COLLECTION GRID TOPOLOGIES FOR OFF-SHORE WIND PARKS

Bengt FRANKÉN[1], Henrik BREDER[1], Mikael DAHLGREN[1], Erik K NIELSEN[2]
[1]ABB AB – Sweden, [2]ABB A/S - Denmark
bengt.franken@se.abb.com, henrik.breder@se.abb.com, mikael.dahlgren@se.abb.com, erik.k.nielsen@dk.abb.com

ABSTRACT

Off-shore wind parks are expected to be a growing market for the future wind power industry. Today, some off-shore wind parks are erected, especially around the coast of Denmark, and future expansions will be seen in Denmark and in the rest of northern Europe as well as in other parts of the world. The existing wind parks are in sizes up to about 200 MW, covering areas up to 20 – 30 km^2. The sizes of the erected wind turbine generators, WTG are about 1-2 MW and the distances between the towers are from 600-700 m almost up to 1000 m. The collection grid of an off-shore wind park interconnects all the WTG, into switchgear and step-up transformers on a platform if long distances from shore or, at short distances, in a land-based switchyard. The off-shore platform is then connected to the main grid on shore by sub-sea transmission cables. As the wind parks cover large areas, it requires a quite lot of sub-sea cable to interconnect all the WTG in a wind park. The total sub-sea cable length of a collection grid of a size of 150 MW wind park is assumed to be as much as 50 km or maybe more.

This paper discusses system grounding, switching over-voltages, and reliability of supply for a number of alternative configurations of off-shore collection grids.

INTRODUCTION

The choice of configuration and voltage level of the electrical collection grid can be done in several ways, but limitations exist, mainly due to the lack of space off-shore to locate equipment on. The limited space on fundaments/platforms at sea level and also the limited space in the nacelles set a limit for the number of transformers to be used in the collection grid. The nacelle is mounted at the top of the tower and houses the gearbox, generator, transformer, etc. Another issue is the WTG transformer in the nacelle, which is of a dry, solidly insulation transformer type. These exist today only for voltages up to 36 kV and limit the maximum system voltage of the collection grid, [1].

Further, the collection grid is also a separate subsystem thus a grounding system has to be determined. For the topology alternatives which exist at the planning stage, it is also important that switching over-voltages are considered, especially due to the large cable system involved, and that appropriate over-voltage protection is included.

The investment costs for the electrical system, collection grid, platform, platform switchgear and sub-transmission is in the range of 10-15 % of the total investment costs of the off-shore wind park. Horns Reef Off-shore Wind Park in Denmark presents an investment cost of about 15 % for the electrical system, [2]. The most cost driven electrical equipment is the platform with switchgear (including erection costs) and the sub-sea cables (including cable laying costs). Therefore, it is important to choose solutions which decrease the life-cycle costs. In these circumstances, there is a most optimal collection grid solution, which can be found by evaluating the costs of the different topology alternatives of the collection grid, [3].

FUTURE LAYOUTS OF OFF-SHORE WIND PARKS

In the future it is expected that the off-shore wind parks are larger, both in total installed power, up to 1000 MW or more, and in covered area. Larger WTG's, perhaps up to as much as 6 MW, are expected. As the WTG grow in size, it is also expected that the distance between the WTG is longer, maybe 1000 – 1500 m. In those wind parks where the topography of the sea floor allows, it can also be expected that the distances of the layouts are increased, in order to avoid shadow effects. Due to these circumstances, the distance between the peripheral WTG at opposite ends of the wind park will probably be longer; 5-10 km exists today and 20-30 km is not impossible in future for the same size of wind park. Even longer distances can be realistic for larger wind parks.

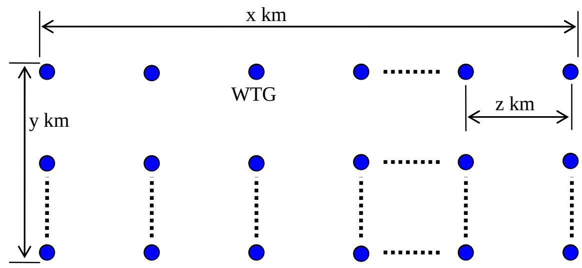

Figure 1: Hypothetic trend of an off-shore wind park layout – increased distances

One hypothetic layout is presented in figure 1. The real future layouts will, of course, be affected by many other things such as topography of the sea floor, possibility to capture wind energy, shadow effects, etc. However increased future wind park sizes, WTG size and risk of turbine shadow effects will surely increase layout distances.

TOPOLOGIES OF COLLECTION GRIDS

The circumstances, given in the previous section, have influence on the electrical system. For the feeder cables in the collection grid, which connect a number of WTG to the centrally located platform, the longest feeders will be long,

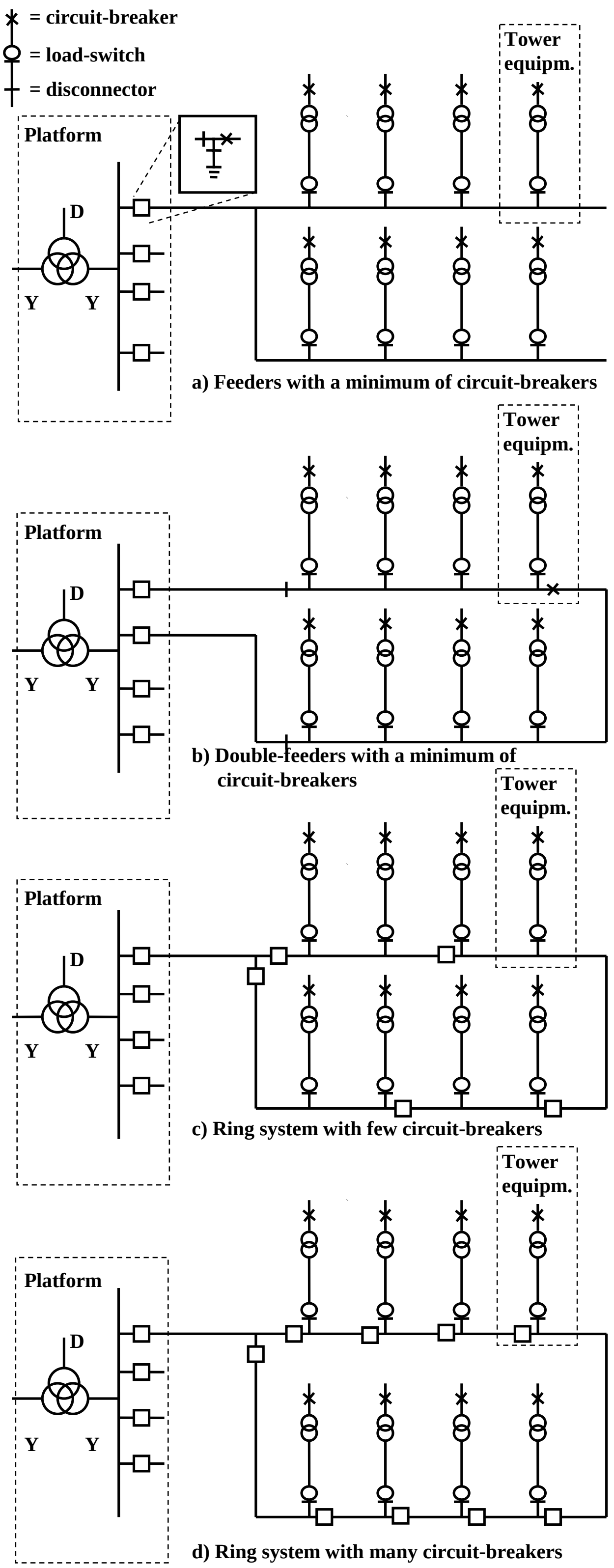

Figure 2: Topologies considered in this report

especially for the peripheral WTG subsystem. On the other hand in case of a land-based station on-shore, all feeders will be quite long. It is also assumed that more sub-sea cables are required to interconnect all the WTG. Further, it is assumed that the WTG are interconnected into a number of subsystems, where each subsystem is connected to the platform (or station on-shore) in one, or perhaps two, feeder cables.

Four topologies are considered in this report and one subsection of each topology is shown in figure 2. Each subsection is assumed having 32 MW installed, consisting of 8 WTG's of 4 MW size. The first topology is a radial system with few circuit breakers considered, shown in figure 2a. This system has a protection system in the platform switchgear and communications to the WTG control systems, which is essential at feeder disconnections and trips. In each tower bottom there is a load-switch for manual operation. A similar system with a second feeder cable is considered in figure 2b, [6]. In figure 2c, a ring system with a couple of sectionalizing switches is considered. This system has a distributed control system, which can detect and locate faults within sub-sections and communication links between control units for selective disconnections. The last topology, in figure 2d, is also a ring system, where more circuit breakers are used including control systems and communication links.

These four topologies have (same for all of them) a two- or a three-winding step-up transformer in order to arrange adequate grounding system for both the collection grid and the grid of the sub-transmission. In figure 2, three-winding step-up transformers are shown. Further, the step-up transformer is equipped with tap regulation in order to control the collection grid voltage mainly at power variations and shift in reactive power of the WTG's. However, the number of steps and the size of the steps are not discussed here.

SYSTEM GROUNDING

The system grounding of a subsystem can be made in different ways, and these are well documented in literature, [4].

- Effectively grounded system
- Low-impedance grounded system
- High-impedance grounded system
- Isolated system

The low- and high-impedance grounding methods are made by resistors and/or reactors while the isolated grounding method is either isolated or high-impedance grounded through a voltage transformer/resistor arrangement.

These methods have different properties and give different features to the network, especially at earth-faults. One method is suitable for one type of grid while quite inconvenient for another. Traditionally, the effectively grounded system is used for EHV and UHV systems. The reactor grounded system is used mainly in MV and HV over-head line systems as tuned arcing coils. The resistor grounded systems are MV and HV cable systems and generator neutral grounding systems. The isolated alternative is used for smaller LV and MV networks with or without neutral voltage transformers.

However, the system grounding method chosen for a subsystem is the result of considerations at the first planning stage. For a large existing subsystem, it is quite expensive to change grounding method. Therefore, it is also important to choose a system grounding which is satisfactory to those issues which are valuable during the whole life-cycle of the system. These issues are fault-current levels, detections, localizations, arcing grounds, double earth-faults, over-voltages in healthy phases, etc.

For off-shore collection grids of different topologies, with many kilometers of sub-sea cables, all the features above are important. For topologies with more sectionalizing circuit breakers, such as in figure 2c and 2d, which offer an improved redundancy, localization might be even more important.

Therefore, a low-impedance grounded system by a resistor is an attractive solution. It offers a low earth-fault current (100-200 A), localization and detection possibilities and low probability of occurrence of arcing grounds and double earth-faults, [5].

The resistive grounded system can be arranged in separate grounding transformers or in the YNynd coupled three-winding step-up transformer in the platform (or land-based) switchgear as is shown in figure 2. In case of a three-winding step-up transformer, the extra delta-connected winding is mainly used to have a path for the zero-sequence current in the transformer coming from the HV side or from the MV collection grid side. At the same time, the extra D-winding can be used for other equipment such as phase compensation equipment at the same voltage as the collection grid. The off-shore collection grid can be grounded by a resistor in the Y-connected winding without affecting the HV sub-transmission grounding system, which can be grounded according to the main grid system grounding, probably effectively grounded.

SWITCHING OVERVOLTAGES

Large cable systems, such as off-shore collection grids, are capacitive in nature. In such systems, it is important to have appropriate breaker equipment in order to connect, disconnect or trip the cable system properly. If not, charging/discharging currents can cause resonance and reflection phenomena to appear in a severe manner. These switching over-voltages occur at a level, which stresses the collection grid equipment and can make the circuit breakers to pre- or re-strike. If a disconnecting circuit breaker starts to re-strike, additional energy from the active grid will be injected into the collection grid system and resonance will be maintained or worsened. Transformers may be saturated by switching over long cables.

Considering all the topologies presented in figure 2, switching over-voltages or repetitive re-strikes in vacuum circuit breakers can be a problem for all of them, as long feeder cables in combination with short cables and transformers are involved. These phenomena are known from literature, [7], to occur in combination with vacuum circuit breaker operation. These phenomena are related with system parameters found in industrial plants as well as in off-shore collection grids, due to the extensive use of cables, regardless of the type of vacuum circuit breaker. Such phenomena involve insulation stress in excess of standard testing, unless considered [8].

An over-voltage study shows that one severe situation can occur if the WTG circuit breakers do not receive any trip signal from protection in the platform switchgear. In that case, the doubly-fed induction generator, DFIG, or basically the frequency converter in the DFIG acts as a source and will through the rotor and then the stator circuits inject energy to the isolated collection grid. Consequently large over-voltages will occur due to resonance between feeder cable capacitance and the nacelle transformer saturation differential inductances. It is important that this situation is avoided and adequate protection exist, as voltage stress will affect all the MV collection grid components, as well as the DFIG. The DFIG will accelerate, perhaps to an over-speed when the main grid is lost, if no external stop signal is received, [9].

In figure 3, a simulation of an earth-fault followed by circuit breaker trips for the ring system of topology 2c is presented. The simulation is made in PSCAD/EMTDC and the three phase voltages in the feeder cable are shown in figure 3. An earth-fault in the feeder cable occur at 20 ms, the feeder circuit breaker trips at 40 ms, the DFIG circuit breakers trip at 60 ms while the ring sectionalizing switches trips at 80 ms. The DFIG units are modeled by wound rotor induction generators, and the frequency converters are modeled by resistors and current sources, [1]. The system is low-resistively grounded and is modeled without surge arresters and RC-circuits. The over-voltages are considerable without over-voltage protection, as resonance between cable capacitances and transformer saturation differential inductances occur and become worsened after trip of all sources.

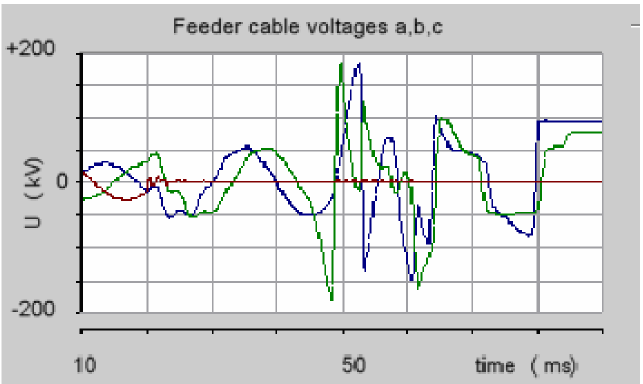

Figure 3: Three phase feeder cable voltages in kV at trip after earth-fault in the feeder cable of the ring system of topology 2c and without over-voltage protection

For the topologies in figure 2a and 2b, the long feeder cables would be de-energized together with all the nacelle transformers in the feeders, as all these components create one protective zone. Control system communication links between the platform switchgear and the WTG, to be used especially at feeder trips. These two topologies are required to have surge arresters in Y-connections at the platform end of the feeder cables and at least surge arresters in a Neptune design close to each nacelle transformer, [10]. Neptune design is 4 identical surge arresters connected into a common point while the opposite ends are connected to phases and earth.

The topologies in figure 2c and 2d have circuit breakers which separate the long feeder cable with the ring system cables and the nacelle transformers. This will avoid resonance phenomenon between the feeder cable and the nacelle transformers, if the circuit breakers will act simultaneously. On the other hand, disconnection of a cable section can cause re-strikes in vacuum circuit breakers due to reflections, if inadequate over-voltage protection is inserted. This is important to study from case to case, so that appropriate over-voltage protection in the form of surge arrester arrangement and/or RC-circuits is inserted. These two topologies would use surge arresters in Y-connections in both ends of the feeder cable, and RC-circuits are used close to the nacelle transformers, [10]. The topologies require a more distributed control system in order to trip correctly and also to locate the place of the fault.

RELIABILITY ANALYSIS

The reliability of the topologies is studied using the analytic tool SubRel^{TM}, developed by ABB Inc., USA, [11] and [12]. The topologies, shown in figures 2a to 2d, including equipment failure rates are set up. The used failure rates are presented in table 1, where also the equipment is divided into the categories ‘apparatus’ or ‘cable’. The outage duration, OD, of each configuration is computed.

Equipment	Failure rate	Device
Breaker	0.05 [1/year]	Apparatus
Earth-switch	0.015 [1/year]	Apparatus
Disconnector	0.025 [1/year]	Apparatus
Load-switch	0.025 [1/year]	Apparatus
Nacelle transformer	0.015 [1/year]	Apparatus
5 km feeder cable	0.015 [1/year, km]	Cable
1.2 km tow-tow cable	0.015 {1/year, km]	Cable
80 m tower cable	0.015 [1/year, km]	Cable

Table 1: Failure rates and MTTR device

Experiences from off-shore wind parks show that the time to repair is long. During the winter seasons, it may be necessary to wait until spring before the service crew can enter the towers and start the work of localization and repair. Therefore, in this study, the variation in mean-time to repair, MTTR is quite large, from 240 h (10 days) up to 2180 h (3 months). In figure 4, the OD results are shown when the MTTR for ‘cable’ is varied while MTTR for ‘apparatus’ is constant at 240 hours. In figure 5, the MTTR for ‘apparatus’ is varied while the MTTR for ‘cable’ is constant at 2160 hours. It is shown that the OD is reduced, especially for topology 2d but also for topology 2b and 2c.

The expected OD reductions, for configurations 2b to 2d, compared to configuration 2a, are presented in table 2, where the MTTR is 240 h for ‘apparatus’ and 2180 h for ‘cable’.

These hours of expected OD reductions can also be expressed in GWh energy savings. Assume a typical annually attained power of 3000 h for a 160 MW off-shore wind park. For the studied 32 MW subsection, the expected output is assumed to be 96 GWh per year. The expected GWh savings for the total wind park of 5 subsections is shown in table 3.

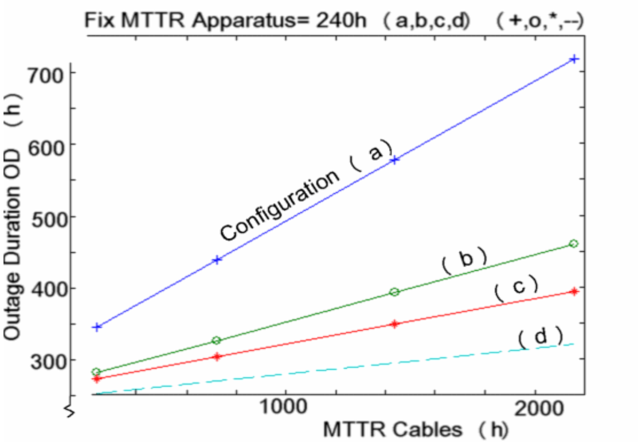

Figure 4: Outage duration – apparatus MTTR of 4 topologies when ‘apparatus’ MTTR is 240 hours

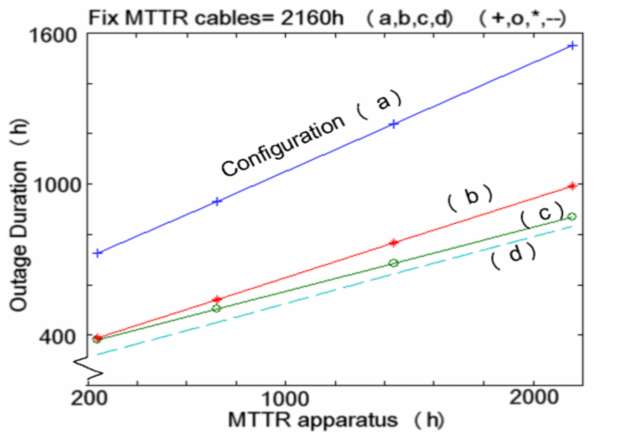

Figure 5: Outage duration – cable MTTR of 4 topologies when ‘cable’ MTTR is 2180 hours

Top.	OD reduction over topology 2a
2b	302 [hour/year]
2c	318 [hour/year]
2d	390 [hour/year]

Table 2: Expected outage duration reductions at MTTR of 240 h for ‘apparatus’ and 2180 h for ‘cable’

Top.	Increased annual operation over topology 2a	Increased annual energy production over topology 2a
2b	3.5 [%]	16.6 [GWh]
2c	3.6 [%]	17.4 [GWh]
2d	4.5 [%]	21.4 [GWh]

Table 3: Expected improvement in annual energy production

Top.	Saved installed power over topology 2a	Saved no of WTG's over topology 2a
2b	5.5 [MW]	1-2 [pcs]
2c	5.8 [MW]	1-2 [pcs]
2d	7.1 [MW]	~2 [pcs]

Table 4: Expected improvement in installed power

The OD reductions, as shown in table 3, can also be expressed in terms of installed power or in number of WTG's in the total wind park, see table 4. These results indicate that instead of erection of 40 WTG's in the studied wind park designed as configuration 2a, 39 or 38 WTG's are required for configurations 2b to 2d, for the same expected production.

CONCLUSIONS

This paper has discussed system grounding, switching over-voltages and reliability of supply for collection grids of off-shore wind parks. Four different topologies have been used in this discussion. One topology is radial, having only feeder circuit breakers while the other three topologies include more redundancy in form of more cables or with more circuit breakers and disconnectors.

The collection grids are large cable systems, connecting and disconnecting long cables, short cables and transformers. Therefore, studies of resonance and reflection phenomena must be solved on a case to case basis in order to; provide appropriate voltage protection, prevent from vacuum circuit breaker re-strikes, etc.

It is preferable to use a low-resistive grounded system in these collection grids. It offers a low earth-fault current, localization and detection possibilities and low probability of occurrence of arcing grounds and double earth-faults.

Based on the reliability analysis, the more advanced topologies provide higher reliability and thereby a larger expected production over a typical year. Higher reliability of supply comes at the expense of more circuit breakers and more complicated control and protection arrangements, and thereby a few WTG can be saved.

For off-shore collection grids, it is recommended that system studies of presented issues, as well as other topics, should be performed in the process of evaluating the most attractive solution.

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