LAND CABLE INTERFERENCE MODEL AND CABLE CROSSINGS WITH POWER INTERCONNECTS

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Abstract: Fault currents on high voltage power grid cables can cause interference to neighbouring cables. This problem is sometimes overlooked when constructing a new cable system. As a result, an estimation tool was developed which uses magnetic field theory to investigate how large this effect can be. This paper describes the theoretical model and compares its outputs applied to a landing station prone to interference from power interconnects, against actual measurements. The results show the estimation tool is accurate to +/- 20%. The proximity of power cables and the planning of land cables / offshore power cables can therefore play an important role in avoiding such problems.

1. INTRODUCTION

Submarine system land power cables between the terminal station and the beach manhole can be vulnerable to transient interference from power cables in the event of a fault. This is most commonly observed as voltage and current disruptions in the PFE (Power Feed Equipment) performance logs and may cause multiple alarms. This interference could potentially affect traffic by causing the PFE to shut down. An illustrative example of a generic cable system is shown in Figure 1 (not to scale). The problem area of interest is marked as “Interference Area” in this high level view.

This paper was motivated by a problem seen at a cable station which accommodates more than one cable system. On numerous occasions the PFE had gone through a warm re-boot. Suspected defective cards were returned to the supplier for investigation and returned with no faults found. An in-depth investigation of Performance Monitoring (PM) logs highlighted that all cable systems coincidentally exhibited line current peaks, suggesting that an external event could have been the root cause. A typical example of a submarine system land power cable used in the field is shown in Figure 2.

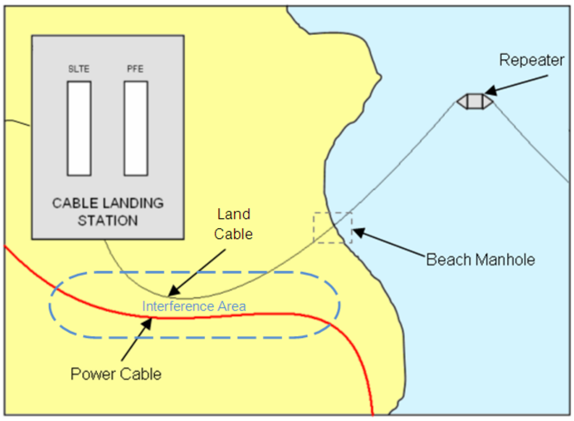
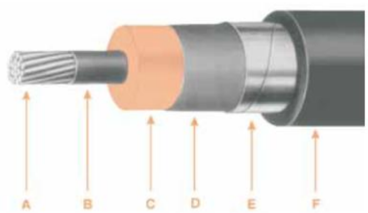


Figure 1: High level view of cable landing and interference area of interest



Key

A	Uncoated Copper Conductor
B	Strand Screen
C	Insulation
D	Insulation Screen
E	Shielded Coated Copper Tape
F	Jacket

Figure 2: Submarine system land cable [1]

2. BACKGROUND THEORY

The magnetic field produced due to a large current flowing in a cable which is in close proximity to another is one of the key areas of study. When a current flows with little or no change, it can be said to be in a steady state. However, a large instantaneous fault current on the cable is referred to as a transient. A transient with a magnitude of ten to fifty times the normal current per phase would be large enough to have an impact on neighbouring cables.

Equation 1 is used to calculate the Magnetic Field (B) at a given distance (r) with a current flowing (I) through the power cable.

$$B = \frac{\mu_o I}{2\pi r}$$

Equation 1: Magnetic field

Where:
$B =$ Magnetic Field (T)
$\mu_o =$ Permeability of Free Space (Hm^{-1})
$I =$ Current - power cable (A)
$r =$ Radial distance from conductor (m)

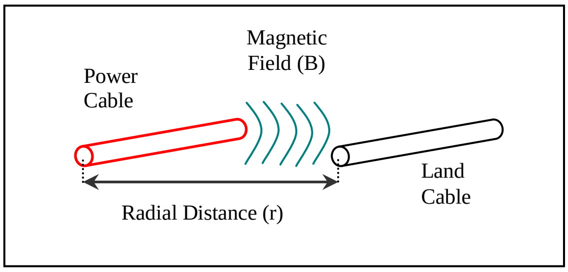


Figure 3: Illustration of Magnetic Field (B) when a current flows through the Power Cable

In this instance we assume that both cables are parallel to one another. With the magnetic field (B) known from Equation 1, we are able to apply Lenz's Law to find the induced voltage on the land cable. This is calculated using Equation 2:

$$\varepsilon = Bl\omega$$

Equation 2: Formula used to calculated induced voltage on the Land Cable

Where:
$\varepsilon =$ Induced Voltage (V)
$B =$ Magnetic Field (T)
$l =$ Length of land cable (m)
$\omega =$ Angular Frequency (rad/s)

The angular frequency can be substituted by the AC frequency of the power cable. The relationship between the two is given in Equation 3.

$$\omega = 2\pi f$$

Equation 3: Relationship between angular frequency and frequency

Where:
$\omega =$ Angular Frequency (rad/s)
$f =$ Frequency (Hz)

The impedance of a cable is dependent upon frequency. Typical land cables may have impedances of (Z) 124 Ω at 50 Hz or 113 Ω at 60 Hz. If the induced voltage and cable impedance is known, Ohm's Law can be applied to calculate the current which flows through the cable. This is given in Equation 4.

$$I = \frac{\varepsilon}{Z} \Leftrightarrow \frac{Bl2\pi f}{Z}$$

Equation 4: Substitution of Equation 2 using Ohm's Law

Where:
$I =$ Current
$\varepsilon =$ Induced Voltage (V)
$Z =$ Impedance (Ω)

This equation only remains valid when the following two criteria are met:

- Criterion 1: The cable has no screen or the screen has a high impedance
- Criterion 2: Two cables are in parallel

This is not always the case in the field; therefore these two conditions need to be analysed further to overcome this limitation.

3. CABLE RESISTANCE ANALYSIS

It is normal for a land cable screen to have multiple earth points, for example; it would normally be earthed at the beach manhole where the shield is connected to earth rods which are effectively in series with the screen resistance. In addition, the screen would also be earthed at each pulling chamber and at the station. Therefore the induced magnetic field at the core is reduced compared to a land cable with no screen. The extent of change seen at the core is minimal with the inclusion of screen resistance, however it allows for a more accurate model. The soil resistivity at each of the earth points will alter the total screen resistance; two extreme scenarios are as follows:

- Cable earthed in wet sand under the water close to the sea – this gives an extremely low resistivity of about 2 Ωm. This leads to a larger current induced in the screen
- Cable earthed in dry sandy soil – this gives an extremely high resistivity of about 2,000 Ωm. for such high values the current is low and modelled as the un-screened cable

An illustrative example for either case is shown in Figure 4.

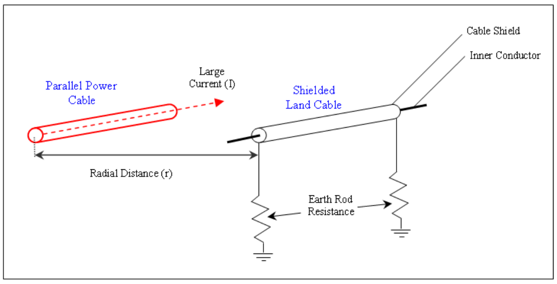


Figure 4: Land cables connected to earthing rods

Earth rods are buried below surface level at each earth point. The efficiency of these points are dependent on many factors; these include but are not limited to:

- Dimensions of the rods
- Number of rods
- Burial depth
- Soil resistivity
- Rod spacing

The earth resistance of a single rod driven vertically into the ground can be calculated using Equation 5.

$$R_g = \frac{\rho}{2\pi L}\left[\ln\left(\frac{8L}{d}\right) - 1\right]$$

Equation 5: Formula used to calculate earth resistance [2]

Where:

R_g = Earth resistance (Ω)

ρ = Soil resistivity (Ωm)

L = Buried length of electrode (m)

d =diameter of electrode (m)

For comparison purposes, typical values for soil resistivity are given in Table 1.

Type of Soil or Water	Typical Resistivity (Ωm)	Resistivity Range (Ωm)
Sea Water	2	0.1 to 10
Wet / Muddy Ground	30	2 to 50
Silt & Sand Clay	100	20 to 260
Sandy Ground	200	50 to 3,000
Stony & Rocky Ground	2,000	100 to 8,000
Solid Granite	25,000	10,000 to 50,000
Ice	100,000	10,000 to 100,000

Table 1: Variations of soil resistivity [2][3]

The resistance of a single earth rod can be calculated using Equation 5; the total screen resistance of the shield can be calculated using Equation 6.

$$R_{tot} = R_1 + R_2 + ... + R_n + Rs$$

Equation 6: Total screen resistance

Where:

R_{tot} = Total Resistance (Ω)

R_1 = First resistance - rod one (Ω)

R_2 = Second resistance - rod two (Ω)

R_n = Resistance of nth rod (Ω)

Rs = Screen resistance (Ω)

4. CONTOUR CABLE ANALYSIS

As per criterion 2, the magnetic field and current induced on a segment of the land cable are both calculated based on the assumption they are parallel. Although this can prove to be a quick and easy way to determine what impact parallel cables will have, in reality this is not often the case due to the contours of the land cables.

The interference area highlighted in Figure 1 is investigated further. The power and land cables are split into smaller segments with arbitrary values assigned. This is shown in Figure 5.

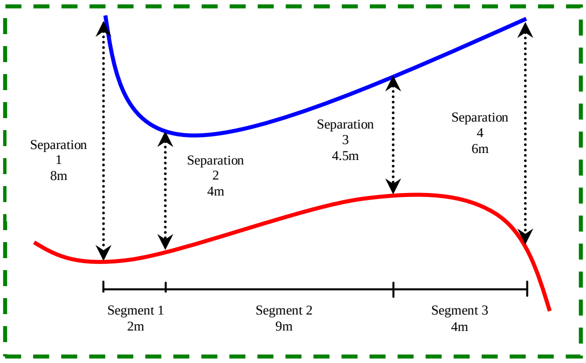


Figure 5: Segment analysis of interference Area

The rate of change in distance between the two cables will define the induced current on the land cable for a given segment. Using simple geometry, the gradient and the angle between the two cables can be found.

A graphical representation of segment 1 analysis is given in Figure 6.

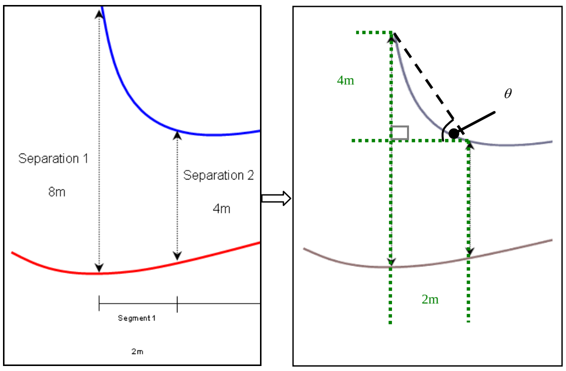


Figure 6: Analysis of the cables on Segment 1

The angle theta for the submarine system land cable be calculated using Equation 7. The same principal is applied to the power cable, and the sum of both angles gives the total angle for this segment.

$$\theta = \tan^{-1}\left(\frac{Opposite}{Adjacent}\right)$$

Equation 7: Calculation for angle shown in Figure 6

This change in interference due to the varying distance can be incorporated into Equation 1, giving us Equation 8.

$$B_n = \frac{\mu_o I}{2\pi r_{av}}(\cos\theta)$$

Equation 8: Magnetic field on land cable with varying angle

The magnetic field of all segments cannot simply be summed together and applied directly in Equation 4. This is due to the varying lengths of the segments. Therefore the total current induced on the land cable is the sum of current per segment. This is given in Equation 9.

$$I_t = \frac{B_1 l_1 \omega}{Z_i} + \frac{B_2 l_2 \omega}{Z_i} + ... + \frac{B_n l_n \omega}{Z_i}$$

Equation 9: Total current seen on a contour land cable

Where:

I_t = Total current seen on the Land Cable

B_1 = Magnetic field of Segment 1

B_2 = Magnetic field of Segment 2

B_n = Magnetic field of nth Segment

This forms the basis of the estimation tool and can be applied to any number of segments. It is best practice to have smaller segment lengths, and to place segment boundaries at sharp bends. This ensures the rate of change in distance is captured effectively, which reduces errors.

5. THEORETICAL MODEL AND DISCUSSION

The results of measurements taken at the cable station were compared with the output results for the tool. It is difficult to be precise as the fault current can vary from ten to fifty times the normal current per phase.

Given this limitation, the model gives values within 20% of those measured at the cable station. This is sufficient to aid planning a new cable route or assisting in finding the source of interference.

Planning for the largest possible distance between power and land cables for new builds is the best solution. The sensitivity of various suppliers' equipment varies, but research into a filter which detects transients could be implemented to existing systems to identify such interference.

With the widespread construction of off-shore wind farms, it is inevitable that power cables will share beach landing space. They may also share limited space on the sea floor and land routes. Understanding the potential interference that these wind farm cables could produce is an area of investigation for the future.

The model could be adapted and developed further to output an estimated level of interference that wind farm power cables could cause. This analysis would limit the risk to existing cable owners if a wind farm is being proposed to be built. Alternatively, it could guide new cable owners who have restricted paths for routing their submarine cable. In either case, the proximity of power cables and the planning of land or submarine cables can play an important role in avoiding such problems.

6. ACKNOWLEDGEMENTS

The author would like to thank Mr Phil Lancaster, Senior Submarine System Engineer (Cable&Wireless Worldwide) for useful discussions and suggestions.

7. REFERENCES

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