



Università degli Studi di Padova

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE
Corso di Laurea Magistrale in Ingegneria dell'Energia Elettrica

TESI DI LAUREA MAGISTRALE

Modelling and testing of light polarisation in Optical Ground Wires (OPGW)

Candidato:

Daniele Danieli

Matricola 1156761

Relatori:

Prof. M. Haddad

School of Engineering, Cardiff University

Prof. R. Turri

Dipartimento di Ingegneria Industriale

Contents

1	Introduction	9
2	Overhead conductors	11
2.1	Introduction	11
2.2	Optical ground wires	12
2.3	Faraday effect	15
2.4	At the Lightning Laboratory	18
3	Analysis	23
3.1	Introduction	23
3.2	Analytical model	24
3.3	Comsol model to verify the results	26
3.4	Eight wires model	28
3.5	Influence of α on the parameters	29
3.6	Double layer cable	38
4	Modelling	41
4.1	Introduction	41
4.2	Modelling problems	42
4.3	Basic setup for the models	44
4.3.1	Verification of the first setup	49
4.4	Uniform current distribution model	52
4.5	Non-uniform current distribution model	57
4.5.1	Verification of the results	58
4.5.2	Relationship between μ and the Bz peak	62
4.6	Correlation between the Comsol and Matlab models	65
5	Conclusions	69

List of Figures

2.1	Ground wire on overhead line	12
2.2	Structure of an optical fiber	13
2.3	Reflection of the light	14
2.4	Electromagnetic wave	15
2.5	General ellipse in the propagation plane	16
2.6	Some polarisation cases	16
2.7	Faraday effect causing a polarisation angle [1]	17
2.8	Magnetic flux density due to a twisted wire	18
2.9	Measurement setup [9]	19
2.10	Angles in the propagation plane	19
2.11	Poincaré sphere	20
2.12	Movements on the Poincaré sphere [10]	21
3.1	Geometric view of the model analyzed	24
3.2	Comsol model	26
3.3	Magnetic flux density z-component	27
3.4	Mathematical model with all the 8 wires	28
3.5	Comsol model with all the 8 wires	29
3.6	Geometrical representation	30
3.7	Length of one twist	31
3.8	B_z component for different pitch angles	32
3.9	Polarisation angle for different pitch angles	33
3.10	Polarisation angle per unit length and unit current	34
3.11	Dependence of B_z	35
3.12	Magnetic flux density with unitary current	36
3.13	Stokes parameters S_1 and S_2	37
3.14	Section of the double layer cable	38
3.15	Influence of α on the double layer cable	40
4.1	Injected current and displacement currents with $\sigma = 1[S/m]$	42
4.2	Helix tool in Comsol	43
4.3	Section of the optical cables [9]	43
4.4	Work plane in Comsol	44
4.5	Results by the same model for different values of permeability	45

4.6	Differences on the noise amplitude with different meshes	45
4.7	Different currents used	47
4.8	Current injected	48
4.9	Linear relationship between Bz and the current	49
4.10	Bz component over time	50
4.11	Bz for different rise times	51
4.12	Magnetic flux density with a periodic boundary condition	51
4.13	Periodic condition in Comsol	52
4.14	Maximum B_z component during time	53
4.15	B_z component along the cable	53
4.16	Maximum B_z component during time	54
4.17	Damped sine waveform	55
4.18	Magnetic flux density, z-component	55
4.19	Comsol result with damped sine waveform	56
4.20	Currents measured in the current distribution experiment	57
4.21	Verify of Comsol results	59
4.22	Bz waveforms for different current values	60
4.23	Differences between Comsol and Matlab model	61
4.24	Relationship between Bz and the permeability	62
4.25	Behaviour of Bz min values	63
4.26	Relative trends of max and min Bz values	64
4.27	Relative loss of B_z	65
4.28	Points analyzed	66
4.29	Relative loss of B_z for three different points	67
4.30	Relationship between magnetic flux density	68

Abstract

The OPGW are very useful nowadays and they have basically two functions: they allow to transmit a lot of informations thanks to the optical fiber inside the conductor and they are a protection against the lightnings [9]; unfortunately when a lightning strikes the overhead conductor it also generates a magnetic field inside it that changes the polarisation of the light transmitted by the optical fiber [10]. This is a problem because the main consequence is the lost of the informations that were sending. It was easily possible to find in the lightning the cause of the fast transient of SOP (State Of Polarisation) [4], the difficult part is to understand how the lightning current affects the magnetic field in the middle of the cable and consequently also the angle of polarisation (Faraday effect). In order to understand this phenomenon Huawei started a study commissioned to the Cardiff University, an experiment was setup at the Morgan-Botti Lightning Laboratory and some math computations were made to create a model that can study the OPGW cable. The Comsol Multiphysics software has been used to have a comparison with the computed values.

Chapter 1

Introduction

The purpose of this thesis is to give an overview on the magnetic effects that a lightning causes when it hits an OPGW (optical ground wire), it is known that when a polarised light gets through a parallel magnetic flux density the Faraday effect occurs changing the angle of polarisation. Since this phenomena brings to communication problems, it is important to understand how the lightning current affects the speed wherewith the polarisation angle changes.

This study has been commissioned by Huawei to Cardiff University and in particular the experiments are made at the Morgan-Botti lightning laboratory.

The principal aim of this study is to find a 3D model that can simulate the magnetic flux density in the middle of the cable, in order to do this the Comsol Multiphysics software was used and to compare its results also an analytical approach was made. The principal module used in Comsol is the *magnetic fields* one and the main study adopted is the time-dependent, even if some tries were made with either the stationary study or the frequency domain one.

Further on in the chapters the following aspects will be presented:

- overview on the Faraday effect
- analytical approach to the problem
- influence of the twist pitch on the magnetic properties
- models in Comsol
- comparison between Comsol and Matlab results
- relationship with the permeability

the models built in Comsol have been compared also to a Matlab model, in this way was possible to obtain another confirm on them and also to find a correlation about the permeability factor (this aspect will be well explained in the model chapter).

Moreover a lot of useful data were collected from the experiments at the laboratory and afterwards used also as the input on the FEM model.

Chapter 2

Overhead conductors

2.1 Introduction

This chapter has the aim to provide a summary about both the overhead conductors and the optical fibers inside them, giving also some physical bases on the polarisation of the light phenomenon. Nowadays it is important to constantly increase and keep the reliability and power quality levels of electric systems, the principal source of faults on overhead lines are indeed the lightnings [8]. Another important factor is that a lightning can affect a transmission line even if it does not strike it directly, in fact also the lightnings that hit near the line produce an electromagnetic effect, a study to understand the damages of a lightning was performed by the analysis on lightning location searching of Global Positioning System [4].

For the high values of voltage most of the transmission lines are overhead power lines, hence, in order to protect them from the lightnings, a ground wire (or shield wire) is placed above them. This wire does not have conduction functions because it is a passive conductor, its only aim is to be hit from the lightnings protecting in this way the phase conductors.

As can be seen in Figure 2.1 the *protecting angle* β guarantees, with a good probability, that if the lightning strikes then the ground wire will be struck saving the phase conductors. Usually the protecting angle is approximately of 40° .

Since the ground wire is placed to protect the line from lightning strikes, it is unavoidable that it will be stricken and, as is explained further on, this can cause some problems when you are transmitting information inside the ground wire.

When a lightning hits the current is split at the strike point causing the generation of two voltage waves that propagate along the line in opposite directions, the principal effects due to the strikes are faults, interruptions and overvoltages [8]. The current injected by a lightning does not depend on the object hit because the wave impedance of the discharge channel is too high compared with the ones used to connect the overhead lines with the ground, for this reason the lightnings can be seen as current generators.

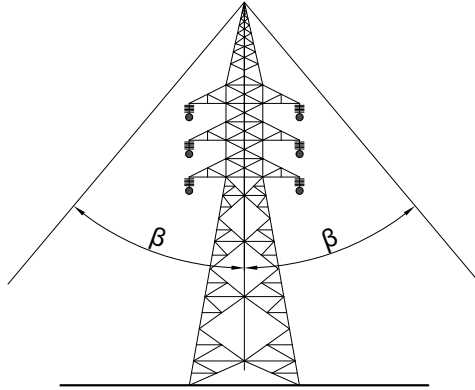


Figure 2.1: Ground wire on overhead line

2.2 Optical ground wires

The ground wire is a passive conductor, in normal conditions the current inside it should be zero; for this reason it is useful to combine this feature of the transmission lines with the optical fibers that allow to transmit information, hence the OPGW are cables with a double function: protection from lightnings and at the same time a telecommunication media. The fiber is placed in a metal tube in the center of the cable and it is protected by one or more armouring layers, in this way it is possible to obtain a cheap deployment of the fibers.

In recent years, field and laboratory measurements, indicate that the magnetic field caused by lightning current and generated along the axis of the conductors changes the state of polarization (SOP) of light in the fiber very rapidly. This becomes an issue when using coherent optical polarization multiplexed transmission schemes of 100+Gb/s [9].

Looking at the definition an optical fiber is a cylindrical dielectric waveguide made of low-loss materials, as an example the silica glass, which has the function to guide the light with low losses [11].

A communication system based on optical fibers works with light signals, in order to define the complete system it is necessary to introduce also other elements: the input signal is electric as usual, so the first part consists in a transmitter that can convert this signal into a light beam; then the optical fiber can guide the light through the line and at the end there is a receiver to reconvert the light into an electrical signal. Moreover just after the transmitter there is a light source (LED or laser) to generate the beam in a range of frequencies from 800[nm] to 1600[nm] [6].

Dimensions and materials used to build the fiber can change on the specific situation in which the cable is used, however the main layers of an optical fiber are the ones depicted in Figure 2.2:

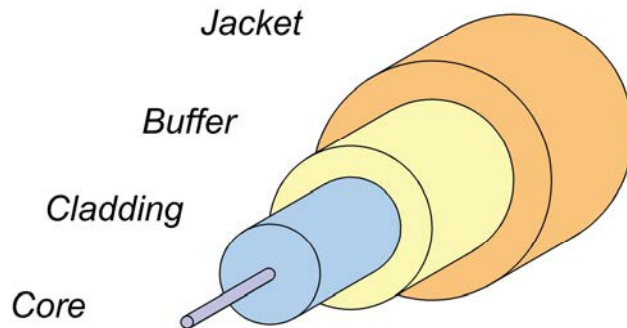


Figure 2.2: Structure of an optical fiber

- the *core* is the inner part in which the light travels, it has a size of few micrometers and it is typically made of glass. It is characterized by the index of refraction n_1 : a dimensionless number that determines the speed of the light's propagation inside the material

$$n_1 = \frac{c}{v} \quad (2.1)$$

c is the speed of light in vacuum instead v is the speed of light in the medium, hence the refractive index tells how much faster the light travels in the vacuum respect to a specific medium [7].

- the *cladding* is made with the same materials as the core but it has different optic properties in fact its index of refraction n_2 is lower than the core one, this allows to obtain a confinement effect of the light inside the core: if the light goes into the cladding it will be reflected
- the *buffer* has the function to protect the fiber from the mechanical point of view
- the external *jacket* adds an extra external protection from environmental and mechanical issues

In order to better understand how the light propagates inside an optical fiber it is sufficient to look at the Snell's law considering that $n_1 > n_2$:

$$n_1 \sin(\phi_1) = n_2 \sin(\phi_2) \quad (2.2)$$

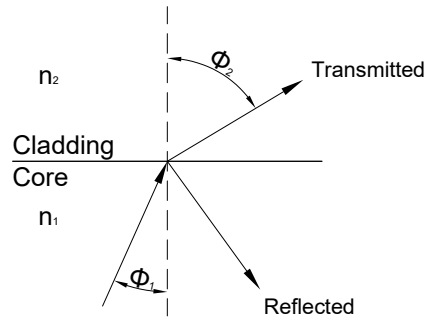


Figure 2.3: Reflection of the light

looking at the (2.2) with the angle defined in Figure 2.3 it is clear that $\phi_2 > \phi_1$, so it is possible to say that for increasing values of the angle ϕ_1 there is a *critical angle* at which the transmitted light becomes parallel to the surface between the two layers. Hence if the incident angle is greater than the critical one, then the light can propagate inside the fiber and it will be a total reflection case [3].

2.3 Faraday effect

As was said before, the optical fibers use LEDs or lasers to transfer signals and information at high speed. Hence, in order to understand what happens when a lightning strikes a cable with an optical fiber inside in which a signal is travelling, it is necessary to study the light as an electromagnetic wave.

From the name itself it is possible to understand that the light is a combination of both electric and magnetic waves travelling through the space (in red and blue respectively on the following figure).

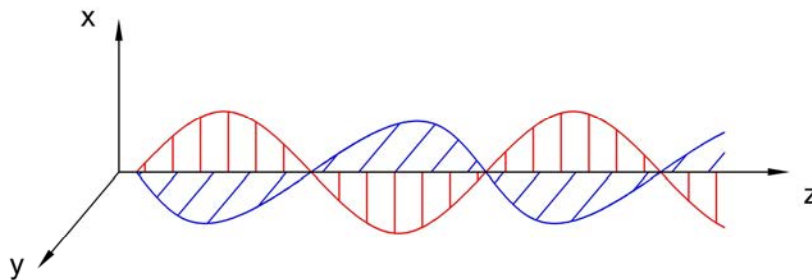


Figure 2.4: Electromagnetic wave

In an isotropic medium ¹ the electric field vector is perpendicular to the direction of propagation, hence moving towards the z direction, as in Figure 2.4, it is possible to define some planes of propagation in which we can see the behaviour of the electric field \vec{E} , this can be of four different types: horizontal, vertical, 45° and circular polarisation. Tracking the movements of the electric field within this plane it is possible to determine the E_x and E_y components, the relationship between these defines the polarisation of the light.

In general these two vectors trace an ellipse on the xy plane while the electric field vector rotates with a certain angular speed, and depending on the angle of the vectors this ellipse can assume different shapes as shown in Figure 2.6.

¹where ε and μ are scalar quantities

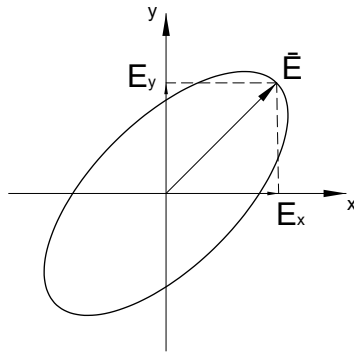


Figure 2.5: General ellipse in the propagation plane

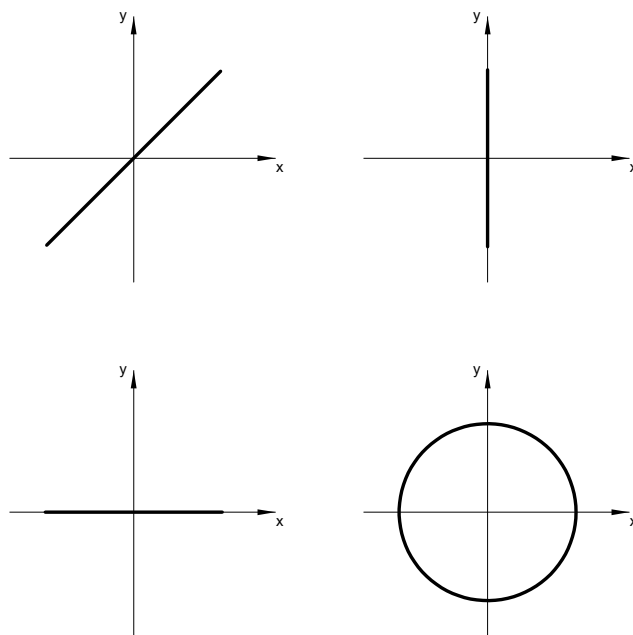


Figure 2.6: Some polarisation cases

Starting from these polarisation cases it is now possible to introduce the Faraday effect: if the wave moves in the same direction of the magnetic field (or parallel to one of its components) then the transmitted light will be rotated by an angle directly proportional to the strength of magnetic field component parallel to the direction of propagation; calling this angle θ it is possible to determine it by the following equation:

$$\theta = B\nu l \quad (2.3)$$

where ν is the Verdet constant that gives an information about the strength of the Faraday effect in a specific material; for the simulations at the Lightning Laboratory Huawei gave some indications about this constant, in particular for the cables used it should be within $0.52 \left[\frac{\text{rad}}{\text{T}\cdot\text{m}} \right]$ and $0.60 \left[\frac{\text{rad}}{\text{T}\cdot\text{m}} \right]$.

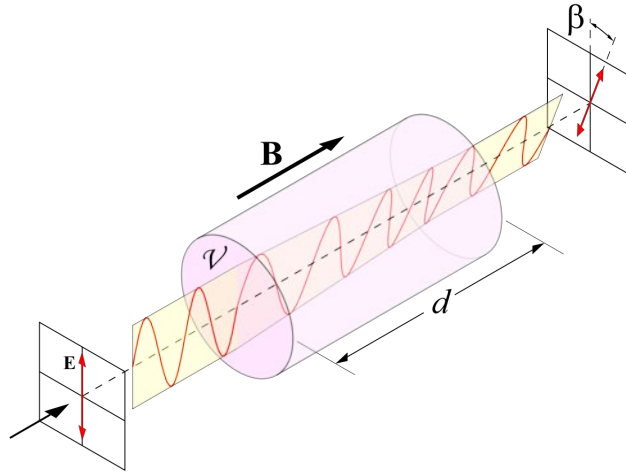


Figure 2.7: Faraday effect causing a polarisation angle [1]

The principal problem during the communication of information is the speed of changing this polarisation angle, if it is low can be possible to restore the original signal but if the speed is too high the information will be lost and consequently another signal will be sent to repeat the lost one. Unfortunately when a lightning hits the OPGW the maximum state of polarisation speed (max SOP speed) can reach few $M\text{rad}/s$ and for this reason it is impossible to continue the transmission of the signal.

An important detail is that in (2.3) B is the component of magnetic flux density parallel to the direction of the cable, hence this problem is due to the fact that the wires around the central conductor are twisted: in this way they generate a component of magnetic flux density that is parallel to the direction of propagation, for this reason the more twisted are the conductors the more parallel magnetic flux density is produced and the bigger the Faraday effect is. The extreme case is with the straight conductors, they would be parallel to the cable so the magnetic flux density would be all perpendicular (following the right-hand rule) with a consequent Faraday effect equal to zero.

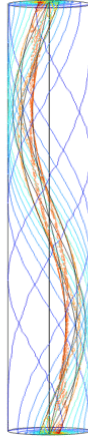


Figure 2.8: Magnetic flux density due to a twisted wire

The effect of the twist is clear, the figure above is a contour plot created in Comsol and it is possible to see that the magnetic flux density lines are twisted as the external wire, for this reason a component parallel to the cable is generated causing the Faraday effect to the light that travels in the optical fiber inside the cable.

2.4 At the Lightning Laboratory

The lightning laboratory allows to research about the direct effects of lightnings, testing for the aerospace and power sectors. There are test facilities to aeronautical standards ED14, ED84 and ED105, there is a DC test source enabling the generator of all four of the required lightning test components (A, B, C and D).

It is known from lightning modelling that 1% of negative first strokes of lightning show a peak current of at least $150[kA]$. At the Morgan-Botti lightning laboratory a systematic experimental setup was developed to measure the SOP on two types of OPGW cables under lightning current up to and above $150[kA]$.

Three lengths of OPGW were considered and all tests were repeated three times to examine repeatability and variability of the results [9].

The configuration used to test these cables is depicted in Figure 2.9, a bank of capacitors charged from $5[kV]$ up to $55[kV]$ injects the current in the cable and the selected shape of the impulse was a variant of the ‘A’ waveform described in the ED-84 (EUROCAE Document).

The cables that have been tested are the following:

- 20[m] single layer (6 aluminium wires and 2 aluminium clad steel wires)
- 20[m] double layer (18 aluminium wires and 5 aluminium clad steel wires)
- 50[m] double layer (18 aluminium wires and 5 aluminium clad steel wires)

for dimensional reasons and because the start and the end points are close each other, the cables had a part in which the conductors were running parallel, this parallel path was as short as possible and at the maximum distance in order to minimize the interaction. The Figure 2.9 describes briefly the setup for the tests at the laboratory.

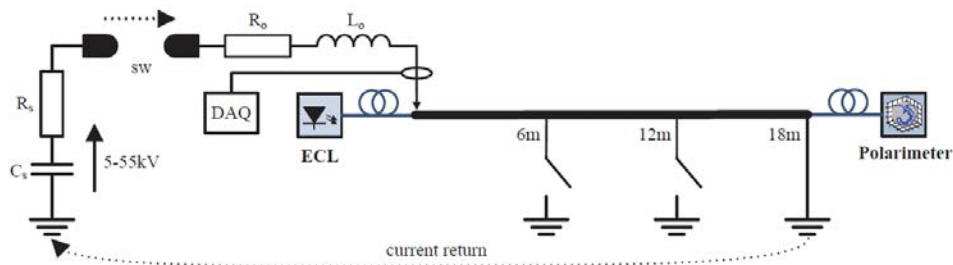


Figure 2.9: Measurement setup [9]

Hence with the polarimeter at the end of the cable it is possible to measure the state of polarisation after the effect produced by the current injected, to read the result another representation is used, as described below.

Looking again at the polarisation plane xy and defining some specific angles allows to create a relationship with other quantities as it is possible to see in the next page

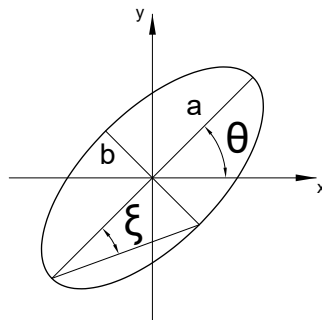


Figure 2.10: Angles in the propagation plane

in which:

- a and b are the semi axis of the ellipse
- θ is the orientation angle

- we can define the *ellipticity* as $\epsilon = \frac{a}{b}$ and the *eccentricity* as $e = \sqrt{1 - \frac{1}{\epsilon^2}}$
- $\xi = \text{atan}(\frac{b}{a})$

Another way to represent the state of polarisation is with the Stokes parameters S_1 , S_2 and S_3 that are the representation of the three components of SOP: respectively the horizontal linearly polarized component, the 45° linearly polarized component and the right-rotation circularly polarized component [5]. Hence their combinations can create all the cases of polarisation, as a simple example the vector with $(S_1, S_2, S_3) = (1,0,0)$ corresponds to the horizontal linearly polarized case; there is also the parameter S_0 that gives an information about the total intensity, as default this parameter is equal to 1 so the Stokes parameters are referred to an unitary intensity.

Moreover it is possible to refer this three parameters to the angle previously described:

$$\tan(2\theta) = \frac{S_2}{S_1} \quad (2.4)$$

$$\tan(2\xi) = \frac{S_3}{\sqrt{S_1^2 + S_2^2}} \quad (2.5)$$

and this is useful when we want to represent the SOP in a more visual way, referring to the Poincaré sphere which is built with

$$S_1^2 + S_2^2 + S_3^2 = 1 \quad (2.6)$$

using this vector the result is that the polarisation effect is much easier to see, because it will be a point that moves on the sphere depending on the state of polarisation.

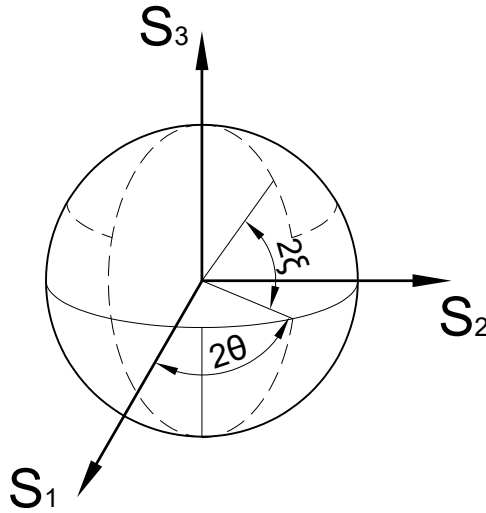


Figure 2.11: Poincaré sphere

At the Morgan-Botti lightning laboratory using three polarizers and a laser source it is possible to inject a signal with a defined start SOP (configurable with the polarizers) into an optical fiber, then using banks of capacitors the A waveform is injected in the cable in order to simulate a lightning, afterwards the output part of the fiber is connected to a polarimeter that measures the polarisation of light. Starting from this measure Stokes parameter, max SOP speed and the Poincaré sphere are obtained, the Figure 2.12 depicts an example of Stokes vector that moves on the sphere after a current injection in the cable, the red point indicated by the arrow represents the initial state of polarisation and then the blue line follows the movement of the Stokes vector along the sphere.

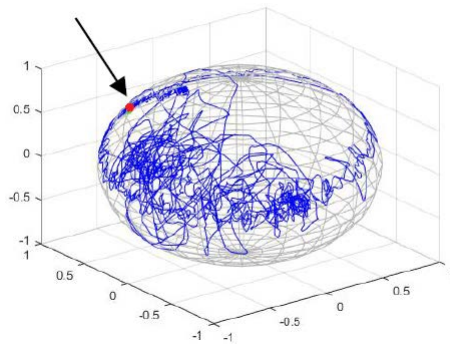


Figure 2.12: Movements on the Poincaré sphere [10]

Chapter 3

Analysis

3.1 Introduction

The aim of this chapter is to give an overview about the simple mathematical equations used to estimate the value of the magnetic flux density in the middle point of the cable. It was necessary to make some simplifications (in terms of current distribution and current waveform) but the final purpose of this chapter is only to make a comparison between the analytical results and the ones calculated in the finite element software (i.e. Comsol Multiphysics).

Since the problem is very difficult in order to simplify it and obtain a quick response for the simulations two basic cases have been considered: the first one is very simple and it sees all the currents as filaments laid down on the surface of the internal conductor, then a little step further is considered and it consists on moving the currents by a distance r_{wire} far from the central conductor, in this way we are considering a punctual current distribution concentrated in the centre of the external wires twisted around the central one. Moreover the first try considers only one wire, instead the second model has all the external wires for a better representation of the real case.

This mathematical model was used also to simulate a simple double layer cable that was tested at the lightning laboratory, for this type of cable another Comsol model will be developed, hence this analytical study presents only a first estimation of what could be the behaviour of this other cable.

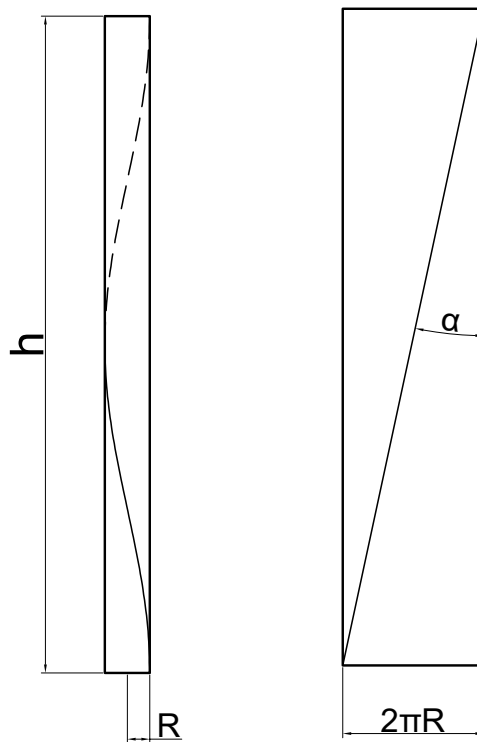
No specific current distribution analysis have been considered because the values of the impedances are not known yet, so it does not have a lot of sense to start a try and error procedure to find the right values of R , l and c that give the right current distribution measured in the experiments.

In the final part of this chapter the influence of the α angle is studied, the main purpose of this computation is to investigate for the relationship between the geometrical angle, defined by the twist of the external conductors, and the magnetic properties of the field inside it. Of particular interest is how this angle affects the z-component magnetic flux density and also the polarisation angle θ .

3.2 Analytical model

The first step was to find a simple mathematical computation that could give a feedback on the results of the models with a good accuracy, the simplest possible way is to take the cylinder and then unroll it, in order to obtain a rectangle with the same height of the cylinder and with a width of $2\pi R$ (where R is the radius of the cylinder).

For geometrical reasons it is sufficient to consider one wire at time and afterwards multiply the solution by 8, because the cable has an axial simmetry and initially a uniform current distribution is supposed, hence every wire gives the same contribution; so the model is the one depicted in Figure 3.1.



(a) *View of the cable*

(b) *Cylinder unrolled*

Figure 3.1: Geometric view of the model analyzed

Therefore in order to calculate the length of the twisted wires and the pitch angle it is necessary to unroll the cylinder to obtain a surface in which the twisted wires become straight lines as is shown in Figure 3.1b (the helix in 3.1a has become the straight line in 3.1b).

It has been measured that a complete twist of the wire occurs every $18[cm]$, so it is possible

to compute the angle between the horizontal axis and the wire as is shown in Equation 3.1.

$$\alpha = \text{atan} \left[\frac{2\pi(r_{cen} + r_{wire})}{h} \right] = 7.7^\circ \quad (3.1)$$

Then the length of the twisted wire around the central conductor is easily find using the triangle that it forms with the height and the width of the unrolled cylinder.

$$l = \frac{h}{\cos(\alpha)} = 181.6[\text{mm}] \quad (3.2)$$

where:

- $r_{cen} = 3.85[\text{mm}]$
- $R = r_{cen} + r_{wire}$
- $h = 180[\text{mm}]$
- for this first case $r_{wire} = 0$ (filament wires)

So, considering the cylindrical geometry, every point in the line wire is at a fixed distance R from the centre of the cable because the wires are twisted around it. In this case we have $R = r_{cen}$ because we are assuming filament wires; knowing this it is now possible to calculate the magnetic flux density in the middle with the Ampere's law and afterwards its z-component:

$$B = \frac{\mu_0 I}{2\pi R} \quad (3.3)$$

$$B_z = B \sin(\alpha) \quad (3.4)$$

In order to obtain a better estimation it is necessary to consider also the radius of the external wires, the pattern to follow is the same with the only difference that now r_{wire} is equal to $2.3[\text{mm}]$ and not zero anymore.

Hence the updated values are the following:

- $\alpha = 12.1^\circ$
- $l = 184.1[\text{mm}]$
- $B = 325.2[\text{mT}]$
- $B_z = 68.3[\text{mT}]$

All these results were obtained using a total injected current of $10[\text{kA}]$; moreover, as mentioned in the introduction of this chapter, the current distribution was assumed to be uniform. For this reason we are considering a ideal case in which the current splits itself in eight equal sub-currents, one for each wire.

3.3 Comsol model to verify the results

In order to obtain a way to confirm these values a simple Comsol model has been made, it has one external wire but it is without the central one, in this way it was possible to avoid a geometrical problem due to the drawer included in the software (this problem will be discussed further on in the model chapter). For a first analysis and only to verify the theoretical values this simplification can be accepted. Moreover initially all the wires are made of the same material and with a unitary permeability, also this is not true in reality.

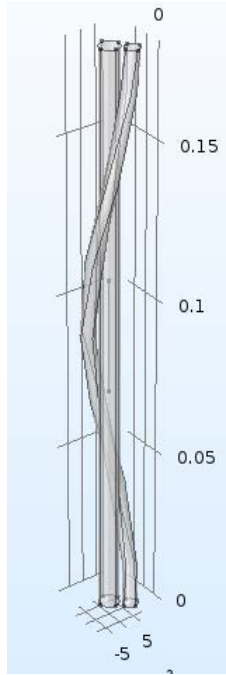


Figure 3.2: Comsol model

An image of the cable modeled in Comsol is depicted in Figure 3.2, it is possible to see the central line that is used to calculate the z component of the magnetic flux density due to the currents that are flowing in the twisted wire.

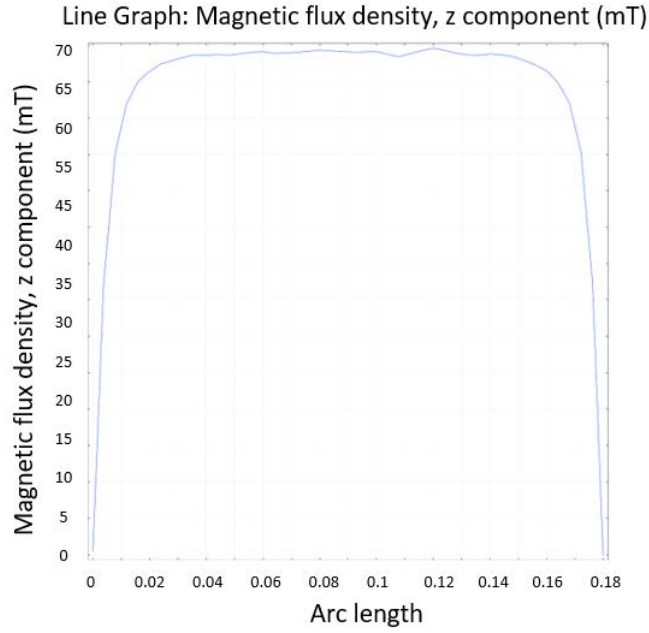


Figure 3.3: Magnetic flux density z-component

The Figure 3.8 shows the B_z component of magnetic flux density calculated in the middle of the cable, it should be a flat line but at the extremities Comsol is forced to bring the value to zero (later a model with a periodic boundary condition will be analyzed). However it is possible to see that the value found in Comsol is near to the computed one: the value

<i>Matlab</i>	
$B_{z_{tot}}$	68.3[mT]
<i>Comsol</i>	
$B_{z_{tot}}$	69.1[mT]

from Comsol is an average of the magnetic flux density along the middle line within the cable. In both the cases a $10[kA]$ current has been injected in a single wire twisted around the central conductor, as this was the first simple try only one wire has been taken into account.

3.4 Eight wires model

It is quite easy to consider all the wires if we think about the cylindrical symmetry of the cable, in fact every wire sooner or later will be in the position of the one consider in this first model.

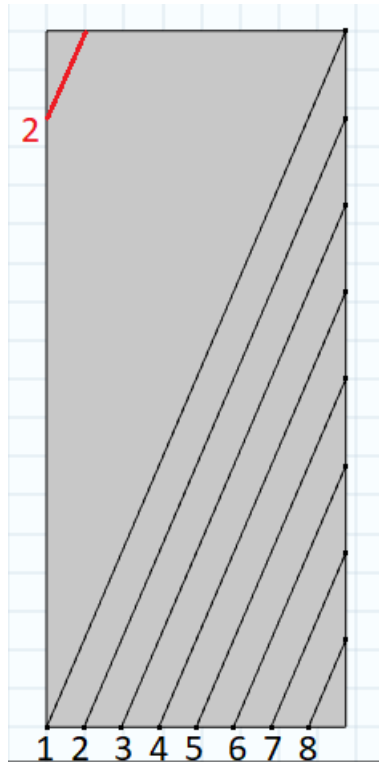


Figure 3.4: Mathematical model with all the 8 wires

In Figure 3.4 there is only the first part of the wires from 2 to 8 for simplicity of drawing (otherwise the figure would have been difficult to understand), the second part would be in the left side to complete the twist around the cable, as is shown by the red line only for the wire number 2. In this case $1250[A]$ were injected in each wire ($\frac{1}{8}$ of the total current) and from the mathematical computation result that every wire creates a B_z component equal to $8.53[mT]$ (not considering the induced currents), afterwards it is possible to compute the total contribution simply adding all the component with the superimposition of the effects. In this ideal computation we find again the same result as before ($8.53 \cdot 8 = 68.3[mT]$).

To verify this another Comsol model has been used, this time it has 8 wires and each one of them has a current of $1250[A]$. Figure 3.5 shows the geometry of this model, the small helix between the wires functions to improve the mesh in those narrow regions so they don't change the magnetic contribution in the middle of the cable. Again the value found in Comsol is near to the computed one:

<i>Matlab</i>	
$B_{z_{tot}}$	68.3[mT]
<i>Comsol</i>	
$B_{z_{tot}}$	68.6[mT]

hence it seems feasible the hypothesis done for the analytical study to imagine the cylinder unrolled and consider the helix as straight conductors.

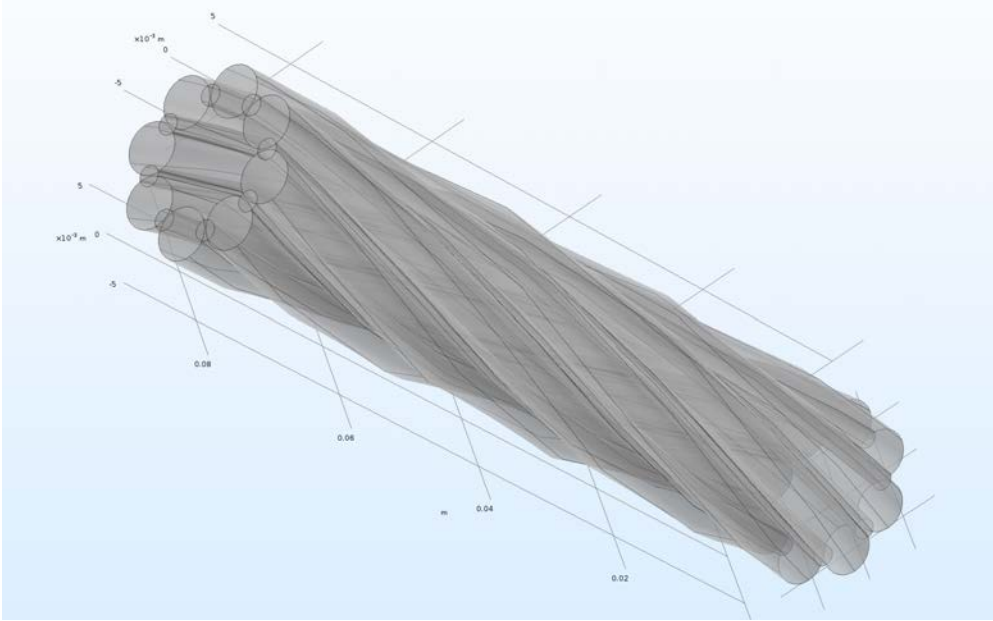


Figure 3.5: Comsol model with all the 8 wires

These simple models have only the purpose to verify the analytical data and for this reason they have a lot of initial simplifications and a normal mesh as well, obviously better models that take into account the different materials of the wires and the non unitary permeability of the two clad steel aluminium wires will be presented. For those models a very good mesh is required so it was necessary to upload them on the Cardiff University supercomputer to obtain the results with a feasible computational time.

3.5 Influence of α on the parameters

A step further was taken searching the correlation between the twist angle α and the magnetic properties of the cable, the purpose was to find a parameter that can tell how will be the polarisation effect looking only at the pitch of the wires.

The values of α considered are within the range from 0° to 90° , in this way it is possible to study all the cases between the two extremities, respectively the coil case (for α near to 90°) and the straight conductors case (for $\alpha = 0^\circ$).

Remembering that the single layer cable at the laboratory has twisted conductors with a pitch factor of 18[cm], the width R was kept fixed and varying the twist around the central conductor was possible to obtain all the cases described above. The z-component of magnetic flux density should be higher for values of α near to 90° and vice versa lower for low angles.

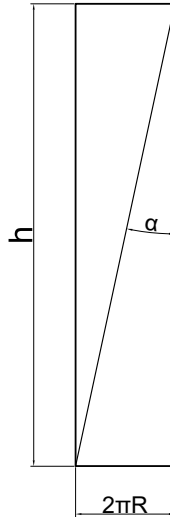


Figure 3.6: Geometrical representation

The Figure 3.6 is the representation of the unrolled cylinder and it is possible to see two different cases, the continuous line represents the real situation whilst the dashed lines are only two of the whole cases described above. There is a important fact to highlight: the width of the cylinder is kept fixed so all the cases with the dashed line below the continuous one (with an angle higher than the one depicted) will have a shorter height because the wire will finish the twist around the central conductor in less space. The opposite situation happens for the cases with an angle lower than α in the figure, in these cases the wires will finish the twist around the central conductor in more space. This is due to the fact that the width is considered as a constant for this particular study.

Starting from the angle it is not difficult to obtain all the geometry quantities that are needed, moreover all the following plots have a red circle that represents the point corresponding to the real cable, all the other points are calculated only for the purpose to find the relationship but in the reality there will be the value found by the red circle. In order to have a comparison with the Matlab model the input current is now set equal to the one used in Matlab ($I = 7147.7[A]$).

Below are listed all the features calculated:

- length of the twisted conductors

it is easy to understand that for a fixed R , the length of the conductors to have a complete twist will be longer for lower α values. Instead with α that goes towards higher values the case that corresponds to a coil situation; if we look at the length of a complete twist, this value will increase until the infinite for $\alpha = 0^\circ$.

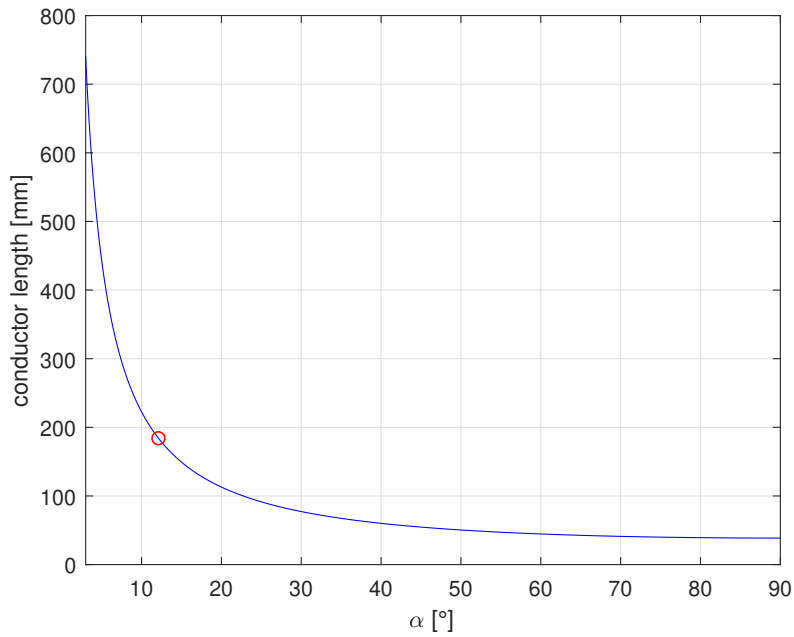


Figure 3.7: Length of one twist

Looking at this figure it is possible to see that the length necessary to complete a twist around the central conductor with an arbitrary angle decreases uniformly. The equations used are the following:

$$h = \frac{2\pi R}{\tan(\alpha)} \tag{3.5}$$

$$l = \frac{2\pi R}{\sin(\alpha)} \tag{3.6}$$

and considering the extreme cases we will have:

$$\alpha = 0^\circ \rightarrow l = \infty \tag{3.7}$$

$$\alpha = 90^\circ \rightarrow l = 2\pi R \tag{3.8}$$

- B_z component

the z-component of magnetic flux density depends on the twist angle ($B_z = B \cdot \sin(\alpha)$), hence changing the pitch of the helix it is possible to find different B_z values:

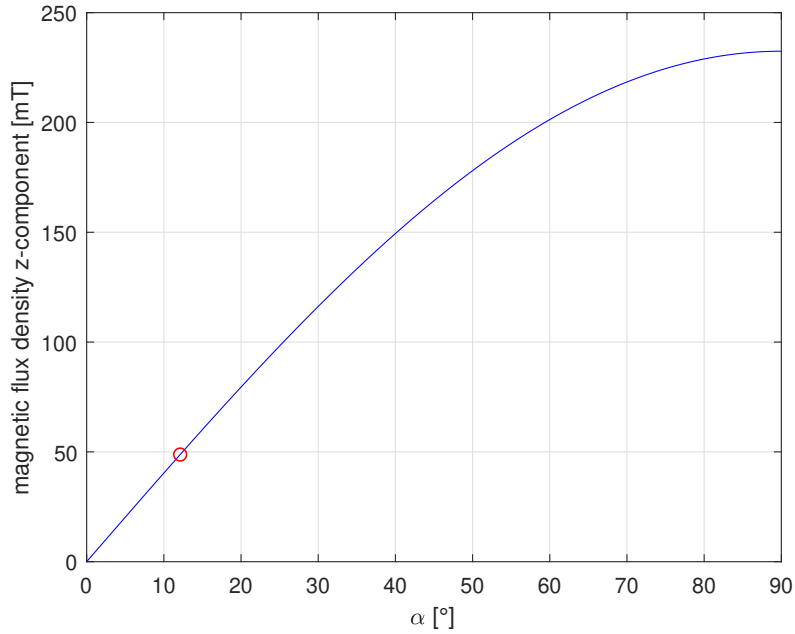


Figure 3.8: B_z component for different pitch angles

with this injected current the red circle finds a magnetic flux density of $48.8[mT]$ in the real case, this value corresponds to the result from the script in Matlab (that uses the Biot-Savart law).

Increasing the angle it is possible to see that the B_z component tends to the maximum with a decreasing derived, that maximum value corresponds to the coil case, not possible in the reality because of the wire thickness, in which the magnetic flux density has only z-component ($\sin(\alpha) = 1$).

- polarisation angle

since the polarisation angle depends on the B_z component, it depends also on the twist angle. Recalling the equation:

$$\theta = B_z \nu l \quad (3.9)$$

for the Verdet constant were used two values given by Huawei ($0.52[\frac{rad}{T \cdot m}]$ and $0.60[\frac{rad}{T \cdot m}]$), the plot below depicts how the twist angle affects the polarisation angle:

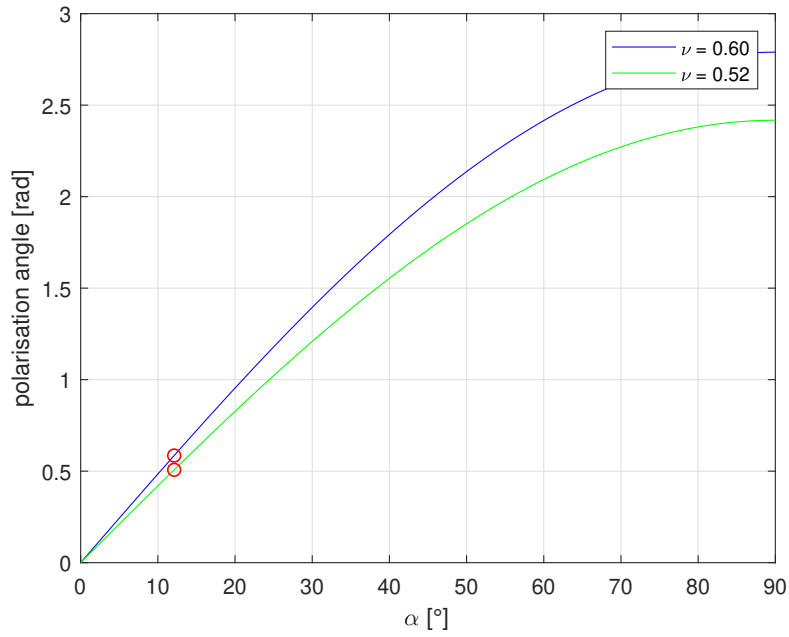


Figure 3.9: Polarisation angle for different pitch angles

the figure depicts both the cases with different Verdet values, the cases between those are in the middle of the blue line and the green one.

This figure is obtained for a length of the cable of $20[m]$ because it corresponds to the real case, but in order to create a better result in terms of generality it is necessary to express the polarisation angle per unit length and also per unit current, doing this it will be sufficient to find the point corresponding at the desired pitch of the twist and multiply it by the total length of the cable and by the current injected, adding in this way the possibility to use Figure 3.10 for different cables:

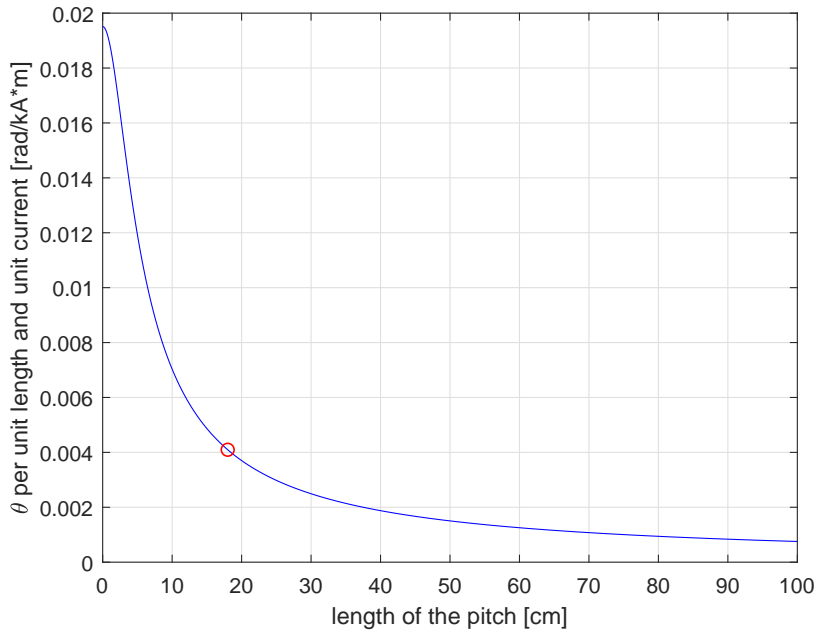


Figure 3.10: Polarisation angle per unit length and unit current

Hence, from a general point of view, looking at the results it is possible to reach some conclusions: changing the pitch of the helix obviously affects both the magnetic flux density in the middle of the cable and the polarisation angle, in particular reducing the angle α (increasing the length of the pitch) brings to lower values of B_z and θ , on the other hand the length of the external conductors will be longer so more materials will be needed.

The problem to plot this quantities against the angle α is that it is not immediate to see it, it is necessary to calculate it from some geometrical measures, can be useful to look also at then dependence of these quantities to the length of the pitch, this is the same as did before with the twist angle because these two are correlated, but from the following pictures it is possible to see the value of the magnetic flux density and the polarisation angle directly from a quantity that is easily measurable:

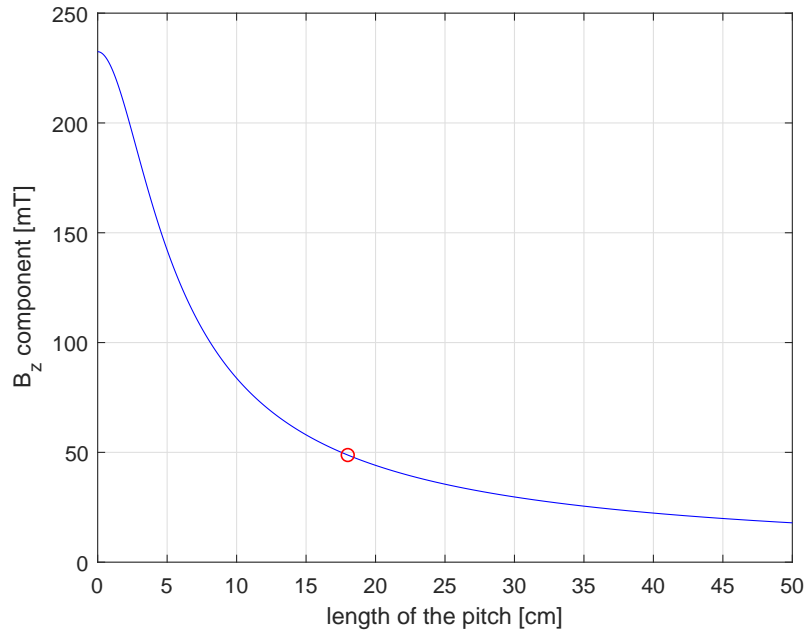


Figure 3.11: Dependence of B_z to the length of the pitch

It is clear that for low values of the length of the pitch it is convenient to make it longer because B_z and θ change a lot for a small change of the x coordinate, instead if we look at the opposite situation (the figures continue until infinity, where there is no B_z component because is the case with straight conductors) it is possible to see that the higher the pitch the more it is necessary to change it in order to obtain a lower magnetic flux density.

A possible conclusion is that if the cable has twisted conductors with a low pitch could be convenient to change the conductors choosing ones with a longer pitch, in this way the z-component of the magnetic flux density in the middle will be lower.

Obviously this conclusion regards only the magnetic point of view, in reality it is necessary to consider also other factors that can change with a different pitch: as an example the structural integrity of the OPGW would need to be considered.

These results refer to a specific current level injected in order to get close to the experimental one, in order to obtain a more general method can be useful to refer the magnetic flux density plot to an unitary current to obtain a B_z value per unit of current:

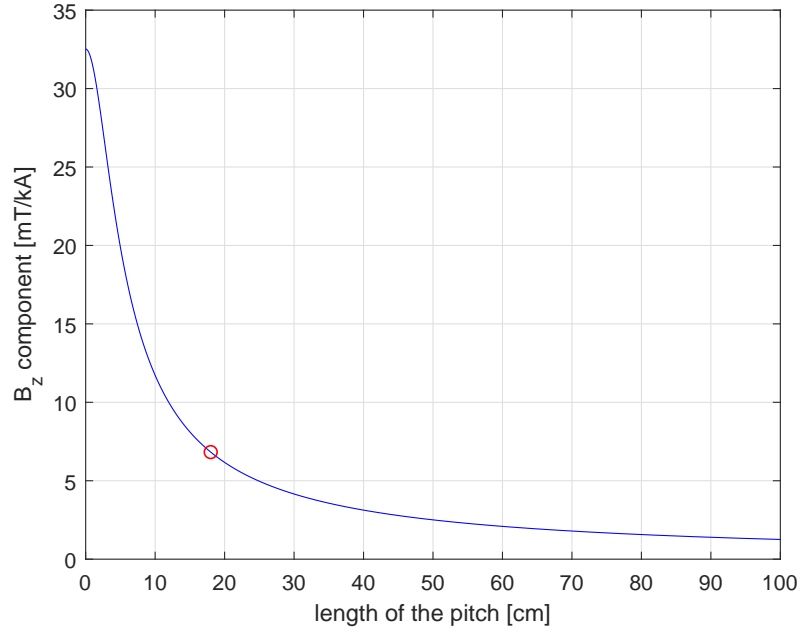


Figure 3.12: Magnetic flux density with unitary current

hence multiplying each point of this curve by the current value needed it is possible to find the correspective value of B_z component for every pitch length of the conductors. Once obtained the polarisation angle it is also possible to calculate the Stokes parameters as well, looking at the Poincaré sphere (Figure 2.11) the following equations are used:

$$S_1 = \cos(2\theta) \quad (3.10)$$

$$S_2 = \sin(2\theta) \quad (3.11)$$

hence for the fact that the polarisation angle θ changes with the pitch, even the Stokes parameters are influenced by this variation and their combination will depend on the α angle chosen; this computation takes into account on the linear Faraday rotation, so S_3 is equal to zero

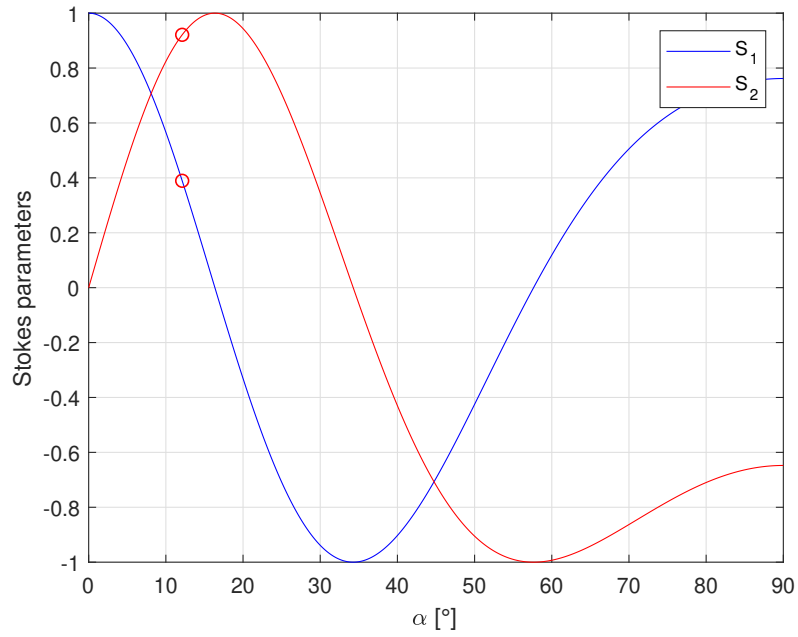


Figure 3.13: Stokes parameters S_1 and S_2

as can be seen for an angle equal to zero corresponds a vector $(1,0,0)$, because this is the case of straight conductors ($\alpha = 0$) so the magnetic flux density has a z-component equal to zero, the consequence is that the Farady effect is null so the electric field will not undergo the Farady effect.

3.6 Double layer cable

The other type of cable tested at the lightning laboratory is the double layer OPGW, the structure of this cable is shown in Figure 3.14

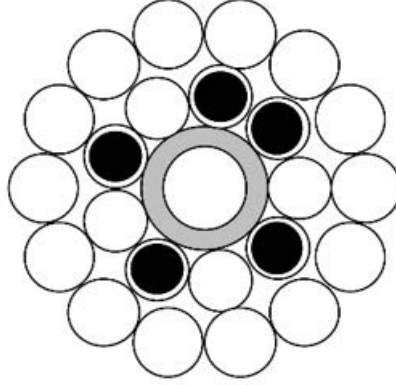


Figure 3.14: Section of the double layer cable

it has two different layers: the inner one has a left handed lay and nine twisted conductors (four of aluminium and five of aluminium clad steel), whereas the outer layer has a right handed lay and fourteen aluminium twisted wires.

The radius are reported in this table:

r_{inner}	$1.5[mm]$
r_{outer}	$1.65[mm]$
$r_{central}$	$3[mm]$

the procedure of the mathematical model is the same as the one for the single layer cable with the difference that this time the external wires have two different pitches, the inner layer has a pitch of $18[cm]$ and the outer layer has a $20[cm]$ pitch; the combination of these pitches and the different lay gives a different z-component of the magnetic flux density in the middle.

Once calculated the distance of each layer from the central point of the cable it is sufficient to repeat the same calculations of the previous computation, the main hypothesis is the uniform current distribution between the two layers: the current is divided equally between the layers. In order to get comparable results I have injected the same total current as in the single layer computation ($10[kA]$), with this new study it is sufficient to consider one layer at time at the sum the results using the superimposition of effects.

Hence the inner layer gives a contribution of:

$$B_z = \frac{\mu_0 I}{2\pi R_{in}} \cdot \sin(\alpha_{in}) = -32.35[mT] \quad (3.12)$$

where

- D_{in} is the distance between the inner layer and the center of the cable, it corresponds to $r_{central} + r_{inner} = 4.5[mm]$
- α_{in} is the geometrical angle that corresponds to a $180[mm]$ pitch: $\alpha_{in} = atan\left(\frac{2\pi R_{in}}{180}\right) = 8.9^\circ$

the negative sign of the magnetic flux density is due to the left handed lay, it creates a B_z component that goes in the opposite direction.

With the same calculations are found the results for the outer layer, they are reported in the following table

B_z	$28.65[mT]$
R_{out}	$7.65[mm]$
α_{out}	13.51°

now simply adding the two quantities it is possible to find the total contribution of magnetic flux density:

$$B_{zTOT} = -3.7[mT] \quad (3.13)$$

a small value of B_z is reasonable because the layers generate magnetic flux density in opposite directions, but at the same time it is important to remember that the main role in this cable is taken by the current distribution: the layer with the bigger amount of current will impose its effect on the other layer; in this study was assumed an equal division between the layers for ease of computation, therefore in this model, even more than the single layer one, the current distribution plays a crucial role and without knowing its behaviour it is very difficult to get close to a real result; a step further will be taken when it will be possible to measure the magnetic flux density within the cable in order to have a comparison with the simulated models.

Another step is to analyse the influence of α angle on the magnetic properties, as done with the single layer cable. This time is not as easy as the previous cable for the fact that now there are two different pitches, so it is no possible anymore to change only one of them or consider the same length for both pitches. One possibility could be to keep fixed either the outer pitch or the inner one and see the results in a 2D plot as in the single layer cable, but in this way we are not considering all the cases because both of the pitches need to change in order to find a general plot that can depict the total range of possibilities.

Hence for each value of α_{in} it is necessary to calculate the B_z component for all the values of α_{out} , this is possible in Matlab and the final plot will be a 3D surface, in which the x and y axis represent the two geometrical angles and the z axe contains the B_z value.

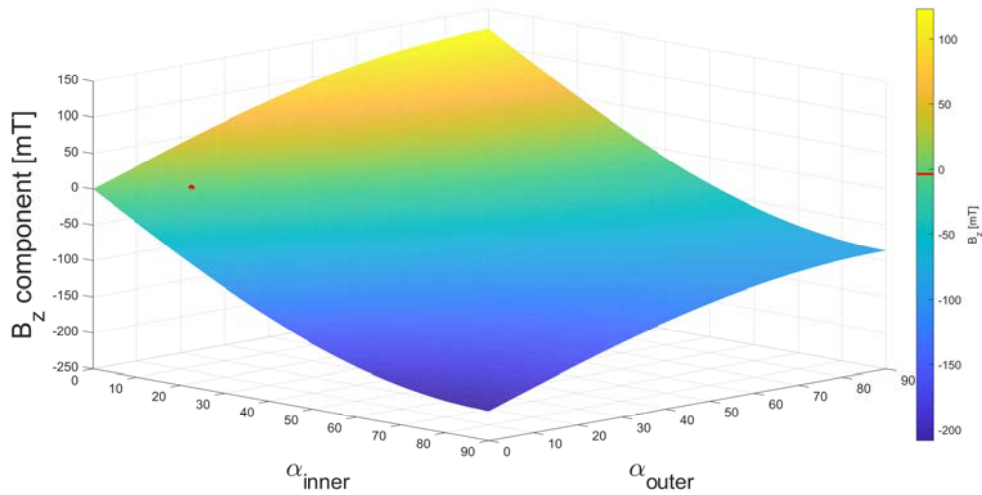


Figure 3.15: Influence of α on the double layer cable

As before the red point represents the situation of the real cable, so the point in which $B_z = -3.7[mT]$ with the current distribution discussed before (evenly split between the layers).

This plot is valid only for the current distribution adopted, for a different distribution it will be different: the more current flows in the outer layer the more positive will be the z-component of magnetic flux density in the middle, vice versa in the case that the major quantity of the current flows in the inner layer.

Chapter 4

Modelling

4.1 Introduction

In this chapter the set of models used to simulate the OPGW cables tested at the Morgna-Botti lightning laboratory will be presented, the main difference between the beginning models and the last ones is the current distribution: the first ones have an uniform current distribution as the input, uniform from the point of view of the distribution along the wires, it means that, even if the current changes during time (in the models with a time-dependent study), all the wires will have the same value of current for each instant; this is obviously not true but it is a good starting point in order to simplify the problem. On the other hand in the last models the current is not the same in each wire but was made a difference between the aluminium wires and the aluminium clad steel wires: using the results on the current distribution obtained with the previous tests at the lightning laboratory was possible to inject a better current in the models, more details about this will be given further on this chapter.

Is is important to highlight that *uniform* or *non-uniform* stand for the spatial distribution of the current along the different wires, they do not mean that the current is constant during the time (in fact only the model used to verify the analysis results has a constant current).

Hence the best approach at the beginning was to start from the models described in [2] trying to modify the setup for a more real case. Basically all the models of this chapter have two different approaches regarding the type of study adopted:

- Stationary study, simple or with a parametric sweep

- Time-dependent study

Before to describe the features of the models will be presented a list of common factors that could be useful for the future develop of next models.

4.2 Modelling problems

During the creation of the models in Comsol few problems came out, this section has the aim to list them and to try to give an explanation for the future works. The following list presents a summary of all this problems:

- electrical conductivity σ_{air}
- helix tool
- narrow regions
- definition with long length

The first problem is about the electrical conductivity of air, its default value in Comsol is $0[S/m]$ but in order to avoid problems of having zero on the matrix diagonal this value should be setted very low and closer to the reality (like $10^{-14}[S/m]$). Unfortunately this can't be done in both frequency and time-dependent study, the minimum value to avoid errors during the computation is $10^{-3}[S/m]$. This could be due to the large order of difference between the current injected and the displacement currents, but a wrong value of *sigma* brings to a wrong value of these currents. To evaluate this potential problem it is sufficient to observe the result in Figure 4.1.

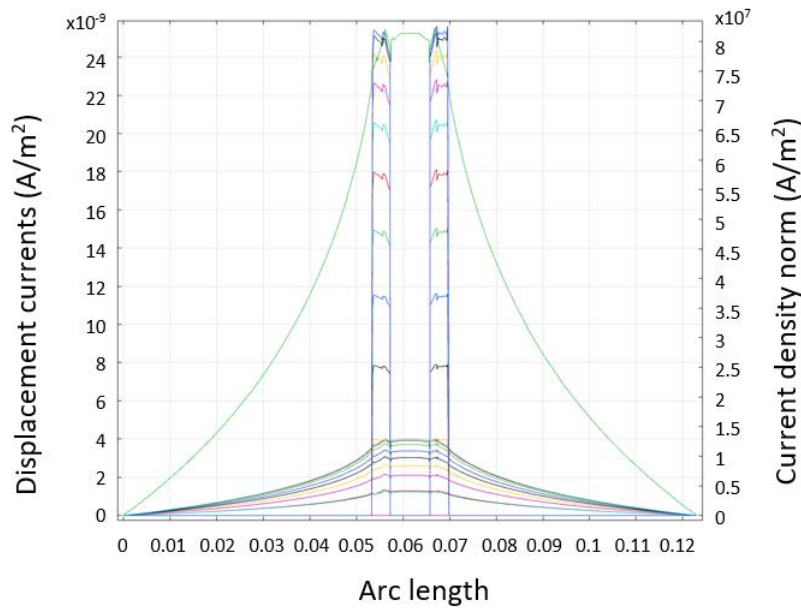


Figure 4.1: Injected current and displacement currents with $\sigma = 1[S/m]$

Even if the electrical conductivity was set to 1 it is possible to see that the displacement currents are very small compared to the injected current because there are twelve magnitude orders of difference between them, hence it is possible to keep $\sigma_{air} = 1$ for ease of

modelling.

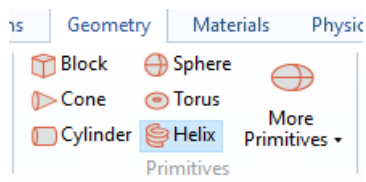


Figure 4.2: Helix tool in Comsol

With the new version of Comsol Multiphysics the helix tool is introduced and it allows to easily draw the twisted wires around the central conductor, but there is a problem: the default setting for the end caps is *Parallel to axis*, instead we need them to be *Perpendicular to axis*. Changing this feature an approximation at the extremities of the helix is introduced and this will cause a worse shape of the magnetic flux density z component. In order to avoid this problem the classical approach with a *Normalized arc length sweep* was used.

Figure 4.3 depicts the cross sections of the two type of OPGW used at the lightning laboratory, as it is possible to see all the wires are in contact and try to replicate this in Comsol using its own drawer is very tough: the precision of this drawer is not very high so a geometry error will be generated after the attempt to build all the structure. To

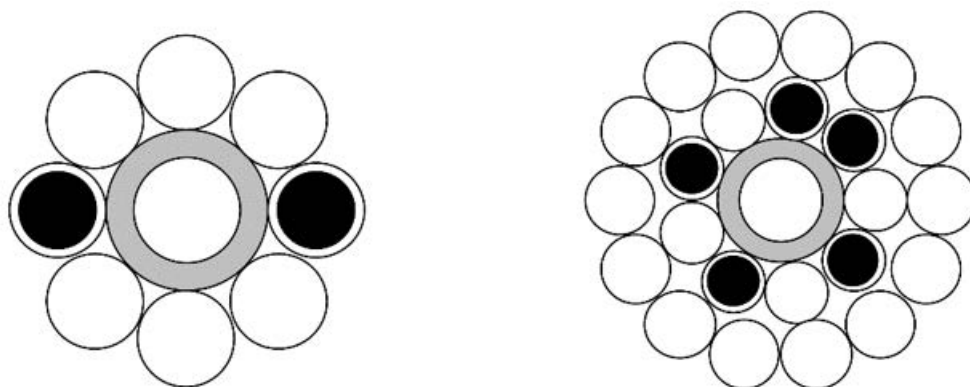


Figure 4.3: Section of the optical cables [9]

avoid this problem a simplification was made removing the central conductor, since we are interested in the magnetic flux density in the middle this can be accepted. Thanks to this it was possible to build the geometry of the model (Figure 3.5), the small circles between the different wires have no geometrical meaning, they were required to get a better mesh in those regions. Hence where should there be air they are made of air, instead within the wires they are made of the same material of the wire.

The last problem is about the bad definition of elements with a relative length, the helix

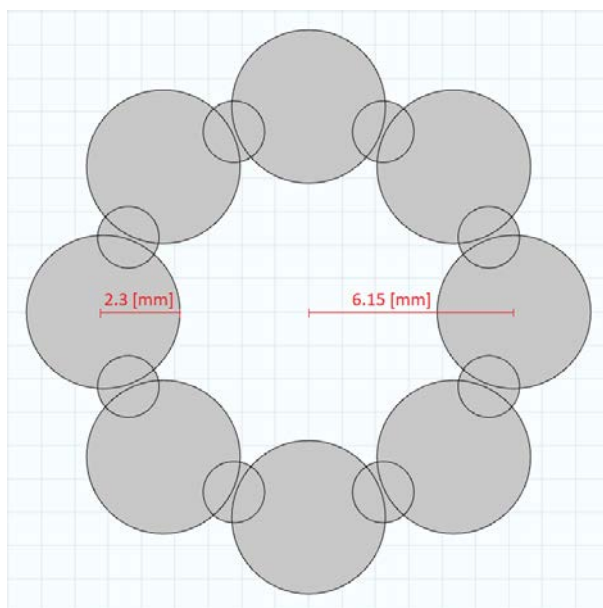


Figure 4.4: Work plane in Comsol

repeats itself every 18[cm] but the major and minor rays of the helix are only few millimeters; for this reason it is very difficult for Comsol to draw a defined helix of that length because it tends to approximate the curve lines with straight ones. The only solution for this problem is to try to use a shorter length, in fact it was reduced from 18[cm] to 9[cm] obtaining a better result (at 9[cm] the model repeats due to the symmetry of the cable).

4.3 Basic setup for the models

At the beginning the same material and unitary permeability were used for all the external wires, hence the first models gave a z component of magnetic flux density higher than the one calculated backwards from the polarization of the light using the equation for Faraday effect:

$$\theta = \nu B l \quad (4.1)$$

this was due to the unitary permeability, so different studies were tried with different values of permeability $\mu = [1, 10, 100, 1000]$ (Figure 4.5).

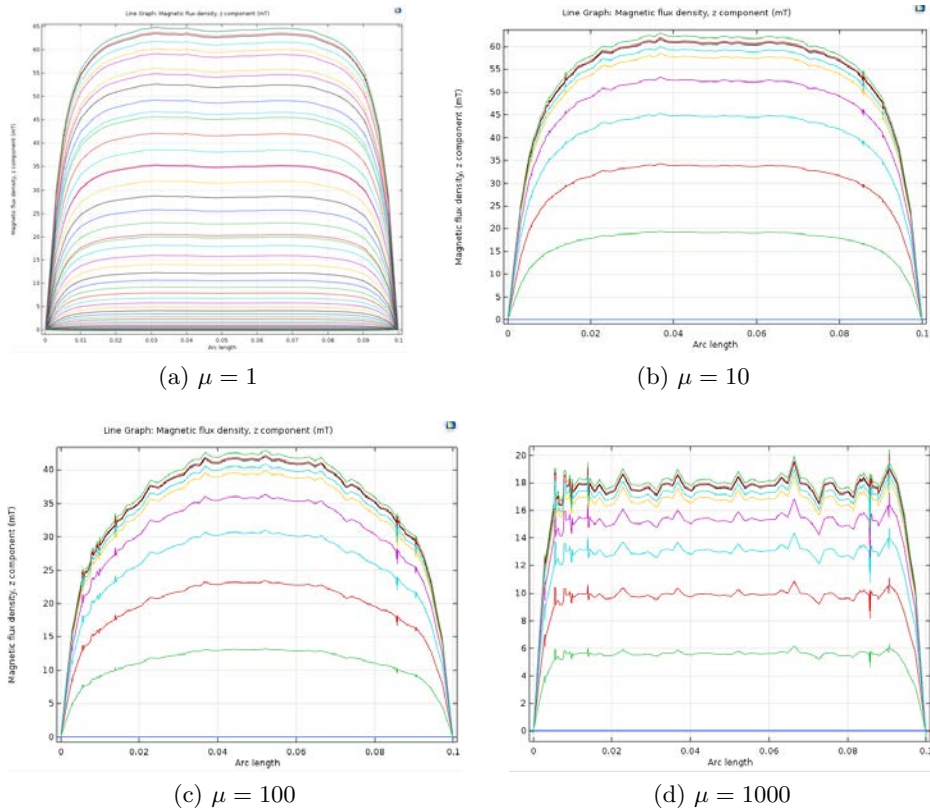


Figure 4.5: Results by the same model for different values of permeability

It is clear that the higher the permeability the lower the B_z component but the higher the noise, hence the mesh has to be made finer with a consequently longer computational time. The improvements due to a better mesh are depicted in Figure 4.6.

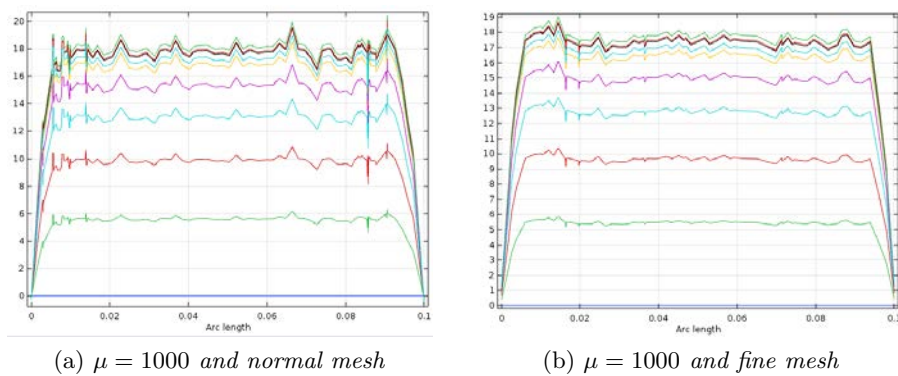


Figure 4.6: Differences on the noise amplitude with different meshes

But these were only some tries to see the how the permeability affects the noise, once we got the right value ($\mu_{clad} = 300$), it was set in the model as a fixed value and afterwards, in order to obtain a clean result, a very fine mesh was created; obviously the model had to be uploaded into the supercomputer to get a solution in reasonable time.

The next step is to inject a current with a correct shape, near to the experimental one, below all the types of current waveform used as the input in the Comsol models are described: obviously at the beginning an easier current waveform was used and then afterwards I started to search for a better current shape, the aim was to go as near as possible to the current that was injected in the experiments at the Morgan-Botti lightning laboratory.

Briefly the types are the following:

- constant current:

is the simplest one, was used for the models with only a stationary study, hence the current at each time is always the same and equal to the peak of the experiment one ($\approx 10[kA]$). Basically the only goal of this current was to verify the first math computations, so an easy and fast model was required.

- sine waveform:

used in the following step, the idea was to inject a current as a sinusoidal waveform with a peak value of $10[kA]$ and a period of $200[\mu s]$, in this way the semi period is equal to $100\mu s$ and the positive part of the sine lasts as long as the sampling time of the experiment currents. Hence this current is like:

$$I = 10^4 \sin(2\pi ft) \quad (4.2)$$

even if this current is better than the constant one it is still far from the real current, also because the raise time is equal to half of the period. With this type of approach a frequency domain study is required in Comsol.

- double exponential curve:

since the sine waveform is very far from the experimental points a double exponential approach was used. The equation is the following:

$$I = K(e^{-A \cdot t} - e^{-B \cdot t}) \quad (4.3)$$

in which the coefficients K , A and B are from the experiment data.

This waveform guarantees with a good precision the same shape as the experimental one but the negative part is still missing. This negative part is very important because it means that the magnetic flux density has an opposite direction in that period of time, hence another try was required.

- damped sine waveform:

to solve the last problem of the double exponential waveform a damped sine curve was the solution:

$$I = Ae^{-\lambda t} \sin\left(\frac{2\pi t}{\omega}\right) \quad (4.4)$$

using this formula a simple Matlab code was set in order to obtain A , λ and ω with a try and error procedure. The final result fits very well the experimental trend, for this reason this current has been chosen as the input for a comparison with the model that takes as input the sampled points from the experiment data.

- data from the experiments:

this is not properly an equation, it is an array of point measured in the Lightning Laboratory and afterwards reduced at 20 in order to have a reasonable computational time in Comsol.

The Figure 4.7 depicts all the cases discussed above, so it is possible to see how much near each current waveform is respect to the measured one.

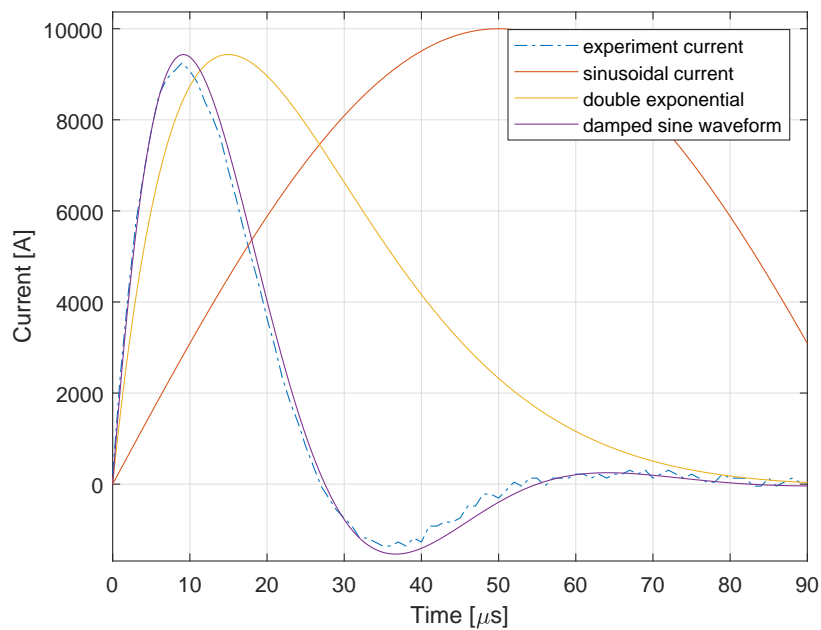


Figure 4.7: Different currents used

Considering the double exponential curve (but it is the same for all the others currents), a uniform current distribution was assumed, in each wire hence there is $\frac{1}{8}$ of the total current, this correspond at the following waveform:

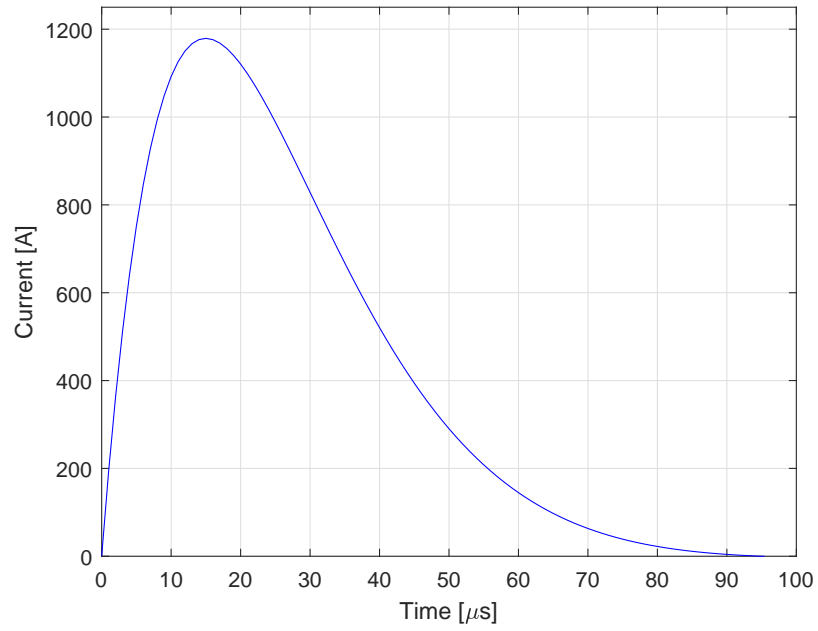


Figure 4.8: Current injected

4.3.1 Verification of the first setup

Then some analysis were made in order only to verify the model done so far, with the aim to see if the model responds as we aspect.

The Ampere's law suggests there should be a linear relationship between B and the current, so a simple parametric sweep was used changing the value of the current injected and evaluating for each iteration the flux density:

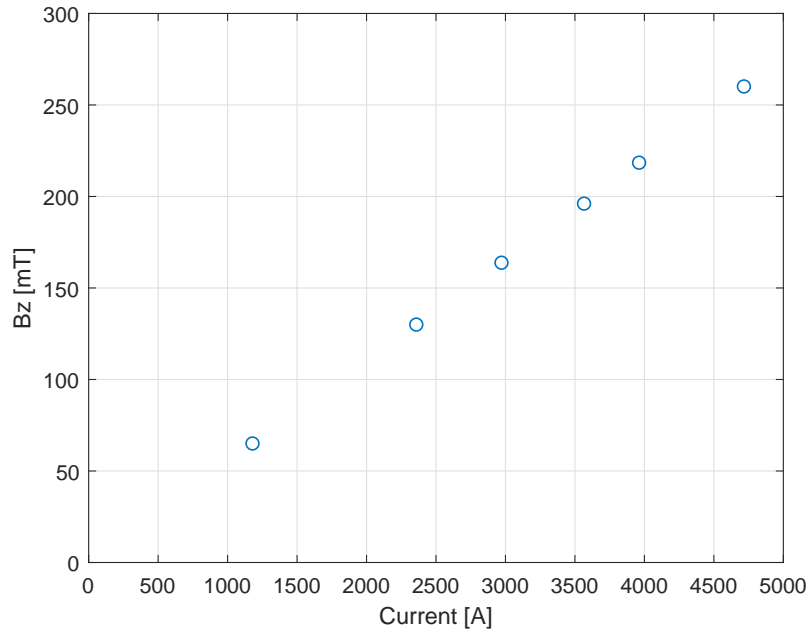


Figure 4.9: Linear relationship between Bz and the current

as it was expected, there is a linear relationship between the peak value of the current and the value of the z-component of the magnetic flux density in the middle of the cable, in Figure 4.9 there are some tries with the current within the range from starting from $\approx 1.2[kA]$ up to $\approx 4.8[kA]$. Another question was if the magnetic flux density has some delay respect to the current, but whether we exclude the possible tiny delay due to the measurement instruments B and I should be in phase. In fact plotting the Bz component along the central line of the cable over time it is possible to see that it follows perfectly the current, with a peak value of $35.04[mT]$:

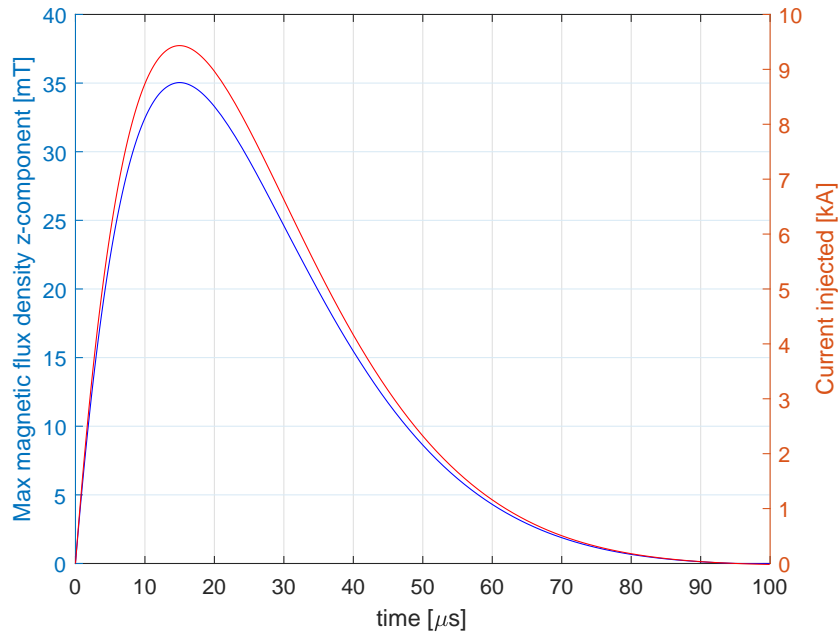


Figure 4.10: B_z component over time

Also different cases have been analyzed varying the rise-time of the current waveform in order to see if it has some influence on the value of the magnetic flux density. As can be seen in Figure 4.11 the magnetic flux density follows the current even if the rise time is different, this is due to the linearity of the model with the current. The higher value of the last case is only due to a different value of the current peak that was slightly higher than the others.

For a better figure only the magnetic field components are depicted, if also the current waveforms were in this figure they would be in phase with their corresponding flux density; the sine waveform has a peak slightly higher only because the sine had a peak of $10[kA]$. All of this above were plots of the maximum B_z component during time, but looking at the B_z component along the space (the imaginary line within the cable in its middle point) it is possible to see that at the extremities the magnetic flux density is zero (for example in Figure 4.5); this is due to the fact that Comsol forces the value of the current at zero on the starting and ending points of the cable, one last try was made in order to see if it is possible to make Comsol see the cable as an infinite length one, in this way it is possible to see a constant value of the magnetic flux density all over the cable. For this purpose a stationary study was set up and uploaded to the supercomputer with a very fine mesh to obtain a good result.

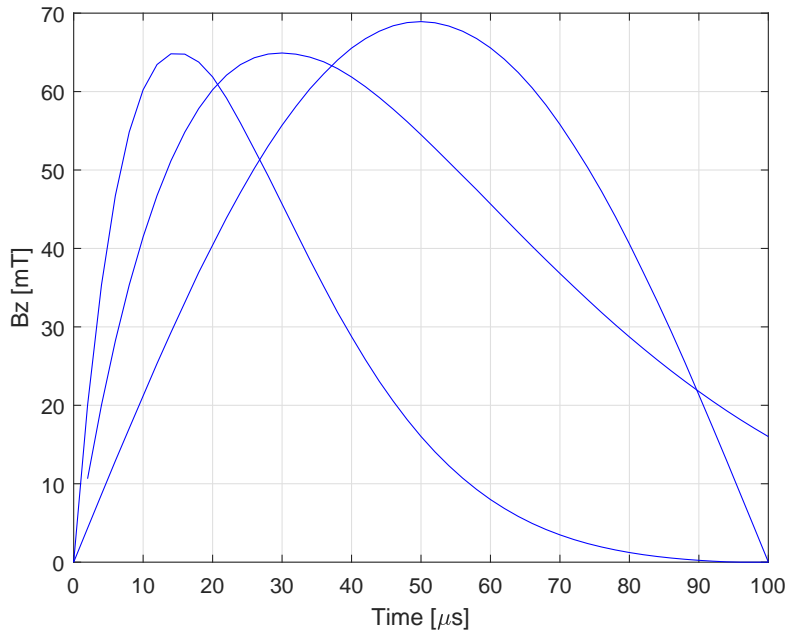


Figure 4.11: B_z for different rise times

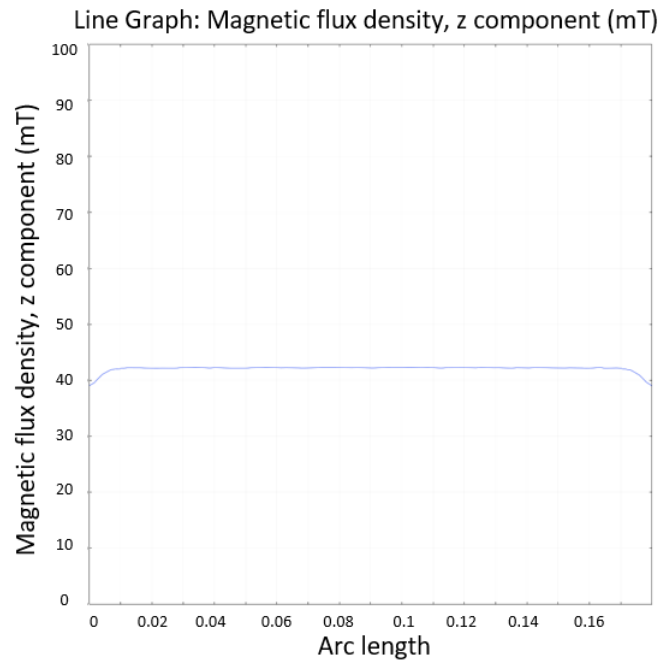


Figure 4.12: Magnetic flux density with a periodic boundary condition

A *periodic boundary condition* was used in Comsol, this tool allows to define the source boundary and the destination boundary, hence defined these boundaries as in the fig.4.13 it is possible to create an infinite length cable. It was also necessary to add a *Gauge fixing node* in order to obtain a convergent solution.

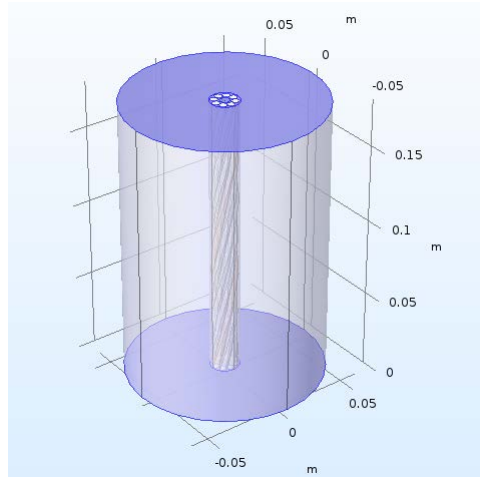


Figure 4.13: Periodic condition in Comsol

Even if the result was the one expected it required a lot of computational time and it was the same to evaluate the B_z component in a straight line inside the cable with a length slightly shorter than the cable itself, in this way was possible to exclude the boundaries from the computation and at the same time obtain a better computational time.

4.4 Uniform current distribution model

The hypothesis of this model is that there is no difference in the currents inside the external wires, hence all the coils in Comsol have the same input and for reason there was no need to define wires of different materials, so the whole cable is made of aluminium. This setting has been used for all the first models because it is quite simple and it doesn't require a lot of efforts to build eight equal coils. But this simplicity has a negative consequence: the situation analyzed is far from the reality, for sure the permeability factor of the aluminium clad steel wires is one of the main properties that change the current distribution and the magnetic flux density strength; considering an unitary permeability for all the wires will bring to an higher B_z component and afterwards to an higher angle of polarisation (as the Faraday effect equation tells).

Besides the case with a constant value of current, also other cases were studied, starting from the sinusoidal current as discussed earlier in this chapter, hence now there is a list of result that came out from the model injecting those specific currents:

the first one is a time dependent model that simulates the sinusoidal current

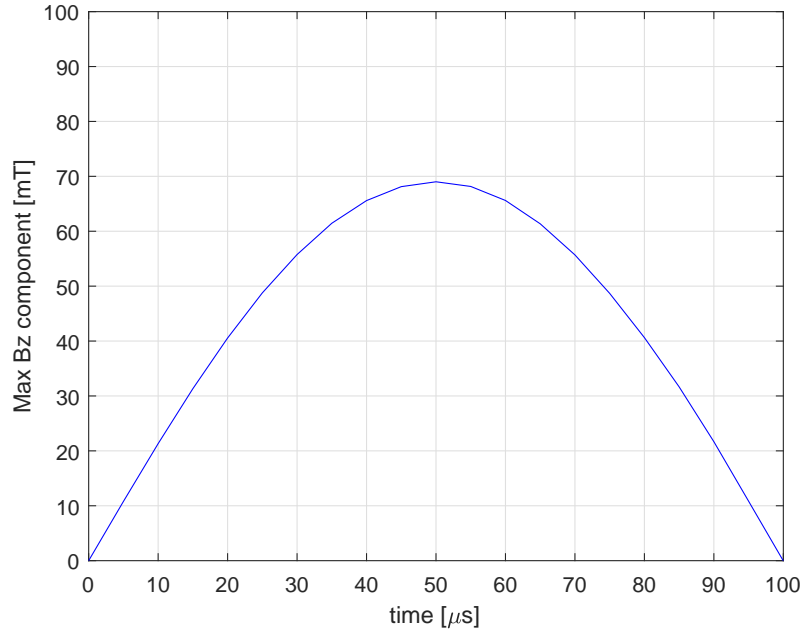


Figure 4.14: Maximum B_z component during time

as expected the maximum value of magnetic flux density during time follows perfectly the sine waveform, the Figure 4.15 depicts instead the spatial behaviour of this component.

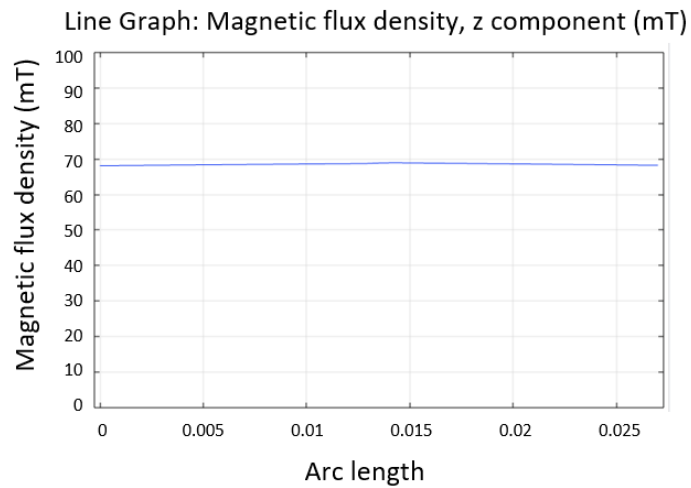


Figure 4.15: B_z component along the cable

It is possible to see the relatively high value of magnetic flux density, this is due to the fact that this model has an unitary permeability.

Moving on with the cases a better current waveform was used, this time the model has as input a double exponential curve and moreover a differentiation on the wires as follow:

- 6 aluminium wires with $\mu = 1$
- 2 aluminium clad steel wires with $\mu = 300$

for this reason it is possible to see that now the magnetic flux density has a lower peak.

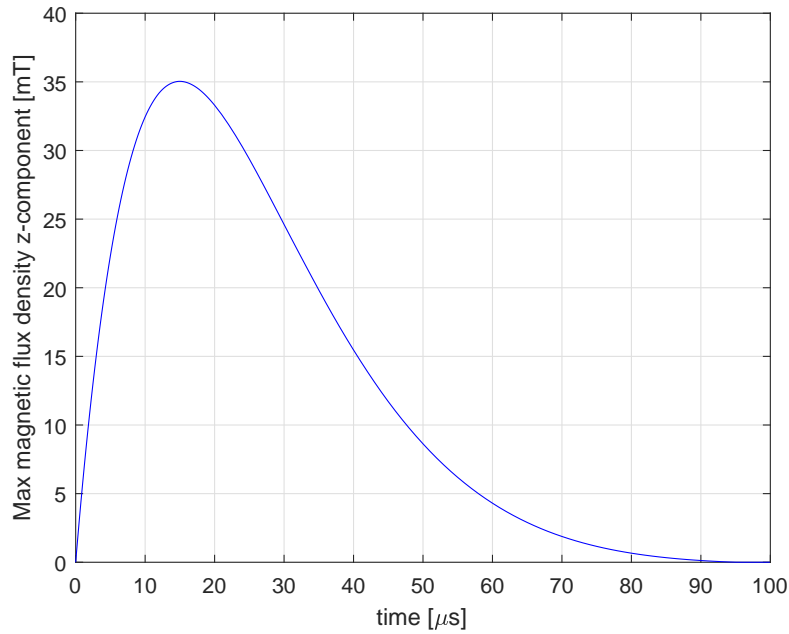


Figure 4.16: Maximum B_z component during time

Looking at this result and comparing it with the one that has the experimental currents it is possible to see two main differences: first of all here is missing the negative part of magnetic flux density and also the peak occurs at $\approx 15[\mu\text{s}]$, instead as it will be shown the currents injected at the laboratory have the peak at $\approx 10[\mu\text{s}]$; this seems to not have a big relevance but for the future study, where will be taken into account also the interaction between magnetic and electric fields, the $\frac{di}{dt}$ will be a critical point since the flux depends on it.

Hence the next improvements it to use a damp sine waveform obtaining the remaining features described above, it is possible to see the final current shape in Figure 4.17

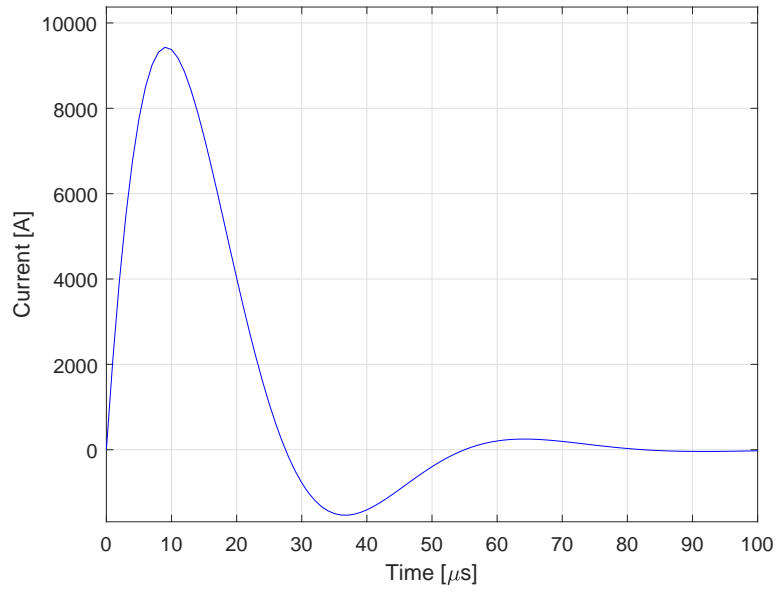


Figure 4.17: Damped sine waveform

consequently the magnetic flux density will follow this trend with the same peak value as before, the following figure depicts the B_z component during time.

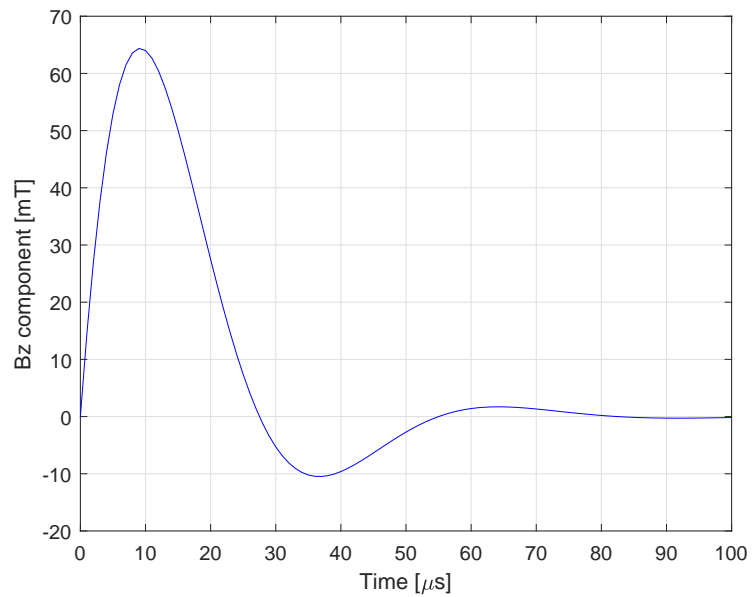


Figure 4.18: Magnetic flux density, z-component

The Figure 4.18 shows the magnetic flux density calculate directly from the current through the Ampere's law in fact the peak value is around $65[mT]$, so it means that it does not take into account about the permeability. To do that a time-dependent model was used obtaining the follow result:

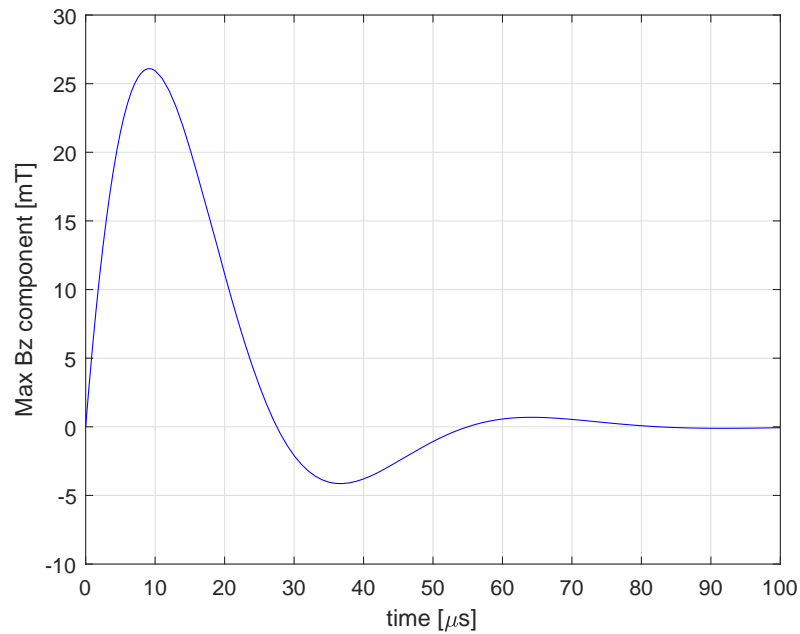


Figure 4.19: Comsol result with damped sine waveform

now the situation is different due to the higher permeability considered for the two aluminium clad steel wires, as can be seen the updated peak value is $26.1[mT]$.

4.5 Non-uniform current distribution model

In the previous models an uniform current distribution was supposed, a step further was taken assuming that in the 6 aluminium clad steel wires there is a different current respect to the other two aluminium wires. Moreover in these tries the input currents are not obtained from an equation but are taken from the measurements done in the Lightning Laboratory, a different current for each wire is not considered yet.

Since the experiment data have a lot of points, Comsol would require long computational time to evaluate the solution for all those points, so only few points will be analyzed (sampled from the whole amount).

From the experiments it is known that if we inject a $10[kA]$ current then the currents in an aluminium wire and in the aluminium clad steel wire are those depicted in the Figure 4.20.

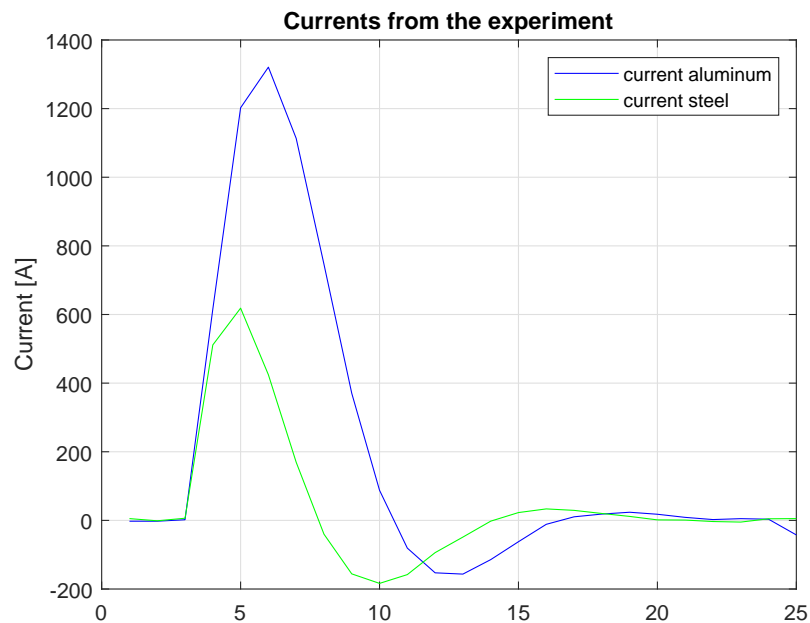


Figure 4.20: Currents measured in the current distribution experiment

These are the main characteristics of the model built:

- stationary study
- parametric sweep injecting the sampled current
- different values of μ ¹
- also different peak values of the current injected

¹only to understand how the permeability affects the magnetic flux density

The parametric sweep allows to simulate the magnetic flux density for each sampled point of the current waveform, different μ and currents can guarantee a good number of results for a better comparison.

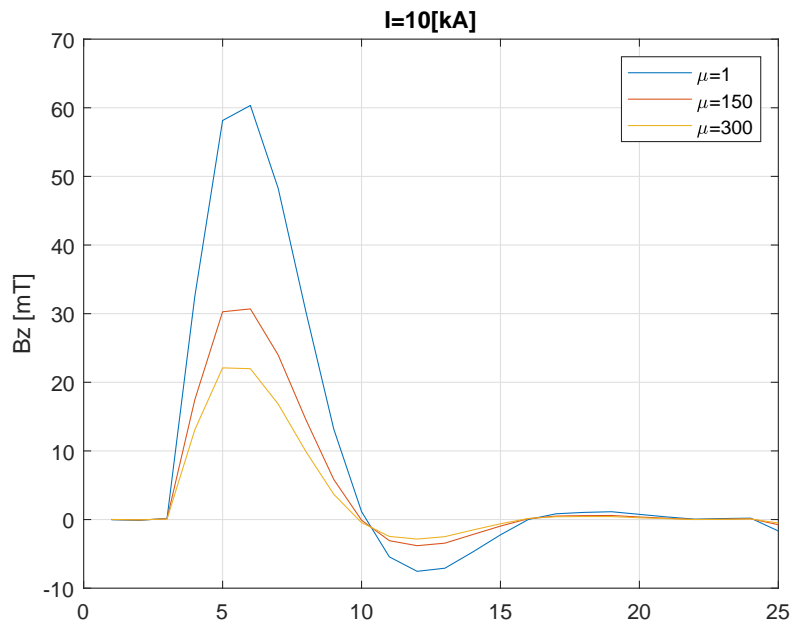
The Comsol model has been developed in parallel with a Matlab model², the main differences between these are that in Comsol is possible to consider a current distributed in a surface instead the Matlab model has punctual currents; moreover the two aluminium clad steel wires in Comsol have the right permeability ($\mu = 300$) whereas in Matlab a unitary permeability for all the wires was considered.

4.5.1 Verification of the results

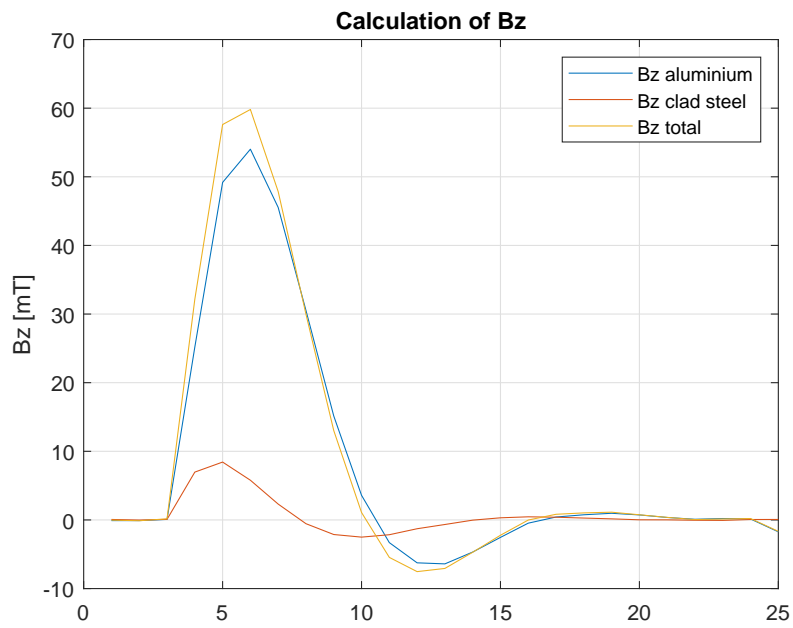
To have a feedback on the values computed from Comsol it is possible to compare those results with the ones calculated in analytical way, obviously it is possible to compare only the $\mu = 1$ case because in the Ampere's law there is only μ_0 . Both the cases have an injected current of $10[kA]$.

As it is possible to see in the next page, there are two main contributions on the magnetic flux density: one due to the aluminium clad steel wires and the other one due to the aluminium wires, decoupling these two effects allows to see the different contributions as is depicted in Fig.4.21b. The total Bz component calculated in the same way as in the math analysis (or simply by adding the two contributions) matches very well the waveform obtained in Matlab with $\mu = 1$ (comparing the positive and negative peaks the largest error is less than 1%).

²developed by Dr Daniel Carr at MBLL



(a) Results from Comsol model



(b) B_z computed with the Ampere's law (Equation 3.3, 3.4)

Figure 4.21: Verify of Comsol results

In order to understand if there is a linear coefficient between the results, two tries were made initially: firstly the one more near to the real case with the correct value of the aluminium clad steel permeability and then also a model with a unitary permeability for all the wires to compare the result with the one from Matlab. In order to reduce the computational time the models of Comsol are calculated in 25 points, instead in Matlab 200 points were analyzed.

It is useful to compare also the results from the experiments with 50[kA] and 110[kA], the model and the simplifications used are always the same. So, considering only the case with $\mu = 300$, it is possible to see the linear relationship of Bz and the current.

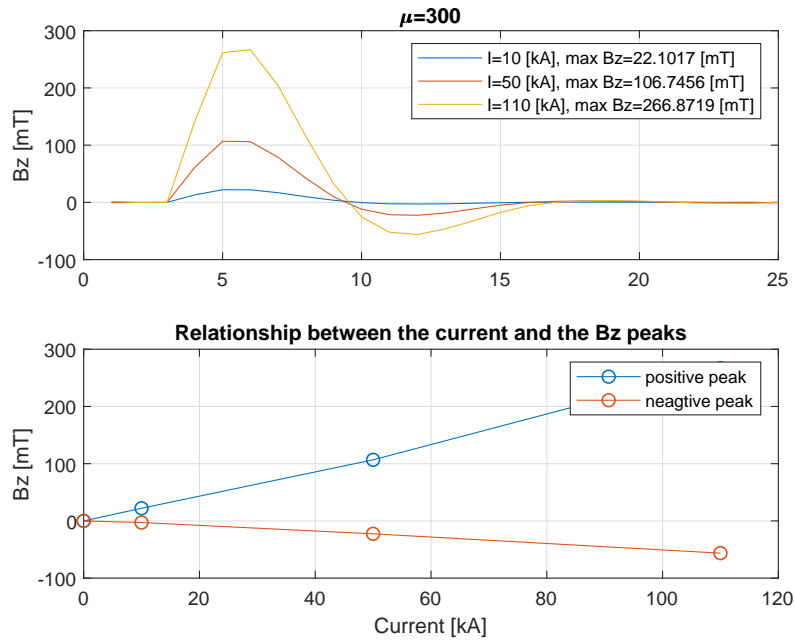


Figure 4.22: Bz waveforms for different current values

The results in Figure 4.22 were expected before to simulate the model because from the theory it is well known that there is a linear coefficient between the magnetic flux density and the current, so even if the current has an opposite sign will be always true that the higher the current the higher the magnetic flux density; it is possible to see this aspect in the figures above, does not matter the sign of the current: the relationship is obviously linear.

In the figure below there is a comparison between the results obtained in Comsol and the one obtained in Matlab:

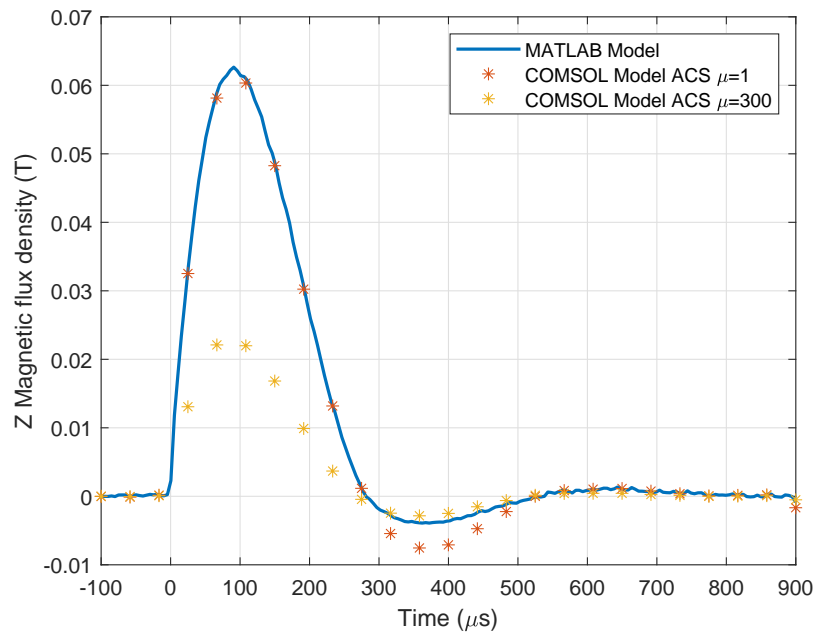


Figure 4.23: Differences between Comsol and Matlab model

4.5.2 Relationship between μ and the Bz peak

From the previous results it is clear that the relationship between the permeability and the Bz is not linear, if we take a middle value from 1 to 300 then the Bz will not be the middle value of the two previous results; in 4.21a it is possible to see that the Bz waveform corresponding at $\mu = 150$ is closer to the $\mu = 300$ than to the $\mu = 1$.

Only to have an idea on the effects of the permeability it is interesting to set up a parametric sweep that will repeat the same study as before but for different values of permeability. The final purpose would be to find a coefficient that can convert the results from Matlab ($\mu = 1$) into the proper $\mu = 300$ for this current level case.

Changing the permeability of the aluminium clad steel wires affect the magnetic flux density in the middle that will be reduced, this is due to the higher μ than the vacuum one; hence the magnetic field lines will be more concentrated in the two aluminium clad steel wires with the consequently decrease of the B_z component in the middle of the cable.

The result of this computation has been exported and then using the Matlab *curve fitting app* it is possible to find the equation of a polynomial that fits the data calculated, in the following figure there is the result:

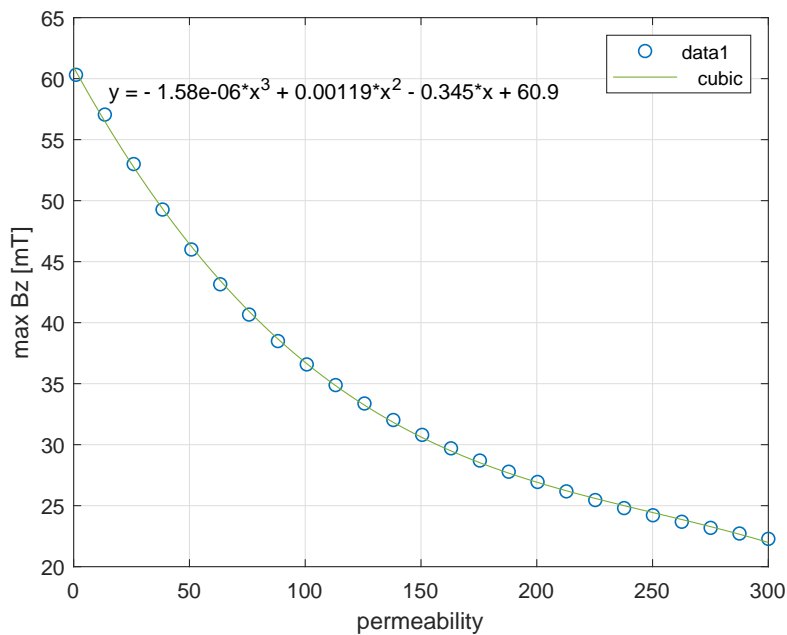


Figure 4.24: Relationship between Bz and the permeability

the blue circles are the points evaluated in Comsol for different values of permeability, the green line is the fitting polynomial. This fitting equation works only for the $10[kA]$ case because as soon as we change the current, also the magnetic flux density for $\mu = 1$ will change, hence the curve will not pass anymore to the point corresponding at $60[mT]$. For this reason will be necessary to consider the relative difference of B_z , in this way the

problem will be avoided as is possible to see in the next section.

The figure above depicts only the behaviour of the maximum Bz value, but obviously the permeability has a correlation with all the others values of Bz as well. Hence in the fig.4.25 is depicted the behaviour of the minimum value of Bz.

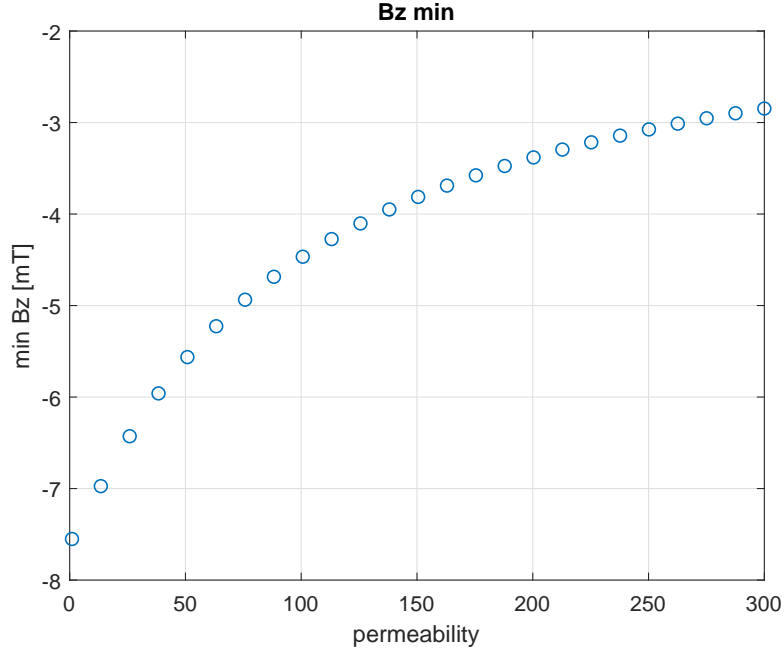


Figure 4.25: Behaviour of Bz_{min} values

To see if the results are similar it is necessary also in this case to think in relative terms, so for example a possibility could be to calculate the difference between the start and the end point respect to the start value:

$$\Delta B_{max_{rel}} = \frac{B_{max(\mu=1)} - B_{max(\mu=300)}}{B_{max(\mu=1)}} = 0.6306 \quad (4.5)$$

$$\Delta B_{min_{rel}} = \frac{B_{min(\mu=1)} - B_{min(\mu=300)}}{B_{min(\mu=1)}} = 0.6230 \quad (4.6)$$

these values (that are in relative terms) are very close, the difference could be due to the mesh of the Comsol model; moreover if we look at all the values of permeability it is possible to see that the trends are the same:

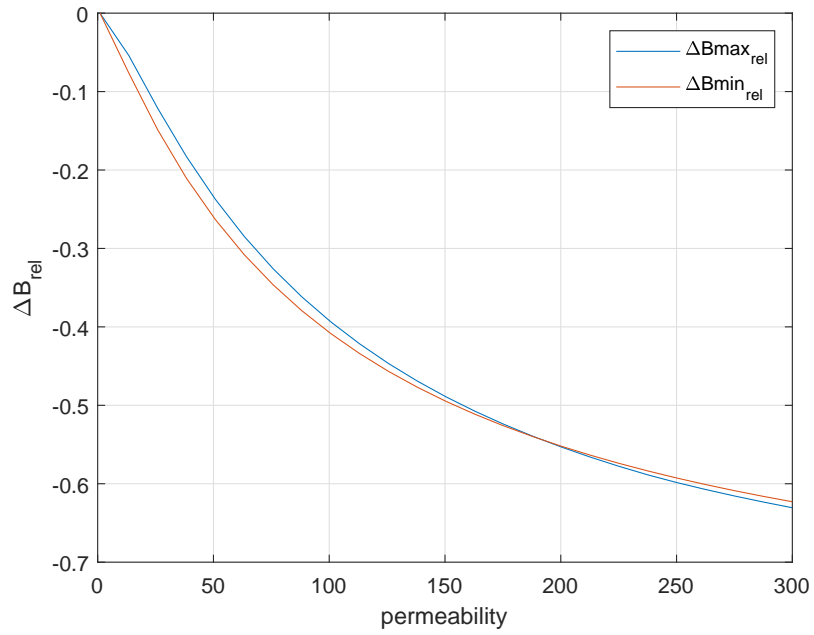


Figure 4.26: Relative trends of max and min Bz values

and this is what was expected because looking at the Ampere's law the magnetic flux density is linearly connected to the current, so the negative sign does not affect the magnitude of the relative loss.

4.6 Correlation between the Comsol and Matlab models

Another important aspect of this thesis was to try to define a relationship from the Comsol results to the Matlab ones that are calculated with a permeability $\mu = 1$, for the fact that the $B_z(\mu)$ is not a linear function it is necessary to study its behaviour. The aim of this study is to try to get a coefficient that can convert the result with unitary permeability into the one with the right value of permeability, once obtain this coefficient could be enough a quicker Matlab computation converted afterwards with the right value of permeability. Hence a parametric sweep was defined with the following features:

- different currents between aluminium wires and aluminium clad steel wires
- stationary study
- parametric sweep for the permeability (only two steps: $\mu = 1$ and $\mu = 300$)
- parametric sweep for the currents

the idea is to take the peaks current in the wires for the 10[kA] case and then for the 110[kA] one, once done this it is sufficient to determine a fixed number of points within these extremities and the two parametric sweeps will go through all the current values for each permeability value.

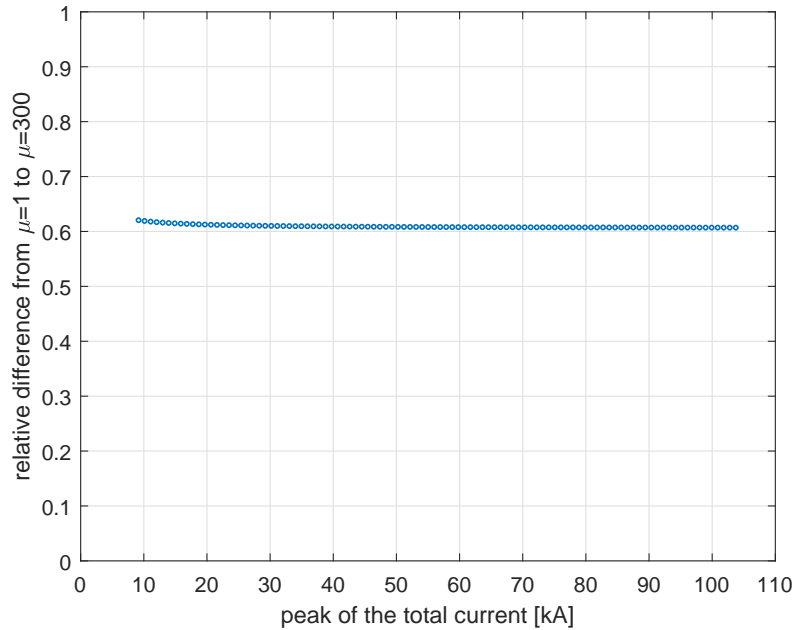


Figure 4.27: Relative loss of B_z

The results from Comsol have been elaborated in Matlab and at every step the script computes the relative difference between the B_z with $\mu = 300$ and the B_z for $\mu = 1$ (4.5).

This relative difference tends to decrease very slowly for higher current values, however we can consider the average value to obtain a valid approximation of this trend:

$$\Delta B_{rel_{avg}} = 60.9\% \quad (4.7)$$

it means that passing from unitary permeability to $\mu = 300$ the magnetic flux density decreases of about sixty percent.

All this results were obtained under a first hypothesis very rough: was supposed that the peak of the current in the aluminium wires happens in the same time of the aluminium clad steel one, this is not true (as can be seen in Figure 4.20). In order to obtain a better result a second approach was taken: it is based on the same Comsol model as the previous one but this time three different points are considered, to better understand the setup it is useful to look again at the waveforms injected:

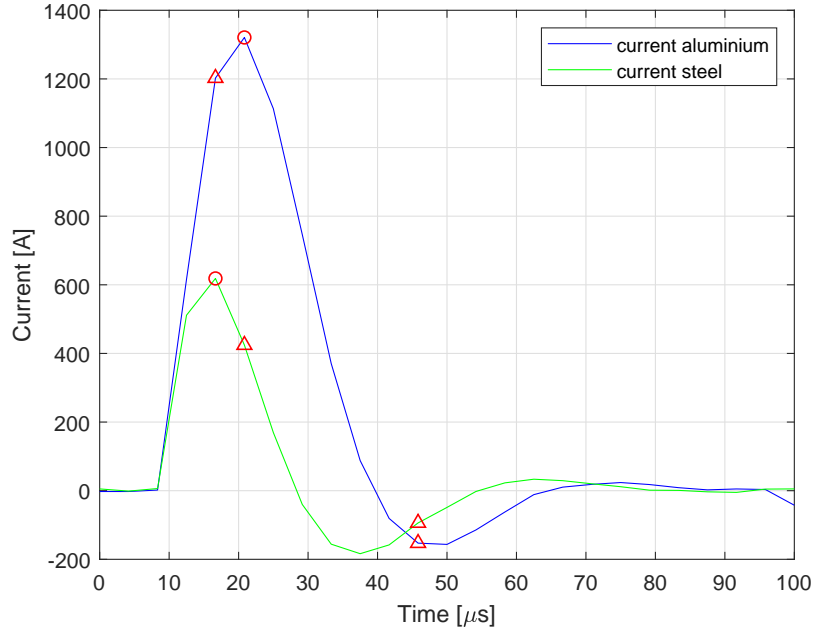


Figure 4.28: Points analyzed

in this case the couples of points taken into account are the circles and the triangles depicted in red in the figure, the first two circles are respectively the peak of the current in the aluminium clad steel wires and the one in the aluminium wires, for each of these circle also the corresponding triangle in the other waveform is considered. In this way we have setted two points in the total current waveform (where $I_{tot} = 6 \cdot I_{Al} + 2 \cdot I_{steel}$), the third point is found with the opposite process: instead of take two points of the currents in the wires and than find the total one, this time the minimum point of the total current is considered (it is not possible to see it in the plot for the different scales) and afterwards it is possible to obtain the two values of current in the wires that give that minimum peak.

Now the situation is better because we are not assuming anymore that the peaks of current in the wires occur at the same time, but it is still present the hypothesis that from the low values of current to the high values there is a linear relationship in the waveforms: this was assumed to obtain the parametric sweep in Comsol, it starts from the first couple of points for the 10[kA] case and it goes up to 110[kA] with linear steps.

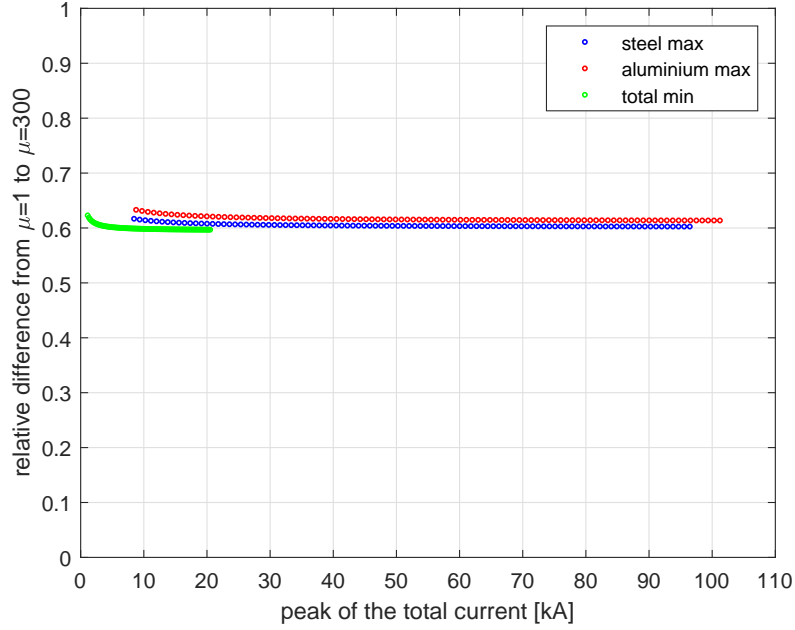


Figure 4.29: Relative loss of B_z for three different points

In this figure the blue points represent the first point analyzed, hence the maximum current in the aluminium clad steel wire and the corresponding point in waveform of the aluminium wire; the red points represent the opposite situation: maximum current in the aluminium wire and the corresponding value on the other current waveform; finally the green points represent the case with the minimum value of the total current.

These three points have slightly different trends but if we look at the average values the results are the following:

- first point

$$\Delta B_{rel_{avg}} = 60.5\% \quad (4.8)$$

- second point

$$\Delta B_{rel_{avg}} = 61.7\% \quad (4.9)$$

- third point

$$\Delta B_{rel_{avg}} = 60\% \quad (4.10)$$

and then taking the average value overall:

$$\Delta B_{rel_{avg}} = 60.7\% \quad (4.11)$$

hence it is possible to utilize this correction factor to pass from the results with unitary permeability to the ones with $\mu = 300$, obviously it is necessary to take into account that ΔB_{rel} is the amount of magnetic flux density lost, so will be necessary to multiply $B_{z_{\mu=1}}$ by $(1 - \Delta B_{rel})$. Looking at the results from this study has been found that this converting factor is equal to 0.393.

Plotting the magnetic flux density z-component with $\mu = 1$ against the one with unitary permeability it is possible to see a linear relationship well approximate by the coefficient 0.393:

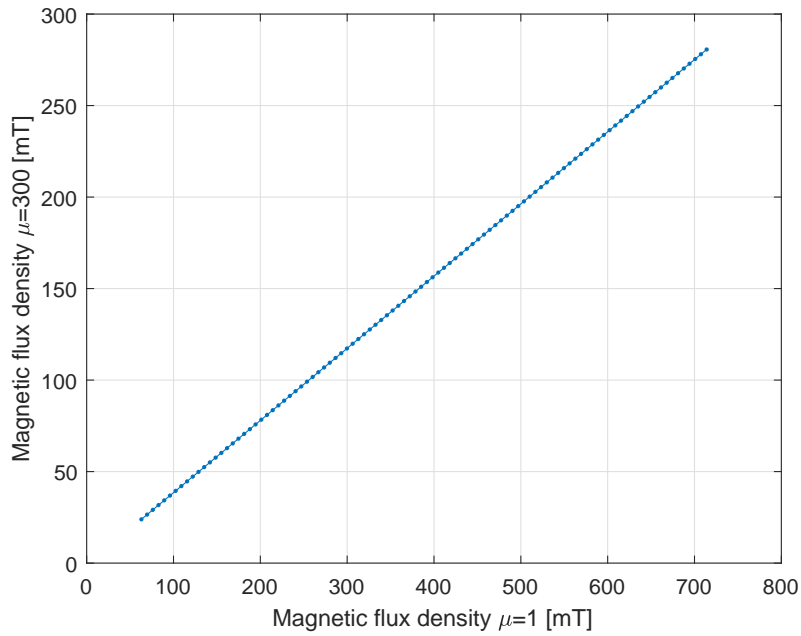


Figure 4.30: Relationship between magnetic flux density

Chapter 5

Conclusions

The main purpose of this thesis was to find a model built in Comsol Multiphysics that could approximate the results obtained from the experiments at the Morgan-Botti lightning laboratory in Cardiff.

The problem was analyzed also from a theoretical point of view, in fact with the mathematical model was possible to compare the results and also obtain a quick estimation about them. At the beginning all the models had an unitary permeability and a $10[kA]$ current injected, moreover the very first model had only one wire twisted around the central conductor, afterwards all the eight wires were considered.

The results of these models are respectively the following:

- mathematical model with one twisted wire: $B_z = 68.3[mT]$
- Comsol model with one twisted wire: $B_z = 69.1[mT]$

instead for the eight wires models the current was divided evenly in all the wires, the analytical result is exact the same because the total current is constant instead the Comsol model has a slightly different magnetic flux density for the different mesh used when all the wires are present:

- mathematical model: $B_z = 68.3[mT]$
- Comsol model: $B_z = 68.6[mT]$

In order to make the approach to the problem easier in Comsol the magnetic fields module was used, in this way we are assuming that the magnetic fields do not have effect from the electrical point of view: when a current is injected in the model, this takes into account only about the magnetic field generated by that current; the currents that would generate in the other wires to contrast the first current are not considered, basically there are no induced currents.

Afterwards the right value of permeability was adopted ($\mu = 300$), hence the B_z component in the middle of the cable is reduced due to the higher permeability of the aluminium clad steel wires: with a current injected similar to the one used at the laboratory the z-component of magnetic flux density is around $26[mT]$.

Every Comsol model has been compared with a Matlab script to see the reliability of the results; obviously Matlab can not consider the right value of permeability, hence computing a model with a parametric sweep on the permeability values was possible to find the relationship between the magnetic flux density and the permeability, which is not linear.

The coefficient 0.393 gives a good approximation about the B_z component at $\mu = 300$, it is sufficient to multiply the result from Matlab by this coefficient to find an estimation of the Comsol model. The principal advantage of this coefficient is the time saving of modelling in Matlab, Comsol requires a long computational time hence using this coefficient it is possible to obtain a good result in a short time.

The geometrical analysis based on the α angle had the aim to find a quick correlation between the geometry quantities and the magnetic properties, finding this correlation is possible to estimate the B_z component and the polarisation angle θ measuring only a simple geometrical factor as the pitch of the twisted wires.

To obtain universal plots they are expressed in per unit current (the θ against the pitch length also in per unit length), hence once found the length of the pitch of a generic cable is sufficient to look at these plots and a quick estimation of the magnetic properties is given. In order to obtain the right value it is necessary to multiply these result by the correction factor that considers also the permeability, as explained above.

With a good model that can simulate the reality could be possible to study the effect of the magnetic flux density in the middle of the cable, even with an optical fiber that it is not only parallel to the direction of the cable but, as in the reality, that is twisted as well; in this case it is important to consider all the components of the magnetic flux density, not only the B_z one.

Future works have to:

- magnetic and electric study in Comsol
- double layer model
- investigation on the current distribution in the double layer cable
- measure the magnetic field in the middle of the cable

Acknowledgements

I want to use few rows to thanks all the people that helped me on the writing of this thesis.

Thanks to the two supervisors that followed me and gave me important suggestions: Professor Manu Haddad from the Cardiff University and Professor Roberto Turri from the Padova University.

Then I also want to show my appreciation to all the researchers and PhD students that I met in this period abroad, a particular thanks to Daniel Carr and Christopher Stone that in the lightning laboratory helped me day by day, thanks to Jonathan Colin James for the help with Comsol, thanks to Maurizio Albano and Michail Michelarakis for the advices at the high voltage laboratory.

A special thanks to all the people that have supported me during the whole university period and in particular during this last experience.

Last, but not least, I want to thank my family for the trust. This work has been possible because you believed in me.

Bibliography

- [1] (2019). Faraday effect. *Wikipedia*.
- [2] Amatruda, M. (2018). Magnetic field characterisation for optical ground wire conductors (opgw).
- [3] Hadjifotiou, T. (2008). Optical fibers. In *The Cable and Telecommunications Professionals' Reference (Third Edition)*, pages 111–144. Elsevier.
- [4] Huang, J., Chen, X., and Xu, J. (2009). Investigation and analysis of an opgw lightning strike incident. In *Proc. 58th Int. Wire Cable Symp.*, pages 389–392.
- [5] Kurono, M., Kuribara, M., and Isawa, K. (1999). Field measurements and a study of transient state of polarization produced in opgw by lightning. *Electrical Engineering in Japan*, 128(4):55–64.
- [6] Massa, N. (2000). Fiber optic telecommunication. *Fundamentals of Photonics. University of Connecticut*.
- [7] Peatross, J. and Ware, M. (2011). *Physics of light and optics*. Brigham Young University, Department of Physics.
- [8] Piantini, A. and Prof Luciano, A. (2008). Lightning protection of overhead power distribution lines. *Proc. 29th Int. Conf. Lightning Protection*.
- [9] Pittalà, F., Stone, C., Clark, D., Kuschnerov, M., Xie, C., and Haddad, A. M. (2018a). Laboratory measurements of sop transients due to lightning strikes on opgw cables. In *Optical Fiber Communication Conference*, pages 4–5. Optical Society of America.
- [10] Pittalà, F., Xie, C., Clark, D., Kuschnerov, M., Stone, C., and Haddad, A. (2018b). Effect of lightning strikes on optical fibres installed on overhead line conductors. In *2018 34th International Conference on Lightning Protection (ICLP)*, pages 1–5. IEEE.
- [11] Saleh, B. E., Teich, M. C., and Saleh, B. E. (1991). *Fundamentals of photonics*, volume 22. Wiley New York.