Reliability Study

Analysis of Electrical Systems within Offshore Wind Parks

Elforsk report 07:65

Bengt Frankén STRI AB

November 2007

Energimyndigheten Vindforsk ELFORSK

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Preword

The purpose of the project was to provide information on estimations of redundancy and possibly increase the output from the wind farm.

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Electricity and Power Production

Summary

In this report a reliability optimization method is presented that may be used for investment decisions concerning sub-sea cable systems of offshore wind parks. The method is based on reliability computations in different designs of the collection grid for the wind park. The method is using reliability data of involved components such as failure rates, repair times and switching times.

The method consists of three distinctive stages:

- In the first stage, the expected annual energy not supplied is derived for the basic configuration. In principle, the basic configuration can be any configuration, but a configuration without any redundancy could be an appropriate choice. The expected annual energy not supplied is calculated.
- In the second stage, redundancy is built into the collection grid. The choice of redundancy is based on the contribution of each component to the expected annual energy not supplied. The difference between the energy not supplied in the basic and in the new configuration is the additional energy that can be supplied.
- The third stage is an economical evaluation where the additional energy that can be supplied is converted to additional income per year or over a whole life-cycle. At this stage the method is using assumptions regarding the energy price and the number of years in a life-cycle.

The method can be used for comparison of different configurations or for comparison of additional income versus additional investment in redundancy. The method can also be used to estimate the expected annual energy production of an existing wind park or an existing design.

The method is applied for case studies of three different sizes of offshore wind parks: small; medium-size; and large. A typical topology without redundancy for each size is used as basic configuration. The experiences from the case studies can be summarized in the following conclusions:

- The main contribution to the expected annual energy not supplied is due to the long repair time of components at an offshore location.
- Redundancy is introduced in the form of spare capacity in sub-sea cables and additional cables and transformers.
- Two levels of redundancy should be distinguished based on the type of switchgear used. Remote-controlled load-switches in combination with remote indication of faulted segment will result in a restoration time between several minutes and one hour. Circuit-breakers with appropriate protection equipment will reduce the number of interruptions.

- The additional gain of installing circuit-breakers is limited whereas the costs are typically very high. The costs may include the costs of switchgear able to withstand the higher fault currents.
- The gain of installing remote-controlled load-switches is significant as it reduces the duration of a production stoppage from several weeks or months to one hour or less.
- There is an optimal number of load-switches, above which additional ones only increase costs and complexity without significant further gains in expected annual energy production.

The method described in this report is a probabilistic method, which is inherently associated with uncertainty. Some care should be taken in comparing rather accurately known investment costs with uncertain gain in annual production. A small difference in total costs between two design alternatives should not be seen as significant and a base for an investment decision. There are, however, no general rules for how to handle this and a further discussion on this is beyond the scope of this report.

A change in input parameters (failure rate, expected repair time, investment costs, value of non-delivered energy) may impact the preferred design under the method described in this report. As several of the input parameters are in itself uncertain, this would introduce an additional uncertainty in the final decision. However, it is generally accepted in power system reliability that the outcome of the comparison is not impacted when the most-likely value is used for all input parameters and when the difference between the design is not too small.

Sammanfattning

Rapporten presenterar en metod för tillförlitlighetsberäkningar som kan användas vid beslut om investeringar i samband med sjökabelsystem för vindkraftsparker till havs. Metoden är baserad på tillförlitlighetsberäkningar med olika utföranden av kabelkonfigurationer av vindkraftsparker. Metoden använder tillförlitlighetsdata på ingående komponenter såsom felfrekvens, reparationstid och omkopplingstid.

Metoden består av tre huvuddelar:

- I första delen beräknas den förväntade årliga icke levererade energin för en baskonfiguration. I princip kan baskonfigurationen vara vilken konfiguration som helst men en konfiguration utan redundans är ett lämpligt val. Den förväntade årliga icke levererade energin beräknas således.
- I del två bygger man in redundans i sjökabelsystemet. Valet av redundans är baserat på de bidrag som varje ingående komponent ger till den förväntade årliga icke levererade energin. Skillnaden mellan den icke levererade energin i baskonfigurationen och i den nya konfigurationen är den extra energin som kan bli levererad.
- Tredje delen är en ekonomisk utvärdering där den extra energin som kan bli levererad omräknas till en extra inkomst per år eller under hela dess livslängd. I detta steg görs antaganden om energipris och livslängd.

Metoden kan användas för att jämföra olika konfigurationer eller för att jämföra extra inkomster mot extra investeringar i form av redundans. Metoden kan också användas till att ge en uppskattning av den förväntade årliga energiproduktionen för en existerande vindkraftspark eller en existerande konfiguration.

Exempel på metoden visas också i några fallstudier med tre olika storlekar på havsbaserade vindkraftsparker: liten; medel-stor; och stor. För varje parkstorlek används en typisk konfiguration utan redundans som baskonfiguration. Erfarenheterna från dessa fallstudier kan summeras enligt följande:

- Det största bidraget till den förväntade årliga icke levererade energin är den långa reparationstiden för komponenter placerade ute till havs.
- Redundans introduceras i systemet genom extra kapacitet i sjökablar och extra kablar och transformatorer.
- Två nivåer av redundans kan urskiljas beroende på vilken typ av ställverk som används. Fjärrmanövrerade lastfrånskiljare i kombination med fjärrindikering av felande kabelsegment resulterar i återuppbyggnadstider på några minuter upp till en timme. Brytare försedda med

lämplig reläskyddsutrustning kommer däremot att reducera antalet avbrott.

- Den extra vinst som kan göras genom att installera brytare är begränsad då kostnaden är relativt hög. Kostnaden för detta kan även inkludera kostnaden för att ställverket ska tåla den högre felströmmen.
- Vinsten av att installera fjärrmanövrerade lastfrånskiljare är betydande då varaktigheten för ett produktionsstopp kan minskas från flera veckor eller flera månader till en timme eller ännu mindre.
- Det finns ett optimalt antal av lastfrånskiljare som bör installeras. För många lastfrånskiljare ökar kostnaden och komplexiteten, men den förväntade årliga energiproduktionen ökar endast marginellt.

Metoden som beskrivs i denna rapport är en sannolikhetsmetod, där osäkerhet är en faktor att beakta. Försiktighet måste därför gälla då man jämför kända investeringskostnader med osäkra resultat vad beträffar förbättring i årlig energiproduktion. En liten skillnad i den totala kostnaden mellan två konfigurationer ska inte vara avgörande i ett investeringsbeslut. Med andra ord, så finns det inga generella regler för hur detta ska hanteras och ytterligare diskussion i ämnet är utanför arbetet i rapporten.

En förändring av en indataparameter (felfrekvens, förväntad reparationstid, investeringskostnad, värde av icke levererad energi) kan påverka den rekommenderade konfigurationen. Då flertalet av indataparametrarna i sig är osäkra, kommer de att i sin tur generera ytterligare osäkerhet för det slutgiltiga beslutet. Generellt sett i samband med tillförlitlighetsberäkningar i kraftsystemssammanhang, så påverkas inte resultatet av jämförelsen när värden med hög sannolikhet används som indataparametrar och när skillnaden mellan konfigurationer inte är alltför liten.

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1 Introduction

The aim of this project is to present a method for reliability optimization of power supply of the electrical system of offshore wind parks, consisting of collection grids and AC sub-transmission grids.

1.1 Background

Access to offshore wind turbines for service, maintenance, fault detections, reparations, etc. in the Nordic region, is strongly weather (and thus season) dependent. Therefore, it will be limited to a couple of months per year, basically the summer months, [1] and [2]. This will cause longer repair times after faults. This condition will also concern the internal collection cable system, the switchgear platform(s) and the sub-transmission cables to the PCC (Point of common coupling) station on shore. A large part of the collection grid consists of sub-sea cables, where it is possible that the failure rate of these cables will be higher compared to cables on land. Movements in the sea floor can cause extra mechanical stress. Anchors from ships or devices from fishing boats can cause damages to the cables as it is experienced that offshore wind parks will attract fishes. However, today there is lack of knowledge regarding failure rates associated to sub-sea cables within wind parks.

Due to the large initial costs for the offshore wind park and also for the electrical equipment of the wind park, redundancy in these existing electrical systems may not exist at all or redundancy exists, but maybe not on the most effective parts of the offshore wind park. The consequence is that the availability of feeder sections, of wind park sections or of total wind parks are low.

1.2 Study outline

The main issue of this study is to present a method for reliability calculations of different wind park configurations and sizes. The output results would be in additional income over the life-cycle time of the wind parks, as the energy not supplied, ENS (one of the measured quantities) is used in the study. A short description of the method is presented in chapter 2.

Three hypothetical wind park configurations are studied. These configurations are:

- Type 1: Small offshore wind park (40 MW) close to the grid on shore (less than 5 km)
- Type 2: Medium-size offshore wind park (160 MW) far away from the grid on shore (5 km to 25 km)

- Type 3: Large offshore wind park (640 MW) far away from the grid on shore (5 km to 25 km)

The reason for this choice is that different wind park sites around the Swedish coast are being built or are discussed for exploitations, and these are all of different sizes and at different distances from the grid. As examples, Lillgrund with 110 MW is a medium-size offshore wind park and Kriegers Flak with about 600 MW is a large wind park, also at large distance from the grid.

The study has the following outline:

1. The basic topologies of the studied offshore wind parks, according to Type 1, Type 2 and Type 3 above, are determined, chapter 3.
2. Data is determined, both electrical parameters and reliability data, chapter 4. The reliability data consists of:
    a. Failure rate, λ for the involved components in the transfer paths, see Appendix A.
    b. Mean Time To Repair, MTTR for involved components. MTTR for the offshore equipment is estimated combined with new information from offshore wind parks, see Appendix B.
    c. Mean Time To Switch, MTTS for involved circuit-breakers, disconnectors and load-switches, see Appendix C.
3. Reliability calculations in Neplan software package, [13], are performed for all topologies, chapter 5. Important result for this study is the energy not supplied, ENS and the average service availability index, ASAI for the alternative configurations of the wind parks. These values are used to measure the improvement in the availability between different topologies. (Remark: the ENS is based on continuous rated power production and the value itself should not be used. This study is using this value for different topologies in order to compare and measure the improvement which each alternative configuration can offer.)
4. An alternative topology with redundant transfer paths compared to the previous topology is determined. This is made in terms of more subsea cables, circuit-breakers, disconnectors, load-switches, transformers, control systems, etc. In some of the alternatives, a redundancy transfer path is switched in after the protection system trips the faulty component. Other alternatives can require manual reconfiguration by load-switches in order to utilize the redundant transfer paths.

    Alternative topologies, which have too complicated redundant transfer paths or would cause a higher short-circuit capacity in the internal grid compared to the basic topologies, are not considered.
5. Stated as examples in chapter 6, one for each type of wind park configuration given above, it is calculated what these alternative topolo-

gies can mean in additional annual supplied energy, and to be compared to additional equipment required for the redundancy of the electrical collection system.

1.3 Assumptions and limitations

1. The study is analysing the reliability of the electrical system containing the collection cable grid, switchgear and transformers on platforms (if any) and the sub-transmission cables to a land station. The study is therefore limited by the different delivery points such as the connection in the tower bottom of the wind turbines in one end and the switchgear in the PCC in the other end (the busbar in the grid station on shore is not included).
2. The wind turbines used in the study are rated 3.33 MW each and connected to a Medium Voltage, MV collection grid of 36 kV. It is assumed that each wind turbine has a load-switch at the delivery point, typically in the tower bottom. The distance between two wind turbines is 1 km.
3. It is assumed that there is additional High Voltage, HV equipment in each substation, other than circuit-breakers and disconnectors, such as earth-disconnectors, surge arresters, instrument transformers, etc. It is found by experiences that the number of failures in this equipment is small compared with the number of failures in cables. Therefore, this equipment is normally neglected in this type of studies, alternatively those failures are considered to be included in the failure rate of the cables. The eventual contribution of station-based equipment is however less than the uncertainty in the failure rate of the undersea cables. It is also in this study assumed that this equipment have a low contribution to the energy not supplied and therefore neglected in this study.
4. The sub-transmission cable from a platform to shore is operated at a transmission voltage of 150 kV.
5. All included cables are assumed to be 3 core cables with sheath and armour.
6. Failure rates for electrical apparatuses (sub-sea cables excluded) are taken from corresponding equipment from land based distribution and industrial systems. (It might be argued that the environmental stress at offshore exploitation will in a longer time perspective increase the failure rates, but no quantitative information on this is available.)
7. A recent study by Strathclyde university, [15] has been used for 1 km sub-sea cable values for time between failure between 90 and 275 year (0.00365 to 0.01095 failure/year and km). According to the authors of that study, these values were based on practical experience with sub-sea cables. For this study a value somewhere within this range has been used: 125 year (0.008 failure/year,km).

8. Repair times can be found from experiences in distribution and industrial system as well. However, for offshore wind parks, it will be assumed that these repair times will be more decisive of the access possibilities of the platform and the wind turbines, transportations at sea, waiting time for appropriate ship to be on duty and time for the actual repair. For the Nordic countries it is assumed that these access possibilities are reduced. In this study, therefore, longer repair times are used.
9. It is assumed that all the switchgear equipment on the platform or cables from the platform to shore can be repaired within 30 days (720 h) anytime of the year. However, for a platform transformer the repair time is assumed to be 6 months (4320 h) as faulty platform transformers may require replacements. Availability of spare transformers, lifting and shipping arrangements are quite uncertain. Therefore, a long repair time is assumed.
10. For equipment placed inside the wind turbine or cables from the wind turbines to shore/platform, the access possibilities are assumed to be worse. It is reported from one offshore wind park in Denmark that the access to the wind turbines from the sea were not possible during 40 % of that perticular year of study (note that the total availability of the wind turbines were not reported). Therefore, a waiting time is derived and added to the repair time. For six months of the year during the spring and summer seasons, it is assumed that the repair time is 30 days without any waiting time, except the last month of the summer season, where repair can not be finalized before the winter season and the waiting time for this month is 6 months. Further, during the autumn and winter (six months) the reparations may be postponed until spring. Therefore these months have waiting times, falling from 5.5 months (average of 6 months in the beginning and 5 months in the end of the month) to 0.5 month. The average waiting time for one year is calculated as:

    $$\text{waiting time per year} = \frac{6 + \sum_{i=1}^{6}(6.5 - i)}{12} = 2\,\text{months} = 60\,\text{days}$$

    The average waiting time of 60 days is added to the repair time of 30 days and the final repair time is 90 days (2160 h) for these type of components.
11. It is assumed that a circuit-breaker is more expensive than a load-switch. As the problem for an offshore wind park is the long reparation time, a short interruption due to switching of load-switches (instead of fast reconfiguration by circuit-breakers) has minor effect on the reliability. Therefore, the collection grid is normally operating in a radial string and faults in the string are isolated by a circuit-breaker on a platform or on land. Remote controlled load-switches with over-current indicators can inform where faults are located. After reconfiguration, the remaining part of the feeder string goes into

operation again. This switching duration time for a load-switch, from fault to operation again, is assumed to be 20 minutes.

12. The analysis presents the expected annual energy not supplied, ENS and the average service availability index, ASAI, and it is the first quantity what is used to compare different alternatives to each other and to identify components which have a high contribution to the expected annual energy not supplied.
13. The life cycle for an offshore wind park is assumed to be 20 years.
14. In the examples, where the expected additional income due to higher availabilities is calculated, the energy price for an Independent Producer, IP is assumed to be 0.03 € per kWh (about 0.3 SEK per kWh).

2 Description of the reliability method

The reliability method used in this study consists of the following parts:

1. Definition of the wind park configuration
2. Calculation of expected annual energy not supplied
3. Calculation of expected annual energy that can be supplied
4. Evaluation of additional income against additional investment

2.1 Definition of the wind park configuration

The studied configurations of the offshore wind parks are set up in Neplan, including sub-sea cables, switchgear, power transformers and wind turbines. Basic topologies for small, medium-size and large wind parks, respectively are set up. Wind turbines are assumed to be operating at rated power level.

2.2 Calculation of expected annual energy not supplied

Reliability data is added to these components in the Neplan set up, which should be included in the reliability evaluation. The reliability data is:

- Failure rate, λ in failure/yr (or failure/yr,km for cables)
- Mean time to repair, MTTR in h
- Mean time to switch, MTTS in min (for circuit-breakers and load-switches)

For a radial distribution system, which is comparable to a collection grid of an offshore wind park, with 'i' number of series components supplying load 's' (or generator 's' is the same), the ENS and the ASAI can be calculated as, [16]:

$$\text{Average failure rate for load, } \lambda_s = \sum_i \lambda_i \text{ in failure/year}$$

$$\text{Average annual outage time for component, } U_i = \lambda_i * r_i \text{ in h/year}$$

$$\text{Average annual outage time for load, } U_s = \sum_i \lambda_i * r_i \text{ in h/year}$$

$$\text{Average outage time for load, } r_s = \frac{U_s}{\lambda_s} = \frac{\sum_i \lambda_i * r_i}{\sum_i \lambda_i} \text{ in h}$$

$$\text{Average load, } L_i \text{ in MW}$$

$$\text{Annual energy not supplied for component, } ENS_i = L_i * U_i \text{ in MWh/year}$$

$$\text{Annual energy not supplied for load, } ENS_s = \sum_i ENS_i \text{ in MWh/year}$$

$$\text{Average service availability index for load, } ASAI_s = \frac{8750 - U_s}{8750} * 100 \text{ in \%}$$

Example:

Consider a radial system of series components interconnecting a generator to a grid, as shown in figure 1. The average generation is assumed to be 5 MW.

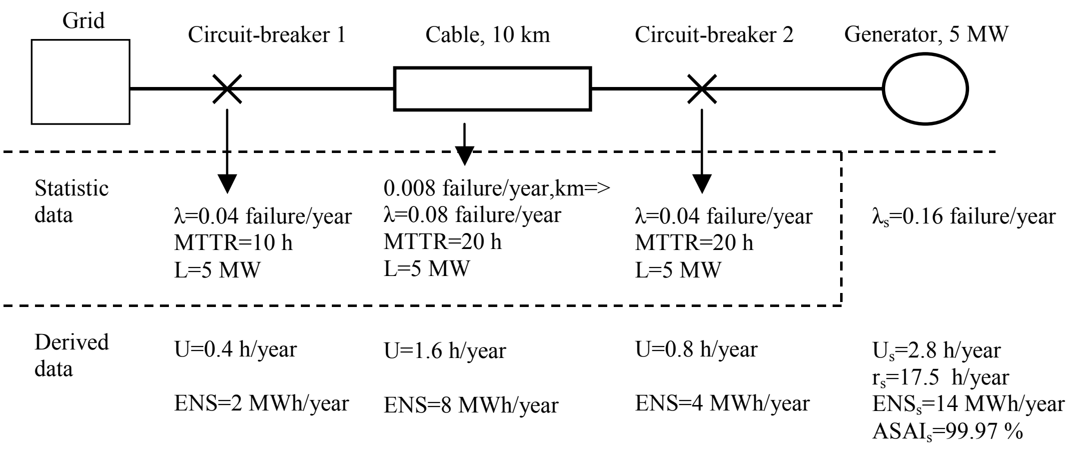

Figure 1: Example – a system of 3 series components

<u>Circuit-breaker 1:</u>

The circuit-breaker is assumed to have 25 years to a failure, e.g. the failure rate, λ is 0.04 failure/year and the MTTR is 10 h.

The following can be derived:

$\text{Failure rate}, \lambda_1 = 0.04 \text{ failure / year}$
$\text{Mean time to repair, } MTTR_1 = 10\,h$
$\text{Average annual outage time}, U_1 = 0.4 \text{ h / year}$
$\text{Average load, } L_1 = 5\text{ MW}$
$ENS_1 = L_1 * U_1 = 2.0\,\text{MWh / year}$

Cable:

The cable is 10 km and have a statistic information of 125 year and km to a failure. The MTTR is 20 h. This means:

$\text{Failure rate}, \lambda_2 = 0.008 \text{ failure / year,km} * 10\,\text{km} * = 0.08 \text{ failure / year}$
$\text{Mean time to repair, } MTTR_2 = 20\,h$
$\text{Average annual outage time}, U_2 = 1.6 \text{ h / year}$
$\text{Average load, } L_2 = 5\text{ MW}$
$ENS_2 = L_2 * U_2 = 8.0\,\text{MWh / year}$

Circuit-breaker 2:

The circuit-breaker have a statistic failure information of 25 year to a failure and the MTTR is 20 h. This means for this component:

$\text{Failure rate}, \lambda_3 = 0.04 \text{ failure / year}$
$\text{Mean time to repair, } MTTR_3 = 20\,h$
$\text{Average annual outage time}, U_3 = 0.8 \text{ h / year}$
$\text{Average load, } L_3 = 5\text{ MW}$
$ENS_3 = L_3 * U_3 = 4.0\,\text{MWh / year}$

Total for the generator:

Together, the three series components create a system where the reliability results for the generator can be derived as:

Average failure rate, $\lambda_s = \sum_{i=1}^{3} \lambda_i = 0.16$ failure / year

Average annual outage time, $U_s = \sum_{i=1}^{3} \lambda_i * r_i = 2.8$ h / year

Average outage time, $r_s = \frac{U_s}{\lambda_s} = \frac{5.2}{0.28} = 17.5$ h

Energy not supplied, $ENS_s = \sum_{i=1}^{3} ENS_i = 14.0$ MWh / year

Average service availability index, $ASAI = \frac{8750 - U_s}{8750} * 100 = 99.97\,\%$

As can be seen from the example above, the highest contribution to the total ENS is the cable. Addition of components especially series components, expected to have outages, will increase the energy not supplied. Addition of parallel components creating a parallel transfer path which can be used separately during failures of the other circuit, are reducing the energy not supplied. At full redundant transfer path, where the parallel circuit is completely taking over the transfer path, the contribution to the energy not supplied is zero or at a small value caused by the switching times of those couplers involved in the reconfiguration of the path. This is not shown in this report.

An example of a Neplan reliablity calculation of the ENS and the ASAI can be seen in appendix E.

2.3 Calculation of expected annual energy that can be supplied

The reliability data is first computed for the basic wind park topologies. The ENS on individual components are derived and new topologies are suggested where improvements are made at transfer paths having high ENS contributions. The procedure is repeated a couple of times until the ENS of the last topology for each wind park size is reasonable lower than the basic topology. The basic topologies and one of the new topologies for each wind park size are chosen for further evaluations. The derived total ENS values for the wind parks are based on average production at rated power of each wind turbine. This is not the case, especially not for wind turbines. Therefore, the average annual production level is estimated in this report, see Appendix F, and is used to estimate realistic ENS values for the chosen wind park topologies. The adjusted total ENS for the new suggested topology is compared to corresponding ENS value for the basic topology, and the difference is the ”energy that can be supplied” for each wind park size.

2.4 Evaluation of additional income against additional investment

The "energy that can be supplied" values are converted to additional income for a small, medium-size and large wind park. This is based on estimated energy price and expected life-cycle of the wind turbines. The additional income is then compared to the additional equipment required for each wind park size to fulfil the new wind park configurations.

2.5 Summary of uncertainties

The reliability method used here is going through a couple of steps as described above. In the method, there is assumptions made which create uncertainties, and these can be summarized as follows:

- Uncertainty in used failure rates.
- Uncertainty in used MTTR.
- Uncertainty in derived ENS after assumed average production level of the wind turbines.
- Uncertainty in used energy price.
- Uncertainty in used life-cycle time.
- Uncertainty in derived additional income during a life-cycle.
- Uncertainty in estimated additional cost in redundancies.

However, with these uncertainties in mind, the method is a strong feature to find components with high contribution to the total ENS and to compare different topologies. It can also give a first indication if additional investment in redundancy is profitable or not.

3 Basic configurations of offshore wind parks

Three types of wind park are studied. These are:

1. Type 1: Small offshore wind park (40 MW) close to the onshore grid (less than 5 km)
2. Type 2: Medium large offshore wind park (160 MW) far from the on-shore grid (5 km to 25 km)
3. Type 3: Large offshore wind park (640 MW) far from the onshore grid (5 km to 25 km)

3.1 Type 1: Small offshore wind parks

Type 1 can be characterized as being small (in number of wind turbines and in installed MW) and has short distance (4 km) to PCC. The wind turbines are connected to PCC with one feeder cable.

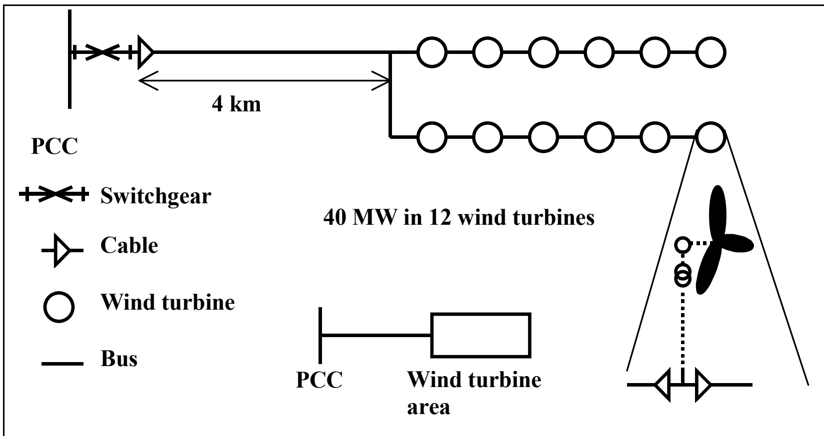

Figure 2: Basic configuration of a small wind park (type 1)

3.2 Type 2: Medium-size offshore wind parks

Type 2 can be characterized as being medium-size and has long distance (20 km) to PCC. The wind turbines are connected in a feeder fork to a platform and one sub-transmission cable to PCC. The average feeder cable length is assumed to be 2 km.

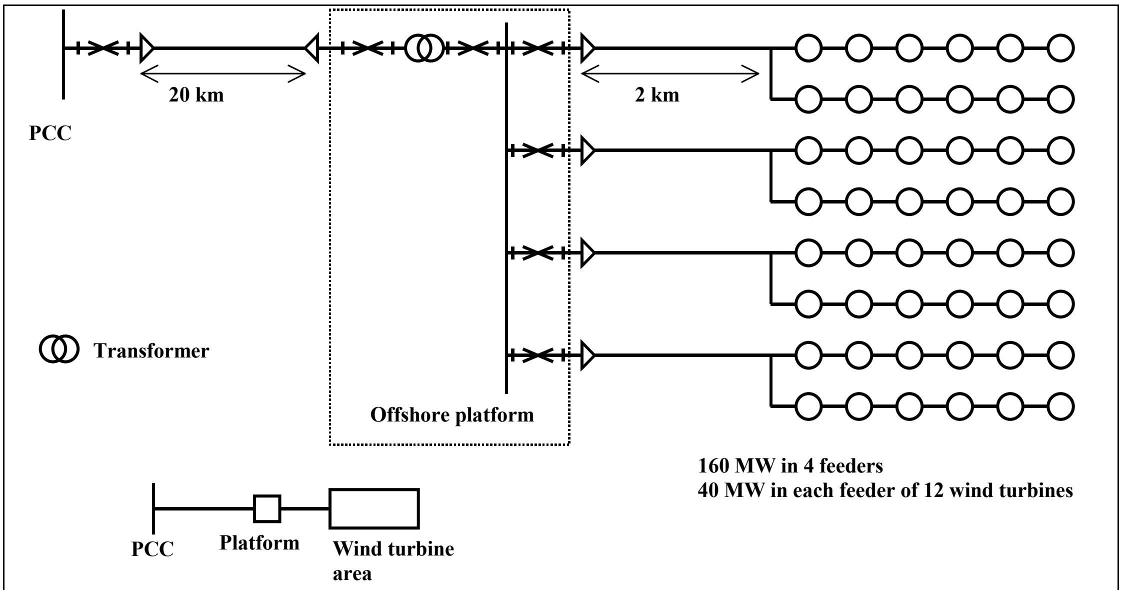

Figure 3: Basic configuration of a medium-size wind park (type 2)

3.3 Type 3: Large offshore wind parks

Type 3 can be characterized as being large and has long distances, to PCC (20 km) and between far end wind turbines. The wind park consists of four park sections, each identical to a medium-size wind park as type 2.0.

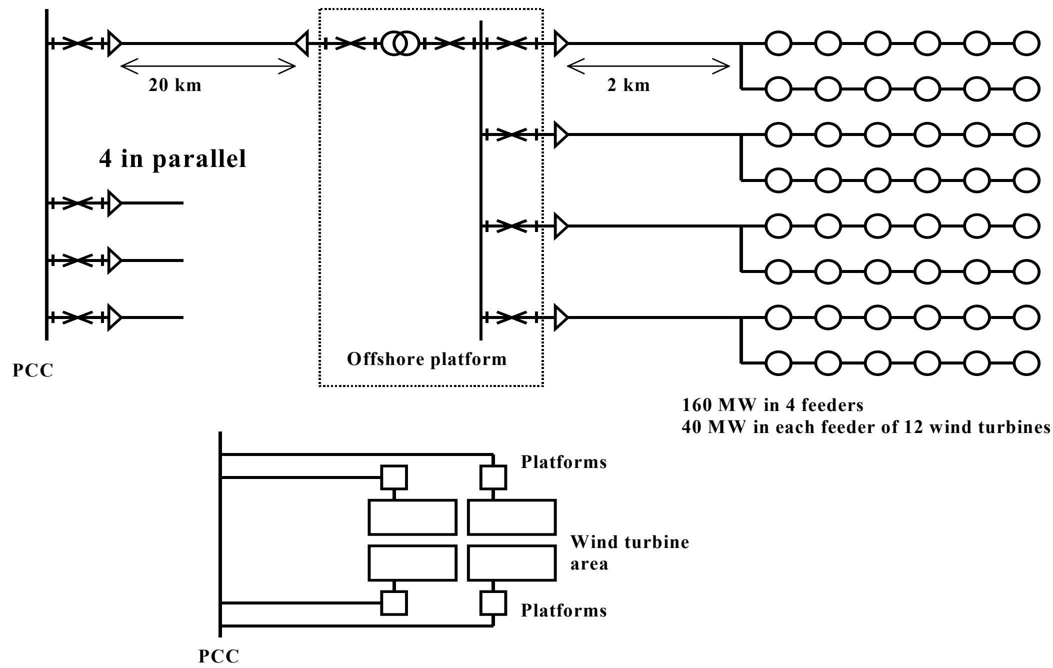

Figure 4: Basic configuration of a large wind park (type 3)

4 Data requirements

Data, which is required, is electrical data for cables and transformers, failure rates (λ) and repair times (MTTR) for cables, transformers, circuit-breakers, load-switches and busbars in offshore environment and switching times (MTTS) for circuit-breakers and load-switches.

Electrical parameters:

Transformer:

For the platform transformers the following data is used:

- Rated power is 160 MVA
- u_k is 12 %

Cables:

For the sub-sea cables, which are defined from cable area and voltage level, the following data is used:

Copper core cables with a current density of 1.25 A/mm^2 are used in the core area determination.

36 kV wind turbine interconnecting cables and feeder cables:

- Cable for 20 MW Nominal current 320 A => 250 mm^2; 300 mm^2 is used
- Cable for 40 MW Nominal current 640 A => 500 mm^2; 600 mm^2 is used
- Cable for 80 MW Nominal current 1280 A => 1000 mm^2; 1200 mm^2 is used

150 kV sub-transmission cables:

- Cable for 160 MW Nominal current 580 A => 460 mm^2; 600 mm^2 is used

From the Cu core area, the series resistance per km is derived. For the series reactance per km and the shunt capacitance per km, these are set to 0.110 ohm per km and 0.200 μF per km, respectively, for all used cables.

For the current limits of the cables, the final area, the current density, the rating factor of 1.05 due to sea water temperature and the rating factor 0.9 due to the screen and the armour, have been used.

The chosen electrical data in this study is shown in appendix D.

Statistical or assumed interruption data:

The failure rate, the repair time and the switching time data used in the study is shown in appendices A, B and C.

- In the land station, repair times for distribution and industrial systems are used.
- For sub-sea cables from shore to a platform and equipment on the platform (excluding platform transformers), the repair times of 720 hours (30 days) are used.
- For platform transformers, the repair times of 4320 hours (180 days) are used. This repair time include delay time for replacement which requires lifting and shipping arrangements and availability of spare units.
- For sub-sea cables from the platform to the wind turbines, interconnecting wind turbine cables and equipment placed in the tower bottom of the wind turbines, the repair times of 2160 hours (90 days) are used. This repair time includes a waiting time of 1440 hours (60 days) due to delays cause during the winter seasons.

5 Reliability calculations of electrical interconnecting systems

The power flow and the reliability calculation modules of Neplan are used in the aim of deriving the improved hourly operations per year for each basic and redundant alternative configuration.

The reliability calculation is performed with the following general settings:

System state analysis:	Capacity flow (current limit check)
Failure model:	Single independent failure
Loading limit:	Long-term 100 %
Duration to remote switching:	20 minutes

This set up means that the probability of interruptions of the network is examined for single outages and power supply is not allowed at over-loaded conditions of redundant components. The duration to remote switching is used for those load-switches used in the cable system, which means that reconfiguration by load-switches can not be made immediately. The duration of remote switching is the same as Mean Time To Switching, MTTS.

Results from Neplan Reliability are given for the total system and for each component in the studied network. The results can be used to identify components which have high contribution to the derived unavailability.

In the following analysis, the small wind park including some alternatives is examined first. This type 1 alternative, which results in less expected annual energy not supplied, is reused in the medium-size wind parks. Further, the type 2 alternative of less expected annual energy not supplied, is reused in the large wind park part.

The analysis is made at full MW production and the average values of the interruption data according to appendices A, B and C are used. The presented expected annual energy not supplied should only be used in order to compare different alternatives and also to identify components which have high contribution to the expected annual energy not supplied.

5.1 Small offshore wind parks

Basic topology 1A, with one cable feeder and all wind turbines are connected in one line (can also be connected in several lines, in a star, etc.), is shown in figure 5.

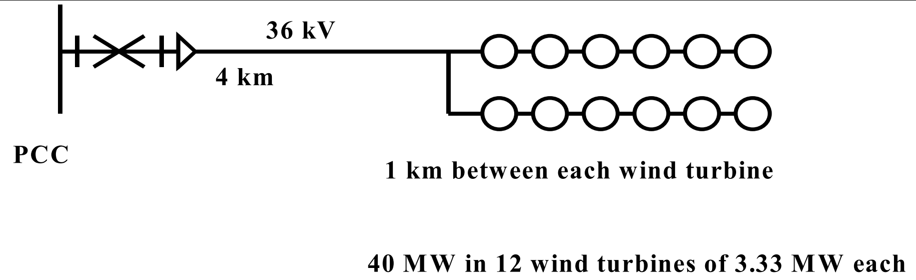

Figure 5: 1A - Basic topology of type 1 – total cable lengths is 15 km

All 12 wind turbines are connected together without load-switches and the feeder cable can transfer 40 MW. The study shows that the expected annual energy not supplied is **<u>10.362 GWh</u>** (annual energy supplied at rated generation is 350 GWh). The contribution is of course from the cables. As the feeder cable is much longer than each of the interconnecting cables, high contribution comes from the feeder cable.

Let us insert an additional feeder cable (1B), shown in figure 6.

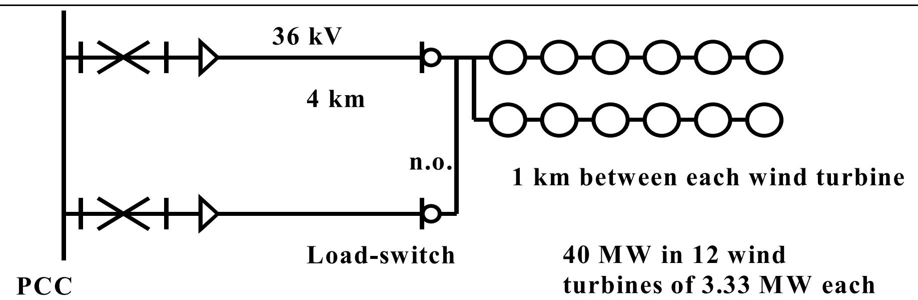

Figure 6: 1B - Alternative topology of type 1 – total cable lengths is 19 km (plus 4 km)

Alternative topology 1B, where an additional feeder is used. The redundancy consist of an additional feeder cable, an additional circuit-breaker in the PCC, two wind turbine-placed load-switches and remote-control system. The expected annual energy not supplied is **<u>9.324 GWh</u>** (350 GWh). The main contribution is from all the interconnecting wind turbine cables.

Next step is to reconfigure the collection grid into a interconnecting cable loop (1C), as is shown in figure 7.

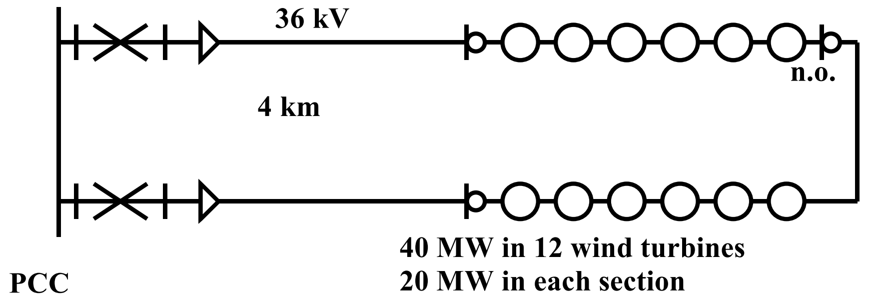

Figure 7: 1C - Alternative topology of type 1 – total cable lengths is 15 km

Alternative topology 1C, with load-switches installed in some wind turbines. The redundancy consist of an additional feeder cable, an additional switchgear in the PCC, five wind turbine-placed load-switches and control system. The expected annual energy not supplied is **5.526 GWh** (350 GWh). The contribution from the interconnecting cables is still high.

Next step is to introduce more load-switches (1D), as is shown in figure 8.

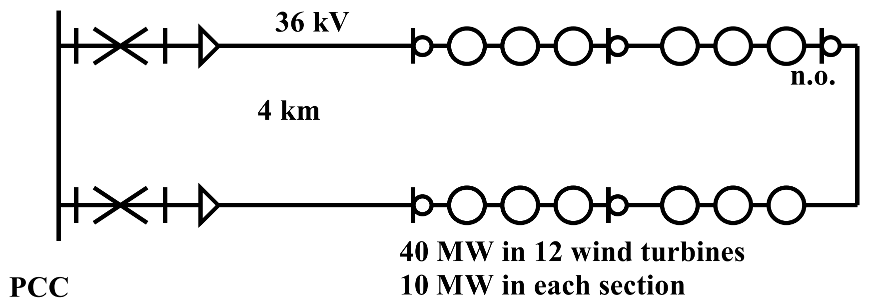

Figure 8: 1D - Alternative topology of type 1 – total cable lengths is 19 km (plus 4 km)

Alternative topology 1D, with double feeder cables, a normally opened cable loop and load-switches. The redundancy consist of an additional feeder cable, an additional switchgear in the PCC, three wind turbine-placed load-switches and control system. The system is radial and both feeder cables can transfer 40 MW each. The study shows an expected annual energy not supplied of **4.491 GWh** (350 GWh).

Let us insert more load-switches (1E), as is shown in figure 9.

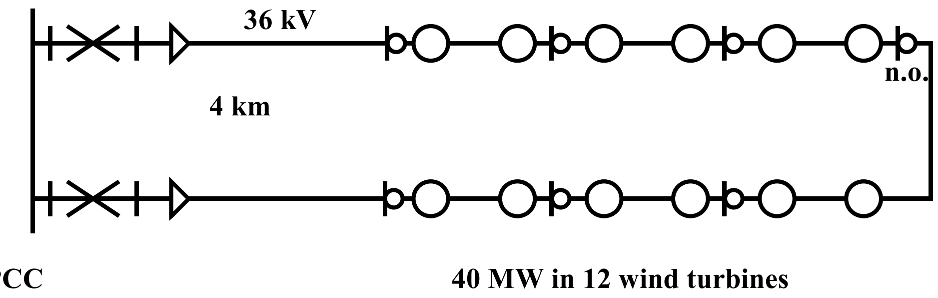

Figure 9: 1E - Alternative topology of type 1 – total cable lengths is 19 km (plus 4 km)

Alternative topology 1E is topology 1D with more load-switches. The redundancy consist of an additional feeder cable capable of 40 MW, an additional switchgear in the PCC, seven wind turbine-placed load-switches and control system. The system is radial and both feeder cables can transfer 40 MW each. The expected annual energy not supplied for this system is **4.146 GWh** (350 GWh).

The results from the Neplan reliability calculations are shown in table 1.

Config. Type 1	Energy at rated power generation [GWh/year]	Expected energy not supplied [GWh/year]	Average service availability index, ASAI [%]	Energy not supplied compared to topology 1A [%]	Component with highest contribution
1A	350	10.36	97.04	100	Feeder and internal cables
1B	350	9.32	97.34	90.0	Load-switch, internal cables
1C	350	5.53	98.42	53.4	Load-switches, internal cables
1D	350	4.49	98.72	43.3	Load-switches, internal cables
1E	350	4.15	98.82	40.1	Load-switches, internal cables

Table 1: Result from reliability study of topology type 1

Topology 1E is reused as one of the alternative topologies in the study of topology type 2. Topology 1E is also used in the economical evaluation in a later section.

Remarks:

If the wind park is connected to a strong grid, the short-circuit capacity can be high within the wind park. Adding parallel paths may increase the short-circuit current above the rating of the switchgear. To prevent this, the redundant components are operated normally-open on one side. This will prevent them to contribute to the fault current, whereas faults in these redundant components will still be detected.

5.2 Medium-size offshore wind parks

Basic topology 2A, with 4 cable feeders and wind turbines interconnections in "forks". One sub-transmission cable, see figure 10.

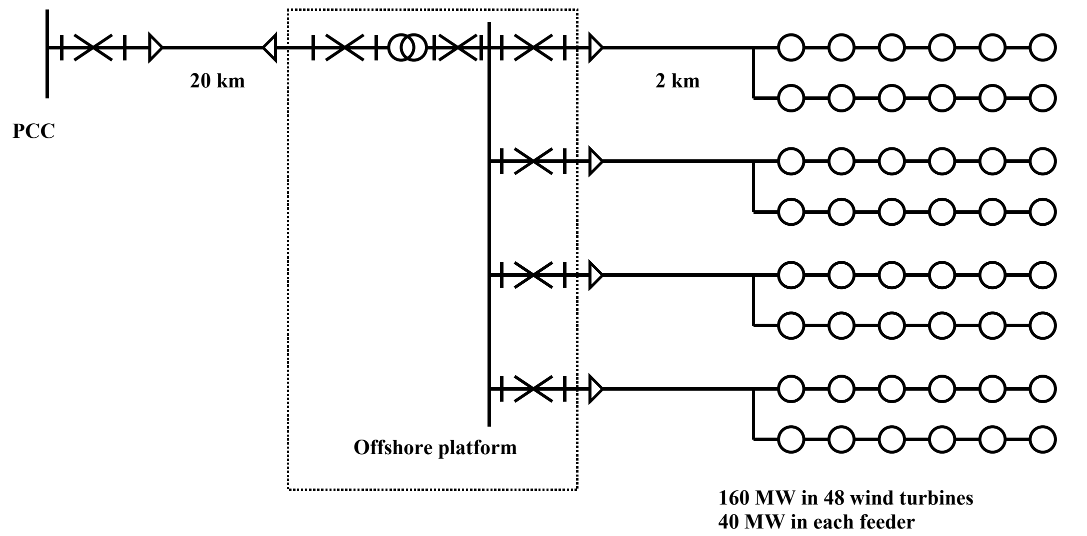

Figure 10: 2A - Basic topology of type 2

Each feeder is capable to transfer 40 MW and the sub-transmission cable can transfer 160 MW. The study shows that the expected annual energy not supplied is **82.540 GWh** (annual energy supplied at rated generation is 1400 GWh). The main contribution is from the 150 kV sub-transmission cable.

Next step is to insert a redundant 150 kV sub-transmission cable (2B), as is shown in figure 11.

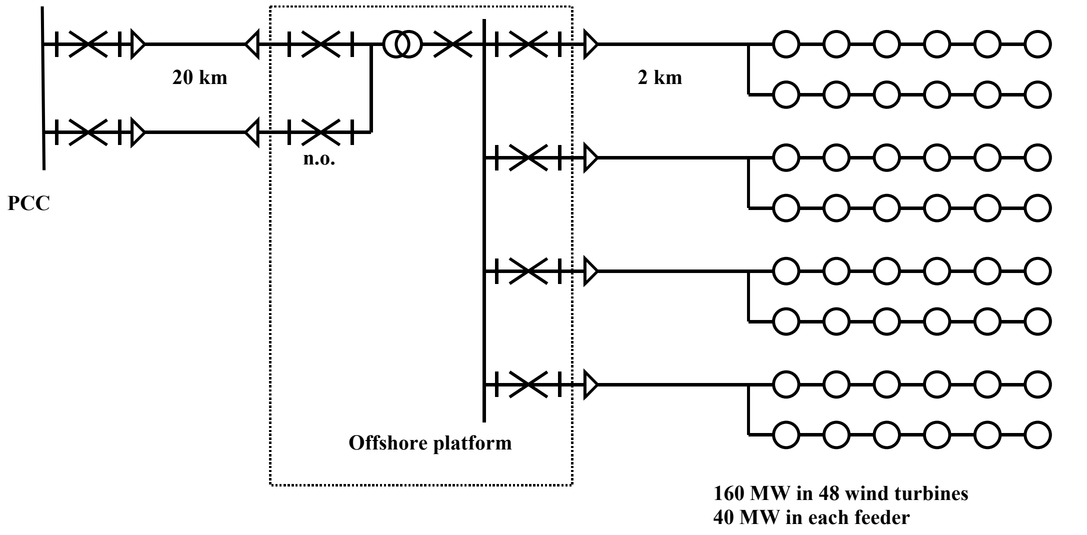

Figure 11: 2B – Alternative topology of type 2

Alternative topology 2B, with 2 sub-transmission cable. The redundancy consists of an additional 150 kV sub-transmission cable capable to transfer 160 MW, a 150 kV switchgear in PCC, a 150 kV switchgear on the platform and control system. The study shows that the expected annual energy not supplied is **60.442 GWh** (1400 GWh). The biggest contribution from a single component is from the 150 kV platform transformer, which has a contribution of 13.8 GWh/year. However the total contribution from all 36 kV feeder sections is much more.

Let us also insert the interconnecting cable system of type 1E, resulting in 2C, as is shown in figure 12.

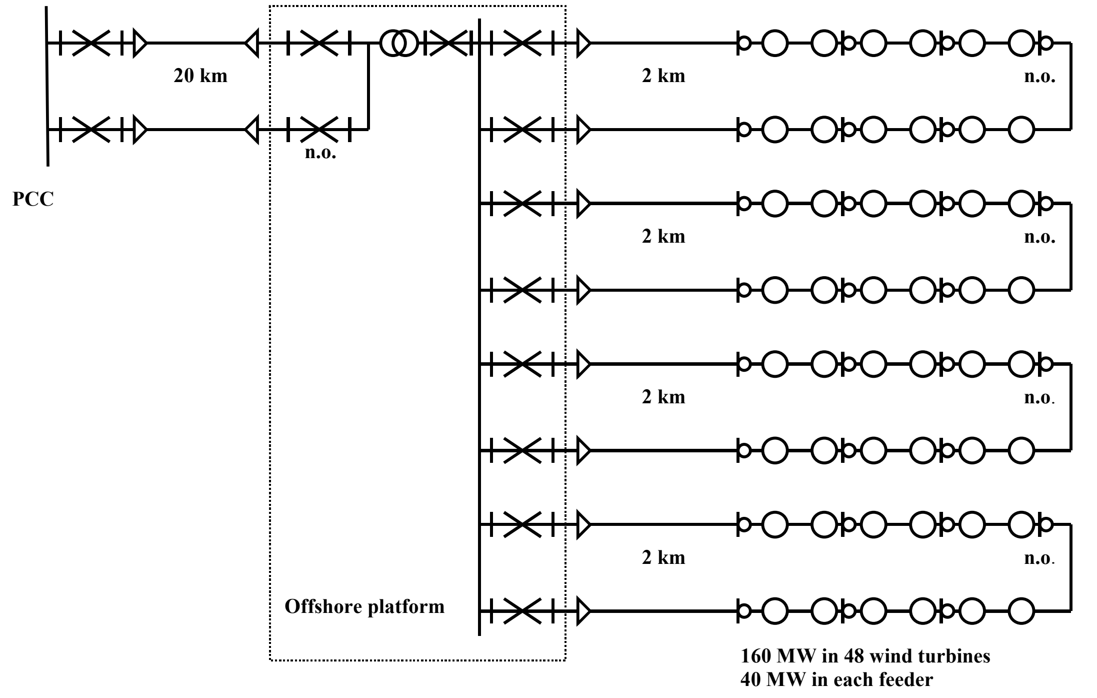

Figure 12: 2C – Alternative topology of type 2

Alternative topology 2C, with 2 sub-transmission cables and four feeder systems as topology type 1E. Per feeder section this includes one additional feeder cable which can transfer 40 MW, one additional platform feeder bay and seven wind turbine placed load-switches. The additional sub-transmission cable can transfer 160 MW. The study shows that the expected annual energy not supplied is **39.204 GWh** (1400 GWh). The main contribution is from the platform transformer and its circuit-breaker on the medium-voltage side.

Next step is to also insert an additional circuit-breaker between the platform transformer and the 36 kV busbar (2D), as is shown in figure 13.

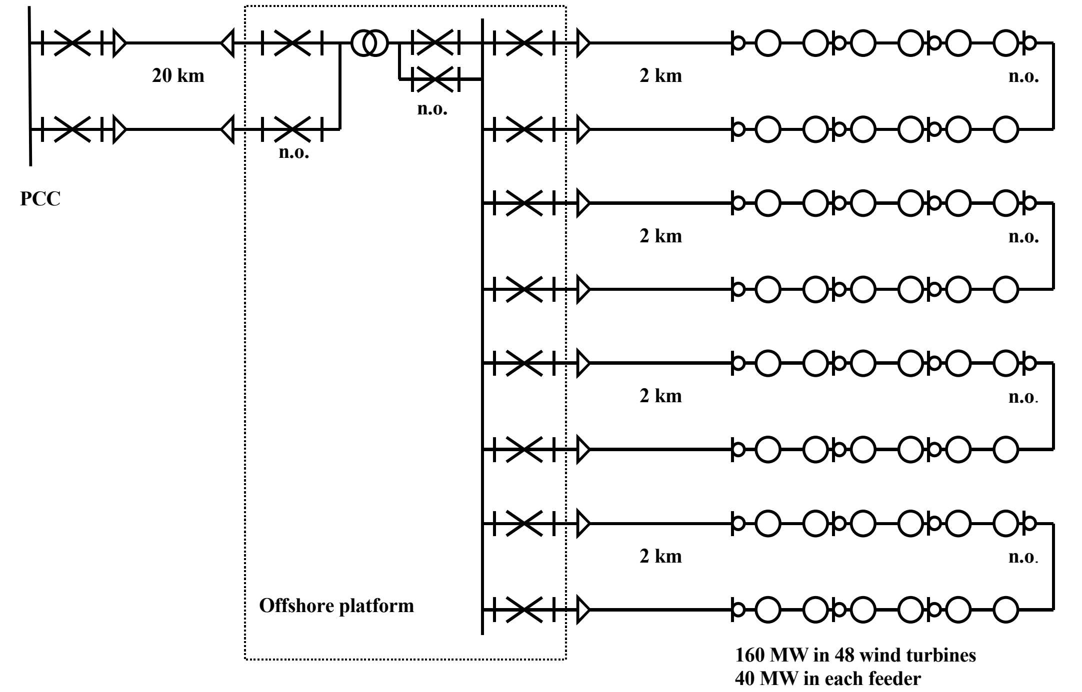

Figure 13: 2D – Alternative topology of type 2

Alternative topology 2D, with 2 sub-transmission cables, 1 platform transformers. Per feeder section this includes one additional feeder cable of capacity of 40 MW, one additional platform feeder bay and seven wind turbine placed load-switches. In the sub-transmission there is one additional 150 kV cable, capable to transfer 160 MW and one additional 160 MW platform transformer. The study shows that the expected annual energy not supplied is **36.996 GWh** (1400 GWh). The main contribution is from the platform transformer.

Next step is to also insert an additional platform transformer and a parallel circuit-breaker (2D), as is shown in figure 14.

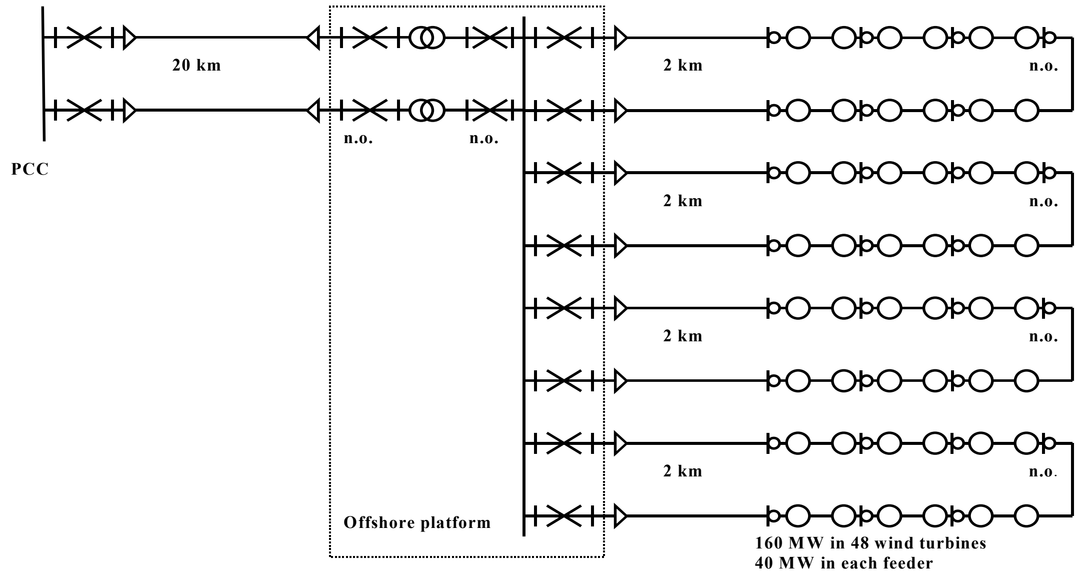

Figure 14: 2E – Alternative topology of type 2

Alternative topology 2E, with 2 sub-transmission cables, 2 platform transformers. Per feeder section this includes one additional feeder cable of capacity of 40 MW, one additional platform feeder bay and seven wind turbine placed load-switches. In the sub-transmission there is one additional 150 kV cable, capable to transfer 160 MW and one additional 160 MW platform transformer. The study shows that the expected annual energy not supplied is **19.873 GWh** (1400 GWh). The main contribution is from the load-switches.

The results from the Neplan reliability calculations are shown in table 2.

Config. Type 2	Energy at rated power generation [GWh/year]	Expected energy not supplied [GWh/year]	ASAI [%]	Energy not supplied compared to 2A [%]	Component with highest contribution
2A	1400	82.54	94.10	100	Sub-transmission cable
2B	1400	60.44	95.68	73.2	4 feeder cables
2C	1400	39.20	97.20	47.5	Platform transformer, 36 kV switchgear
2D	1400	37.00	97.36	44.8	Platform transformer
2E	1400	19.87	98.58	24.1	Load-switches

Table 2: Result from reliability study of topology type 2

Topology 2E is used in the economical evaluation in a later section.

Remarks:

Regarding the short-circuit capacity of type 2, non of the alternatives 2B – 2E will change the level as all reconfigurations with circuit-breakers or load-switches are operated in radially.

5.3 Large offshore wind parks

Basic topology with 4 subsystems, each with a platform switchgear and wind turbines in a fork as figure 15.

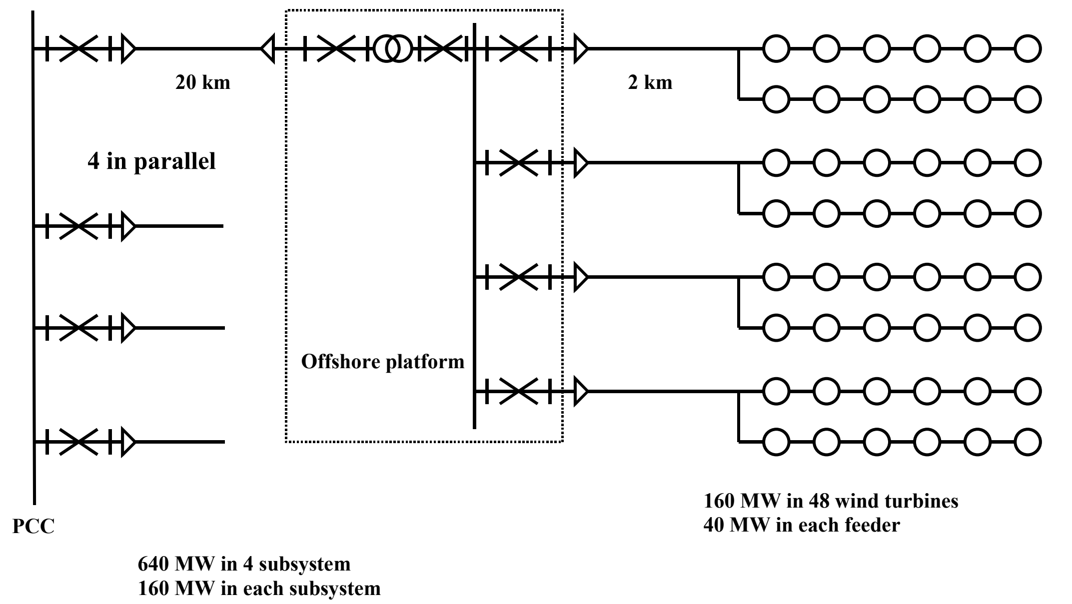

Figure 15: 3A - Basic topology of type 3

This is four times the same topology as 2A. The expected annual energy not supplied (at rated operation) will be 4 times 82.54 GWh, which is **330.16 GWh** (annual energy supplied at rated generation is 5600 GWh).

The basic topology studied, will be divided into a first part where the sub-transmission is studied and a second part where a large wind park is studied. The basic sub-transmission configuration will be as figure 16.

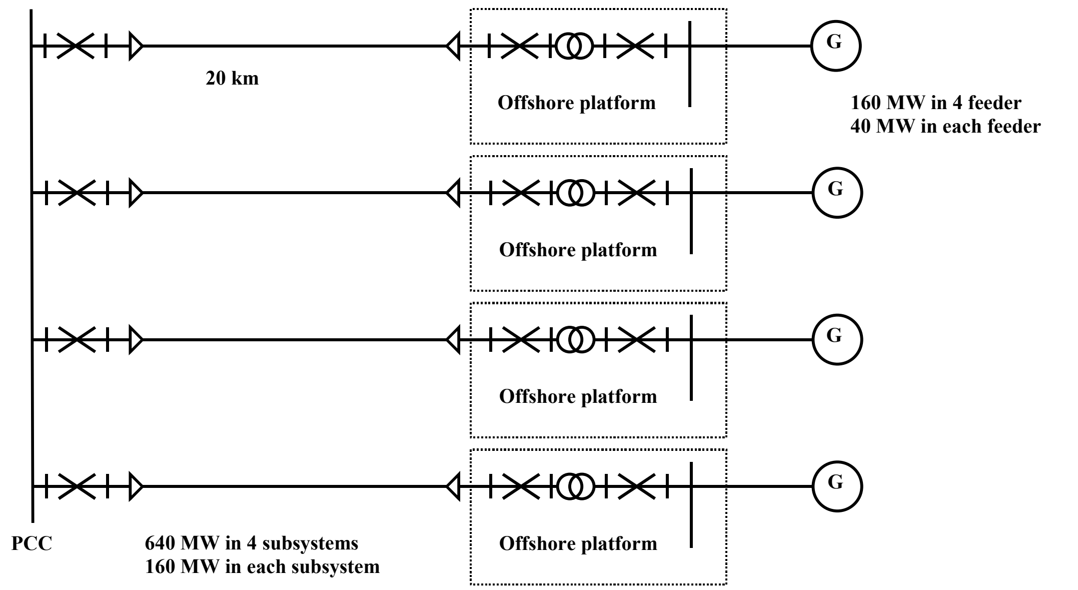

Figure 16: 3A1 - Basic sub-transmission topology of type 3

Topology 3A1, where each sub-transmission cable is carrying 160 MW. The study shows that the expected annual energy not supplied is **165.924 GWh** (note: when the whole wind park is studied the expected annual energy not supplied is 330.16 GWh) . The main contribution is from the 150 kV sub-transmission cables.

Let us insert one common 150 kV sub-transmission cable (3A2), as shown in figure 17.

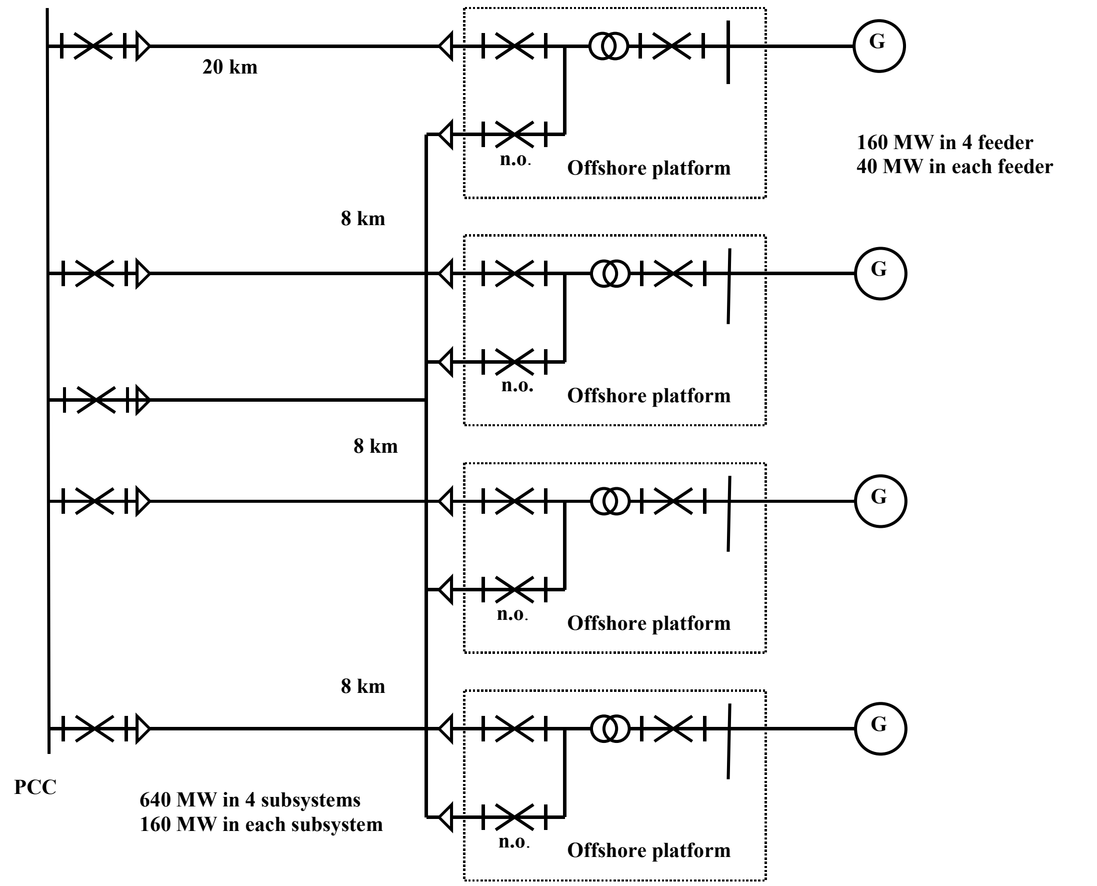

Figure 17: 3A2 - Alternative sub-transmission topology of type 3

Alternative topology 3A2, with one additional sub-transmission cable common for all four subsystems. The redundancy consists of 44 km additional 150 kV sub-transmission cable capable to transfer 160 MW, one additional set of 150 kV switchgear in PCC and four 150 kV platform switchgear bays. The study shows that the expected annual energy not supplied is **82.010 GWh** for the sub-transmission part. The main contribution is from the four transformers.

Next step is to add four 150 kV platform transformers (3A3), as is shown in figure 18.

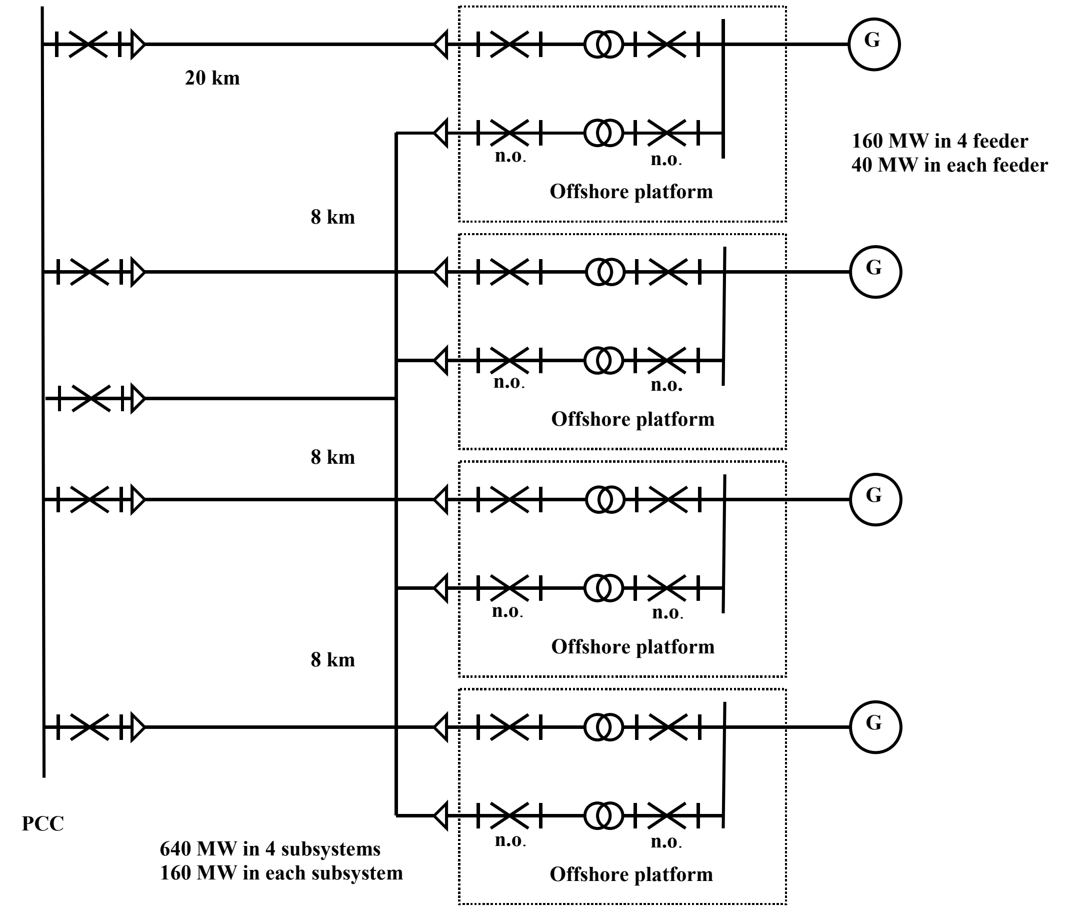

Figure 18: 3A3 - Alternative sub-transmission topology of type 3

Alternative topology 3A3, with one additional sub-transmission cable common for all four subsystems and four additional platform transformers. The redundancy consists of 44 km additional 150 kV sub-transmission cable capable to transfer 160 MW, one additional 150 kV circuit-breaker in the PCC, four 160 MW platform transformers, four 150 kV switchgear bays at the platforms and four 36 kV platform switchgear bays. The study shows that the expected annual energy not supplied is **2.788 GWh** for the sub-transmission part. The main contribution is from disconnectors on the platform.

The results from Neplan reliability calculations of the sub-transmission systems are shown in table 3:

Configuration Type 3	Expected annual energy not supplied [GWh/year]	Component with highest contribution	Expected energy not supplied compared to topology 3A [%]
3A1	165.92	Sub-transmission cables	100
3A2	82.01	Platform transformers	49.4
3A3	2.79	Disconnectors	1.7

Table 3: Result from reliability study of the sub-transmission topology type 3

The total set up of the large wind park will be done by using topology 1E and 3A2 in the following part of this section.

Is it possible to use those experiences gained in the set up of electrical systems of offshore wind parks and the conclusions from reliability study, in order to configure a large offshore wind park of 640 MW?

The following experiences are gained:

- Radial cable systems – reduce short-circuit capacity and fault detection and fault isolation are less complicated.
- Reconfiguration is made from a radial cable system into another radial cable system.
- Reconfigure by remote controlled load-switches – less expensive and the time to switching can be neglected.
- Alternative transfer paths – mainly by sub-sea cables, in the collection grids normal operated cables designed for large capacity than normal loads, in the sub-transmission redundant but radial operated cables and transformers.
- Reduce complexity – Too many load-switches including control systems will create complexity, without much gain in reliability.

Let us assume a large offshore wind park of 640 MW, consisting of 192 wind turbines of 3.3 MW each. The wind turbines are interconnected with sub-sea cables and load-switches according to topology 1E, i.e. wind turbines in groups of 2 and 2. The wind park contains 32 groups of wind turbines, as is shown in figure 19. The wind park is assumed to consists of 12 rows and 16 columns of wind turbines in a squared area.

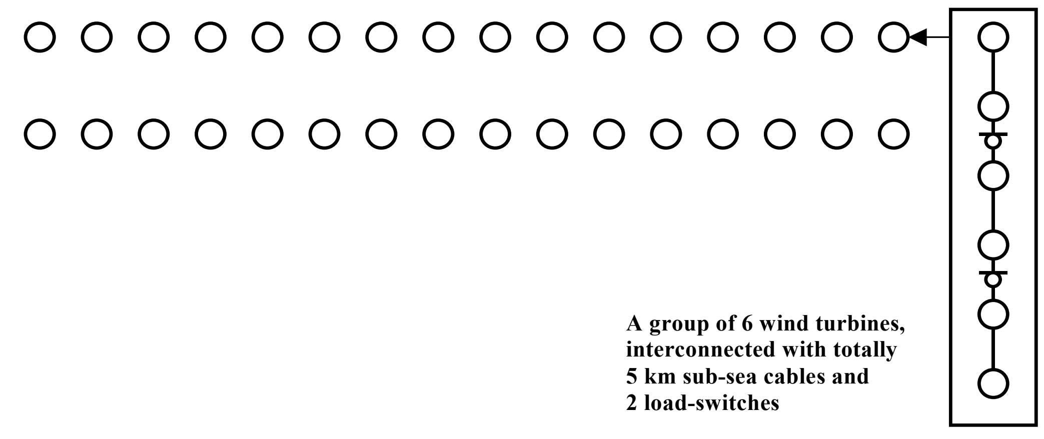

Figure 19: 640 MW offshore wind park – 12 rows of 16 wind turbines in each row

Insert 40 MW feeder cables to each wind turbine group from platform switch-gears to load-switches at the first wind turbine in the group, as is shown in figure 20.

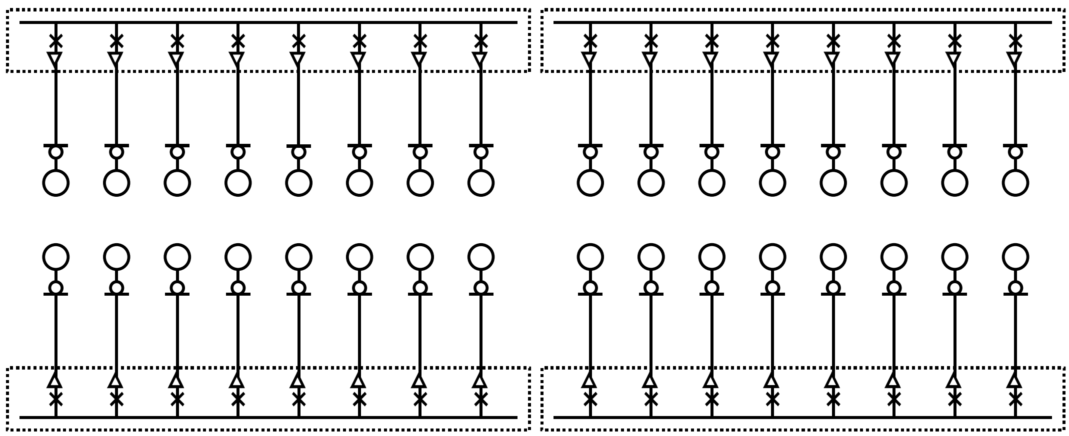

Figure 20: Large wind park – fed from platform busbars

Interconnect groups of wind turbines by sub-sea cables and normally opened load-switches inside the wind park, as is shown in figure 21. The number of load-switches and the interconnection can be discussed, but in this case topology 1E is used and the number of load-switches is 28.

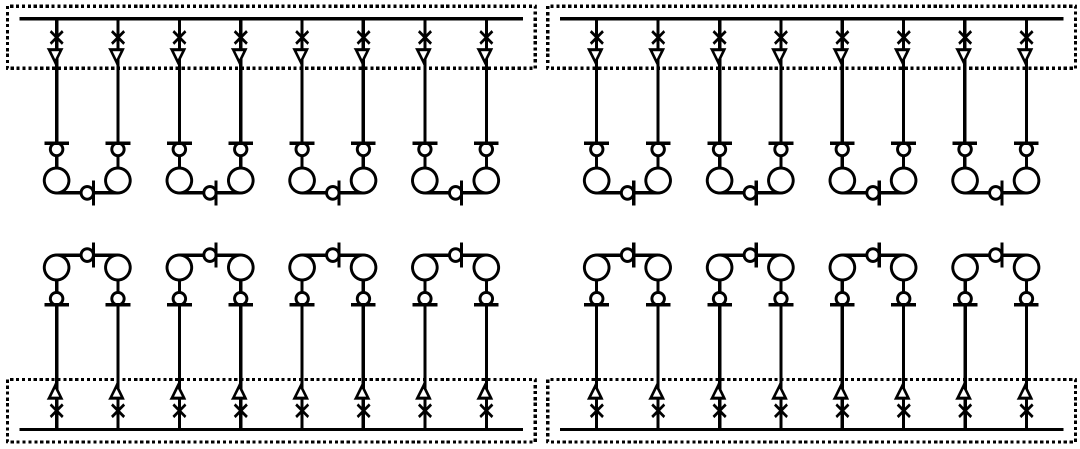

Figure 21: Large wind park – interconnected as topology 1E

Insert sub-transmission cable systems including one common alternative sub-transmission cable, according to topology 3B, as is shown in figure 22.

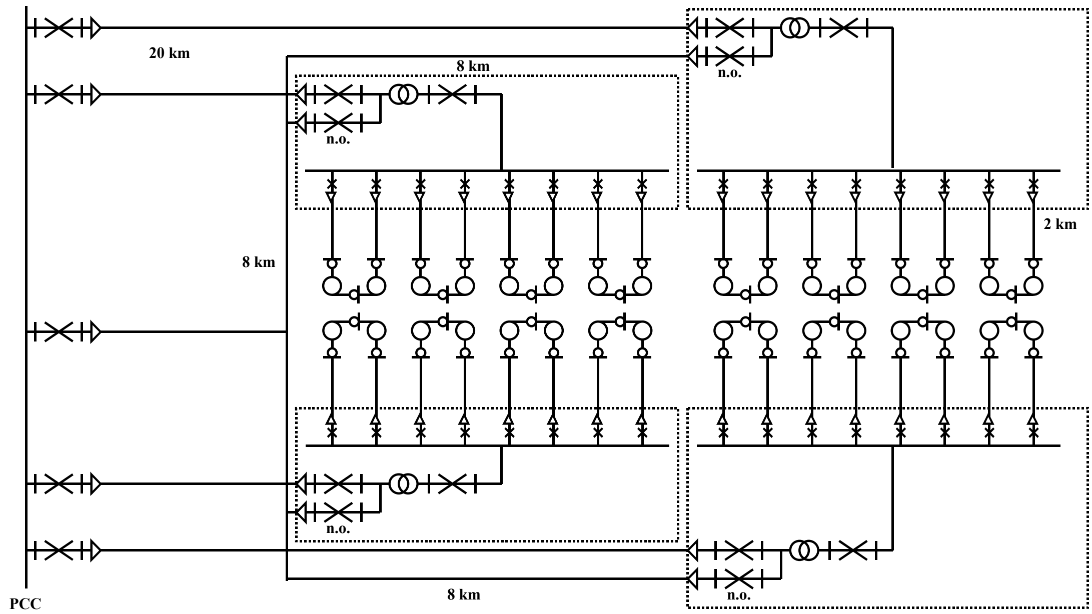

Figure 22: 3B – Topology for a large wind park, sub-transmission as 3A2

The expected annual energy not supplied for this large wind park is **<u>157.113 GWh</u>**, which can be compared to the basic topology 3A, which is 330.64 GWh.

The result of a large wind park can be seen in table 4.

Config. Type 3	Energy at rated power generation [GWh/year]	Expected energy not supplied [GWh/year]	ASAI [%]	Energy not supplied compared to top. 3 [%]	Component with highest contribution
3A	5600	330.16 (4 times top. 2A)	94.10	100	Sub-transmission cables
3B	5600	157.11	97.20	47.6	4 platform transformers

Table 4: Result from reliability study of a large wind park

Remarks:

Regarding the short-circuit capacity of type 3, non of the alternatives 3A1-3A3 and 3B will change this level as none of them are operated in parallel paths.

5.4 Summary of reliability calculations

The study has evaluated the availability of the electrical system of three different sizes of offshore wind parks. A number of possible alternative configurations have been studied and for the large wind park only the reliability of the sub-transmission system has been studied. The reliability study has considered single failures only and neglected multiple failures, outages combined by maintenance, common mode failures, etc. The expected annual energy not supplied is one of the main outputs from Neplan reliability calculations, both for individual components and for the total system. These values have been used to measure the improvements made in the availability for an alternative topology and to identify critical components.

The results of the reliability study of the small wind park is shown in table 5.

Config. Type 1	Name of the topology	Energy not supplied compared to topology 1A [%]
1A	Basic small wind park	100
1B	2 feeders (one normally opened)	90.0
1C	Open cable ring and 3 load-switches	53.4
1D	Open cable ring and 5 load-switches	43.3
1E	Open cable ring and 7 load-switches	40.1

Table 5: Results from reliability study of small wind parks

In the economical evaluation in the next section, the topology with an open cable ring and seven load-switches (1E) is chosen to be used as an example, where comparison is made to the basic small wind park (1A).

The results of the study of medium-size wind parks can be seen in table 6.

Config. Type 2	Name of the topology	Energy not supplied compared to topology 2A [%]
2A	Basic medium-size wind park	100
2B	2 sub-transmission cables	73.2
2C	2 sub-transmission cables and cable rings	47.5
2D	2 sub-transmission cables, 2 36 kV circuit-breakers and cable rings	44.8
2E	2 sub-transmission systems and cable rings	24.1

Table 6: Results from reliability study of medium-size wind parks

In the economical evaluation in the next section, the topology with 2 sub-transmission cables and open cable rings in the wind park sections (2E) is chosen to be used as an example, and comparison is made to the basic medium-size wind park (2A).

In the study of the large wind park, table 7 shows the results.

Config. Type 3	Name of the topology	Energy not supplied compared to topology 3A [%]
3A	Basic large wind park	100
3B	Additional common sub-transmission cable and open cable rings	47.6

Table 7: Results from reliability study of large wind parks

In the economical evaluation in the next section, the large wind park topology 3B with one additional common sub-transmission cable and open cable rings in the wind park sections is used as an example and comparison is made to the basic large wind park (3A).

6 Additional income probability

Examples of additional income of redundancies.

The following procedure is used in order to calculate the additional income:

1. Expected annual energy not supplied (ENS) for the basic topology and for the alternative topology as:

   $ENS_{40} = ENS * 40\%$

   where 40 % is taken from Appendix F.

2. Additional expected annual energy that can be supplied is derived as the difference between the ENS_{40} of the basic topology and the studied topology.

3. Additional expected energy that can be supplied over 20 years.

4. The expected additional income in M€ over 20 years. We assumed the value of each kWh to be 0.03 €.

The additional energy that can be supplied for the three topologies selected in the reliability study can be seen in table 8.

Wind park topology	Energy not supplied at rated power [GWh/year]	Energy not supplied at 40 % generation [GWh/year]	Additional energy that can be supplied [GWh/year]
Basic small wind park (1A)	10.36	4.14	
Small with cable ring (1E)	4.15	1.66	2.48
Basic medium-size wind park (2A)	82.54	33.02	
Medium-size with 2 sub-transmission cables and cable rings (2E)	19.87	7.95	25.07
Basic large wind park (3A)	330.16	132.06	
Large with one additional common sub-transmission cable and cable rings (3B)	157.11	62.85	69.21

Table 8: Additional annual energy

The additional income over 20 years at 0.03 €/kWh can be seen in table 9.

Wind park topology	Add. annual energy [GWh/year]	Add. energy in 20 years [GWh]	Add. income in 20 years [M€]
Small with cable ring (1E)	2.48	50.0	1.50
Medium-size with 2 sub-transmission cables and cable rings (2C)	25.07	501	15.0
Large with one additional common sub-transmission cable and cable rings (3B)	69.21	1380	41.5

Table 9: Additional income over 20 years at an energy price of 0.03 €/kWh

The expected additional income in 20 years of operation should be compared to the extra investments for the additional equipment. This is not done in this report. Additional equipment can, however, be seen below.

Small wind park:

Additional equipment required for a small wind park with a cable ring according to topology 1E can be seen in table 10. The expected additional income in 20 years at 0.03 €/kWh is 1.5 M€. It is expected that the additional investment is profitable.

Quantity	Component
4 km	36 kV sub-sea cable
7	36 kV load-switch in wind turbine incl. control system
1	36 kV circuit-breaker in PCC incl. control system

Table 10: Additional equipment for a small wind park

Medium-size wind park:

Additional equipment for the medium-size wind park with 2 sub-transmission cables and cable rings in the wind park sections according to topology 2E can be seen in table 11. The expected additional income in 20 years at 0.03 €/kWh is 15.0 M€. It is hard to estimate the additional investment at sea but it is expected that the additional investment is not profitable.

Quantity	Component
20 km	150 kV sub-sea cable
8 km	36 kV sub-sea cables
1	150 kV circuit-breaker in PCC incl. control system
1	150 kV circuit-breaker on platform incl. control system
1	160 MW 150/36 kV platform transformer (and additional space)
5	36 kV circuit-breaker on platform incl. control system
28	36 kV load-switch in wind turbine incl. control system

Table 11: Additional equipment for a medium-size wind park

Large wind park:

Additional equipment for a large wind park with one additional common sub-transmission cable and cable rings in the wind park sections according to topology 3B is shown in table 12. The expected additional income in 20 years at 0.03 €/kWh is 41.5 M€. It is hard to estimate the additional investment at sea but it is expected that the additional investment is profitable.

Quantity	Component
44 km	150 kV sub-sea cable
1	150 kV circuit-breaker in PCC incl. control system
4	150 kV circuit-breaker on platform incl. control system
16	36 kV circuit-breaker on platform incl. control system
32 km	36 kV sub-sea cables
112	36 kV load-switch in wind turbine incl. control system

Table 12: Additional equipment for a large wind park

Conclusive remark: The three wind park topologies with redundancy show that the incomes can be increased over 20 years. These incomes will be affected of the expected energy price and the assumed life-cycle time, and not only of from statistical reliability data. In a concrete wind park reliability study, the additional income should be compared to the additional investment costs. However, this is left out in this study as it is hard to estimate the additional costs for extra equipment installed offshore.

7 Conclusions

In this report a reliability optimization method is presented that may be used for investment decisions concerning sub-sea cable systems of offshore wind parks. The method is based on reliability computations in different designs of the collection grid for the wind park. The method is using reliability data of involved components such as failure rates, repair times and switching times.

The method consists of three distinctive stages:

- In the first stage, the expected annual energy not supplied is derived for the basic configuration. In principle, the basic configuration can be any configuration, but a configuration without any redundancy could be an appropriate choice. The expected annual energy not supplied is calculated.
- In the second stage, redundancy is built into the collection grid. The choice of redundancy is based on the contribution of each component to the expected annual energy not supplied. The difference between the energy not supplied in the basic and in the new configuration is the additional energy that can be supplied.
- The third stage is an economical evaluation where the additional energy that can be supplied is converted to additional income per year or over a whole life-cycle. At this stage the method is using assumptions regarding the energy price and the number of years in a life-cycle.

The method can be used for comparison of different configurations or for comparison of additional income versus additional investment in redundancy. The method can also be used to estimate the expected annual energy production of an existing wind park or an existing design.

The method is applied for case studies of three different sizes of offshore wind parks: small; medium-size; and large. A typical topology without redundancy for each size is used as basic configuration. The experiences from the case studies can be summarized in the following conclusions:

- The main contribution to the expected annual energy not supplied is due to the long repair time of components at an offshore location.
- Redundancy is introduced in the form of spare capacity in sub-sea cables and additional cables and transformers.
- Two levels of redundancy should be distinguished based on the type of switchgear used. Remote-controlled load-switches in combination with remote indication of faulted segment will result in a restoration time

between several minutes and one hour. Circuit-breakers with appropriate protection equipment will reduce the number of interruptions.

- The additional gain of installing circuit-breakers is limited whereas the costs are typically very high. The costs may include the costs of switchgear able to withstand the higher fault currents.
- The gain of installing remote-controlled load-switches is significant as it reduces the duration of a production stoppage from several weeks or months to one hour or less.
- There is an optimal number of load-switches, above which additional ones only increase costs and complexity without significant further gains in expected annual energy production.

The method described in this report is a probabilistic method, which is inherently associated with uncertainty. Some care should be taken in comparing rather accurately known investment costs with uncertain gain in annual production. A small difference in total costs between two design alternatives should not be seen as significant and a base for an investment decision. There are, however, no general rules for how to handle this and a further discussion on this is beyond the scope of this report.

A change in input parameters (failure rate, expected repair time, investment costs, value of non-delivered energy) may impact the preferred design under the method described in this report. As several of the input parameters are in itself uncertain, this would introduce an additional uncertainty in the final decision. However, it is generally accepted in power system reliability that the outcome of the comparison is not impacted when the most-likely value is used for all input parameters and when the difference between the design is not too small.

8 References

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Appendix

Appendix A: Failure rate
Appendix B: Reparation time
Appendix C: Switching time
Appendix D: Electrical data of sub-sea cables
Appendix E: Example of Neplan Reliability Results
Appendix F: Average production level

Appendix A: Reliability data – Failure rates (□)

In the following table the failure rate data is presented. These data has been used in the Neplan reliability calculations for the different studied topologies of the collection grids.

Component	Failure rate [failure/year]
Sub-sea cables (150 kV)	0.008 [failure /year,km]
Sub-sea cables (36 kV)	0.008 [failure /year,km]
Platform transformers (160 MW, 150 kV)	0.020
Circuit-breakers (36 kV on land)	0.024
Circuit-breakers (36 kV on platform)	0.024
Circuit-breakers (36 kV in wind turbine)	0.024
Circuit-breakers (150 kV on land)	0.032
Circuit-breakers (150 kV on platform)	0.032
Disconnectors (36 kV on land)	0.0024
Disconnectors (36 kV on platform)	0.0024
Disconnectors (150 kV on land)	0.012
Disconnectors (150 kV on platform)	0.012
Load-switches (36 kV in wind turbine)	0.020
Busbars (36 kV on offshore platform)	0.004
Busbars (150 kV on offshore platform)	0.020

Table 13: Failure rates used in the study

Appendix B: Reliability data – Reparation times (MTTR)

In the following table the reparation time data is presented.

Component	Repair time [h]	Comment
Sub-sea cables (150 kV)	720	2)
Sub-sea cables (36 kV)	2160	3)
Platform transformers (160 MW, 150 kV)	4320	4)
Circuit-breakers (36 kV on land)	4	1)
Circuit-breakers (36 kV on platform)	720	2)
Circuit-breakers (36 kV in wind turbine)	2160	3)
Circuit-breakers (150 kV on land)	4	1)
Circuit-breakers (150 kV on platform)	720	2)
Disconnectors (36 kV on land)	4	1)
Disconnectors (36 kV on platform)	720	2)
Disconnectors (150 kV on land)	12	1)
Disconnectors (150 kV on platform)	720	2)
Load-switches (36 kV in wind turbine)	2160	3)
Busbars (36 kV on offshore platform)	720	2)
Busbars (150 kV on offshore platform)	720	2)

Table 14: Repair times used in the study

1) Based on statistic information for distribution and industrial systems.
2) Based on assumption of longer repair times for offshore equipment in this study.
3) Based on additional delay times due to waiting times for reparation during the winter seasons in this study.
4) Based on delay times due to replacement of platform transformers which require lifting, transportation and spare units.

Appendix C: Reliability data – Switching times (MTTS)

The switching time data is presented in the table below.

Component	Switching time [min]
Circuit-breakers (all)	20
Disconnectors (all)	20
Load-switches in wind turbine	20

Table 15: Switching times used in the study

Appendix D: Electrical data of sub-sea cables

The following electrical data is used for the sub-sea cables.

Voltage [kV]	Cable area [mm^2]	Resistance [ohm/km]	Reactance [ohm/km]	Capacitance [μF/km]	Current limit [A] ([MW])
36	300	0.056	0.110	0.200	355 (20)
36	600	0.028	0.110	0.200	710 (40)
36	1200	0.014	0.110	0.200	1420 (80)
150	600	0.028	0.110	0.200	710 (160)

Table 16: Electrical cable data used in the study

Appendix E: Example of Neplan Reliability Results

The different topologies of the collection grids of the offshore wind parks have been executed in the Reliability module of Neplan software package. The evaluation results of the processing of the basic topology 1A are presented in tables 17 and 18.

Topology 1A

Index	Unit	Value	Description
ASAI	%	97.040	Average service availability index
λ	Failure/year	0.149	Average failure rate
r	h	1742.7	Average outage time
U	min/year	15558.9	Average annual outage time
ENS	MWh/year	10362.2	Annual energy not supplied

Table 17: Neplan results of total topology 1A

Name	Type	λ [1/year]	r [h]	U [min/year]	ENS [MWh/year]
*** Total ***		0.149	1742.7	15558.9	10362.2
FeederCable	Cable	0.032	2160.0	4147.2	2762.0
Intercable-1	Cable	0.008	2160.0	1036.8	690.5
Intercable-2	Cable	0.008	2160.0	1036.8	690.5
Intercable-3	Cable	0.008	2160.0	1036.8	690.5
Intercable-4	Cable	0.008	2160.0	1036.8	690.5
Intercable-5	Cable	0.008	2160.0	1036.8	690.5
Intercable-6	Cable	0.008	2160.0	1036.8	690.5
Intercable-7	Cable	0.008	2160.0	1036.8	690.5
Intercable-8	Cable	0.008	2160.0	1036.8	690.5
Intercable-9	Cable	0.008	2160.0	1036.8	690.5
Intercable-10	Cable	0.008	2160.0	1036.8	690.5
Intercable-11	Cable	0.008	2160.0	1036.8	690.5
Circuit-Breaker	Circuit breaker	0.024	4.0	5.760	3.836
Disconnector-2	Disconnector	0.002	4.0	0.576	0.384
Disconnector-1	Disconnector	0.002	4.0	0.576	0.384

Table 18: Neplan results of total topology 1A and of individual components

Appendix F: Average production level

The value of one hour of generation depends on many factors that are unknown at this stage of the study, e.g. wind speed, electricity price, availability of balancing power within the company. etc.

In order to get an estimate of the loss in income to the unavailability of the wind park, an estimation has been made of the average value of one hour of generation.

Information from four sites in table 19, is used to estimate an annual average production level and it is set in relation to the installed capacity. 8750 h is used for the annual operating hours.

Wind park	Expected energy [GWh/year]	Average generation [MW]	Installed capacity [MW]	Related to installed capacity [%]
Kriegers Flak	2100	240	~600	~40
Lillgrund	~330	37.7	110	~35
Horns Reef	~600	68	160	~42
Kentish Flat	~280	32	90	~36

Table 19: Estimation of average production level

These four sites in table 19, give an average production between 35 and 42%.

A value within the same range can also be obtained from the annual average wind speed for the specific site and tower height. Higher average wind speed means higher expected produced energy. The annual average wind speed is between 8 and 9 m/s for offshore wind parks in typical Nordic surroundings. Locations suitable for wind parks, showing annual average wind speeds of 9 m/s or more are rare. Further, for the wind turbine generator, WTG, the rated (100 %) real power generation is not exceeded until wind speed around 12 m/s. At the annual average wind speed at 8.5 m/s, and WTG’s reaching rated power at 12 m/s, the real power generation is:

$P = P_n$ at $v_n = 12$ m / s and $P = f(v^3) =>$

$$P = \left(\frac{v}{v_n}\right)^3 * P_n = \left(\frac{8,5}{12}\right)^3 * P_n = 0.36 * P_n$$

where P is actual generation
P_n is nominal generation
v is actual wind speed
v_n is wind speed at nominal conditions

This value, which is 36 % of nominal power, is within the range derived before. From this we conclude that an annual average wind speed will result in an average real power generation per hour which is somewhere around 36 %. The distribution of the wind speed at the site is needed for a more accurate calculation.

In the study, 40 % is used as an approximate value.