacitive cable charging current needs to be considered:

- thermal capacity only due to DC current \( I_d \)
- resistive voltage drop due to DC current Length* \( R_{dc} \)*\( I_d \)

Technical limits will only be limited by a reasonable voltage drop at the inverter terminal, however this is free adjustable since there is no direct coupling to the AC grid voltage. Figure 12 provides typical limits of transmission length for different 50 Hz AC cables compared to HVDC and to a circuit with 16 2/3 Hz system frequency. Comparison is based on approx. 950 -1000 A cable current and 150 kV XLPE AC cables against 250 kV DC with the HVDC scheme in bipolar or monopolar metallic return operation with two DC cable conductors.

Figure 12: Power Capacity of AC- / DC transmission versus. Length and Frequency

Both economical and physical limits / optimisation need to be considered. Figure 13 shows the comparison of investment costs of AC / HVDC substations and cables. AC cables will have a physical limitation around 120km – 150 km in case the capacitive charging current is higher than the transmitted real active current (Real Power). HVDC Cable transmission can be built for transmission lengths more than 450 km (see HVDC Basslink Australia – Tasmania, 500 MW, 400 kV DC, 1250 A DC).

AC cables (if only one circuit will be laid) will be different from availability in cases of cable failures compared to a bipolar / dual monopolar HVDC transmission system. Also with HVDC the cable transmission can be designed with some inherent overload capacity since HVDC converters can be designed for inherent or short time up to 150 % nominal power overload capacity, which can be used in case on HVDC station/cable pole is not available.

Figure 13: Break Even and Limitations AC- / HVDC Cable Transmission for Wind Parks
10.2 LIMITATIONS OF CAPACITY BY SUBSTATION/DISTRIBUTION DEVICES

There are theoretically no limitations for an offshore remote AC-collector distribution grid. However, in practice, if distribution for industrial or wind turbine feeders needs to be sized in the range between 100 MW (for 13.8 kV, 4000 A rms) and 230 MW (for 33 kV, 4000 A rms) or larger, conventional MV medium voltage switchgear will be close to the maximal operational thermal limits of breakers and bus bars (limits assumed at 4000 A rms). In such a case the total installed power needs to be split up into several branches comprising transformers and sectionalising of the MV bus bars for current reduction.

10.3 LIMITATIONS BY FAULT CURRENTS

In case of large wind parks or power plants, medium voltage switchgear ratings should be checked with respect to maximum thermal and dynamical short circuit current capability. In case of AC-cable transmission, both the remote offshore generators and the short circuit capacity of the onshore grid need to be considered for the rating of the offshore located medium voltage equipment. In case of exceeding typical values (31.5 kA rms, 36 kV, S ≈ 1800 MVA) transformer splitting (or three-winding transformers) and/or introduction of transformer short circuit impedances with high limiting reactances can be used to overcome the limits. Limitation of fault currents also needs to be checked inside the internal MV cable connector grid (between the individual wind turbines and adjacent switchgear inside the towers).

10.4 LIMITATIONS BY HARMONICS AND RESONANCES WITH AC-CABLES

Uncontrolled harmonic amplification and harmonic interaction between offshore installations and onshore grid can occur more severely for AC transmission schemes than for DC transmission schemes. For HVDC schemes in general harmonic AC filters are provided in the scope of supply and detailed studies will be carried out to mitigate such harmonic interaction sufficiently.

In the past normally such resonance phenomena were not studied in such detail for AC cable transmission. For very long AC cables in conjunction with a step-up transformer on the onshore main substation a potential magnification of low order harmonic voltage pre-distortion (inherently 3rd, 5th, and 7th from the main grid) may occur. Hence AC cables for long distance transmission can be additionally stressed significantly in addition to the fundamental frequency ratings. Also some of these harmonics will amplify and cause significant stresses down to the offshore medium voltage distribution system (a typical arrangement is shown in Fig. 14). This should be avoided and operational harmonic cable stresses need to be analysed and checked carefully.

The attached example in Fig. 15 shows results of a harmonic current study on low order harmonics flowing in a 170 kV AC long distance cable connector connected to a 200 MW offshore wind park with approx. 90 km distance to the remote location. As seen from the study cases with different number of wind turbines energised, resonance phenomena and critical frequencies vary with the loading and actual configuration of the topology connected to the offshore MV wind park collector system.

Figure 14: Harmonic Resonance Phenomena (AC-Transmission with Transformer + Cable)

Figure 15: Low Order Harmonic Current Amplification (170 kV AC Cable)

The harmonic resonance frequency / amplification varies in frequency and magnitude dependent on the number of cables and turbines in service.

11. SYSTEM STUDIES

The experiences from recent AC Offshore Wind Power Projects under construction by SIEMENS (120 MW Lilgrund / Sweden and 180 MW Lynn-Inner Dowsing / UK) concluded are important for further planning / studying new large wind power installations effectively and covering all important system design aspects.

System Planning / Integration has to serve several interfaces such as Cable Manufacturer, HV/MV Equipment Manufacturer, Turbine Manufacturer and Maritime / Civil Work Contractors. Private Investor driven Projects need also clarifications, demonstration and final acceptance by the DNO.
Distribution Network Owner according to the relevant Grid Code standards. The relevant Grid Code standards are normally operational performance requirements during various steady state and dynamic operation. In addition to the Grid Code further more detailed electrical input data of the DNO’s distribution system and substation are necessary to finalise the ratings of all components of a wind park installation. The most important design critical values needed to start the final design as listed below are in the most cases not available at the begin of the final system design studies.

12. IMPORTANT INPUT DATA FOR DESIGN

- Wind Park Topology / Final Cable Lengths
- Wind Turbine Data / Characteristics
- Grid Code Performance Requirements
- Final Wind Turbine Ratings / Data
- Min. / Max. Operating Voltages
- Min. Max. Operating Frequencies
- Arrester and Insulation Protective Levels
- Grid at PCC (Point of Common Coupling)
- Earth Fault Factor at PCC
- Max. / Min. Short Circuit Equivalents at PCC (3p & 1p), Weakness of System
- Harmonic Grid Impedances
- Background Harmonic Voltages at PCC
- Harmonic Performance Targets \( D_p, D_{\text{max}}, D_{\text{tot}} \), max. Order of Harmonic \( h \), TIF or THFF
- Detailed AC System Equivalents for Dynamic Studies / Control & Protection

Figure 16 depicts an more detailed overview how the individual input data can be classified. Some of the electrical system data in excess to the general Grid Code Requirements are specifically related to the “as existing or to be built” substations at the PCC Point of Common Coupling. In most cases experienced this specific information has been provided too late during the final planning of the wind park connector. It is therefore strongly recommended to provide substation design data as early as possible (before the tendering or bidding stage of such a complex project). System studies and station engineering need to be planned in a logical sequence since there are iterative design processes with regard to optimisation of final cable ratings, reactive power compensation (MVar and location of reactive power compensation equipment) and finally loss optimisation of the cable arrays. Figure 17 provides an detailed overview of the necessary study & engineering steps. Some of the performance studies need to be adopted case by case to the relevant specific Grid Code requirements of the DNO. In case some sub-systems of such an installation will be purchased / delivered in separated “contract lots” projects, early co-ordination of the technical interfaces and their corresponding technical ratings are one of the most important key issues for a successful project execution.

13. CONCLUSIONS

New offshore installations of wind parks will be more efficient and economic - there are no general rules which of the solutions is the best / most viable for each individual application of an offshore power transmission project. Proven technologies used for onshore projects can be adapted to individual solution packages. Technologies are available between some MW up to a rated power more than 1000 MW over distances of more than 300 km. Offshore cable technologies for AC- and for DC- transmission are experienced with various sub sea systems world wide in commercial operation. It is desirable to secure such applications with the relevant electrical system studies to demonstrate and prove the selected technical solution. In the business of privately owned/invested wind farm projects electrical performance needs to be demonstrated to the system operator/owner of the high voltage onshore transmission system. Environmental aspects, right of way, extreme water depth and license/permitting approvals to demonstrate environmental protection requirements were not discussed in this paper. Such requirements can influence the selection of the technical concept and may have a significant impact on the economical aspects (investment costs/ financial feasibility, etc...).

14. REFERENCES


15. ATTACHMENTS

Figure 16: Classification of Input Data for System / Engineering Studies

Figure 17: Overview on System Studies and Engineering for Large Wind Park Interconnectors