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Summary

ORE Catapult has a requirement to explore the feasibility of using extra-large AC cables for offshore wind farm export applications. Extra-large export cables have the potential for reducing the number of circuits and hence installation costs thereby contributing towards the industry drive to reduce the cost of offshore wind farm developments.

A fatal flaw study has shown that there is no fundamental reason to prevent extra-large cables being used for offshore wind farm applications.

Edif ERA has undertaken a study in this area and our findings are as follows:

Three cable manufacturers advise that their upper conductor size limit for 220kV cables ranges from 1600mm^2 to 1800mm^2. A fourth claims their upper limit to be 2500mm^2.

Information from subsea cable installers indicates that the upper limit for 3-core cables having copper conductors is 1600mm^2, whilst cable with 2500mm^2 aluminium conductors can be accommodated.

Combining the costs of installation, losses and failures results in a 9% saving for the 220kV cable and a 21% saving for the 275kV cable, compared to the 132kV base case.

For a 10 ton vessel approximately 61km of extra-large 275kV cable can be loaded.

Mixed systems where copper conductors are used at the thermal pinch point and aluminium conductors are used elsewhere are viable and type tested solutions are available from several manufacturers

With regard to power transmission limitations, harmonic distortion is only a factor for cable lengths greater than 60km, whilst the Ferranti effect and Temporary Overvoltage are only significant for cable lengths greater than 120 km

Reactive compensation costs are higher for both large cables compared to the base case.

The high reactive power compensation costs for long cable lengths suggest that consideration should also be given to HVDC cables as an alternative, but this is outside the scope of this study.

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1. Introduction

ORE Catapult has a requirement to explore the feasibility of using extra-large AC cables for offshore wind farm export applications. Extra-large export cables have the potential for reducing the number of circuits and hence installation costs thereby contributing towards the industry drive to reduce the cost of offshore wind farm developments.

This report presents the findings of an Edif ERA study on the technical and economic feasibility of using extra-large cables for offshore wind farm export applications. The cable manufacturing and installation costs have been evaluated comparing currently available export cables with the potential extra-large cable design. In addition cable manufacturing and installation (vessel) methods are assessed to determine if the technology used limits the introduction of extra-large cables.

The practical electrical limitations of the extra-large design have been determined taking into consideration the impact on rest of the cable system, and electrical equipment such as switchgear and reactive compensation.

The outputs of the study form a fatal flaw study to establish if there are any major roadblocks to the adoption of extra-large cables on offshore wind farm developments. The project is concluded with a cost benefit analysis to gauge the potential economic benefits for selecting extra-large cable designs over and above smaller, lower voltage alternatives.

2. Assumptions

The assumptions used on this study were discussed and agreed with ORE Catapult and their stakeholders. They are summarised in Table 1. The majority of input data for the base case and extra-large cable design are taken from a recent Southampton University report, also performed on behalf of ORE CATAPULT.

Table 1 Project Assumptions

#	Task	Assumption	Description	Source/s
1	Export cable Manufacturing costs	Cable Design Base Case	132kV three core 800sq mm copper conductor XLPE	Southampton Uni report
2		Extra-large cable	275kV three core 2000mm² copper conductor XLPE (*note extra-large case dependant on the size a particular manufacturer can produce)*	Southampton Uni report
3	Export cable installation costs	Cable Design Base Case	132kV three core 800sq mm copper conductor XLPE	Southampton Uni report
4		Extra-large cable	275kV three core 2000mm² copper conductor XLPE	Southampton Uni report

5	Mixed conductor systems (Al/Cu)	Base Case Cables	220kV three core 1000sq mm copper conductor XLPE 220kV three core 1000sq mm Aluminium conductor XLPE	
7		Extra-large cable	275kV three core 2000 sq mm copper conductor XLPE 275kV three core 2000 sq mm aluminium conductor XLPE	Southampton Uni report
8		Route Properties	Sea bed Tr = 0.7K.m/W^{-1} Sea water temp = 15°C Burial depth (subsea) = 3m HDD bore = 2.5*cable O.D HDD thickness = 90mm (PE) Backfill = Bentonite Bentonite Tr = 1.0K.m/W^{-1} HDD burial depth = 10m max Onshore soil Tr = 1.1K.m/W^{-1} Onshore soil temp = 15°C J-tube bore = 2.5*cable O.D J-tube thickness = 30mm J-tube position = outside Solar radiation = 1000Wm^{-2} (IEC value) Solar absorption = 0.4 Emissivity = 0.9 Air temp = 20°C	Southampton Uni report
9		Route length	20km	ERA assumption
10		Load profile	To be agreed	
11	Cable cost of energy	Cable losses	As per results of mixed systems study for the base case and extra-large designs	Mixed system study
12	Charging current and reactive compensation	Base Case Cable	220kV three core 1000sq mm copper conductor XLPE	
13		Extra-large cable	275kV three core 2000 sq mm copper conductor XLPE	Southampton Uni report
14	Power transmission limitations	Extra-large cable	275kV three core 2000 sq mm copper conductor XLPE	Southampton Uni report
15		Cable Design Base Case	220kV three core 1000 sq mm aluminium conductor XLPE	
16	Availability and	MTBF	0.00365 to 0.01095 failure/year and km (we do	Strathclyde

	loss of energy		not consider this figure is accurate)	Uni report*
17		MTTR	60 days (we do not consider this figure is accurate)	Cigre/DNV
18		Failure rate	0.007 per occ/yr/100km (we do not consider this figure is accurate)	Cigre/DNV
19		Base Case Cable	220kV three core 1000sq mm copper conductor XLPE	
20		Extra-large cable	275kV three core 2000 sq mm copper conductor XLPE	Southampton Uni report
21		Terminations base case	GIS dry type to IEC 62271-209	
22		Wind Farm Capacity	600MW	
23		Reactive Compensation	220kV end to end option	
24			220kV mid-point span option	
25		Switchgear	8DN9-2 (220kV)	

3. Discussion

3.1 Cable Manufacturer's Capabilities and Costs

The manufacturing cost of a subsea export power cable is dependent on many factors, which include but are not limited to, the following:

- Raw materials (Copper, Aluminium, XLPE insulation etc.)
- Product and compound development
- Factory overheads including energy costs and new manufacturing technology (uprated laying up machines, load out equipment etc.)
- Factory manufacturing capacity (supply and demand)
- Production scrap rates and material wastage
- Process and line speeds
- Testing and calibration
- Requirements for factory joints
- Cable storage facilities and capacity
- Revenue and profit margins
- Logistics
- Jointer training

Many of these parameters are commercially sensitive and precise data is not in the public domain nor divulged by cable manufacturers or raw material suppliers.

Edif ERA took a practical approach to determining the relative costs of standard and extra-large cables by requesting general rather than precise commercial information. A number of leading export cable manufacturers were asked the following questions:

- What is the upper limit of your current submarine cable factories for 3 core cables regarding conductor size and system voltage?
- If you have plans to make large 3-core cables in the future and if so over what timescale?
- What would be the relative cost of a 3 core cable compared to 3 single core cables?
- What would be the limiting factors on installation, e.g. load out, vessel size?

The cable makers responses received are detailed in Appendix A.

With regard to manufacturing capability, this is summarised in Table 2.

Table 2 Cable maker's capabilities to manufacture large 3 core subsea cables

Manufacturer	Cross sectional area (mm^2)	
	3-core 220kV	3-core 400kV
A	2500	1600
B	1800	-
C	1600	1400
D	1600	1600

The four manufacturers contacted were as expected extremely reluctant to provide any detailed information on the costs of cables so Edif ERA has developed raw material cost models for 132kV and 275kV 3-core cables having either copper or aluminium conductors. Whilst cable costs will increase when overhead recovery and profit factors are applied it can be assumed that the same overhead rates and profit will be applied for different sizes of three core cables over the voltage range 132kV to 275kV so comparisons between raw material costs are valid. The raw material models developed have been further validated by comparing the predicted cable weights derived in the models with published data for smaller 3-core 132kV and 275kV cables.

From the Table 1 the agreed base case was a 3 core 132kV cable having 800mm^2 copper conductors. The raw material costs of 275kV cables having copper and aluminium conductors are compared with that of the base case in Figure 1.

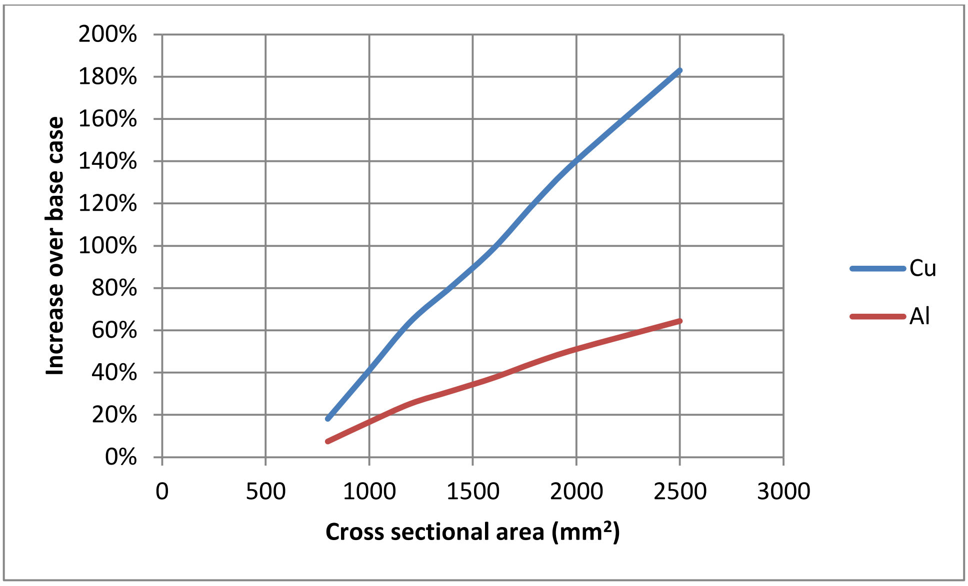

Figure 1 Cost increase over base case (132kV) Vs Al and Cu conductor size for a 275kV cable

From Figure 1 a 275kV cable having 2000mm^2 copper conductors costs 140% more than the base case and a similar cable with aluminium conductors costs 50% more.

Cable makers were unwilling to provide purchase costs of cable: they regard selling prices as commercially sensitive and will flex their selling prices depending on factory capacity; also prices will be lower if they want to win the contract and higher if they do not. The only way forward was for Edif ERA to use the raw material cost model together with our knowledge of overhead recovery rates and profits to estimate the purchase prices of the 3 cables under consideration as follows:

- 132kV 800mm^2 3 core cable: £517/m
- 220kV 1000mm^2 3 core cable: £730/m
- 275kV 1600mm^2 3 core cable: £1,243/m

These values have been used in Excel model that accompanies this report.

3.2 Installation Capabilities and Costs

Edif ERA asked installers the following questions:

As an installer we would be interested to know your viewpoints, for example:

Do you consider current installation vessels and equipment can handle the larger designs?

What issues you think may hinder extra-large cable installation with current technology and methods?

We have received one detailed response from a cable installer. This is contained in Appendix B. In addition Edif ERA has also undertaken a literature search on the capacity of Subsea Cable Installation Vessels (see Table 3). The largest vessel has a capacity of 10,000te and most have capacities between 4,600te and 7,000te.

Table 3 Maximum tonnage of subsea cable installation vessels

Operator	Vessel	Total Cable capacity (te)
Jan de Nul	Isaac Newton	10000
Jan de Nul	JDN8625	4000
VBMS	Ndurance	5000
VBMS	Ndeavor	2000
VBMS	Stemat Spirit	4600
Global Marine	Cable Innovator	7000
Global Marine	C.S.Sovereign	4600
Global Marine	Networker	750
Nexans	C/S Nexans Skagerrak	7000
Van Oord	Nexus	5000
A2SEA A/S	Atlantic Carrier	500
Orange Marine	Pierre de Fermat	2000
Deepocean	Maersk Connector	7000

The cable manufacturers point out that the capacity of the installation vessel is a limiting factor in installation. It is therefore instructive to examine the weights of large three core cables and compare these with the capacity of the installation vessels. These are shown in Table 4.

Table 4 Cable weights for large 3-core cables (kg/m)

	132kV		275kV	
CSA (mm^2)	Cu	Al	Cu	Al
800	78	61	101	84
1000	90	68	112	90
1200	102	74	125	97
1400	110	79	133	102
1600	120	84	143	107
1800	130	89	154	112
2000	140	94	164	118
2500	162	106	186	129

The vessel with the largest capacity has an upper limit of 150kg/m for the cable weight and can accommodate a maximum cable diameter of 350mm. From Table 4 this means that the upper limit for 275kV 3 core cables is 1600 mm^2 for three core cables with copper conductors. This upper limit could well be lower for vessels that have lower cable weight tonnage capacity. Cables with aluminium conductors having cross sections up to 2500mm^2 can be accommodated. Further discussions with installers are necessary to establish whether a mixed conductor design can be used where the majority of the cable has aluminium conductors and the cable at each end of the circuit has copper conductors. (See Section 3.3).

From the cable weights in Table 3 and the installation vessels in Table 4 the maximum length of cable that a number of installation vessels can accommodated has been calculated in Table 5.

Table 5 Three core cable 275kV lengths (km) accommodated by various installation vessels

CSA	4600te capacity		7000te capacity	
(mm^2)	Cu	Al	Cu	Al
800	46	55	70	84
1000	41	51	62	78
1200	37	48	56	72
1400	34	45	52	69
1600	32	43	49	66
1800	-	41	-	62
2000	-	39	-	59
2500	-	36	-	54

With regard to installation costs there are two components, the vessel cost and an installation cost that varies with the length of the cable.

As well as the weight of the cable, one restriction for the length of cable than can be loaded onto a vessel and laid is the capacity of the vessel carousel (cable turntable).

Referring back to Table 4, the larger tonnage capacity vessels will generally have larger carousels or even two carousels (one above deck and one below deck/ hold). In simple terms the volume available for cable is dependent on the carousel barrel (inner) diameter and outer diameter, and height. The barrel is normally designed to be expanded to suit cable MBR that can also reduce volume and cable length.

The volume of cable that can be loaded into the carousel will still be restricted by the vessel weight restriction for cable laying. Hence it is possible to exceed the cable laying weight restriction with cables loaded to the volume capacities of carousels.

Edif ERA looked at a number of vessel scenarios for extra-large cables to get a picture of the limits for cable volume. The scenarios are based on the worst case 275kV, 2000mm sq parameters, e.g. largest and heaviest cable.

A combination of Edif ERA discussions with European cable manufactures during this project, and the dimensions quoted in the Southampton University report, a worst case 275kV cable is 295mm diameter and 164kg/m weight (Cu conductor). MBR is also assumed to be >4.5m.

Edif ERA created a simple spreadsheet tool for cable coiling volume based on the aforementioned 275kV cable parameters and dimensions taken directly from publically available vessel data sheets, as well as assuming as close to a 100% carousel utilisation as is achievable.

For a 10 ton laying vessel approximately 61km of the extra-large cable can be accommodated, both within the carousel volume and below the maximum cable laying weight. Therefore for the 20km base case export cable length used in the model for this report, the required extra-large cable can easily be accommodated in one campaign.

A leading subsea cable installer was sent the cable parameters and their own calculations for the vessel used in this study correlated well with the Edif ERA numbers.

Therefore for wind farms with three core export cable lengths requiring vessel installation, the same number of installation campaigns will be required for export lengths approximately ≤61km for both base case (132kV and 220kV) and extra-large (275kV) cable sizes. This assumes use of a 10 ton or greater vessel.

In a previous study carried out some years ago, the variable installation cost was estimated to be £500/m excluding vessel and survey costs. Whilst these costs will now be higher, it is reasonable to assume that they will be same for the base case and two larger cables under consideration in this study.

Vessel costs are notoriously variable depending on their availability and the time of year. Cable laying is performed in campaigns, governed by the length of the cable that can be carried on the vessel (as discussed earlier), achievable lay rate and weather windows. Edif ERA were recently involved in an export cable repair which was delayed for a number of months due to weather. Another factor is whether the cable laying vessel needs to return to the factory to reload or whether it can be supported by barges. Large 3-core cables will mean a reduced choice of vessel and may require additional joints so these vessels will cost more than the base case.

We estimate that for the case of the larger 220kV and 275kV cables we would expect the vessel costs to be at least 10% higher than the 132kV 800mm^2 base case.

3.3 Mixed Conductor Systems

Edif ERA have carried out continuous current ratings for key export cable installation for the base case 220kV and extra-large case 275kV 3-core cables, both Aluminium (Al) and copper (Cu) conductor options.

The results are presented in Table 6 where Edif ERA has carried out thermal current rating calculations in accordance with the methods set out in BS IEC 60287. The ratings in J-tubes have been determined in accordance with the basic methods set out in ERA Report No 88-0108 (1988) and further developments by Edif ERA to account for wind speed in J-tube rating calculations. Note the wind speed used for this study is 8m/s. The calculations have been carried out using spreadsheets developed by Edif ERA.

There has been debate within the industry that the IEC factors due armour losses are somewhat conservative: in the calculations shown in Table 6 the armour loss contributions have therefore been reduced to 20% to reflect this.

Table 6 Continuous current ratings for 3-core subsea cables

Condition	**Current rating (A)**			
	220kV 1000mm^2 Cu	**220kV 1000mm^2 Al**	**275kV 2000mm^2 Cu (Milliken)**	**275kV 2000mm^2 Al (Milliken)**
Sea bed	969	820	1208	1061
HDD* Landfall	728	615	874	773
J tube, solar only	979	837	1231	1098
J tube, wind + solar	1116	954	1251	1251

* Horizontal Directional Drilling

Some of these calculations are consistent with carried out by Southampton University[1] in that the thermal pinch point is the landfall HDD condition. This suggests that a cable copper conductor could be used for the HDD section and a cable with aluminium conductors be used for the seabed and J tube sections of the circuit.

Subsequent to the release of Issue 1 of this report Edif ERA have rerun rating calculations for the 132kV 800mm^2 3-core copper conductor cable and compared them with the results obtained by Southampton University. We find good agreement for the buried sea bed and FE model approach but obtain a higher rating for the J tube condition: we found a continuous current rating of 868A whilst Southampton calculated this to be 681A. Discussions have been held between Edif ERA and Southampton and Edif ERA has found an error in Southampton University's calculation so we now have agreement in the cable rating for the J tube condition.

From Table 6 a 220kV system would consist of a 3-core cable with 1000mm^2 copper conductors at the HDD landfall section, and 1000mm^2 aluminium conductors for the rest of the circuit. At 275kV the combination would be cables with 2000mm^2 copper conductors and either 2000mm^2 or possibly 1800 mm^2 aluminium conductors. We would expect the HDD landfall section to be 1km in length, so for the agreed circuit length of 20km the cable with aluminium conductors would be 19km in length, with the last km in the J tube.

Three of the four cable manufacturers contacted have confirmed their capability to produce such mixed conductor systems, including transition joints between the two conductor materials.

Edif ERA would recommend that reliability analysis is performed in future to assess the impact of additional conductor connections in the export cable circuit.

3.4 Energy losses

The energy losses for 3-core cables, again with a reduced factor for armour losses, have been derived from the current rating calculations discussed earlier and are shown in Table 7.

[1] Southampton University Report 15242-RE2-v6 dated 19th November 2015

Table 7 Power losses for 3-core cables

Condition	Total Losses per Cable (W/m)			
	220kV 1000mm^2 Cu	220kV 1000mm^2 Al	275kV 2000mm^2 Cu	275kV 2000mm^2 Al
Sea bed	106	104	125	121
Landfall	59	60	66	70
J tube, solar only	108	108	130	130
J tube, wind + solar	140	140	167	167

For the projected scenario of 1km HDD Landfall/18km sea bed/1km J tube the total losses for the 220kV and 275kV options are 2,198kW and 2,594kW respectively. Current wholesale energy prices have been indicated by Ofgem to be £55/MWh. This figure has been used to calculate cost of losses per year for 50% and 100% operation in Table 8.

Table 8 Annual costs of losses based on 50% and 100% operation

Operational period	Losses on 220 kV System (£k)	Losses on 275 kV System (£k)
50%	530	625
100%	1,059	1,249

The power losses have also been calculated where the load in each section is limited to the maximum circuit load, i.e., the landfall rating. These are shown in Table 9.

Table 9 Power losses for 3-core cables (limited load)

Condition	Total Losses per Cable (W/m)				
	132kV 800mm^2 Cu	220kV 1000mm^2 Cu	220kV 1000mm^2 Al	275kV 2000mm^2 Cu	275kV 2000mm^2 Al
Sea bed	53.7*	63.3	61.4	71.7	69.8

Landfall	53.7*	59.7	67.6	67.6	66.6
J tube, solar only	53.7*	63.3	71.7	71.7	69.8
J tube, wind + solar		63.3	61.4	71.7	69.8

*Based on Rx value provided by Southampton University and current values calculated by Edif ERA

For the projected scenario of 1km HDD Landfall/18km sea bed/1km J tube the total losses for the 220kV and 275kV options under limited load are 1,248kW and 1,399kW respectively. Current wholesale energy prices have been indicated by Ofgem to be £55/MWh. This figure has been used to calculate cost of losses per year for 50% and 100% operation in Table 12.

Table 10 Annual costs of losses based on 50% and 100% operation at limited load

Operational period	Losses on 220 kV System (£k)	Losses on 275 kV System (£k)
50%	300	337
100%	601	674

3.5 Charging Current and Reactive Compensation

The capacitive current of a cable depends on the applied voltage and the capacitance of the cable.

As the voltage withstand of the cable rises, the thickness of the insulation also increases and as a result the capacitance of the cable also increases.

At the critical cable length, the cable current rating is completely consumed by the capacitive current and no active power can flow through the cable.

Shunt reactive power compensation installed along the cable route can rectify this issue.

Reactive power surplus in any operating condition causes a power-frequency voltage rise, not only at the cable terminations but also at adjacent nodes in the grid.

In normal operating conditions, a voltage step of 3% is allowed while connecting or disconnecting a cable for a typical installation.

To keep voltages within acceptable margins, reactive power compensation is usually necessary. This compensation can be achieved using shunt reactors, typically installed at both ends of a cable, and/or by the installation of Static Var Compensators.

The amount and location of shunt compensation influences the voltage profile along the cable.

Theoretically, uniformly distributed shunt compensation may produce the best voltage profile, but at a high cost. The external system also plays a role.

Calculation for alternative ratios of compensation for 132kV 800mm^2, 220kV 1000mm^2 and 275kV 2000mm^2 cases are presented in Tables 11, 12 and 13.

Table 11 Compensation calculations for the 132kV base case

Cable Length	Compensation Applied								
	100 / 0		50/50		70/30		30/30/30		
km	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	30.9	0.0	15.4	15.4	21.2	9.1	9.1	9.1	9.1
40	61.7	0.0	30.3	30.3	42.4	18.2	18.2	18.2	18.2
60	94.3	0.0	45.7	45.7	64.8	27.8	27.8	27.8	27.8
80	129.1	0.0	61.1	61.1	86.8	37.2	37.2	37.2	37.2
100	167.4	0.0	77.1	77.1	110.0	47.1	47.1	47.1	47.1
120	202.9	0.0	93.1	93.1	135.2	57.9	57.9	57.9	57.9
140	220	0	110.0	110.0	160.0	68.6	68.6	68.6	68.6
160	254	0	126.9	126.9	186.4	79.9	79.9	79.9	79.9
180			144.6	144.6	212.52	91.08	89.8	89.8	89.8
200			162.9	162.9	239.4	102.6	99.8	99.8	99.8
220			188.6	188.6	277.2	118.8	109.8	109.8	109.8

Table 12 Compensation calculations for 220kV 1000mm^2 cable

Cable Length	Compensation Applied								
	100 / 0		50/50		70/30		30/30/30		
Km	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	54.0	0.0	27.0	27.0	37.1	15.9	15.9	15.9	15.9
40	108.0	0.0	53.0	53.0	74.2	31.8	31.8	31.8	31.8
60	165.0	0.0	80.0	80.0	113.4	48.6	48.6	48.6	48.6
80	226.0	0.0	107.0	107.0	151.9	65.1	65.1	65.1	65.1
100	293.0	0.0	135.0	135.0	192.5	82.5	82.5	82.5	82.5
120	355.0	0.0	163.0	163.0	236.6	101.4	101.4	101.4	101.4
140			192.5	192.5	280.0	120.0	120.0	120.0	120.0
160			222.0	222.0	326.2	139.8	139.8	139.8	139.8
180			253.0	253.0			157.2	157.2	157.2
200			285.0	285.0			174.7	174.7	174.7
220			330.0	330.0			192.1	192.1	192.1

Cable Length	Power Received				Maximum Received Current			
	100/0	50/50	70/30	30/30/30	100/0	50/50	70/30	30/30/30
km	MW	MW	MW	MW	kA	kA	kA	kA
0	314.37	314.37	314.37	314.37	0.825	0.825	0.825	0.825
20	256.56	285.60	272.49	288.42	0.673	0.750	0.715	0.757
40	198.49	251.84	230.57	262.39	0.521	0.661	0.605	0.689
60	139.92	221.05	189.42	238.16	0.367	0.580	0.497	0.625
80	80.55	190.26	147.85	213.27	0.211	0.499	0.388	0.560
100	20.16	160.46	103.23	190.14	0.053	0.421	0.271	0.499
120	0.00	130.66	67.56	169.99	0.000	0.343	0.177	0.446
140		102.20	27.51	149.22		0.268	0.000	0.392
160		74.11	0.00	130.78		0.195		0.343
180		47.36		107.30		0.124		0.282
200		21.57		83.98		0.057		0.220
220		0.00		60.32		0.000		0.158

Table 13 Compensation calculations for 275kV 2000mm^2 cable

Cable Length	Compensation Applied								
	100 / 0		50/50		70/30		30/30/30		
Km	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	102.0	0.0	51.0	51.0	71.4	30.6	34.0	34.0	34.0
40	204.0	0.0	102.0	102.0	142.8	61.2	68.0	68.0	68.0
60	306.0	0.0	153.0	153.0	214.2	91.8	102.0	102.0	102.0
80	409.0	0.0	204.5	204.5	286.3	122.7	136.3	136.3	136.3
100	511.0	0.0	255.5	255.5	357.7	153.3	170.3	170.3	170.3
120			307.0	307.0	429.8	184.2	204.6	204.6	204.6
140			358.0	358.0			238.6	238.6	238.6
160			409.0	409.0			272.6	272.6	272.6
180			470.0	470.0			313.3	313.3	313.3
200			522.0	522.0			348.0	348.0	348.0
220			574.0	574.0			382.6	382.6	382.6

Cable Length	Power Received				Maximum Received Current			
	100/0	50/50	70/30	30/30/30	100/0	50/50	70/30	30/30/30
km	MW	MW	MW	MW	kA	kA	kA	kA
0	538.23	538.23	538.23	538.23	1.13	1.13	1.13	1.13
20	433.59	484.74	464.31	501.70	0.910	1.018	0.975	1.053
40	328.23	431.21	390.24	465.17	0.689	0.905	0.819	0.977
60	221.44	377.67	315.94	428.54	0.465	0.793	0.663	0.900
80	112.41	324.61	241.54	392.48	0.236	0.682	0.507	0.824
100	0.00	271.07	166.33	355.71	0.001	0.569	0.349	0.747
120		218.01	90.83	319.46		0.458	0.191	0.671
140		164.47	0.00	282.45		0.345	0.000	0.593
160		110.93		245.35		0.233		0.515
180		67.45		221.63		0.142		0.465
200		14.91		185.62		0.031		0.390
220		0.00		149.13		0.000		0.313

Further information of typical export cable installations in use today are as follows

London Array – 53.5km

http://www.4coffshore.com/windfarms/london-array-united-kingdom-uk14.html

Gwynt y Mor – 21.3 km

http://www.4coffshore.com/windfarms/gwynt-y-m%C3%B4r-united-kingdom-uk09.html

Sheringham Shoal – 22 km

http://www.4coffshore.com/windfarms/sheringham-shoal-united-kingdom-uk27.html

Walney – 43.7 km

http://www.4coffshore.com/windfarms/walney-phase-2-united-kingdom-uk32.html

3.5.1 Reactive Compensation Costs

The shunt reactor and GIS substation inputs to costings are given in Tables 14 and 15.

Table 14 Shunt reactor costs

Voltage (kV)	Base Size (Mvar)	Onshore Cost (£M)	Offshore Cost (£M)
33	40	1.4	1.5
132	50	3.0	3.2
220	100	3.6	3.9
275	150	3.8	4.0
400	200	4.0	4.2

The maximum individual shunt reactor size is 250Mvar. For higher Values of Mvar there would be an increase of 20% per additional reactor.

Table 15 GIS substation costs

Voltage (kV)	Onshore Cost (£M)	Offshore Cost (£M)
33	0.4	0.5
132	1.1	1.2
220	2.1	2.3
275	2.5	2.8
400	3.5	3.9

It is assumed that only one switch bay will be required for reactive compensation at each location. i.e. each additional reactor, if required, will connect to the same switchgear.

The cost of a mid-point platform is estimated at £15million, which increases with size and number of reactors.

From the inputs above, the costs of reactive compensation for a variety of alternatives have been calculated as a function of cable length in Tables 16, 17 and 18 for the three cable cases under consideration.

Table 16 Reactive compensation costs (£million) for 132kV 3-core 800mm^2 cable

Cable Length	Compensation Applied												
	100 / 0			50/50			70/30			30/30/30			
km	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Midpoint	Offshore	Total
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	3.7	0.0	3.7	3.4	3.7	7.1	3.3	3.5	6.8	3.3	18.5	3.8	25.6
40	4.3	0.0	4.3	3.7	4.0	7.7	3.5	3.7	7.2	3.5	18.7	4.2	26.4
60	5.0	0.0	5.0	4.0	4.3	8.3	3.7	3.9	7.6	3.7	18.9	4.6	27.2
80	5.7	0.0	5.7	4.3	4.6	9.0	3.8	4.1	8.0	3.8	19.1	5.0	28.0
100	6.4	0.0	6.4	4.6	5.0	9.6	4.0	4.3	8.4	4.0	19.3	5.5	28.8
120	7.2	0.0	7.2	5.0	5.3	10.3	4.3	4.6	8.8	4.3	19.6	5.9	29.7
140	7.5	0	7.5	5.3	5.7	11.0	4.5	4.8	9.3	4.5	19.8	6.3	30.6
160	9.6	0.0	9.6	5.6	6.0	11.7	4.7	5.0	9.7	4.7	20.0	6.7	31.5
180				6.0	6.4	12.4	4.9	5.2	10.2	4.9	20.2	7.2	32.3
200				6.4	6.8	13.2	5.2	5.5	10.6	5.1	20.5	7.6	33.2
220				6.9	7.4	14.2	5.5	5.7	11.2	5.3	20.7	8.0	34.0

Table 17 Reactive compensation costs (£million) for 220kV 3-core 1000mm² cable

Cable Length	Compensation Applied												
	100 / 0			50/50			70/30			30/30/30			
km	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Midpoint	Offshore	Total
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	5.1	0.0	5.1	4.8	5.3	10.1	4.9	5.1	10.1	4.7	20.1	5.1	29.9
40	5.8	0.0	5.8	5.1	5.6	10.7	5.4	5.3	10.7	4.9	20.3	5.3	30.5
60	6.5	0.0	6.5	5.5	5.9	11.4	5.9	5.5	11.4	5.1	20.5	5.5	31.1
80	7.2	0.0	7.2	5.8	6.3	12.1	6.3	5.7	12.1	5.3	20.7	5.7	31.8
100	9.2	0.0	9.2	6.1	6.7	12.8	6.8	6.0	12.8	5.5	21.0	6.0	32.4
120	10.1	0.0	10.1	6.5	7.0	13.5	7.3	6.2	13.6	5.7	21.2	6.2	33.2
140				6.8	7.4	14.2	9.0	6.5	15.5	5.9	21.5	6.5	33.9
160				7.2	7.8	15.0	9.7	6.7	16.4	6.2	21.7	6.7	34.6
180				8.6	9.4	18.0				6.4	21.9	6.9	35.3
200				9.1	9.9	19.0				6.6	22.2	7.2	35.9
220				9.7	10.6	20.3				6.8	22.4	7.4	36.6

Table 18 Reactive compensation costs (£million) for 275kV 3 core 2000mm^2 cable

Cable Length	Compensation Applied												
	100 / 0			50/50			70/30			30/30/30			
km	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Midpoint	Offshore	Total
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	5.9	0.0	5.9	5.5	5.9	11.4	5.6	5.7	11.4	5.3	20.8	5.8	31.9
40	6.8	0.0	6.8	5.9	6.4	12.3	6.2	6.0	12.2	5.6	21.1	6.1	32.7
60	8.6	0.0	8.6	6.3	6.8	13.2	6.8	6.3	13.1	5.9	21.4	6.4	33.6
80	9.7	0.0	9.7	6.8	7.3	14.0	8.4	6.6	15.0	6.2	21.7	6.7	34.5
100	12.1	0.0	12.1	8.1	8.7	16.9	9.2	6.8	16.0	6.5	22.0	7.0	35.4
120				8.7	9.3	17.9	9.9	7.1	17.0	6.8	22.3	7.3	36.3
140				9.2	9.8	19.0				7.0	22.6	7.6	37.2
160				9.7	10.4	20.0				8.3	23.9	8.9	41.1
180				10.3	11.0	21.3				8.7	24.3	9.3	42.4
200				12.2	13.0	25.2				9.1	24.7	9.7	43.5
220				12.8	13.7	26.5				9.4	25.1	10.1	44.6

From Tables 16 to 18 it can be seen that Mid-point compensation is uneconomic even for extremely long cable circuits. This is due to the estimated £15m cost of the additional platform necessary to house the equipment.

A comparison of the costs for different ratios of reactive power compensation for the two large cables compared to the base case is given in Table 19.

Table 19 Reactive power compensation cost comparison over base case

Length (km)	220kV 1000mm² copper				275kV 2000 mm² copper			
	100/0	50/50	70/30	30/30/30	100/0	50/50	70/30	30/30/30
20	38%	42%	49%	17%	59%	61%	68%	25%
40	35%	39%	49%	16%	58%	60%	69%	24%
60	30%	37%	50%	14%	72%	59%	72%	24%
80	26%	34%	51%	14%	70%	56%	88%	23%
100	44%	33%	52%	13%	89%	76%	90%	23%
120	40%	31%	55%	12%		74%	93%	22%
140		29%	67%	11%		73%		22%
160		28%	69%	10%		71%		30%
180		45%		9%		72%		31%
200		44%		8%		91%		31%
220		54%						

There is a range of percentage cost increases for reactive compensation over the base case for both large cables.

The high reactive power compensation costs for long cable lengths suggest that consideration should also be given to HVDC cables as an alternative, but this is outside the scope of this study.

3.6 Power Transmission Limitations

3.6.1 Ferranti Effect

Long transmission cables draws a substantial quantity of charging current. If the cable is open circuited or very lightly loaded at the receiving end, the voltage at receiving end can increase to a greater voltage than sending end due to capacitive reactance, this is known as Ferranti Effect. Both capacitance and inductance are responsible for this effect. The capacitance is small in short cable but significant in medium or long cables. The voltage rise is proportional to the square of the line length.

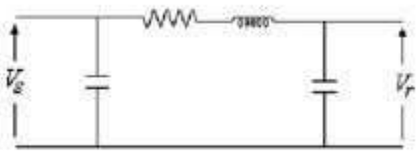

Figure 2 Charging capacitance

The resistance is small compared to the reactance of the cable; therefore the resistance can be neglected. Using the π-model, $V_S = V_R - V_L$, as the circuit is open circuit, $V_S = V_R – (I_CR + I_Cj\omega L)$, i.e. the receiving end voltage is greater than the sending end voltage, known as the Ferranti Effect.

When the load current is increased, the resultant current lags due to the inductive voltage drop; therefore the receiving end voltage is less than the sending end under full load conditions.

The Ferranti Effect can be calculated using the following equation:

$$V_R = \frac{V_S}{1 - \omega^2 . \frac{C}{2} . L}$$

Where:
V_R is the voltage at the receiving end.
V_S is the voltage at the sending end
C is the cable capacitance
L is the cable inductance

Voltage rise due to the Ferranti effect rise for 220kV and 275kV cables as a function of length is shown in Figure 3. The limiting factor is the voltage variation limit of +/- 10% at the point of connection.

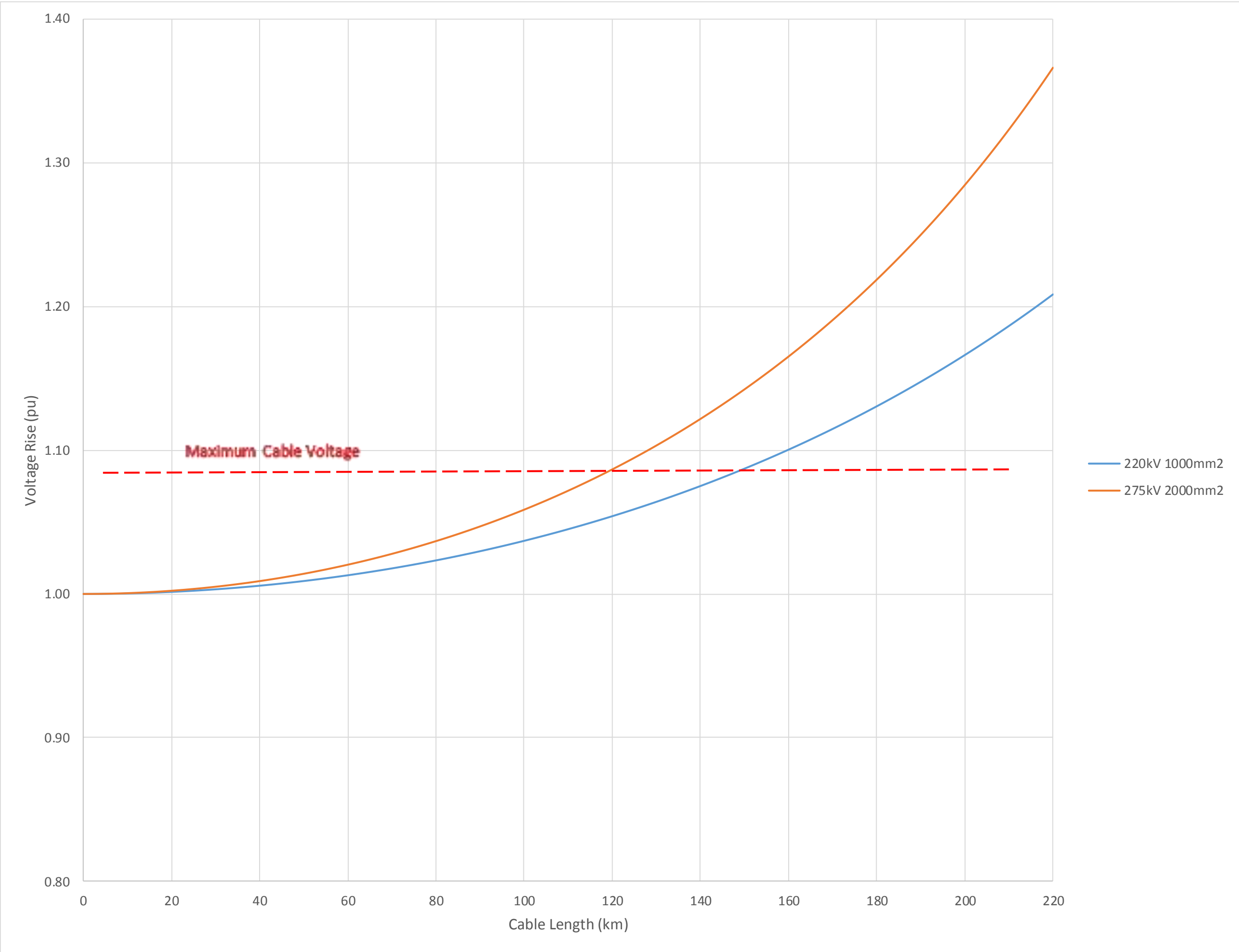

Figure 3 Voltage rise vs length for large 3 core cables due to Ferranti Effect

From Figure 2 the limiting length for large 3-core cables due to the Ferranti Effect is 120km and 150km for 220kV and 275 kV cable respectively.

The shunt reactors required for reactive compensation purposes may help in reducing this voltage, thus extending the limiting length due to the Ferranti Effect.

3.6.2 Harmonics/Temporary overvoltages

Temporary overvoltages (TOVs) are oscillatory phase to ground or phase to phase overvoltages at a given location of a relatively long duration (seconds or minutes), this is likely to be un-damped or weakly damped IEEE Standard 1313.1-1996.

Overvoltage conditions can cause problems on a transmission system through: insulation failures, overheating or mis-operation. Increasing the magnetic flux in the magnetic cores of equipment such as transformers and shunt reactors, this produces heat in the transformer cores, and can cause the equipment to fail. Mis-operation of equipment such as surge arresters causing short circuits, or causing circuit breakers to fail interrupting power flow.

Resonance is a special concern with cables as they lower the system resonant frequencies. Under normal switching conditions, transient voltages may be damped.

However, where there is an excitation current at a resonant frequency, overvoltages may be sustained for several seconds, damaging protective devices such as surge arresters and other equipment. In general system configuration, equipment characteristics, protection methods and operating procedures all affect TOV. Common causes of TOV are: system faults, load rejection, line energisation, line dropping/fault clearing, and reclosing, and transformer energisation.

TOV can be caused by parallel resonance on a system with long HVAC cables:

The inductance of the shunt reactors and the distributed capacitance of the cables form a parallel resonant circuit.

This is usually characterised by large impedance at the resonant frequencies. Large current may circulate through the resonant inductance and capacitance producing higher transient voltages.

The most onerous condition is a long length of cable combined with low system strength. Consideration of the length of cable in the design phase is key to avoiding issues in this case, as can be seen from Figure 4.

The first resonant frequency due to the interaction of the cable capacitance with the AC system impedance at minimum and maximum fault levels.

The limiting factor for harmonic distortion purposes was considered as 250Hz (5^{th} harmonic) as distortion at that harmonic order is both present at a high level on the transmission system and is a notable frequency generated by power electronic converters, particularly on wind turbines. A resonance at or below this frequency will require the grid compliance of the generation to be significantly more complicated.

The limiting factor for temporary overvoltages was considered to be 150Hz (3rd harmonic). Below this frequency the overvoltage magnitudes could become a very significant issue.

Mitigation measures can be implemented to counter the effects of the harmonic resonance or temporary overvoltages.

For harmonic mitigation purposes, AC harmonic filters can be installed. The effectiveness of these filters in reducing harmonic voltage distortion due to the harmonic resonance is dependent on the particular network operating condition and sources of harmonic current distortion (e.g. wind turbine converters). As harmonic filters are added the harmonic resonance would typically reduce further (for an inductive AC transmission system) although this can be mitigated somewhat by the combined use of shunt reactors and AC harmonic filters. If the particular configuration of AC transmission network and offshore wind system is favourable then it may be possible to extend the length of the cable. It should be noted that as harmonic resonance order reduces the mitigation becomes more difficult and more expensive.

The mitigation of temporary overvoltages is also highly dependent on the configuration of the systems. This is discussed in detail in the EDIF ERA report for EirGrid "INVESTIGATION INTO MITIGATION TECHNIQUES FOR 400/220KV CABLE ISSUES" http://www.eirgridgroup.com/site-files/library/EirGrid/Investigation-into-Mitigation-Techniques-for-Cable-Issues.pdf.

As with harmonic resonance issues, mitigation measures may allow some extension of the length of the cable (e.g. by the use of shunt reactors) but it becomes more difficult and expensive the lower the order of the resonance.

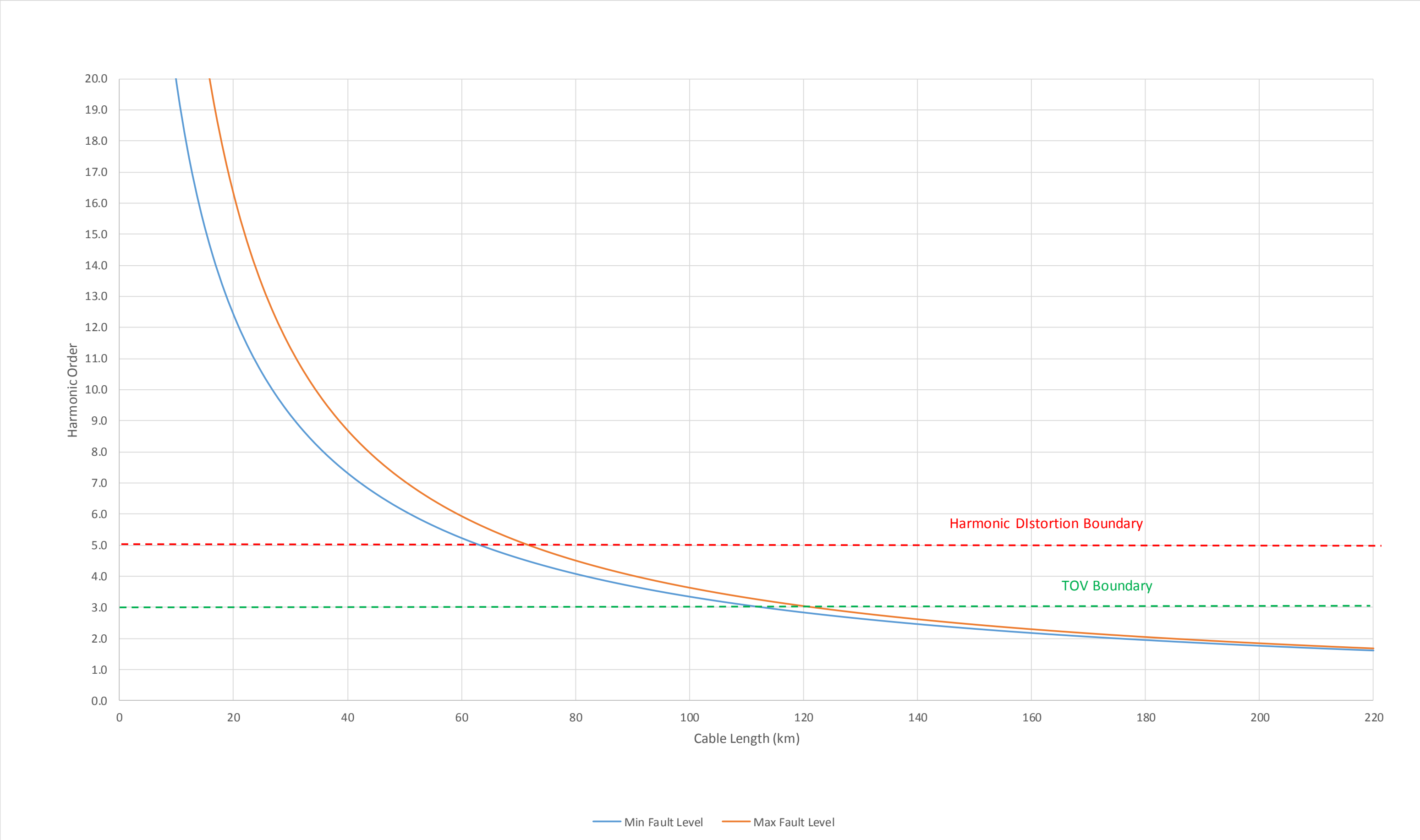

Figure 4 Harmonic resonance of 220kV 1000mm^2 cable at maximum and minimum fault level

From Figure 4 the maximum cable length with regard to harmonic distortion is between 60 and 70km; the maximum cable length with regard to temporary overvoltages is between 110km and 120km.

3.7 Availability and Loss of Energy

Calculation of availability data is reliant on accurate failure rate data and hence Mean Time Between Failure (MTBF) figures, as well as repair data. Information regarding the failure and hence reliability of export cables used for offshore wind applications is lacking in the public domain. This is because failures are commercially sensitive and there is a general underreporting of such information. All figures presented in this section of the report are based on publically available failure information. However the accuracy of the data is questionable and some explanations are provided below. As a general recommendation outside the scope of this project the industry requires an up to date subsea cable failure exercise to be carried out and 'lessons learned', especially given the proliferation of XLPE systems at the higher subsea voltage levels.

Edif ERA has carried out a number of physical dissections and root cause analysis of failed export cables and accessories from wind farms over the last two years, the findings of which are confidential and not publicised. Thus it is likely that the full extent of issues experienced on wind farms in that time, and hence failure rates are not known at present with a high level of confidence.

For a large proportion of Industry RAMS type studies for offshore wind farms Cigré technical brochure TB379 is often cited as one of the few studies that has gathered subsea cable failure from a number of operational sources.

Even at the time of study there were reported subsea cable data limitations as follows:

1. There was insufficient data to report failure rate on accessories. Furthermore, Edif ERA considers it is imperative to understand the failure mode and root cause (materials, workmanship, manufacture, installation, service conditions, third party etc.) to assess the overall impact on system reliability.

2. 14% of cases were of an unknown failure

3. 33% of reported cases were for 'other' reasons

4. No failure statistics are reported for AC 3-core radial barrier, or non-radial barrier cables at and above 220kV and 110kV respectively.

5. The reports states that it expects there was an underreporting failure data relating to key accessories related to long subsea connections including factory joints, transition joints and terminations.

6. In the years 1994 to 2005 only ~950km of AC 3 core XLPE radial barrier cables are reported as installed in the 110-219kV voltage range. None were greater than 219kV.

7. Only a total number of four AC XLPE faults were reported between 1990 to 2005. None of the AC XLPE failures reported in 1990 to 2005 are attributed to an accessory.

9. Only one reply to the Cigré questionnaire was received for a subsea cable in the UK. As a comparison 11 responses were from Norway; Edif ERA considers it important to know the proportion of solid dielectrics for each region and this information is not stated in the report.

Since the Cigré study improvements in cable engineering such as dielectric raw materials as well as cable protection methods, survey, vessel equipment and DP, condition monitoring, as some examples, would notionally improve failure statistics for subsea applications. However as voltage increase as for the extra-large case the decrease in critical defect size that could potentially cause a failure in for example the dielectric and jointing process, and the need to maintain jointing areas to a higher cleanliness level could potentially increase the rate. Furthermore the increased weight and size of extra-large cables could influence failure rates due to influence of their mechanical properties on the vessel installation and burial process.

Furthermore as offshore wind farms mature export cable failure data predominated by manufacturing, handling, installation, commissioning and early life third party faults may also be influenced by age related mechanisms which are not considered in detail in current RAMS studies.

The best failure data currently available is shown in Table 20. The failure rate data was obtained from a Siemens Round 3 wind Farm reliability model for the Hornsea project. It's one of the few sources that lists failure rates for array cables and export cables individually. Note that a 0.1 failures per 100km per year failure rate would be used to calculate the MTBF for the export cable. The array cable rate is higher at 0.84 on account of a higher number of pull-in operations and termination failures per km of cable compared to the export cable which potentially increases the failure rate.

Table 20 Cable failure rates per 100km

Cable in-service fault rates	Cable faults per 100 km per year
Array cable	0.84
Subsea export cable	0.10
Land export cable	0.05

From discussions with offshore wind farm operators the effect of an export cable being out of service will be similar to that shown in Table 21. These percentage losses have been used to determine the loss of output if an export cable fails after the wind farm has begun operation.

Table 21 Effect of one export cable failure on wind farm output

Number of export cables	Output reduction due to loss of one export cable %
1	100
2	37
3	20
4	10

In reality the loss of production due to the non-availability of an export cable will be affected by the wind speed throughout the period when the cable is not available. A power curve for a Siemens 3.6MW wind turbine is shown in Table 22.

Table 22 Power curve for 3.6MW wind turbine

Wind Speed m/s	Power kW	Wind Speed m/s	Power kW	Wind Speed m/s	Power kW
1	0	6	507	11	3082
2	0	7	824	12	3488
3	0	8	1243	13	3591
4	131	9	1778	14	3600
5	276	10	2432	15	3600

Estimated costs and repair times for offshore export cables are compared with other types of cable in Table 21.

Table 23 Estimated costs and repair times

Cable type	Material Cost	Repair times (days)
Offshore array cable	£140,000	10
Onshore export cable	£40,000	12
Offshore export cable	£225,000	21

The above costs exclude other time factors such as time to get spares, mobilisation and waiting for weather. Edif ERA has experience of a recent 3 core export cable repair where the rate for vessel/crew hire per day in UK waters was approximately £100k.

4. Cost Modelling

As part of the project an Excel cost model [Ref: 3 Core Export Cable Cost Model 1.3] has been produced, populated with the data generated in this report. A number of fields have been left unlocked to permit users to input their own data. From this model the annual costs for installation, losses and failures have been compiled in Table 24 to enable comparison of the two options with the base case.

Table 24 Annual costs comparison from Excel model

Cable	Annual costs (£)				Saving over base case (%)
	Installation	Losses	Failures	Total	
132kV 800mm^2	3,271,000	776,180	1,353,564	5,400,744	-
220kV 1000mm^2	2,770,000	608,560	1,492,099	4,870,659	9.8%
275kV 1600mm^2	2,083,000	344,462	1,838,772	4,266,234	21.0%

Compared to the 132kV base case, Table 24 shows that there is a 9% saving for the 220kV cable and a 21% saving for the 275kV cable.

5. Fatal Flaw study

One of the aims of this project was to asses each output of each tasks and determine if it constituted a 'fatal flaw' for extra-large cables. A fatal flaw is defined as any task output that is deemed to preclude the feasibility of developing the use of the technology, which may be technical or economic in nature. Table 25 Summarises this study.

Table 25 Fatal Flaw Study summary

Task	Output	Fatal Flaw?
Cable Manufacture	There are European manufacturers capable of producing three core extra-large subsea cables. These may need to be type tested to prove the designs, which may extend commercialisation of such cables.	No
Cable Accessories	Accessories for three core extra-large cable systems are technically feasible (field joints, terminations etc.), including transition joints. However reliability is unknown until service life experience is built up. Additionally Type Testing of the joints would be required.	No
Cable Installation	Export cable laying vessels are capable of handling large three core cables upto ~1600mm² for Cu, and 2,500mm² for Al in lengths of around 50km for the larger vessels. Vessels may require modification to handle extra-large cable weights for Cu conductors >1600mm².	No (although vessel modification may be required for larger Cu conductor sizes).

Reactive compensation (charging current)	For the extra-large case compensation configurations will allow for ~100km three core export length.	No
Shunt reactor and GIS substation costs	Euipment costs for the extra-large case are higher, but depending on the project it can be compensated by possible installation and through life cost savings	No
Ferranti Effect	Maximum cable voltage rise for extra-large cables ‘Ferranti Effect’ is not an issue for export circuit lengths <120km	No.

6. Conclusions

- A fatal flaw study has shown that there is no fundamental reason to prevent extra-large cables being used for offshore wind farm applications.
- Three cable manufacturers advise that their upper conductor size limit for 220kV cables ranges from 1600mm^2 to 1800mm^2. A fourth claims their upper limit to be 2500mm^2.
- Information from subsea cable installers indicates that the upper limit for 3-core cables having copper conductors is 1600mm^2, whilst cable with 2500mm^2 aluminium conductors can be accommodated.
- For a 10 ton vessel approximately 61km of extra-large 275kV cable can be loaded.
- Combining the costs of installation, losses and failures results in a 9% saving for the 220kV cable and a 21% saving for the 275kV cable, compared to the 132kV base case.
- Mixed systems where copper conductors are used at the thermal pinch point and aluminium conductors are used elsewhere are viable and type tested solutions are available from several manufacturers
- The Ferranti effect is only significant for cable lengths greater than 120 km
- Harmonic distortion is only a factor for cable lengths greater than 60km
- Temporary overvoltage effects are only an issue cable lengths greater than 120 km
- Reactive compensation costs are higher for both large cables compared to the base case.
- The high reactive power compensation costs for long cable lengths suggest that consideration should also be given to HVDC cables as an alternative, but this is outside the scope of this study.

Appendix A
Responses from Cable Makers

A.1. Manufacturer A

We can manufacture cables of 1600mm² at system voltage 220kV and greater, i.e. 420kV three core cables in service. Detailed design and limitations are defined during tender stage.

Normally it is more cost effective to supply and install one three core cable compared to three single core cables but it may depend on distance and ambient conditions. Vessel loading limitation to be determined when the site conditions are known (mix of vessels is rather common depending on depth etc.).

We have manufactured and tested 2500mm² three core cables at 220kV. Developments are of course continuously ongoing for large cross sections at higher voltages but I cannot mention where we are here.

To joint cables with conductors with different material (Cu to Al) is not an issue at all and we have done before.

A.2. Manufacturer B

We are able to produce 3-core cables with large conductors. I would say 3x1600 or 3x1800 is the upper limit for 3-core cables at 220 kV. In terms of voltage for AC operation 420 kV is the upper limit but for this type of cable we normally produce them as single core and not 3-core. For single core cables we would be able to produce conductors up to around 2000mm^2. Currently we have references for 3-core 220 kV up to 3x1200mm^2 and 420 kV up to 1x1200mm^2.

For 3-core 220kV I would say the current size of cables are within the limitations for production, load out, transportation and laying of existing facilities/vessels. Even though 3-core 420 kV is feasible I think the cables will very quickly become so large and heavy that it will limit supply chain and complicate potential repair operations.

Relative costs between single and three core cable are very difficult to estimate without any concrete information. Normally both material and installation cost would be higher for single core design when comparing same conductor cross sections.

A.3. Manufacturer C

Our capability is 1 core cable: 400km per year; 3 core cable: 140km per year based on 132KV 3C 500sqmm

We are capable of making large 3 core cables now; we are able to manufacture 3 core cable up to 220KV 1600sqmm and 400KV 1400sqmm.

We have many plans to develop and actually under development for DC XLPE submarine cable as well as AC cable.

With regard to relative cost, 3 core cables would be expensive but cost effective in the aspects of cable installation.

There are many factors relating to cable installation e.g. size and weight of cable, coilability of cable, vessel size. Each cable has different limitation factors based on cable characteristic.

A.4. Manufacturer D

We have experience in manufacturing 3 core cables with conductor cross section up to 1600 mm^2 at 220 kV. Some larger cross sections could be feasible but not convenient owing to skin effect the corresponding current rating increase would be very limited. We have not experience in manufacturing 400 kV three core because generally the power rating required at that voltage exceeds what can be achieved by one three core cable. We could manufacture three core cables with cross section in the 1000-1200 mm^2 range.

The larger cost relative cost of single-core cables is due to the need of a copper armour and higher installation cost. The answer would be project specific.

The limiting factors on installation include vessel cable storage size, bending radius during installation, maximum pulling tension (relevant in case of deep water installation).

Appendix B
Responses from Installer

B.1. Installer A

Installer A owns and operates a cable installation vessel that can take 10,000 tonne of cable

This subsea cable installation vessel is capable to cope with cable design particulars up to:

- Outer diameter: 350 mm
- weight/meter 150 kg/m
- Flexural rigidity E*I: 100 kNm²

For storing the cable, two carousels can be used. The deck carousel can take up to 7,400tonne, whilst the below deck carousel can take 5,000tonne with following specifications:

Hold turntable:

Outside diameter [m] (inner side outer wall)	22.860
Inside diameter [m] (outer side inner wall)	4.6
Turntable height [m]	4.5
Capacity [ton]	5,000
Max cable diameter [mm]	350
Max cable weight/meter [kg/m]	150
Flexural rigidity E*I [kNm²]	100
Max MBR [m]*	4

(*) Inner hub can be enlarged by means of a bull ring.

Deck turntable:

Outside diameter [m] (inner side outer wall)	27.3
Inside diameter [m] (outer side inner wall)	8.0
Turntable height [m]	7
Capacity [ton]	7,400

Max cable diameter [mm]	350
Max cable weight/meter [kg/m]	150
Flexural rigidity E*I [kNm^2]	100
Max MBR [m]	4

Whilst a large MBR of the supplied cable could volume restrict the capabilities of the turntables, the inner hub can always be increased by installing a bull ring. However, there is a maximum MBR that can be handled and the supplied cable should not exceed certain bending stiffness values as shown above that could not be derived from the below referenced document.

