Benefits in moving the intra-array voltage from 33 kV to 66 kV AC for large offshore wind farms

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Abstract:

It has been found that wind farms operating at higher intra-array voltages than is currently the norm will benefit from a reduction in cost of energy of up to 1.5%. This paper highlights the potential for higher voltage intra-array systems to reduce the number of cable strings entering a platform as more wind turbines can be connected per string, reduce system loses, to increase availability, reduce overall cable length and the number of substations. This delivers significant cost benefit to the design of future offshore wind farms. In addition, as the power rating of modern turbines continues to increase, the reduction in the cost of energy due to a 66 kV intra-array circuit increases further, meaning that the move to higher voltage is a natural choice.

A detailed comparison of 33 kV AC (rated at 36 kV) radial and ring intra-array systems with 48 kV AC (rated at 52 kV) and 66 kV AC (rated at 72.5 kV) radial and ring intra-array systems was undertaken. This involved analysis and design work for all key technical components of the system, i.e. cables, switchgear, transformers, wind turbine structures and offshore substations. In particular, design packages were completed by cable, switchgear and transformer designers/ manufacturers in order to optimise equipment to be used a higher voltages to ensure that designs could be realistically achieved and provide realistic inputs for the cost benefit analysis. The intra-array designs were optimised and compared. A detailed cost-benefit analysis was carried out in order to compare the systems. This included CAPEX, operation and maintenance, cost of system losses and cost of losses due to cable failure for an assumed wind farm lifetime of 25 years. A further qualitative comparison was performed to identify other risks and benefits, including supply chain, health and safety and operation and maintenance considerations. Finally, the optimal higher voltage system was identified and a roadmap was developed to identify the route to commercialisation.

It was found that moving to either 48 kV or 66 kV demonstrated a material improvement in the full life costs compared with 33 kV. However, the improvement for 66 kV was the highest and the number of 48kV equipment vendors is limited compared to 66kV, which gives little reason to prefer 48kV over 66kV.

1 Introduction

In January 2010 The Crown Estate in the UK announced the successful bidders for each of the nine zones in Round 3 of its offshore licensing programme. These zones represent a total capacity of 25 GW, which together with 8 GW from Round 1 and Round 2 programmes leads to a potential UK offshore wind capacity of 33 GW. Whilst this will potentially be a major contributor towards the UK Government's 2020 target of 15% of all energy to be supplied by renewable sources by 2020, there are significant challenges in developing offshore wind to be overcome. In July 2011, the Government made it clear in its UK Renewable Energy Roadmap [2] that the cost of electricity from offshore wind would have to fall significantly by 2020.

The current cost of around £140 per MWh need to be reduced to around £100 per MWh in order to maximise the size of the industry [3][4]. The industry therefore faces a significant challenge to reduce lifetime costs, hence innovation and new technology is required to contribute towards this cost reduction.

The intra-array network of an offshore wind farm collects power from individual wind turbines. At present, the standard intra-array voltage is 33 kV and for larger wind farms the voltage is stepped up at an offshore substation with power being transmitted back to shore at either a higher alternating current (AC) voltage (such as 132 kV or 220 kV) or using VSC-HVDC (direct current, DC) technology, depending on the transmission distance to shore.

The Carbon Trust's Offshore Wind Accelerator (OWA) is a collaborative R&D program between the Carbon Trust and eight major offshore wind developers – DONG Energy, E.ON, Mainstream Renewable Power, RWE Innogy, ScottishPower Renewables, SSE Renewables, Statkraft and Statoil – that aims to reduce the cost of offshore wind by 10%. One key focus area of this ground breaking collaborative R&D program is to reduce costs and increase availability by optimising intra-array electrical systems. Higher voltage arrays have been identified to deliver significant cost benefit to the design of future offshore wind farms. Previous work has examined the potential for higher voltages (48 kV or 66 kV) to be used to connect wind farms without an offshore substation [1] but this is the first time that a full analysis has been carried out for the use of higher voltage intra-array systems for wind farms that are far offshore and still incorporate a high voltage AC or high voltage DC (HVAC or HVDC) transmission system. The work described in this paper has analysed the viability and cost benefit of moving to higher voltage arrays by evaluating, in detail, all the elements of a large scale offshore wind farm that change as a result of the move to a higher array voltage. This has included detailed cost information obtained from manufactures and concept designs to ensure that the systems are practically achievable.

Stage 1 of this electrical workstream was carried out by TNEI and identified the potential for higher voltage arrays to deliver significant cost benefit to the design of future offshore wind farms. The objective of Stage II was to extend this work to explore the viability and cost benefit of moving to higher voltage arrays by evaluating, in detail, all the elements of a large scale offshore wind farm that change as a result of the move to a higher array voltage.

2 Methodology

Electrical intra-array systems at 33 kV (for the base case), 48 kV and 66 kV were designed. Two projects were used for the analysis. Project A consisted of 279 3.6 MW wind turbines, sited 20 km from shore at a water depth of 20 m. Project B consisted of 201 5 MW wind turbines, sited 50 km from shore at a water depth of 45 m.

Designs with three substations were made for voltages of 33 kV and 48 kV. At 66 kV it was found that the total generation could be connected to one substation, so designs were carried out for one and two substations for 66 kV. DIgSILENT was used to analyse the designs. This is an industry standard power systems analysis tool for the analysis for industrial, utility and commercial electrical power systems. It was used to check the fault levels and the currents, and to model the instantaneous losses and thereby enable the system energy losses to be calculated. Finally, a discounted cash flow (DCF) calculation was carried out to enable the systems to be compared

2.1 Power Systems Analysis

Load flow analysis was carried out in DIgSILENT. The 40% and 100% load losses were measured at the shore in each case. The 40% loss value was used to calculate the energy losses – i.e. it was assumed that the wind farm had an average capacity factor of 40%.

The losses were measured at the shore in order to ensure that the overall wind farm loss was comparable with the figure obtained in the 33 kV base case. The intra-array cables were sized in order to achieve a similar loss and also to ensure that the cables were not overloaded. As the losses were measured at the shore, it was ensured in the models that the transmission from the substation to the shore was the same (i.e. the number and sizes of cables were not changed), so that transmission losses were the same for all the cases and the change in losses was due only to the change in the array voltage and configuration.

The load flow calculation also enabled the current at offshore substations to be determined. It was checked for each design that these current values were within reasonable limits.

Fault level calculations were also performed to ensure that the fault levels at the switchboards and in the intra-array circuits were below 25 kA.

2.2 Ring and Radial System Design

The maximum number of turbines on each string was determined by calculating the cable conductor required for full output power, modelling the losses at 40% load and calculating the array cable CAPEX. There is clearly a trade-off between reducing losses (using larger cables) and reducing CAPEX (by minimising the cable size). The higher voltage designs were carried out by considering the 33 kV loss as the target loss value. In many cases, lower losses were achieved for the higher voltage designs. As for the 33 kV base case, a tapered design was used in which two cable sizes were selected with the larger cables being found nearest the substation. In wind farm design, either two or three different cable cross sections are generally selected for the radial strings, depending on the trade-off between cable CAPEX and installation costs (i.e. more cable cross sections will introduce more installation complexity and hence cost). The largest intra-array cable size was taken to be 630 mm^2 for the intra-array designs.

Cable redundancy can be achieved by joining pairs of radial strings with a cable between the furthermost generators on the string. The worst case failure would be in the instance in which the cable failure was incurred in the cable nearest to the substation, in which case the cables would be required to carry the total capacity of the two strings. 75% rated rings were designed for all three system voltages (i.e. the ring could carry out to 75% of the total power of the two joined radial strings). 75% rated rings were selected for the 33 kV base case because 100% rated rings are very difficult to implement at this voltage due to the size of cable required, so this rating was selected as a compromise between an achievable design and minimising the lost energy.

Cable failures lead to significant energy losses and NPV penalties with increasing size of ring configurations, depending on cable failure rate, time to repair and repair costs. This strengthens the case for fully rated rings, which were also designed for the 48 kV Project B and 66 kV Project B.

Schematic showing radial and ring designs of one substation for the 33 kV base case are given in Figure 1 and Figure 2.

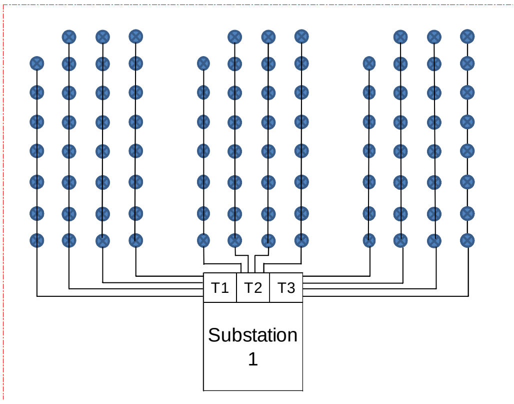

Figure 1 – Schematic of a radial design for the 33 kV base case showing a single substation

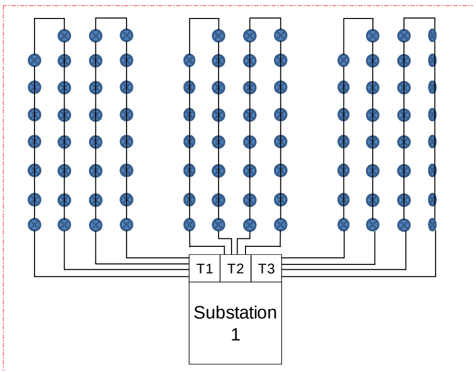

Figure 2 – Schematic of a ring design for the 33 kV base case showing a single substation

2.3 Availability Calculation

Wind farm availability is a function of both generator availability and availability of other equipment such as cables, transformers and switchgear. For the analyses carried out it was assumed that the generator availability was 100%, because it was important to focus on the differences between systems at different voltage levels and it could be assumed that generator availability would be the same for any intra-array system voltage.

The most important component in terms of availability, and the one that could potentially change the most between the base case and the higher voltage systems, was the cable availability. This was because the lengths of the radial strings differed between the base case and the higher voltage designs, and the size of the rings for the ring intra-array designs also changed. In order to understand the effect of cable availability, it was necessary to identify the Mean Time to Repair (MTTR) and the failure rate of the cable. It was found that life cycle cost is very sensitive to cable failure rate assumptions and therefore a wide range was used. The worst failure rate assumed 3 failures per year on a 1 GW wind farm with 200 wind turbines and 200km of cable installed. In contrast the best failure rate assumed one failure every 6 years on the same wind farm. As no values are published yet by Cigré for wet type intra-array cables, these values were based on published data for other cable types. The values were varied as sensitivities and agreed with the industry partners and are given in Section 2.5.

In order to calculate the reliability of the intra-array system, taking into account the cable failure rate and the mean time to repair, the following formula was applied:

$$\begin{aligned} &Lost\ Generation\ in\ MWh/annum \\ &\qquad = MTTR \times r \times G \times l \end{aligned}$$

where:

- MTTR = Mean Time to Repair (hours)
- r = failure rate/km/annum
- G=lost generation when cable failure occurs (MW)
- l=cable length (km)

It was assumed that on average the cable would fail half way along the string, hence slightly more than half the generators in a string would be lost on average (e.g. four generators would be lost for a seven-generator string).

2.4 Discounted Cash Flow

A discounted cash flow was carried out for each model, which included the cash flows from each year of the operation of the project. The inflows were the yearly delivered power multiplied by the energy price (i.e. the revenue), taking into account the availability calculations and the outflows included capital costs and O & M costs.

The NPV of the reduction in lost revenue was calculated using the standard formula, i.e.

$$NPV = \sum_{t=1}^{N} \frac{R}{(1+i)^t}$$

where:

- N = number of years
- R = net cash flow
- i = discount factor (%)
- t = time of cash flow (i.e. the year number)

The difference in the NPV between the base case and the higher voltage systems was therefore calculated, and this enabled an economic comparison to be made for each option considered.

2.5 Assumptions

The assumptions that were used as inputs to the cost-benefit model are given in Table 1.

Parameter	Value
Discount Rate	7%
Energy Price	£150/MWh
Interest Rate	3%
Cable Availability Failure Rate	Best = 0.0008 failures/km/annum Mid = 0.0094 failures/km/annum Worst = 0.015 failures/km/annum
Cable Availability MTTR	Best = 1 month Mid = 2 months Worst = 3 months
Transformer Availability Failure Rate	Best = 0.0131 failures/km/annum Mid = 0.0131 failures/km/annum Worst = 0.0131 failures/km/annum
Transformer Availability MTTR	Best = 10 days Mid = 20 days Worst = 30 days
Wind Farm Life Time	25 Years

Table 1 – Input Assumptions for Modelling

A "best case" cable failure was defined to be a combination of best case cable failure rate and shortest Mean Time to Repair (MTTR), whilst the "worst case" cable failure was defined as a combination of the worst case cable failure rate and the longest MTTR.

3 Higher Voltage Switchgear and Transformers

As part of this programme of work, a number of suppliers for higher voltage switchgear and transformers provided information regarding available equipment that could be used for the higher voltage systems. Two options for switchgear available at 48 kV were found to be relatively low cost and had the ability to fit within a wind turbine tower.

Hybrid GIS/AIS 66 kV switchgear appeared to be particularly promising. The cost was found to be considerably cheaper than the cost of full GIS equipment, which is specified on a project basis and can have complex arrangements.

The switchgear of both suppliers was also identified by Garrad Hassan as potential switchgear for higher voltage arrays in [1].

A slim type transformer was particularly promising, as these transformers are already commonly used in 33 kV systems and fit within the wind turbine tower. It was found that a naturally cooled transformer could be made available for the 48 kV systems which would also fit within the wind turbine tower. For the 66 kV systems, a force cooled version was identified. Both transformer types were found to have reasonable costs when compared with the 33 kV transformers on a cost per rated MW basis.

4 Higher Voltage Wet Type Cables

"Wet-type" cables without a lead sheath are currently used for the intra-array system at 33 kV and these are significantly cheaper than "dry-type" cables which incorporate the lead sheath. The water blocking for wet type cables is performed by the XLPE or EPR insulation. As part of this programme, two cable manufacturers put forward designs for 48 kV and 66 kV wet type cables. Whilst both cable types were marginally more expensive than a 33 kV cable, this cost increase was more than outweighed by the increase in power transmission capability that a higher voltage cable could provide, as illustrated in Figure 3. Both cable manufacturers also provided cable parameters (i.e. capacitance, inductance, resistance and current capability) which were used as inputs into the power systems modelling. However, such cables are not yet certified and commercially available on the market.

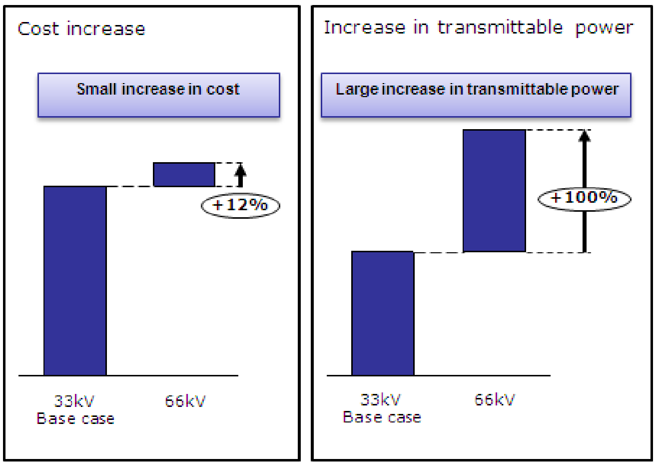

Figure 3 – Increase of cost and power transmission capability

5 Wind Turbine Structural Costs

Work was also carried out to assess the increase in structural costs associated with moving to a higher intra-array system voltage. The options that were considered were:

- All equipment inside the wind turbine tower
- Transformer outside and high and low voltage switchgear in the tower
- Transformer and low voltage switchgear outside and high voltage switchgear in the tower

Initially it had been thought that higher voltage equipment might not fit within the tower, but in fact higher voltage equipment was identified that could be incorporated in the tower for both 48 kV and 66 kV systems. In order for a comparison to be made with the 33 kV systems, a structural package cost for 33 kV was calculated from the outcome of a structural design package.

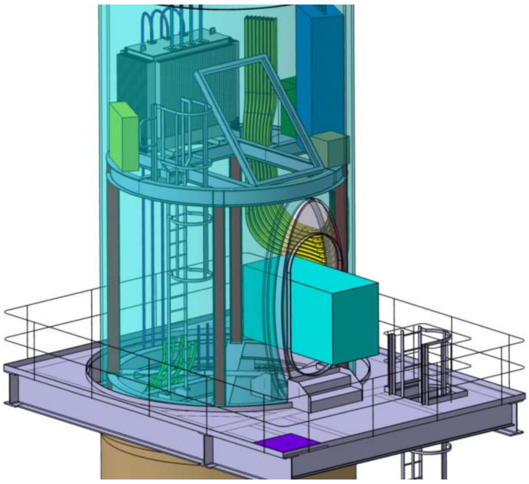

Figure 4 – Conceptual diagram showing switchgear passing through the wind turbine tower door

However, in order to maintain flexibility, options for housing equipment outside the wind turbine tower were also assessed. These options gave the advantages that wind turbine developers would be free to specify the equipment (rather than equipment being provided by the wind turbine manufacturers). In addition, larger types of equipment could be selected which would give further component choice. It was assumed that a marinised container would be required to house the equipment externally in order to protect equipment and reduce the routine maintenance required. However, it was found that the marinised container itself introduced a significant cost penalty into the overall system cost.

6 Other Included Costs

Costs for all the additional offshore substation equipment were included in the detailed CAPEX model as the quantities of these components were subject to change for different offshore substation configurations. These additional components were:

- Offshore substation switchgear
- Feeder protection and control equipment
- Substation transformer protection
- SCADA
- Ancillary equipment
  - LVAC board
  - Voltage transformers
  - Cables
  - Earthing
  - AC and DC systems distribution boards

7 Results

An example of the reductions in cost of energy for a 66 kV configuration versus the 33 kV radial base case are displayed in Figure 5. It should be noted that the 66 kV results were obtained for fully-rated rings, and compared with 75% rated rings for the 33 kV base case. At 33kV only 75% rated rings were realistic given the cable sizes required. It can be seen that for best availability the benefits of increased availability does not outweigh the additional cost of a 33 kV ring. However, at 66 kV use of a ring is better than use of a 33 kV radial design for all availability figures.

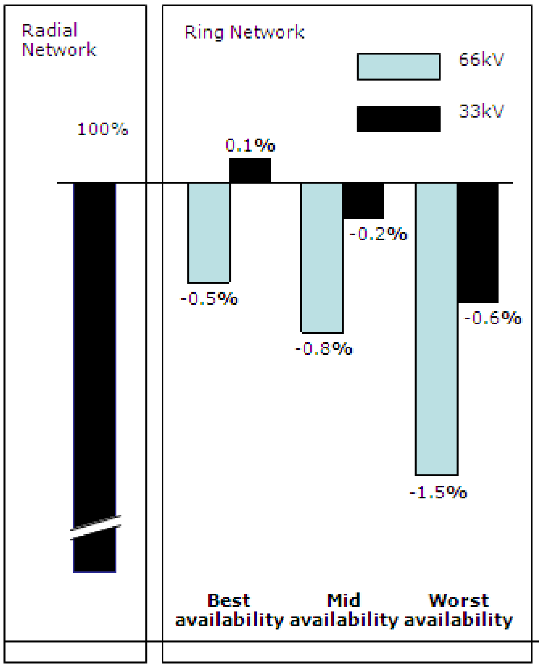

Figure 5: Reductions in cost of energy for a 66kV configuration

If the case of best availability is assumed, the % reduction in the cost of energy is 0.6% for a radial 66 kV design compared with a radial 33 kV design because an offshore platform structure can be removed. Therefore, even if experience shows that the best availability figure is most likely, a greater benefit could be obtained from a radial design.

Figure 6 illustrates an example of a copper XLPE ring system at 66 kV compared to a 33 kV radial system in copper XLPE for the worst case cable availability. It can be seen that the improvement in NPV is driven by the reduction in the number of substations and associated equipment (i.e. a saving of two substations versus the 33 kV configuration with three substations) and the reduced lost revenue due to increased availability (i.e. the ring design). There is some cost penalty in terms of wind turbine equipment – i.e. transformers and switchgear are slightly more expensive and there is an increased structural cost to accommodate the heavier equipment. However, as low cost equipment at 66 kV was identified, these cost penalties are far outweighed by the benefits. In addition, the cable CAPEX is slightly higher due to cables being sized for a fully rated ring.

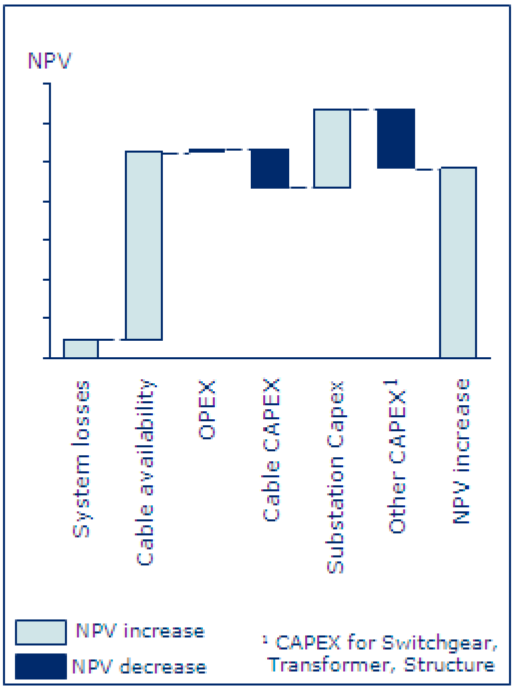

Figure 6: Costs and Benefits for the Copper XLPE Fully Rated Ring Design versus the 33 kV Radial Base Case for Worst Case Cable Availability

8 Roadmap for Implementation

The concept of Technology Readiness Levels (TRLs) was introduced in order to develop a roadmap for implementation of the 66 kV intra-array system. TRLs are widely used across many different industries to describe the process by which an insight or scientific breakthrough becomes a real-world operational system. They are principally used for technology, but are applicable to any concept-to-launch cycle.

The qualification and type testing for the new higher voltage cables was found to be the critical path for a higher voltage system. 66 kV switchgear and transformers were found to be available at a reasonable cost but some modifications and improvements could be made, particularly for the 66 kV transformers, such as reducing dimensions.

Following the cables, the next longest lead time was predicted to be for the wind turbine manufacturers to develop 66 kV turbines. A number of turbine manufacturers including Siemens, REpower and Vestas are already considering 66 kV systems – Vestas has announced a 66 kV 7MW turbine – so as long as this technology option is included in their new products, it is not expected to be on the critical path for commercializing 66 kV. Further detailed engagement with wind turbine manufacturers is recommended to emphasis the demand for 66 kV turbines from offshore wind developers.

9 Conclusions

Both of the higher voltage systems were found to exhibit NPV improvements versus the 33 kV systems. The 66 kV system exhibited greater NPV improvements than the 48 kV system.

A key benefit of moving to 66 kV is that it should be possible for an intra-array cable to carry double the power with only a small increase in its cost. This leads to the ability to implement ring array systems economically and with viable electrical designs at 66 kV. At 33 kV only 75% rated rings were realistic given the cable sizes required. From a design perspective, the 66 kV fully rated ring was found to have a more optimal design than the 48 kV fully rated ring as only 12 J-tubes with 630mm^2 cable were required per offshore platform rather than 16 J-tubes with 630mm^2 cable.

In addition, for a given installed wind turbine nameplate power density (MW/km^2) a higher voltage array permits the energy from a larger area to be collected and exported through a single offshore platform. This may become a greater advantage as wind farms move even further offshore and offshore platforms potentially become even more expensive. This is possible because more turbines can be connected to a sting and therefore the number of J-tube connections to the platform is reduced. Also, when the voltage is doubled the current is halved, and therefore more strings of wind turbines can be accommodated at the substation busbar.

Housing equipment externally was found to have a CAPEX impact that outweighed any operation and maintenance improvements. Therefore, it was recommended that equipment should be placed within the tower. However, there may be other advantages in housing equipment externally, such as greater flexibility for wind farm developers to specify their own electrical equipment. There would be merit in investigating these advantages further.

The final recommendation therefore was that the offshore intra-array voltage should move to 66 kV and that the optimal solution is for wind turbine equipment to be accommodated within the tower. In order to implement the 66 kV system, it was recommended that a qualification test or tests should be encouraged for wet type 66 kV cable designs and that further engagement with wind turbine manufacturers should be carried out to ensure that 66 kV wind turbines are developed.

In summary, the key benefits in moving to 66 kV were identified as:

- Reduction in CAPEX for radial and ring intra-array designs
- Reduction in the number of offshore substations required for a 66kV voltage system
- Many more design options available including the option to connect all the power to a single platform and the feasibility of cheaper aluminium cables
- Fully rated rings are viable, both from an economic and a design and installation perspective, and provide a significant NPV benefit for medium and worst case intra-array cable availability figures. However, for the best availability figure the higher voltage radial design presents a benefit compared with the 33 kV radial design. The level of benefit achieved for the higher voltage systems was found to be very sensitive to the cable failure rate.

References

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