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Vattenfall Wind Power Ltd

Thanet Extension Offshore Wind Farm

Cable Ratings Study

June, 2018, Revision A

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June, 2018

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CABLE RATINGS FOR SANDWICH ROAD AND THANET CABLE CROSSING

THANET EXTENSION OFFSHORE WIND FARM

CLIENT:	Vattenfall Wind Power Limited
REFERENCE:	REP 1526/029/001D
CLIENT REFERENCE:	Not applicable

Notes

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Acronyms

Acronym	Full Term
AC	Alternating Current
DC	Direct Current
HDPE	High Density Polyethylene
HV	High Voltage
IEC	International Electrotechnical Commission
kV	kilovolt
MW	Megawatt
PE	Polyethylene
t	Thickness
TOWF	Thanet Offshore Wind Farm
TEOWF	Thanet Extension Offshore Wind Farm
VWPL	Vattenfall Wind Power Limited
XE	Xero Energy Limited
XLPE	Cross-linked polyethylene
ρT	Thermal resistivity

Executive Summary

General

Xero Energy Limited (XE) has been commissioned by Vattenfall Wind Power Limited (VWPL) to perform current rating calculations and cable sizing for the onshore export cables of the proposed Thanet Extension Offshore Wind Farm (TEOWF), which is proposed to have a maximum output of 340MW. This study analyses the TEOWF onshore export cables, proposed to be comprised of four 66kV circuits, twelve cables in total. The overall aim is to assess the technical feasibility of a cable route through Sandwich Road for the TEOWF cables.

The route in Sandwich Road would be approximately 800m in length, from the Baypoint sports ground to the north half of the Pegwell Bay Country Park. The TEOWF cables would be installed parallel to the existing Thanet Offshore Wind Farm (TOWF) 132kV double circuit export cables for this route section. This study is concerned with the cable ratings for the installation in the road and at the crossing locations, both for the TEOWF cables and the thermal impact to the existing TOWF cables.

Near Ebbsfleet Lane, the TOWF cables cross from the west side to the east side of the road. The TEOWF cables would need to cross underneath the TOWF cables at this point. Beyond this point, the proposed route for TEOWF cables turns south-easterly into the Baypoint sports ground. This would require a second crossing with the TOWF cables.

The technical issues concern the impact that the installation in Sandwich Road and the crossing would have on the thermal rating of the existing TOWF cables, the rating and cable specification required for the TEOWF cables, and the required general arrangement of the cable installation. This study has therefore been grounded on and underpinned by cable rating and sizing calculations according to the IEC 60287 standard. The study uses the general conditions to be found along the road route and does not consider other constraints in the road that may exist, other than the TOWF cables.

Methodology

For this study, an indicative general arrangement was determined for the TEOWF cables, based on the anticipated space in Sandwich Road. The TEOWF cables were modelled based on typical 66kV cables based on XE's experience and with reference to cable brochures, using a high voltage cable design with a copper wire screen with an overlaid copper equalisation tape. This model was then used to determine the ratings for the TEOWF cables for the general arrangement in Sandwich Road, for a design cable current of 783A, in isolation from TOWF.

Next, the TOWF cables were modelled based on the as-built TOWF cable data sheets and experience from similar assessments. The losses and rating of the model were validated against the TOWF cable design report [1], in isolation from TEOWF, for a design cable current of 690A.

The TEOWF and TOWF cable ratings, taking into account mutual heating between the cables of the two projects, were then modelled for the installation condition in Sandwich Road, with 3m separation. Sensitivity analyses of screen bonding type, and varying separation between the two projects were also performed.

Next the cable crossing was studied. A general arrangement for the cable crossing with ideal crossing angle and spacing was developed. The TEOWF and TOWF cable ratings, taking into account mutual heating between the cables of the two projects, were then modelled for this installation condition. Sensitivity analysis of screen bonding type, crossing angle, circuit separation and burial depth were performed for the cable crossing.

The following results and conclusions have been drawn from the study work.

Results – Sandwich Road cable route

The space along the Sandwich Road cable route is very limited due to the TOWF cables and other services, and for this reason the TEOWF cable installation has been assumed to be in a single trench in square formation, with horizontal spacing of 1m and vertical spacing of 0.9m between circuits. The square formation of the cable circuits is viewed as necessary to be able to accommodate them in the road. This is an unusual formation, and would present additional safety risks in terms of access to the bottom cables of the formation. The formation is not ideal for cable maintenance or repair.

For this installation arrangement, it is possible from a thermal rating perspective to have the TEOWF cables installed in Sandwich Road, and a base case solution has been identified for this installation condition. It would be strongly recommended to maintain at least 3m separation between the TEOWF and the TOWF cables due to mutual thermal heating effects between the two projects.

From a practical standpoint, the installation would be difficult to achieve given the necessary infrastructure required (e.g. multiple cable circuits, joint bays, link boxes), and the potential additional constraints in the road – known as a minimum to consist of telecoms and other distribution power supply cables. The cables would need to be cross-bonded. The stranded conductor sizes would be 2000mm^2 aluminium or 1400mm^2 copper. For Milliken type conductors, the sizes would be 1800mm^2 aluminium or 1000mm^2 copper.

Results – Cable crossings with TOWF

The crossing of the TOWF cables would be difficult to achieve, particularly for the first crossing. A base case has been developed with 3m burial depth, 3m group separation and a 90° crossing angle. In addition to this generous spacing and ideal crossing angle, an optimal design for rating in terms of screen design, cable insulation and screen bonding has been assumed for the study. Even then, the study shows that only the largest cable size studied of 2400mm^2 copper Milliken would satisfy thermal ratings.

With the 2400mm^2 copper Milliken cable, the TOWF cables at the crossing location would operate very close to their rated limit if both projects are at full output – 89.4°C versus the continuous operating temperature of 90°C. It is good practice to allow headroom on rating, and elimination of all the existing headroom will very likely not be acceptable to the owner of the TOWF cables.

The first crossing of TOWF would require 10m road width where the cables 'fan out', for 3m group spacing, and thus would likely require the entire available width of the road. The width can be reduced by modifying the crossing angle, however at a detriment to the cable ratings.

If the separation, burial depth or crossing angle cannot be achieved, this would result in higher cable temperatures, potentially exceeding the cable 90°C maximum continuous operating temperature, which could damage the cable insulation and compromise its performance. If the cable insulation is damaged, the damaged cable section would need to be removed and replaced.

The 2400mm^2 size is anticipated to be at the limit of capability of the cable manufacturers and would require further discussion with the supply chain. Cable size availability above 2500mm^2 is unlikely.

This cable size is significantly heavy and large in terms of diameter, and would be very challenging to transport, handle and install. Furthermore, consideration is needed with how this cable would be jointed to potentially different cable sizes on adjacent sections of the cable route.

The size of cable also means that the cable section length will be reduced, requiring more joints along the cable route. This adds time to the duration of the works and the duration the road will need to be closed for construction. It will increase the traffic in terms of number of cable deliveries. The additional number of joints also increases the probability of a cable failure.

The required size of cable and installation arrangements makes this route marginal in terms of feasibility. Further, it would eliminate the existing headroom on the TOWF cables and is unlikely to be acceptable to the asset owner, which would make the cable crossing not feasible.

1 Introduction

1.1 General

Xero Energy Limited (XE) has been commissioned by Vattenfall Wind Power Limited (VWPL) to perform current rating and cable sizing calculations for the onshore export cables of the proposed Thanet Extension Offshore Wind Farm (TEOWF), if installed in the Sandwich Road. As part of this, XE has investigated the feasibility of crossing the installed Thanet Offshore Wind Farm (TOWF) export cables with the proposed TEOWF export cables.

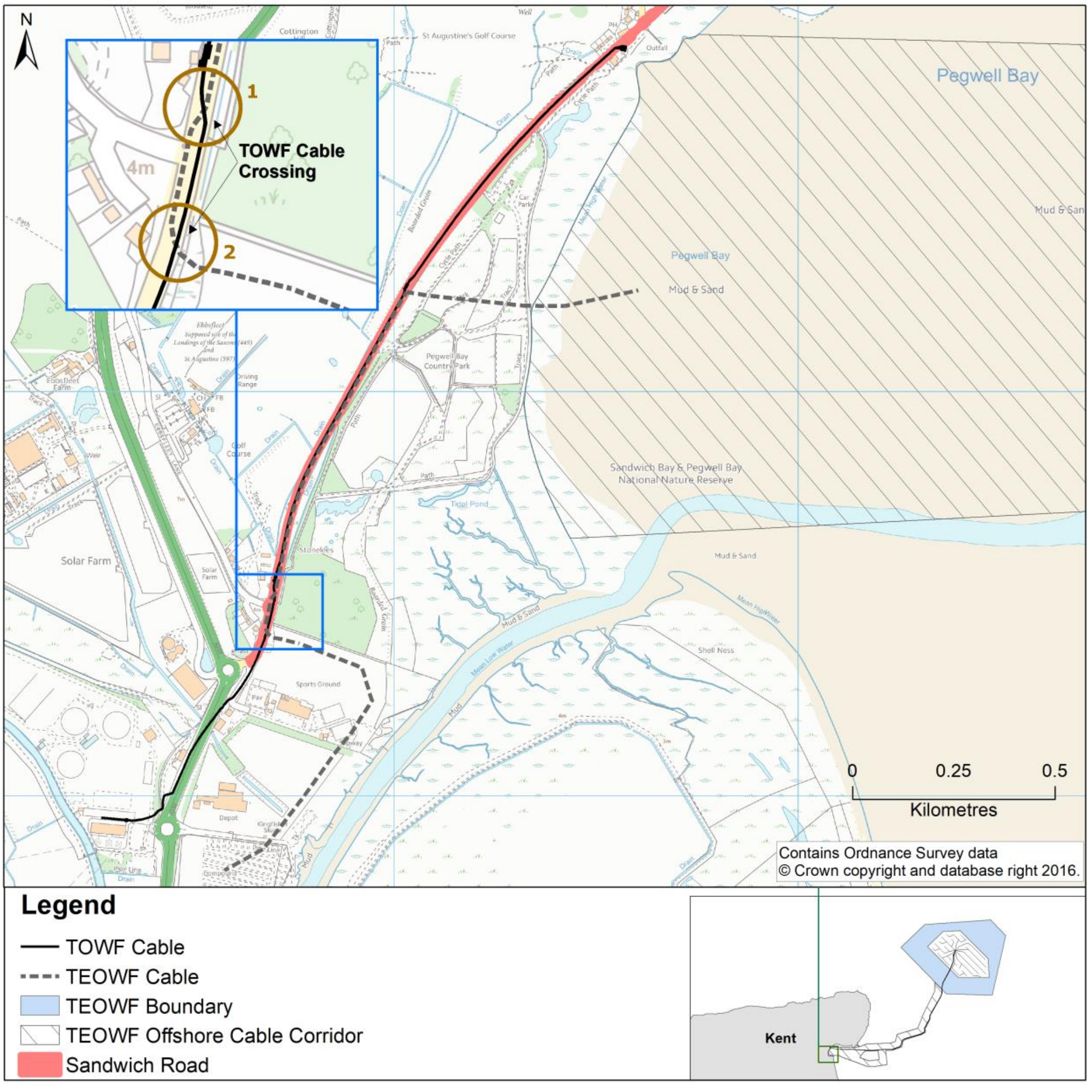

Figure 1-1: Overview of proposed Sandwich Road cable installation and location of the two proposed crossings of TOWF cables by TEOWF cables

After making landfall, the TEOWF cables may follow the onshore route shown in Figure 1-1. For this option, the TEOWF cables would make landfall at Pegwell Bay then follow parallel to the route of the existing Thanet Offshore Wind Farm (TOWF) 132kV cables along Sandwich Road. It is understood that the TOWF cables are installed in the west side (northbound) of the road along this section, and so TEOWF would need to be installed in the east side of the road.

Near Ebbsfleet Lane, the TOWF cables cross from the west side to the east side of the road. Therefore, the TEOWF cables would need to cross underneath the TOWF cables at this point (referred to herein as ‘Crossing 1’. After this crossing point, the proposed route for TEOWF cables turns south-easterly into the Baypoint sports ground. This would require a second crossing with the TOWF cables (referred to herein as ‘Crossing 2’) about 95m south of Crossing 1, and a crossing with the High Voltage Direct Current cables of the Nemo Link interconnector project another 30m beyond Crossing 2 (refer to document [2]). The two locations where TEOWF would cross the TOWF cables are shown in the inserted blue box in Figure 1-1.

This study is concerned with the cable ratings for the installation in the road and at the crossing locations, both for TEOWF cables and the impact to the existing TOWF cables.

The crossing of the Nemo Link cables could also impact on the thermal rating of the TEOWF and TOWF cables at Crossing 2. The potential effect of this has been excluded from the scope of this study.

TEOWF is proposed to have an output of up to 340MW. VWPL is considering onshore cables between 66kV and 220kV. This report analyses the four circuit 66kV option, as it is likely to present a worst case for installation in the Sandwich Road both in terms of space and heating.

1.2 Scope and aims

The study has the following key aims.

1. Assess the thermal ratings and potential sizing of the 66kV TEOWF export cables for the installation conditions found along Sandwich Road.
2. Assess the mutual thermal heating effects between the proposed TEOWF and existing TOWF cables. Understand the impact on installation design and sizing of the TEOWF cables for both the TEOWF and TOWF cables to be adequately rated and remain within rating.
3. Assess the mutual thermal heating effects between the proposed TEOWF and existing TOWF cables at the two crossing points.
    - From the above, assess the thermal ratings and sizing of the 66kV TEOWF export cables for the installation conditions at the crossings.
    - From the above, size the TEOWF cables and design the crossings to ensure the TOWF cables are not adversely affected and remain within rating.
4. Determine the permissible general physical arrangements and TEOWF cable sizes for the crossings based on the results.

This report discusses the methodology and assumptions used in ascertaining the above, together with the results and conclusions of the study.

1.3 Report layout

This report is organised with the following layout:

- Section 1 Introduction
- Section 2 Cable modelling methodology
- Section 3 Modelling data
- Section 4 Installation arrangements
- Section 5 Results
- Section 6 Summary
- Section 7 References
- Section 8 Appendix A Sensitivity Analysis

2 Cable modelling methodology

2.1 Introduction

XE has used the International Electrotechnical Commission (IEC) International Standard 60287: "Electric cables – calculation of the current rating" Parts 1-1, 2-1 and 3-3 [3, 4, 5] to assess current rating and heating effects. Part 1-1 [3] models the electrical losses within the cable, Part 2-1 [4] models the thermal resistances of the cable elements and surrounding medium and Part 3-3 [5] examines the effects of cables crossing other heat sources.

2.2 Verification of methodology

XE has verified the IEC methodology on numerous previous studies, thus establishing a validated set of calculation tools. The methodology has additionally been verified by calculating the cable rating and losses for the existing TOWF export cables and comparing these with the results of the design studies for those cables [1].

2.3 XLPE AC cable design and technical characteristics

A typical high voltage single-core alternating current (AC) land cable consists of the conductor, an insulation layer made of cross-linked polyethylene (XLPE), a metallic screen and an outer polyethylene (PE) serving [3]. A typical cable design showing heat dissipation is given in Figure 2-1 below. The cable is a single-core type as is commonly used onshore.

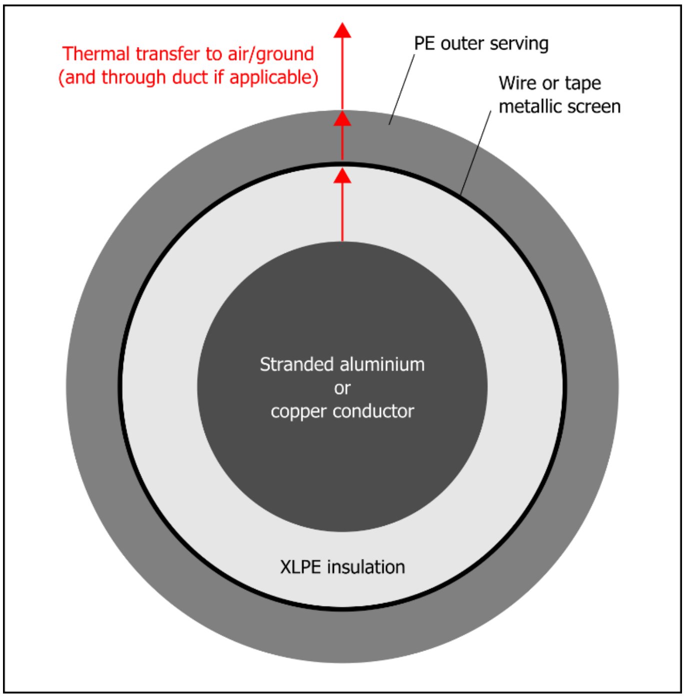

Figure 2-1: Typical cable design

The main cable related factor that drives the current rating of a cable is the conductor size. Cables with larger conductor sizes have less resistance and thus fewer losses (equal to $I^2{\cdot}R$). The losses generate heat within the cable. There is a limit to how much heat the elements of the cable can be exposed to during continual operation. This defines the current rating of the cable.

The resistance of the conductor is also affected by the conductor material, but this has a smaller effect, since the typical conductor materials are either copper or aluminium.

Another factor that influences the rating of the cable, but usually not to the same degree, is the metallic screen. The metallic screen can introduce circulating and eddy currents (depending on the screen bonding method) which generate heat, and therefore affect the thermal rating of the cable.

Other technical characteristics, such as the insulation thickness and the outer serving thickness, also influence the current rating of the cable, but to a much smaller degree. They determine how the heat is transferred from the conductor to the outside environment through the non-metallic layers of the cable. A high thermal resistance of a cable component means a higher temperature rise and lower current rating (Equation 1 in Section 2.4).

2.4 Current rating of AC cables

The IEC 60287 standard offers the full method of calculating the permissible current through a cable, taking into account factors such as cable layout, installation conditions, skin effect, and eddy and circulating current losses etc. The formula for the temperature rise due to the current is given in [3] as follows.

$$\Delta\theta = \left(I^2R + \tfrac{1}{2}W_d\right)T_1 + [I^2R(1+\lambda_1) + W_d]nT_2 + [I^2R(1+\lambda_1+\lambda_2) + W_d]n(T_3+T_4)$$

Equation 1

Where

- $\Delta\theta$: the conductor temperature rise above the ambient temperature (K)
- I : the current flowing in the cable (A)
- W_d : the dielectric loss per unit length for the insulation (W/m)
- R : AC resistance of the conductor at operating temperature (Ω/km)
- T_1 : thermal resistance between one conductor and the sheath (K·m/W)
- T_2 : thermal resistance of the bedding between sheath and armour (K·m/W)
- T_3 : thermal resistance of the external serving of the cable (K·m/W)
- T_4 : thermal resistance between the cable surface and the surrounding medium (K·m/W)
- n : the number of load-carrying conductors in the cable
- λ_1: the ratio of losses in the metal sheath to total losses in the conductors
- λ_2: the ratio of losses in the armour to total losses in the conductors

For a group of cables (e.g. three single-core AC cables, or direct current cable pair) the calculations refer to the hottest cable of the group.

The factor $\Delta\theta$ is the difference between the maximum permitted operating temperature of the conductor (90°C for the cables used) and that of the environment it is buried within (usually taken as 15°C for the UK).

2.5 Groups of buried cables

TEOWF is proposed to have four cable circuits installed parallel to one another. To calculate the heating effects of multiple buried cable circuits installed near one another, the method outlined in IEC 60287 Part 2-1 has been used [4]. This method for unequally loaded cables considers the heat output from each group of cables and its effect on the thermal conditions of the ground.

This method uses the principle of superposition to calculate the temperature rise of a cable due to the thermal contribution of the other cables, depending on the distance between cable groups and the heat dissipated from them.

The total temperature rise $\Delta\theta_p$ caused by all the other cables is then added to the surrounding soil temperature and a new value of $\Delta\theta$ in Equation 1 is calculated from the new ambient temperature and the steady state current I. This is done for the cable with the highest temperature rise due to the others, which is taken as the worst case.

The process is repeated recursively with the new calculated temperatures for the worst-case cable until convergence had been reached. XE has undertaken sufficient iterations to establish the operating temperature of the cable within an accuracy of 0.1%. Finally, the resulting operating temperature of the conductor is examined to see if it exceeds the maximum allowable conductor temperature.

2.6 Cables in ducts

Installing cables in ducts is a common installation method, as it aids the process of cable pulling and provides additional protection for the cables. The TOWF cables are installed with one cable in each duct and it is proposed to install the TEOWF cables with the same method.

2.7 Cables crossing heat sources

The TEOWF cables are proposed to cross the existing TOWF cables. To calculate the thermal impact on both sets of cables at the crossing point, the method given in IEC 60287 Part 3-3 has been used [5]. This considers the heat output from a heat source that crosses the rated cable and its effect on the thermal conditions of the ground where the cable is buried.

This method uses the principle of superposition to calculate the temperature rise of a cable due to the thermal contribution of the heat source, depending on the distance between the cable and the heat source, the heat dissipated from the source and the crossing angle.

The temperature rise of the cable will be highest at the crossing point, decreasing along the cable axis away from the crossing point. Because of the varying temperature rise along the cable length, a longitudinal heat flux is generated in the conductor, which leads to a reduction in the conductor temperature rise at the crossing, compared to the case when this longitudinal flux is ignored. This heat flux within the rated cable is considered to be negligible 20m from the crossing point [5].

For the present study, both the TOWF and TEOWF cables need to be treated as heat sources. The method requires several simultaneous iterative processes to calculate the heating effect that the TEOWF cables will have on the installed TOWF cables and vice versa.

2.8 Parallel cables and cable crossings

This section discusses the method used to address the two TOWF cable crossings, given the additional complexity that the two projects' cables would be installed parallel to each other on the approach to the crossing.

Figure 2-2 contains a close-up view of the locations of the two TOWF cable crossings.

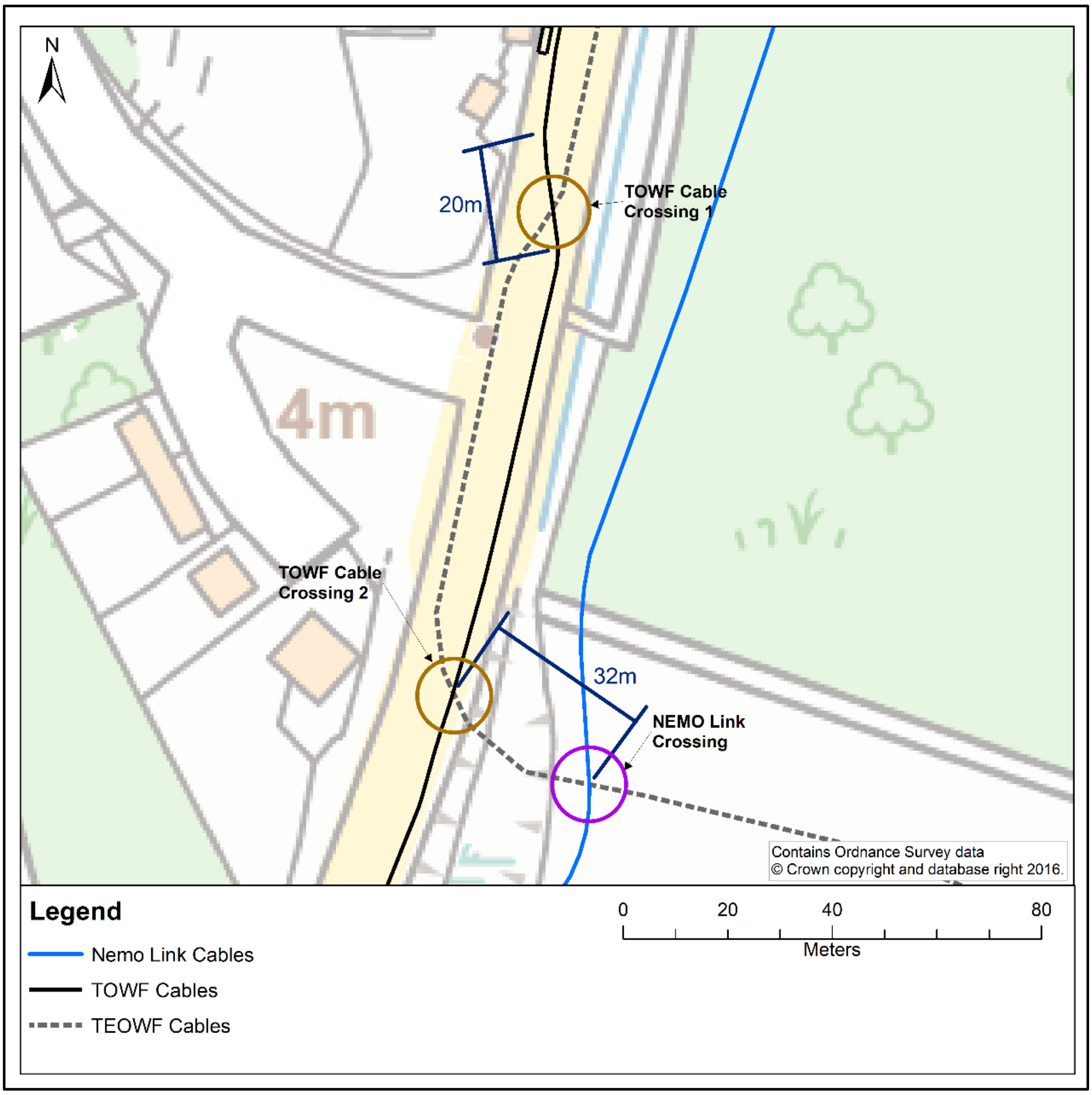

Figure 2-2: TOWF Cable crossing general layout

It can be seen in Figure 2-2 that on both sides of Crossing 1 the TOWF and TEOWF cables would be installed parallel to one another. For these sections of the cable route, it is proposed that the four TEOWF circuits are laid in a square formation, which is described in Section 4.3. For the crossing itself, it is proposed that the four TEOFW circuits are laid at the same burial depth (i.e. a common horizontal axis), beneath and perpendicular to the TOWF circuits, which is described in Section 4.5. The TEOWF cable groups would therefore 'fan out' before the crossing, from the square formation to the 'flat' formation of trefoil groups for the crossing.

Between crossings 1 and 2, the TOWF and TEOWF cables would also be installed parallel to one another, possibly as described in Section 4.4. For Crossing 2, it is proposed that the four TEOFW circuits are arranged at the same burial depth (i.e. a common horizontal axis), beneath and perpendicular to the TOWF circuits, as described in Section 4.5. On the other side of Crossing 2, the TEOWF cable circuits would continue perpendicular to the TOWF cable circuits, and would most likely remain in this formation as they approach the Nemo Link crossing cables (refer to report [2] on the Nemo Link cable crossings).

The additional methods used to model these aspects of the two crossings are described in the following sections.

2.8.1 Crossing 1

The method given in IEC 60287 Part 3-3 [5] for cables crossing heat sources, outlined in Section 2.7, takes account of different crossing angles, but does not take account of the situation where cables run parallel to each other, cross each other and then again run parallel to each other. The method also does not take account of the cable formation changing close to the crossing location. Crossing 1 is therefore quite complex to model accurately.

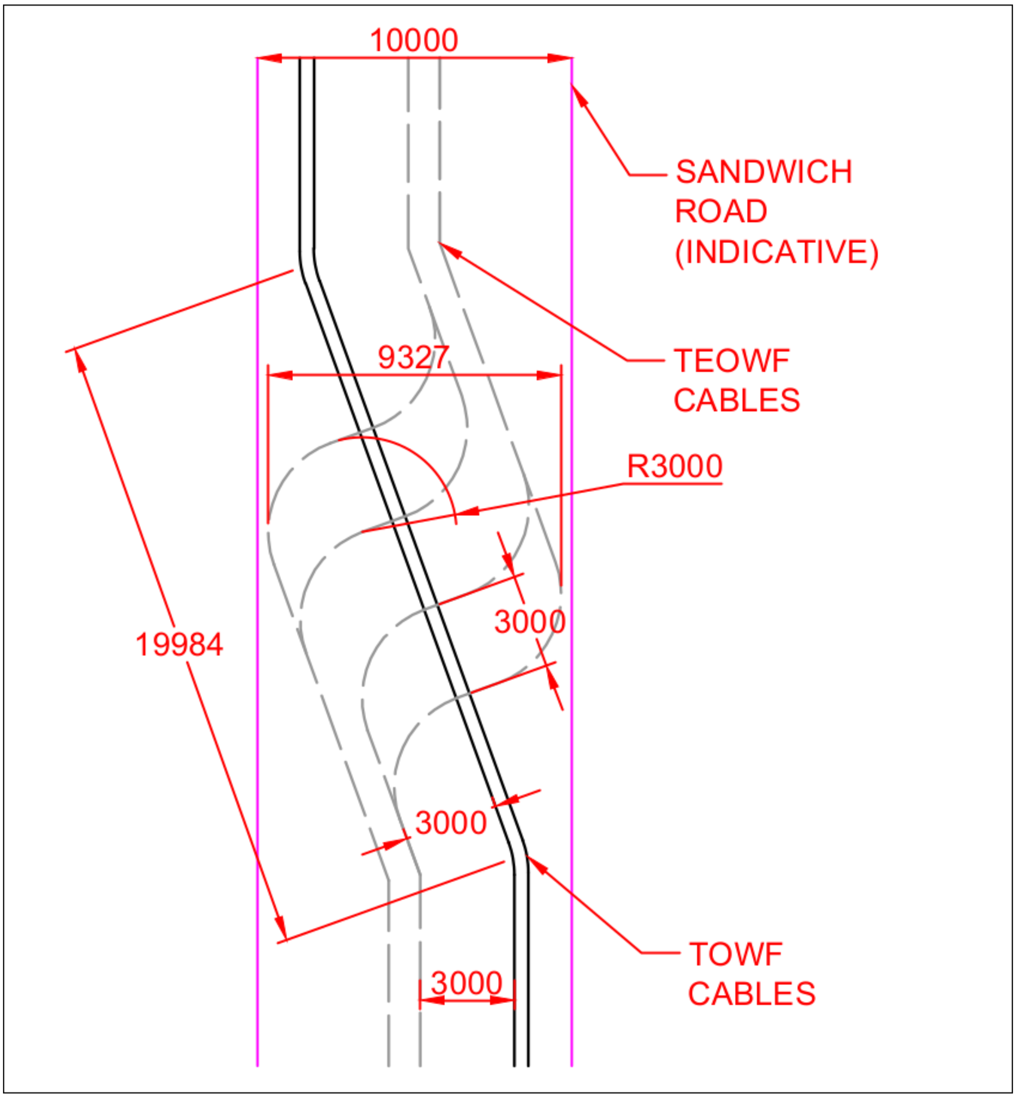

Figure 2-3: Indicative plan arrangement of TOWF Crossing 1 [6]

Crossing 1 is illustrated in Figure 2-3 as a plan view, with indicative dimensions. Each line in the figure represents one circuit, comprising three single core cables, each in an individual duct and the three ducts in trefoil. There are four TEOWF circuits, which are in a square formation to the left and right of the crossing, as described in Section 4.4. The four circuits fan out into a ‘flat’ formation, described in Section 4.5, as they cross under the TOWF circuits.

XE has taken the following additional steps to accurately model Crossing 1.

For the TOWF cables, XE has included the heating effect of the parallel sections of the TEOWF cables on the TOWF rated (hottest) cable, as if the TOWF and TEOWF cables were laid continuously parallel to one another, without the crossing. This was done using the method described in Section 2.5. XE considers that adding this heat source to the others already modelled will provide an upper estimate of the temperature rise at the crossing point in the TOWF rated cable.

For the TEOWF cables, which at the crossing point are beneath and perpendicular to the TOWF cables, XE has modified the method described in Section 2.7, to take account of the heating effect of the sections of TOWF cables that are parallel to the TEOWF cables either side of the crossing. This is done by neglecting the longitudinal heat flow along the TEOWF rated cable conductor away from the crossing point. The reason for this is that the parallel TOWF cable sections either side of the crossing will heat the TEOWF cables, so reducing the temperature gradient within the TEOWF conductors from the crossing point towards the parallel sections. XE considers that adding this modification to the method described in Section 2.7 will provide an upper estimate of the temperature rise at the crossing point in the TEOWF rated cable.

2.8.2 Crossing 2

Crossing 2 is illustrated in Figure 2-4 as a plan view.

As shown in the figure, on one side of Crossing 2 the TOWF and TEOWF cables are parallel to one another and on the other side they are perpendicular to one another. The mutual heating effects between the TOWF and TEOWF cables will therefore be less and the consequent cable temperatures will be lower for Crossing 2 than for Crossing 1, provided the other installation conditions are the same.

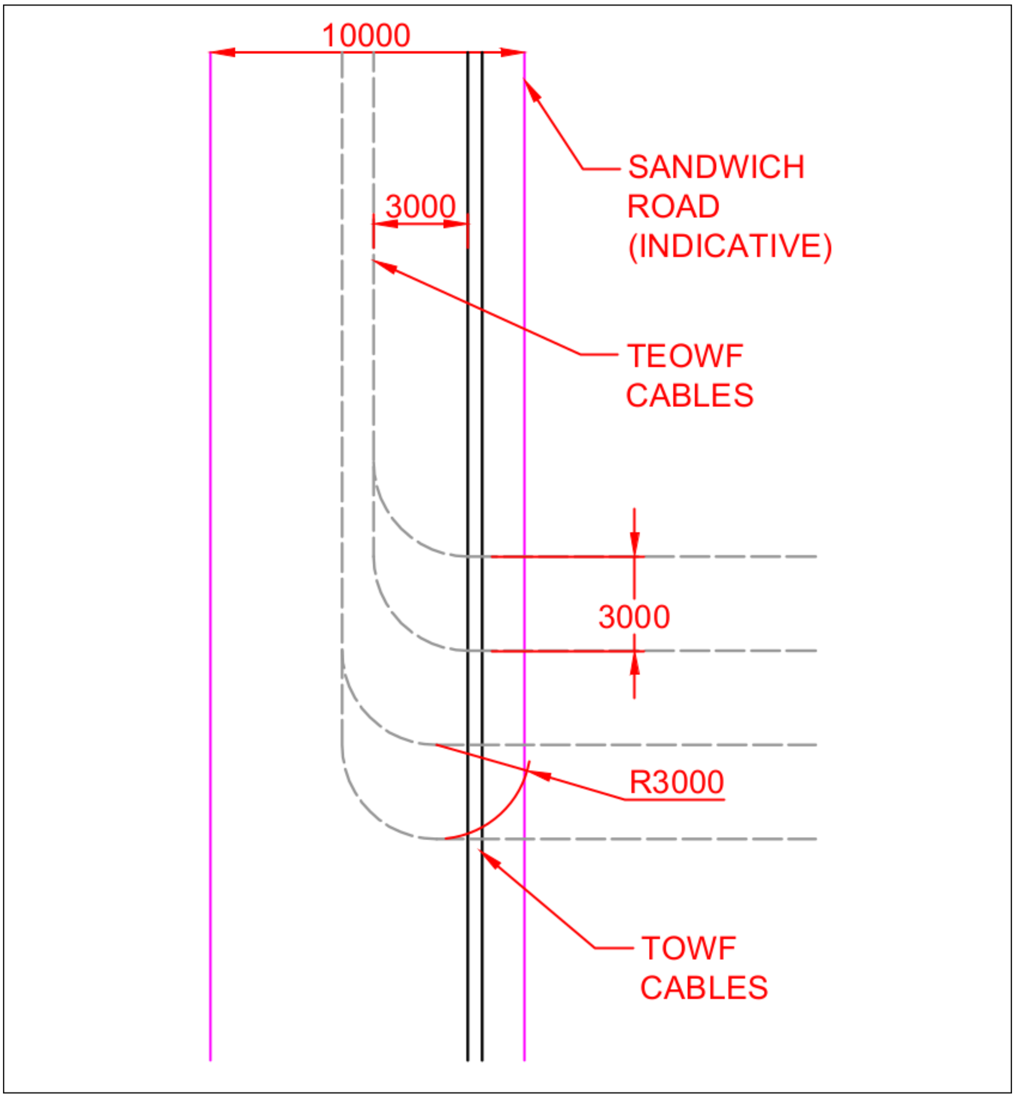

Figure 2-4: Indicative plan arrangement of TOWF Crossing 2 [6]

Crossing 2 is close to the crossing with Nemo Link cables in the sports ground, however these two crossing locations are estimated to be at least 30m apart. The longitudinal heat flux in the rated cable conductor due to crossing a heat source is considered to be negligible 20m from the crossing point [5]. Therefore, none of the crossings are expected to impact one another thermally.

This study therefore focuses on identifying a solution for Crossing 1, which in principle will also work for Crossing 2.

2.9 Format of results

XE has assembled the above components of the IEC 60287 methodology as one interlinked cable rating model. The results of cable sizing for TEOWF are presented in two ways: in terms of maximum allowable current of TEOWF, and in terms of cable temperatures with all cables at nominal maximum loading.

The maximum acceptable current allowed for the TEOWF cables is based on the hottest single TEOWF cable of the group. The maximum acceptable current is defined as the point at which the hottest of either the TOWF or the TEOWF cables reaches the maximum rated operating temperature of 90°C. For each result, the TEOWF maximum acceptable current, the TEOWF cable temperature, and the TOWF cable temperature are given.

Ratings and temperature results are based on steady-state currents (the maximum that could occur) through the cables.

The results are colour-coded according to Table 2-1, with green cells indicating cable ratings which are above the required current of 783A[1], amber cells near but within the requirement, and red cells below the requirement.

Colour	Description
Green	The calculated cable rating meets the current requirement, or the cable temperature is within its operating limit.
Amber	The calculated cable rating is near but meets the requirement, or the cable temperature is near but within its operating limit. Acceptability to be confirmed with asset owners.
Red	The calculated cable rating does not meet the current requirement, or the cable temperature is above its operating limit.

Table 2-1: Colour grading for cable rating results

2.10 Other notes

This study only considers full load continuous current ratings whereas both the TOWF and TEOWF cable loading will be cyclic according to wind farm output with a lower long-term average (load factor).

[1] Based on 340MW, 0.95 power factor, and four 66kV circuits.

3 Modelling data

3.1 Introduction

This section presents the cable data and cable loading assumptions used for the study.

3.2 Thanet

3.2.1 Cable design

This section reviews the cable parameters used in the study. The TOWF cable model has been based on the as-built TOWF cable data sheets and experience from similar assessments [7, 8]. The TOWF cable design is shown in Figure 3-1 below. The design features a Milliken four segment aluminium conductor and lead sheath.

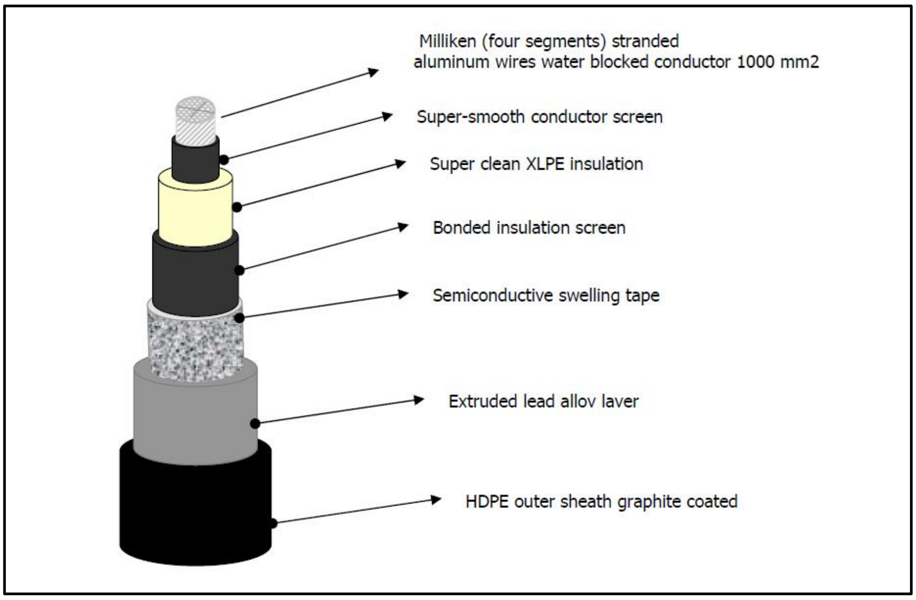

Figure 3-1: Cable design for TOWF cables based on provided data sheets [7, 8]

XE has made informed assumptions for the various cable layers where data on them has not been available. A review of some of the key cable assumptions is given below.

Conductor - The DC resistances (at 20°C) for the aluminium conductor is taken from IEC 60228 [9], which agree with the cable data sheet [8]. The Milliken four-segment conductor design reduces the conductor losses by reducing the AC conductor resistance (R in Equation 1).

Insulation - The insulation material is XLPE, which has a maximum continuous operating temperature of 90°C [10]. A thermal resistivity of 3.5K·m/W has been assumed, as given in IEC 60287 Part 1-1 [3]. The insulation thickness is 15.5mm according to the data sheet. Part 1-1 [3] gives parameters for filled and unfilled XLPE insulation for HV cables. Filled XLPE gives a higher dielectric loss (W_d in Equation 1) and hence lower cable rating, than unfilled XLPE.

The TOWF data sheets [7, 8] do not specify the type of XLPE insulation, however the dielectric loss in the TOWF design calculations suggests that the cable specification is unfilled XLPE insulation. This assumption has therefore been used.

Metallic screen - The TOWF cable design has a 3.5mm thick lead sheath. Circulating currents and eddy currents can flow in high voltage (HV) cable screens, depending on the screen type and screen bonding method. The TOWF cable screens are cross-bonded [11]. This reduces the circulating current loss to a negligible level and the eddy current loss becomes the significant screen loss (about 2% of the conductor loss for TOWF) [1].

Outer serving - The outer serving material is high density polyethylene (HDPE) with a thickness of 4mm [7].

Design temperature - The design temperature refers to the conductor temperature limit, to which the cable can be continuously loaded, without affecting the cable design life. This is determined by the insulation material, which could degrade or fail at high temperatures. The assumed maximum temperature is 90°C which is typical for XLPE cables. This is also implied in [1, 8].

The general TOWF cable specifications are summarised in Table 3-1.

Item	Description
Assembly type	Single-core unarmoured
Nominal operating voltage	132kV AC
Design temperature	90°C
Max. DC resistance at 20°C [Ω/km]	0.0291
Conductor type	1000mm^2 4-segment Milliken stranded aluminium
Conductor diameter [mm]	40.5 (40 to 41 specified in [7])
Conductor screen	Type not specified (semi-conductive assumed) Thermal resistivity (ρ_T) = 3.5K·m/W (assumed), Thickness (t) =2.0mm
Insulation	XLPE (unfilled assumed) ρ_T = 3.5K·m/W (assumed), t=15.5mm
Insulation screen	Type not specified (semi-conductive assumed) ρ_T = 3.5K·m/W (assumed), t=1.2mm
Semi-conductive swelling tape	ρ_T = 6.0K·m/W (assumed), t=0.5mm
Metallic sheath	Lead t=3.5mm
Outer serving	HDPE ρ_T=2.5K·m/W, t=4.0mm
Outside diameter [mm]	94.0
Duct specification	Polyethylene (PE) (assumed) P_T=3.5K·m/W, outer diameter=160.0mm Filled with air

Table 3-1: Summary of the TOWF cable design [7, 8]

3.2.2 Power output

The TOWF design report [1] gives the required current for each of the two 132kV power export circuits as 690A. The design report calculates the summer cable current rating for the installation as 735A. XE has therefore first used the 735A current value to validate the results of the design report. Following this, the design current of 690A has been used in the calculating the mutual thermal effects between the TOWF and TEOWF cables.

The above assumptions for TOWF and TEOWF and the corresponding design cable current are summarised in Table 3-2 below.

Item	Value
Power Factor	-
Power Output [MW]	-
Number of circuits	2
Voltage [kV]	132
Cable rating [A]	735
Required cable current [A]	690

Table 3-2: Current carrying assumptions and requirements for TOWF [1]

3.3 Thanet Extension

3.3.1 Cable design

This section reviews the cable parameters used for the TEOWF cables in the study.

The TEOWF cables have been based on typical 66kV cables based on XE's experience and with input from ABB's high voltage cable brochure [10] as a reference. The assumed TEOWF cable design is shown in Figure 3-2. This is a standard high voltage cable design with a copper wire screen with an overlaid copper equalisation tape.

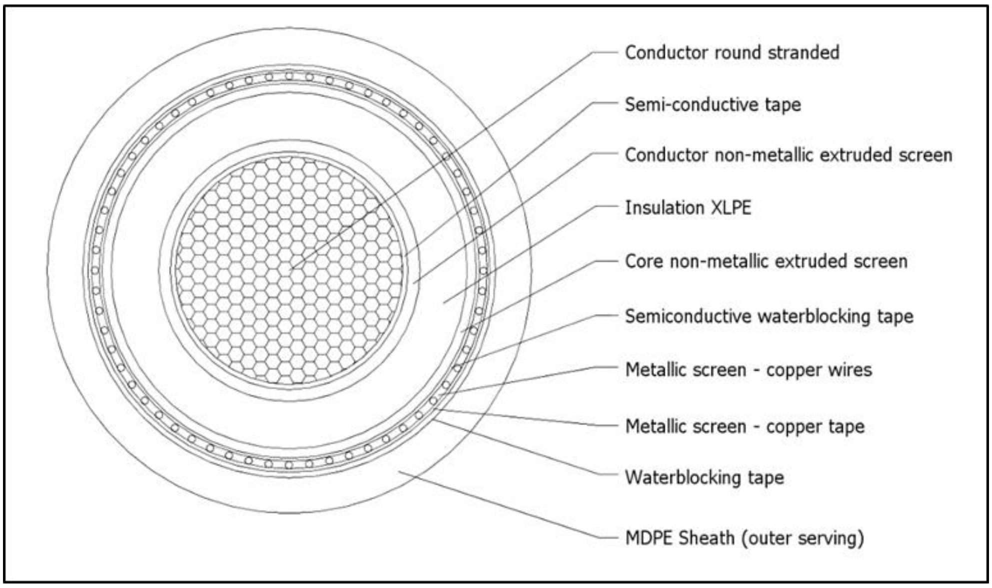

Figure 3-2: Cable design for TEOWF cables

XE has made informed assumptions for the various cable layers where data has not been available. Key cable assumptions are described below.

Conductor - The DC resistances (at 20°C) for aluminium and copper conductors are taken from IEC 60228 [9]. The TEOWF cables have been examined for both stranded conductors as shown in Figure 3-2 and also Milliken type segmental conductors.

For copper type Milliken conductors, a best case of all wires insulated has been examined. Alternative types of Milliken may also be possible but would have a lower rating.

Insulation - The insulation material is XLPE, which has a maximum continuous operating temperature of 90°C. A thermal resistivity of 3.5K·m/W has been assumed, as given in IEC 60287 Part 1-1 [3]. The insulation thickness is 9mm.

Cable manufacturers are continually improving cable design and one aspect of this is XLPE insulation filling material that improves its long-term dielectric strength. IEC 60287 Part 1-1 [3] gives parameters for filled and unfilled XLPE insulation for HV cables. Filled XLPE gives a higher di-electric loss (W_d in Equation 1) and hence lower cable rating, than unfilled XLPE.

Unfilled XLPE insulation has been assumed for this study which yields a better rating than filled insulation.

Metallic screen - Circulating currents and eddy currents can flow in cable screens, depending on the screen type and screen bonding method. The TEOWF cables have been assumed to have copper wire screens overlaid with a copper equalisation tape [10], for which eddy currents are considered to be negligible. For the TEOWF cables, XE has modelled two screen bonding methods: both end bonding and cross-bonding. For screens bonded at both ends of the cable route, which is the method commonly used for a short cable route such as this, circulating currents flow in the cable screens creating losses, which contribute to cable heating and so reduce the cable current rating. For cross-bonded screens these circulating currents are reduced to a negligible level.

Outer serving - The outer serving material is PE. For the TEOWF cables XE has assumed a thickness of 3.8mm for all cable sizes tested.

Design temperature - The design temperature refers to the conductor temperature limit, to which the cable can be continuously loaded, without affecting the cable design life. This is determined by the insulation material, which could see performance degradation or failure at critical temperatures. The assumed maximum temperature is 90°C which is typical for XLPE cables.

The general TEOWF cable specifications are summarised in Table 3-3 and the parameters by cable size are summarised in Table 3-4.

Item	Description
Assembly type	Single-core unarmoured
Nominal operating voltage	66kV AC
Design temperature	90°C
Conductor type	Copper or aluminium Stranded or Milliken type
Conductor screen	Semi-conductive tape plus extruded screen ρ_T = 3.5K·m/W, t=1.0mm
Insulation	Unfilled XLPE ρ_T = 3.5K·m/W, t=9.0mm, ε=2.5, tan δ=0.001
Insulation screen	Semi-conductive screen and water blocking tape ρ_T = 3.5K·m/W, t=1.5mm
Insulation water blocking	Water swelling semi-conducting tape ρ_T=6.0K·m/W, t=0.5mm
Metallic screen type	Copper wire screen with copper equalisation tape t=1.5mm
Outer serving	PE ρ_T = 3.5K·m/W, t=3.8mm

Table 3-3: Summary of assumptions for the design of the TEOWF cables [10]

TEOWF cable size (Conductor Cross Sectional Area)	Conductor diameter [mm]	Cable diameter [mm]	Copper Max. DC resistance at 20°C [Ω/km]	Aluminium Max. DC resistance at 20°C [Ω/km]
1000mm^2	37.90	70.5	0.01760	0.02910
1200mm^2	42.80	75.4	0.01510	0.02470
1400mm^2	46.40	79.0	0.01290	0.02120
1600mm^2	49.80	82.4	0.01130	0.01860
1800mm^2	52.03	84.6	0.01010	0.01650
2000mm^2	54.40	87.0	0.00900	0.01490
2200mm^2	57.79	90.4	0.00808	0.01334
2400mm^2	60.49	93.1	0.00740	0.01221

Table 3-4: Summary of parameters by conductor size of the TEOWF cables [10]

It shall be noted that 3000mm^2 size is a recognised absolute cut-off for cable manufacturing. However, the limit of size available will vary by cable manufacturer, and at least two are known to have a limit of 2500mm^2 cross-sectional area. Therefore, 2400mm^2 size has been assumed to be the largest size available for this study.

Also, feasibility for installation, particularly for heavier copper conductor cables, will need to be checked with installation contractors.

3.3.2 Power output

TEOWF is planned to have a maximum output of 340MW and this study considers four 66kV power export circuits. TEOWF is expected to operate within a power factor range of 0.95 leading to 0.95 lagging. A 0.95 power factor (exporting reactive power) has been assumed as a worst case, because it increases reactive flows in the cable and hence currents. This results in a maximum current flow of 783A.

The above assumptions for TEOWF and the corresponding design cable current are summarised in Table 3-5 below.

Item	Value
Power Factor	0.95
Power Output [MW]	340
Number of circuits	4
Voltage [kV]	66
Design cable current [A]	783

Table 3-5: Current carrying assumptions and requirements for TEOWF

4 Installation arrangements

4.1 Introduction

This section discusses and describes the installation cases studied. Of concern are the space restrictions in Sandwich Road and the consequent impacts on the cable arrangements and separation of TEOWF from TOWF.

There are severe space constraints for TEOWF cables to be laid in Sandwich Road, due to the identified utilities already installed within it, including TOWF cables, telecoms and distribution power supply cables. The proposed cable installation for most of the Sandwich Road cable route is therefore to install the four TEOWF circuits in a square formation in a single trench alongside the existing TOWF cables. The impact of this installation scenario was covered in the previous revision of this report [12], and has been updated for this revision B.

The study also examines the two locations where the TEOWF cables would cross the TOWF cables. To do this, it is proposed that the TEOWF cables would 'fan out' from the square formation, to four trefoil groups at the same burial depth (i.e. a common horizontal axis). The TEOFW cables would pass under the TOWF cables in this formation. Each trefoil cable group (circuit) would comprise three single core cables, each cable in an individual duct.

Between the two crossing points (Crossing 1 and Crossing 2 described in Section 2.8), for the purposes of the study, it has been assumed that the TEOWF cables would resume the square formation used for most of the Sandwich Road route. It is possible that that the cables could maintain a similar formation as for the crossing if space permits.

For the cable route section between Crossing 2 and the Nemo Link crossing, the TEOWF cables would most likely continue with the same formation of the four trefoil groups spaced out at the same burial depth.

The details of the layout for the installation in Sandwich Road and the two TOWF crossings are described in the following sections.

4.2 General arrangement TOWF in Sandwich Road (model validation)

The TOWF installation layout is shown in Figure 4-1 below [13]. It is understood that this arrangement is used for most of the cable route beneath the Sandwich Road carriageway.

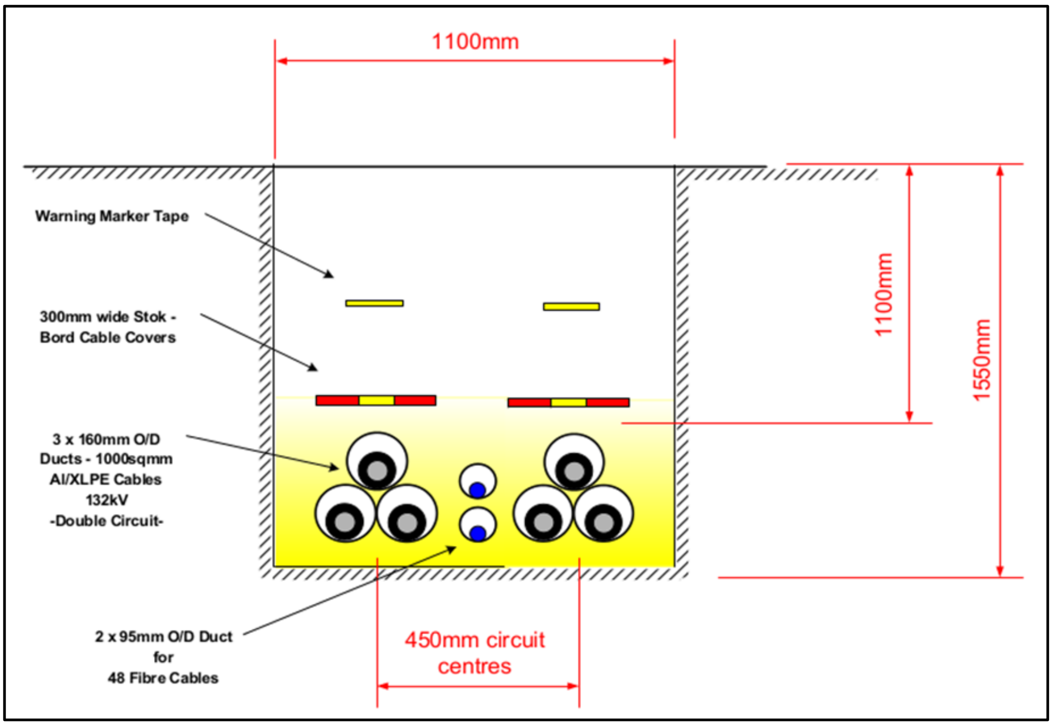

Figure 4-1: General arrangement of the TOWF cable layout [13]

It can be seen in Figure 4-1 that each cable is installed in an individual duct with a 160mm outside diameter and the ducts for each circuit are laid in a touching trefoil group. The depth to the top of each trefoil group is 1100mm and the spacing between the circuits is 450mm. The ducts are filled with air.

For the initial TOWF validation calculations, XE has modelled the cables with the layout shown in Figure 4-1 in isolation from any other circuits and heat sources.

4.3 General arrangement TEOWF in Sandwich Road

The proposed TEOWF installation layout is shown in Figure 4-2 below. Note that fibre optic cables, warning tapes and any protective tiles are not shown.

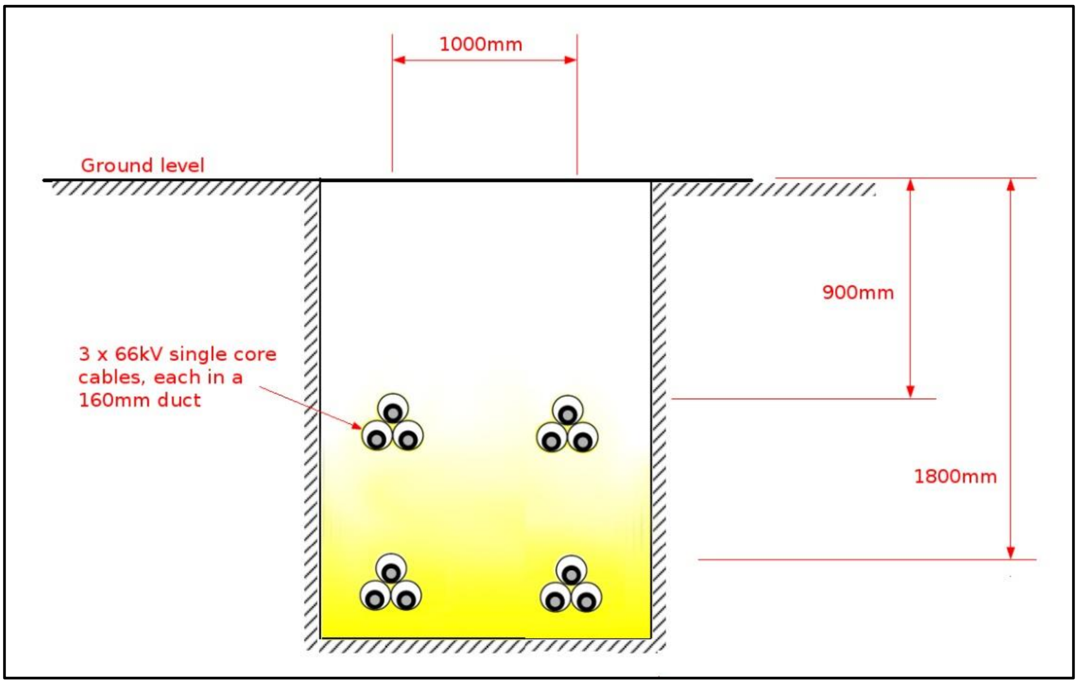

Figure 4-2: General arrangement of the proposed TEOWF cable layout for Sandwich Road

It can be seen in Figure 4-2 that the four circuits are laid out in a square shape, with 1000mm horizontal separation and 900mm vertical separation. Each circuit comprises three single core cables, each in an individual 160mm air-filled duct and the ducts are laid in a touching trefoil arrangement.

This arrangement for the TEOWF cables is adopted due to space restrictions with the TEOWF cables needing to be in a single trench, with a horizontal separation of not more than 1000mm. Typically cables circuits would be laid in parallel on the same horizontal axis, with each cable group separated by some distance. The above arrangement is very unusual for onshore power cable installation but has been examined due to the space restrictions in the road.

Sandwich Road already contains a wide variety of service cables and pipelines. These include UK Power Networks distribution power cables, British Telecom telecommunication cables, water mains, sewer mains, and the TOWF 132kV cables. Other services are believed to be installed, e.g. an anaerobic digestion plant pipeline, or planned to be installed, e.g. a new Southern Water sewer main.

XE has reviewed the route and mapped the services from records [14] as well as walked the route [15]. In addition, the route has been reviewed and walked by a cable installation contractor [16]. A set of service maps for Sandwich Road as recovered from records in 2016 is included along with this report in file GIS 1526/029/001, reference [17].

Based on the work undertaken in surveying the route, it is believed that only a single trench can be dug for the purposes of TEOWF cable installation. Such a trench could be wide enough for two circuits laid side by side with a reasonable separation but would require a vertical arrangement for four circuits.

4.4 General arrangement TEOWF and TOWF in parallel in Sandwich Road

The existing TOWF installation and the proposed TEOWF installation are shown together in Figure 4-3 below.

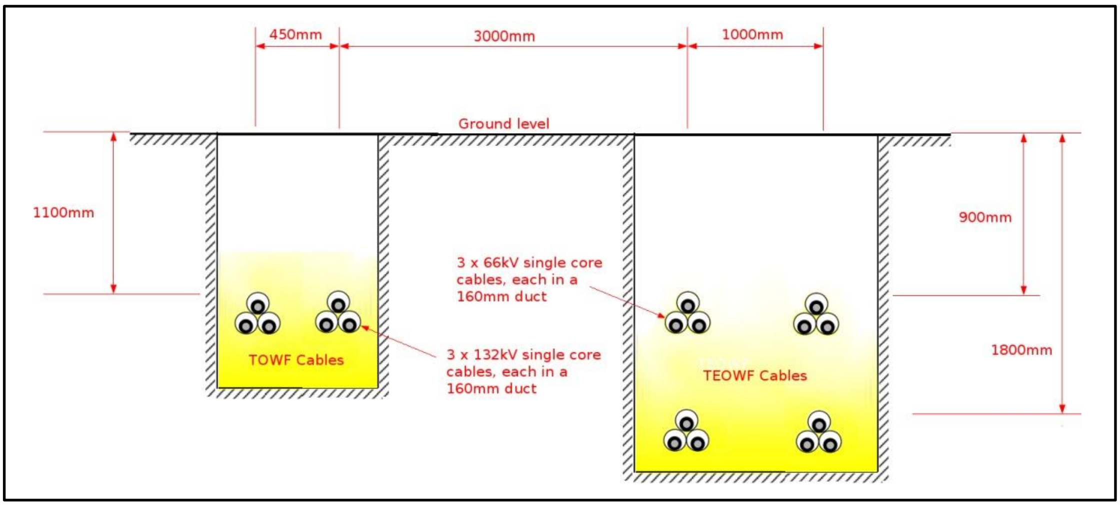

Figure 4-3: General arrangement of TOWF and TEOWF in parallel in Sandwich Road

The burial depths and distances between the TOWF circuits and between the TEOWF circuits are the same as in Figure 4-1 and Figure 4-2.

Figure 4-3 shows the base case solution for TEOWF cables in Sandwich Road. The main features of this base case solution are:

- TEOWF cable burial depth: 0.9m
- Horizontal distance between TEOWF circuits: 1m
- Vertical distance between TEOWF circuits: 0.9m
- Horizontal distance between TEOWF and TOWF circuits: 3m

XE understands that the nominal width of Sandwich Road is about 8m. TOWF is installed in the northbound (west) side of the road for much of this section. This means that it may only be possible to achieve up to about 5m separation between TOWF and TEOWF, as measured between the centres of the inner cable groups. The minimum advised separation is 1m between TEOWF and TOWF cable groups to ensure the TOWF cables are not disturbed or damaged during installation and also because of thermal considerations.

A smaller separation results in a larger mutual heating effect between the two projects, requiring larger TEOWF cables.

4.5 General arrangement TOWF and TEOWF cable crossing

The existing TOWF installation and the proposed TEOWF installation for Crossing 1 are illustrated in Figure 4-4. The detailed general arrangement is shown in Figure 4-5. Note that fibre optic cables, warning tapes and any protective tiles are not shown.

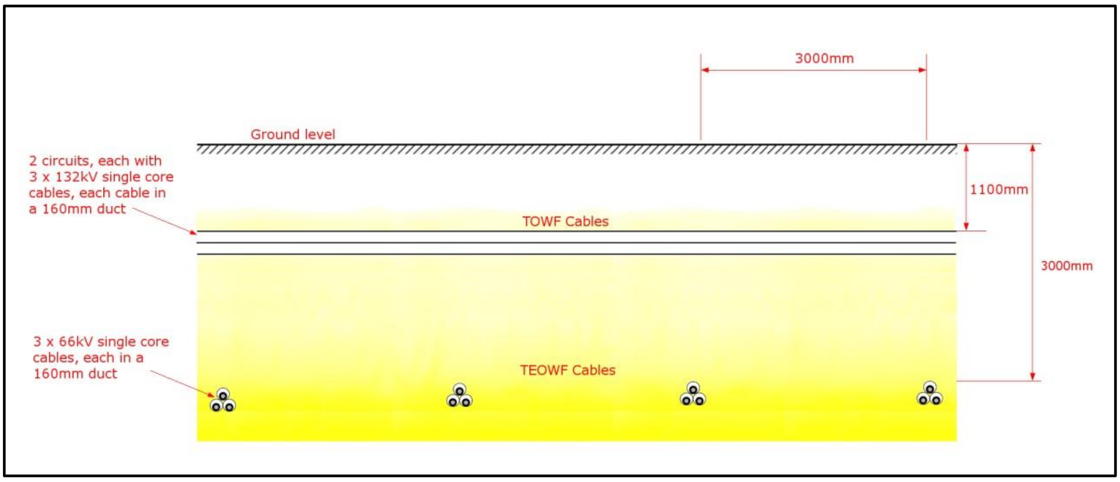

Figure 4-4: General arrangement of TOWF and TEOWF cable crossing

In these figures the TOWF and TEOWF cables are perpendicular to each other. The burial depth and distance between the TOWF circuits are the same as in Figure 4-1.

For the TEOWF cables, the layout would transition from the ‘square’ formation described in Sections 4.3 and 4.4, to all four circuits being installed at the same burial depth of 3m (i.e. a common horizontal axis), with 3m between cable groups. As before, each circuit would comprise three single core cables, each in an individual 160mm air-filled duct and the ducts laid in a touching trefoil arrangement.

The arrangement shown in Figure 4-5 is the base case solution, for which the crossing would satisfy the thermal ratings of all cables, maintaining all the cable temperatures below the maximum permissible 90°C, with rated current flowing in all the circuits.

The main features of this base case solution for Crossing 1 are:

- Horizontal separation between TEOWF circuits: 3m
- Burial depth of TEOWF circuits: 3m
- Horizontal separation between TEOWF and TOWF circuits either side of the crossing: 3m
- Crossing angle: 90°

The crossing would need to be accomplished by manual excavation techniques to ensure the TOWF cables are not disturbed. The TEOWF cable ducts would be installed in place and then the individual cables would be pulled through each of the cable ducts. Both the TEOWF and TOWF cable ducts have been assumed to be filled with air for this study.

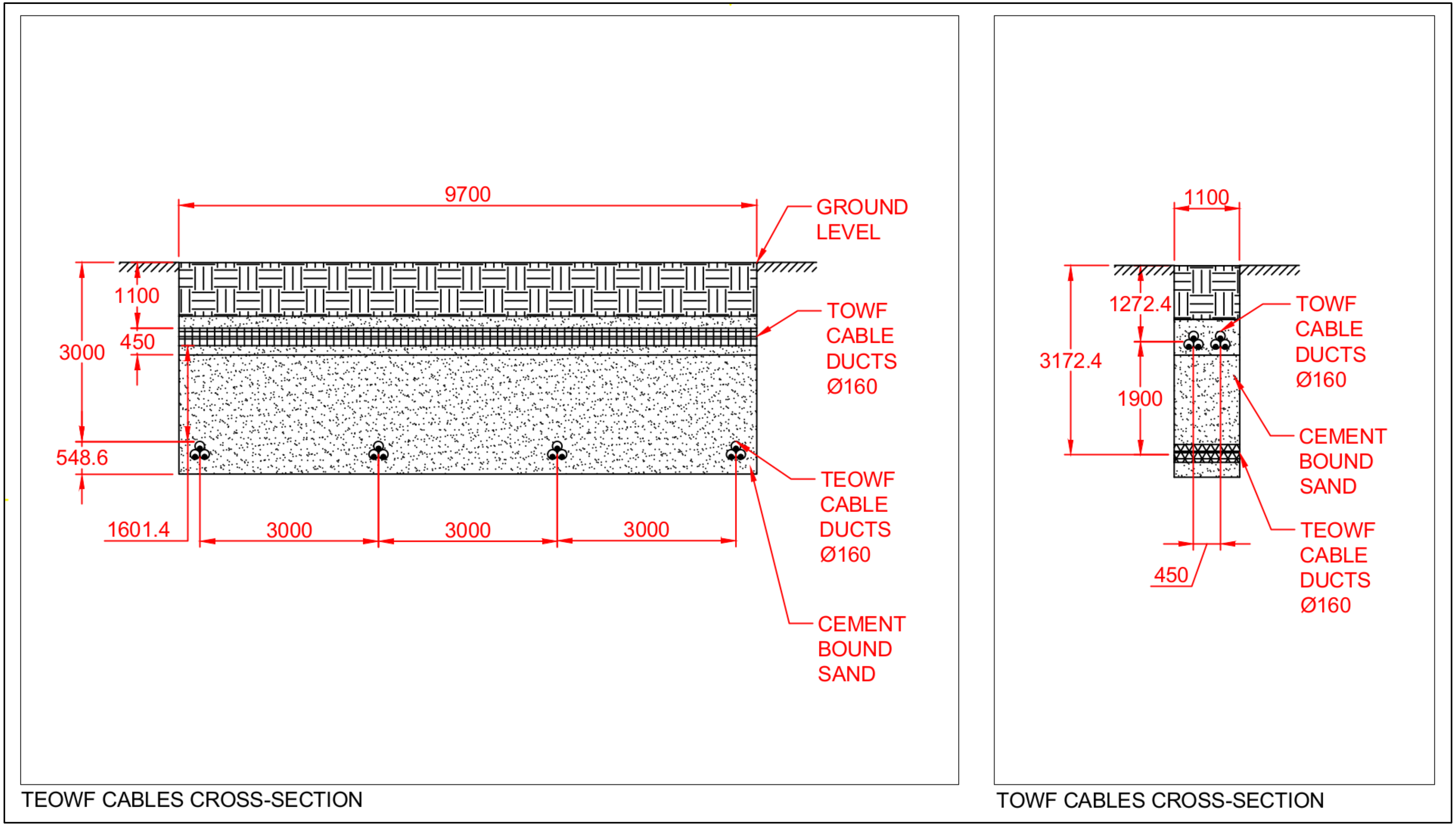

Figure 4-5: Detailed general arrangement of the TOWF and TEOWF cable crossing [18]

4.6 Other installation cases

The arrangements described above are understood to be suitable for most of the cable route beneath Sandwich Road and the two TOWF cable crossings. However, there are locations for which these arrangements will not be suitable, e.g.

- The TOWF cables pass through a concrete duct bank to cross a culvert [19]. TEOWF would need to assess the options for crossing the culvert also and this may prove difficult given it will introduce additional space constraints.
- There may be other services in the road which would need to be circumvented by the TEOWF cables. Different spacing / separation of the cables may be required at these locations. The exact locations of these services can only be pinpointed with utilities detecting equipment or via intrusive surveys.

These issues are not studied in this report and have the potential to create both engineering difficulties and localised hot spots. If it is decided that the TEOWF cables are to follow the TOWF cable route, the cable installation arrangements necessary at these locations would need to be analysed to ensure that the TOWF and TEOWF cable ratings at these locations are acceptable. This additional analysis would be a natural follow on from this report if the findings of this report are satisfactory.

Furthermore, TEOWF will need to find space for joint bays and link boxes if the screens are to be cross-bonded which further increases the difficulty of installation within the constraints found in Sandwich Road.

4.7 Ground thermal resistivity

For all the cases described above, the cables are considered to be bedded in selected sand [13] and the sand and surrounding soil are assumed to have a thermal resistivity of 1.2K·m/W. This is the standard value recommended for the United Kingdom in IEC 60287 Part 3-1 [20].

4.8 Ground temperature

The ground ambient temperature is assumed to be 15°C, which is the recommended value for the United Kingdom in IEC 60287 Part 3-1 [20].

5 Results

5.1 Introduction

The results for the installation arrangements described in Section 4 are described in this section. This includes the validation of the TOWF cable rating, for TEOWF installed in Sandwich Road by itself, for TEOWF in Sandwich Road taking account of TOWF, and the cable crossings with TOWF.

The results for the base case installation arrangement are presented, which is the arrangement which would reasonably satisfy cable thermal conditions of all cables. The base case has been determined by sensitivity analysis, which is presented in Appendix A, Section 8.

The results of cable sizing for TEOWF are presented in two ways: in terms of maximum allowable current of TEOWF, and in terms of cable temperatures with all cables at nominal maximum loading. Results are presented for different TEOWF cable sizes and conductor types.

5.2 TOWF in Sandwich Road (model validation)

A model of the TOWF cables has been created using the method of IEC - 60287 [3, 4] as described in Section 2, and the cable parameters described in Section 3.2.1.

The model has been validated against the summer rating for the TOWF cables based on documentation held by the client and the data for TOWF described in Section 3.2.1. The summer current rating of the TOWF cables is 735A for which the cable reaches a 90°C temperature, for an ambient ground temperature of 15°.

For the rated nominal current of TOWF of 690A, the cable temperature would be 79.5°C according to the validation model.

5.3 TEOWF in Sandwich Road, without TOWF

A model of the TEOWF cables was created using the method of IEC 60287 [3, 4] described in Section 2, the cable parameters described in Section 3.3.1, and the cable layout described in Section 4.3. The mutual heating between the four 66kV TEOWF circuits was taken in account, but no other heat sources were considered.

This was done for 1200mm^2, 1600mm^2, 2000mm^2, 2400mm^2 copper conductors, and 2000mm^2 aluminium conductors, with the screens cross-bonded. Only stranded type conductors are presented because these satisfy the temperature requirements. Milliken type conductors could also be an option which would allow use of a smaller cross-section (typically 200-400mm^2 smaller size). The results are for the screen design outlined in Section 3.3.1.

The results are shown in Table 5-1 below.

TEOWF cable size	TEOWF cable temp. at 783A [°C]	TEOWF cable current rating at 90°C [A]
Stranded conductors		
2000mm^2 aluminium	87.2	796
1200mm^2 copper	82.7	819
1600mm^2 copper	70.0	901
2000mm^2 copper	62.8	964
2400mm^2 copper	58.2	1015

Table 5-1: Cable temperatures and ratings for TEOWF cable group

The results show that without the heating effects of TOWF, the 1200mm^2 copper or 2000mm^2 aluminium cables would satisfy the requirements of TEOWF. This is with stranded conductors and cross-bonded cable screens.

5.4 TEOWF in Sandwich Road

5.4.1 Installation conclusions

This section presents the base case solution for the cables installed in Sandwich Road parallel to TOWF. The results show the cable sizes which would preserve the thermal integrity of both the TEOWF and TOWF cables.

Through sensitivity analysis presented in Appendix A, Section 8, the study has identified several requirements for the solution to form the base case:

- ➔ The installation is feasible only if the separation between TOWF and TEOWF can be maintained to about 3m or more, as shown in Table 8-3 in Section 8.2. This is the distance between the centres of the inner groups of each projects' cables. This distance of 3m should be viewed as a minimum and would be subject to further detailed design and discussion with asset owners. There is a risk that it may need to be increased further.
- ➔ The TEOWF cables would need to be cross-bonded instead of both end bonded.
- ➔ There is not much available headroom on the ratings of the existing TOWF cables, and therefore any thermal impact from TEOWF must be kept to a minimum. This is likely to necessitate use of large size conductor cables, and Milliken type conductors.

The separation between the two projects' cables is critical, as demonstrated by the sensitivity analysis in Appendix A, Section 8.2. This shows that the solution is not feasible if there is only 1m separation. For 2m separation, a minimum 1600mm^2 copper Milliken cable would be required. Separation of 3m or more is favourable, though the benefit to cable ratings of increased separation diminishes beyond 3m. The TOWF cables reach maximum operating temperature before TEOWF and therefore are the limiting factor.

The base case solution is therefore taken to be a 3m horizontal separation between the TEOWF and TOWF cables, as shown in Figure 4-3. The results show that the minimum TEOWF cable size required for this case would be:

- ➔ For stranded type conductors, 2000mm^2 aluminium or 1400mm^2 copper cable, cross-bonded.
- ➔ For Milliken type conductors, 1800mm^2 aluminium or 1000mm^2 copper cable, cross-bonded.

These cables are significant in size. The aluminium cables would have large diameters and therefore would be delivered in short lengths, requiring more cable drum deliveries and more joint bays along the route. The copper cables would be very heavy, and therefore be difficult for the installation contractors to transport, handle and manoeuvre.

Additionally, one or two sizes above these minima may be considered to allow headroom on rating, particularly for the TOWF cables, as these cables do not have much existing headroom on cable rating. These cable sizes would allow for the full load currents of 783A for TEOWF and 690A for TOWF, without cables of either project exceeding the maximum operating temperature limit of 90°C.

5.4.2 Cable temperatures

Table 5-2 contains the results in terms of cable temperatures which would occur for TEOWF operating with 783A loading and TOWF with 690A loading, for the base case installation solution for Sandwich Road. The results are presented for different cable sizes, and for aluminium and copper, stranded and Milliken type conductors.

The results are colour-coded according to the legend in Table 2-1 of Section 2.9.

TEOWF cable size	TEOWF cable temp. [°C]	TOWF cable temp. [°C]
Stranded conductors		
2000mm^2 aluminium	**89.5**	**89.4**
2400mm^2 aluminium	80.6	88.1
1200mm^2 copper	90.7	89.4
1400mm^2 copper	**82.8**	**88.3**
1600mm^2 copper	77.6	87.6
2000mm^2 copper	70.3	86.5
2400mm^2 copper	65.5	85.9
Milliken conductors		
1800mm^2 aluminium	**82.3**	**88.3**
2000mm^2 aluminium	75.6	87.3
2400mm^2 aluminium	64.9	85.8
1000mm^2 copper	**89.2**	**89.1**
1200mm^2 copper	78.0	87.5
1600mm^2 copper	63.1	85.4
2000mm^2 copper	55.2	84.3
2400mm^2 copper	50.2	83.6

Table 5-2: Cable temperatures for TEOWF loading of 783A and TOWF loading of 690A, Sandwich Road, 3m separation between projects (hottest cable temperature shown)

The results show that the 2000mm^2 aluminium or 1400mm^2 copper stranded conductor cable for TEOWF would just allow the cables of both projects to operate at full load without exceeding 90°C, given 3m separation between the projects. The 1800mm^2 aluminium or 1000mm^2 copper Milliken (insulated wire type Milliken) conductor cable may alternatively be used. These results are highlighted with the dashed box in the table.

Given these results are close to the 90°C cable temperature limit, they represent the smallest possible cables that can be used (with the assumptions the study has made).

5.5 TEOWF and TOWF cable crossings

5.5.1 Crossing conclusions

This section presents potential solutions for the crossings between TEOWF and TOWF cables, which would preserve the thermal integrity of both the TEOWF and the TOWF cables.

This section focuses on Crossing 1, which is the worst case, because the TOWF and TEOWF cables are installed parallel to each other on either side of the crossing. For Crossing 2, the two projects' cables would be parallel to each other on the west side of the crossing only.

Crossing 2 is close to the crossing with Nemo Link cables in the sports ground, however these two crossing locations are estimated to be at least 30m apart. Similarly Crossing 1 is estimated to be about 90m away from Crossing 2. As the heat flux is considered to be negligible 20m from the crossing point [5], none of the crossings are expected to impact one another thermally. Therefore Crossing 1 has been taken to be the worst case.

Through sensitivity analysis presented in Appendix A, the study has identified several requirements for Crossing 1, to form the base case:

- ➔ A crossing is very challenging in terms of not having the TOWF cables exceed thermal ratings. This is because there is not much headroom on rating on the existing TOWF cables as they are.
- ➔ The TEOWF cables would likely need a burial depth of at least 3m to maintain adequate separation from TOWF and therefore minimise the thermal effect of TEOWF on the TOWF cables.
- ➔ The TEOWF cables would likely need to have 3m between cable groups to facilitate cable ratings because of the greater burial depth.
- ➔ The separation between the projects on either side of Crossing 1 impacts the thermal conditions of Crossing 1 as well (refer to Appendix A, Section 8.2)

Therefore, the base case is 3m burial depth, 3m cable group separation, 90° crossing angle, with TOWF and TEOWF separated by 3m in Sandwich Road (i.e. the 'TEOWF in Sandwich Road' base case presented in Section 5.4). For the base case crossing solution, the results show that the minimum cable size required for TEOWF would be:

- ➔ 2400mm^2 copper cable with Milliken type conductor, cross-bonded.

This cable is considered to be marginal in terms of installation feasibility.

This cable size is very heavy and has a large diameter. If this size is used across the entire onshore route, it would require delivery in short lengths, requiring more cable drum deliveries and more joint bays along the route. The cables would also be very heavy, increasing the difficult of handling and transport for the installation contractors.

It is recommended that this is confirmed with contractors as to transport and handling for installation along the route and for such a crossing arrangement.

Furthermore, even at this cable size, if TOWF and TEOWF are at full rated output, the temperature of the TOWF cables would be at the 90°C limit which is understood not to be acceptable from an operational and risk perspective.

The solution would require a 10m permanent corridor for Crossing 1 where the TEOWF cables ‘fan out’ with 3m separation between cable groups. This is illustrated in Figure 2-3 [6].

If this is not possible then the crossing angle would need to be less than 90°, which would result in higher cable temperatures at the crossing point. The cable 90°C maximum continuous operating temperature could be exceeded which could damage the cable insulation and compromise its performance (refer to Table 8-4 in Section 8.3).

The bending radius of circa 3m seems to be within limits. The recommended minimum bending radius to use for planning purposes is 20 times cable diameter which equals about 1.9m for the 2400mm^2 cable.

5.5.2 Cable temperatures

Table 5-3 contains the results in terms of cable temperatures which would occur for TEOWF operating with 783A loading and TOWF with 690A loading, for the base case solution for Crossing 1.

The results are colour-coded according to the legend in Table 2-1 of Section 2.9.

TEOWF cable size	TEOWF cable temp. [°C]	TOWF cable temp. [°C]
Stranded conductors		
2400mm^2 aluminium	85.7	100.2
2400mm^2 copper	72.1	94.8
Milliken conductors		
2400mm^2 aluminium	72.0	94.7
2000mm^2 copper	63.2	91.1
2400mm^2 copper	**58.6**	**89.4**

Table 5-3: Cable temperatures for TEOWF loading of 783A and TOWF loading of 690A, base case solution for Crossing 1 (hottest cable temperature shown)

The results show that the 2400mm^2 Milliken copper cable TEOWF cable and the base case crossing solution would just allow the cables of both projects to operate at full load without exceeding 90°C, although the TOWF cables would be right on its maximum operating temperature. These results are highlighted with the bold text in the table.

The screen design and bonding examined are an optimal design for rating.

The results are given for a 90° perpendicular crossing angle. The effect of crossing angle is shown in Appendix A, Section 8.3. This shows that the crossing angle would need to be between about 65° and 90°.

Appendix A, Sections 8.4 and 8.5 also show the effect of group separation and burial depth on cable rating.

Given these results are close to the 90°C cable temperature limit, the 2400mm^2 copper Milliken cable represents the smallest possible type of cable that can be used (with the assumptions the study has made) for the crossing with the TOWF cables. This cable size is likely to be at the limit of capability of the cable manufacturers.

6 Summary

6.1 General

Xero Energy Limited (XE) has been commissioned by Vattenfall Wind Power Limited (VWPL) to perform initial current rating calculations and cable sizing for the onshore export cables of the proposed Thanet Extension Offshore Wind Farm (TEOWF), which is proposed to have a maximum output of 340MW. This study concerns the installation of TEOWF in Sandwich Road, which is space constrained due to the presence of existing services and the Thanet Offshore Wind Farm (TOWF) 132kV circuits. The overall aim is to assess the technical feasibility of having TEOWF cables installed in Sandwich Road, parallel with the existing TOWF cables, and having TEOWF cables cross TOWF cables at two locations.

This study analyses one option for the TEOWF onshore export cables, which comprises four 66kV circuits, laid alongside the existing TOWF 132kV double circuit export cables. The study uses the general installation conditions to be found along the road route and examines two specific locations of cable crossings. The space along this cable route is very limited due to the TOWF cables and other services and for this reason the TEOWF cable installation is assumed to be in a single trench in square formation, with horizontal spacing of 1m and vertical spacing of 0.9m between circuits.

6.2 Method

Cable models for both the TOWF and TEOWF cables have been created based on the IEC 60287 standard [3, 4, 5]. The study has first modelled and validated the TOWF design report [1] cable rating and losses, in isolation of TEOWF. The TEOWF cables have been based on typical 66kV cables based on XE's experience and with input from ABB's high voltage cable brochure [10] as a reference.

The suitability of the crossings for the TOWF and TEOWF cables has then been assessed using sensitivity analysis on different variables, including TEOWF cable type and size, screen bonding arrangement, vertical separation between TEOWF and TOWF, group separation, project separation, and crossing angle.

The results have been presented in this study from two perspectives: the temperature of the hottest cable of each project for maximum current (783A for TEOWF and 690A for TOWF); and, the maximum allowable current of the TEOWF cable without the temperature of either TOWF or TEOWF exceeding the maximum allowable temperature of 90°C.

6.3 Results

The study has analysed the TEOWF four 66kV circuit general arrangement in Sandwich Road, in isolation from TOWF. It shows that 1200mm^2 copper or 2000mm^2 aluminium cables with stranded conductors would be sufficient for the maximum steady state TEOWF current of 783A, based on the assumed cable screen design and with the screens cross-bonded.

The study then has analysed the mutual heating effects between the two TOWF 132kV circuits and the four TEOWF 66kV circuits. This analysis uses the maximum TOWF output current of 690A and the maximum TOWF output current of 783A. The study results in a base case solution which calls for there to be at least 3m separation between the centres of the inner groups of the two projects' cables. This would allow 1400mm^2 copper or 2000mm^2 aluminium cables with stranded conductors to be used.

Use of Milliken conductors could also be a possibility. This typically allows the conductor size to be reduced by 200mm^2 to 400mm^2 in size. Other measures could also be examined such as use of thermal grout in the ducts, or adjusting or improving the cable or duct design to assist with thermal rating. The screen design and bonding examined in this study are an optimal design for rating.

In addition to the above there are other thermal and space pinch points along the Sandwich Road route, including the need to find space for a culvert crossing, and the need to find space for TEOWF joint bays and link boxes if cross-bonded (which seems to be essential). These add to the overall difficulty and the latter will introduce localised hot spots which given the results of the general analysis are unlikely to be favourable in terms of acceptability.

The TEOWF cables would also need to cross TOWF twice within a 100m span. This is because the side of the road TOWF is installed transitions from the northbound lane to the southbound lane near around Ebbsfleet Lane. The study has analysed the crossing, and a base case has been developed which would have the TEOWF cables transition from the 'square' formation in Sandwich Road to four trefoil cable groups in a 'flat' formation, i.e. at the same burial depth. The base case is for TEOWF to be installed at 3m burial depth and with 3m group separation (4m may also be possible). For this, the only TEOWF cable specification which would satisfy both projects' cable ratings is the 2400mm^2 copper Milliken conductor cable. This is based on the assumed cable screen design and cross-bonding, which is an optimal design for rating.

6.4 Conclusions

The following conclusions have been reached from the study:

General

- ➔ The TEOWF cable screens would need to be cross-bonded instead of both end bonded. The study has used a screen design which is optimistic for rating. This has been shown to be necessary.

Sandwich Road installation

- ➔ Installation of TEOWF in Sandwich Road is theoretically possible from a thermal rating perspective, and a base case solution has been identified. However, it would be strongly recommended to maintain at least 3m separation from the TOWF cables.
- ➔ It has been assumed that a square formation of the cable circuits would be necessary to accommodate them in the road. This is an unusual formation, and would present additional safety risks in terms of access to the bottom cables of the formation. The formation is not ideal for cable maintenance or repair.
- ➔ It seems that the installation in Sandwich Road may be difficult to achieve given the necessary infrastructure required (e.g. joint bays, link boxes), and the constraints in the road (e.g. culvert crossing, BT services, other potential services in the road, etc.).

Cable crossings

- ➔ Crossing of the TOWF cables at two locations would be very difficult to achieve. A base case solution has been developed but it only works for the largest cable size studied of 2400mm^2 copper Milliken.
- ➔ Even then, the TOWF cables at the crossing location would operate very close to their rated limit if both projects are at full load. It is good practice to allow headroom on rating, and elimination of all the existing headroom may not be acceptable to the owner and operator of the TOWF cables.
- ➔ The solution for Crossing 1 would require a 10m permanent corridor at the crossing point where the TEOWF cables 'fan out' with 3m separation between cable groups. It is recommended that the width of the road at Crossing 1 is measured.
- ➔ Such a large cable size would need consideration of how it would be jointed to other, smaller, cables along the route. This needs to be explored with the cable manufacturers.
- ➔ The size of cable means that the cable section length will be reduced, requiring more joints along the cable route. This adds time to the duration of the works and the duration the road will need to be closed for construction. It will increase the traffic in terms of number of cable deliveries. The additional number of joints also increases the probability of a cable failure.
- ➔ Furthermore, this cable size is significantly heavy and large in terms of diameter, and would be challenging to transport, handle and install.

It can be concluded that the level of difficulty in terms of space and thermal issues makes this an extremely unfavourable cable route for TEOWF. Given the significant risk of this option being both technically and commercially unviable it is recommended that it is avoided. The specification of cable may prove to be impractical for transport, handling and installation, or certainly would have higher health and safety risk and cost compared to alternative routes which may allow for smaller and lighter cables.

7 References

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8 Appendix A – Sensitivity analysis

8.1 Screen bonding

There are two possible screen bonding arrangements for the TEOWF onshore cables, as described in Section 3.3.1: bonding at both ends and cross-bonding. The base case installation solutions are with cross-bonded cable screens. Analysis has shown that bonding at both ends is not feasible for a project current requirement of 783A (340MW).

This is demonstrated by the results in Table 8-1 for TEOWF in Sandwich Road as described in Section 4.4, parallel to the TOWF cables, and with 3m separation between TEOWF and TOWF closest cable groups.

TEOWF cable size	TEOWF cable temp. at 783A [°C]	TEOWF cable current rating at 90°C [A]
Stranded conductors		
2400mm^2 Copper	159.0	539
Milliken conductors		
2400mm^2 Copper	171.1	527

Table 8-1: TEOWF cable temperatures and ratings for both end bonding, TEOWF in Sandwich Road parallel to TOWF cables, 3m separation between projects

The circulating current losses for both ends bonding are largely dependent on the screen design. The design of the screen is normally driven by earth fault rating requirements and consideration of cable rating. A larger or more robust screen, such as copper wires, has a higher fault rating and lower resistance, and results in higher circulating current losses for both end bonded systems.

IEC 60287 Part 1-1 states that for both ends bonding, the eddy current losses can be ignored for stranded conductors but must be considered for Milliken conductors. This explains why the Milliken conductor has less rating compared to stranded conductor for both ends bonded cable screens.

Furthermore, analysis has shown that it is preferable to have a screen design of copper wires with equalisation tape, which results in negligible eddy current losses[2]. This is a reasonable design to assume, and has therefore been used for the main results of this study.

[2] It is not clear from the IEC 60287 standard [3] whether this screen design would have negligible eddy current losses for cables with Milliken conductors and both ends bonded cable screens.

8.2 TEOWF in Sandwich Road – horizontal separation between projects

Sensitivity analysis has been performed on the separation between the TEOWF and TOWF cables. The separation refers to the distance between the centres of the inner groups of each projects' cables, as shown in Figure 4-3.

Table 8-2 below shows the minimum TEOWF cable specifications that would be required as a function of separation between the projects, from 1m to 5m, in 1m increments. The overall corridor width of both projects is also shown.

Separation between TEOWF and TOWF [mm]	Overall width required for both projects [mm]	Minimum required TEOWF cable specifications
1,000	3,100	Greater than 2400mm^2 copper Milliken
2,000	4,100	1600mm^2 copper Milliken
3,000 (base case)	5,100	2000mm^2 aluminium stranded 1400mm^2 copper stranded 1800mm^2 aluminium Milliken 1000mm^2 copper Milliken
4,000	6,100	2000mm^2 aluminium stranded 1200mm^2 copper stranded 1600mm^2 aluminium Milliken 1000mm^2 copper Milliken
5,000	7,100	2000mm^2 aluminium stranded 1200mm^2 copper stranded 1600mm^2 aluminium Milliken 1000mm^2 copper Milliken
6,000	8,100	1800mm^2 aluminium stranded 1200mm^2 copper stranded 1600mm^2 aluminium Milliken 1000mm^2 copper Milliken

Table 8-2: Effect of project separation, showing minimum requirement for TEOWF cable specification, based on TEOWF loading of 783A and TOWF loading of 690A

The results show that there is significant thermal heating between both projects cables for separation of less than 3m. At 3m and beyond this effect is significantly reduced.

Separation of 1m is not technically feasible as the required cable size would be larger than 2400mm^2 copper Milliken cable. The 2400mm^2 copper cable size is heavy and has a large diameter and so is marginal in terms of installation feasibility. Therefore, a larger cable size than this is very likely not feasible for installation.

For 2m separation, a 1600mm^2 copper Milliken cable would be required. Stranded and aluminium type cables have been found to not be feasible in terms of thermal rating.

For 3m separation, 1200mm^2 copper stranded and 1000mm^2 copper Milliken would be possible to use, and there are aluminium equivalents less than 2400mm^2 in size. Beyond 3m, the possible cables are only slightly smaller. Therefore, 3m separation has been selected as the base case for installation in Sandwich Road.

The separation in Sandwich Road also impacts the crossing cable rating calculation, as discussed in Section 2.8. The 3m separation before the crossing has therefore also been used for the crossing calculations.

A full set of results is shown for completeness in Table 8-3 overleaf for various cable sizes and separation of 1m to 5m, in 1m increments.

TEOWF cable size	1m distance between TOWF and TEOWF		2m distance between TOWF and TEOWF		3m distance between TOWF and TEOWF		4m distance between TOWF and TEOWF		5m distance between TOWF and TEOWF	
	TEOWF cable temp. [°C]	TOWF cable temp. [°C]	TEOWF cable temp. [°C]	TOWF cable temp. [°C]	TEOWF cable temp. [°C]	TOWF cable temp. [°C]	TEOWF cable temp. [°C]	TOWF cable temp. [°C]	TEOWF cable temp. [°C]	TOWF cable temp. [°C]
Stranded conductors										
2000mm^2 aluminium	105.0	110.4	94.6	96.0	89.5	89.4	86.8	86.0	85.2	84.0
2400mm^2 aluminium	95.4	106.4	85.5	93.8	80.6	88.1	78.0	85.2	76.5	83.5
1200mm^2 copper	106.2	110.3	95.8	95.9	90.7	89.4	88.0	86.0	86.4	84.0
1600mm^2 copper	92.1	104.5	82.4	92.9	77.6	87.6	75.0	84.8	73.5	83.2
2000mm^2 copper	84.4	101.3	75.0	91.2	70.3	86.5	67.8	84.1	66.3	82.7
2400mm^2 copper	79.3	99.2	70.1	90.1	65.5	85.9	63.1	83.7	61.6	82.4
Milliken conductors										
1800mm^2 aluminium	98.4	107.4	87.6	94.2	82.3	88.3	79.5	85.2	77.9	83.5
2000mm^2 aluminium	91.1	104.3	80.7	92.6	75.6	87.3	72.8	84.6	71.2	83.1
2400mm^2 aluminium	79.7	99.4	69.8	90.0	64.9	85.8	62.3	83.6	60.7	82.4
1000mm^2 copper	105.6	109.8	94.6	95.5	89.2	89.1	86.4	85.8	84.7	83.9
1200mm^2 copper	93.6	104.9	83.2	92.9	78.0	87.5	75.3	84.7	73.7	83.2
1600mm^2 copper	77.5	98.2	67.9	89.4	63.1	85.4	60.5	83.4	59.0	82.2
2000mm^2 copper	69.0	94.6	59.8	87.5	55.2	84.3	52.7	82.6	51.2	81.7
2400mm^2 copper	63.6	92.3	54.7	86.3	50.2	83.6	47.7	82.2	46.3	81.4

Table 8-3: Cable temperatures for TEOWF loading of 783A and TOWF loading of 690A, variable spacing between projects (hottest cable temperature shown)

8.3 TEOWF and TOWF crossing – crossing angle

The base case solution results are for the TEOWF cables crossing the TOWF cables at an angle of 90°. The effect of the crossing angle has been examined and is shown in Table 8-4 for 2400mm^2 copper Milliken conductor for the base case solution for Crossing 1, which is described in Section 4.5.

Crossing angle between TEOWF cables and TOWF cables [degrees]	TEOWF cable temp. [˚C]	TOWF cable temp. [˚C]
90 (base case)	58.6	89.4
75	58.6	89.6
60	58.7	90.1
45	58.8	91.0
30	58.9	92.6

Table 8-4: Effect of crossing angle on cable temperatures, showing hottest cables for TEOWF loading of 783A and TOWF loading of 690A, base case solution for Crossing 1, TEOWF 2400mm^2 copper Milliken cables

For crossing angles close to 90°, and down to around 75°, there is no significant difference in the thermal effects on the cables. As the angle reduces however the impact starts to become more pronounced.

The cable temperatures are satisfied for crossing angles between 90° and about 65°. This would be required for Crossing 1.

8.4 TEOWF and TOWF cable crossing – group separation

Sensitivity analysis has been performed on the group separation between the TEOWF cables (the horizontal distance between TEOWF circuits) for the crossing. The results of this analysis are shown in Table 8-5 for 2000mm^2 copper Milliken cables. This cable size has been selected for this sensitivity analysis to illustrate what reduction in cable size may be possible when the group separation is increased.

TEOWF group horizontal separation [mm]	TEOWF cable temp. [˚C]	TOWF cable temp. [˚C]
800	80.3	98.2
2,000	67.8	93.3
3,000 (base case)	63.2	91.1
4,000	60.6	89.9
5,000	58.9	89.2
6,000	57.7	88.7

Table 8-5: Effect of group separation on cable temperatures, showing hottest cables for TEOWF loading of 783A and TOWF loading of 690A, 2000mm^2 copper Milliken cables

The sensitivity analysis shows that group separation has a significant impact on the cable temperatures of both TEOWF and TOWF.

The base case of 3m group separation has been selected on the basis that it appears to just be achievable for Crossing 1, based on an estimated available corridor width through this section of Sandwich Road of 10m.

This is demonstrated in the plan view of Crossing 1 in Figure 2-3 which shows the overall corridor of the crossing relative to the road to be about 9.3m with 3m group spacing. The width of Sandwich Road has also been estimated to be about 10m from Google Earth. It is recommended that the actual width of the road is confirmed via site measurements.

For 4m group spacing, the overall corridor of Crossing 1 relative to Sandwich Road would just exceed 10m and possibly the width of available space in the road. However, if the actual measured is greater than 10m and can accommodate this, then 4m group spacing would be feasible and would just allow 2000mm^2 Milliken cable to be used. This would be a step change in size compared to the larger size 2400mm^2 Milliken cable associated with 3m group spacing.

8.5 TEOWF and TOWF cable crossing – burial depth (vertical separation)

Sensitivity analysis has been performed on the burial depth of the TEOWF cables, which also influences the vertical separation between the TEOWF cables and TOWF cables. The results of this analysis are shown in Table 8-6 for 2400mm^2 copper Milliken cables.

Vertical separation [mm]	TEOWF burial depth [mm]	TEOWF cable temp. [˚C]	TOWF cable temp. [˚C]
200	1,600	72.8	89.9
1,000	2,400	61.5	89.7
1,600 (base case)	3,000 (base case)	58.6	89.4
2,200	3,600	57.3	89.1
2,800	4,200	56.8	88.8

Table 8-6: Effect of burial depth on cable temperatures, showing hottest cables for TEOWF loading of 783A and TOWF loading of 690A, 2400mm^2 copper Milliken cables

The sensitivity analysis shows that the burial depth has marginal impact on TEOWF and TOWF cable temperature, based on 3m horizontal group spacing, and with this size and type of cable conductor for TEOWF. The base case has been selected on the basis that it allows the largest cable size studied (2400mm^2) whilst maintaining some practical separation between the two projects' cables.