Project Title/ Location	MeyGen Tidal Energy Project, Phase 1a. Inner Sound.
Date:	03/09/2015

MeyGen Tidal Energy Project Phase 1

Electromagnetic Fields Best Practice Report

Rev	Prepared	Sign Off	Checked	Sign Off	Approved	Sign Off	Date of Issue	Comments
1	Ed Rollings	[redacted]	Fraser Johnson	[redacted]	Ed Rollings	[redacted]	30/07/2015	
2	Ed Rollings	[redacted]	Fraser Johnson	[redacted]	Ed Rollings	[redacted]	03/09/2015	Consultation response from MSLOT and MSS

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EXECUTIVE SUMMARY

This document has been prepared by MeyGen Ltd. to enable Condition 3.2.1.1 of the Marine Licence to be discharged.

The document details the best practice in manufacture and installation related to minimising the attenuation of electromagnetic fields from the Turbine Subsea Cables proposed for the MeyGen Project, Phase 1a.

The document will be submitted to the Scottish Ministers for their written approval, in consultation with SNH and any other ecological advisors as required at the discretion of the Scottish Ministers.

Construction Method Statements for the related Turbine Subsea Cable works have been approved by Scottish Ministers (MEY-1A-40-HSE-F-001-ConstructionMethodStatementHDD, MEY-1A-40-HSE-F-004-CMSConstructionWorks).

1 INTRODUCTION

The MeyGen Tidal Energy Project Phase 1 (“the Development”) received a Marine Licence under The Marine (Scotland) Act 2010 from the Scottish Ministers on 31st January 2014 (“the Marine Licence”). This document is prepared to enable Condition 3.2.1.1 of the Marine Licence (“the Condition”) to be discharged. Condition 3.2.1.1 states:

> *The licensee must, no later than three months prior to the commencement of the works, provide the licensing authority for their written approval a report detailing current 'best practice' relating to the attenuation of field strengths of cables by shielding or burial designed to minimise effects on electro-sensitive and migratory fish species. Such 'best practice' guidance as is identified must be incorporated into the Construction Method Statement, in respect of which condition 9 of the section 36 consent relates.*

Phase 1a of the Development is a 6MW, 4 tidal turbines initial phase to be installed and operated under the restriction placed on the Development by Condition 2 of the S.36 Consent.

This document, as agreed with the licensing authority, covers the installation of the Phase 1a infrastructure (4 x Horizontal Directionally Drilled (HDD) bores, Tidal Turbine Generators (TTG), Gravity-base Turbine Support Structures (TSS) and Turbine Subsea Cables (TSC), collectively described as “**the Works**”.

2 ELECTROMAGNETIC FIELDS

Ambient electric (E) and magnetic (B) fields detected within the marine environment are generated by both natural and anthropogenic sources. The predominant naturally occurring EMF in the marine environment is from the earth's geomagnetic field, however, E-fields can also be naturally emitted as a result of biochemical, physiological and/or neurological process within an organism, known as bioelectric fields (Gill & Bartlett, 2010). Anthropogenic sources of EMF include those from subsea power cables.

Power cables, such as those used to export electricity generated from tidal arrays, produce E- and B-fields when current passes through them. The B-field is detectable outside of the cable structure and this in turn creates a further induced E field (iE). Studies have shown that EMF radiate beyond the cable into both seawater and the seabed. However, the field emitted by the cables are limited spatially and the field decays rapidly with horizontal and vertical distance from the cables (Normandeau *et al*., 2011).

3 ELECTRO - SENSITIVE AND MIGRATORY FISH SPECIES

3.1 Key species and associated legislation

A number of fish species able to detect electric and magnetic fields. Elasmobranch species (includes sharks, ray and skates) are the main group of organisms which are known to be able to detect E-fields. A number of protected Elasmobranch species are likely to be present in or transit through the MeyGen site, in particular Porbeagle (*Lamna nasus*) and Common skate (*Dipturus batis*) are known to be found in the Pentland Firth region.

Other fish species, including migratory species that are electro-sensitive that do not possess specialised electroreceptors, but are able to detect induced voltage gradients associated with water movements and geomagnetic emissions. These include Atlantic salmon (*Salmo salar*) and European eel (*Anguilla anguilla*); in addition, sea trout (*Salmo trutta*) are also capable of detecting B-fields.

Of those fish species listed on Annex II of the EU Habitats Directive 92/43/EEC (as amended), Atlantic salmon has the potential to be present in the Pentland Firth.

3.2 Research

A report of the COWRIE EMF study (CMACS, 2003) based on offshore wind developments made the following findings:

- There is no direct generation of an E-field outside of the cable;
- B-fields generated by the cable created induced E-fields (iE) outside of the cable, irrespective of shielding;
- B-fields are present in close proximity to the cable and the sediment type in which a cable is buried has no effect on the magnitude of B-field generated;

- The magnitude of the B-field on the 'skin' of the cable (i.e. within millimetres) is approximately 1.6μT which will be superimposed on any other B-fields (e.g. Earth's geomagnetic field); and

- The magnitude of the B-field associated with the cable fall to background levels within 20m.

EMF emitted by an industry standard subsea cable will induce E-fields (single 132 kV AC, three-core subsea cable carrying 350A);

- Cables will emit approximately 91μV/m at the seabed adjacent to a cable buried to 1m. This level of E-field is on the boundary of E-field emissions that are expected to attract and those that repel elasmobranchs;

- The iE-fields calculated from the B-field were also within range of detection by elasmobranchs;

- Changing the permeability or conductivity of the cable may effectively reduce the magnitude of the iE-field; and

- To reduce the iE-field that is below the level of detection of elasmobranchs will require a material of very high permeability, hence any reduction in E-field emission would minimise the potential for an avoidance reaction by a fish if it encountered the field but may still result in an attraction response.

In addition to this, further research funded by COWRIE conducted by Gill *et al*. (2009) in which the impact of controlled EMF within mesocosm (with the magnitude and characteristics associated with offshore wind farm) on electro-sensitive fish was conducted. From which the following was found:

- There is evidence that benthic elasmobranch species studied did respond to the presence of EMF emitted by a subsea cable. The responses were, however, variable within a species and also during times of cable switch on and off, day and night;

- The overall spatial distribution of fish was non-random, and dogfish were more likely to be found within the zone of EMF emission during times when the cable was switched on; and

- There did not appear to be any differences in the fish response by day or night or over time.

Gill and Bartlett (2010) were commissioned by SNH to review the current state of knowledge with regard for the potential for Atlantic salmon, European eel and sea trout to be affected by marine energy developments, focusing on an understanding of EMFs (as well as noise), on behaviour of the three species. The main findings of the report in relation to EMF were:

- Atlantic salmon and European eel can use the earth's magnetic field for orientation and direction during migrations. Juvenile sea trout respond to both the earth's magnetic field and artificial magnetic fields;

- Current knowledge suggests that EMFs from subsea cables and cabling orientation may interact with migrating eels (and possibly salmonids) if their migration or movement routes take them over the cables, particularly in shallow waters (<20m). The effect if any could be a relatively trivial temporary change in swimming direction, or potentially a more serious avoidance response or delay to migration. Where this will represent a biologically significant effect cannot yet be determined;

- All three species are likely to encounter EMF from subsea cables either during adult movement phases of their life or their early life stages during migration within shallow, coastal waters adjacent to the natal rivers; and

- The review identified no clear evidence that either attraction or repulsion due to anthropogenic EMF will have an effect on any of three fish species identified in the report.

A report produced for the Department of the Interior in the US (Normandeau *et al*., 2011) provides a comprehensive review of studies to date on potential effects of EMF on marine fauna. The report modelled the expected EMF's from a range of power cables and reviewed the available information on sensitive marine species. The report drew the following conclusions:

- The field is strongest directly over the cable and decreases rapidly with horizontal and vertical distance from the cable;

- The cable magnetic field is perpendicular to the direction of the cable. A water current or organism moving parallel to the cable magnetic field will not generate an induced electric field. Orientation of the cables relative to the flow of water and migration routes can reduce the potential impacts;

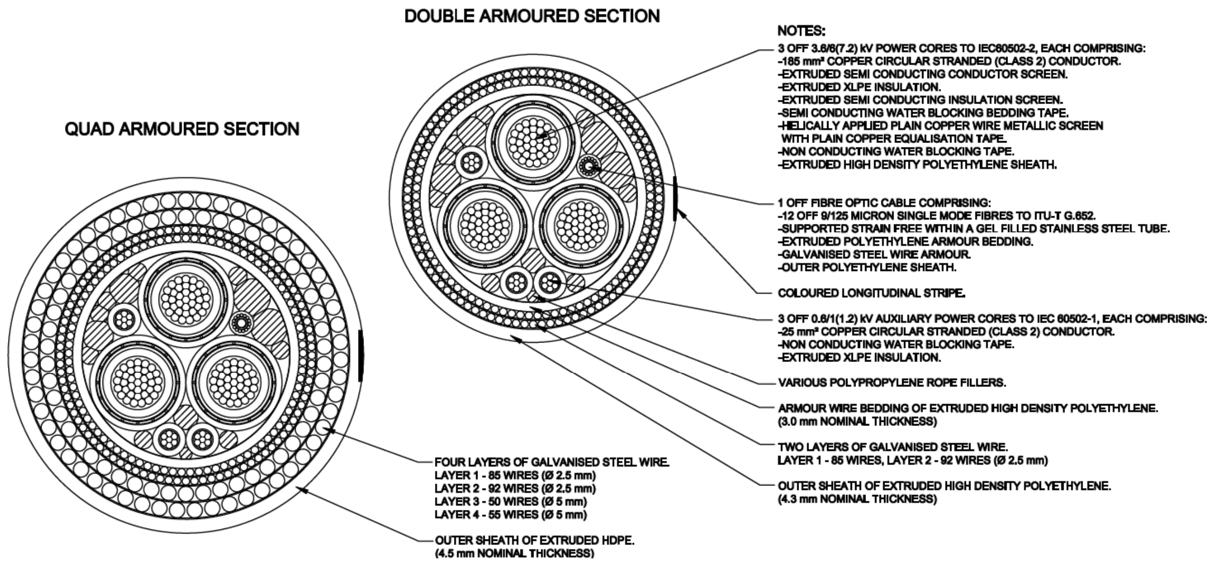
- Marine species are more likely to react to the magnetic fields of DC cables than AC cables. DC cables were found to have a greater impact as they can influence the intensity of the local geometric field;

- The risk of interference only exists in the areas surrounding the cables where sensory capabilities overlap with the cable EMF; and

- Magnetic fields can be minimised by placing the cables close together, allowing the field vectors to cancel each other out.

4 TURBINE SUBSEA CABLE

4 x Turbine Subsea Cables (TSC) are to be installed as part of the MeyGen Tidal Energy Project Phase 1a. The TSC is rated at 4.4kV and 250A, a TSC cross section is shown in Figure 1. Each TSC is made up on 3 power cores, 3 auxiliary power cores and a fibre optic cable. Part of the TSC is quad armoured and part is double armoured.



MECHANICAL PROPERTIES	DOUBLE ARMOUR	QUAD ARMOUR
OUTSIDE DIAMETER	94 +/- 2 mm	116 +/- 2.5 mm
OUTER SHEATH MATERIAL	HIGH DENSITY POLYETHYLENE	
OUTER SHEATH COLOUR	BLACK WITH COLOURED STRIPE	
CABLE ARMOURING	GALVANISED STEEL WIRE	
MBR - MANUFACTURE, STORAGE & LOADOUT	1,160 mm	
MBR - DUCT PULL-IN	1,900 mm	N/A
MBR - DEPLOYMENT	2,250 mm	
APPROXIMATE WEIGHT IN AIR	18,010 kg/km	36,190 kg/km
APPROXIMATE WEIGHT IN SEAWATER (UNFLOODED)	10,890 kg/km	25,350 kg/km
MINIMUM BREAKLOAD	470 kN	1,590 kN
CABLE MAX SAFE WORKING LOAD	95 kN	
MAX. CONDUCTOR TEMPERATURE	90 °C	

Figure 1 TSC cross section and specification

The section of TSC that is quad armour is installed on the seabed; the double armour section is the length of TSC installed through the HDD bore to the onshore site (Figure 2).

The seabed in the Inner Sound and along the TSC route from HDD bore exit to the TTG is scoured bedrock with very little superficial sediments (Figure 3). As such the TSCs cannot be buried; the TSC route will use the bedding plains and fractures in the rock to minimise exposure to wave and tidal loading.

The 4 TSCs follow 2 routes from the HDD exit to the TTG location in the Inner Sound, at 3 points along the routes they will converge through gates (Figure 4). At a number of locations along the routes the TSCs will require further stability measures. These will be 3 x rock bags placed over the TSCs (total height 1.2m).

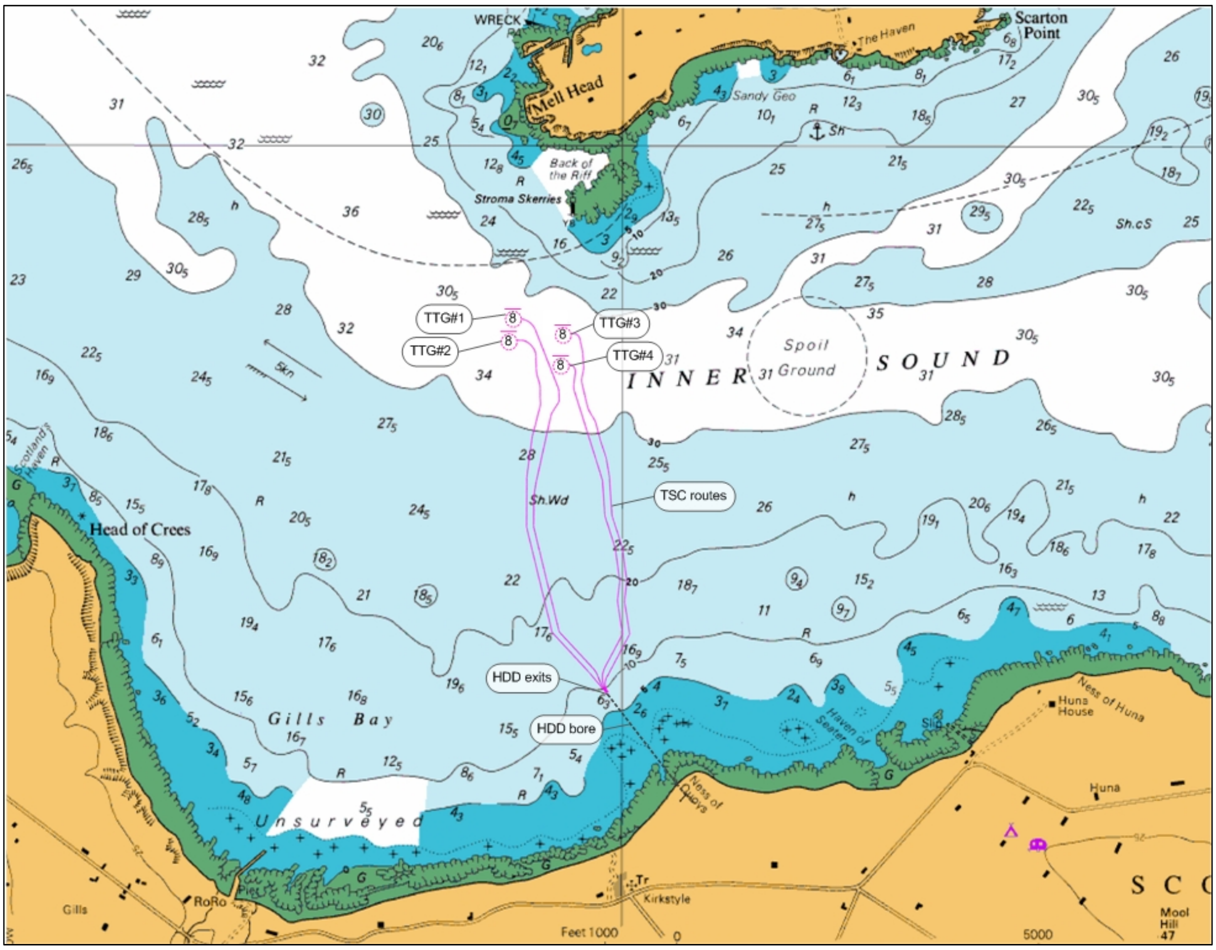


Figure 2 Construction Works Location

Figure 3 Inner Sound seabed images

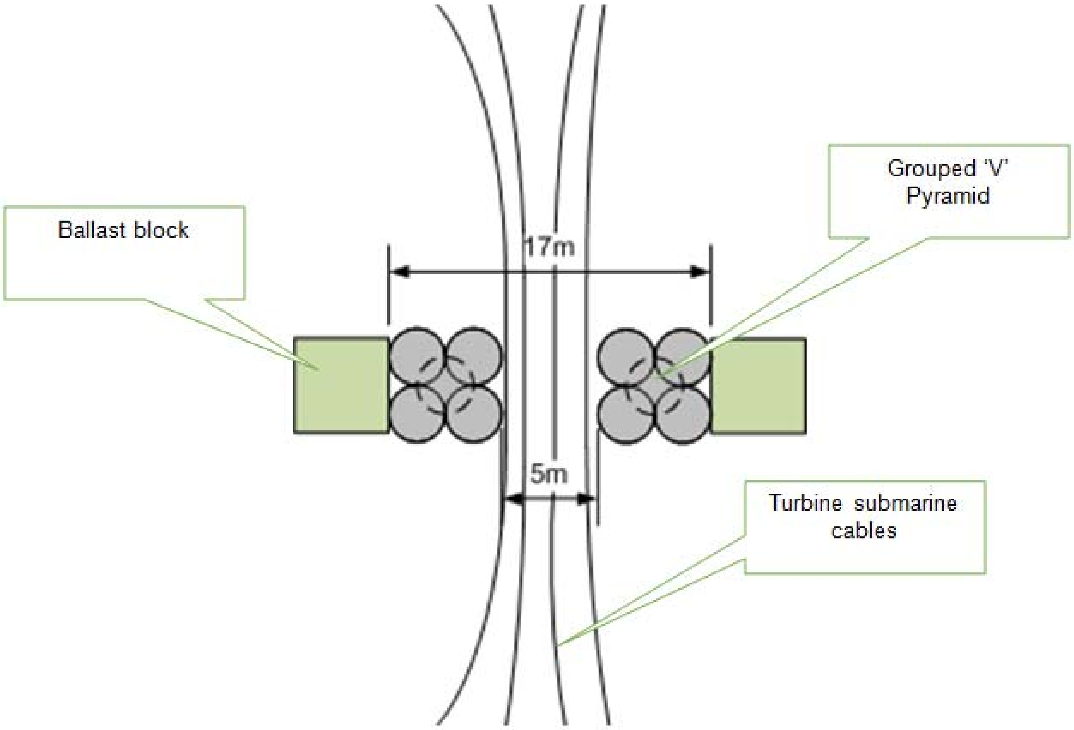


Figure 4 TSC gate

5 MITIGATING EMF IMPACTS

The TSC manufacture, JDR, have provided an EMF report on induced voltage field in seawater around a 6 x 300mm^2 core cable (Appendix A). This cable is a typical design for a 6kV - 30kV cable.

The report indicates that the peak value of the electric field induced around the cable when carrying a full current is less than 3.5μVm^{-1} 100mm away from the centre line and 0.5μVm^{-1} 500mm away from the centre line. The MeyGen TSC is 3 x 180mm^2 cores rated at 4.4kV, so it is assumed that the peak values will be less that those seen in the test and significantly less than the COWRIE EMF study. They area also noticeably lower than E-field emissions considered to attract or repel elasmobranch species (CMACS, 2003).

JDR has incorporated the following best practices into design of the MeyGen TSC:

- Balanced geometry for the medium voltage cores (central triad);
- Screening of the cores; and
- Armouring around the finished cable construction; including quad armour on the TSC sections on the seabed.

As well as best practice incorporated into the TSC design, other aspects should reduce the potential EMF:

- Most studies and reports consider the cables at 100% load, however the MeyGen TSCs will not reach 100% load during their lifetime. In general loads will be well below 100% and during periods of slack water, low tidal velocities and high tidal velocities when the TTG are not generating electricity the TSCs will not produce any iE-fields as there will be no load on the TSCs.
- When the TSCs are within the HDD bores it is considered that the EMF impact is quickly negated as the bores drop to over 30m below the seabed before rising again to the onshore site.
- Where TSCs are not within HDD bores they cannot be buried to reduce EMF as the seabed is scoured bedrock, however the TSC route has been designed to follow nature bedding plains and fractures, ensuring the majority of the TSC route is as low as possible on the seabed.
- At the 3 TSC gates all the cables will converge which could minimise EMF attenuation where field vectors cancel each other out.
- Rock bag protection at certain points (up to 1.2m depth of cover) will provide some reduction in EMF attenuation.

Whilst the potential impacts of EMF on Elasmobranch and other sensitive species are unclear. MeyGen proposes to implement the best available techniques to limit EMF through TSC and project design.

MeyGen will continue to monitor the results of ongoing research by Marine Scotland and other bodies for further information on the potential impacts of EMF and mitigation strategies.

6 DOCUMENT REVIEW AND CONSULTATION

This document will be reviewed and commented on by the licensing authority, SNH, and other such advisors that may be required at the discretion of the Scottish Ministers.

The document will be submitted to the licensing authority for distribution to the stakeholders and for approval. Any changes deemed necessary must be reviewed and approved by the ECoW, before it is submitted for approval to the licensing authority.

Version control will be conducted by the revision review block on the front page of the document.

7 REFERENCES

CMACS (2003). A baseline assessment of electromagnetic fields generated by offshore windfarm cables. COWRIE Report EMF -01-2002 66.

Gill & Bartlett (2010). Literature review on the potential effects of electromagnetic fields and subsea noise from marine renewable energy developments on Atlantic salmon, sea trout and European eel. Scottish Natural Heritage Commissioned Report No.401

Gill, A.B., Huang, Y., Gloyne-Philips, I., Metcalfe, J., Quayle, V., Spencer, J. & Wearmouth, V. (2009). COWRIE 2.0 Electromagnetic Fields (EMF) Phase 2: EMF-sensitive fish response to EM emissions from sub-sea electricity cables of the type used by the offshore renewable energy industry. Commissioned by COWRIE Ltd (project reference COWRIE-EMF-1-06).

Normandeau, Exponent, Tricas, T and Gill. A.(2011). Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Pacific OCS Region, Camarillo, CA. OCS Study BOEMRE 2011-09.

8 LIST OF ABBREVIATIONS

Abbreviation	
CMS	Construction Method Statement
ECoW	Ecological Clerk of Works
HDD	Horizontal Directional Drilling
MHWS	Mean High Water Springs
ML	Marine Licence under the Marine (Sotland) Act 2010
MLWS	Mean Low Water Springs
SAC	Special Area of Conservation
SNH	Scottish Natural Heritage
TSC	Turbine Submarine Cable
TSS	Turbine Support Structure
TTG	Tidal Turbine Generator

APPENDIX A: JDR EMF REPORT

DOCUMENT FRONT SHEET

1	02/03/15	Issued for Information	AM	SDi	DG
Rev.	**Date**	**Reason for Issue**	**Issued**	**Checked**	**App'd**

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MeyGen

EMF Report

CLIENT DOCUMENT NUMBER: JDR-1A-20-REP-010

JDR CONTRACT REF: 101100

1	**Reviewed without comments**	
2	**Reviewed with minor comments revise and resubmit**	
3	**Work may not proceed revise and resubmit (rejected)**	
4	**Retained for information**	

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DOCUMENT FRONT SHEET

24/Nov/09	00	First Issue	PWW	SD	PM
Date	**Rev**	**Reason for Issue**	**Issued**	**Checked**	**App'd**

DESIGN REPORT

THE INDUCED VOLTAGE FIELD IN SEAWATER AROUND 6 X 300mm^2 CABLE

JDR Doc. No.:

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Executive Summary

The peak value of the electric field induced around the 6-core export cable when carrying full line current is less than 3.5 µVm^{-1} 100mm away from the centre line of the cable

The peak value of the electric field induced around the 6-core export cable when carrying full line current is less than 0.5 µVm^{-1} 500mm away from the centre line of the cable

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1 Introduction

An AC electric field is generated around current carrying conductors and although the far field is zero as the currents circulating through the conductors are balanced and cylindrically symmetrically arranged, as a result of their geometric disposition there is a non-zero near field.

The resultant magnetic field can be calculated and an analytic solution for the field at any point exists from which the induced electric field arising from the time variant magnetic field can be calculated. However rather than solve the analytic equations directly, it is more practical to use Finite Element packages to directly calculate the induced electric field directly from the practical cable geometry and it is this route that has been followed.

1.1 Referenced Documents

IEC 60502-2 (2003)	Part 2: Power Cables with extruded insulation and their accessories for rated voltages from 6 kV (Um = 7.2 kV) up to 30 kV (Um = 36 kV) ISO
Maxwell's Equations	Huray, P G. (2009), Wiley Blackwell ISBN: 978-0470542767
AC Multi-Physics Modelling	COMSOL http://www.comsol.com

1.2 Scope

This report is confined to calculating the induced near electric field arising from a balanced three phase AC current carried by conductors arranged as described in Appendix 1.

1.3 Objective

- To quantify the induced electric field around the cable.
- To permit the client to establish compliance with environmental standards.

1.4 Methodology

The problem of electromagnetic analysis on a macroscopic level is the problem of solving Maxwell's equations subject to certain boundary conditions. Maxwell's equations are a set of equations, written in differential or integral form, stating the relationships between the fundamental electromagnetic quantities. These quantities are the electric field intensity **E**, the electric displacement or electric flux density **D**, the magnetic field intensity **H**, the magnetic flux density **B**, the current density **J**, and the electric charge density, ρ.

The equations can be formulated in differential or integral form. The differential form is presented here, because it leads to differential equations that the finite element method can handle. For general time-varying fields, Maxwell's equations can be written as:

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$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

The first two equations are also referred to as Maxwell-Ampere's law and Faraday's law, respectively. Equation three and four are two forms of Gauss' law—the electric and magnetic form, respectively.

Another fundamental equation is the equation of continuity, which can be written as

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t}$$

Out of the five equations mentioned, only three are independent. The first two combined with either the electric form of Gauss' law or the equation of continuity form such an independent system.

To obtain a closed system, the equations include constitutive relations that describe the macroscopic properties of the medium. They are given as:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$$

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$$

$$\mathbf{J} = \sigma \mathbf{E}$$

Here ε_0 is the permittivity of vacuum, μ_0 is the permeability of vacuum, and σ the electric conductivity. In the SI system, the permeability of vacuum is chosen to be 4π·10–7 H/m. The velocity of an electromagnetic wave in vacuum is given as c_0 and the permittivity of vacuum is derived from the relation:

$$\varepsilon_0 = \frac{1}{c_0^2 \mu_0} = 8.854 \cdot 10^{-12}\ \mathrm{F/m} \approx \frac{1}{36\pi} \cdot 10^{-9}\ \mathrm{F/m}$$

The electric polarization vector **P** describes how the material is polarized when an electric field **E** is present. It can be interpreted as the volume density of electric dipole moments. **P** is generally a function of **E**. Some materials can have a nonzero **P** also when there is no electric field present.

The magnetization vector **M** similarly describes how the material is magnetized when a magnetic field **H** is present. It can be interpreted as the volume density of magnetic dipole moments. **M** is generally a function of **H**.

For linear materials, the polarization is directly proportional to the electric field, **P** = $\varepsilon_0 \chi_e$ **E** , where χ_e is the electric susceptibility. Similarly in linear materials,

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the magnetization is directly proportional to the magnetic field, **M** = χ_m **H** , where χ_m is the magnetic susceptibility. For such materials, the constitutive relations can be written

$$\mathbf{D} = \varepsilon_0(1+\chi_e)\mathbf{E} = \varepsilon_0\varepsilon_r\mathbf{E} = \varepsilon\mathbf{E}$$
$$\mathbf{B} = \mu_0(1+\chi_m)\mathbf{H} = \mu_0\mu_r\mathbf{H} = \mu\mathbf{H}$$

The parameter ε_r is the relative permittivity, and μ_r is the relative permeability of the material. These are usually scalar properties but they can, for a general anisotropic material, be 3-by-3 tensors. The properties ε and μ (without subscripts) are the permittivity and permeability of the material.

Generalized forms of the constitutive relations are well suited for modelling nonlinear materials. The relation used for the electric fields is

$$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E} + \mathbf{D}_r$$

The field $\mathbf{D}_r$ is the remnant displacement, which is the displacement when no electric field is present.

Similarly, a generalized form of the constitutive relation for the magnetic field is:

$$\mathbf{B} = \mu_0\mu_r\mathbf{H} + \mathbf{B}_r$$

where $\mathbf{B}_r$ is the remnant magnetic flux density, which is the magnetic flux density when no magnetic field is present.

For some materials, there is a nonlinear relationship between **B** and **H** such that:

$$\mathbf{B} = f(|\mathbf{H}|)$$

The relation defining the current density is generalized by introducing an externally generated current J^e. The resulting constitutive relation is

$$\mathbf{J} = \sigma\mathbf{E} + \mathbf{J}^e$$

1.5 Solving equations to Boundary Conditions

Under certain circumstances it can be helpful to formulate the problems in terms of the electric scalar potential V and the magnetic vector potential A. They are given by the equalities:

$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$$

The defining equation for the magnetic vector potential is a direct consequence of the magnetic Gauss' law. The electric potential results from Faraday's law. In the magneto static case where there are no currents

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present, Maxwell-Ampère's Law. When this holds, it is also possible to define a magnetic scalar potential by the relation:

$$\mathbf{H} = -\nabla V_{\mathrm{m}}$$

For time-harmonic quasi-static systems solving for an A formulation, the reduced potential formulation results in the following PDE:

$$(j\omega\sigma - \omega^2\varepsilon)(\mathbf{A}_{\mathrm{ext}} + \mathbf{A}_{\mathrm{red}}) + \nabla\times(\mu^{-1}\nabla\times(\mathbf{A}_{\mathrm{ext}} + \mathbf{A}_{\mathrm{red}})) = \mathbf{J}^{\mathrm{e}}$$

A consequence of Maxwell's equations is that changes in time of currents and charges are not synchronized with changes of the electromagnetic fields. The changes of the fields are always delayed relative to the changes of the sources, reflecting the finite speed of propagation of electromagnetic waves. Under the assumption that you can ignore this effect, it is possible to obtain the electromagnetic fields by considering stationary currents at every instant. This is called the quasi-static approximation. The approximation is valid provided that the variations in time are small and that the studied geometries are considerably smaller than the wavelength.

1.6 Model Software

Where these equations cannot be solved analytically, numerical solutions will be determined using Finite Element Analysis techniques contained within the commercial software package COMSOL 3.5a with AC/DC Module with licence number 1057662.

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2 Modelling

2.1 Model Parameters

To simplify the modelling, it is assumed that the system is cylindrically symmetric and therefore a 2D representation is adequate to perform the analysis.

The basic model analysis package was set from the AC/DC Module to:

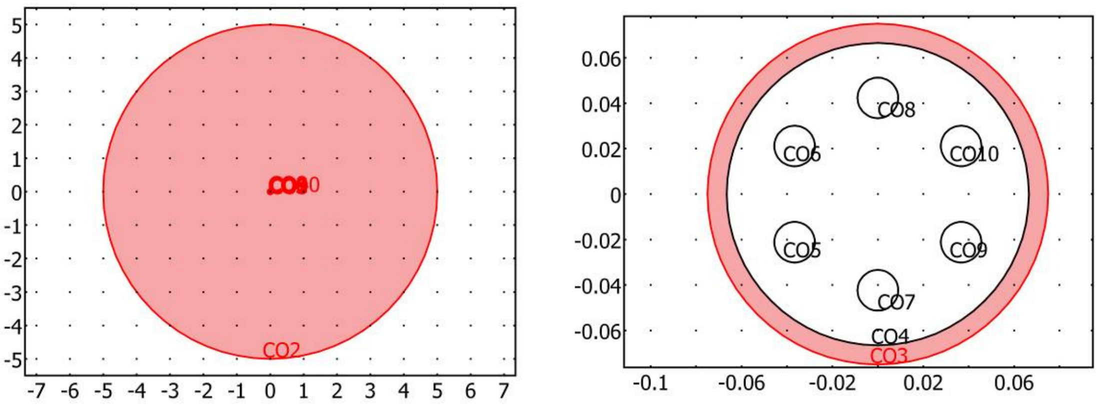
2D Statics, Magentics

Perpendicular Induction Currents, Vector Potential, *emqa* (3D Quasi-Statics, Electromagnetic)

2.2 Geometry

A simplified model of the cable system was transferred to the FE modeller from a 2D CAD drawing package as shown in Figure 1 where C02 is the sub-domain 5m around the cable, with the zoomed view to its right.

Figure 1

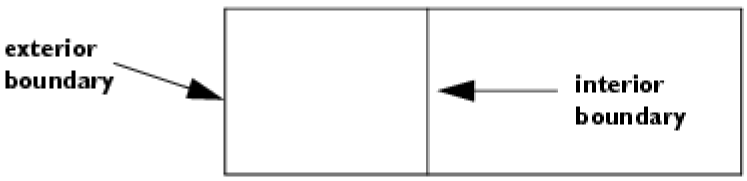


2.3 Boundary Settings

When specifying boundary and interface conditions, COMSOL Multiphysics differentiates between exterior and interior boundaries as shown in Figure 2.

- An exterior boundary is an outer boundary of the modelling domain.
- An interior boundary is a dividing interface between two sub domains in the modelling domain.

Figure 2



2.3.1 External Boundary

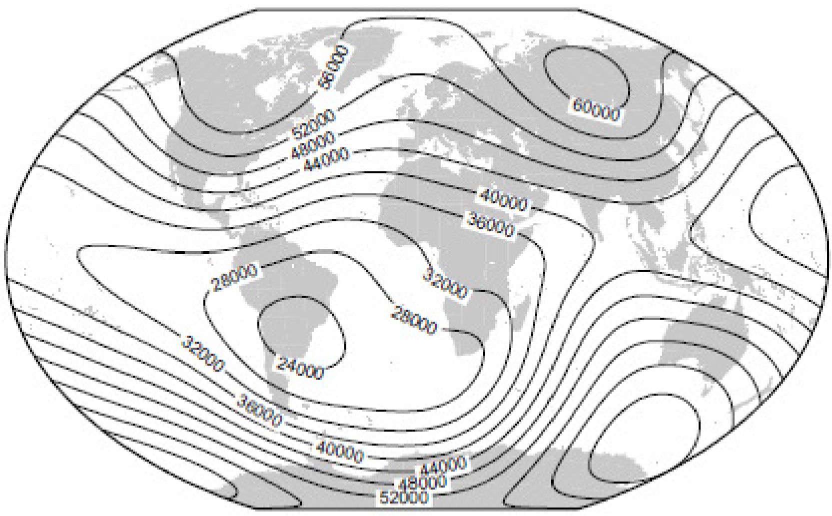
This uses a simple Direchlet requirement on CO2, the sea water.

$$\mathbf{n} \times \mathbf{H} = \mathbf{n} \times \mathbf{H}_0$$

where the magnetic field value, H_0,is set to zero. Whilst it is known that the earth's DC magnetic is around 50 µT, as shown in Figure 3, the far AC field is zero as the phase currents are fully balanced, this simplification of setting the value to zero at a finite distance provides a reasonable approximation to enable the model to calculate the residual near field.

Figure 3 Earth's Magnetic Field

Total intensity (nT) at 2005.0.



2.3.2 Internal Boundary

All internal boundaries between sub-domain 1 and sub-domain 2, are set to *continuity.* The equation defining this arises as the magnetic field in sub-domain 1, $\mathbf{H}_1$ is set to equal the magnetic field in sub-domain 2, $\mathbf{H}_2$ as shown below.

$$\mathbf{n} \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{0}$$

2.4 Sub-Domain Parameters

Each domain within the model each sub-domain may have different parameters. The time invariant (DC) parameters are described in Table 1.

2.4.1 Time Invariant Parameters

Table 1 Sub-Domain Parameters

Name	Magnetic Properties			Electric Properties			
	Velocity	**B**(**H**)	μ_r	Length	|J| (A)	σ (S/m)	ε_r
Sea Water	0	$B=\mu_r \mu_0 H$	1	1	0	5.5	1
Air	0	$B=\mu_r \mu_0 H$	1	1	0	0	1

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Name	Magnetic Properties			Electric Properties			
	Velocity	**B**(**H**)	μ_r	Length	|J| (A)	σ (S/m)	ε_r
Copper	0	$B=\mu_r \mu_0 H$	1	1	487	$6.0*10^{+7}$	1
Iron	0	$B=\mu_r \mu_0 H$	4000	1	0	$1.2*10^{+7}$	

2.4.2 Time Dependent Parameters

The time domain aspect of the system is specified by defining the current in its complex form as:

$J_1(t) = J_o \exp(j\omega t)$

$J_2(t) = J_o \exp(j(\omega t + 2\pi/3))$

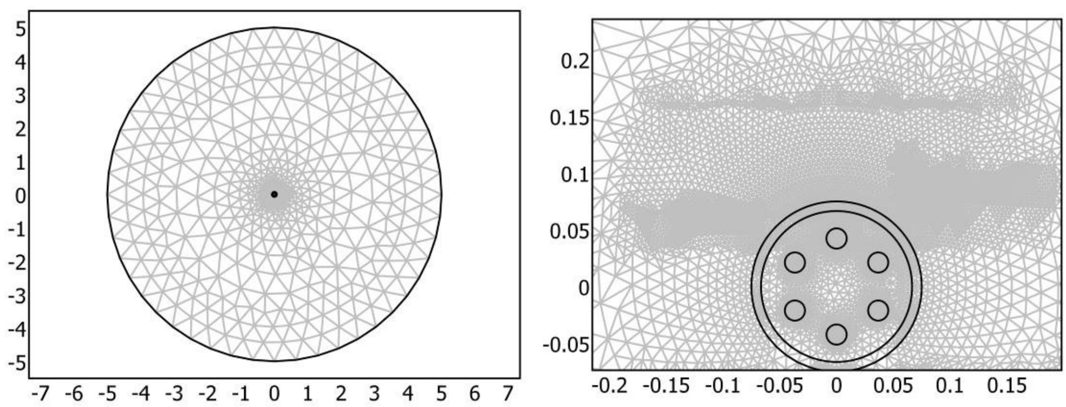
$J_3(t) = J_o \exp(j(\omega t + 4\pi/3))$

where $j = \sqrt{(-1)}$ and J_0 is the RMS value of the external current, 487 amps, and ω, the angular frequency is set to 2π*50 Hz.

2.5 Mesh

The following shows the mesh within the model which has been refined at the top of the cable system to enable a more reliable calculation of the near field.

Figure 4 Mesh



The particular mesh has over 15,000 elements and 30,600 degrees of freedom as shown Figure 4.

2.6 Solution

The induced electric field normal to the cross-section is calculated and a graphical surface representation shown in where it can be seen that the field falls rapidly to zero quickly approaching the far field asymptote, zero.

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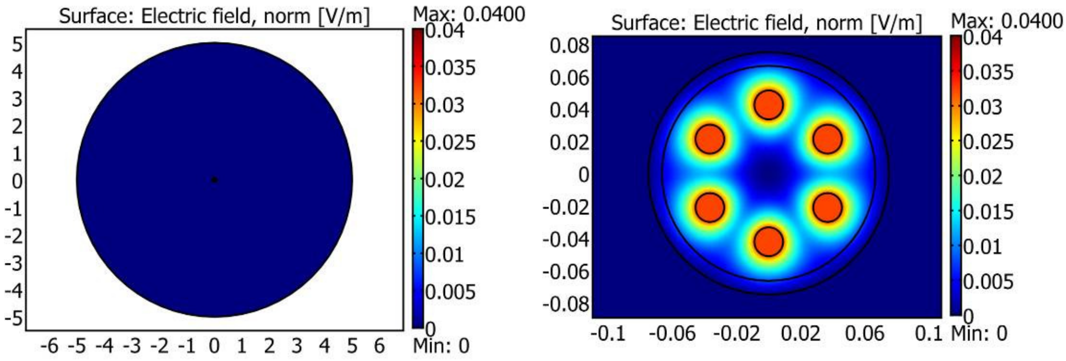
Figure 5 Induced Electric Field Surface



It is possible to plot the electric field along lines of interest as shown

Figure 6 Evaluation Points of Electric Field

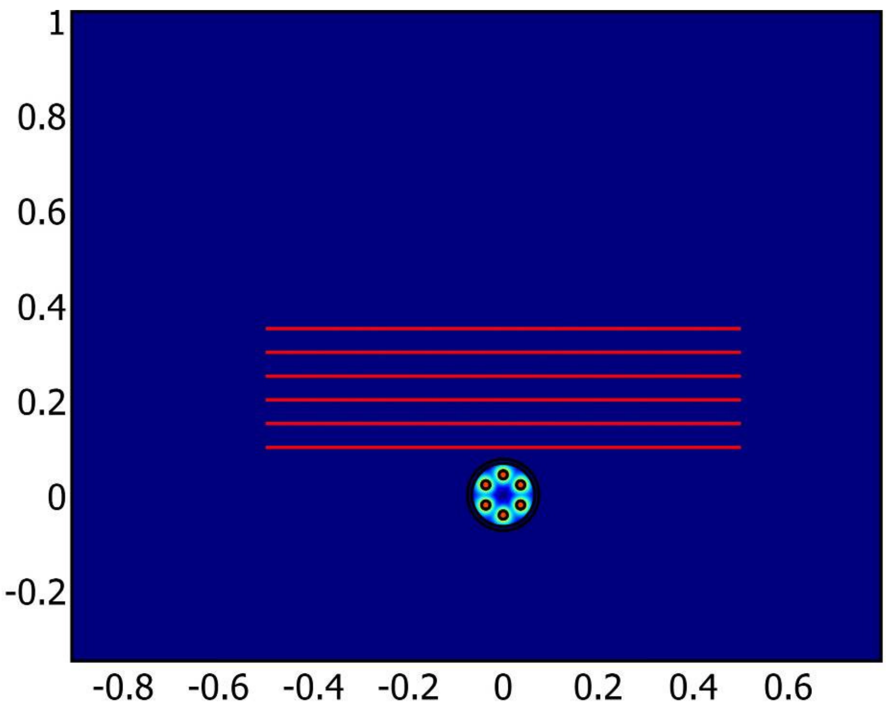


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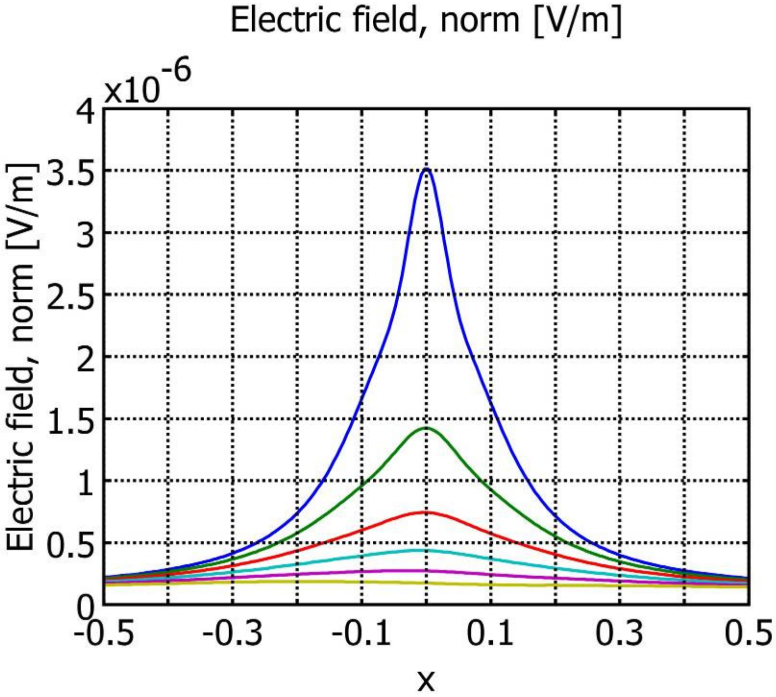
Figure 7 The Induced Electric Field

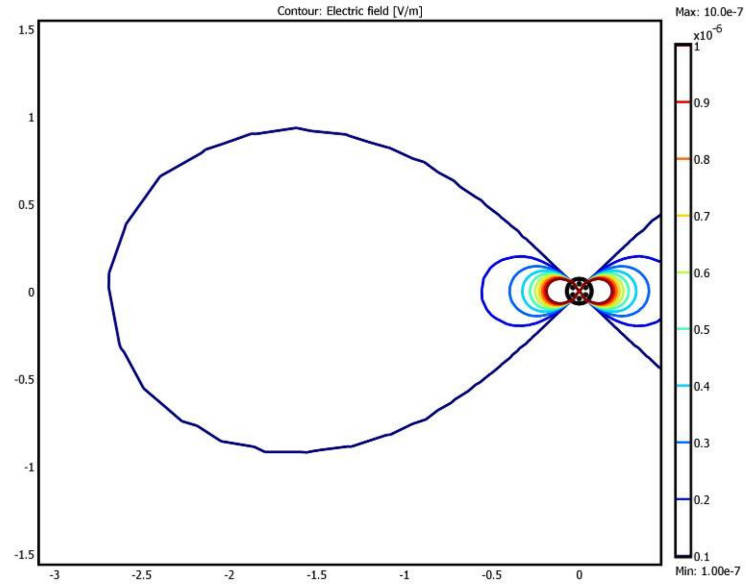


2.7 Summary

The peak value of the induced electric field is 3.5 µVm^{-1} at 0.1 m above its centre line falling inversely to less than 100 nVm^{-1} at 2m from the cable centre.

Constant Field strength contours are plotted in Figure 8 between 1 µVm^{-1} and 100 nVm^{-1} in 10 steps. This *propeller* will rotate at 50 rpm, at the mains frequency.

Figure 8 100nVm^{-1} Contour



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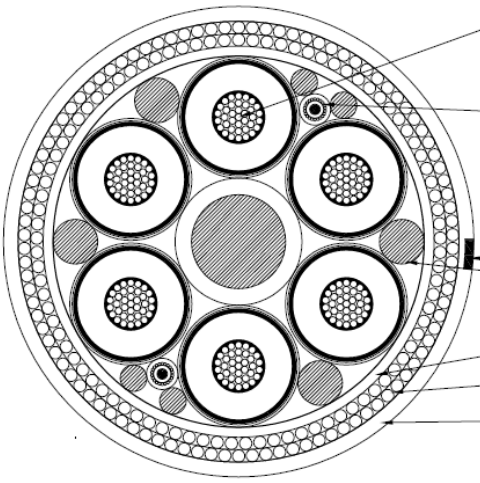
3 Appendix 1

Main Cable

DO NOT SCALE IF IN DOUBT - ASK



NOTES:

6 OFF 18/30(36)kV IEC60502-2 POWER CORES, EACH COMPRISING:
-300mm² COPPER CIRCULAR STRANDED (CLASS 2) CONDUCTORS.
-CONDUCTORS INCLUDE LONGITUDINAL WATER BLOCKING.
-EXTRUDED SEMICONDUCTING CONDUCTOR SCREEN.
-EXTRUDED XLPE INSULATION.
-EXTRUDED SEMICONDUCTING CORE SCREEN.
-COPPER TAPE SCREEN
- OD: 41.1mm +/- 2%
- MBR: 410mm

2 OFF FIBRE OPTIC CABLES COMPRISING:
-24 OFF 9/125 MICRON SINGLE MODE FIBRES TO ITU-T G.652.
-SUPPORTED STRAIN FREE WITHIN A GEL FILLED STAINLESS STEEL TUBE.
-INNER POLYETHYLENE SHEATH.
-GALVANISED STEEL WIRE ARMOUR.
-OUTER POLYETHYLENE SHEATH.
- OD 10.7mm
- MBR 230mm

CO-EXTRUDED POLYETHYLENE IDENTIFICATION STRIPE.

VARIOUS POLYPROPYLENE FILLERS.

ARMOUR WIRE BEDDING OF EXTRUDED POLYETHYLENE.
(3mm APPROX THICKNESS)

DOUBLE LAYER OF CONTRA HELICAL GALVANISED STEEL WIRES.
(WIRE Ø 4.25mm)

OUTER SHEATHING OF EXTRUDED POLYETHYLENE.
INCLUDING CO-EXTRUDED HIGH VISIBILITY STRIPE.
(5mm APPROX THICKNESS)

OUTSIDE DIAMETER	160mm +/- 3mm
OUTER SHEATH MATERIAL	EXTRUDED POLYETHYLENE
OUTER SHEATH COLOUR	BLACK + YELLOW STRIPE
SHEATH REINFORCEMENT MATERIAL	GALVANISED STEEL WIRE
STATIC MINIMUM BEND RADIUS	1,600mm
DYNAMIC MINIMUM BEND RADIUS	2,400mm
WEIGHT IN AIR	51,180 kg/km
WEIGHT IN SEAWATER - UNFLOODED	30,560kg/km
WEIGHT IN SEAWATER - FLOODED	32,390kg/km
MINIMUM BREAKLOAD	580kN
UMBILICAL MAX SAFE WORKING LOAD	115kN
TORSIONAL STIFFNESS	148.8kN.m/deg
ESTIMATED AXIAL STIFFNESS	464MN
ESTIMATED BENDING STIFFNESS	11.78kN/m²

REVISION	DATE	REV	DRWN	CHKD	APPD.
INITIAL ISSUE	22/07/09	00	SG	PW	PM

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Subsea Power Cables

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