# A comparison of internal grid topologies of offshore wind farms regarding reliability analysis

T. Pereira and R. Castro

*Abstract*—**In the last decade, offshore wind farms emerged as an important renewable energy solution, characterized by higher winds, higher investment and higher operation and maintenance costs compared to onshore solutions. This highlights the importance of an increased reliability on offshore wind farms, because the occurrence of a failure can result in higher downtimes due to inaccessibility of the site during harsh weather conditions.**

**This study performs a reliability analysis of the internal grid of an offshore wind farm, comparing different topologies and their economic benefits. Since interruptions in power production lead to income losses, the challenge is to find which topology has the right balance between high reliability and acceptable costs. To increase the topology reliability, this study uses a redundancy between each pair of two strings or a redundancy between already redundantly paired sets of strings. It also considers two different approaches for the cable rating selection.**

**The results show that the use of a redundancy can lead to a positive Net Present Value and an interesting Internal Rate of Return, which can be an appealing investment. Moreover, it is more profitable to simply rate the cables to support a normal operation scenario for rated power rather than increasing the cable ratings to support all failure scenarios. Overall, the topology that presents the best economic results combined with a good reliability result is the topology with cable ratings based on regular conditions with a redundancy in the middle of the string between each pair of two strings.**

***Index Terms*—cable rating, economic evaluation, internal grid topology, offshore wind farm, redundancy, reliability analysis.**

## I. Introduction

IT was only in 1990 that the first offshore wind farm appeared off the coast of Sweden, with a rated power of 220kW. The first commercial offshore wind farm was installed a year later in Denmark, with a rated power of 450kW [1].

From then onwards, the size of the wind turbines, the distance to shore and the water depth where the turbines are installed kept increasing, as well as the size of the offshore wind farms. Among all of the operational offshore wind farms, one that is worth mentioning is the London Array (630 MW) in the United Kingdom [2]. This is the largest offshore wind farm in the world and is composed of 175 wind turbines. Currently in its construction stage, there is one large offshore site that is also worth mentioning - the Gemini (600 MW), in the Netherlands, which will be operational in 2017 (expected) [3].

The main difference between onshore and offshore sites lies in the fact that, due to the lack of surrounding obstacles, wind is much less turbulent in the sea, which does not happen in onshore sites [4]. Therefore, offshore wind farms experience higher winds resulting in higher production, but investment costs and operation and maintenance costs are also higher compared to onshore solutions. This highlights the importance of increased reliability on offshore wind farms, because a single failure may result in a long downtime period, due to the inaccessibility of the site during harsh weather conditions. The topology of the internal collection system is a key issue, as it determines the redundancy levels (alternative paths to drain the electrical energy) of the offshore wind farms. Since interruptions in power production from an offshore wind farm lead to income losses, the challenge in designing offshore wind farms is to find the right balance between high reliability and acceptable costs.

The objective of this study is to perform a reliability performance analysis of the internal grid of an offshore wind power system, comparing different topologies and their economic benefits. By comparing different topologies, it is possible to determine and evaluate which is the most reliable installation. To perform a reliability assessment, it is required to simulate the reliability for each component in the system, determine the impact of each contingency on each load point, determine the frequency of production interruption and sum up the impact of all contingencies. Overall, this study addresses the reliability impact of different topological solutions while maintaining an economic rationale between the layout design and the energy production output.

## II. Software Description

For a reliability analysis and economic evaluation of the proposed topologies, a software was developed in MATLAB® (its open-source package MATPOWER®[1] [5] was also used). This developed software calculates the reliability indices and

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Tiago Pereira is with the Instituto Superior Técnico, University of Lisbon, Portugal (e-mail: tiagopaispereira@tecnico.ulisboa.pt).

Rui Castro is with the INESC-ID/IST, University of Lisbon, Portugal (email: rcastro@tecnico.ulisboa.pt).

[1] Available at http://www.pserc.cornell.edu/matpower/

investment costs of a proposed topology, and with those results proceeds to do the economic evaluation. For the reliability analysis, it calculates the power flow for each possible scenario. In order to do the economic evaluation, the software needs a base reference topology to compare with the one being analysed, so that the added income and additional investment can be calculated. This base topology is created from the proposed topology, excluding all the elements added for reliability increase, namely the redundancies and the added equipment. The resulting base topology is known as the radial design. This is the design with less reliability levels, for which the occurrence of a fault causes all the equipment in a string to be out of service [6], [7].

The software considers the variation of the wind by simulating twenty-two scenarios, each one associated with a probability. All these scenarios give the opportunity to consider wind variations in a trustworthy way and to reliably analyse all the topologies proposed. For a proposed topology, the software identifies every possible failure caused by protection elements and submarine cables, simulating each one for the twenty-two wind scenarios. Associating the results of all the simulations with the reliability data, the software calculates all reliability indices and investment costs. Finally, with those results the software proceeds to do the economic evaluation.

When choosing the topology to be analysed, a user does not need to specify the cable ratings, since they are automatically selected by the developed software, which identifies the most suitable ratings for each topology. This ensures that no money is wasted on improving ratings when it is not needed. The software selects the cable ratings from two different approaches. The ratings selected in the first approach are those necessary to handle every faulty scenario that may occur. The ratings selected in the second approach are those necessary to handle all scenarios for regular conditions (with no faults).

### A. *Power Generation Scenarios*

For a trustworthy reliability analysis, it is necessary to simulate various scenarios for the output power of the wind generators. It is not enough to simulate just the rated power or even the average power. To compare different topologies, it is necessary to consider a wind probability density function.

So, it is necessary to define the power generation scenarios that will be used in the software for the reliability analysis and the economic evaluation of the proposed topologies. To accomplish that some assumptions are made and presented below.

Analysing the European Wind Atlas Offshore and choosing the coast of Portugal, the annual average wind speed for a height of 100 m in open sea (more than 10 km offshore) is between 7.5 m/s to 8.5 m/s [8]. So, selecting one value from this interval, the assumption considered in the simulations for the annual average wind speed is 8.5 m/s.

The selected wind turbine was the Vesta V90-3MW [9], which is the turbine used in one of the biggest Offshore Wind farms, Thanet (300 MW) [10]. This turbine is characterized by a rated power of 3.0 MW, a cut-in speed of 3.5 m/s, a rated wind speed of 15 m/s and a cut-out speed of 25 m/s. The height of the tower is 105 m and the considered power factor was always 0.96 inductive (injective reactive power).

Since the height of the hub is different from the height of the assumed annual average wind speed, it is necessary to extrapolate it through the Prandtl law. In order to do that a surface roughness needs to be selected. So, the surface roughness for a calm open sea is 0.0002 m [4]. So, the assumed average annual wind speed at the hub height is 8.532 m/s.

Now it is possible to define the probability distribution of the wind speed using the Rayleigh distribution. The only parameter of this distribution is the annual average wind speed, which was just calculated. With the cumulative distribution function, it is possible to calculate a probability of a wind speed interval:

$$Probability\,[a;b] = F(a) - F(b) \tag{1}$$

where $Probability\,[a;b]$ is the probability of the wind speed to be in the interval defined between $a$ and $b$ [%], $a$ is the initial value for wind speed interval [m/s], $b$ is the final value for wind speed interval [m/s], $F(a)$ is the cumulative probability for wind speed $a$ [%], and $F(b)$ is the cumulative probability for wind speed $b$ [%].

Using this definition, it is possible to set twenty-two wind scenarios and associate each one with a probability [11]. From the power curve of the turbine [9], the average power generation for each wind speed interval can be calculated. Finally, it is possible to define the power generation scenarios to be simulated, with the average power generation and the probability associated with each wind speed interval. The numerical values are presented in Table. I.

So, the software simulates each scenario, where the power generated in the wind turbines is the average power generation for each of them, and multiplies the reliability results with their associated probability.

TABLE I
EACH POWER GENERATION SCENARIO FOR THE WIND GENERATORS ASSOCIATED WITH A PROBABILITY

| Initial Value [m/s] | Final Value [m/s] | Probability [%] | Power at Initial Value [MW] | Power at Final Value [MW] | Avg. Power [MW] |
|---|---|---|---|---|---|
| 3.5 | 4.0 | 3.47 | 0.000 | 0.077 | 0.0385 |
| 4.0 | 5.0 | 7.79 | 0.077 | 0.190 | 0.1335 |
| 5.0 | 6.0 | 8.55 | 0.190 | 0.353 | 0.2715 |
| 6.0 | 7.0 | 8.87 | 0.353 | 0.581 | 0.4670 |
| 7.0 | 8.0 | 8.81 | 0.581 | 0.886 | 0.7335 |
| 8.0 | 9.0 | 8.40 | 0.886 | 1.273 | 1.0795 |
| 9.0 | 10.0 | 7.73 | 1.273 | 1.710 | 1.4915 |
| 10.0 | 11.0 | 6.89 | 1.710 | 2.145 | 1.9275 |
| 11.0 | 12.0 | 5.96 | 2.145 | 2.544 | 2.3445 |
| 12.0 | 13.0 | 5.00 | 2.544 | 2.837 | 2.6905 |
| 13.0 | 14.0 | 4.08 | 2.837 | 2.965 | 2.9010 |
| 14.0 | 15.0 | 3.24 | 2.965 | 2.995 | 2.9800 |
| 15.0 | 16.0 | 2.51 | 2.995 | 3.000 | 2.9975 |
| 16.0 | 17.0 | 1.89 | 3.000 | 3.000 | 3.0000 |
| 17.0 | 18.0 | 1.39 | 3.000 | 3.000 | 3.0000 |
| 18.0 | 19.0 | 1.00 | 3.000 | 3.000 | 3.0000 |
| 19.0 | 20.0 | 0.70 | 3.000 | 3.000 | 3.0000 |
| 20.0 | 21.0 | 0.48 | 3.000 | 3.000 | 3.0000 |
| 21.0 | 22.0 | 0.32 | 3.000 | 3.000 | 3.0000 |
| 22.0 | 23.0 | 0.21 | 3.000 | 3.000 | 3.0000 |
| 23.0 | 24.0 | 0.13 | 3.000 | 3.000 | 3.0000 |
| 24.0 | 25.0 | 0.08 | 3.000 | 3.000 | 3.0000 |

$$ENS_{Topology} = \sum_i ENS_{Scenario\ i} \times Probability_{Scenario\ i} \quad (2)$$

where $ENS_{Topology}$ is the Energy Not Supplied for the analysed topology [MWh], $ENS_{Scenario\ i}$ is the Energy Not Supplied for the analysed topology and the power generation scenario $i$ [MWh], and $Probability_{Scenario\ i}$ is the probability of the wind speed to be in the interval defined for the power generation scenario $i$ [%].

### B. Reliability Analysis

To increase the reliability of a topology, different types of protection elements can be used, such as circuit breakers, load switches and disconnectors. The circuit breakers are the elements that take automated action, switching on and off automatically to protect all other elements when a fault occurs. Their switching action can also be remotely controlled. The load switches are protection elements that are only remotely controlled, this means that a status change only takes place through a remote command. The disconnectors are protection elements that can only be controlled manually, meaning that their switching status only change if someone goes to the site directly. All these elements are considered correctly dimensioned and treated as ideal elements during the power flow calculation.

Since all the protection elements and the submarine cables have failures, the failure rates for each one are considered in the reliability analysis [12], [13]. The software identifies all possible failures caused by each element and simulates them all. The reliability results from each failure are then multiplied by their associated probability - their failure rate:

$$ENS_{Scenario\ i} = \sum_k ENS_{Failure\ k} \times Failure\ Rate_{Failure\ k} \quad (3)$$

where $ENS_{Scenario\ i}$ is the Energy Not Supplied for the analysed topology and the power generation scenario $i$ [MWh], $ENS_{Failure\ k}$ is the Energy Not Supplied for the analysed topology and the power generation scenario $i$ when the failure $k$ occurs [MWh], and $Failure\ Rate_{Failure\ k}$ is the probability of a fault occurring in the equipment that caused the failure $k$ [%].

The failure rates for each equipment are presented in Table. II. This table also presents the repair time needed to repair an element when a failure occurs, and the switching time needed to switch the status of a protection element (this time varies if the element is remotely controlled or manually operated) [12], [13].

The automated action of the circuit breaker that protects all the elements when a fault occurs is assumed to be instantaneous. However, the switching action of this equipment that is remotely controlled is not and the assumed time for that action to take place is 20 minutes. The disconnector's switching time is very high because it needs to be performed by service personnel going to the turbine by boat.

TABLE II
RELIABILITY DATA

| Equipment | Failure Rate [failure/year] | Repair Time [hours] | Switching Time [min] |
|---|---|---|---|
| Submarine Cables | 0.004 | 672 | - |
| Disconnectors | 0.02 | 168 | 10080 |
| Circuit Breakers | 0.03 | 168 | 20 |
| Load Switches | 0.03 | 168 | 20 |

### C. Fault Analysis

The faults that are considered in the reliability analysis are cable faults, circuit breaker faults, disconnector faults and load switch faults. Each possible failure is identified by the software, then all of them are simulated and the reliability indices are calculated according to (3).

Analysing the reliability data in Table. II, for the submarine cable faults, three periods in which the number of online turbines is different can be seen. The first period is characterized by the automated action of the protection equipment when the fault occurs. So, in this period, the string of wind turbines where the fault occurs will be out of service. The second period is characterized by the switching of the remote protection equipment. In this period, depending on the location of the redundancy, an increase in the number of online turbines may happen. The third and final period happens when the disconnector is manually switched and an increase in the number of online turbines may also happen. This period ends when the cable is finally repaired.

So, the calculation of the total Energy Not Supplied if a failure occurs, considering all the three identified periods, can be made by

$$ENS_{Failure\ k} = \sum_p ENS_{Period\ p} \quad (4)$$

where, $ENS_{Failure\ k}$ is the Energy Not Supplied for the analysed topology and the power generation scenario $i$ when the failure $k$ occurs [MWh], and $ENS_{Period\ p}$ is the Energy Not Supplied for the analysed topology and the power generation scenario $i$ when the failure $k$ occurs for the situation o period $p$ [MWh].

The calculation of the Energy Not Supplied if a failure occurs for each period can be made by

$$ENS_{Period\ p} = \Delta t_{Period\ p} \times (Power\ Supplied_{Regular\ Conditions} - Power\ Supplied_{Period\ p}) \quad (5)$$

where, $ENS_{Period\ p}$ is the Energy Not Supplied for the analysed topology and the power generation scenario $i$ when the failure $k$ occurs for the situation at period $p$ [MWh], $\Delta t_{Period\ p}$ is the duration of the period $p$ when the failure $k$ occurs [h], $Power\ Supplied_{Regular\ Conditions}$ is the power supplied for the analysed topology for the power generation scenario $i$ for regular conditions (with no failures) [MW], and $Power\ Supplied_{Period\ p}$ is the power supplied for the analysed topology for the power generation scenario $i$ when the failure $k$ occurs for the situation at period $p$ [MW].

Analysing the data in Table. II, the first period starts with the automated action of the circuit breakers (which is instantaneous) and ends when the switching of the remote protection equipment (circuit breakers and load switches) happens, so the duration of this period is 0.33 h. The second period starts with the switching action of the circuit breakers and the load switches and ends when the disconnector's manual

TABLE III
THREE-CORE CABLE WITH COOPER WIRE SCREEN [14]

| Cross-section of conductor [$mm^2$] | Diameter of conductor [mm] | Insulation Thickness [mm] | Diameter over insulation [mm] | Cross section of screen [$mm^2$] | Outer diameter of cable [mm] | Cable weight (Aluminium) [kg/km] | Cable weight (Copper) [kg/km] | Capacitance [μF/km] | Charging current per phase at 50 Hz [A/km] | Inductance [mH/km] | Transmission capacity [MVA] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 95 | 11.2 | 8.0 | 29.6 | 16 | 104.0 | 17.7 | 19.5 | 0.18 | 1.0 | 0.44 | 20 |
| 120 | 12.6 | 8.0 | 31.0 | 16 | 107.0 | 18.4 | 20.7 | 0.19 | 1.0 | 0.42 | 23 |
| 150 | 14.2 | 8.0 | 32.6 | 16 | 110.5 | 19.3 | 22.1 | 0.21 | 1.1 | 0.41 | 25 |
| 185 | 15.8 | 8.0 | 34.2 | 16 | 114.0 | 20.1 | 23.6 | 0.22 | 1.2 | 0.39 | 28 |
| 240 | 18.1 | 8.0 | 36.5 | 16 | 118.9 | 21.4 | 25.9 | 0.24 | 1.3 | 0.38 | 33 |
| 300 | 20.4 | 8.0 | 38.8 | 16 | 123.9 | 22.6 | 28.2 | 0.26 | 1.4 | 0.36 | 37 |
| 400 | 23.2 | 8.0 | 41.6 | 16 | 129.9 | 24.6 | 32.0 | 0.29 | 1.6 | 0.35 | 41 |
| 500 | 26.2 | 8.0 | 45.0 | 16 | 137.3 | 26.7 | 36.0 | 0.32 | 1.7 | 0.34 | 46 |
| 630 | 29.8 | 8.0 | 48.6 | 16 | 145.1 | 29.2 | 40.9 | 0.35 | 1.9 | 0.32 | 52 |
| 800 | 33.7 | 8.0 | 52.5 | 16 | 154.4 | 32.2 | 47.2 | 0.38 | 2.1 | 0.31 | 57 |
| 1000 | - | - | - | - | - | - | - | 0.41 | - | 0.30 | 65 |
| 1200 | - | - | - | - | - | - | - | 0.43 | - | 0.29 | 71 |

An extrapolation of the capacitance, inductance and transmission capacity was performed for cable ratings 1000mm$^2$ and 1200mm$^2$.

switching takes place, so its duration is 167.67 h. And finally, the third period ends when the cable failure is repaired, so its duration is 504 h.

A similar reasoning than the one done for a cable fault can be made for circuit breaker faults, disconnector faults and load switch faults. However, instead of having three periods, only the first two occur. This happens because the repair time of these equipments is not greater than the switching time of the disconnectors, which is when the third period starts. So, the second period when a failure occurs in circuit breakers, disconnectors and load switches ends when the protection equipment is repaired.

It is important to note that the redundancies which are included in the proposed topologies are out of service during the regular operation of the wind farm. This means the reliability analysis does not analyse the occurrence of a fault in the redundancy cables.

The focus of this work is to perform a reliability analysis of the internal grid of an offshore wind farm. This means that for faults that occur outside the internal grid, the analysis is outside the scope of this work, because the additional elements added in the internal grid will not bring any increase of reliability to those failures.

### D. *Cable Ratings*

Another important element to select is the cables that are to be used for the collector system. For this, it is necessary to calculate the power flow and the power losses of the system. Since the most common rated voltage used in the wind farm collector system is 33 kV, the selected submarine cable is the three-core cable with copper wire screen [14]. This type of cable has a wide range of available cross-sections, which are presented in Table. III. However, the selection is made by the software according to the power capacity that each cable must collect.

The software calculates simultaneously reliability and economic indicators from two different approaches for the selection of the cable ratings. The ratings selected in the first approach are those necessary to handle every faulty scenario that may occur. This means they are designed to handle all power produced by all online turbines when any fault occurs. The topologies with the first approach will be named Topologies with Rating Upgrades (TRU). From this approach, it is never necessary to turn off a wind turbine because the cable wouldn't be able to handle its power in the occurrence of a fault. The ratings selected in the second approach are those necessary to handle all scenarios for regular conditions (with no faults). The topologies with the second approach will be named Topologies with Ratings for Regular Conditions (TRRC). This means that if a failure occurs, it may be necessary to turn off some turbines because the cables are not capable of handling all the power. The reasoning behind the second approach is that both the failure rates and the probability of a wind turbine operating at the rated power are very low. So, the probability of a failure occurring while the wind turbines are operating at the rated power is even lower. Therefore, rating the cables at regular conditions means they will be able to handle most of the cases when the power produced by the wind turbines is less than the rated power. This means that in some scenarios it is not necessary to turn off turbines because of the cable ratings. In short, the reason for analysing this approach is to see if it is reasonable to increase the cable ratings (as in the first approach) just to account for some scenarios that are very unlikely. Finally, the TRRC approach will have lower reliability indices (but not much lower, since this approach is limited for the less likely scenarios) than the TRU approach, but will have a lower investment cost.

### E. *Investment Costs*

Since this work is analysing the reliability of the use of a redundancy, only the additional costs for introducing the

TABLE IV
DATA USED FOR INVESTMENT COSTS

| Equipment or Service | Cost |
|---|---|
| Vessel and Installation of the Cable | 200 k€/km |
| Load Switch (with voltage and current measurement) | 10 k€ |
| Cable with a cross section of 95 mm$^2$ | 100 k€/km |
| Cable with a cross section of 120 mm$^2$ | 110 k€/km |
| Cable with a cross section of 150 mm$^2$ | 140 k€/km |
| Cable with a cross section of 185 mm$^2$ | 160 k€/km |
| Cable with a cross section of 240 mm$^2$ | 180 k€/km |
| Cable with a cross section of 300 mm$^2$ | 220 k€/km |
| Cable with a cross section of 400 mm$^2$ | 240 k€/km |
| Cable with a cross section of 500 mm$^2$ | 270 k€/km |
| Cable with a cross section of 630 mm$^2$ | 300 k€/km |
| Cable with a cross section of 800 mm$^2$ | 350 k€/km |
| Cable with a cross section of 1000 mm$^2$ | 360 k€/km |
| Cable with a cross section of 1200 mm$^2$ | 370 k€/km |

reliability increment are considered and compared to the additional income made by the use of this redundancy. The cost of the additional equipment added to increase the reliability of the wind farm is presented in Table. IV [13].

### F. Economic Evaluation

To proceed to the economic evaluation, it is necessary to compare the reliability indices and the investment costs with a reference base topology so that the new income (Cash Flow) and the additional necessary investment ($I_0$) are calculated. The topology used for comparison is called Base Topology. This topology is a radial design where all the elements added to the analysed topology to increase the reliability are excluded, namely the redundancies and the added equipment. The reason for choosing the radial design to be the Base Topology is because it is the design which has the lower reliability indices [6], [7], so every single increment in reliability is considered when evaluating the proposed topology. All reliability processes are evaluated for the Base Topology too. However, it is not necessary to perform the two approaches for cable rating selection, since this topology does not have any redundancies, so the results for each would be the same.

After calculating the reliability indices for the two topologies (proposed topology and base topology), it is possible to calculate the new income (Cash Flow) and additional investment ($I_0$) necessary to accomplish the proposed topology.

$$CF_y = (ENS_{Base\ Topology} - ENS_{Proposed\ Topology}) \times Selling\ Price \quad (8)$$

where, $CF_y$ is the cash flow at year $y$ [€], $ENS_{Base\ Topology}$ is the Energy Not Supplied for the base topology [MWh], $ENS_{Proposed\ Topology}$ is the Energy Not Supplied for the proposed topology [MWh], and $Selling\ Price$ is the energy selling price [€/MWh].

$$I_0 = Investment\ Cost_{Proposed\ Topology} - Investment\ Cost_{Base\ Topology} \quad (9)$$

where, $I_0$ is the additional investment at year 0 [€], $Investment\ Cost_{Proposed\ Topology}$ is the total investment cost for the base topology (see Table. IV) [€], and $Investment\ Cost_{Base\ Topology}$ is the total investment cost for the proposed topology (see Table. IV) [€].

From these results, all economic indicators necessary for the evaluation of the proposed topology are calculated, such as the NPV and IRR. For the calculation, it is necessary to make assumptions for the expected lifetime of the wind farm, for the discount rate and for the expected income per MWh. These assumptions are presented in Table. V.

### G. Software Validation

The topology used for the validation of the software is much simpler than the ones that are being simulated in this work. It is a double-sided half ring design composed of two strings, each one with four Vestas V90-3MW wind turbines. The base topology used to compare this topology is a radial design where all the elements added to the analysed topology to increase the reliability are excluded. For an easier calculation, it was considered that the wind turbines were operating at the rated power (3 MW) all of the time.

TABLE V
DATA USED FOR ECONOMIC EVALUATION

| Investment Data | Value |
|---|---|
| Expected lifetime of the wind farm | 20 years |
| Discount rate | 0.07 |
| Selling price | 100 €/MWh |

Two different validations were conducted, one where all the calculations were made by hand and another one where all the calculations were made by a third-party reliability software.

For the results obtained by the calculations made by hand, the reliability results presented a small divergence in the ENS values (less than 0.31%) can be seen. This happens because in the hand calculations the power losses are not considered, for simplicity. The results of the investment cost are equal. The differences in the economic indicators are caused by the previously mentioned divergence in the ENS values.

For the results obtained by the third-party software, the reliability results presented a small divergence in the ENS values (less than 0.63%) can be seen. This is due to the way the third-party software makes its reliability analysis calculations: since wind generators are modelled as loads and the delivery point as a generator, the power flows end up with directions opposite to the real ones. The results of the investment cost are equal, because the third-party software does not select the cable ratings, it only analyses the reliability for the given topology. The differences in the economic indicators are caused by the divergence within the ENS values.

## III. WIND FARM PROPOSED TOPOLOGIES

The proposed topologies analysed in this work can be separated in two different groups. The first one is all the topologies with a redundancy between each pair of two strings (Redundancy between two strings). The other proposed topologies introduce a new design, which is characterized by a redundancy between the already redundantly paired sets of strings (Redundancy between two redundantly paired strings).

### A. Redundancy between two Strings

The topology that was tested in this work is the double-sided half ring design, since this is the one which presents better reliability and economic results [6],[7]. Since the reliability analysis needs a base topology to compare the increase or decrease in reliability to, the topology adopted for that is the one presented in Fig. 1. The topologies that are being reliability analysed have a redundancy between the two strings and they are based on the double-sided half ring design. The purpose of this analysis is to evaluate which location is the best for the redundancy. These are composed of two strings with 10 wind turbines each and one redundancy. Each proposed topology has a different location for this redundancy. There are eight possibilities for the location of the redundancy for this design which are presented in Fig. 2. The first topology has a redundancy in location 1, the eighth topology has a redundancy in location 8 and the other six are the other possible locations

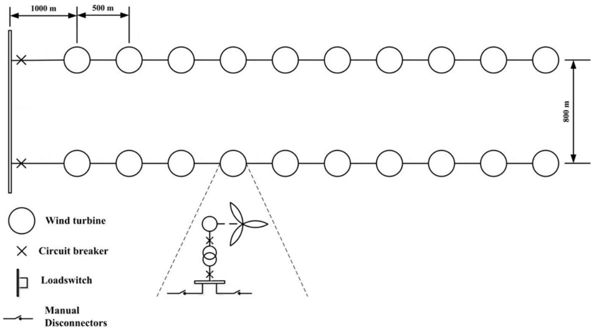


Fig. 1. Base case: topology without redundancy.

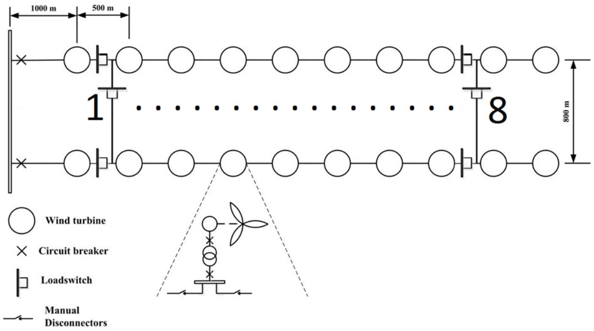


Fig. 2. Proposed topology: topology with eight possible locations for redundancy.

between them.

### *B. Redundancy between two Redundantly paired strings*

In most recent years, large offshore wind farms are appearing like the London Array (630 MW) in the United Kingdom or the Gemini (600 MW), in the Netherlands, which will be operational in 2017 (expected). This highlights the importance of using redundancies in wind farms and researching new topology designs. Until now, topologies only introduce redundancies between two isolate strings. In this work, a new type of topology design is proposed. These topologies analyse analyse the introduction of a redundancy between an already redundantly paired set of strings. At first glance, these topologies give an important advantage with the introduction of one more redundancy - if a fault occurs, the power generated by the wind turbines within the faulted string can be distributed to the others strings. This means that it will not be needed to increase the cable ratings much more for them to be able to handle all the generated power.

The first proposed topology of this kind is based on the double-sided half ring design and double-sided ring design and is presented in Fig. 3. The second one is based only on the double-sided half ring design and is presented in Fig. 4. The other four topologies proposed are based on the double-sided half ring design, but the location of the redundancy is different. The location of the redundancy for these topologies is between locations 3 and 6, as defined above. One example of these proposed topologies is one with a redundancy in location 5, presented in Fig. 5. It is important to note that the topologies defined in Fig. 2 only introduce redundancies between two strings, they do not introduce a redundancy between each redundantly paired set of strings, like the proposed topologies just mentioned.

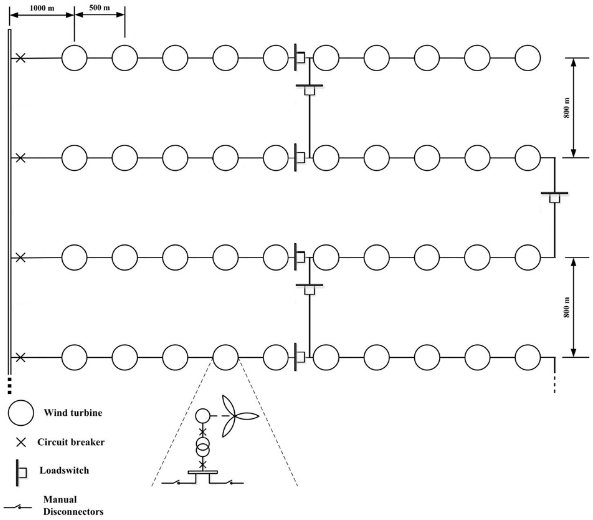


Fig. 3. First proposed topology: based on double-sided half ring design and single-sided ring design.

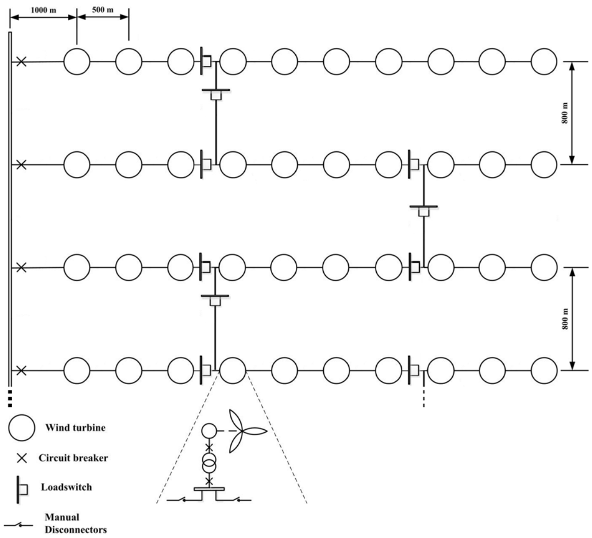


Fig. 4. Second proposed topology: based on double-sided half ring design.

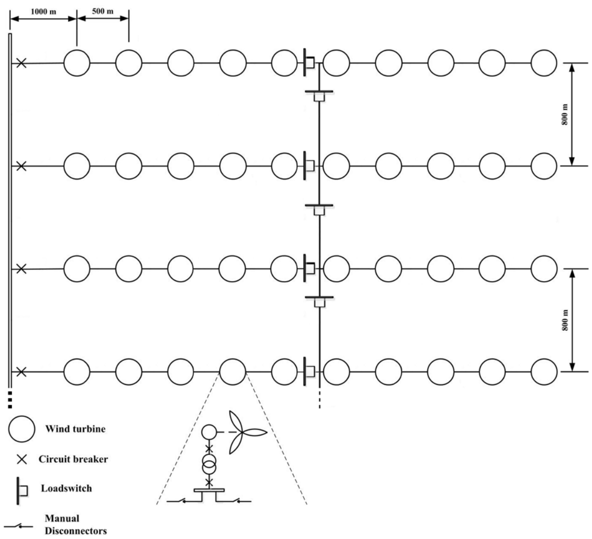


Fig. 5. Fifth proposed topology: redundancy on location 5 and based on double-sided half ring design.

## IV. RESULTS

The first analysis made was to evaluate the proposed topologies characterized by a redundancy between two strings (classical redundancy design). Also, a sensitivity analysis was developed for these topologies. The last analysis made was to evaluate new designs which are characterized by a redundancy between the already redundantly paired sets of strings (new redundancy design). An additional simplified sensitivity analysis was then performed for the best topologies for both designs evaluated in this work.

### A. *Classical Redundancy Design*

One of the focus of this work is to select the best location for the redundancy of all the possible locations on the double-sided half ring design. The double-sided half ring design which was presented in [6] only considered the location of the redundancy in the middle of the string. However, more possibilities exist, and each one has its pros and cons. So, it is necessary to analyse all of them and evaluate which one presents the best economic indicators. To accomplish that, eight different topologies were proposed (see Fig. 2) and analysed. As explained before, the developed software analyses two different approaches for the selection of the cable ratings that will lead to two different sets of results.

#### *1) Topology with Rating Upgrades*

The first approach for cable rating selection was the TRU, where the cables are rated to handle all the power produced by all online turbines when any failure occurs.

The reliability results for the TRU approach for all possible locations of the redundancy are presented in Fig. 6. As it can be seen the location that has the best Energy Not Supplied (ENS) is the 5th. This result can be explained by the fact that this location divides the string into two equal parts, which gives the best ratio for all possible faults.

For the Investment Cost and since this topology rates the cables to handle all of the power, depending on the redundancy location more cables may need upgrading. If the location is moved on to the right, more cables must be upgraded. This justifies an increase in the Investment Cost when the redundancy is moved to the next spot. These results can be seen in Fig. 7.

After the reliability results and the Investment Costs, the calculation of the economic indicators, which are the NPV

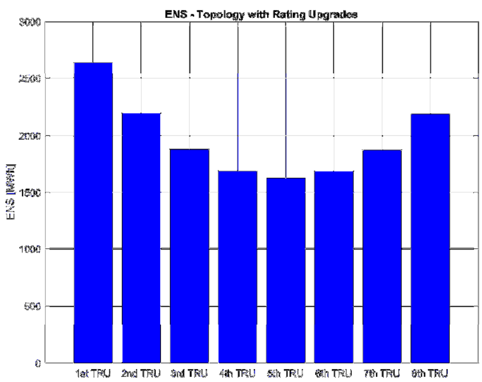


Fig. 6. ENS for the proposed topologies with rating upgrades (TRU).

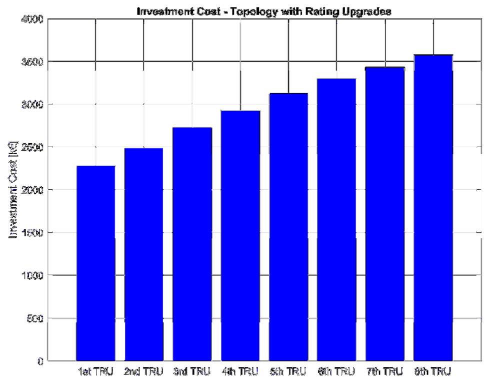


Fig. 7. Investment cost for the proposed topologies with rating upgrades (TRU).

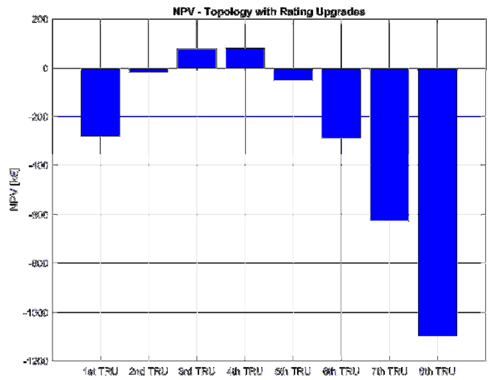


Fig. 8. NPV for the proposed topologies with rating upgrades (TRU).

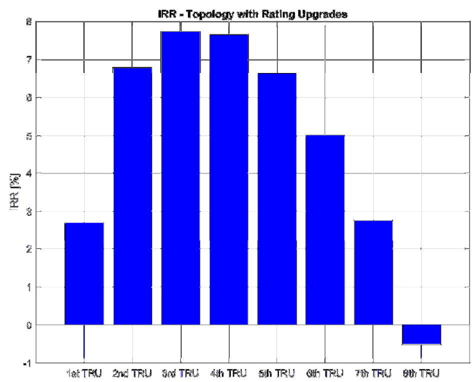


Fig. 9. IRR for the proposed topologies with rating upgrades (TRU).

(presented in Fig. 8) and the IRR (presented in Fig. 9), can now be made. Analysing both, it is possible to conclude that only the 3rd and 4th redundancy locations present positive results. Although the 4th location presents the best $NPV = 79.9\ k€$, the 3rd location is the one which has the best $IRR = 7.73\%$.

#### *2) Topology with Ratings for Regular conditions*

The second approach for cable rating selection was the TRRC, where the cables are rated to handle all the scenarios for regular conditions (where no faults occur).

The reliability results for the TRRC approach for all the possible locations of the redundancy are presented in Fig. 10. As it can be seen, the location that has the best Energy Not Supplied (ENS) is the 5th. The explanation made above for the

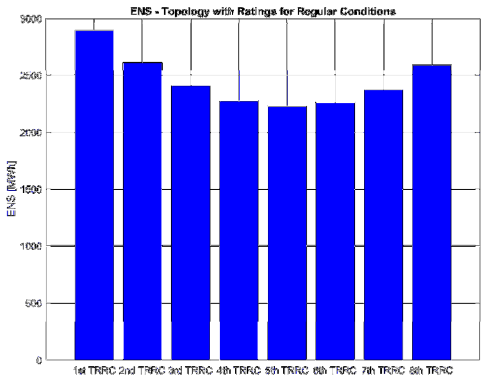


Fig. 10. ENS for the proposed topologies with ratings for regular conditions (TRRC).

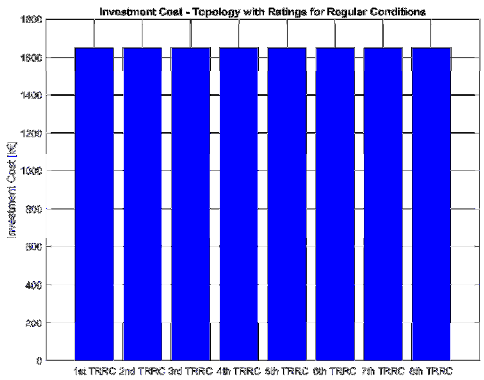


Fig. 11. Investment cost for the proposed topologies with ratings for regular conditions (TRRC).

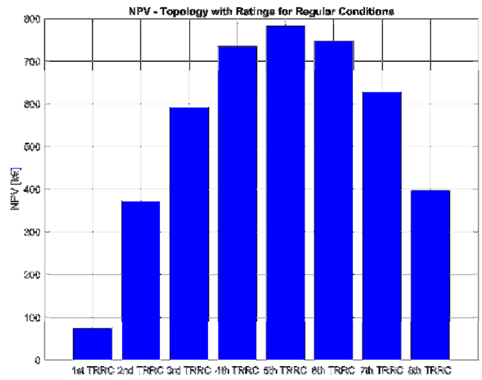


Fig. 12. NPV for the proposed topologies with ratings for regular conditions (TRRC).

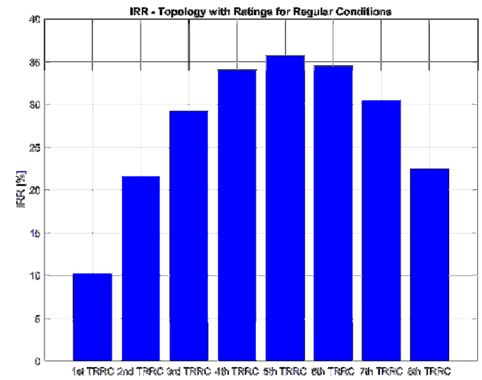


Fig. 13. IRR for the proposed topologies with ratings for regular conditions (TRRC).

TRU approach also applies here. So, depending on the location, each side will have greater or less severe situations and it is only possible to determine the location which has the best adequate situations through numerical simulations.

The Investment Cost results are presented in Fig. 11. As it can be seen, all possible locations have the same results. That is a consequence of the approach for cable rating selection that is being used. This selection is made for the regular conditions, that are the same for all possible redundancy locations.

After the reliability results and the Investment Costs, the economic indicators (NPV presented in Fig. 12 and IRR presented in Fig. 13) can now be calculated. Analysing both, it is possible to conclude that all the possible redundancy locations present positive results. The one that presents the best economic results is the 5th location, with $NPV = 783.1\ k€$ and $IRR = 35.76\%$.

*3) Discussion*

After analysing all the possible redundancy locations for both rating approaches, the pros and cons of each one become more evident. For the reliability results it is clear, comparing both approaches, that the TRU presents the best results as far as the ENS is concerned. This is a consequence of the ratings being chosen to handle all the power for all possible scenarios, unlike what happens for the TRRC.

The differences within the Investment Costs are significant and the TRRC approach is the one which presents the lower values, as expected. This can be explained by the fact that the cable ratings are the same for the regular conditions and the base topology, so the investment cost only represents the cost of the introduction of the redundancy. This does not happen for the TRU approach, where the cable upgrades represent an increase in the Investment Costs.

Analysing the economic indicators, it is clear that the TRRC approach presents the best results in this area. Comparing both approaches, the results can be explained by the fact that the higher ENS obtained for the TRRC approach is compensated by the decrease of the investment costs. So, it is proven that the money invested to increase the cable ratings to handle all the possible faulty scenarios is not worth it for an investor, since the most severe scenarios have a really low probability.

Comparing the economic indicators for the best topologies from both approaches, it is possible to conclude that overall the best topology is the TRRC approach with a redundancy in the 5th location.

## *B. Sensitivity Analysis*

A sensitivity analysis is a tool for finding out how the results from the reliability analysis vary when the input parameters are changed. This type of analysis is suitable when the input data suffers from a high degree of uncertainty. This is the case for the reliability data (presented in Table. II), the investment costs (presented in Table. IV) and the energy selling price (presented in Table. V). For the reliability data there is a lack of information and the one that exists is not coherent [15], [6], [12], [13]. The main reason for this variation is the uncertainty of the weather conditions, which leads to uncertain failure rates and outage times. There is a lack of information for the investment costs too, which can be explained by the confidentiality involved in the Offshore Wind Farm projects. For the selling energy price, the values can vary a lot depending on the country which is being considered [16]. The sensitivity analysis was performed for the two cable rating approaches for all proposed topologies with a redundancy between two strings.

So, to reach trustworthy results, the sensitivity analysis was performed through various simulations where each identified input varied separately. The range of variation of the selected inputs are based on the values presented in the academic literature [15], [6], [12], [13]. For the reliability data, a separate analysis was performed for the failure rates of the submarine cable (varying from 0.2% to 1.2%), the disconnector (varying from 0.5% to 4%), the circuit breaker (varying from 1.5% to 6%), the load switch (varying from 0.5% to 4%) and the outage time (all the repair time maintain the ratios between them and that ratio varying from 1 to 3). An analysis varying the investment costs (ratio varying from 0.5 to 2) and the selling price (varying from 50 €/MWh to 200 €/MWh) was also performed.

For the NPV results, the variations on the input parameters will lead to higher variations for the TRU approach than for the TRRC. This happens because the TRU approach handles more power scenarios leading to a higher increase of the income cash flow. However, the opposite happens for the IRR. Since the investment cost for the TRU approach is much higher than for the TRRC, the additional extra income cash flow for the TRU is lower when indexed to the investment made.

### C. *New Redundancy Design*

This last analysis was made to evaluate a new type of design, characterized by introducing redundancies across sets of two strings already paired by one redundancy. These topologies give an important additional advantage – if a fault occurs, the power generated by the wind turbines within the faulted string can be distributed to the others strings. Because of that only the TRU approach will be analysed. These topologies are composed of ten strings with 10 wind turbines each, and have been called 1st NRD, 2nd NRD, 3rd NRD, 4th NRD, 5th NRD and 6th NRD. In order to compare the results obtained from this analysis with the results already shown above for the best classical topologies in the previous sections (TRRC with redundancy in the 5th location and TRU with redundancy in the 3rd location), all of them are shown side by side.

The reliability results for the new redundancy design topologies are presented in Fig. 14. The location that gives the lowest Energy Not Supplied (ENS) is the 2nd NRD. This has the same explanation than the one presented before – the location of the redundancies divide each string into 3 equal parts. It is visible that all the new proposed topologies present better ENS results than the ones which only had one redundancy between each pair of strings.

For the Investment Cost, and since the topology approach for the cable rating was the TRU, depending on the redundancy locations different cables must be upgraded. All the results can be seen in Fig. 15. It is visible that the 1st and 2nd NRD are the ones which show higher investment costs. This can be explained because in case of a failure all the distributed generator power of the faulted string needs to flow over to the cables in the centre of the strings, so the rating of these cables and the ones on the left side must be upgraded, resulting in higher investment costs. The difference between these two is that the 2nd NRD needs to use more load switches compared with the 1st topology, as seen in Fig. 3 and Fig. 4. For the other ones, since the location is the same for every redundancy, all the strings are only divided into two, so there are not cables in the middle of the string that are necessary for the distribution of the power when a failure occurs. This will result in lower investment costs.

After the reliability results and the Investment Costs, the economic indicators, which are the NPV (presented in Fig. 16) and the IRR (presented in Fig. 17), can now be calculated. Analysing both indicators, the topology that presents the best economic results is the 5th NRD, with $NPV = 3934.7\ k€$ and $IRR = 16.75\%$. One important thing to note is that all the new proposed topologies are investor attractive – they all have positive economic indicators.

Comparing these topologies with the topologies that only have one redundancy between every two strings, it can be seen that the 5th NRD topology is the one which presents the higher

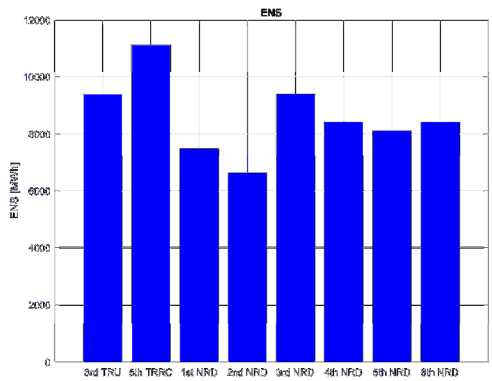


Fig. 14. ENS for the proposed topologies with redundancy between two redundantly paired of strings.

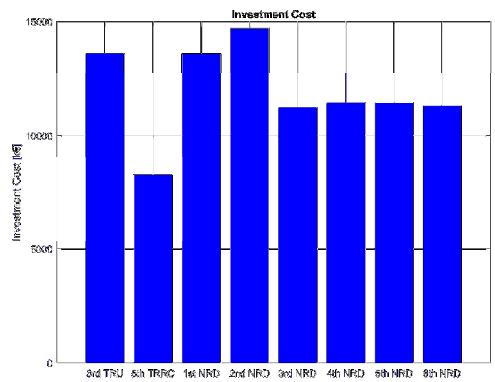


Fig. 15. Investment cost for the proposed topologies with redundancy between two redundantly paired of strings.

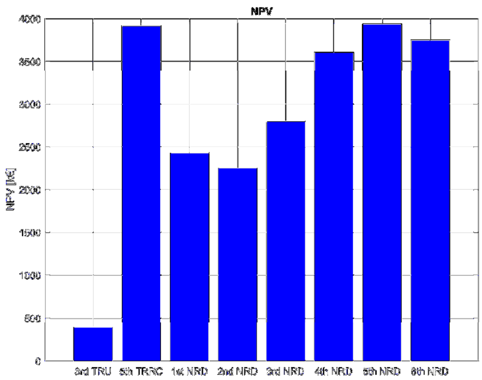


Fig. 16. NPV for the proposed topologies with redundancy between two redundantly paired of strings.

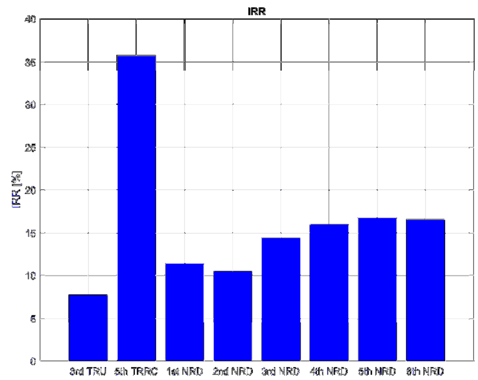


Fig. 17. IRR for the proposed topologies with redundancy between two redundantly paired of strings.

NPV from all the topologies studied in this work. As far as the IRR is concerned, it is visible that the topology with the cable ratings based on the TRRC approach with a redundancy in the 5th location is the one which shows the best results. This is caused by its lower investment cost, compared to the others. So, this is the topology that is more worth the invested money for an investor (with $NPV = 3915.7\ k€$ and $IRR = 35.76\ \%$).

A simplified sensitivity analysis was performed to evaluate how the results from the reliability analysis vary for the best classical redundancy design topology (5th TRRC) and the best new redundancy design topology (5th NRD). Since this is a simplified analysis, the input parameters chosen to be variable are the ones which present more sensitivity variation on the output. These parameters are the outage time, the investment cost and the selling price. The range for the variation was the same as the before sensitivity analysis. Since the NRD topologies are based on the TRRC approach, the conclusions from the NPV and IRR results are: for the NPV results, it is visible that the variations on the input parameters will lead to higher variation for the 5th NRD approach than for the 5th TRRC; for the IRR results, the variations on the input parameters will lead to higher variation for the 5th TRRC approach than for the 5th NRD.

## V. Conclusions

From all the results, the topologies characterized by a redundancy between already redundantly paired sets of strings are the ones with best reliability results. However, the topology with cable ratings based on the TRRC approach with a redundancy in the 5th location is the one that is more attractive for an investor (high NPV and highest IRR).

For future studies, it would be interesting to refine the software piece to test other rating approaches. For example, an intermediate approach, to be capable of handling more scenarios than the TRRC, but not to handle all of them like the TRU. It could also test every possible combination for the ratings and find out the best one. An interesting refinement that could also be made to the software piece would be to have it receive as an input just the locations of the wind turbines, and have it calculate the best topology arrangement. For this it would have to test every possible topology with every possible redundancy, perform a reliability analysis and calculate the respective economic indicators.

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