



UNIVERSITÀ DEGLI STUDI DI PADOVA

CORSO DI LAUREA MAGISTRALE IN INGEGNERIA ELETTRICA

TESI DI LAUREA MAGISTRALE

CRITERIA AND METHODS FOR ASSESSING  
INTERFERENCE BETWEEN HIGH-VOLTAGE  
POWER LINES AND PARALLEL LINEAR  
INFRASTRUCTURES

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ANNO ACCADEMICO 2012-2013



*To my father,  
who always believed in me.*



# Index

Sommario.....	1
Introduction.....	3
Company Presentation.....	5
1. CEI 304-1: description of the Italian standard .....	7
1.1 Wrong and misleading expressions.....	8
2. Inductive Coupling.....	11
2.1 Length of exposure.....	11
2.2 Mutual distances.....	12
2.3 Self and Mutual impedances.....	14
2.3.1 Carson Series form.....	15
2.3.2 Polynomial form.....	16
2.3.3 Carson-Clem form .....	17
2.3.4 Comparison between mutual impedance's expressions.....	18
2.3.5 Relevance of components in Carson Series expressions .....	19
2.3.6 Self impedances.....	22
2.4 Correction factor k.....	23
2.4.1 Correction factor k – Cigrè Guide.....	23
2.4.2 Correction factor k – General Case – CCITT directives.....	26
2.5 Induced e.m.f (steady state condition).....	28
2.5.1 Three phase line, balanced currents, no earthwires.....	29
2.5.2 Three phase line, balanced currents, one or two earthwires.....	32
2.5.3 Three phase line, balanced currents, two earthwires (approximation).....	34
2.5.4 DCSB line configuration, balanced currents, no earthwires.....	35
2.5.5 DCSB line configuration, balanced currents, one or two earthwires.....	36
2.5.6 DCLR line configuration, balanced currents, no earthwires.....	36
2.5.7 DCLR line configuration, balanced currents, one or two earthwires.....	37
2.5.8 Correction factor k4: transposition of the effects of a DCLR to a three-phase line.....	38
2.5.9 HV cables, balanced currents.....	38
2.5.10 Comparison between e.m.f expressions (aerial HV lines).....	39
2.5.11 E.m.f values: comparison between HV cables and HV aerial lines without earthwires.....	47
2.6 Induced e.m.f (fault condition).....	49
2.7 Induced Circuit.....	51
2.7.1 Pipeline series impedance .....	52
2.7.2 Pipeline admittance .....	52
2.8 Induced Voltage.....	53
2.8.1 Pipeline's system.....	53
2.8.2 Impedance's matrix of the pipeline.....	54
2.8.3 Pipeline's circulating currents.....	55
2.8.4 Voltage to ground.....	55
3. Conductive Coupling.....	57
3.1 Ground potential rise of towers.....	57
3.2 Potential transferred to an underground pipeline.....	59
4. Admissible voltage.....	61
4.1 Limitations for danger to people.....	61
4.2 Limitations for danger to pipeline's system.....	61
5. Mitigation.....	63
5.1 Measures applied to the HV line.....	63
5.2 Measures applied to the pipeline.....	64
6. Calculation programs.....	65
7. Application to real cases .....	67
7.1 Inductive Coupling: “Feeder Idrovia Saonara”.....	67
7.1.1 Exposure length.....	67

7.1.2 Inducing power lines.....	69
7.1.3 Induced e.m.f's results.....	70
7.1.4 Induced Voltage's results .....	72
7.1.5 Mitigation.....	74
7.2 Conductive Coupling .....	76
Conclusion.....	79
Appendix A.....	81
Appendix B.....	85
Appendix C.....	93
Appendix D.....	99
Appendix E.....	105
Appendix F.....	111
Bibliography.....	151
Acknowledgments.....	153

# Sommario

Questa tesi è il risultato di un tirocinio in Terna Rete Italia Spa. Lo scopo di questa esperienza è stato lo studio dei criteri e metodi per la valutazione delle interferenze elettromagnetiche tra linee elettriche in alta tensione e infrastrutture parallele, come gasdotti.

Il mio lavoro è iniziato con lo studio della normativa italiana e la comprensione del fenomeno dell'interferenza. È stata fatta un'analisi della norma di riferimento, la CEI 304-1 [1], la quale, riguardo i metodi di calcolo, indica la Guida Cigré [2]: la norma infatti non fornisce precise espressioni, ma si basa su linee guida, in primis la Guida Cigré sulle interferenze.

L'oggetto della mia analisi è stato in particolare lo studio dell'accoppiamento induttivo, nello specifico le tensioni indotte da una linea elettrica su circuiti ad essa parallela, a causa dell'accoppiamento magnetico. A seguito di un'accurata analisi ho individuato delle criticità nelle espressioni della guida, quali errori di segno, convenzione o semplicemente errori di trascrizione, ma anche lacune sui casi trattati: le uniche linee elettriche trattate sono infatti le linee aeree e i cavi trifase in semplice terna, mentre vengono trascurate le linee aeree in doppia terna simmetrica e antisimmetrica. È stato necessario quindi uno studio approfondito sulle direttive ITU (in precedenza note come CCITT) [3], citate dalla norma come riferimento teorico per la costruzione di un metodo di calcolo. Ho appreso, quindi, il metodo "k-factor general", il quale mi ha permesso di riformulare le espressioni della Guida e di formulare nuove equazioni valide per i tipi di linea sopracitati, che non erano contemplati. Ho dunque analizzato i limiti di applicabilità di queste equazioni e costruito un programma Matlab che segue la logica del metodo, ma che può ampliarne l'applicabilità a seconda delle funzioni di base che si scelgono: partendo, per esempio, dalle espressioni della mutua impedenza di Carson-Clem si possono ottenere le espressioni semplici delle forze elettromotrici indotte, utili per un calcolo veloce ma con limiti di applicabilità; basandosi invece sulle relazioni Carson Series o Carson Polinomiale si va oltre i limiti, ma ciò è possibile solo con la costruzione di un programma di calcolo, dato che le equazioni finali sarebbero troppo complesse.

Cercando di ottenere espressioni semplici e adatte a un calcolo approssimato, dal confronto del campo magnetico prodotto da una linea elettrica aerea trifase in semplice terna con quello prodotto da una linea in doppia terna antisimmetrica, ho creato un parametro che potesse semplificare ulteriormente l'analisi con linee in doppia terna antisimmetrica, fornendo in appendice delle tabelle per calcoli veloci.

Per completare l'analisi viene proposta l'analisi semplificata dell'accoppiamento conduttivo, seguendo le indicazioni della Guida Cigré.

Vengono inoltre descritti i possibili interventi di mitigazione illustrati nella Guida Cigré, necessari qualora i livelli di tensioni indotte fossero superiori ai limiti consentiti dalla norma.

Infine è analizzato un caso pratico di interferenza fra un metanodotto e due linee elettriche di futura costruzione da parte di Terna Rete Italia, con una mia indicazione sul possibile intervento da porre in atto per abbassare i livelli di tensione indotta.

In appendice sono presenti degli approfondimenti su alcuni argomenti che vengono trattati nel corso della tesi.

La tesi è scritta in lingua inglese.





# Introduction

The construction of new power lines is strategic for the economic growth of a nation. The modernization of the transmission system is essential to reduce energy losses and ensure a good level of reliability against blackouts. However, this must impact with the territory in the most appropriate way, taking into account the possibility of interference with infrastructures that are critical to the operation of the national system, such as gas pipelines. This interference may be related to induced voltage, and consequently to safety problems (danger for people coming in contact with the metallic pipe), the damage to pipeline coating, pipeline metal, flanges and all the equipment connected to the pipeline.

This thesis is based on methods for assessing cases of interference: my work began with the study of the Italian standards concerning this topic to understand the phenomenon and how it is handled. I focused my study on inductive coupling, which is the electromagnetic interference between two parallel circuits, such as power lines and pipelines, strictly related to the magnetic field generated by currents in HV lines: as far as Faraday-Neumann and Lenz laws are concerned, alternate currents induce in nearby circuits electromotive forces. As a result, parallel pipelines may be affected by induced voltage that can reach the highest value in case of fault in the power line. To complete the analysis I even read about conductive coupling, which regards the ground potential rise in case of fault to earth that may affect nearby pipelines.

Furthermore, I tried to apply the Italian regulations. I started with CEI 304-1, but I didn't find a precise method for the evaluation of the induced electromotive forces in it: in fact the Italian standard leads to Cigré's *Guide on the influence of high voltage AC power systems on metallic pipelines*, that gives the formulas and the method of analysis, which is the summary of the methods in CCITT directives (ITU). I studied both Cigré guide and CCITT directives, because in the first one I found some errors, methods were not explained and only the case of single tree phase line inducing on a pipeline was considered: while in CCITT directives I found the theory to build equations for all line configurations.

The theory for building equations for assessing the e.m.f, described in the CCITT directives, led me to build a MATLAB program, which was useful for the plan of rationalization of the high voltage transmission system of the north-east of Italy planned by Terna S.p.A. (the Italian electricity transmission system operator), and developed by the engineering division of Terna Rete Italia in Padua (Italy). During the period of my employment, I was asked to analyze the effects of electromagnetic coupling between HV power lines to be built and an existing gas pipeline, called "Feeder Idrovia Saonara", and provide solutions in case of problems for the interference.

This thesis is divided into seven chapters. In the chapter one I describe the Italian regulations. In the following chapter I analyze the inductive coupling. In the third I study the conductive coupling. In the fourth I analyze Italian standard's limits. In the fifth I summarize methods for mitigation. In the sixth chapter I describe my Matlab program. Finally, in the last one I analyze real cases of interference.

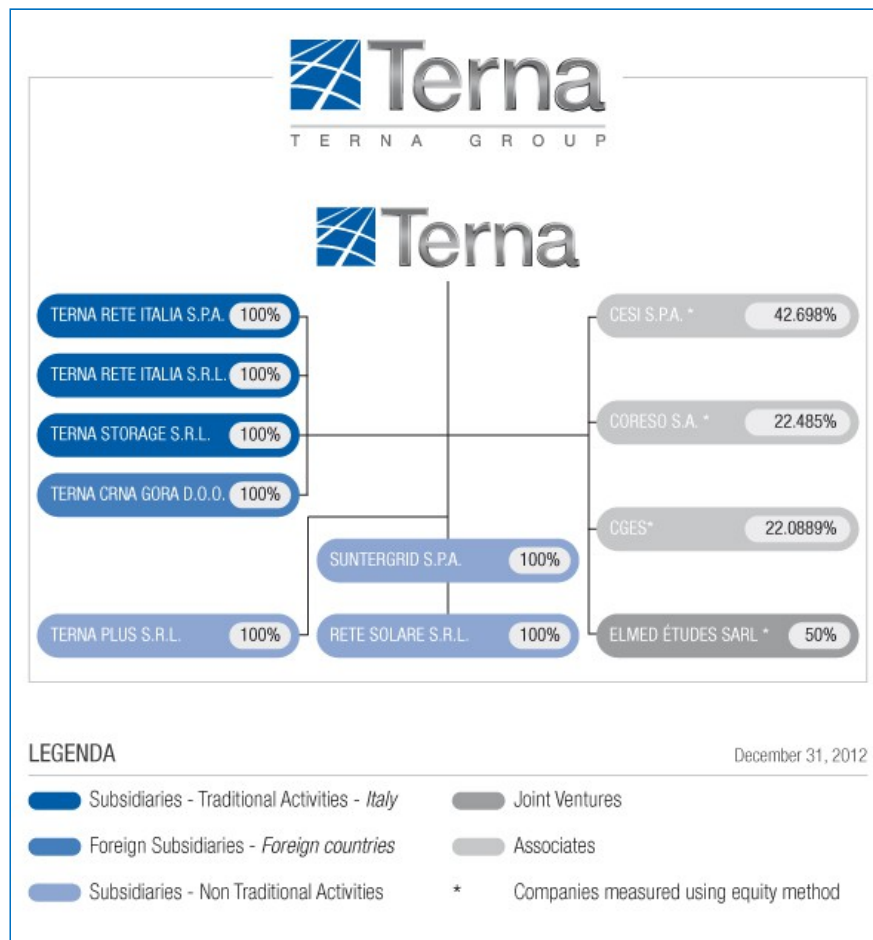


# Company Presentation

Terna S.p.A. - Rete Elettrica Nazionale is the Italian high-voltage electricity transmission system operator based in Rome, Italy. Terna is the first electricity transmission operator in Europe and the sixth in world through 63500 km of HV power lines (98% of the Italian high-voltage power transmission system), managed by the division Terna Rete Italia.

Terna even follows new business opportunities and unconventional activities, in Italy and abroad, through Terna Plus.

The following figure shows the whole company structure [14].





# Chapter 1

## ***CEI 304-1: description of the Italian standard***

CEI 304-1 Italian standard is about electromagnetic interference produced by electric power lines on metallic pipelines. The Italian standard indicates the steps to follow for assessing the induced e.m.f:

1. Evaluation of length of exposure and linearization (for Inductive Coupling);
2. Choice of the case of coupling (for buried pipelines: Inductive Coupling and Conductive Coupling);
3. Determination of the inducing current (fault conditions – steady-state conditions);
4. Calculations of coupling effects;
5. Comparison between results of calculation and admissible limits;
6. Mitigation

In the following chapters I will describe the steps for the inductive coupling and the conductive coupling.

CEI 304-1 doesn't provide any formulas for the calculations: in the section *Calculation Methods* we can read:

*“There are reference documents that describe fully the methods of calculation used to determine the results of the interference generated by electric power lines on metal pipes. However, you can use the following guidelines for this task. In 1995, CIGRE published the document "Guide on the Influence of High Voltage AC Power Systems on Metal Pipelines", which summarizes the main elements for the calculation. Furthermore, the large part of the contents of this document are derived from: ITU-T (CCITT) Directives Concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines.”*

This means that there isn't a specific way to assess the interference.

As far as inductive coupling and Cigré Guide are concerned I realized that:

- three phase lines (aerial or cable) are taken into account, while double circuit low reactance lines (DCLR) are not considered;
- formulas contain some errors.

So studying the CCITT directives (ITU) I found the way to build equations, in all configurations, even DCLR lines.

In CCITT directives there is the complete explanation of methods that can be used:

1. “two conductor system” with “correction factors”
2. “Multiconductor Line Solution”

The first method is followed by the Cigré Guide, and consists in assessing the induced e.m.f on a pipeline

by a single inducing circuit. In case of several inducing conductors results are given by superposition of the effects of the single conductor on the induced one. Screening conductors, such as earthwires or sheaths of cables, are taken into account with the theory of “correction factors”. This thesis will explain and give a complete set of equations for this method: equations will be solved with a specific Matlab program.

The second method is more performing than the previous one, because the presence of screening conductors is considered in a more precise way: all the conductors are taken into account in a specific matrix, then the results come from the resolution of a system of differential equations.

As far as conductive coupling is concerned, equations in Cigré Guide and CCITT directives are the same, if we consider a simple case of fault to earth through the tower.

In the next paragraph I will show the wrong formulas for the inductive coupling from Cigré guide.

## 1.1 Wrong and misleading expressions

Some errors I found in Cigré Guide were caused by a misleading definition of the reference system for current and voltage. In fact even in CCITT directives the reference system changes in the chapters: sometimes we find the same expressions with different signs. In this thesis I choose a reference system (as we can see in the following figure) that will never change.

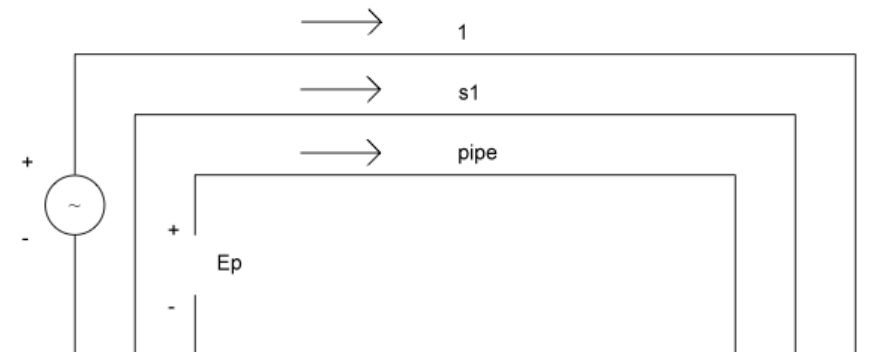


Figure 1.1: Reference system for voltage (+ -) and current (→)

This convention for positive values of voltage (+) and currents (arrowhead) won't lead to mistakes.

Another singularity is the reference of currents in the three phase system: Cigré Guide uses the *direct sequence* of currents, while CCITT directives use the *inverse one*. In the following chapters I'll show how this difference is relevant during calculations.

Errors are much more serious if we consider the following expressions from the Cigré Guide:

- Induced e.m.f on a pipeline by a three phase line with one earthwire – the expression is wrong, in fact dimensions are not consistent;

$$(E)_1 = \left\{ -\frac{jf \mu_o I}{2} \left( \ln \frac{d_{2p} d_{3p}}{d_{1p}^2} + j\sqrt{3} \ln \frac{d_{2p}}{d_{3p}} \right) - \frac{Z_{4x}}{Z_{44}} \left( \ln \frac{d_{24} d_{34}}{d_{14}^2} + j\sqrt{3} \ln \frac{d_{24}}{d_{34}} \right) \right\} (V/m)$$

(F.2)

Figure 1.2: Induced e.m.f on a pipeline by a three phase line with one earthwire [2]

- Polynomial expression for the mutual impedance – the expression is wrong because the parameter d is not the distance between conductors (it's a function of the distance), and the numerical parameters are approximated in a wrong way;

d) Another expression, which can be useful for calculations on computers is given in the CCITT Directives [1]. Its domain of validity is very broad

$$Z_m = [f_1(d) + j f_2(d)] 10^{-9} j \omega (\Omega/m) \quad (C.5)$$

with

$$f_1(d) = a_1 - a_2 d + a_3 d^2 - a_4 d^3 + a_5 d^4 - a_6 d^5 - a_7 e^d + a_8 \ln d$$

$$f_2(d) = -b_1 + b_2 d - b_3 d^2 + b_4 d^3 - b_5 d^4 + b_6 d^5 + b_7 e^{-d} - b_8 e^d - b_9 \ln d$$

d = distance between conductors (m)

Table 1 gives the coefficient  $a_i$  and  $b_i$

Figure 1.3: Polynomial expression for the mutual impedance [2]

$f_1(d)$		$f_2(d)$	
$a_1$	123.31	$b_1$	339.03
$a_2$	1.69	$b_2$	193.67
$a_3$	23.93	$b_3$	49.76
$a_4$	4.96	$b_4$	6.97
$a_5$	0.44	$b_5$	0.52
$a_6$	0.01	$b_6$	0.01
$a_7$	0.00	$b_7$	180.41
$a_8$	199.98	$b_8$	0.00
		$b_9$	0.27

Table C.1

Figure 1.4: Coefficients [2]

1. CEI 304-1: description of the Italian standard

- Expression for the corrective factor in presence of two earthwires (fault conditions) – the expression between brackets is the expression of the corrective factor: this expression is wrong;

If the line is provided with two earthwires 4 and 5, the exact expression for  $E_p$  is given by

$$E_p = - Z_{p1} I \left( 1 - \frac{Z_{44} Z_{51} - Z_{45} Z_{41}}{Z_{44} Z_{55} - Z_{45}^2} \frac{Z_{p4}}{Z_{p1}} - \frac{Z_{55} Z_{41} - Z_{45} Z_{51}}{Z_{44} Z_{55} - Z_{45}^2} \frac{Z_{p5}}{Z_{p1}} \right) \quad (E8)$$

Figure 1.5: Corrective factor in presence of two earthwires [2]

Arrows and circles highlight the errors I will discuss and correct in the following paragraphs.



# Chapter 2

## *Inductive Coupling*

Pipelines that run parallel to or in close proximity to HV transmission lines or HV cables are subjected to induced voltage caused by the time-varying magnetic fields produced by the currents in the transmission lines. As far as Faraday-Neumann and Lenz laws are concerned, the induced electromotive forces (e.m.f) can be expressed by the following expressions:

$$E = -Z_m I \quad (2.1)$$

where: E [V/m] – induced e.m.f on the induced circuit; Z [ $\Omega$ /m] – mutual impedance between the inducing circuit and the induced one; I [A] – current circulating in the inducing circuit.

As far as CEI 304-1 and Cigré Guide are concerned, I will follow the logical steps of the standard in order to assess the interference.

### **2.1 Length of exposure**

Exposure length is the length of the zone where the influence is significant: this means that effect on an induced circuit must be considered only if the distances are lower than a certain value, as we see in the following equation.

$$d < 200 \sqrt{\rho} \quad (2.2)$$

Where: d [m] – distance between inducing and induced circuit;  $\rho$  [ $\Omega$ m] – soil resistivity.

The following table shows the variation of the distance in function of soil resistivity.

*Table 2.1: Length of exposure*

d [m]	$\rho$ [ $\Omega$ m]
1400	50
2000	100
2800	200

## 2.2 Mutual distances

Once the domain of the analysis is defined, the guide leads to the evaluation of mutual distances between circuits. The zone of influence is generally composed of successions of parallelisms, oblique approaches and crossings: the determination of the induced e.m.f requires a subdivision of the pipeline in sections that can be reduced to parallelisms.

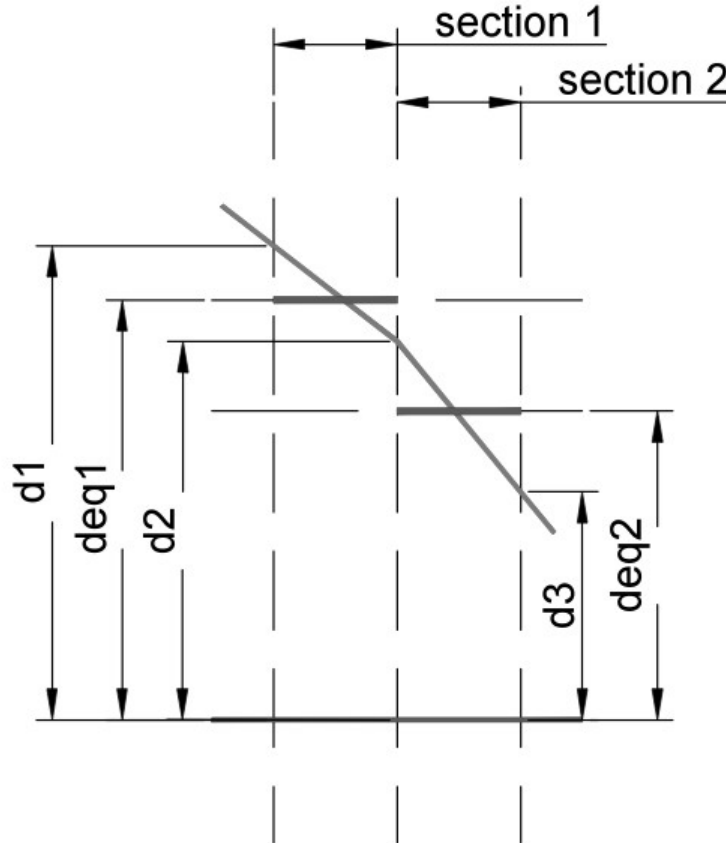


Figure 2.1: Subdivision of the domain in sections

In this way in each section we have parallel conductors: the equivalent distance must respect the following expressions:

$$d_{eq} = \sqrt{d_1 d_2} \quad (2.3)$$

$$\frac{1}{3} \leq \frac{d_1}{d_2} \leq 3 \quad (2.4)$$

When the previous conditions are not fulfilled the oblique approach is subdivided into two more sections. In case of crossing the zone situated within a distance of 10 m on both sides of the line is considered as a special section. If the acute angle between line and pipeline is larger than  $45^\circ$ , the section can be neglected. If the angle is lower, the section is considered as a parallelism with a horizontal separation of about 6 m.

We must even consider the two following cases.

*Double inducing effect*

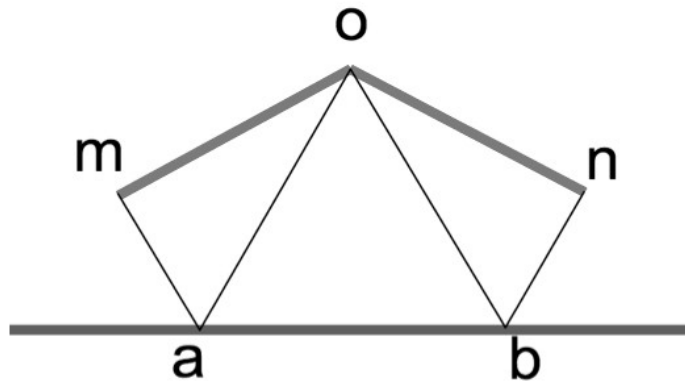


Figure 2.2: Double inducing effect

As we can see in figure, the inducing line is “mon”, the induced one is “ab”: in section “ab” we must take into account a double inducing effect.

*No coupling*

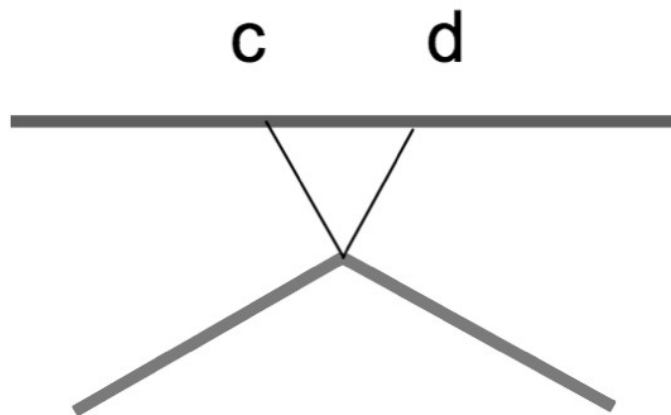


Figure 2.3: No coupling

As we can see in figure, the induced section “cd” must be neglected.

*In practical cases the subdivision of the pipeline is made into a large number of sections to increase precision. Double induced and neglected sections, in parallelism condition, are more or less the same amount, so that we can have compensations. In case of several inducing circuits and a single induced pipeline, a linearization of the pipe is made, in order to have sections of the induced circuits of the same length for the sum of each inducing circuit contribute of emf. For the analysis of practical cases (chapter 7) I will linearize the pipeline, for the analysis of Cigrè Guide's example (Appendix E) I will linearize the HV line, since there's only an inducing circuit.*

### 2.3 Self and Mutual impedances

Expressions of self and mutual impedances are given by the guide. A more precise background is given introducing self and mutual impedances by the basis of Carson's theory.

As we can read in CCITT directives:

*Self Impedance* per unit of length of a conductor (i) with earth return is:

$$Z_{ii} = \frac{E_{ii}}{I_{ii}} \quad (2.5)$$

*Mutual Impedance* per unit of length between two conductors (i and j) both with earth return is:

$$Z_{ij} = \frac{E_{ij}}{I_i} \quad (2.6)$$

where:  $Z$  [ $\Omega/\text{km}$ ] – impedances;  $I$  [A] – currents;  $E$  [V/km] – electric field.

For the evaluation of the impedances we can adopt different formulas, depending on the sphere of applicability of the expressions.

The expressions are:

1. Carson Series form;
2. Polynomial form;
3. Carson-Clem form.

### 2.3.1 Carson Series form

In particular circumstances we need a precise evaluation for self and mutual impedances, such as cases of:

- wide separation;
- low earth resistivity;
- high harmonic orders;

and when we need to consider the variation of impedance with the height of lines above the surface of the earth.

The following formulae are given in CCITT directives.

The *self impedance* is obtained by this expression:

$$Z_{ii}[\Omega/km] = Z_{Oi} + Z_{Ei} \quad (2.7)$$

where the first term is the internal part of self impedance, and the second one the external:

$$Z_{Oi}[\Omega/km] = R_i + j 2 * 10^{-4} \omega \frac{\mu_r}{4} \quad (2.8)$$

$$Z_{Ei}[\Omega/km] = j \omega \frac{\mu_0}{2\pi} \ln \frac{2h_i}{r} + 2(\Delta R_{ii} + j \Delta X_{ii}) \quad (2.9)$$

While *mutual impedance* is given by:

$$Z_{ij}[\Omega/km] = j \omega \frac{\mu_0}{2\pi} \ln \frac{D_{ij}}{d_{ij}} + 2(\Delta R_{ij} + j \Delta X_{ij}) \quad (2.10)$$

Where:

- $D_{ij}$  – distance between conductor i and the image of conductor j, or vice versa;
- $d_{ij}$  – geometrical distance between conductors;
- $\Delta R, \Delta X$  – corrective terms of Carson's expression.

The first terms of equations (2.9) and (2.10) give the impedances in the case of a perfectly conductive earth. The second ones are the correction terms introduced by Carson to take into account the finite conductivity of the earth.

In the original Carson's formulas, these correction terms are given in the form of infinite integrals, while they are provided in form of series in CCITT directives.

In computer calculations it's easy to use the form in series. Increasing the number of terms in the series more precise results can be obtained.

In the following chapters I will use Carson's correction terms in form of series for the calculations (adopting a Matlab routine developed by ing. Marco Caneva).

### 2.3.2 Polynomial form

This expression is taken from the CCITT directives, because the Cigré Guide gives a wrong formula: it is valid for evaluating the mutual impedance between two conductors (i and j) both with earth return.

$$Z_{ij} [\Omega/m] = j 2\pi f (M_{\text{R}} + j M_{\text{S}}) * 10^{-9} \quad (2.11)$$

Where:

$$x = \alpha d \quad (2.12)$$

$$\alpha = \sqrt{\left(\frac{\omega\mu_0}{\rho}\right)} \quad (2.13)$$

if  $x \leq 10$ ;

$$M_{\text{R}} = a_1 - a_2 x + a_3 x^2 - a_4 x^3 + a_5 x^4 - a_6 x^5 + a_7 e^x - a_8 \ln x \quad (2.14)$$

$$M_{\text{S}} = -b_1 + b_2 x - b_3 x^2 + b_4 x^3 - b_5 x^4 + b_6 x^5 + b_7 e^{-x} - b_8 e^x - b_9 \ln x \quad (2.15)$$

if  $x > 10$ ;

$$M_{\text{R}} = 0 \quad (2.16)$$

$$M_{\text{S}} = -\left(\frac{400}{x^2}\right) \quad (2.17)$$

and:

Table 2.2: Coefficients for polynomial expression of Z

a <sub>1</sub>	123.36	b <sub>1</sub>	339
a <sub>2</sub>	1.69	b <sub>2</sub>	193.67
a <sub>3</sub>	23.937	b <sub>3</sub>	49.77
a <sub>4</sub>	4.9614	b <sub>4</sub>	6.979
a <sub>5</sub>	0.44212	b <sub>5</sub>	0.5243
a <sub>6</sub>	0.01526	b <sub>6</sub>	0.01672
a <sub>7</sub>	0.001215	b <sub>7</sub>	180.42
a <sub>8</sub>	200	b <sub>8</sub>	0.00146
		b <sub>9</sub>	0.274

The polynomial form is valid in the whole range of  $x$  since it's obtained from Carson's formula by applying the method of curve fitting.

These expressions even make it possible to calculate the external part of the self inductance by using:

$$x = \alpha r \quad (2.18)$$

The symbols are:  $r$  [m] – radius of the conductor;  $d$  [m] – mutual distance between conductors;  $\omega$  [1/s] – angular frequency;  $\mu$  [H/m] – vacuum permeability;  $\rho$  [ $\Omega$ m] – soil resistivity.

### 2.3.3 Carson-Clem form

The expression for Carson-Clem mutual impedance is:

$$Z_{ij} [\Omega/m] = \mu_0 \frac{\pi f}{4} + j \mu_0 f \left( \ln \left( \frac{2}{g \alpha d} \right) + \frac{1}{2} \right) \quad (2.19)$$

Where:  $g = 1.7811$  (Euler's constant);  $d$  – geometrical distance between conductors;

This expression is only valid if:

$$d < \sqrt{\left( \frac{\rho}{f} \right)} \quad (2.20)$$

It's easy to see that Carson-Clem's expression is derived from Carson's one, with the following assumptions:

1. the first logarithmic terms in (2.9) and (2.10) are neglected. The variation of  $Z_E$  and  $Z$  with the height of the conductors can be considered as non relevant;
2. only the first term of  $\Delta R$ , and the first two terms of  $\Delta X$  are taken into account.

### 2.3.4 Comparison between mutual impedance's expressions

In the following picture I will compare Carson Series, polynomial and Carson-Clem formulations in function of the distance between conductors at different values of frequency, in order to focus on the sphere of applicability (values in amplitude).

The reference is Carson Series expression, because with a high number of elements in the series, we have a good evaluation of the mutual impedance.

Soil resistivity is  $100 \Omega\text{m}$  for this examples.

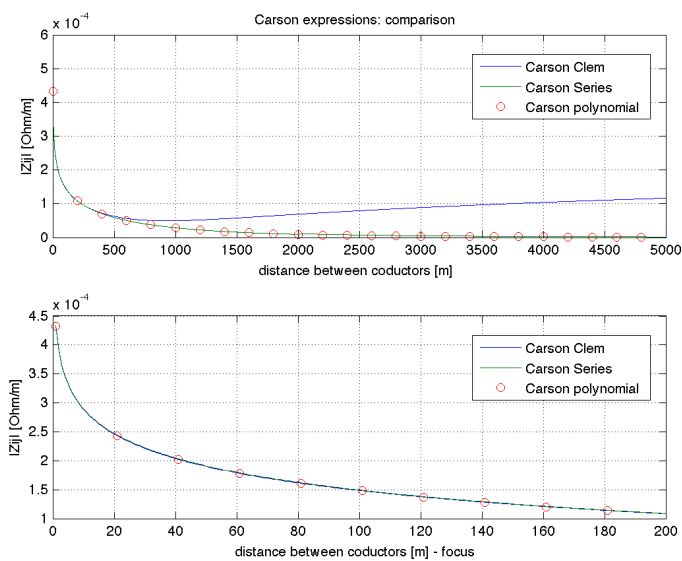


Figure 2.4: Carson expressions ( $f=50$  Hz)

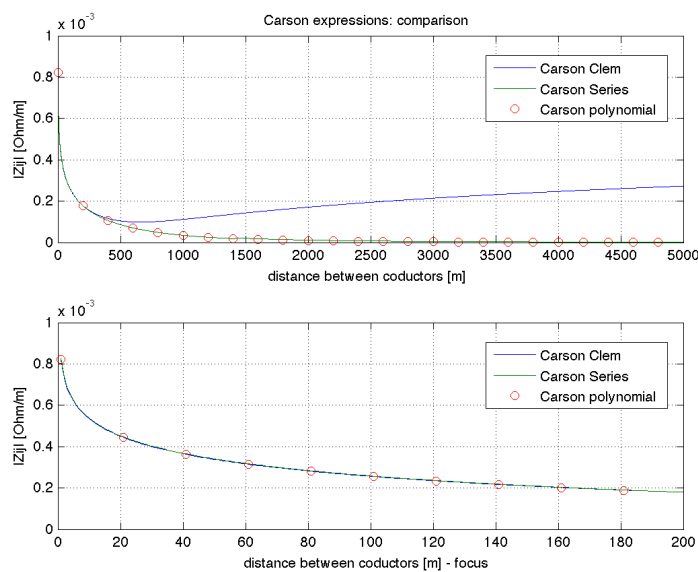


Figure 2.5: Carson expressions ( $f=100$ Hz)



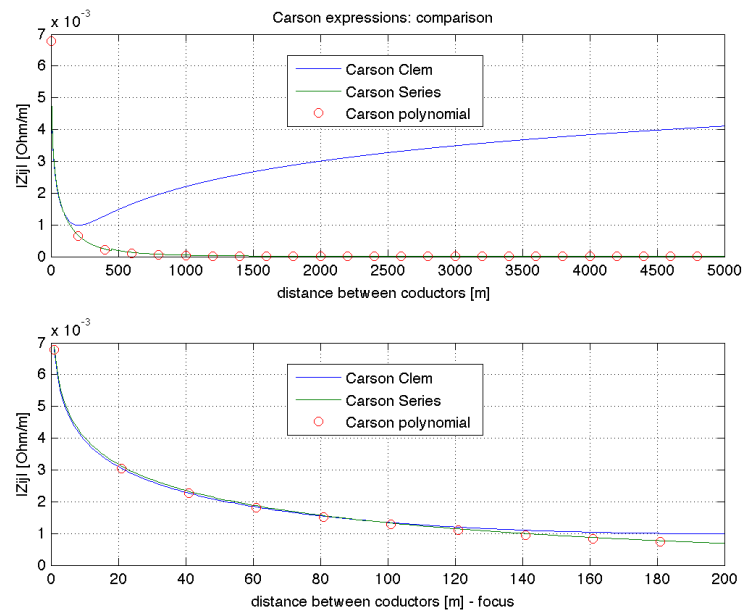


Figure 2.6: Carson expressions ( $f=1\text{kHz}$ )

We can see that:

- according to (2.20), Carson-Clem expression is not valid when distances are high and frequency increases;
- Polynomial form gives a good approximation of the Carson Series expression, and can be easily used for fast calculations;
- Carson-Clem expression is good at low distances, and can be easily used for fast calculations.

### 2.3.5 Relevance of components in Carson Series expressions

As far as Carson Series expressions are concerned, I want to quantify the relevance of each term, and understand why and when simplifications can be done.

In the following figures I will show:

- a comparison between the amplitude of the mutual impedance using Carson Series expressions, in function of the distance between the conductors, in case of 8, 14 and 32 terms in the series;
- a comparison between the logarithmic term of Carson Series expressions and the amplitude of the term in series  $2*(\Delta R + j \Delta X)$ ;
- a focus on short distances of the previous point.

The comparison is made at different frequencies.

## 2. Inductive Coupling

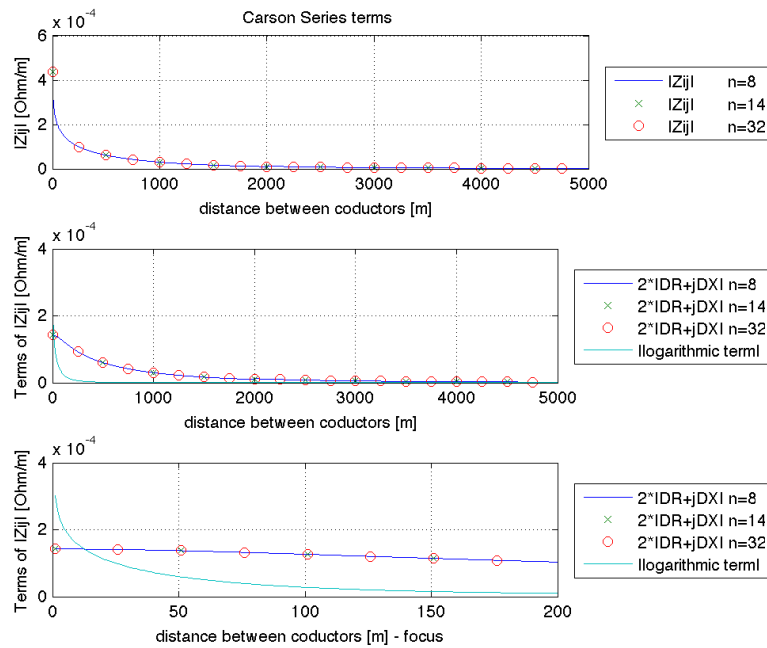


Figure 2.7: Terms of Carson Series expression ( $f = 50$  Hz)

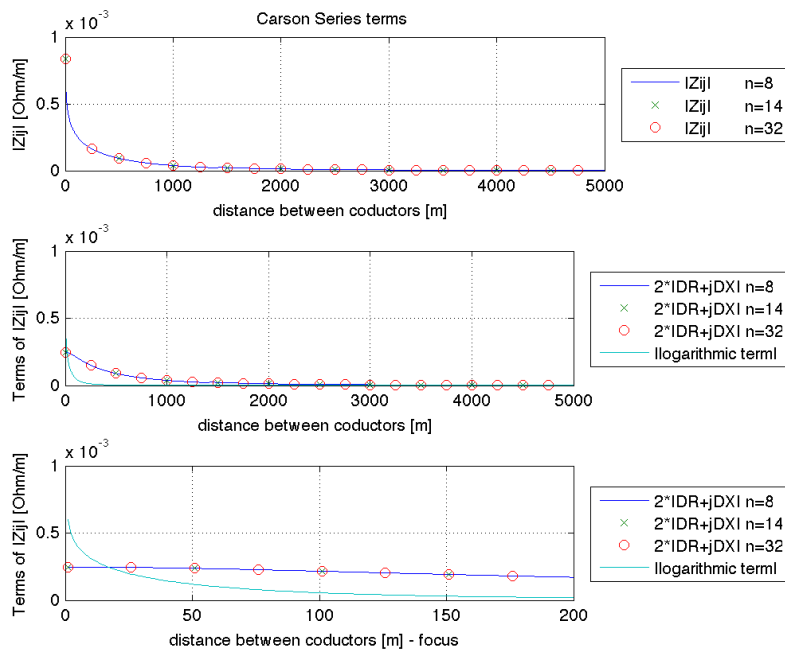


Figure 2.8: Terms of Carson Series expression ( $f = 100$  Hz)

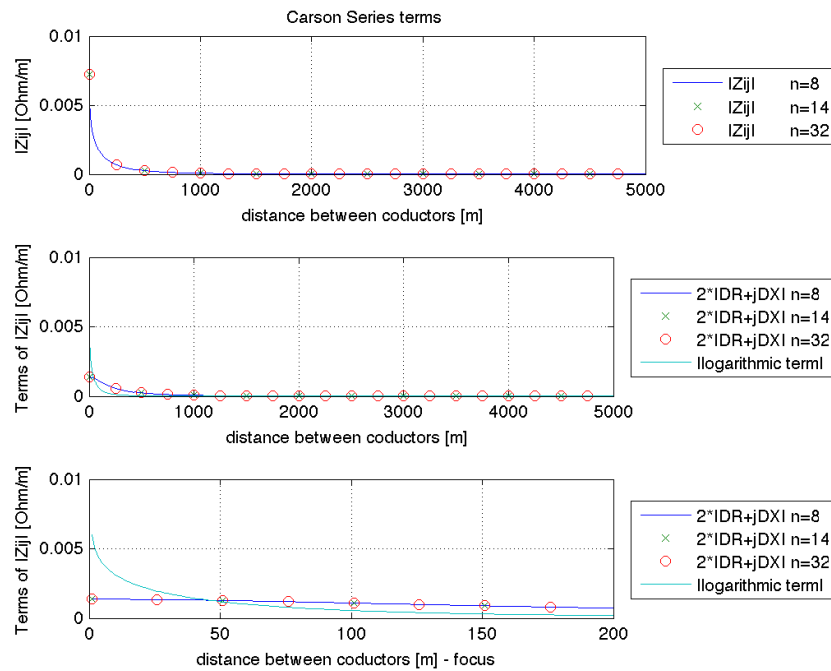


Figure 2.9: Terms of Carson Series expression ( $f = 1$  kHz)

We can see that:

- high number of terms in the series are not necessary (the difference is almost zero). Great differences can be found by the comparison of Carson Series expressions with Carson-Clem's one, where terms in the series are at most two and the logarithmic term is neglected;
- corrective terms are necessary with high distances, because the logarithmic term decreases too fastly.

### 2.3.6 Self impedances

The expressions for the evaluation of the self impedances are given by Cigrè Guide.

They are:

$$Z_{ii} [\Omega/m] = R + \mu_0 f \arctan\left(\frac{\beta}{\beta+1}\right) + j \mu_0 f \left( \ln\left(\frac{2h}{r}\right) + \ln\left(\sqrt{((\beta+1)^2 + \beta^2)}\right) \right) \quad (2.21)$$

Where: R – resistance of the conductor; f – frequency; h – height of the conductor above the soil; ρ – soil resistivity;

$$\beta = \frac{330}{h} \sqrt{\left(\frac{\rho}{2f}\right)} \quad (2.22)$$

and:

$$Z_{ii} [\Omega/m] = \mu_0 \frac{\pi f}{4} + j \mu_0 f \left( \ln\left(\frac{2}{gar}\right) + \frac{1}{2} \right) \quad (2.23)$$

A comparison might be made between the two expressions with the following figure.

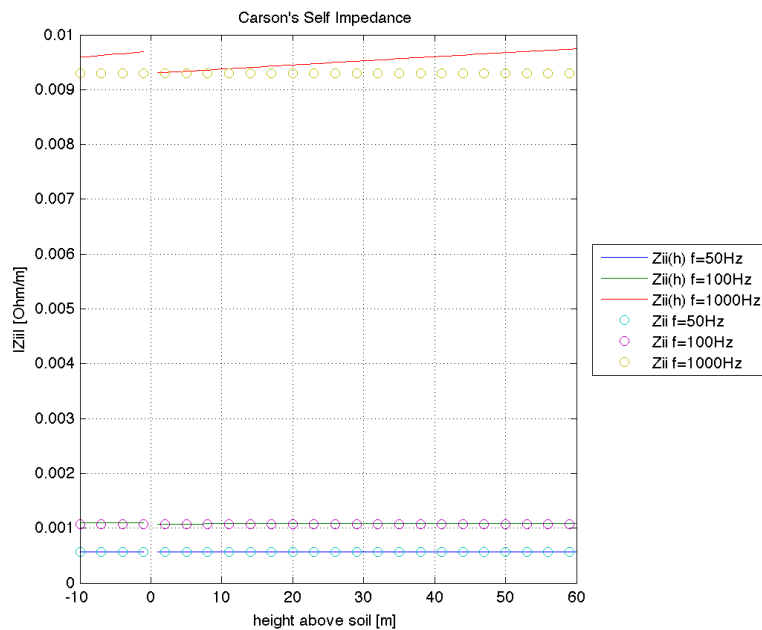


Figure 2.10: Comparison between Self Impedance's expressions

Considering the Self Impedance's expressions shown before, we can see that (2.22) ( $Z_{ii}(h)$  in figure) varies with the height of the conductors above the soil, while (2.24) ( $Z_{ii}$  in figure) doesn't. Differences can be seen only with high values of frequency. As far as this thesis is concerned, I will analyze cases of interference with at industrial frequency (f=50 Hz in Italy), so that expression (2.24) can be used.

## 2.4 Correction factor $k$

In case of single phase fault to earth, the presence of metallic conductors connected to the ground in the zone of influence, such as earthwires can significantly reduce the induced voltage on the pipe: the phenomenon is taken into account with the formulation of a correction factor  $k$ .

In the following paragraphs I will show how this factor is described in the guide and in the CCITT directives. While Cigré guide uses this factor only in faulty conditions, and gives particular expressions for the e.m.f for steady-state conditions for lines with earthwires, the CCITT directives give the complete theory, in order to obtain all the formulations.

### 2.4.1 Correction factor $k$ – Cigré Guide

The guide uses this factor only in case of single phase fault to earth. I think that the contribution of the healthy phases is neglected due to the high impedance of the healthy phases which allows us not to take into consideration the contribution of the induced current in the healthy phases, which would represent an additional screening effect.

In steady state conditions, with lines with earthwires,  $k$ -factor is not used: in fact the guide gives expressions, that I re-wrote from “ $k$ -factor general theory”. Those formulas and the theory are analyzed later.

In the case of an aerial three phase line with a single earthwires, after a fault occurred from phase number 1 to ground, the scheme is the following:

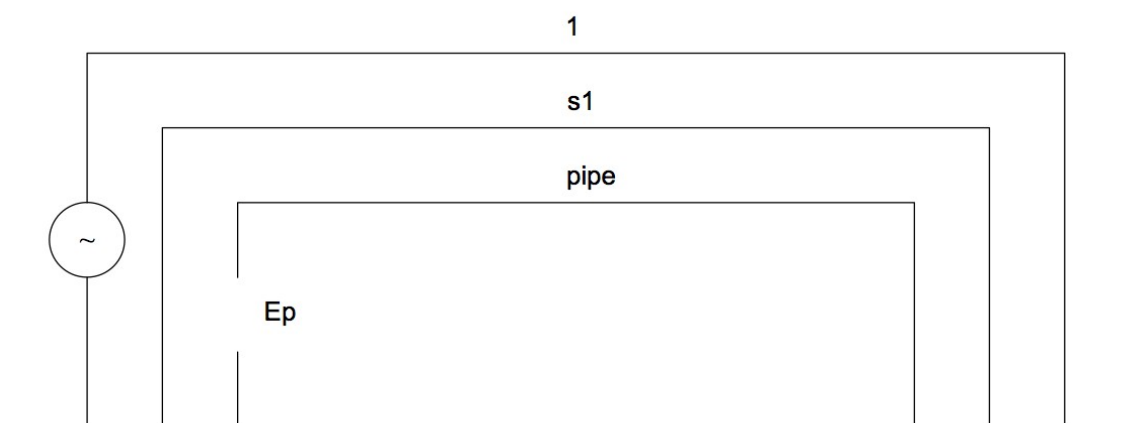


Figure 2.11: Inducing conductor, screening conductor, induced conductor - scheme

Where: 1 – fault conductor; s1 – screening conductor; pipe – induced conductor;  $E_p$  – e.m.f..

## 2. Inductive Coupling

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The reduction factor  $k$  is given by the resolution of the following system:

$$\begin{aligned} Z_{(s1,s1)} I_{s1} + Z_{(s1,1)} I_1 &= 0 \\ Z_{(pipe,s1)} I_{s1} + Z_{(pipe,1)} I_1 &= -E_p \end{aligned} \quad (2.24)$$

So:

$$E_p = -Z_{(pipe,1)} I_1 \left( 1 - \frac{Z_{(s1,1)} Z_{(pipe,s1)}}{Z_{(s1,s1)} Z_{(pipe,1)}} \right) \quad (2.25)$$

This expression is valid assuming that currents in screening conductors do not modify the inducing current.

The  $k$ -factor is thus given by:

$$k = 1 - \frac{Z_{(s1,1)} Z_{(pipe,s1)}}{Z_{(s1,s1)} Z_{(pipe,1)}} \quad (2.26)$$

In case of two earthwires the guide doesn't provide a correct formulation, so I need to solve the following system, in order to obtain a correct expression.

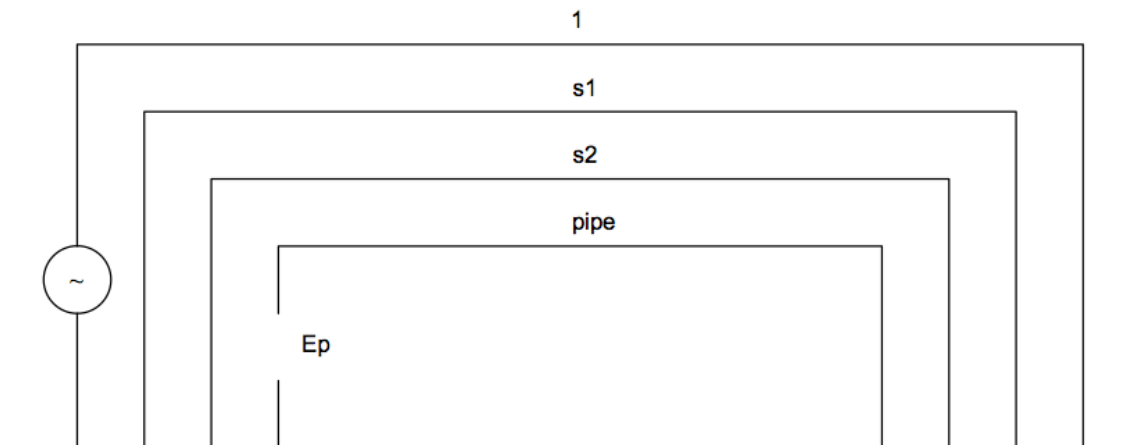


Figure 2.12: Inducing conductor, two screening conductors, induced conductor - scheme

The system is:

$$\begin{aligned} Z_{(s1,s1)} I_{s1} + Z_{(s1,s2)} I_{s2} + Z_{(s1,1)} I_1 &= 0 \\ Z_{(s2,s1)} I_{s1} + Z_{(s2,s2)} I_{s2} + Z_{(s2,1)} I_1 &= 0 \\ Z_{(p,s1)} I_{s1} + Z_{(p,s2)} I_{s2} + Z_{(p,1)} I_1 &= -E_p \end{aligned} \quad (2.27)$$

So the  $k$  factor is:

$$k = 1 - \frac{Z_{(s1,1)} Z_{(p,s1)}}{Z_{(s1,s1)} Z_{(p,1)}} + \left( Z_{(s1,s1)} Z_{(p,s2)} - Z_{(s1,s2)} Z_{(p,s1)} \right) \frac{(Z_{(s1,1)} Z_{(s1,s2)} - Z_{(s1,s1)} Z_{(s2,1)})}{(Z_{(p,1)} Z_{(s1,s1)} (Z_{(s2,s2)} Z_{(s1,s1)} - Z_{(s1,s2)}^2))} \quad (2.28)$$

For an earth fault at the extremity of an HV cable the screening effect of the metallic sheath of the cables earthed at both ends is given by the following expression:

$$k = \frac{r_{(s1,s1)}}{Z_{(s1,s1)}} \quad (2.29)$$

Where:  $Z$  – self impedance of the sheath,  $r$  – real part of  $Z$ .

This expression is a simplification of (2.28), because of the vicinity of screening and inducing conductors: distances between pipe and conductors are practically equal to distances between sheaths and conductors.

According to the Hochrainer theory phase conductors and sheaths can be considered as different conductors with earth return. For calculating sheaths' self and mutual impedances, mutual impedances between phase conductors and sheaths, and between sheaths and pipelines these assumptions must be followed:

- sheath's self impedance – conductor radius is the mean radius of the sheath;
- mutual impedances sheath-conductor – distance between conductors is sheath's mean radius;
- mutual impedances sheath-pipeline – sheaths are filiform conductors, their position corresponds to phase conductors's one.

So mutual inductance between sheath and conductor is practically equal to sheath's self inductance.

## 2.4.2 Correction factor k – General Case – CCITT directives

In Cigrè Guide it is not clear where the expressions for the induced e.m.f in steady-state conditions for lines with earthwires come from. In addition the expression for lines with one earthwire gives doubtful results, in which the dimensions are not consistent.

However CCITT directives provide the formula of k-factor in general cases, and this is the method to obtain the correct expression of the induced e.m.f. for a power line with one (or more) earthwires, as reported below.

Considering to have:

1. an inducing conductor group e, composed of conductors a, b, c, . . . i . . . m;
2. a screening conductor group c, composed of conductors 1,2,3 . . . k . . . n;
3. an induced conductor t.

For n perfectly earthed screening conductors the following matrix equation can be written using the self and mutual impedances with earth return per unit of length of both inducing and compensating conductors.

$$\begin{bmatrix} 0 \\ 0 \\ \dots \\ \dots \\ \dots \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{1a} & Z_{1b} & Z_{1m} & Z_{11} & Z_{12} & Z_{1n} \\ Z_{2a} & Z_{2b} & Z_{2m} & Z_{21} & Z_{22} & Z_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Z_{na} & Z_{nb} & Z_{nm} & Z_{n1} & Z_{n2} & Z_{nn} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ \dots \\ \dots \\ I_1 \\ I_2 \\ \dots \\ I_n \end{bmatrix} \quad (2.30)$$

With the use of submatrices obtained from partitioning (2.30), we can write:

$$[Z_{ce}] = \begin{bmatrix} Z_{1a} & Z_{1b} & Z_{1m} \\ Z_{2a} & Z_{2b} & Z_{2m} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ Z_{na} & Z_{nb} & Z_{nm} \end{bmatrix} \quad [Z_{cc}] = \begin{bmatrix} Z_{11} & Z_{12} & Z_{1n} \\ Z_{21} & Z_{22} & Z_{2n} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ Z_{n1} & Z_{n2} & Z_{nn} \end{bmatrix} \quad [I_e] = \begin{bmatrix} I_a \\ I_b \\ \dots \\ I_m \end{bmatrix} \quad [I_c] = \begin{bmatrix} I_1 \\ I_2 \\ \dots \\ I_n \end{bmatrix} \quad (2.31)$$

$$[0] = [Z_{ce}][I_e] + [Z_{cc}][I_c] \quad (2.32)$$



So the solution is:

$$[I_c] = -[Z_{cc}]^{-1}[Z_{ce}][I_e] \quad (2.33)$$

$I_c$  represents the vector of the induced currents in the screening conductors (screening currents).

The total e.m.f induced on the pipeline is:

$$E[V/m] = E_o + E_c \quad (2.34)$$

Where:

$$E_o[V/m] = -\sum_{i=1}^m Z_{ti} I_i \quad (2.35)$$

$$E_c[V/m] = -\sum_{k=1}^n Z_{tk} I_k \quad (2.36)$$

Where:  $I_i$  – inducing current;  $I_k$  – screening current;  $Z_{ti}$  – mutual impedances between the induced line and the inducing conductor;  $Z_{tk}$  – mutual impedances between the induced line and the screening conductor,  $E_o$  – e.m.f on the pipeline without screening conductors;  $E_c$  – screening effect due to screening conductors.

The reduction factor is:

$$k = \frac{E}{E_o} = \frac{(E_o + E_c)}{E_o} \quad (2.37)$$

This approach is described in the CCITT directives. The directives also say that Multiconductor Analysis is commonly used when there are several inducing lines and several screening conductors.

*Note:*

*The  $k$ -factor general and the theory of superposition of the effects are the basis for my analysis: I try to give a more complete set of equations to solve simple cases of interference.*

### 2.5 Induced e.m.f (steady state condition)

As far as k-factor general theory is concerned, we can write the equations of induced e.m.f in all cases. I will focus on:

1. three phase line (SC – single circuit), balanced currents, no earthwires;
2. three phase line (SC – single circuit), balanced currents, one earthwire;
3. three phase line (SC – single circuit), balanced currents, two earthwires;
4. double circuit super bundle line configuration (DCSB), balanced currents, no earthwires;
5. double circuit super bundle line configuration (DCSB), balanced currents, one earthwire;
6. double circuit super bundle line configuration (DCSB), balanced currents, two earthwires;
7. double circuit low reactance line configuration (DCLR), balanced currents, no earthwires;
8. double circuit low reactance line configuration (DCLR), balanced currents, one earthwire;
9. double circuit low reactance line configuration (DCLR), balanced currents, two earthwires;
10. three phase cable, balanced currents

In 1,2,3 and 10 I will analyze and correct the Cigrè Guide's formulas, while in 4,5,6,7,8 and 9 I will go beyond, creating new expressions.

In fact, as for double circuit low reactance line configuration (DCLR) and double circuit super bundle configuration (DCSB), the guide doesn't give any equation.

*Note:*

*An explanation of this might be that the guide suggests to apply to every triplet of the power line in double circuit configuration the formulas for the single three phase line, then add the rms values of the induced e.m.f in the pipeline. This is strictly correct, but unrealistic for DCLR lines, since this configuration is set to decrease the total magnetic field generated by the power line that we have with a simple three phase line. Consequently, DCLR's emf values are much lower than the sum of two SC line's emf values.*

It's easy to demonstrate, under balanced conditions, that the magnetic field generated by a three phase line (SC) decays with:

$$B_{SC} \approx \frac{1}{r^2} \quad (2.38)$$

Where r is the distance between the induced point and the center of gravity of the phase conductors.

While in case of DCLR configuration:

$$B_{DCLR} \approx \frac{1}{r^3} \quad (2.39)$$

So if the magnetic field decreases faster in DCLR configuration, the e.m.f will be lower than the three phase line arrangement, and cannot be computed as the rms sum of the effect of two three phase lines transporting half power each.

So an integration to the guide would be useful. It can follow two ways:

- Adding to three phase e.m.f expressions a new correction factor  $k_4$ , to have the effects of a DCLR configuration in an equivalent three phase line one;
- Creating new equations, following the k factor theory.

The integration will be done in both ways, and results will be compared.

### 2.5.1 Three phase line, balanced currents, no earthwires

The CCITT directives show how the e.m.f. equation in point x can be obtained. The principle is the superposition of the effects: in fact the total e.m.f on the pipeline is the sum of the e.m.f due to each of the phase conductor, in modulus and phase.

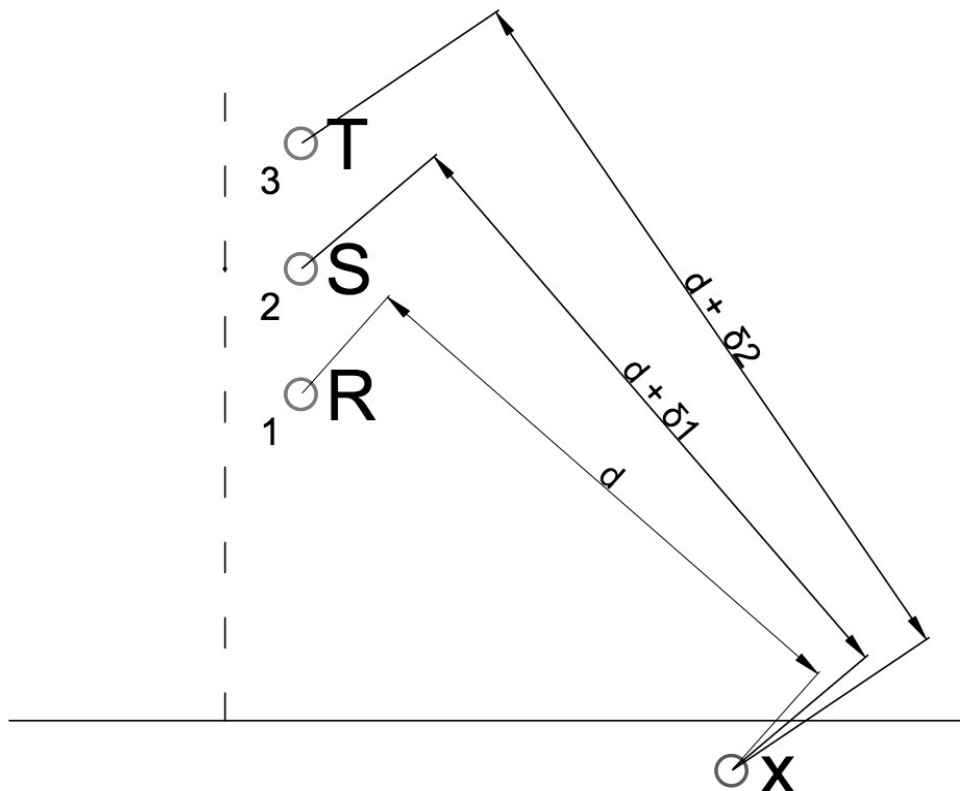


Figure 2.13: Distances between phase conductors and pipeline

Through this approach we have three “two conductor systems”, where the first conductor is the phase conductor, and the second is the pipeline, and we apply formulas from “short line representation”. This approach is the same of the one in paragraph 2.4.2 (k factor – general case), where we consider three inducing conductors and no earthwires.

## 2. Inductive Coupling

The difference between CCITT directives and Cigré Guide approach to this line arrangement is that in the first case the triplet of the currents is considered in the inverse sequence, in the second one in the direct sequence. *It must be emphasized that this leads to different expressions of the induced e.m.f.*

As far as inducing currents are concerned, the difference between direct and inverse currents of a three-phase line is immediately shown in table.

Table 2.3: Comparison between direct and inverse sequence

INVERSE SEQUENCE	DIRECT SEQUENCE
$I_r = I e^{j0} = I$	$I_r = I e^{j0} = I$
$I_s = I e^{(j2\pi/3)} = I(-0.5 + j\frac{\sqrt{3}}{2})$	$I_s = I e^{-(j2\pi/3)} = I(-0.5 - j\frac{\sqrt{3}}{2})$
$I_t = I e^{(j4\pi/3)} = I(-0.5 - j\frac{\sqrt{3}}{2})$	$I_t = I e^{-(j4\pi/3)} = I(-0.5 + j\frac{\sqrt{3}}{2})$

So applying the following expression (given by k factor theory, short line representation theory and two conductors line method):

$$E[V/m] = - \sum_{i=1}^3 Z_{pi} I_i \quad (2.40)$$

where: E – induced e.m.f.;  $Z_{pi}$  – mutual impedances between inducing circuits and pipeline;  $I_i$  – inducing currents:

we obtain the following formulation for the e.m.f. equation induced on a nearby conductor, using Carson Clem expression for mutual impedance (complete calculations in appendix A):

$$E[V/m] = -j f \mu_0 \frac{I}{2} \left( \ln \left( \frac{(d+\delta_1)(d+\delta_2)}{d^2} \right) \right) \pm j \sqrt{3} \ln \left( \frac{(d+\delta_2)}{(d+\delta_1)} \right) \quad (2.41)$$

Where  $\pm$  is:

- +            when adopting the inverse sequence;
- -            when adopting the direct sequence.

In fact the imaginary component of (2.41) is always the same, only the real part's sign changes, as shown in the following figure.

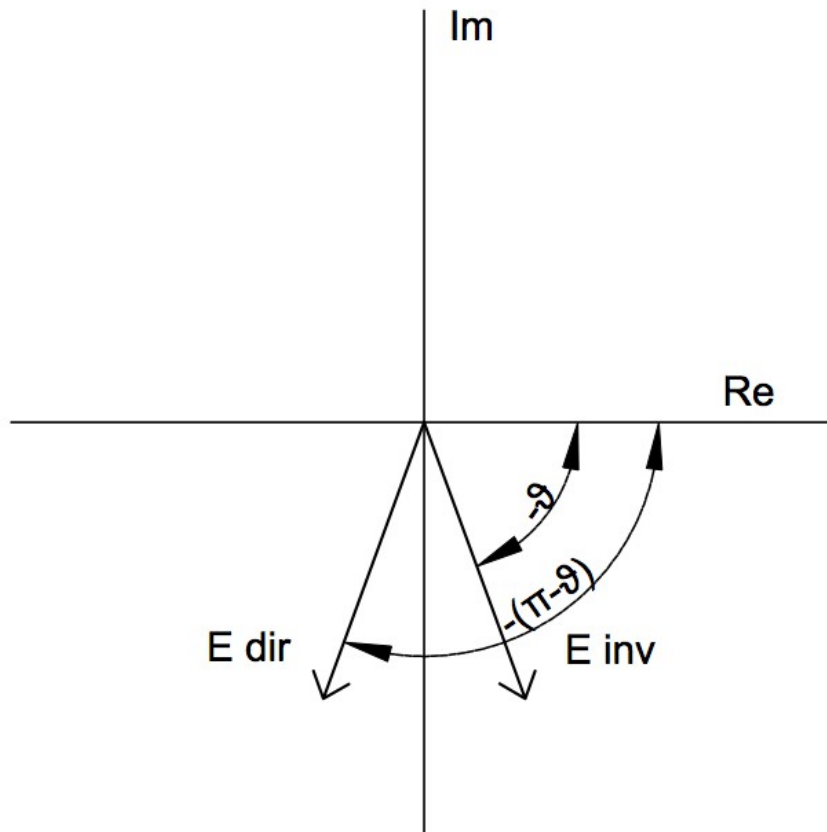


Figure 2.14: Induced e.m.f in three-phase arrangement (Carson-Clem)

We see that amplitude of the e.m.f never changes, while the phase angle changes. It is important to understand how this difference impacts on the results: comparison will be shown later.

During my analysis I will write equations both with direct sequence of currents and inverse sequence, to highlight differences.

In conclusion, I will highlight how this difference won't produce errors if a reference system is set: in fact when operating with sums in complex numbers, for example sums of contributes of emf from several inducing systems, an unclear definition of phase angles leads to different values.

Once we choose the reference system, we can make calculations and sums of components. Changing the reference it's possible to find out the worst case. As for this work, since values of emf during steady-state conditions are very low, it won't be necessary to find out the worst case: I will propose vectorial sum with the direct sequence reference and Italian standard's sum (explained later). In cases of several inducing circuits a more severe analysis could be necessary.

## 2.5.2 Three phase line, balanced currents, one or two earthwires

As far as the k factor general case is concerned, I solved the systems shown before to get an expression for the e.m.f induced on a pipeline by a three-phase line with two earthwires. The formulation will be different from the one given by Cigré guide: the reason is that the expression is clearer, all the terms have precise definitions.

Furthermore, the equation for a three-phase line with one earthwires will be easily derived from the previous one.

In general, we can write:

*Induced emf by a power line with n screening conductors on a pipeline*

$$E[V/m] = E_o + E_c \quad (2.42)$$

*Induced emf by the triplet of phase conductors, without screening conductors*

$$E_0 = - \sum_{i=1}^3 Z_{ti} I_i \quad (2.43)$$

Solving the systems (2.33) and (2.36) we can write:

*Screening effect of the two earthwires*

$$E_c = - \sum_{k=1}^2 Z_{tk} I_k \quad (2.44)$$

$$E_c = - \left( \frac{Z_{(s1, pipe)}}{Z_{(s1, s1)}} G (Z_{(s1, s2)} E_{s2} - Z_{(s1, s1)} E_{s1}) + \frac{Z_{(s2, pipe)}}{Z_{(s2, s2)}} G (Z_{(s1, s2)} E_{s1} - Z_{(s2, s2)} E_{s2}) \right) \quad (2.45)$$

Where:  $I_i$  – inducing current;  $I_k$  – screening current;  $Z_{ti}$  – mutual impedances between the induced line and the inducing conductor;  $Z_{tk}$  – mutual impedances between the induced line and the screening conductor;  $s1$  – earthwire 1;  $s2$  – earthwire 2; pipe – pipeline;  $E_{s1}$ ,  $E_{s2}$  – e.m.f induced on the earthwires;

and:

$$G = \frac{Z_{(s1, s1)}}{(Z_{(s1, s2)}^2 - Z_{(s1, s1)}^2)} \quad (2.46)$$

## 2.5 Induced e.m.f (steady state condition)

We can see now that  $E_0$ ,  $E_{s1}$  and  $E_{s2}$  have similar expressions, all derived from equation (2.41):

$$E_0 = -j f \mu_0 \frac{I}{2} \left( \ln \left( \frac{(d_{2p} d_{3p})}{d_{1p}^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{3p})}{(d_{2p})} \right) \right) \quad (2.47)$$

$$E_{s1} = -j f \mu_0 \frac{I}{2} \left( \ln \left( \frac{(d_{(s1,2)} d_{(s1,3)})}{d_{(s1,1)}^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{(s1,3)})}{(d_{(s1,2)})} \right) \right) \quad (2.48)$$

$$E_{s2} = -j f \mu_0 \frac{I}{2} \left( \ln \left( \frac{(d_{(s2,2)} d_{(s2,3)})}{d_{(s2,1)}^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{(s2,3)})}{(d_{(s2,2)})} \right) \right) \quad (2.49)$$

where:

$d$  – distances; 1, 2 and 3 – phases; s1 and s2 – earthwires; p – pipeline;

(2.47) – induced e.m.f by the three phase triplet on the pipeline;

(2.48) – induced e.m.f by the three phase triplet on the first screening conductor (earthwire);

(2.49) – induced e.m.f by the three phase triplet on the second screening conductor (earthwire);

$$Z_{(s1, s1)} = Z_{(s2, s2)} \quad (2.50)$$

$$Z_{(s1, s2)} = Z_{(s2, s1)} \quad (2.51)$$

For the meaning of “ $\pm$ ” see paragraph 2.5.1.

G factor (see equation (2.45)) is very important, because it permits to reduce expression (2.44) to the one for a power line with *one earthwire*:

$$E_c = - \left( \frac{Z_{(s1, pipe)}}{Z_{(s1, s1)}} E_{s1} \right) \quad (2.52)$$

So the complete equation for the E.m.f induced by a power line with one screening conductor on a pipeline is:

$$E = E_0 - \frac{Z_{(s1, pipe)}}{Z_{(s1, s1)}} E_{s1} \quad (2.53)$$

Applying these expressions in case of fault, considering only one inducing conductor, we will see that expressions will be the same to the ones we use in case of fault.

### 2.5.3 Three phase line, balanced currents, two earthwires (approximation)

For a three-phase line with two earthwires a simplification is given by Cigré Guide.

Assimilating the two earthwires (a and b) to a single fictive earthwire (c) situated at half distance between both earthwires, with:

- resistance equal to parallel resistance of original earthwires

$$R_c = \frac{(R_a R_b)}{(R_a + R_b)} \quad (2.54)$$

- self inductance equal to:

$$l_c = \frac{(l_a + m_{ab})}{2} \quad (2.55)$$

where:  $R_a, R_b, R_c$  – resistances;  $l_a, l_c$  – self inductances;  $m_{ab}$  – mutual inductance;

we can apply the expression for three-phase lines with one earthwire even in cases of two earthwires.

Values of induced e.m.f obtained through the simplified form are compared with the ones obtained with the complete expression.

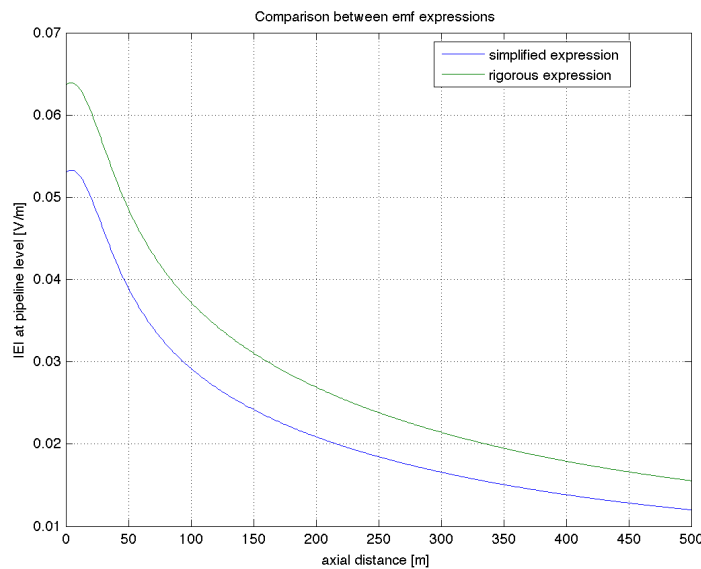


Figure 2.15: Comparison between rigorous and simplified expression for the induced e.m.f on a pipeline by a three-phase line with two earthwires

We can see that the simplified expression gives lower results than those through the rigorous one.



### 2.5.4 DCSB line configuration, balanced currents, no earthwires

The following figure shows a transmission line in SB phasing (homologous phases are symmetrically placed with the respect to the line axis) with references for distances and currents.

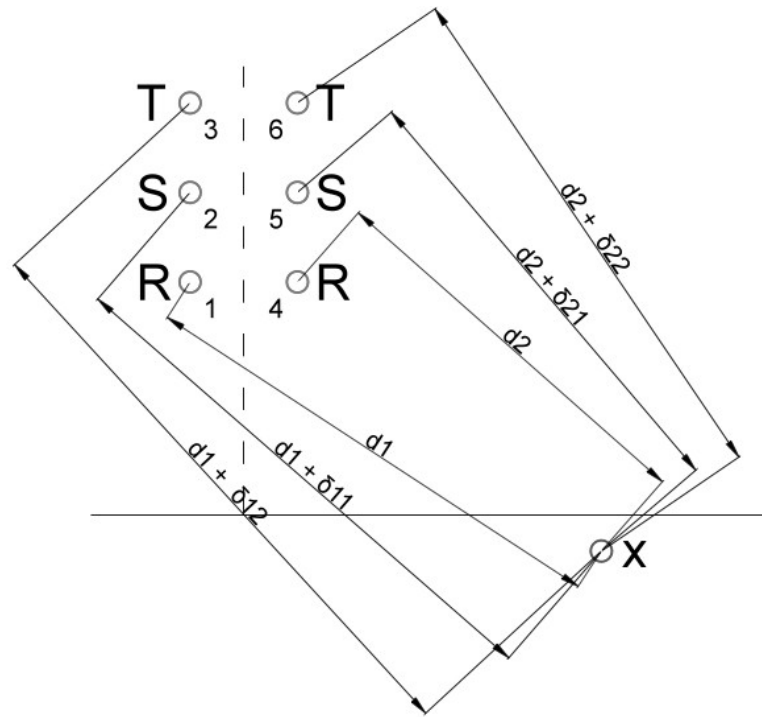


Figure 2.16: Distances between phase conductors and pipeline

Currents in phase R, S, T are the same of table 2.3; 1,2,..6 are the six conductors of the DCSB line configuration.

The k-factor general theory leads to the following expression (using Carson-Clem expression for the mutual impedance):

$$E = -j f \mu_0 \frac{I}{4} \left\{ \ln \frac{((d_1 + \delta_{11})(d_1 + \delta_{12})(d_2 + \delta_{21}))(d_2 + \delta_{22})^2}{(d_1^2 d_2^2)} \pm j \sqrt{3} \ln \left( \frac{(d_1 + \delta_{12})(d_2 + \delta_{22})}{(d_1 + \delta_{11})(d_2 + \delta_{21})} \right) \right\} \quad (2.56)$$

This expression can be obtained by composing the induced e.m.f's expressions of two three-phase lines.

### 2.5.5 DCSB line configuration, balanced currents, one or two earthwires

Equations to be used are (2.42), (2.43) and (2.44): they are built to be useful in several cases. In fact, what we need to do is to choose between one or two earthwires and insert into the equation the following expressions.

*Induced e.m.f by the phase conductors on the pipeline without screening conductors.*

$$E_0 = -j f \mu_0 \frac{I}{4} \left( \ln \left( \frac{(d_{2p} d_{3p} d_{5p} d_{6p})}{(d_{1p} d_{4p})^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{3p} d_{6p})}{(d_{2p} d_{5p})} \right) \right) \quad (2.57)$$

*Induced e.m.f by the phase conductors on the first screening conductor.*

$$E_{s1} = -j f \mu_0 \frac{I}{4} \left( \ln \left( \frac{(d_{(2,s1)} d_{(3,s1)} d_{(5,s1)} d_{(6,s1)})}{(d_{(1,s1)} d_{(4,s1)})^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{(3,s1)} d_{(6,s1)})}{(d_{(2,s1)} d_{(5,s1)})} \right) \right) \quad (2.58)$$

*Induced e.m.f by the phase conductors on the second screening conductor.*

$$E_{s2} = -j f \mu_0 \frac{I}{4} \left( \ln \left( \frac{(d_{(2,s2)} d_{(3,s2)} d_{(5,s2)} d_{(6,s2)})}{(d_{(1,s2)} d_{(4,s2)})^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{(3,s2)} d_{(6,s2)})}{(d_{(2,s2)} d_{(5,s2)})} \right) \right) \quad (2.59)$$

### 2.5.6 DCLR line configuration, balanced currents, no earthwires

The following figure shows a transmission line in LR phasing (homologous phases are *anti-symmetrically* placed with the respect to the line axis) with references for distances and currents.

Currents in phase R, S, T are the same of table 2.3; 1,2,..6 are the six conductors of the DCLR line configuration.

The k-factor general theory leads to the following expression (using Carson-Clem expression for the mutual impedance):

$$E = -j f \mu_0 \frac{I}{4} \left\{ \ln \left( \frac{((d_1 + \delta_{11})(d_1 + \delta_{12}) d_2 (d_2 + \delta_{21}))}{(d_1^2 (d_2 + \delta_{22})^2)} \right) \pm j \sqrt{3} \ln \left( \frac{(d_1 + \delta_{12}) d_2}{(d_1 + \delta_{11}) (d_2 + \delta_{21})} \right) \right\} \quad (2.60)$$

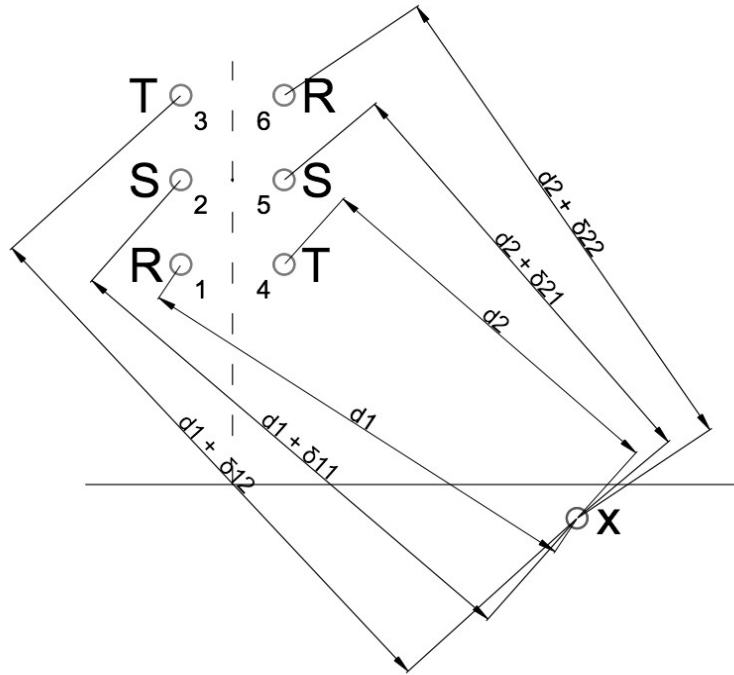


Figure 2.17: Distances between phase conductors and pipeline

### 2.5.7 DCLR line configuration, balanced currents, one or two earthwires

Equations to be used are (2.42), (2.43) and (2.44): they are built to be useful to several cases. In fact, what we need to do is to choose between one or two earthwires and insert into the equation the following expressions.

*Induced e.m.f by the phase conductors on the pipeline without screening conductors.*

$$E_0 = -j f \mu_0 \frac{I}{4} \left( \ln \left( \frac{(d_{2p} d_{3p} d_{4p} d_{5p})}{(d_{1p} d_{6p})^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{3p} d_{4p})}{(d_{2p} d_{5p})} \right) \right) \quad (2.61)$$

*Induced e.m.f by the phase conductors on the first screening conductor.*

$$E_{s1} = -j f \mu_0 \frac{I}{4} \left( \ln \left( \frac{(d_{(2,s1)} d_{(3,s1)} d_{(4,s1)} d_{(5,s1)})}{(d_{(1,s1)} d_{(6,s1)})^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{(3,s1)} d_{(4,s1)})}{(d_{(2,s1)} d_{(5,s1)})} \right) \right) \quad (2.62)$$

*Induced e.m.f by the phase conductors on the second screening conductor.*

$$E_{s2} = -j f \mu_0 \frac{I}{4} \left( \ln \left( \frac{(d_{(2,s2)} d_{(3,s2)} d_{(4,s2)} d_{(5,s2)})}{(d_{(1,s2)} d_{(6,s2)})^2} \right) \pm j \sqrt{3} \ln \left( \frac{(d_{(3,s2)} d_{(4,s2)})}{(d_{(2,s2)} d_{(5,s2)})} \right) \right) \quad (2.63)$$

### 2.5.8 Correction factor $k_4$ : transposition of the effects of a DCLR to a three-phase line

Since Cigré guide does not provide appropriate equations for double circuit low reactance line configuration (DCLR), a way to assess the induced e.m.f is introduced. This method is based on the following logical steps:

1. Magnetic induction is proportional to induced emf;
2. Magnetic induction's values of a three-phase line are higher than DCLR line's one, transporting the same current;
3. The ratio of the two different values of magnetic induction is related to the ratio of induced emf values in each case;
4.  $k_4$  is the ratio of magnetic induction's values;
5. induced emf by a DCLR line can be calculated from the value of an equivalent three-phase line (flag arrangement), transporting the same current, and  $k_4$ .

The *Induced e.m.f by a DCLR line on a pipeline without earthwires* becomes:

$$E_{DCLR} = k_4 \cdot E_{SC} \quad (2.64)$$

where  $E_{SC}$  is the *Induced e.m.f on a pipeline without earthwires by the equivalent three-phase line*. This line must transport the same current, and the centre of gravity of the triplet of conductors must be the same.

A complete explanation of this method is given in appendix B.

### 2.5.9 HV cables, balanced currents

Equations for HV cables (in steady-state conditions) are the same as those for the *induced e.m.f by the three phase aerial line on the pipeline without earthwires*. Sheaths of the cables' screening effect can be neglected if compared to the screening effect of the position of the triplet: in trefoil cables for HV transmission lines distances between phases are very small if compared with the distance with a nearby inducted circuit.

Anyway the effect of the sheaths of the cables can be neglected even because HV cables are installed in cross-bonding. This means that sheaths are periodically transposed and grounded as we can see in the following figure (directly grounded at the beginning of the period, surge arresters in the middle).

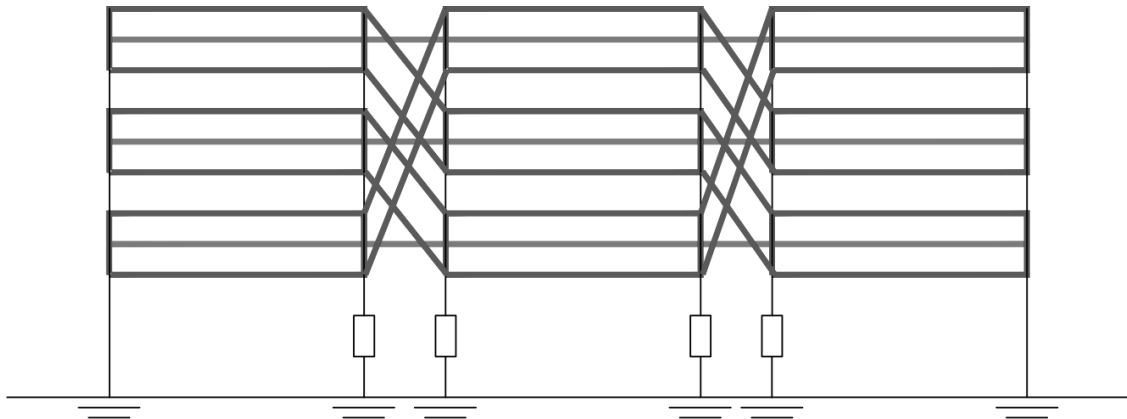


Figure 2.18: Cross Bonding's period

In this way induced voltage in the sheaths are compensated, and no current flows through them during steady-state conditions.

While in case of fault the surge arresters activate, so current circulates through the sheaths. This case is discussed later.

### 2.5.10 Comparison between e.m.f expressions (aerial HV lines)

In this section I will compare results obtained by using previous formulations.

I will analyze:

- three-phase HV line with one or two earthwires (vertical configuration);
- DCLR line configuration with one or two earthwires;
- DCSB line configuration with one or two earthwires;
- lines without earthwires (single triplet – DCLR – DCSB – DCLR through k4)

To make the comparison easy, all the powerlines will transport 2310 A (rms), that is the reference value for HV 380kV aerial power lines' carrying capacity [8].

In 380kV lines there are three conductors for each phase (see appendix D). Every conductor in each phase will transport 770 A [8]: the equivalent phase conductor will transport  $770 \times 3$  A, thus 2310 A.

In addition, soil resistivity will be 100  $\Omega\text{m}$  and Carson-Clem expressions will be used (the approximation is good enough).

Geometrical configurations will be:

2. Inductive Coupling

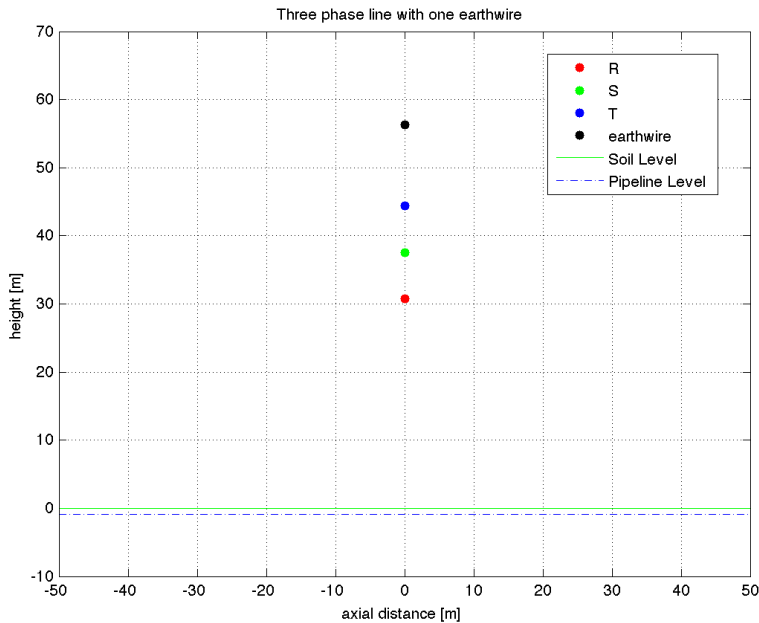


Figure 2.19: Three-phase line with one earthwire

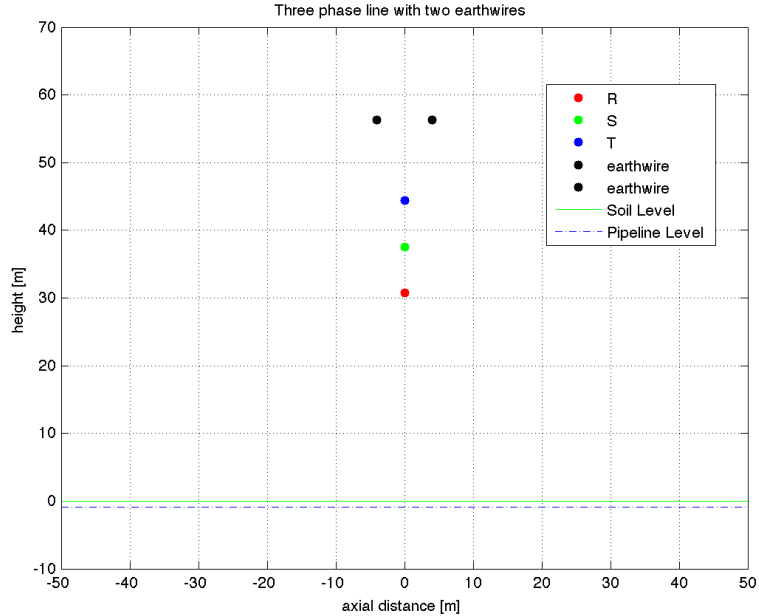


Figure 2.20: Three-phase line with two earthwires

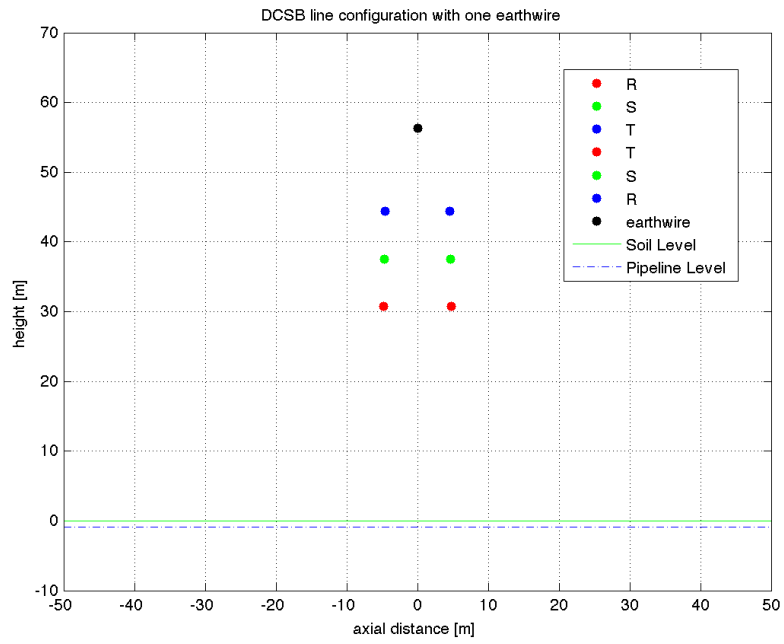


Figure 2.21: DCSB line configuration with one earthwire

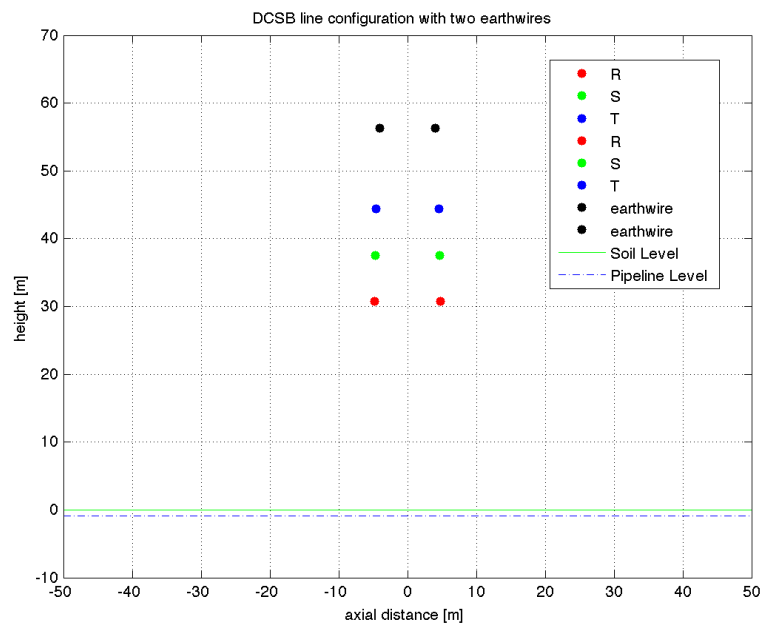


Figure 2.22: DCSB line configuration with two earthwires

2. Inductive Coupling

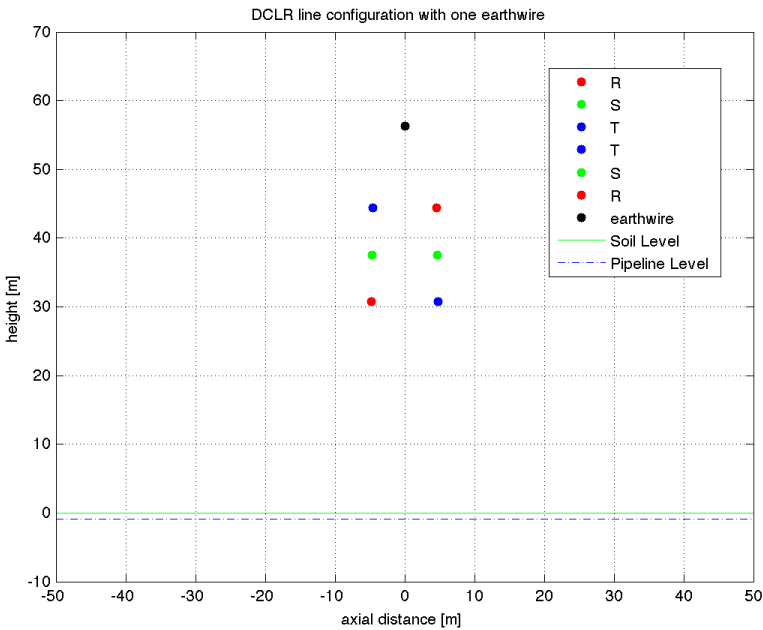


Figure 2.23: DCLR line configuration with one earthwire

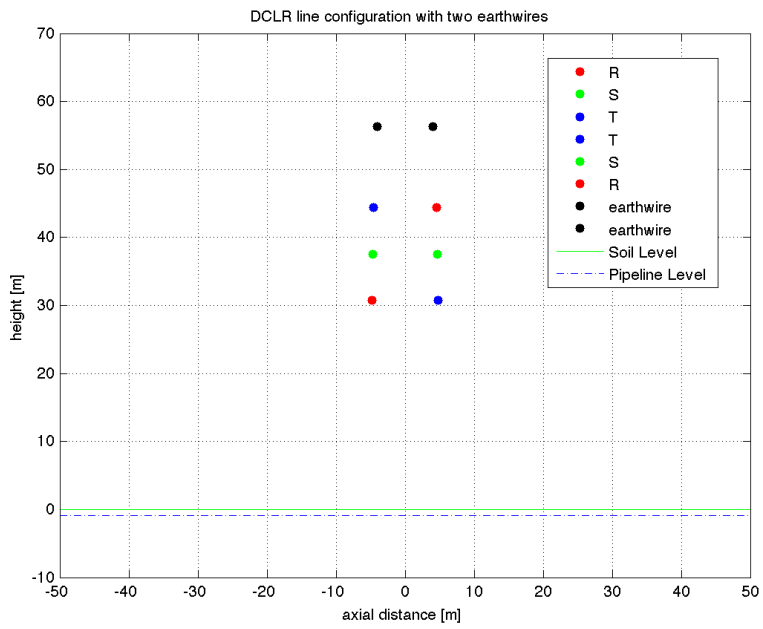


Figure 2.24: DCSB line configuration with two earthwires



## 2.5 Induced e.m.f (steady state condition)

Lines in graphs will be

- $E_0$  – the induced emf by the phase conductors on the pipeline without screening conductors;
- $E_c$  – the screening effect due to screening conductors (one or two);
- $E$  – the total e.m.f induced on the pipeline.

Results of e.m.f will be shown in [V/m] for modulus and [°] for phase, at the height of a buried pipeline in function of the distance from line axis.

The complete expression is:

$$E[V/m] = E_o + E_c \tag{2.65}$$

In the following illustrations there will be also a comparison between expression from the direct sequence and the inverse sequence of the term of currents

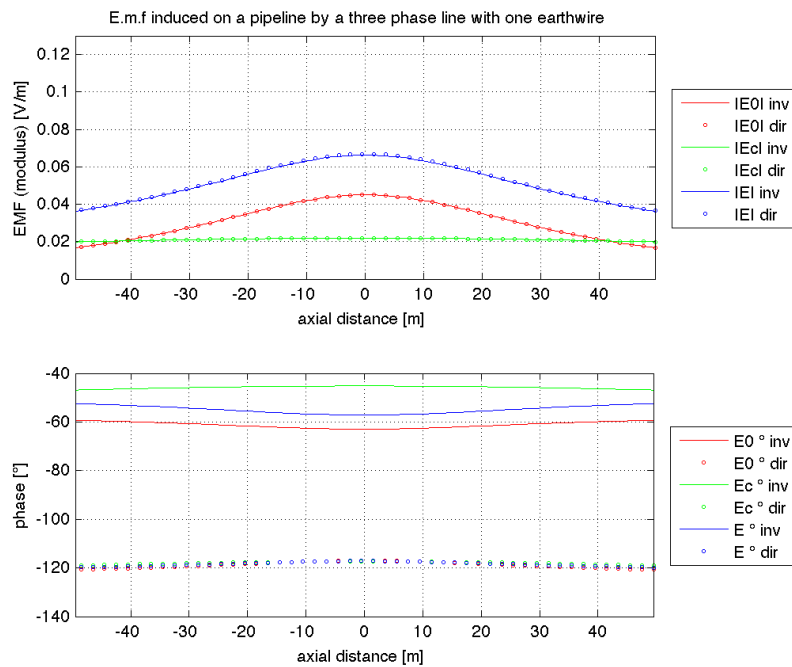


Figure 2.25: Induced e.m.f by a three-phase line – one earthwire

## 2. Inductive Coupling

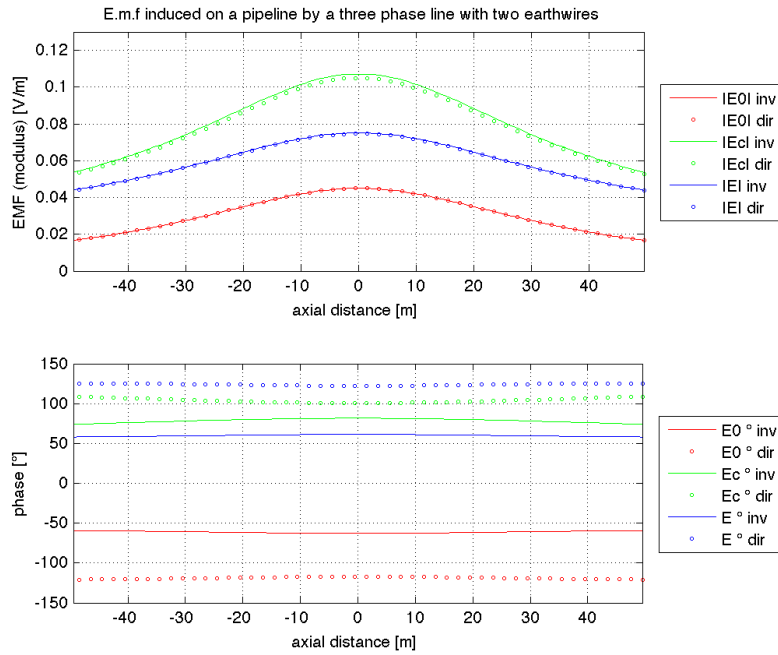


Figure 2.26: Induced e.m.f by a three-phase line – two earthwires

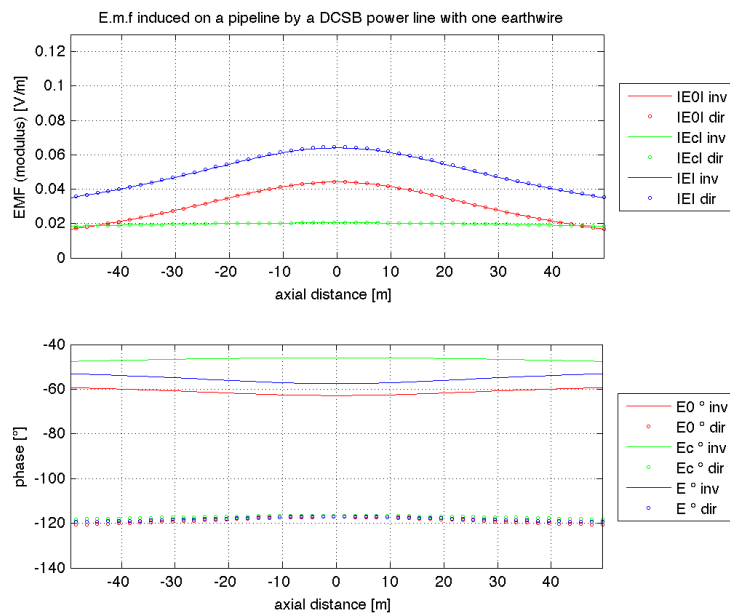


Figure 2.27: Induced e.m.f by a DCSB line – one earthwire

## 2.5 Induced e.m.f (steady state condition)

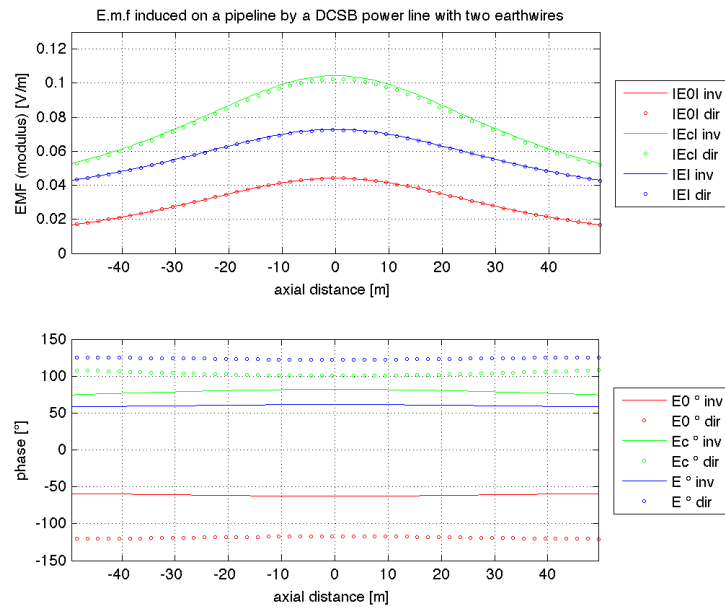


Figure 2.28: Induced e.m.f by a DCSB line – two earthwires

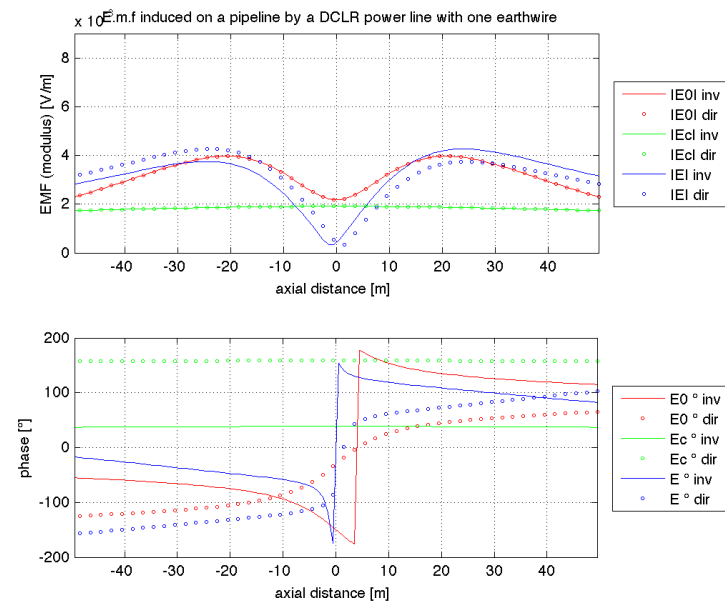


Figure 2.29: Induced e.m.f by a DCLR line – one earthwire

## 2. Inductive Coupling

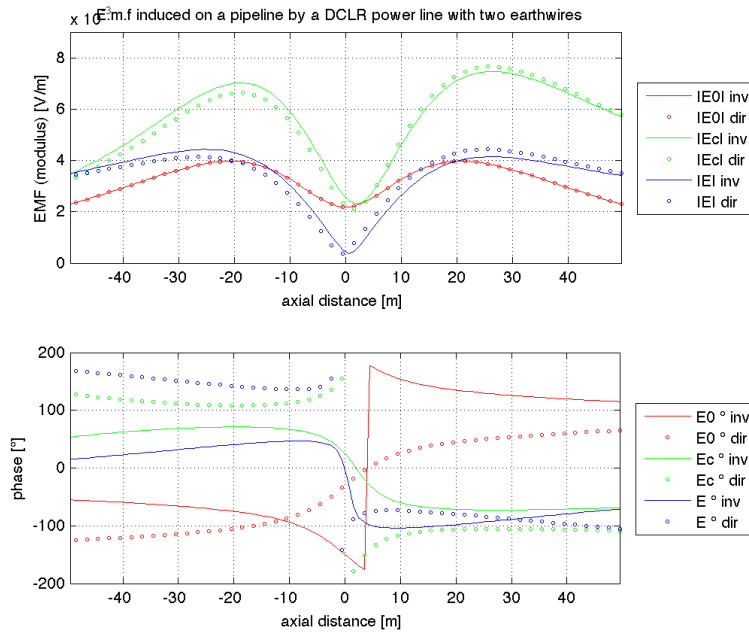


Figure 2.30: Induced  $e.m.f$  by a DCLR line – two earthwires

As we see in illustrations shown before only the  $E_0$ ,  $E_c$  and  $E$  curves derived by the direct sequence are equal in modulus to the ones from the inverse sequence. Negligible differences might be seen with DCLR lines, that may be caused by numerical errors and simplifications. While phase angles are different. *Once we set the reference in triplets of currents we can make all the sums we need, without making errors.*

We can even see how in steady-state conditions the presence of earthwires may increase the total induced emf: a complete description of the phenomenon is done in appendix C.

In the following figure  $E_0$  curves (*Induced e.m.f. without earthwires*) are compared:

- results from three-phase line configuration and DCSB line configuration are practically the same (as shown in previous figures – same results even for  $E$  and  $E_c$ );
- DCLR line configuration produces lower values of induced e.m.f, than the one from DCSB;
- $k_4$  theory produces acceptable results, if simplicity of calculations is concerned – results are precautionary within 20 m from line axis.

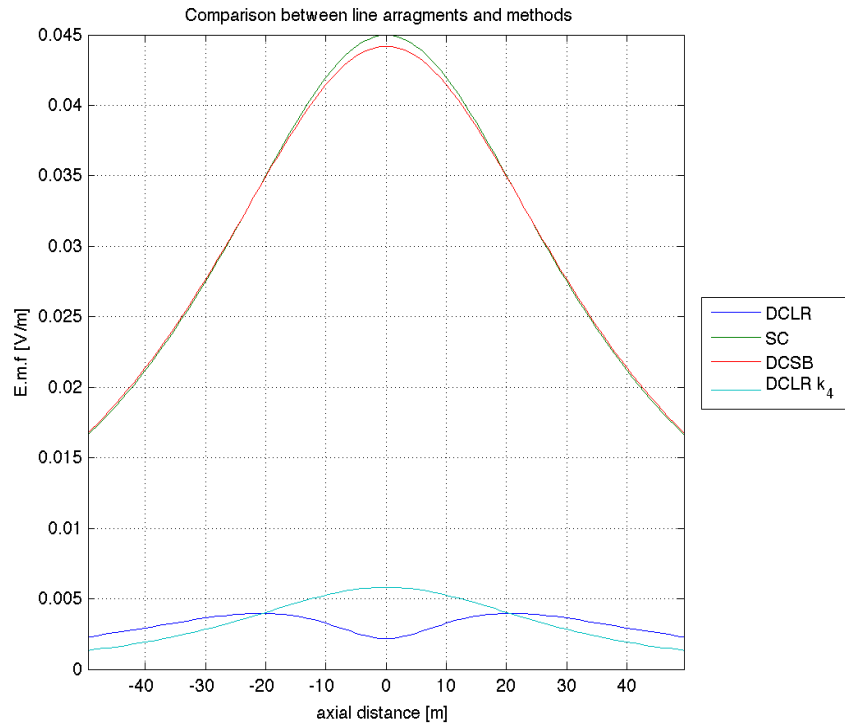


Figure 2.31:  $E_0$  in several cases

## 2.5.11 E.m.f values: comparison between HV cables and HV aerial lines without earthwires

This comparison will make clear that the position of phases may contribute to the screening effect: in fact phases in HV cables are much more closer than the ones in HV aerial lines.

To compare results, current in both lines is  $I=1000$  A, and the e.m.f values are calculated at pipeline level.

In section, lines will be described by the following figures.

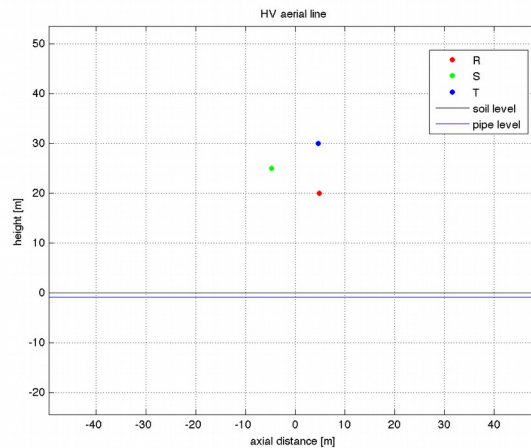


Figure 2.32: HV aerial line without earthwires

2. Inductive Coupling

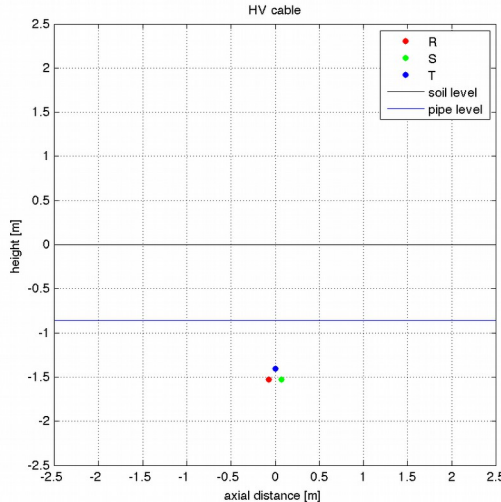


Figure 2.33: HV trefoil cable

Proximity of phases reduces the induced e.m.f at pipeline level, as shown in the following figure.

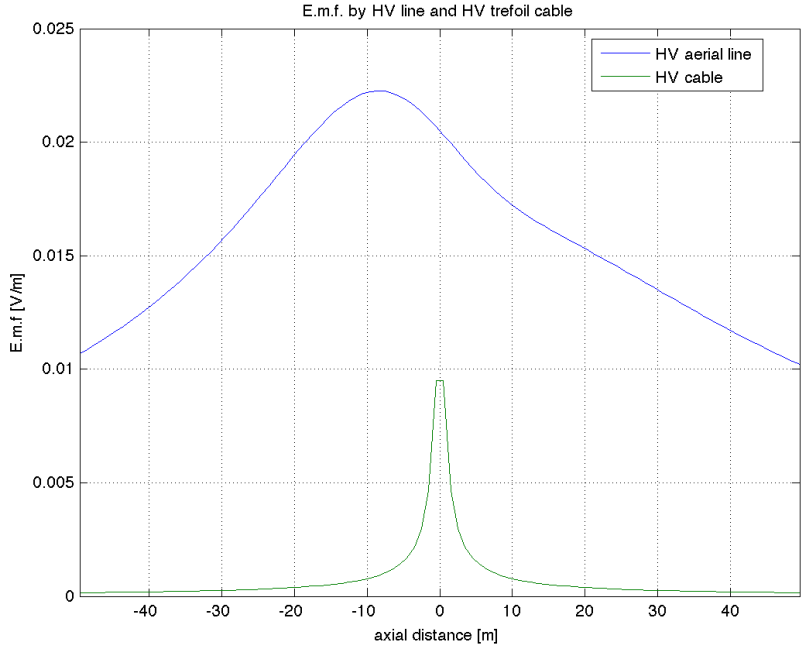


Figure 2.34: Induced e.m.f on a pipeline in function of the distance from line axis

## 2.6 Induced e.m.f (fault condition)

In case of single-phase fault to earth, the following expression is used:

$$E[V/m] = -k Z_m I_f \quad (2.66)$$

where:  $k$  – screening factor,  $Z_m$  – mutual impedance,  $I_f$  – inducing current.

The inducing current is the fault current, and the screening factor is due to the presence earthwires or cable sheaths. Influence of the other phases is not considered.

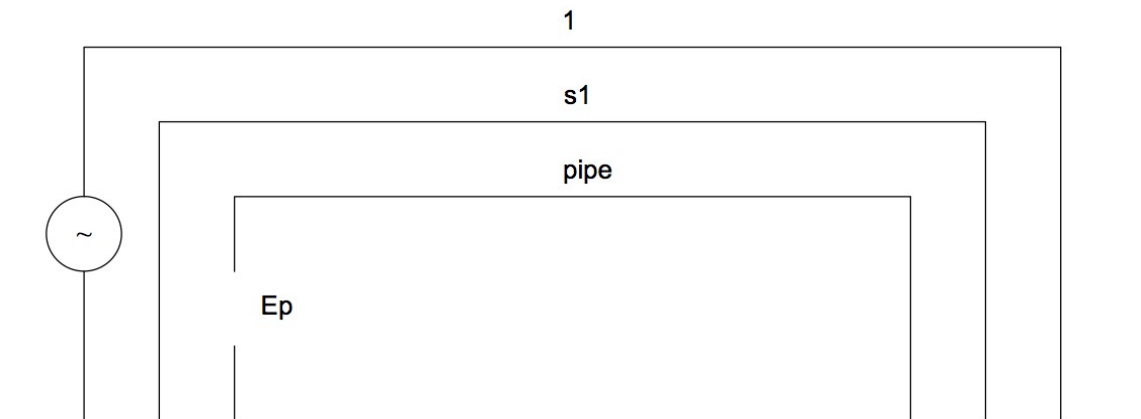


Figure 2.35: Inducing conductor, screening conductor, induced conductor - scheme

Where: 1 – fault conductor; s1 – screening conductor; pipe – induced conductor;  $E_p$  – e.m.f..

During faults earthwires and sheaths always produce a screening effect. In the following example we consider:

- HV aerial line (with one earthwire);
- HV cable;

Induced e.m.f on a pipeline is calculated in function of the axial distance (see fig 2.38 and 2.39), and the screening effects of the earthwire and the sheath of the cable are compared during fault condition (fault current is  $I=10\text{kA}$ ).

## 2. Inductive Coupling

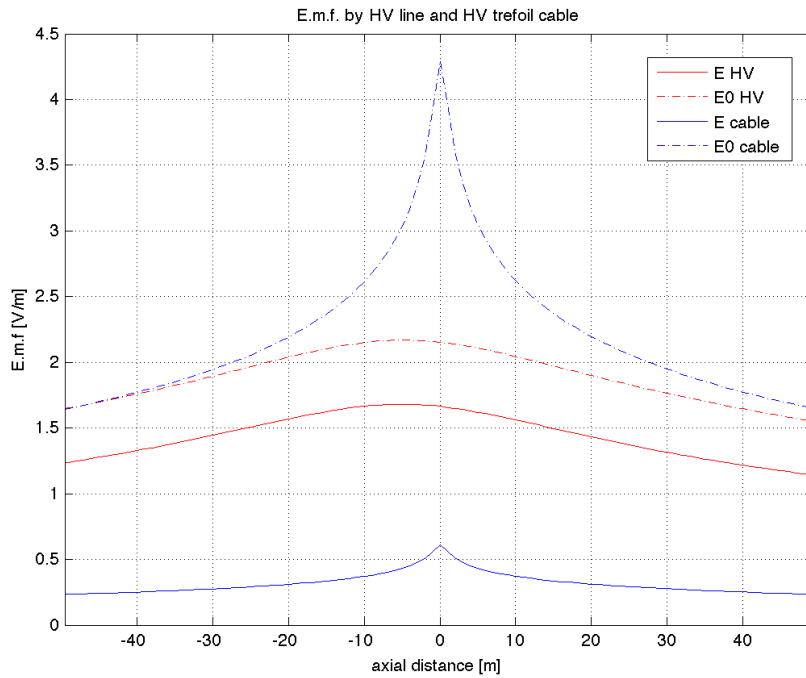


Figure 2.36: Evaluation of screening effects during fault

In the previous figure:

- $E_0$  HV – Induced e.m.f by the HV aerial line without earthwires;
- $E_0$  cable – Induced e.m.f by the HV cable ignoring the effects of the sheath;
- E HV – Induced e.m.f by the HV aerial line with one earthwire;
- E cable – Induced e.m.f by the HV cable considering the screening effect of the sheath.

We can see that induced e.m.f by the HV cable is minimal, and the sheath gives a high screening effect, if compared with the one of an earthwire.

*The explanation is that mutual distances between sheaths and cable's conductors are smaller than distances between aerial phase conductors and earthwires, and much smaller than distances from pipelines.*



## 2.7 Induced Circuit

Once induced e.m.f along the pipe is calculated, it is necessary to build an electrical model of the pipeline, through which output data values of current along the pipe and voltage to the ground are obtained.

The pipeline has been previously divided into small sections: each section will correspond to the following electrical scheme.

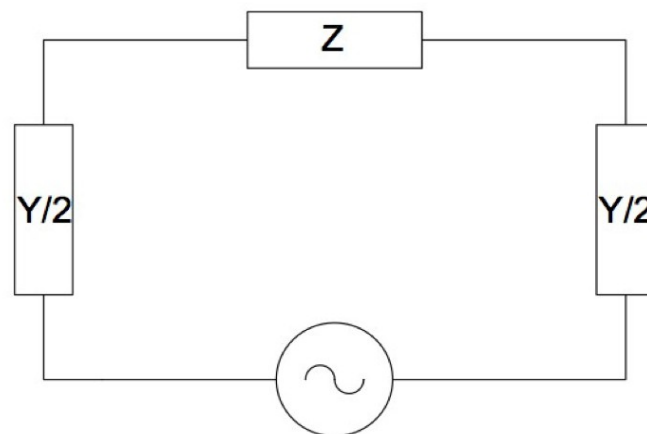


Figure 2.37: Electrical scheme for each section of the pipeline

Where:  $E$  [V/m] – induced e.m.f. in this section of pipe,  $Y$  [S/m] pipeline admittance in the considered section;  $Z$  [ $\Omega$ /m] – pipeline series impedance in the considered section.

Connecting in series all the sections of the pipeline:

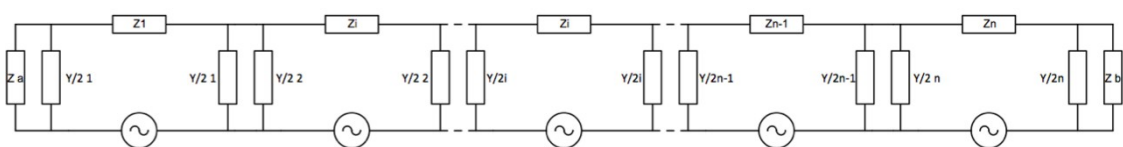


Figure 2.38: Pipeline's electrical model

Where:  $Z_a$  – upstream impedance,  $Z_b$  – downstream impedance.

## 2. Inductive Coupling

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Pipeline's sections that are not subjected to interference are represented by upstream and downstream impedances. These impedances are equal to:

- *characteristic impedance* – if the pipeline's route continues for long distances;
- *grounding impedance* – if the pipeline is locally grounded;
- *infinite impedance* – if the pipeline stops without grounding and if there's an insulating flange

In each section local grounding of the pipeline or the presence of insulating flanges is taken into account by modifying values of  $Z$  and  $Y$ .

### 2.7.1 Pipeline series impedance

Pipeline series impedance is:

$$z\left[\frac{\Omega}{m}\right] = r + j\omega m \quad (2.67)$$

where:

$$r = \frac{\sqrt{(\rho_p \mu_0 \mu_r \omega)}}{(\pi D \sqrt{2})} + \mu_0 \frac{\omega}{8} \quad (2.68)$$

$$\omega m = \frac{\sqrt{(\rho_p \mu_0 \mu_r \omega)}}{(\pi D \sqrt{2})} + \mu_0 \frac{\omega}{2\pi} \ln\left(3.7 \frac{\sqrt{\left(\frac{\rho}{\omega \mu_0}\right)}}{D}\right) \quad (2.69)$$

### 2.7.2 Pipeline admittance

Pipeline admittance for coated pipes is:

$$y\left[\frac{S}{m}\right] = \frac{\pi D}{(\rho_c \delta_c)} + j\omega \varepsilon_0 \varepsilon_r \frac{\pi}{\delta_c} \quad (2.70)$$

Where:  $\omega$  [1/s]– angular frequency;  $D$  [m] – pipe's diameter;  $\mu_0$  [H/m] – vacuum magnetic permeability  $\mu_r$  – pipe's relative permability;  $\varepsilon_0$  [F/m] – vacuum permittivity;  $\varepsilon_r$  – pipe's coating's relative permittivity;  $\rho$  [ $\Omega m$ ] – soil electrical resistivity;  $\rho_p$  [ $\Omega m$ ] – pipe's resistivity;  $\rho_c$  [ $\Omega m$ ] pipe's coating's resistivity;  $\delta_c$  [m] – thickness of the coating.

*Note: Coating's specific resistance is related to coating's electrical resistivity by the following relation:*

$$r_c [\Omega m^2] = \rho_c [\Omega m] \delta_c [m] \quad (2.71)$$

## 2.8 Induced Voltage

Calculation of voltage appearing on the pipelines is normally worked out in two steps:

1. determination of the induced electromotive forces induced along the pipeline;
2. calculation of the voltage to earth and of the circulating currents in response to the induced e.m.f.

A clear distinction has to be made between e.m.f and voltage:

- the emf are assimilated to electric generators in the circuits pipeline-earth described before;
- voltage is the result of the effect of the induced emf on the pipeline.

Solution of pipeline circuit (fig 2.44) is needed for the calculation of the induced voltage. This solution is given by the following steps:

- pipeline's system setup;
- calculation of the impedance's matrix;
- calculation of pipeline's circulating currents;
- calculation of voltage to ground in each section of the pipeline.

### 2.8.1 Pipeline's system

Calculation of voltage to ground along the pipeline requires to solve the following system:

$$[E]=[Z][I] \quad (2.72)$$

where:

- a)  $[E]$  is the vector of the induced e.m.f [V] in pipeline's sections;
- b)  $[I]$  is the vector of the circulating currents in each pipeline's section;
- c)  $[Z]$  is the impedance's matrix of the pipeline.

## 2.8.2 Impedance's matrix of the pipeline

Impedance's matrix of the pipeline is a square matrix if the pipeline is not divided into bifurcations along its route.

If the pipeline is divided into 7 sections (for example), matrix will be the following one:

$$\begin{bmatrix} Z_{11} & Z_{12} & 0 & 0 & 0 & 0 & 0 \\ Z_{21} & Z_{22} & Z_{23} & 0 & 0 & 0 & 0 \\ 0 & Z_{32} & Z_{33} & Z_{34} & 0 & 0 & 0 \\ 0 & 0 & Z_{43} & Z_{44} & Z_{45} & 0 & 0 \\ 0 & 0 & 0 & Z_{54} & Z_{55} & Z_{56} & 0 \\ 0 & 0 & 0 & 0 & Z_{65} & Z_{66} & Z_{67} \\ 0 & 0 & 0 & 0 & 0 & Z_{76} & Z_{77} \end{bmatrix} \quad (2.73)$$

Impedances in the matrix will be:

$$Z_{(i,i+1)} = \frac{2}{(Y_i + Y_{(i,i+1)})} \quad (2.74)$$

$$Z_{(i-1,i)} = \frac{2}{(Y_i + Y_{(i,i-1)})} \quad (2.75)$$

$$Z_{(i,i)} = -Z_{(i-1,i)} + Z_i - Z_{(i,i+1)} \quad (2.76)$$

$$Z_{(i,j)} = Z_{(j,i)} \quad (2.77)$$

In particular:

$$Z_{(1,1)} = -Z_{(0,1)} + Z_1 - Z_{(1,2)} \quad (2.78)$$

$$Z_{(7,7)} = -Z_{(6,7)} + Z_7 - Z_{(7,8)} \quad (2.79)$$

where  $Z_{0i}$  e  $Z_{78}$  are respectively the parallel impedance of  $Y/2_i$  and upstream impedance, and the parallel impedance of  $Y/2_i$  and downstream impedance.

In each section local grounding of the pipeline or the presence of insulating flanges is taken into account by modifying the values of the matrix.

### 2.8.3 Pipeline's circulating currents

Circulating currents are obtained by the solution of the following system.

$$[I]=[Z]^{-1}[E] \quad (2.80)$$

where:

- d)  $[E]$  is the vector of the induced e.m.f [V] in pipeline's sections;
- e)  $[I]$  is the vector of the circulating currents in each pipeline's section;
- f)  $[Z]$  is the impedance's matrix of the pipeline.

So currents in each circuit of the pipeline are calculated: these currents are the real currents that flow in each section of the pipeline.

Currents to earth are calculated with the following expression:

$$I_i = I_j - I_{(j+1)} \quad (2.81)$$

Where: j and j+1 are two adjacent pipeline's sections; i is the connection to earth by pipeline's admittance.

### 2.8.4 Voltage to ground

In each section of the pipeline we obtain local voltage to earth with the following expression.

$$U_i = Z_i I_i \quad (2.82)$$

where: I – current to earth; Z – impedance to earth; U – voltage to earth; i – section of the pipeline.

In case of several inducing circuits, CEI 304-1 introduces this formulation.

$$U[V] = \sqrt{\sum_{i=1}^N |U_i|^2} \quad (2.83)$$

where i are the inducing lines.

*If a correct reference system is set, contributes of different inducing circuits at the same frequency can be taken into account by vectorial sum. If circuits' frequencies are different from each other expression (2.82) is necessary.*



# Chapter 3

## Conductive Coupling

### 3.1 Ground potential rise of towers

During a single phase fault to earth we may have high values of current flowing through the tower to earth: this current is called earth current.

When the line is equipped with earthwires only a part of the fault current flows to the earth: an important part is distributed to the nearby towers through earthwires. In case of absence of earthwires the earth current is equal to the fault current.

So the earth current produces a ground potential rise, or earth potential rise (EPR), as we can see in the following expression:

$$EPR = Z_t I_e \quad (3.1)$$

where EPR – earth potential rise;  $Z_t$  – earth impedance of the grounding system for the tower;  $I_e$  – earth current.

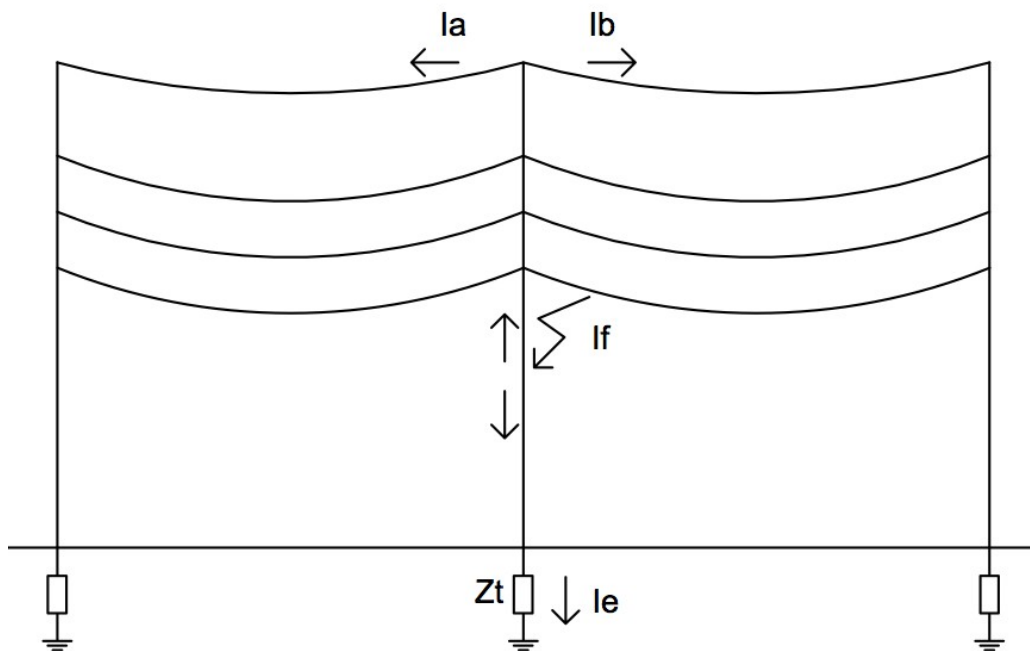


Figure 3.1: Fault to tower

### 3. Conductive Coupling

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According to the previous figure, currents are related by the following relation:

$$I_e = I_f - I_a - I_b \quad (3.2)$$

where:  $I_f$  – fault current;  $I_e$  – earth current;  $I_a$  and  $I_b$  – currents flowing to the other towers through the earthwires.

So without earthwires:

$$I_e = I_f \quad (3.3)$$

In case of lines provided with earthwires for a precise evaluation of the current flowing into the soil the knowledge of the earth resistances of all the towers and the resolution of all the circuits formed by the earthwires and the towers are required.

If earth resistances are more or less the same for all the towers we can easily evaluate the earth current with the following expression:

$$I_e = \frac{Z_{tw}}{(2Z_t + Z_{tw})} k I_f \quad (3.4)$$

where:  $k$  – reduction factor due to the earthwires (see paragraph 2.4.1);  $Z_{tw}$  – impedance of the circuit formed by the earthwire(s) and the towers.

$$Z_{tw} = \frac{1}{2} (Z_s + \sqrt{(Z_s(4Z_t + Z_s))}) \quad (3.5)$$

where:  $Z_s$  – impedance of the circuit formed by the earthwire(s) and the earth between two successive towers.

A much more simplified approach leads to the following relations:

$$I_f = I_a = I_b \quad (3.6)$$

$$I_e = \frac{1}{3} I_f \quad (3.7)$$

This approach is even precautionary: in fact values of  $I_e$  are much higher than the previous ones.



### 3.2 Potential transferred to an underground pipeline

For the evaluation of voltage transferred to a pipeline grounded near the faulty tower we consider a simplified case, where there aren't any insulating flanges, the electric parameters are constant, the pipeline route follows a straight line, the pipe's section exposed to EPR is shorter than the characteristic length and the pipeline extends for a few kilometers without earthing on both ends.

In the following figure we can see the electric circuit model.

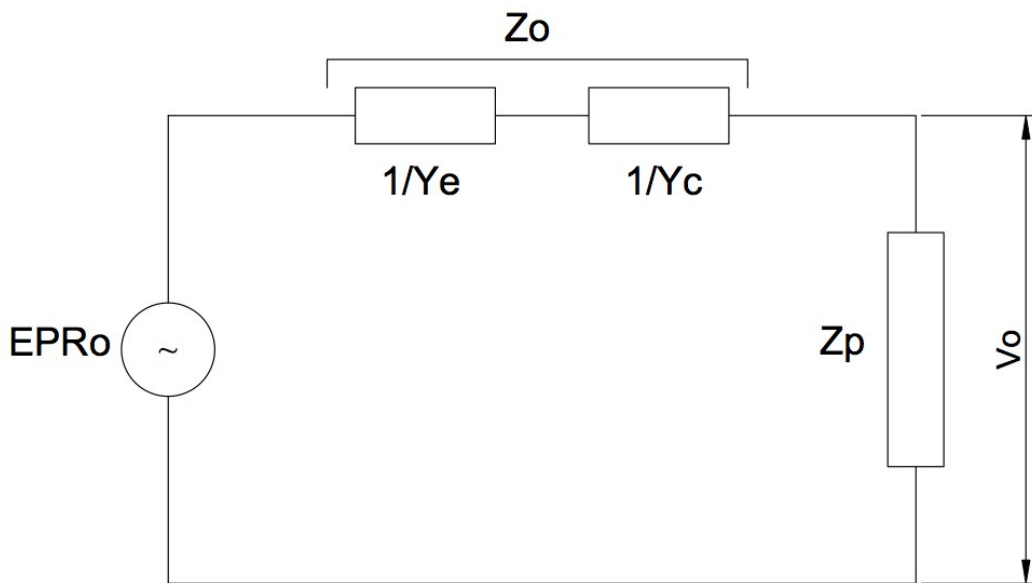


Figure 3.2: Circuit of the transferred potential

Where:  $Z_p$  – impedance of the circuit pipeline-earth outside the zone of injection (equal to  $Z_0/2$  – half of characteristic impedance),  $Z_0$  – the local impedance of the circuit pipeline-earth;  $Y_e$  – local admittance due to earth;  $Y_c$  – local admittance due to coating;  $V_0$  – potential transferred locally to the pipeline (in the section of the pipe near the faulty tower).

So  $V_0$  is the highest value of the transferred potential, which decreases along the pipeline according to the following relation:

$$V(x) = V_0 e^{-|\gamma \cdot x|} \quad (3.8)$$

Where:  $\gamma$  – propagation constant;  $x$  – abscissa of the pipeline route (the origin is taken at the closest point of the tower).

### 3. Conductive Coupling

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The solution of the electric circuit shown before leads to the determination of the value of the maximum transferred potential.

$$V_0 = \frac{Z_p}{\left(\frac{1}{Y_e} + \frac{1}{Y_c} + Z_p\right)} EPR_0 \quad (3.9)$$

If we introduce a new factor R, defined by the following relation, we can easily quantify  $V_0$  values.

$$R = \frac{Z_p}{\left(\frac{1}{Y_e} + \frac{1}{Y_c} + Z_p\right)} \quad (3.10)$$

If pipeline's coating is intact, R values will be very low: the potential difference is concentrated on the coating and pipeline's potential won't rise. In fact:

$$\frac{1}{Y_c} \gg \frac{1}{Y_e}; \quad \frac{1}{Y_c} \gg Z_p; \quad R \approx 0 \quad (3.11)$$

If pipe's coating is damaged near the tower, R value will not be equal to zero, and it must be calculated.  $Y_c$ 's formulation is given in 2.7.2,  $Z_p$  is considered as half of the characteristic impedance (initial hypothesis),  $Y_e$  is given by the following expression.

$$Y_e = \pi \frac{\left(\frac{1}{\rho} + j\omega\varepsilon\right)}{\left(\ln\left(\frac{1.12}{\gamma a}\right)\right)} \quad (3.12)$$

where:  $\varepsilon$  – soil electrical permittivity;  $a$  – equivalent radius of buried pipelines.

$$a = \sqrt{\left(r^2 + 4h_p^2\right)} \quad (3.13)$$

where:  $r$  – pipe's radius;  $h_p$  – pipe's depth.

Values of  $Y_e$  and  $Y_c$  are calculated in the local section of pipeline, the length of which is L'.

# Chapter 4

## Admissible voltage

Dangers for people touching a metallic pipeline subjected to the electrical influence of a HV line are function of the amplitude and the duration of the current injected into the body. Even danger to the pipeline and to object electrically connected must be taken into account.

Although the risk depends on the current, it appears in practice more convenient to define the admissible values as function of voltage.

### 4.1 Limitations for danger to people

#### Fault condition

Table 4.1: Voltage limits for danger to people - fault condition

FAULT DURATION [s]	ADMISSIBLE VOLTAGE [Vrms]
$T \leq 0.1$	2000
$0.1 < T \leq 0.2$	1500
$0.2 < T \leq 0.35$	1000
$0.35 < T \leq 0.5$	650
$0.5 < T \leq 1$	300
$1 < T \leq 3$	150
$T > 3$	60

#### Steady-state condition

The maximum admissible value of voltage is 60 V (rms) under steady-state conditions.

### 4.2 Limitations for danger to pipeline's system

#### Fault condition

Table 4.2: Table Voltage limits for danger to pipeline's system - fault condition

FAULT DURATION [s]	ADMISSIBLE VOLTAGE [Vrms]
$T \leq 1$	2000*
$T > 1$	60

\* - higher values might be accepted; this value is even the value of the maximum potential difference on insulating flanges.

#### Steady-state condition

The maximum admissible value of voltage is 60 V (rms) under steady-state conditions.



# Chapter 5

## *Mitigation*

Mitigating measures are the most generally required in case of close separation between HV lines and pipeline, even if the length of influence doesn't exceed a few hundred meters. In fact close separation may cause interference, such as inductive coupling, and conductive coupling. This interference generates induced voltage on the pipeline.

In the previous chapter standard's limits for induced voltage are shown.

In this section the most common mitigating measures are described; they are divided into two groups: measures on the power line, measures on the pipeline. According to the needs they may also be applied together.

### **5.1 Measures applied to the HV line**

#### *Addition of earth wires (aerial lines)*

Earthwires reduce the induced emf (inductive coupling) during earth faults by providing a screening conductor close to the faulted one and they even reduce the current to earth (conductive coupling) if the fault regards the tower, by connecting all successive towers and providing an alternative path to the local earthing system for the faulty current, with the reduction of the earth potential rise. Anyway, under steady-state conditions, earthwires increase the induced emf (see appendix C). However, this mitigating measure is useful in case of lightning, because the earthwire protects the phase conductors.

#### *Transposition of phase conductors*

A regular transposition of the phase conductors can reduce the voltage induced in steady-state conditions, when the pipe is practically parallel to the electrical line

#### *DCLR lines*

In case of double circuits line, choosing the asymmetrical phase's arrangement for the conductors reduces the magnetic field and the induced emf (inductive coupling). Instead of building a single circuit line, it is more effective to project a DCLR line transporting the same current. (demonstration in chapter 2)

#### *Improving tower earth electrode*

In case of conductive coupling between a tower and a nearby pipeline, it may be possible to reduce the potential rise of the tower and the earth potential rise at pipeline location by improving the tower earth electrode.

#### *Smaller distances between phases*

The reduction of the distances between phases contributes to decrease the magnetic induction and the induced emf: in fact cables produce lower values of magnetic induction than aerial lines, because of the proximity of phases.

### **5.2 Measures applied to the pipeline**

#### *Earthing the pipeline*

Earthing the pipeline is the most classical approach to reduce voltage values due to inductive coupling in steady-state operation or during faults. In the less critical situations the pipeline will be earthed in two points, the extremities of the zone of influence (upstream and downstream sections). In most cases, it will be connected to the earth where the metal is accessible. Earthing may be set through direct grounding or surge arrester (dischargers).

#### *Pipeline insulating flanges*

Insulating flanges are frequently used at the entry of a station to isolate the pipeline from the local earth grid. They will be provided with surge arrested to avoid destruction (in case of fault).

Insulating flanges can also be used to subdivide the pipeline into several section inside a long zone of influence and reduce the inductive influence. However, this mitigating measure will be very expensive if the pipe is already existing and grounded.

#### *Enhanced insulation of the pipeline*

An enhancement of the pipeline's insulating coating can be used to avoid problems due to conductive coupling in the near vicinity of the tower. It can be obtained by increasing the thickness of the coating.

# Chapter 6

## *Calculation programs*

For the solution of inductive and conductive interference with a pipeline two Matlab programs were made. As for inductive coupling, instead of solving the equations, the program solves the “k-factor general theory” system for each case: in addition calculation of mutual impedances can be done by using Carson-Clem or Carson-Series expression with the program, while the analytical expressions are based on Carson-Clem equation.

Cigré guide illustrates the symmetrical component method for the analysis of the influence of unbalanced currents: the unbalanced system is replaced by three balanced systems:

- positive sequence systems;
- negative sequence systems;
- zero-sequence systems.

Instead of using this method, my program permits you to set amplitude and phase angle of each inducing current: the solution is easier and faster.

The application to real cases shown below regards only inducing systems with balanced currents.

In the following figure I will show the steps for the inductive coupling program in case of one inducing system and one induced one. In case of several inducing lines, under steady-state conditions, values of induced voltage must be summed, and a new comparison with Italian standard's limits must be done in order to apply mitigation measures (if these are required).

As for conductive coupling, the program solves Cigré Guide's simplified equations.

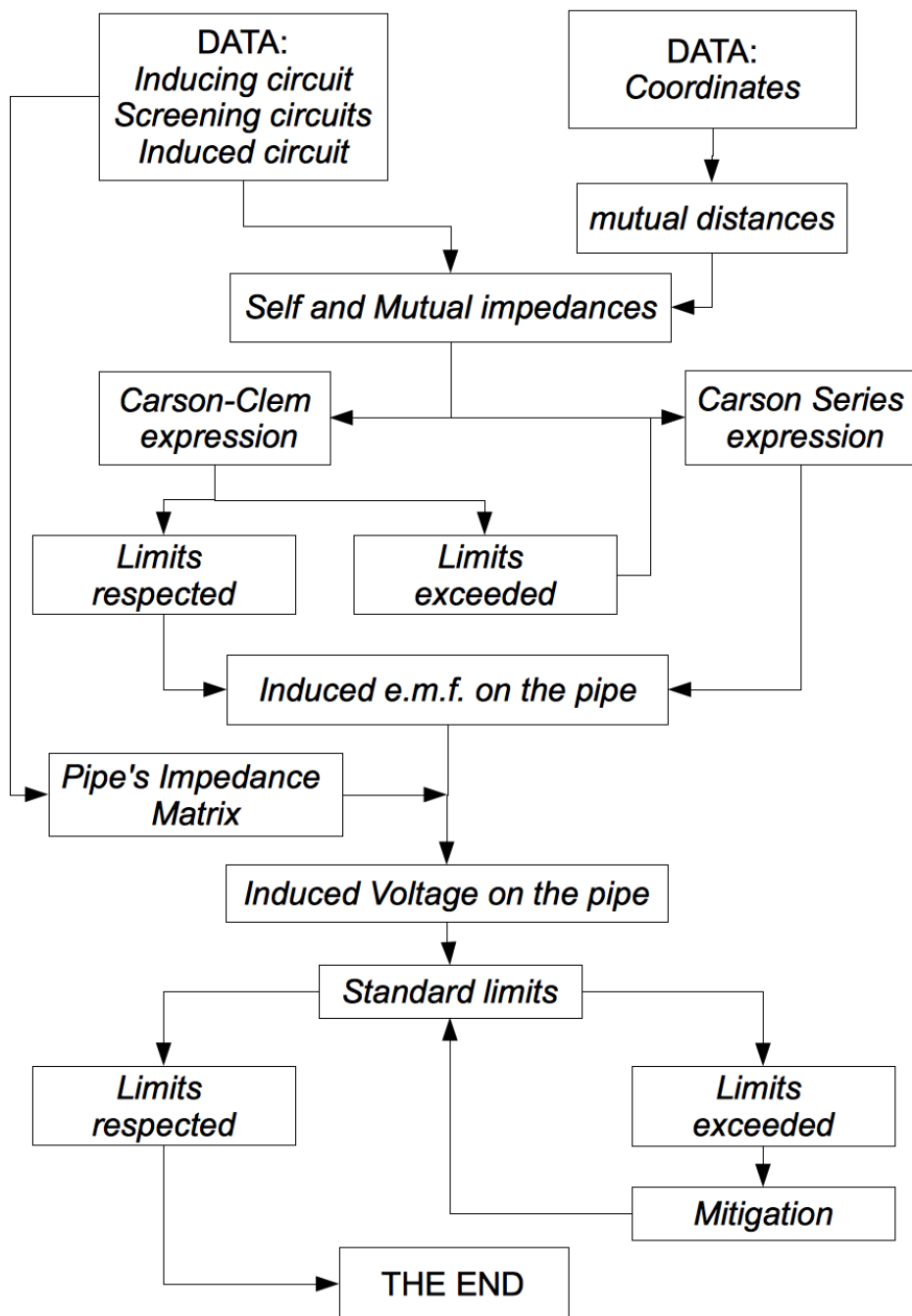


Figure 6.1: Program's flowing chart with one inducing system (Inductive Coupling)



# Chapter 7

## *Application to real cases*

### **7.1 Inductive Coupling: “Feeder Idrovia Saonara”**

In this section the interference of a 220 kV cable and a 380 kV aerial line with a pipeline is analyzed. The two lines take part of the rationalization plan of the high voltage transmission system of the north-east of Italy planned by Terna, and developed by the engineering division of Terna Rete Italia in Padua (Italy). The pipeline is an AcegasAps's pipe, called “Feeder Idrovia Saonara”.

#### **7.1.1 Exposure length**

Exposure length is the length of the zone where the influence is significant: this means that effect on an induced circuit must be considered only if the distances are lower than a certain value, as explained in previous sections.

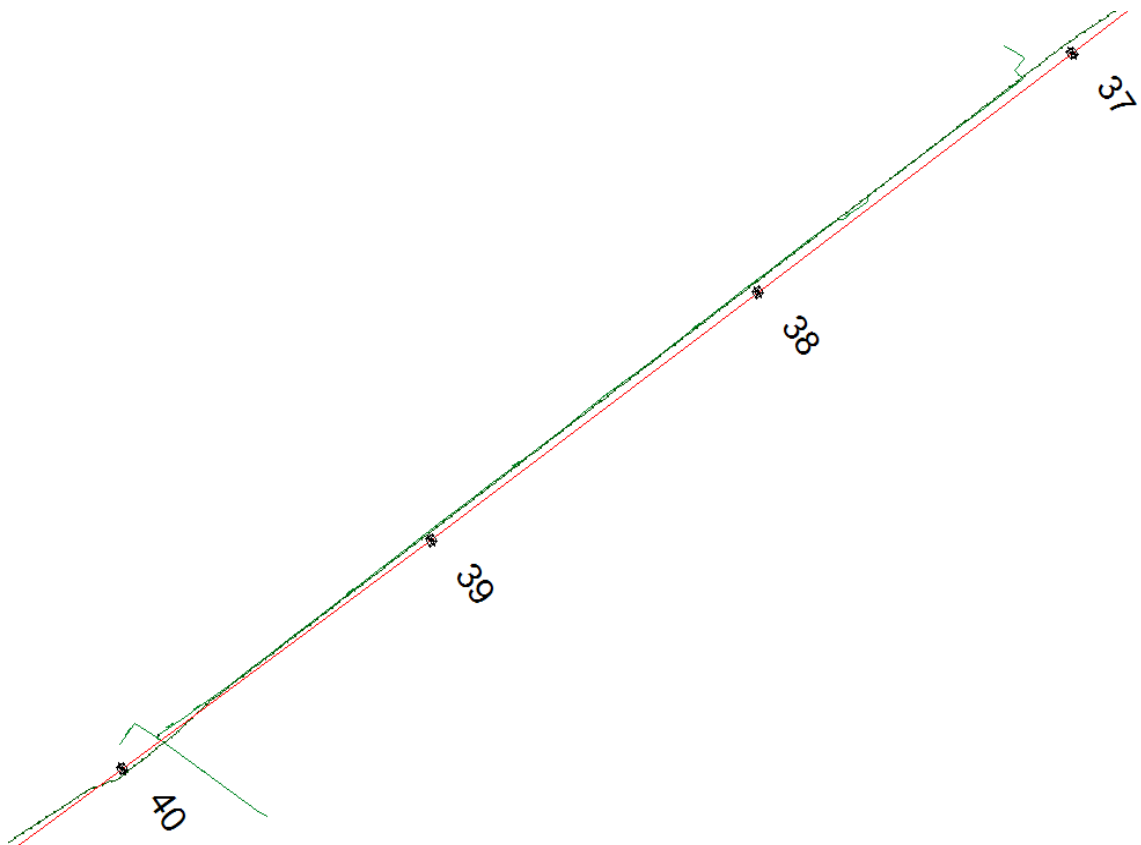


Figure 7.1: Exposure length [16]

## 7. Application to real cases

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In the previous figure analysis' background is exposed:

- red line – 380kV aerial power line – called “Dolo-Camin”;
- green circled line – 220kV cable;
- green line – pipeline.

As a reference, distance between tower 38 and tower 39 of the 380kV line is 321.7 m; length of the zone of influence is 880 m.

In the exposure length power lines are very close to the pipeline: an evaluation of the induced voltage is required.

Pipeline is exposed to magnetic coupling for 880 m. Upstream and downstream sections are now analyzed.

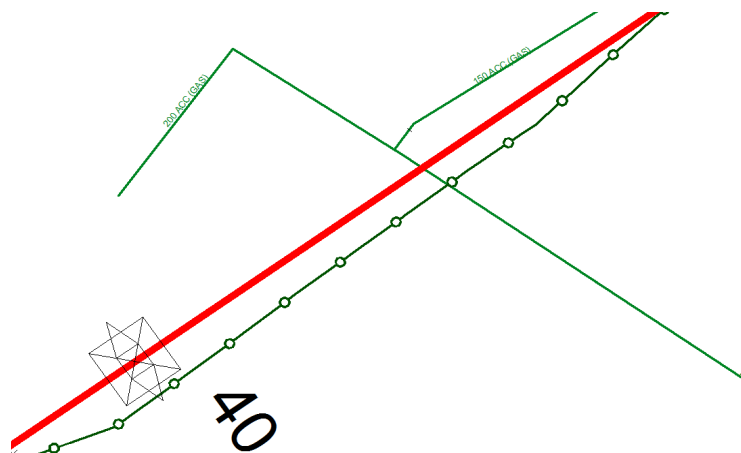


Figure 7.2: Upstream section [16]

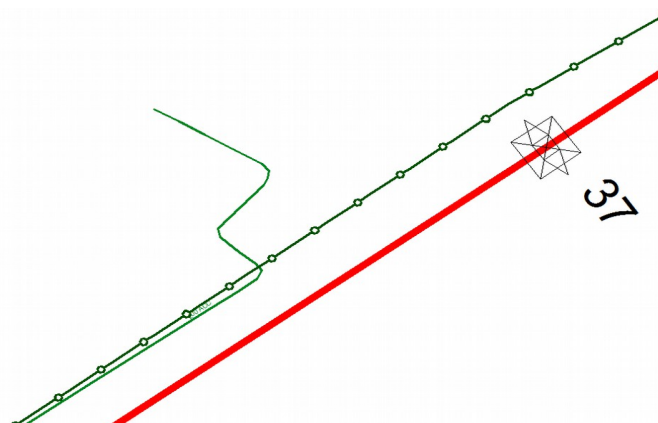


Figure 7.3: Downstream section [16]

In upstream section pipeline is connected to an orthogonal pipe through an insulated joint. The joint is protected through a discharger. The orthogonal pipe is not influenced by coupling, because of the orthogonal position in reference to power lines.

In downstream section pipeline continues its route orthogonally, so without coupling effect.

The zone of influence is the zone between tower 37 and tower 40.

## 7.1.2 Inducing power lines

Power lines are:

- HV 220 kV Trefoil Cable;
- HV 380 kV DCLR line with one earthwire - “Dolo-Camin”.

Geometrical layouts are given in the following figures, more detailed data in appendix D.

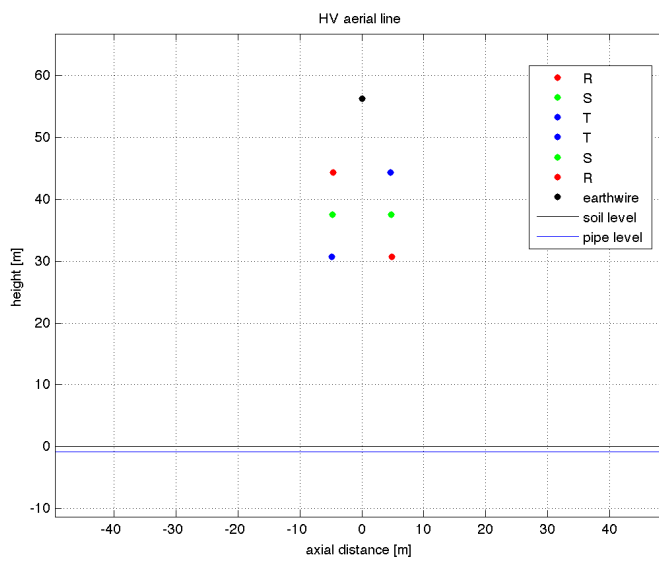


Figure 7.4: Dolo-Camin power line

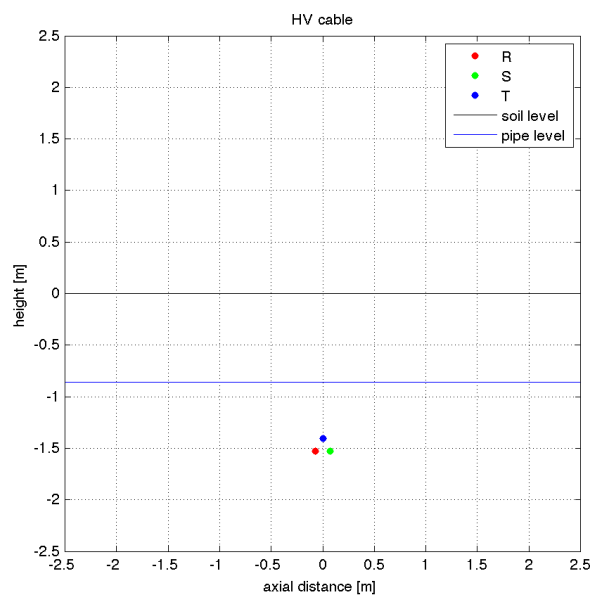


Figure 7.5: 220kV cable

## 7. Application to real cases

Values for inducing currents are:

Table 7.1: Inducing currents

	STEADY STATE CONDITION	FAULT CONDITION
HV 380kV line	2310 A *	14.5 kA **
HV 220kV cable	1000 A ***	10 kA ***

\* - reference value for HV 380kV aerial power lines' carrying capacity [8]

Every conductor in each phase will transport 770 A; since there are three conductors for each phase (see appendix D) the equivalent conductor will transport  $770 \times 3$  A, thus 2310 A.

\*\* - value given by CR Terna division;

\*\*\* - estimated value.

Soil resistivity is 41.86  $\Omega\text{m}$ .

### 7.1.3 Induced e.m.f.'s results

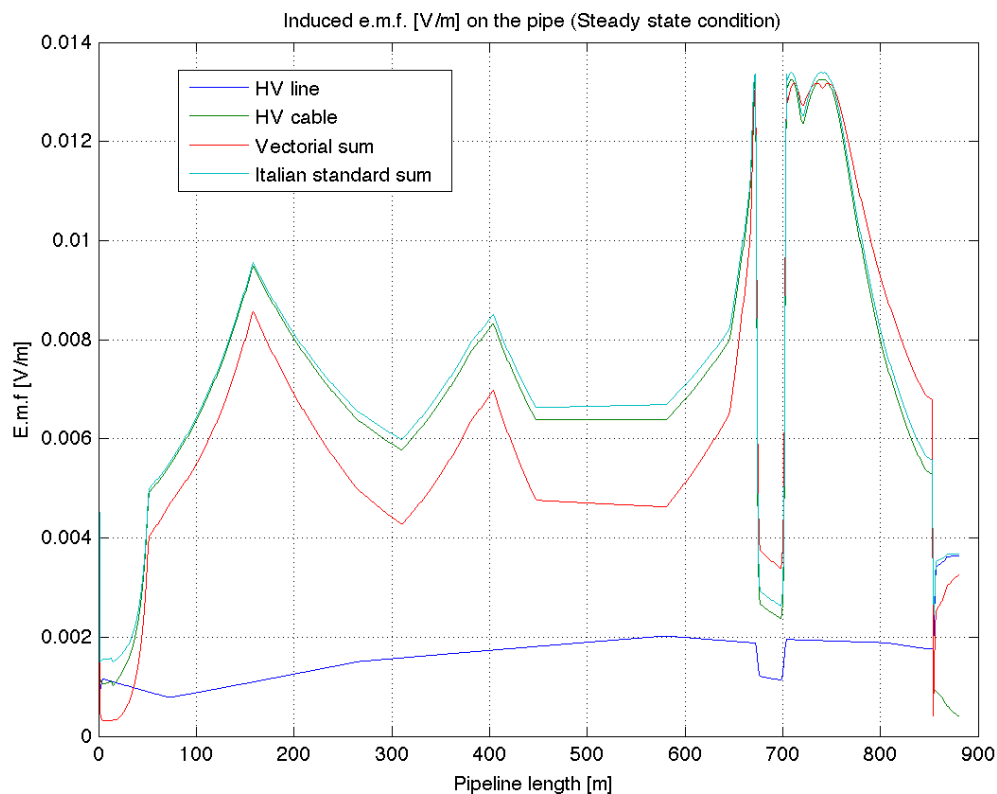


Figure 7.6: Induced e.m.f. - steady-state conditions

## 7.1 Inductive Coupling: “Feeder Idrovia Saonara”

Values of induced e.m.f. under steady-state conditions are compared in the previous figure. We can see that:

- cable's values are higher than the aerial line's one;
- vectorial sum leads to lower values than the standard sum's ones.

*As for the first consideration, cable's values are higher because cable's closer to the pipeline than the HV aerial line, and the earthwires increase the induced emf by the HV aerial line.*

*As far as the second consideration is concerned, vectorial sum leads to different results because compensating effects are taken into account.*

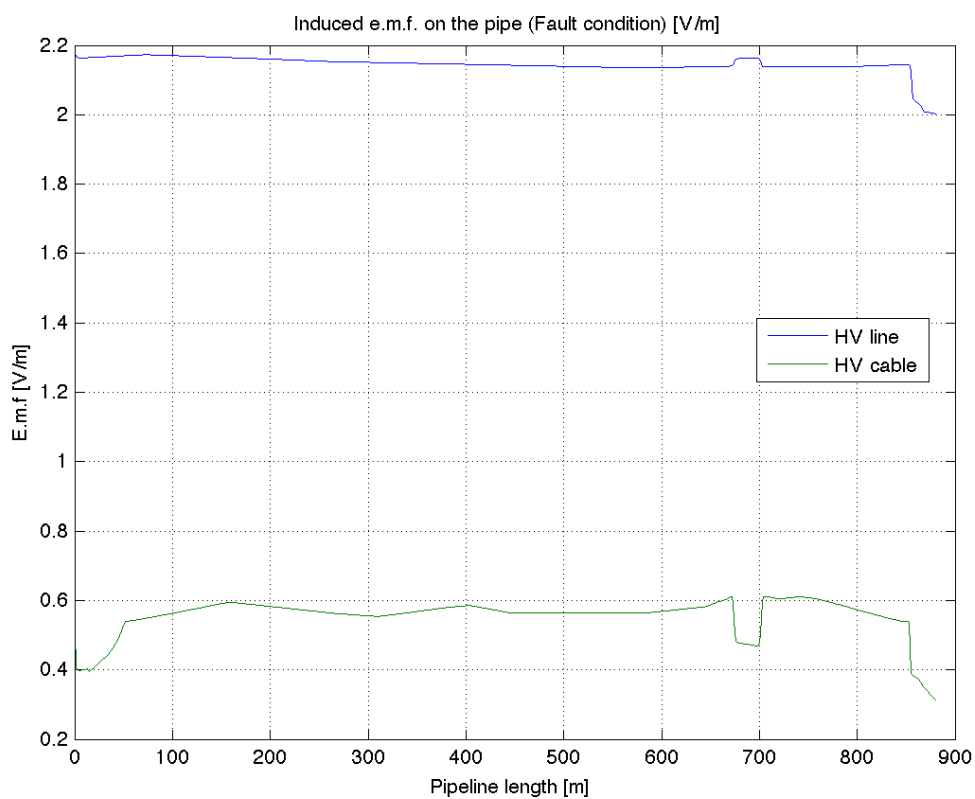


Figure 7.7: Induced e.m.f. - fault conditions

During faults values of e.m.f. by the HV aerial line are much higher than the cable's ones.

*The explanation is that mutual distances between sheaths and cable's conductors are smaller than distances between aerial phase conductors and earthwires, and much smaller than distances from pipelines.*

### 7.1.4 Induced Voltage's results

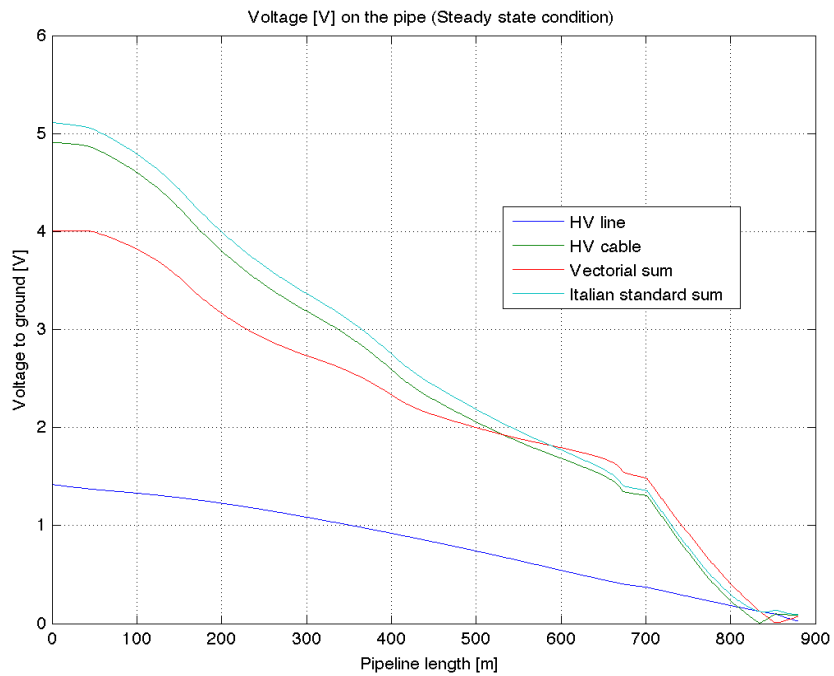


Figure 7.8: Induced voltage – steady-state conditions

Since under steady-state conditions pipeline continues its route downstream and the joint electrically insulates the pipe upstream, pipeline can be considered as an embossed line: this is demonstrated in the previous figure, where voltage's values increase from downstream to upstream position.

Values are much lower than the limit imposed by CEI 304-1: no mitigation measures are required under steady-state conditions.

The limit is 60 V.

## 7.1 Inductive Coupling: “Feeder Idrovia Saonara”

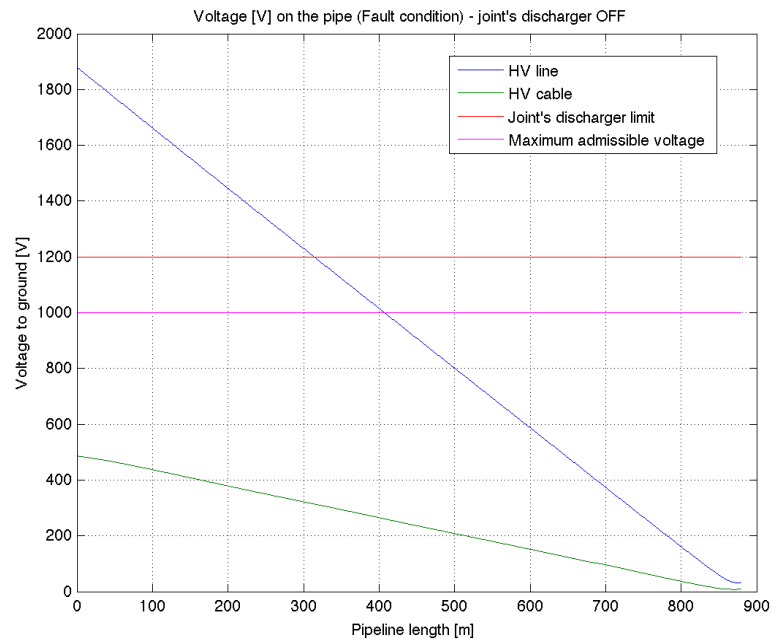


Figure 7.9: Induced voltage – fault conditions

During faults cable's influence can be neglected: in fact cable's values of induced voltage are lower than Italian standard and joint's discharger limit.

While aerial lines' values cause the joint's discharger's activation: effects will be analyzed in the following figure.

In both cases pipeline can be considered as an embossed line, since in upstream section it is insulated, in downstream section it continues its route: in fact voltage's values increase from downstream to upstream position.

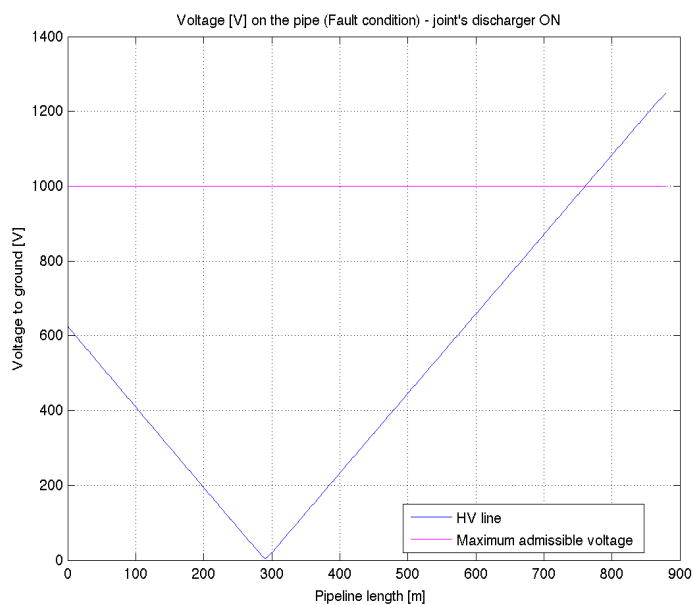


Figure 7.10: Induced voltage by the aerial line after joint's discharger's activation – fault condition

## 7. Application to real cases

With the activation of joint's discharger pipe's connected to the pipeline's grid from both sides: since the grid is not locally earthed and pipe extends a few kilometers outside the zone of influence, pipe 's continuation can be represented by the characteristic impedance. In upstream section, the equivalent impedance is half of the characteristic impedance, because pipe's connected to a forking, in downstream section the equivalent impedance is the characteristic impedance, because pipe extends without forking.

The previous figure shows voltage values after the activation of the joint's discharger, due to the fault in the aerial line. We see that mitigation measures are required: in fact values are higher than Italian standard's limit.

Maximum admissible voltage is 1000 V, if the fault lasts between 0.2 and 0.35 s (expected duration).

### 7.1.5 Mitigation

To reduce induced voltage on the pipeline, in case of HV aerial line's fault, many measures could be applied. In this case the adoption of dischargers on the pipeline gives satisfying results.

Mitigation's application is a process in attempts, because each time you insert new elements into the pipeline (such as dischargers) pipe's matrix impedance changes, and a new calculation of voltage to earth must be done.

As a first attempt, I set a discharger in the downstream position, where the voltage is higher than Italian standard's limit. This discharger will be activated when the downstream level of voltage is higher than discharger's limit.

In the following figure this case is shown.

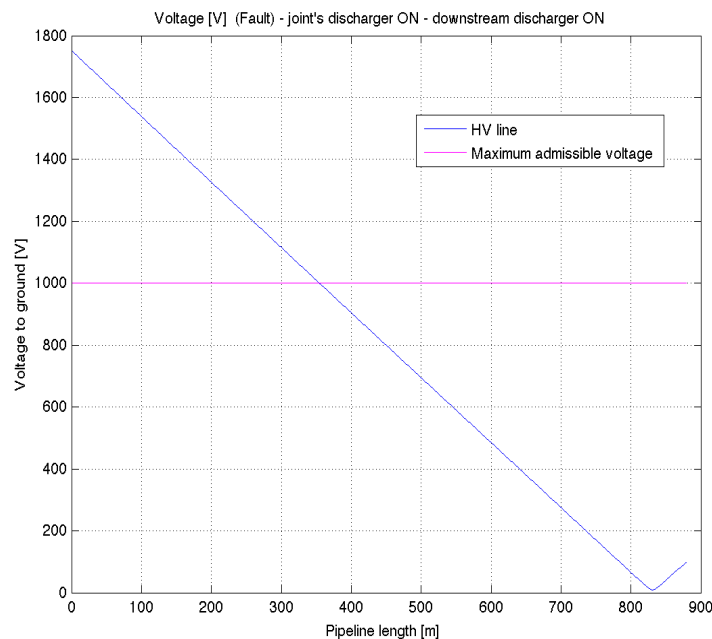


Figure 7.11: HV line's fault with downstream discharger



## 7.1 Inductive Coupling: “Feeder Idrovia Saonara”

If a fault occurs to the HV aerial line, the joint's discharger will be activated. The downstream discharger will be suddenly activated: anyway levels of voltage upstream will not be acceptable.

Secondly I set two discharger on the pipeline: one in upstream position and the other in downstream position.

Values of voltage will be:

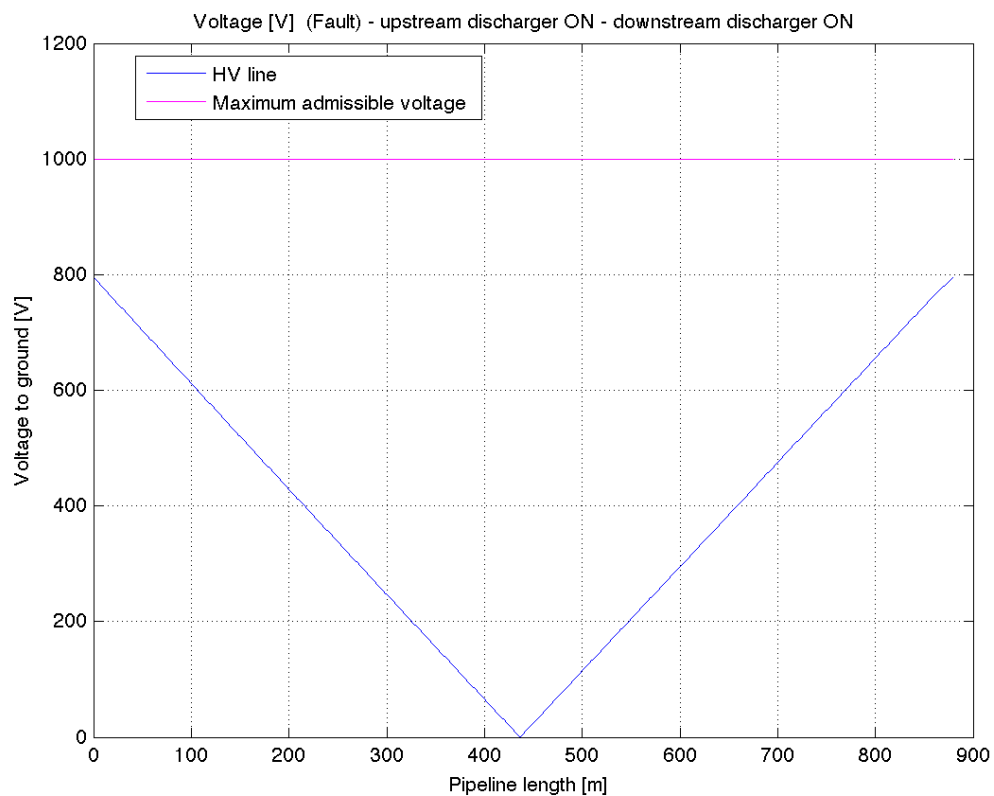


Figure 7.12: HV line's fault with upstream and downstream dischargers

If a fault occurs to the HV aerial line, the two dischargers will be activated: we can see that values of induced voltage are lower than Italian standard's limit.

So adopting two dischargers on the pipeline, one in upstream position and the other in downstream position, CEI 304-1's prescriptions are followed and limits respected.

## 7.2 Conductive Coupling

I will consider the future HV power line called “Dolo-Camin”, in case of fault to tower.

The tower under analysis is number 37: results are compared to the ones given by Roda and Sint's report.

Input data:

Table 7.2: Data [11]

Zt [ $\Omega$ ]	0.74
If [kA]	20

The power line is provided with one earthwire.

My results are calculated both with the complex relation (3.4) and in the simplified way (3.7).

Table 7.3: Results

	Simplified relation	Complex relation
Ie [kA]	6.667	4.338
EPR0 [kV]	4.933	3.210

The report gives the same results of the ones in the first column.

In normal conditions, pipeline's coating has a high impedance, and I suppose that the only problem is exceeding the dielectric strength of the material.

The coating's material is polyethylene, its dielectric strength is 50 kV/mm, and the thickness is 3 mm. So even the highest value of EPR given before is lower than 150 kV, and the material won't suffer for the electric stress. The potential difference is concentrated on the coating and pipeline's potential won't rise.

Instead if the coating presents a little hole in the EPR zone, current will easily flow through the pipeline, causing a high potential rise.

## 7.2 Conductive Coupling

The following picture shows the earth potential rise (green line), calculated by Roda and Sint, with values of current and  $EPR_0$  shown in first column of table 7.3. Values are function of the distance from the tower.

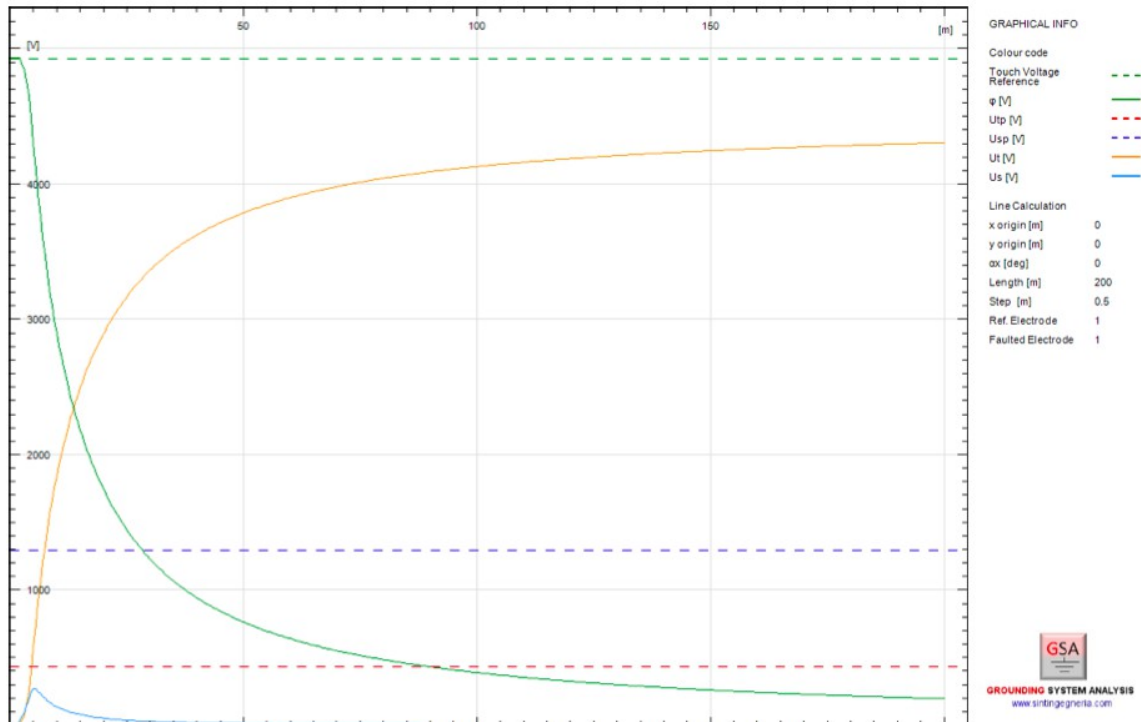


Figure 7.13: EPR in function of the distance from the tower (green line) [11]

These values may cause a potential rise of the pipeline if the coating is damaged: to avoid this problem pipe's coating must be always intact.

If the coating is locally damaged, with the assumptions in section 3.2, R factor's value will be near 0.1: thus values of figure 7.13 must be multiplied by R factor to obtain values of  $V_0$  at each distance between pipe and tower (according to equation 3.9).

Considering tower 38, 39 and 40's EPR graphs, we can repeat calculations of transferred voltage: these will lead to values of voltage transferred to the pipeline in case of fault for each tower in the zone of influence. These values are almost the same for these towers: figure 7.13 is valid for the towers we take into account.

So applying

$$V(x) = V_0 e^{-|y \cdot x|} \quad (7.1)$$

we can estimate values of transferred voltage in function of pipe's length (with the assumptions in section 3.2).

## 7. Application to real cases

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Distances between towers and pipe are:

Table 7.4: Distance tower – pipe

Tower's number	Distance [m]
37	40
38	7
39	6
40	36

Values of transferred voltage are:

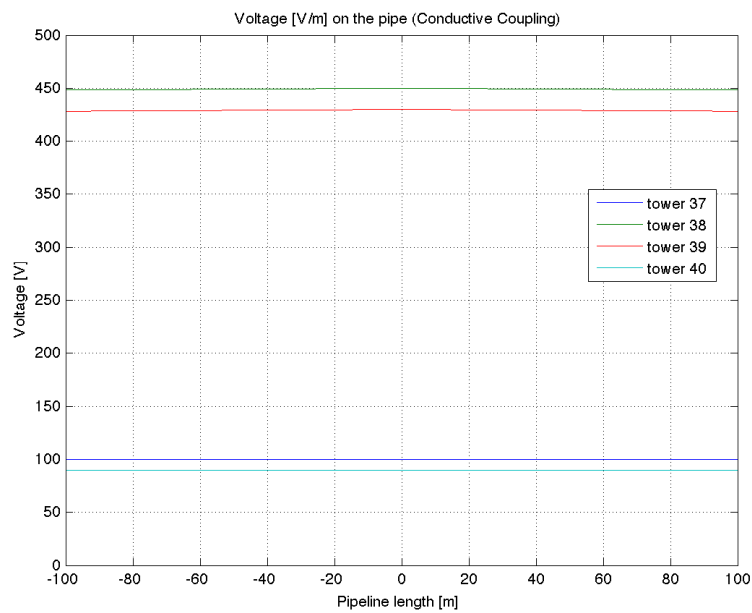


Figure 7.14: Transferred voltage for each tower with damaged coating

Values of transferred voltage are lower than 1000 V in each case: Italian standard is respected.

These values are obtained through a simplified approach, where pipeline extends without earthing and without any joint from both sides in reference to the tower: A complete analysis must be done, in order to obtain values in case of presence of earthing systems and joints.

# Conclusion

With this work I analyzed Italian regulations concerning interference between HV power lines and pipelines. I realized that standard's task is to give simple relations for assessing interference.

As for inductive coupling, it was necessary to integrate and correct this set of equations, and verify the range of applicability. The insiders probably know the errors in the Cigré Guide, but a critical analysis with corrections and integrations have never been made: this is the most important aspect of this thesis. In fact, as for inductive coupling, the insiders use other methods such as Multiconductor Analysis and finite elements methods. Moreover, if we try to solve the example of inductive coupling in the guide with the proposed equations, we will never have similar results: I think that who wrote the guide solved the example with correct equations. The proposed equations were written after calculations.

I've been able to propose a complete set of equations through the application of “k-factor general” theory, from which derives the “k-factor” theory applied in the guide.

A new corrective factor  $k_4$  has been proposed for fast calculations with DCLR lines.

As for conductive coupling, the simple relations in Cigré Guide were useful to assess this phenomenon.

As far as application to “Feeder Idrovia Saonara” is concerned, a complete analysis for inductive coupling has been done. Since values in case of single-phase fault to earth for the aerial line were too high, mitigating measures were applied. Under steady-state conditions values were much lower than standard's limits. As for conductive coupling, results were obtained through a simplified method and they were always lower than maximum admissible ones.

So adopting two dischargers on the pipeline, one in upstream position and the other in downstream position, CEI 304-1's prescriptions and limits are followed in case of inductive coupling. Values in case of conductive coupling were always low: anyway I suggest to check pipe's coating in order to avoid breaks.

A future development of this work could be:

- Multiconductor Analysis (Inductive Coupling), which is just described in this work;
- Conductive Coupling's complete analysis which is neglected here because the analysis is simplified, according to the standard.



# Appendix A

## Complete calculation of induced emf on a pipe

In this appendix I will show how the e.m.f expressions change if we consider the direct sequence or the inverse sequence of currents.

As far as a three-phase line and a nearby conductor are concerned, we can find mutual distances as shown in the following figure:

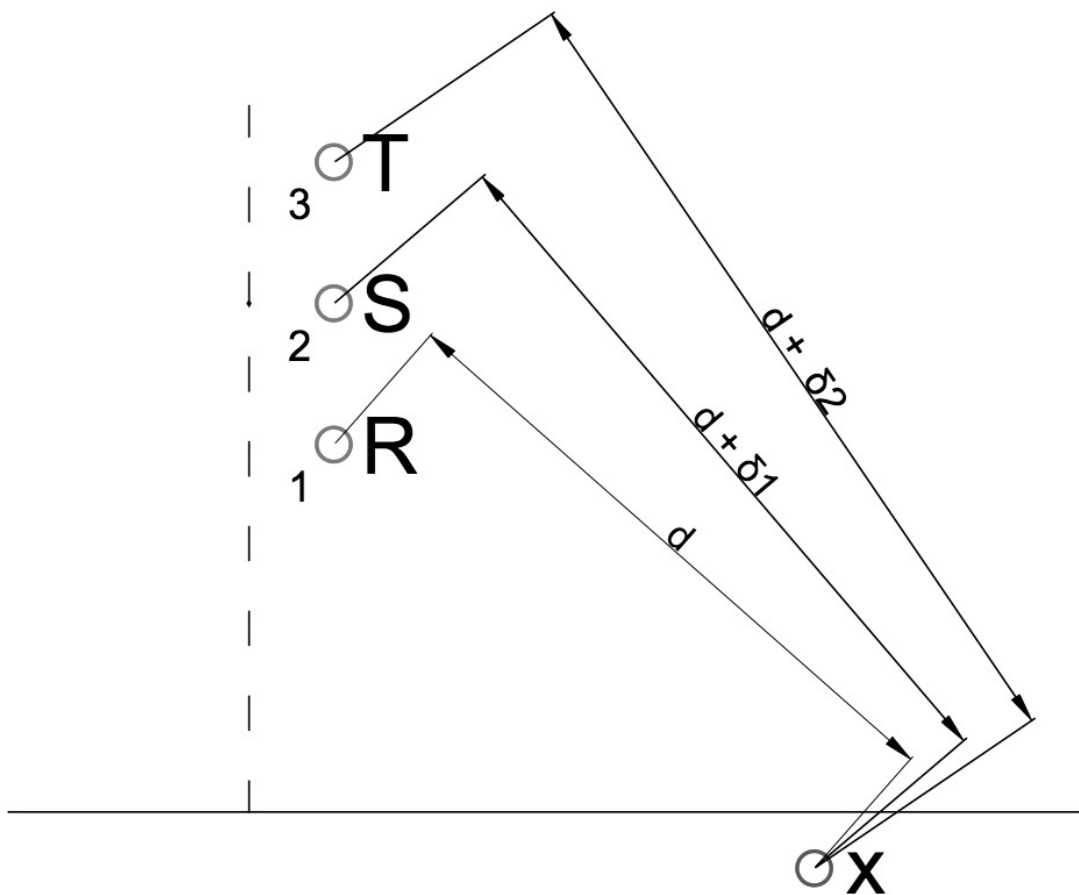


Figure A.1: Distances between phase conductors and pipeline

While current is transmitted in phase conductors, a magnetic field generates induced electromotive forces (e.m.f) in the nearby conductor x (pipeline). Following the theories exposed before, we can consider e.m.f's contributions from each conductor by superposition.

## Appendix A

---

So the general expression is:

$$E[V/m] = -\sum_{i=1}^3 Z_{pi} I_i \quad (A1)$$

where:  $I_i$  – Inducing currents;  $Z_{pi}$  – mutual impedances;  $i = 1, 2$  and  $3$  – phases;  $p$  – pipeline.

### Inducing currents

$$I_1 = I e^{j0} = I \quad (A2)$$

$$I_2 = I e^{\pm(j\frac{2\pi}{3})} = I(-0.5 \pm j\frac{\sqrt{3}}{2}) \quad (A3)$$

$$I_3 = I e^{\pm(j\frac{4\pi}{3})} = I(-0.5 \mp j\frac{\sqrt{3}}{2}) \quad (A4)$$

We consider the inverse triplet of currents with the upper sign, while the inverse one with the lower sign.

### Mutual Impedance

The Carson Clem expression for the mutual impedance is:

$$Z[\Omega/m] = j\omega M \quad (A5)$$

where:

$$M[H/m] = \frac{\mu_0}{4\pi} [2\ln(\frac{2}{g\alpha d}) + 1 + j\frac{\pi}{2}] \quad (A6)$$

$g$  – Euler's constant

$$\alpha = \sqrt{\left(\frac{\omega\mu_0}{\rho}\right)} \quad (A7)$$



Induced electromotive forces

Now I show the most relevant steps that lead to the analytical expression of e.m.f.  
Applying equation (A1) I can write:

$$E = -(j \omega M_{p1} I_1 + j \omega M_{p2} I_2 + j \omega M_{p3} I_3) \quad (\text{A8})$$

$$E = -j \omega [M_{p1} I_1 + M_{p2} I_2 + M_{p3} I_3] \quad (\text{A9})$$

$$M_{p1} I_1 = \left(2 \ln\left(\frac{2}{g\alpha d}\right) + 1 + j \frac{\pi}{2}\right) I \quad (\text{A10})$$

$$M_{p2} I_2 = \left(2 \ln\left(\frac{2}{g\alpha(d+\delta_1)}\right) + 1 + j \frac{\pi}{2}\right) I \left(-0.5 \pm j \frac{\sqrt{3}}{2}\right) \quad (\text{A11})$$

$$M_{p3} I_3 = \left(2 \ln\left(\frac{2}{g\alpha(d+\delta_2)}\right) + 1 + j \frac{\pi}{2}\right) I \left(-0.5 \mp j \frac{\sqrt{3}}{2}\right) \quad (\text{A12})$$

$$\sum_{i=1}^3 M_{pi} I_i = I \cdot (\dots) \quad (\text{A13})$$

where (...) is:

$$\begin{aligned} & \dots + 2 \ln\left(\frac{2}{g\alpha d}\right) + 1 + j \frac{\pi}{2} \dots \\ & \dots - \ln\left(\frac{2}{g\alpha(d+\delta_1)}\right) - \frac{1}{2} - j \frac{\pi}{4} \pm j \sqrt{3} \ln\left(\frac{2}{g\alpha(d+\delta_1)}\right) \pm j \frac{\sqrt{3}}{2} \mp \frac{\sqrt{3}}{4} \pi \dots \\ & \dots - \ln\left(\frac{2}{g\alpha(d+\delta_2)}\right) - \frac{1}{2} - j \frac{\pi}{4} \mp j \sqrt{3} \ln\left(\frac{2}{g\alpha(d+\delta_2)}\right) \mp j \frac{\sqrt{3}}{2} \pm \frac{\sqrt{3}}{4} \pi \dots \end{aligned} \quad (\text{A14})$$

So with the necessary cancellations and applying the theory of logarithms I can write the expression of the induced e.m.f on a pipeline by a three phase line:

$$E[V/m] = -\sum_{i=1}^3 Z_{pi} I_i = -j f \mu_0 \frac{I}{2} \left( \ln\left(\frac{((d+\delta_1)(d+\delta_2))}{d^2}\right) \pm j \sqrt{3} \ln\left(\frac{(d+\delta_2)}{(d+\delta_1)}\right) \right) \quad (\text{A15})$$



# Appendix B

## k<sub>4</sub> Theory

Since Cigré guide doesn't provide appropriate equations for double circuit low reactance line configuration (DCLR), a way to assess the induced e.m.f is introduced. This method is based on the following logical steps:

1. Magnetic induction is proportional to induced emf;
2. Magnetic induction's values of a three-phase line are higher than DCLR line's one, transporting the same current;
3. The ratio of the two different values of magnetic induction is related to the ratio of induced emf values in each case;
4. k<sub>4</sub> is the ratio of magnetic induction's values;
5. induced emf by a DCLR line can be calculated from the value of an equivalent three-phase line (flag arrangement), transporting the same current, and k<sub>4</sub>;

## Magnetic induction levels

According to Biot-Savard law we can write:

$$\vec{B}(P) = \mu_0 \frac{I}{2\pi r} \vec{u}_i \times \vec{u}_r \quad (\text{B1})$$

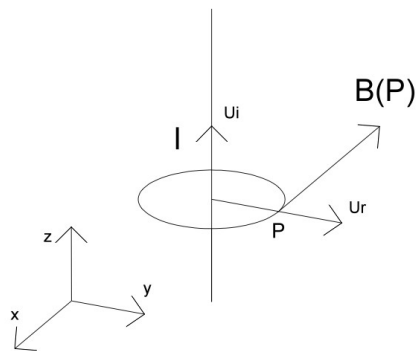


Figure B1: Magnetic Induction in the 3D space

where:  $r$  [m] – distance from the inducing conductor,  $\vec{u}_i$  - versor for the positive direction of the current;  $\vec{u}_r$  - versor for the radial direction;  $B$  [T] – magnetic induction. Vector  $\vec{B}(P)$  lays on the  $\vec{u}_i \times \vec{u}_r$  direction, according to “right-hand rule”.

Appendix B

The magnetic induction generated by a *three-phase line* (transporting  $I=2310$  A) is:

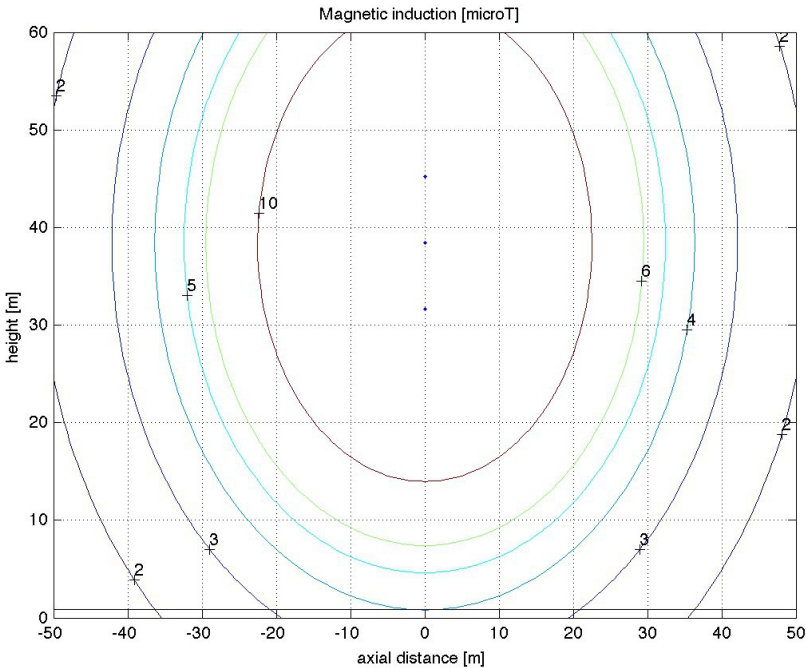


Figure B2: Magnetic Induction by a three-phase line

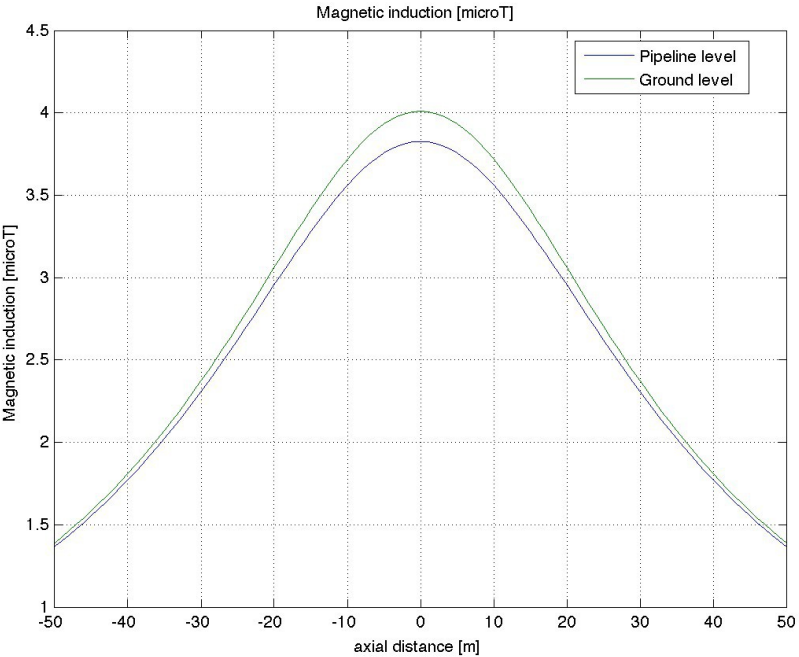


Figure B3: Magnetic Induction by a three-phase line at pipeline level and ground level

The magnetic induction generated by a *DCLR line* (transporting  $I=2310$  A) is:

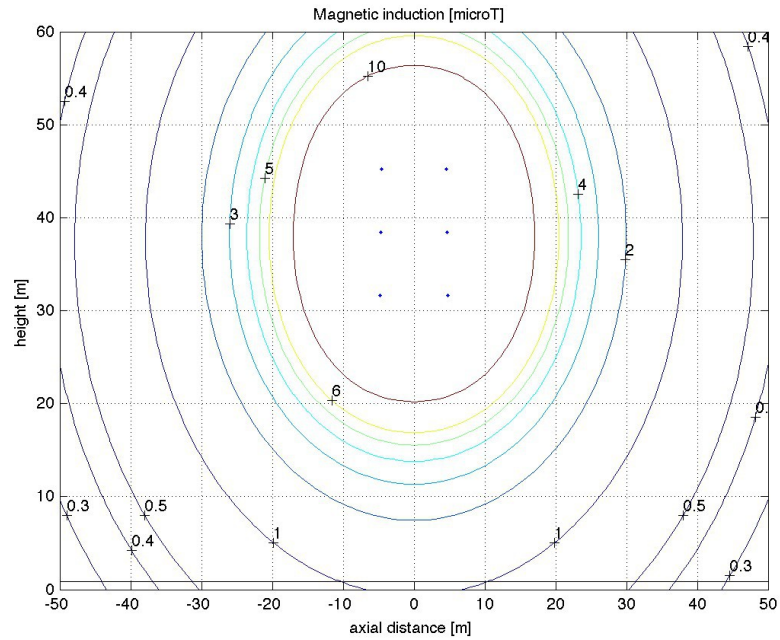


Figure B4: Magnetic Induction by a *DCLR line*

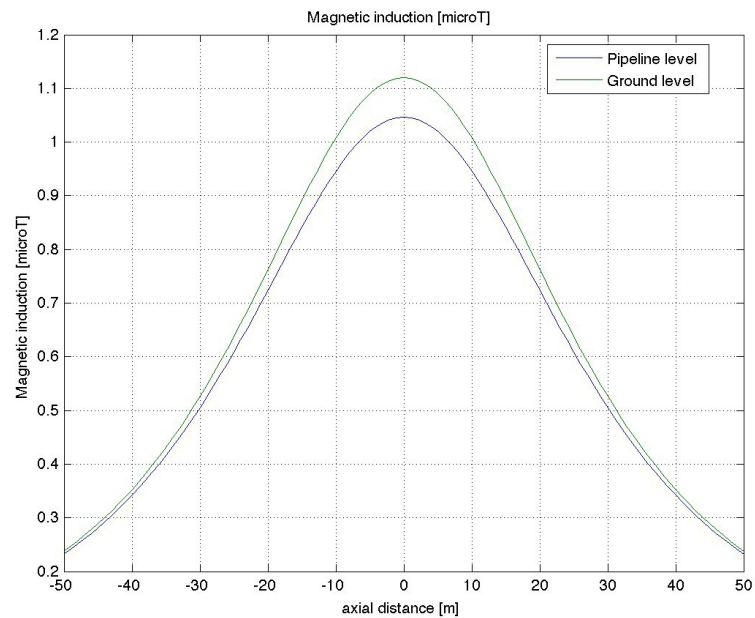


Figure B5: Magnetic Induction by a *DCLR line* at pipeline level and ground level

We can see that magnetic induction with DCLR line configuration is much lower than the one with the three-phase line, transporting the same current: in fact DCLR line configuration is often applied to reduce levels of magnetic induction. Values are obtained through a Matlab program, described in [7].

## k4 expressions

It's easy to demonstrate that, under balanced conditions, the magnetic induction generated by a three-phase line (flag configuration) is (according to [4]):

$$B_{scF} = \mu_0 I \frac{s}{(2\pi R)} \sqrt{\left(\frac{(s^2 + 3R^2)}{(R^4 - 2s^2 R^2 \cos(2\varphi) + s^4)}\right)} \quad (B2)$$

While in case of DCLR configuration:

$$B_{dclr} = \mu_0 I \frac{s}{\pi} \sqrt{\left(\frac{(s^3 + 12w^2)}{R^3}\right)} \quad (B3)$$

Where: R – distance from the centre of gravity of the power line; w – mean distance from the single conductor to the line axis; s – vertical distance between phases;  $\varphi$  – angle between line axis and R.

So I can write  $k_4$  formulation:

$$k_4 = \frac{B_{dclr}}{B_{scF}} = \frac{1}{R^2} \sqrt{\left(\left(\frac{(s^3 + 12w^2)}{(s^2 + 3R^2)}\right)(R^4 - 2s^2 R^2 \cos(2\varphi) + s^4)\right)} \quad (B4)$$

A simplified expression for  $k_4$  is obtained by the following relation

$$k_4' = \frac{B_{dclr}}{(B_{sc}')} \quad (B5)$$

Where  $B_{sc}'$  is the expression of the magnetic induction generated by an equivalent three phase line (flag configuration) which derives from a DCSB line where axial distances between phases are equal to zero ( $w=0$ ) and current is the sum of the currents in each triplet of the DCSB line.

The original expression of the magnetic induction generated by a DCSB line is:

$$B_{dcsb} = \mu_0 \sqrt{3} \frac{s}{2\pi} \frac{(I_a + I_b)}{(R^2 - s^2)} \quad (B6)$$

Where a and b are the reference for the left and the right triplet;

So, with the previous assumptions, the expression of the three-phase line's magnetic induction (flag configuration) becomes:

$$B_{(sc')} = \mu_0 \sqrt{3} \frac{s}{2\pi} \frac{I}{(R^2 - s^2)} \quad (B7)$$

So  $k_4$ 's simplified expression is:

$$k_4' = \frac{B_{dclr}}{(B_{sc'})} = \sqrt{(s^3 + 12w^2)} \frac{(R^2 - s^2)}{(R^3 \sqrt{3})} \quad (B8)$$

Since using the simplified expression of  $k_4$  errors are lower than 3%, expression (B8) can be used for  $k_4$  calculation.

The *Induced e.m.f* by a DCLR line on a pipeline without earthwires becomes:

$$E_{DCLR} = k_4 \cdot E_{SC} \quad (B9)$$

where  $E_{SC}$  is the *Induced e.m.f* on a pipeline without earthwires by the equivalent three-phase line. This line must transport the same current, and the centre of gravity of the triplet of conductors must be the same.

## Application

In the following section I give a table of values of  $k_4$ , in function of the distance from line axis, for fast calculation. Values can be used in the three HV DCLR line voltage levels: 132kV, 220kV, 380kV. For each level geometrical assumptions are made, as specified in the following table.

Table B1: Geometrical assumptions for HV DCLR line arrangements

	132kV line	220kV line	380kV line
$h_1$ [m]	15	15	23.5
$w$ [m]	3.2	4.5	6.3
$s$ [m]	4.7	6	8.3

Where:  $h_1$  – mean height of the lowest conductor;  $w$  – mean distance from the single conductor to the line axis,  $s$  – vertical distance between phases.

Geometrical data are the mean values for each voltage level.

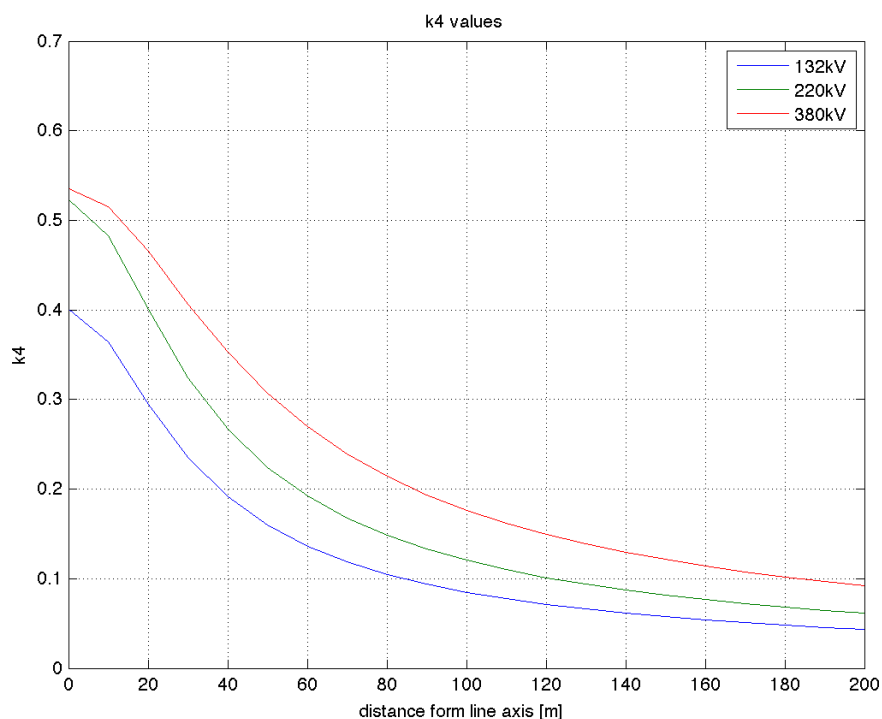
The following table gives the values of  $k_4$  for each voltage level, in function of the distance of the pipe to line axis.

Table B2:  $k_4$  values

Distance from line axis [m]	$k_4$ – 132kV line	$k_4$ – 220kV line	$k_4$ – 380kV line
0	0.401	0.523	0.535
10	0.364	0.482	0.515
20	0.295	0.400	0.465
30	0.235	0.325	0.407
40	0.191	0.267	0.353
50	0.160	0.224	0.307
60	0.136	0.192	0.270
70	0.119	0.168	0.239
80	0.105	0.148	0.214
90	0.094	0.133	0.194
100	0.085	0.120	0.177
110	0.078	0.110	0.162
120	0.071	0.101	0.150
130	0.066	0.094	0.139
140	0.061	0.087	0.130
150	0.057	0.081	0.121
160	0.054	0.076	0.114
170	0.051	0.072	0.108
180	0.048	0.068	0.102
190	0.045	0.065	0.097
200	0.043	0.061	0.092

It's easy to see that  $k_4$ 's reducing effect is stronger where distance between phases is lower. The following figure is the graph of the values in table B2.



Figure B6:  $k_4$  values

For a more detailed evaluation of  $k_4$ , the following expression can be used.

$$k_4 = \sqrt{(s^3 + 12w^2)} \frac{(R^2 - s^2)}{(R^3 \sqrt{3})} \quad (\text{B10})$$

where:  $w$  – mean distance from the single conductor to the line axis;  $s$  – vertical distance between phases;

$$R = \sqrt{(d_{ax}^2 + h_{cg}^2)} \quad (\text{B11})$$

$$h_{cg} = h_1 + s + dpt \quad (\text{B12})$$

$d_{ax}$  – distance from line axis;

$dpt$  – pipe's depth;

$h_1$  – mean height of the lowest conductor.

## Appendix B

Since this simple relation can be used for calculating the *Induced e.m.f by a three-phase line on a pipeline without earthwires*,

$$E_{SC} = -j f \mu_0 \frac{I}{2} \left( \ln \left( \frac{(d_{2p} d_{3p})}{d_{1p}^2} \right) + j \sqrt{3} \ln \left( \frac{d_{3p}}{d_{2p}} \right) \right) \quad (B13)$$

(where: d – distances; 1, 2 and 3 – phases; p – pipeline)

the *Induced e.m.f by a DCLR line on a pipeline without screening conductors* becomes:

$$E_{DCLR} = k_4 \cdot E_{SC} \quad (B14)$$

where  $E_{SC}$  is the *Induced e.m.f on a pipeline without earthwires by the equivalent three-phase line*. This line must transport the same current, and the centre of gravity of the triplet of conductors must be the same.

## Comparison of methods

In this section I will compare results of induced emf by a DCLR line on a pipe using  $k_4$  theory and the complete expression of the induced emf by a DCLR line (transporting 2310 A)

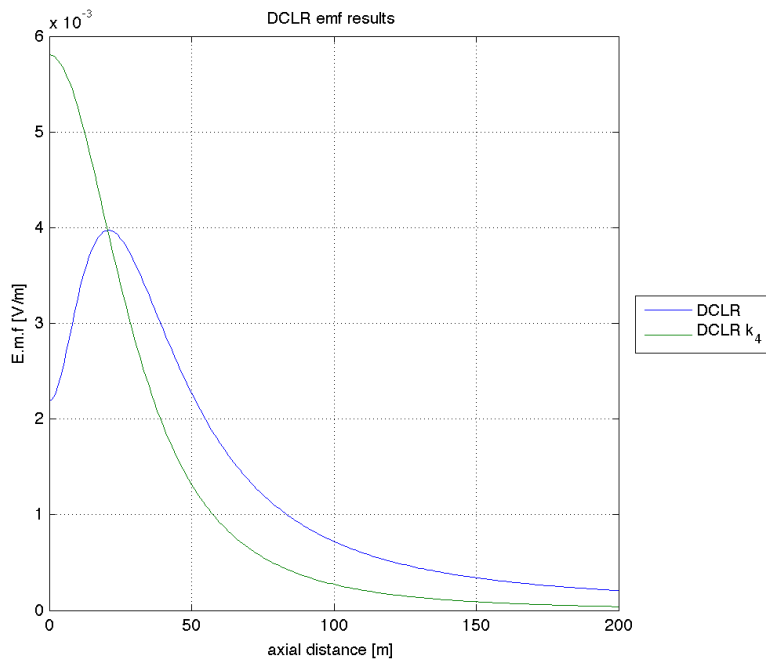


Figure B7: Comparison of DCLR emf results

Values obtained from  $k_4$  theory are close to the ones obtained through the complete expression. The errors are acceptable if the practicality of the method is taken into account.

# Appendix C

## Effect of the earthwires under normal operation

As for HV aerial lines, in previous sections we have seen that:

- under normal operation earthwires produce an increase in induced emf on a pipe;
- during fault (single-phase fault to earth) earthwires reduce the induced emf.

*The explanation of this phenomenon is that during faults the faulty current induces a current in the earthwire, which is in opposition of phase to the inducing one: so earthwire's current screens the phase's current, magnetic induction and induced emf are much lower. Screening current's amplitude is related to the distance between screening conductor and inducing conductor: the screening effect is strong if the distance is low. While, under normal operation, each current of the three-phase system produces its portion of screening current in the earthwire: each portion is shifted of 120 degrees from one another, each portion's amplitude is related to mutual distances between earthwire and phase conductors, so there will be an equivalent current in the earthwire, usually different from zero. This means that during steady-state conditions, in the earthwire there's a current that contributes to the magnetic induction, and to the induced emf. If distances between phase conductors and earthwire are the same, the current will be equal to zero: symmetry in currents and symmetry in distances produce a complete compensating effect. In most common cases symmetry in currents is realistic, but we must consider the asymmetry in distances between phase conductors and earthwires, which causes the increase in emf's values due to earthwires, under steady-state conditions.*

In the following figures I will compare results of different line configurations and earthwire's position. (I=1000A)

### Configuration #1

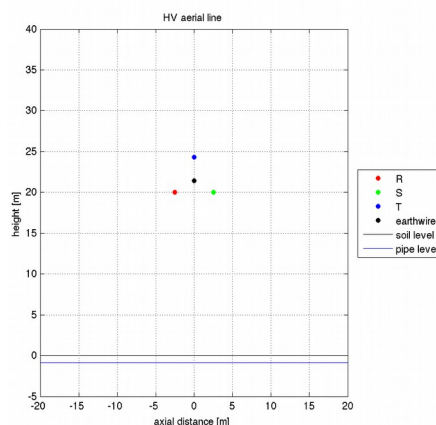


Figure C1: Configuration #1

Configuration #2

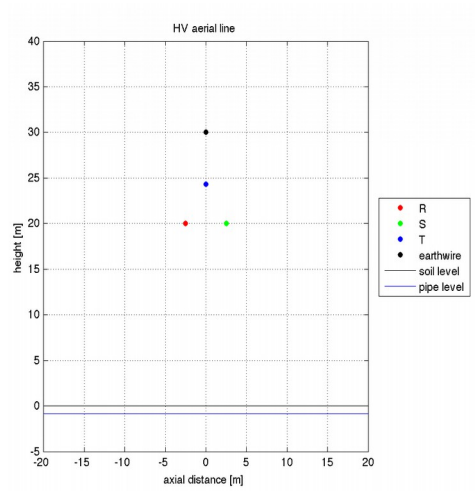


Figure C2: Configuration #2

Configuration #3

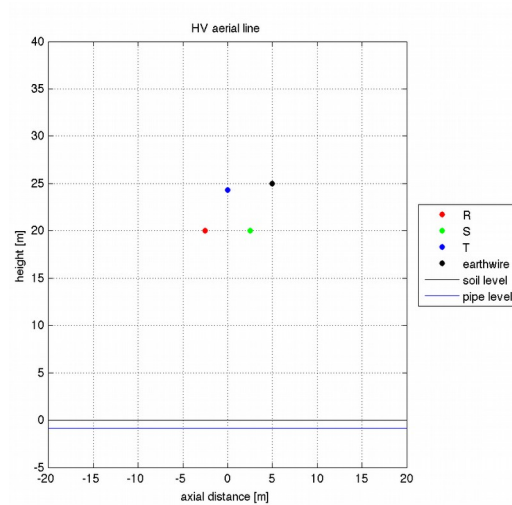


Figure C3: Configuration #3

In configurations #1 to #3 only the earthwire changes its position. Values of induced emf without earthwire will be the same for all these configurations.

## Emf values in configurations #1, #2, #3

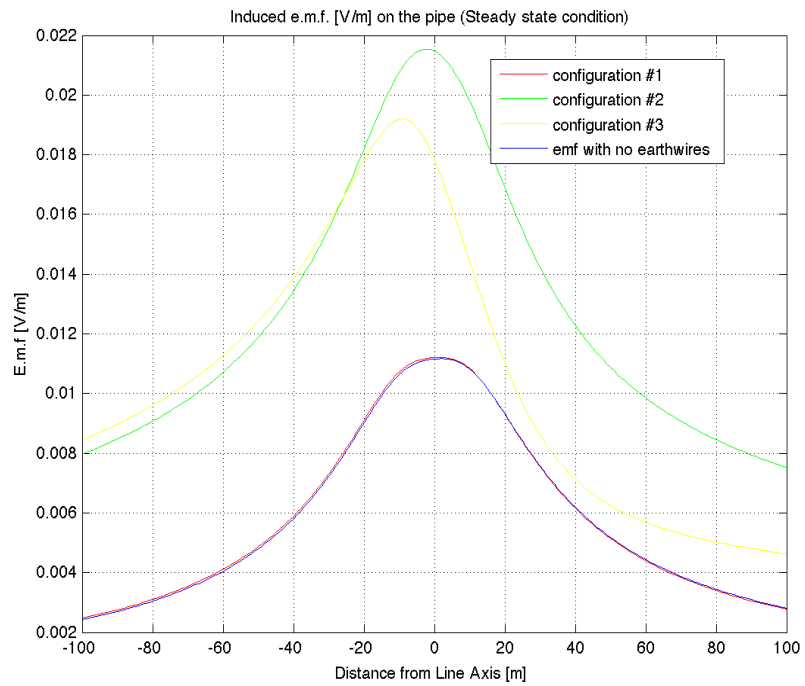


Figure C4: Emf values on the pipe in configurations #1 to #3

In configurations #2 and #3 the induced emf increases for the presence of the earthwire. In configuration #1 the symmetry in currents and the symmetry in distances between phase conductors and earthwire causes the absence of current in the earthwire: there's no emf's increasing effect.

## Configuration #4

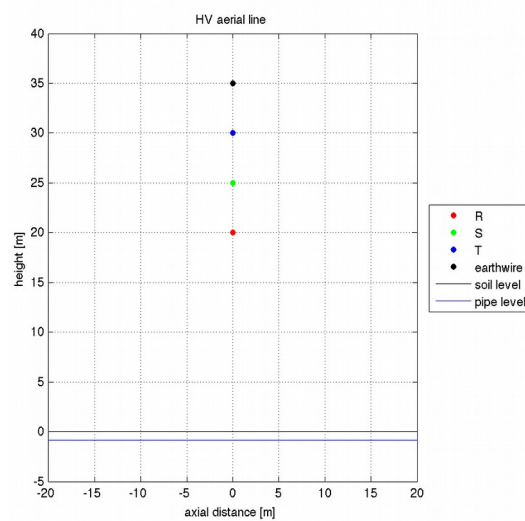


Figure C5: Configuration #4

Configuration #5

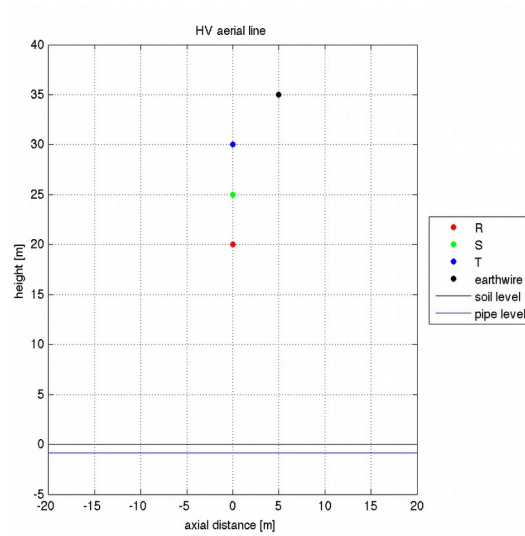


Figure C6: Configuration #5

Emf values in configurations #4 and #5

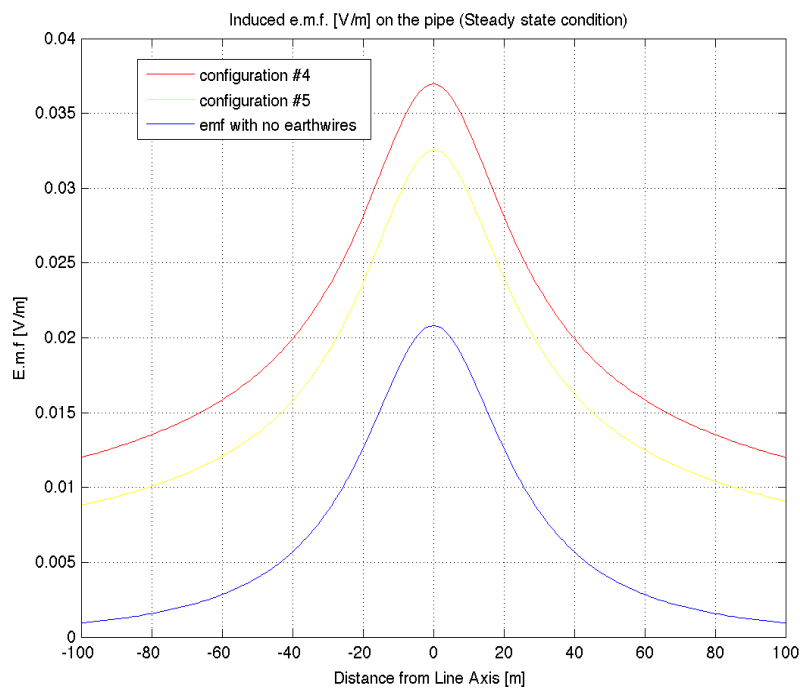
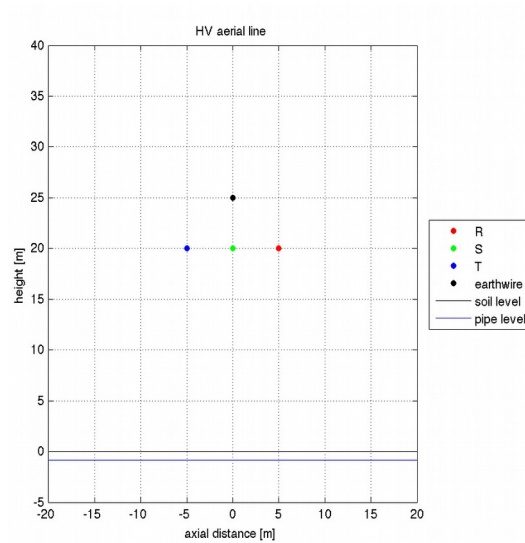
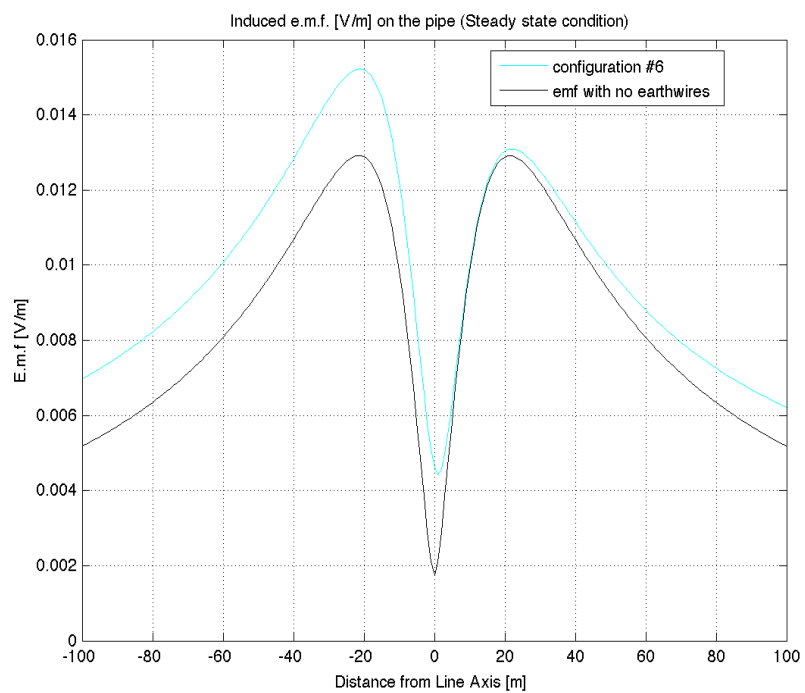


Figure C7: Emf values on the pipe in configurations #4 and #5

In configurations #4 and #5 the induced emf increases because of the presence of the earthwire.

**Configuration #6***Figure C8: Configuration #1***Emf values in configuration #6***Figure C9: Emf values on the pipe in configuration #6*

In this case we can see that earthwire's effect is stronger in the left side.

## *Appendix C*

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In this appendix the effect of the earthwires during steady-state conditions is shown in several cases: induced emf is usually increased, due to the geometric asymmetry. Instead in case of perfect geometric symmetry, no current will flow through the earthwire, and there will not be any increasing effect of emf.



# Appendix D

## Technical Specifications (for chapter 7)

*“Dolo-Camin” 380kV power line*

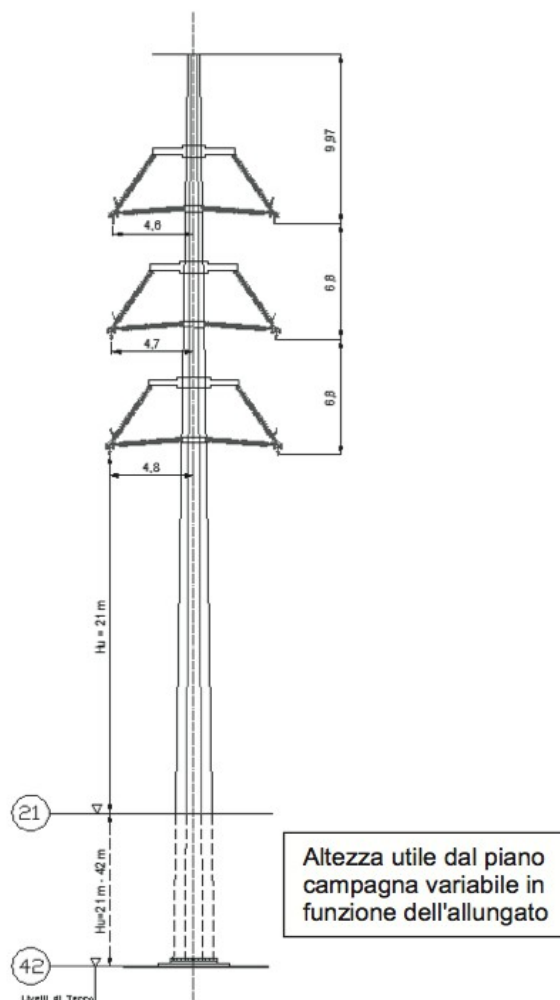


Figure D1: Scheme for tower 37,38,39,40 [16]

## Appendix D

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Table D1: "Dolo Camin"'s Tech Specs [16]

Voltage [kV]	380
Frequency [Hz]	50
Line arrangement	DCLR
Mean height of the lowest conductor [m]	30.76
Vertical distance between conductors [m]	6.8
Number of earthwires	1
Mean height of the earthwire [m]	56.32
Outreach of the lowest phase conductors [m]	4.8
Outreach of the median phase conductors [m]	4.7
Outreach of the highest phase conductors [m]	4.6
Phase conductor's material	Al - Steel
Phase conductor 's diameter [mm]	31.5
Number of conductors for each phase	3
Distance between conductors in each phase [m]	0.4
Equivalent phase conductor diameter [mm] *	272.2
Phase conductor's resistance (20°C) [ $\Omega$ /km]	0.05564
Earthwire's diameter [mm]	17.9
Earthwire's resistance (20°C) [ $\Omega$ /km]	0.28
Single phase fault to earth current [A]	14500
Steady-state condition current [A]	2310
Soil resistivity [ $\Omega$ m]	41.86
Earth resistance (tower 37 – 38 – 39 – 40) [ $\Omega$ ]	0.74

\* Note: The equivalent phase conductor's diameter is obtained through the following expression (Geometrical mean radius expression [2]), useful to consider the three conductors for each phase as an equivalent conductor:

$$D_{eq} = 2 \sqrt[n]{n r R^{(n-1)}} \quad (D1)$$

where:  $D_{eq}$  – equivalent phase's conductor's diameter;  $n$  – number of conductors for each phase;  $r$  – radius of the  $n$  conductor;  $R$  – radius of the circumference where the  $n$  conductors lay.

220kV Cable

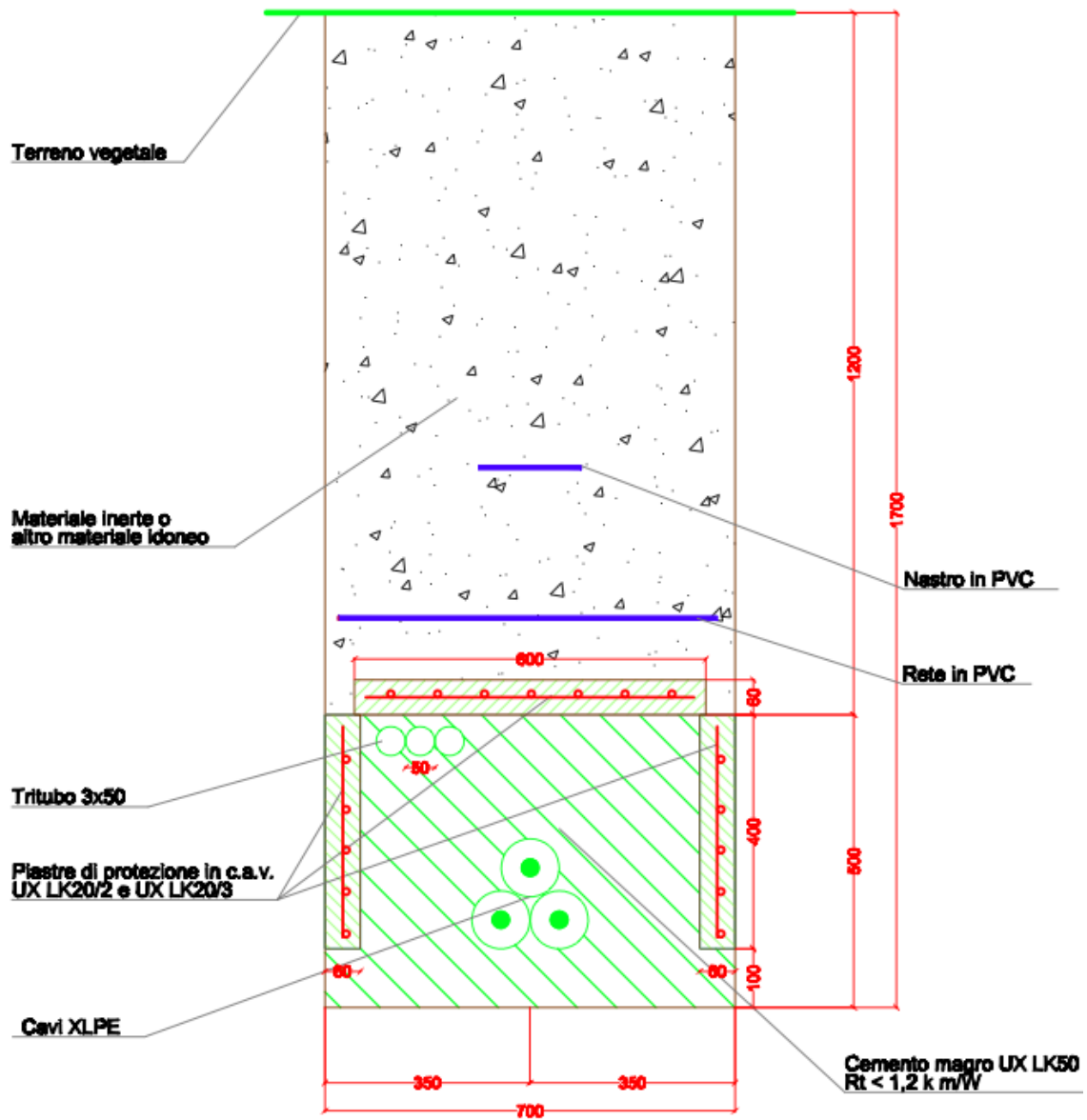


Figure D2: 220 kV trefoil cable [16]

## Appendix D

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Table D2: Cable's Tech Specs [16]

Voltage [kV]	220
Frequency [Hz]	50
Laying	trefoil
Cable's diameter [m]	0.143
Cable's depth [m]	1.6
Sheath's mean radius [m]	0.057
Sheath's resistance [ $\Omega$ /km]	0.085
Single phase fault to earth current [A]	10000**
Steady-state condition current [A]	1000**

\*\* - estimated values

## Pipeline



Figure D3: L245GA pipe's sections [18]

Table D3: Pipeline's Tech Specs [17]

<b>PIPE</b> material	pipeline steel L245GA
Pipe's diameter [m]	0.2191
Pipe's depth [m]	0.97
Pipe resistivity [ $\Omega\text{m}$ ]	$0.16 * 10^{-6}$
Relative magnetic permeability	300
<b>COATING</b> material	polyethylene R3R
Polyethylene relative permittivity	2.3
Coating's thickness [m]	$3 * 10^{-3}$
Coating's specific resistance – $r_c$ [ $\Omega\text{m}^2$ ]	$1.2 * 10^6$

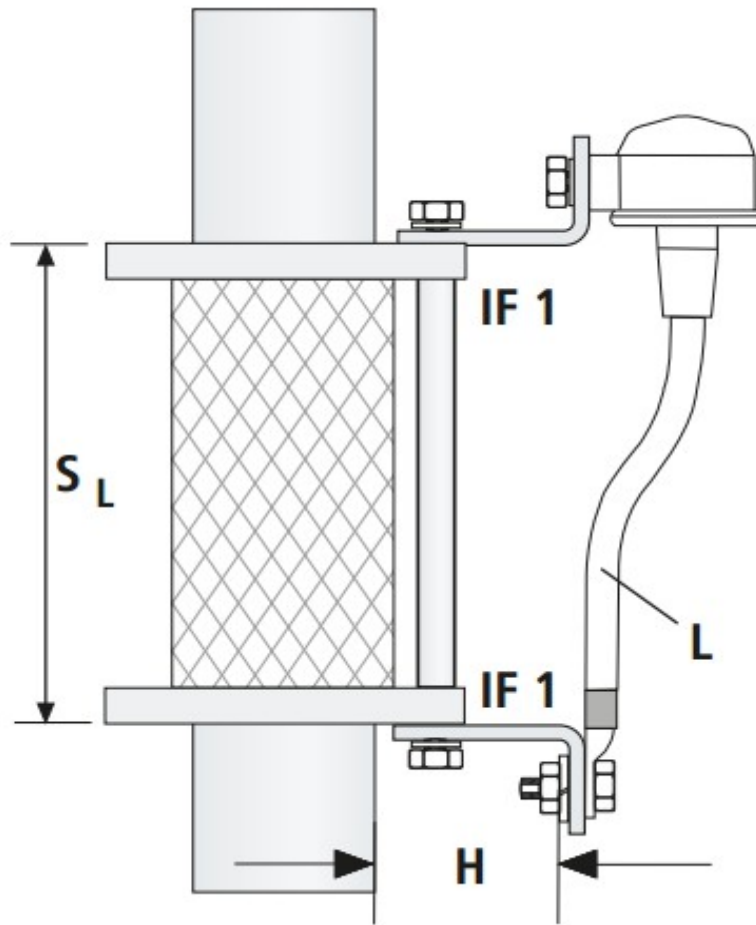


Figure D4: Dielectric joint with discharger [15]

Table D4: Joint's Tech Specs [15]

Lightning impulsive current (10/350)	50 kA
Stress class EN 50164-3	N
Discharging impulsive current (8/20)	100 kA
Discharging voltage – steady-state conditions (50 Hz)	300 V
Discharging impulsive voltage	≤ 2,5 kV
Discharging voltage – fault conditions (50 Hz)	≤ 1,2 kV
Temperature	-20°C +80°C
Protection grade	IP 54

# Appendix E

## Solution of the example of inductive coupling of Cigré Guide

In this section I will show the results of the inductive coupling's example shown in Cigré Guide I give through my program, compared with the ones given by the Guide.

### *Zone of Influence*

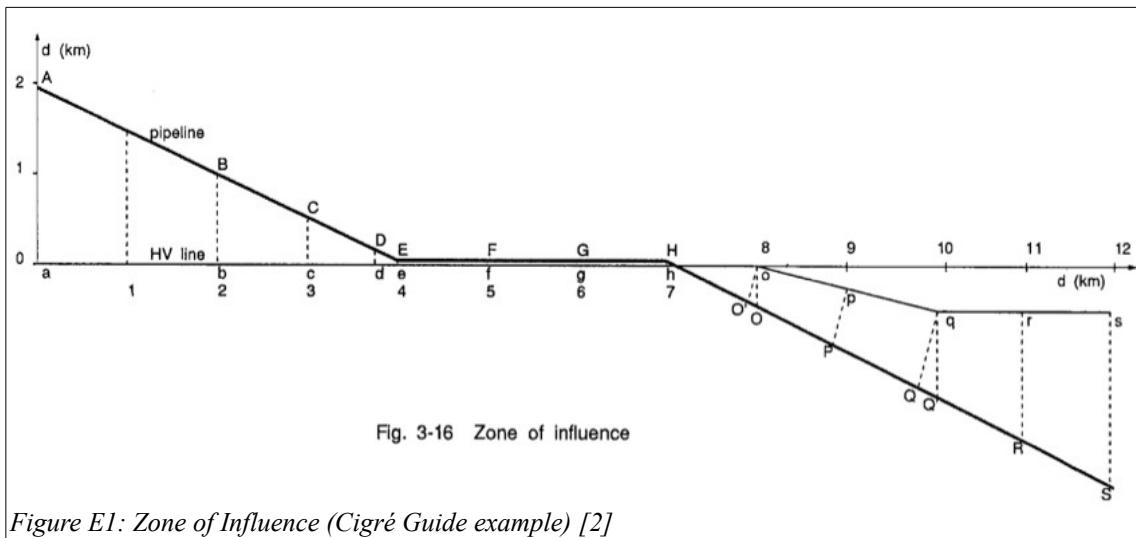


Figure E1: Zone of Influence (Cigré Guide example) [2]

In the previous figure the zone of influence is shown.

### *Inducing circuit*

The inducing circuit is a 400kV aerial line. In the following table line's data are shown.

## Appendix E

Table E1: Line's Tech Specs [2]

Voltage [kV]	400
Frequency [Hz]	50
Line arrangement	SC
Mean height of the lowest conductor [m]	15
Vertical distance between conductors [m]	9
Number of earthwires	2
Mean height of the earthwires [m]	45
Outreach of the lowest phase conductors [m]	7
Outreach of the median phase conductors [m]	8
Outreach of the highest phase conductors [m]	7
Phase conductor's material	Cu
Phase conductor 's cross section [mm <sup>2</sup> ]	561
Number of conductors for each phase	2
Distance between conductors in each phase [m]	0.4
Distance between earthwires [m]	8
Earthwire's cross section [mm <sup>2</sup> ]	154
Single phase fault to earth current [A]	10000
Steady-state condition current [A]	1000
Soil resistivity [ $\Omega$ m]	100

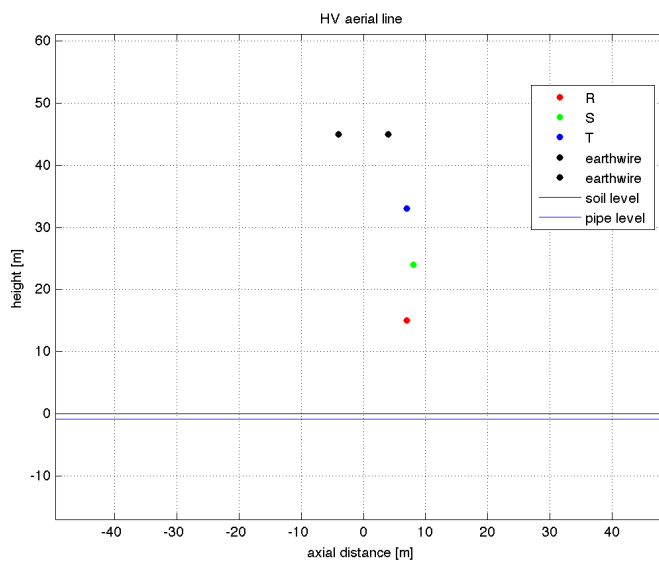


Figure E2: Line's cross section



## Induced circuit

The induced circuit is a pipeline. In the following table pipe's data are shown.

Table E2: Pipeline's Tech Specs [2]

PIPE material	Steel
Pipe's diameter [m]	0.3
Pipe's depth [m]	1
Pipe resistivity [ $\Omega\text{m}$ ]	$0.16 * 10^{-6}$
Relative magnetic permeability	300

Two cases of pipe's insulation coating are analyzed.

### Case A

Table E3: Pipe's Coating's Tech Specs – Case A [2]

COATING material	<b>Bitumen</b>
Coating's relative permittivity	5
Coating's thickness [m]	$4 * 10^{-3}$
Coating's specific resistance – $r_c$ [ $\Omega\text{m}^2$ ]	<b><math>10^3</math></b>

### Case B

Table E4: Pipe's Coating's Tech Specs – Case B [2]

COATING material	<b>Polyethylene</b>
Coating's relative permittivity	5
Coating's thickness [m]	$4 * 10^{-3}$
Coating's specific resistance – $r_c$ [ $\Omega\text{m}^2$ ]	<b><math>10^6</math></b>

## Emf results

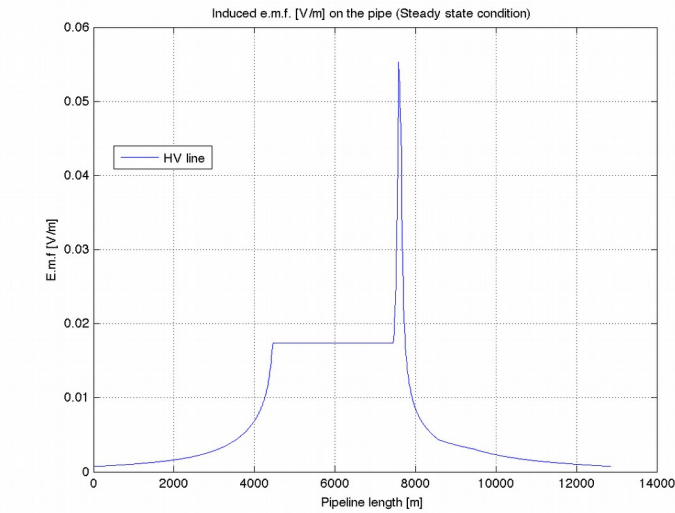


Figure E3: Induced emf of the pipe – steady-state condition

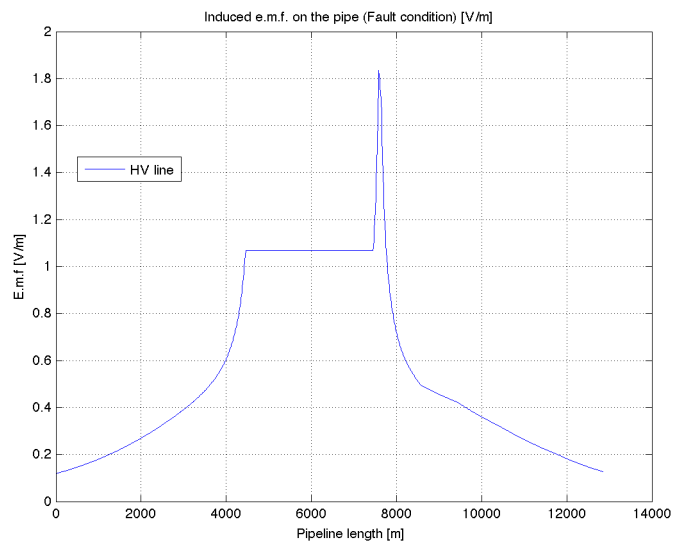


Figure E4: Induced emf of the pipe – fault condition

## Voltage results

In this section I will compare the results I obtained through my program and the ones given by the Guide.

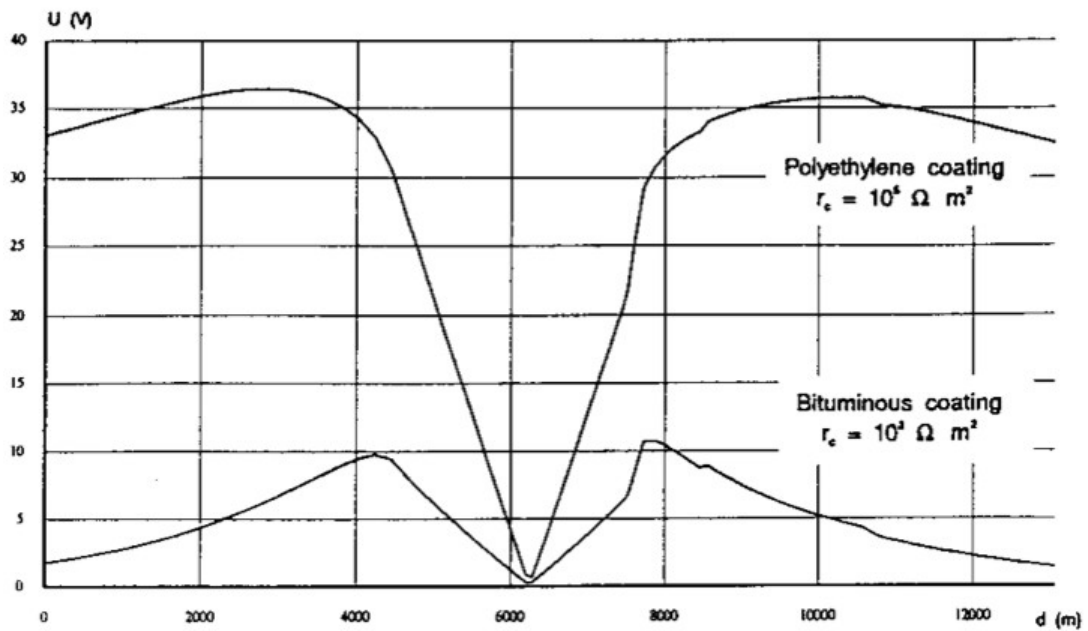


Figure E5: Voltage on the pipe – Steady-state conditions – Cigré Guide [2]

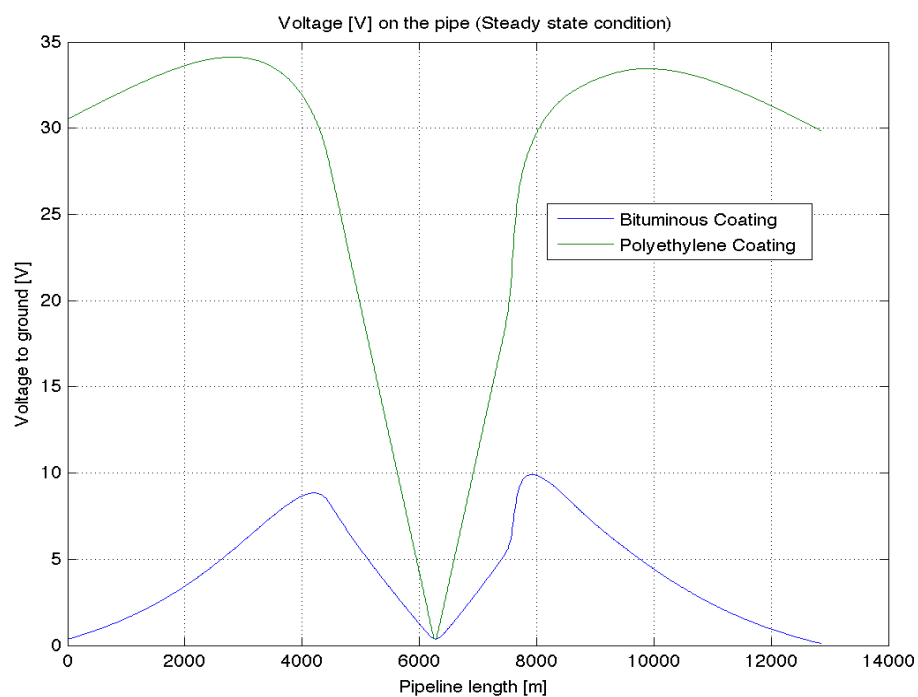


Figure E6: Voltage on the pipe – Steady-state conditions – proposed solution

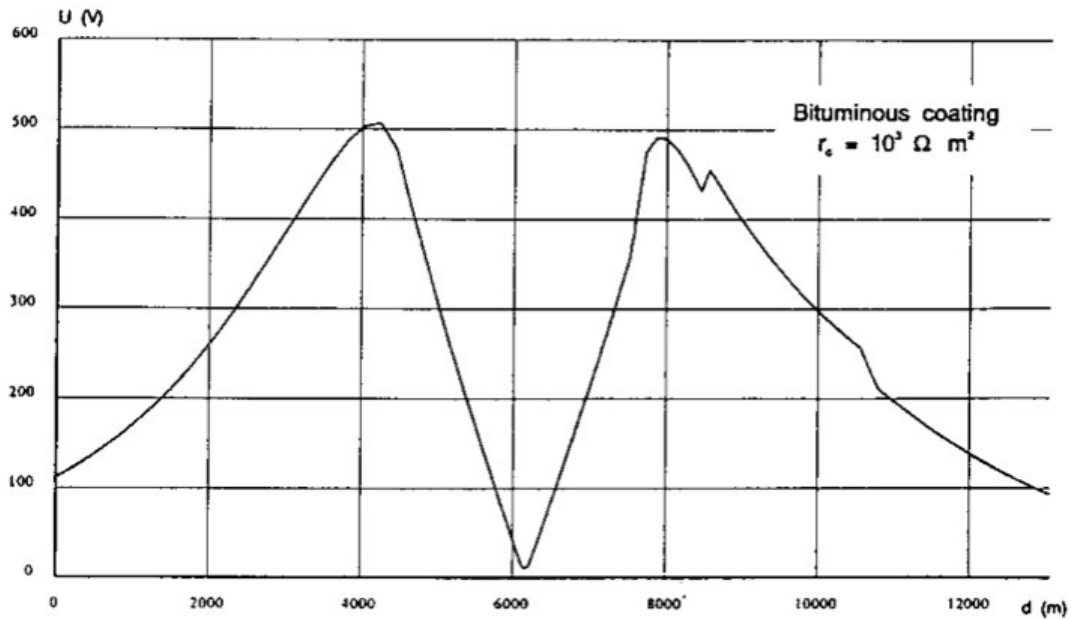


Figure E7: Voltage on the pipe – Fault conditions – Bituminous Coating – Cigré Guide [2]

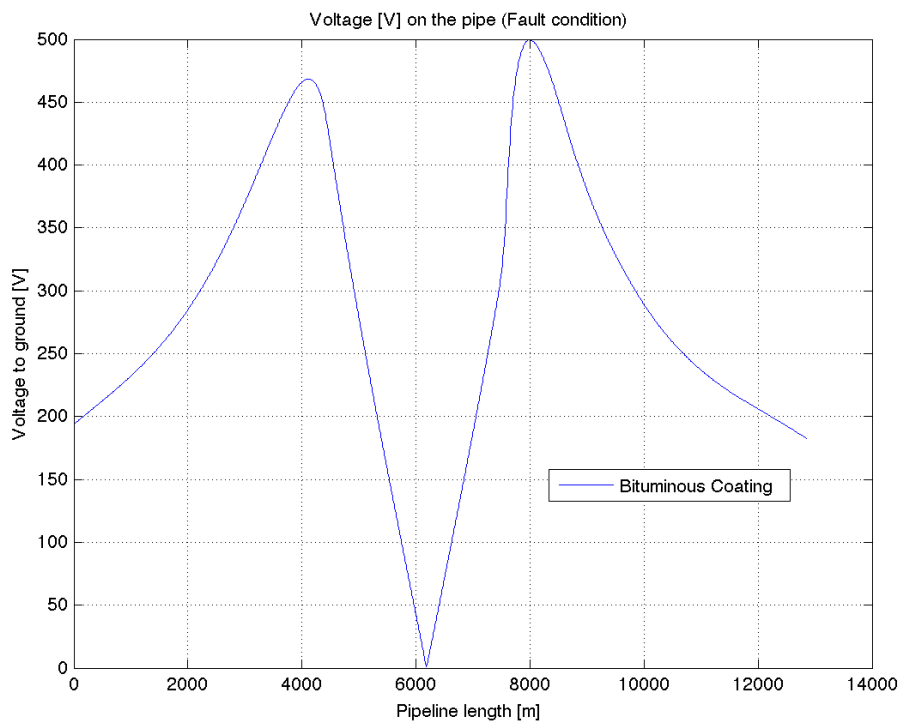


Figure E8: Voltage on the pipe – Fault conditions – Bituminous Coating – proposed solution

We can see that differences are very low. They are caused by the approximations I had to make to build a smart and versatile program. So my program can be used for inductive coupling.

# Appendix F

## Matlab calculation programs

In this section I will show the main programs I used for writing this thesis. The functions called belong to a library that is built from the theory exposed in this work.

### ***Induced Voltage Calculation: End-User Program***

This program is made for any calculation of Induced Voltage on a pipe by:

1. aerial line (SC,DCSB,DCLR) with 0,1 or 2 earthwires;
2. trefoil cable.

You can choose by video input pipeline's border conditions and mitigating measures. In this case I've set the same border conditions and the same mitigating measures I used when analyzing "Feeder Idrovia Saonara" pipeline: they can be changed modifying the impedance's matrix, as explained in section 2.7.

It is possible to analyze induced emf by an aerial line or cable, but you need to declare all variables in data's script for proper operation.

Input coordinates must be obtained after pipeline's linearization.

#### **INPUT DATA:**

```
% dati_input_enduser.m
%
% data for Calculations of Induced Voltage on a pipe by:
% - aerial line (SC,DCSB,DCLR) with 0,1 or 2 earthwires
% - trefoil cable (see cable conditions)
% enter the values of the line on which you want to make the analysis

discr=1; % [m] pipeline's discretization
global f
f=50; % frequency [Hz]
mu0 = 1.26E-06; % [H/m]
eps0 = 8.85*10^(-12); % [F/m]
ro=41.86; % [Ohm*m] soil resistivity

linea=input('Power line [type number]:\n[1] HV aerial line,\n[2] HV trefoil
cable \n'); % aerial=1, cable=2
regime=input('Operating conditions [type number]:\n[1] steady-state
conditions,\n[2] fault conditions \n');% steady-state conditions=1; fault
conditions=2
ICarson=4; % switch mode: 1. Carson Clem
% 4. Carson Series

% pipe's conditions
Risp6=input('Pipeline's upstream conditions [type number]:\n[1] joint's
discharger OFF (present condition),\n[2] joint's discharger ON,\n[3] grounded
upstream through surge arrester \n');
Risp7=input('Pipeline's downstream conditions [type number]:\n[1] the pipe
continues its route downstream ,\n[2] grounded downstream through surge
arrester \n');
% aerial line conditions
tipoterna=2; % 3 - DCSB; 2 - DCLR; 1 - SC
```

## Appendix F

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```
numfuni=1;           % earthwire's number (0,1,2)
Ifase380=2310;      % [A] steady-state current - aerial line
Iguasto380=14500;  % [A] fault current - aerial line
sqnz=-1;           % sequence: 1 inverse, -1 direct

% cable conditions
Ifase220=1000;     % [A] steady-state current - cable
Iguasto220=10000;  % [A] fault current - cable

%% pipe
Dt=0.2191;         % [m] pipe's diameter
Posapipe=-0.97 ;   % [m] pipe's depth
hpipe= (Posapipe+Dt/2); % [m] pipe's axis's depth
rop= 0.16*10^(-6); % [Ohm*m] pipe's resistivity
mur= 300;          % pipe's magnetic relative permeability
Zterra= 0.74 ;    % [Ohm] grounding resistance

%RIVESTIMENTO polietilene r3r
epsr= 2.3;         % polyethylene dielectric relative permittivity
deltac=3*10^(-3); % [m] coating's thickness
Rc=1.2*10^6;       % [Ohm*m2] coating's specific resistance

%% Aerial line
% conductors' data
Daerea=0.2722;    % [m] phase equivalent diameter
Rkm380=0.02077;   % [Ohm/km] r=1.12*r20/3 AlAc31.5 phase
conductor's resistance
diamfg= 17.9/1000 ; % [m] earthwire's diameter
rfg = 0.28 ;      % [Ohm/km] earthwire's resistance
h1 = 30.76;       % [m] mean height of the lowest conductor
hr = 6.8 ;        % [m] vertical distance between phases
hf= 56.32 ;      % [m] earthwire's mean height
Df1f2=8;          % [m] distance between earthwires (if two)
sb1=4.8;          % [m] outreach of the lowest conductor
sb2=4.7;          % [m] outreach of the middle conductor
sb3=4.6;          % [m] outreach of the highest conductor

%% Cable
separaz_cavi=0;
DiamCavo=0.143 ;  % [m] cable's diameter
h_cavo=-1.6 ;     % [m] cable's depth
raggio_medio_schermo= 0.057; % [m] sheath's mean radius
rs=0.085;         % [Ohm/km] sheath resistance 20°C
diam_conduitt= 0.0661; % [m] cable's conductor diameter
r20cavo=0.0072;  % [Ohm/km] cable's conductor resistance 20°C
```

### MAIN PROGRAM

```
% Induced voltage calculations
%
% E0 - induced emf without earthwires or screening circuits
% Ec - induced emf contribute of the screening circuits
% E - induced emf on the pipe
%
% Tensioni - induced VOLTAGE on the pipe

clear

path(path,'tools')
path(path,'tools/Carson')

dati_input_enduser
distanze_equivalenti
alfa=(w(f)*mu0/ro)^0.5;

if linea==1;           % aerial line

% -----
% EMF AERIAL LINE
```

```

% -----
tipoterna=tipoterna;
numfuni=numfuni; % earthwire's number

if numfuni==1;
    Df1f2=0;
end

sb1=sb1; % [m] outreach of the lowest conductor
sb2=sb2; % [m] outreach of the middle conductor
sb3=sb3; % [m] outreach of the highest conductor
h1=h1; % [m] mean height of the lowest conductor
h2=h1+hr ; % [m] mean height of the middle conductor
h3=h1+2*hr; % [m] mean height of the highest conductor
hf=hf ; % [m] mean height of the earthwire(s)

% emf steady-state
if regime==1; %steady-state

[E,Ec,E0,Ifune]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linha,ICarson,tip
oterna,numfuni,Ifase380,Iguasto380,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,mur,e
psr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separaz_c
avi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

% emf fault
elseif regime==2; % fault

[E,Ec,E0,Ifune]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linha,ICarson,tip
oterna,numfuni,Ifase380,Iguasto380,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,mur,e
psr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separaz_c
avi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);
end

elseif linea==2;

% -----
% EMF TREFOIL CABLE
% -----

tipoterna=1; % single triplet (SC)
numfuni=0; % ALWAYS ZERO
% cavo
distanze_equivalenti

sb1=-DiamCavo/2; % [m] x position 1 conductor
sb2=+DiamCavo/2; % [m] x position 2 conductor
sb3=0; % [m] x position 3 conductor
h1=(h_cavo+DiamCavo/2); % [m] y position 1 conductor
h2=(h_cavo+DiamCavo/2) ; % [m] y position 2 conductor
h3=(h_cavo+DiamCavo/2+DiamCavo*sin(pi/3)); % [m] y position 3 conductor

% emf steadystate
if regime==1;

[E,Ec,E0,Ifune]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linha,ICarson,tip
oterna,numfuni,Ifase380,Iguasto380,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,mur,e
psr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separaz_c
avi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

% emf fault
elseif regime==2;

[E,Ec,E0,Ifune]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linha,ICarson,tip
oterna,numfuni,Ifase380,Iguasto380,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,mur,e
psr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separaz_c
avi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);
%corrective factor k - fault - cable
k=(rs/1000)/Zii(2,rs,f,ro,100,2*raggio_medio_schermo);
E=k.*E0;
end

end
end

```

## Appendix F

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```

% -----
% PIPE'S IMPEDANCE MATRIX
% -----

roc=Rc/deltac; % [Ohm*m] coating's resistivity
z=ZserieTUBO(f,ro,rop,mu0,mur,Dt); % [Ohm/m] pipe's series impedance
y=yTUBO(f,Dt,roc,deltac,eps0,epsr); % [S/m] pipe's trasversal admittance
Zc= (z/y)^0.5; % Zc [Ohm] chacteristic impedance
gamma= (z*y)^0.5; % gamma [m^-1]
Li=ones(length(assex),1)*discr;

% Z UPSTREAM
if Risp6==1; % JOINT'S DISCHARGER OFF
    z_monte=2/(y*Li(1));
elseif Risp6==2; % JOINT'S DISCHARGER ON
    z_monte=Zc/(2+y*Li(1));
elseif Risp6==3; % GROUNDED UPSTREAM
    z_monte=Zterra;
end

% Z DOWNSTREAM
if Risp7==1; % PIPE CONTINUES ITS ROUTE
    z_valle= 2*Zc/(2+y*Li(length(Li)));
elseif Risp7==2; % GROUNDED DOWNSTREAM
    z_valle=Zterra;
end

for a=1:length(Li)-1
    yi=y*Li(a);
    yipl=y*Li(a+1);
    diag_sopra = 2/(yi+yipl);
    m_impedenze(a,a+1)= -diag_sopra;
    m_impedenze(a+1,a)= -diag_sopra;
    z_a_terra(a)=diag_sopra;
end
%%%%%% m_impedenze(1,1) e m_impedenze(n,n) %%%
m_impedenze(1,1)= z_monte+z*Li(1)-m_impedenze(1,2);
m_impedenze(length(Li),length(Li))= -m_impedenze(end,end-1)+z*Li(length(Li))
+z_valle;

for b=2:length(Li)-1;
    m_impedenze(b,b)= -m_impedenze(b,b-1)+z*Li(b)-m_impedenze(b,b+1);
end
E=E*discr;
% -----
% VOLTAGE TO GROUND
% -----

% PIPE'S CURRENT
correnti_di_maglia=m_impedenze\E';
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1); %perdo
l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% VOLTAGE TO GROUND

Tensioni=z_a_terra.*correnti_a_terra;

%-----
% GRAPHS
%-----
x=assex;

% EMF

figure(1)
plot(x,abs(E))
xlabel('Pipeline length [m]')
ylabel('E.m.f [V/m]')
grid on
title('Induced e.m.f. [V/m] on the pipe')

```



```

x(end)=[];

% TENSIONI

figure(2)
plot(x,abs(Tensioni))
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
grid on
title('Voltage [V] on the pipe')

```

**SCRIPTS:**

```

distanze_equivalenti.m
% distanze_equivalenti.m
%
if linea==1;
    coord_MET_AEREA %da linearizzazione pipeline
elseif linea==2;
    coord_MET_CAVO %da linearizzazione pipeline
end

assex=coordinate_spezioni(1,1):discr:coordinate_spezioni(end,1);
assey=(interp1(coordinate_spezioni(:,1),coordinate_spezioni(:,2),assex));

for q=2:length(assex);
    %deq(q)=((assey(q))*(assey(q-1)))^0.5;
    deq(q)=((assey(q)+(assey(q-1)))/2;
end

```

**EMF FUNCTIONS:**

```

function [E,Ec,E0,Ifune] =
valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linea,ICarson,tipoterna,numfuni,I
fase380,Iguasto380,sqz,Ifase220,Iguasto220,Dt,hpipe,rop,mur,epsr,deltac,Rc,Da
area,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separaz_cavi,DiamCavo,h_c
avo,raggio_medio_schermo,rs,diam_condutt,r20cavo)

% elabora i dati di una linea aerea con funi e una linea in cavo senza
% schermi, effetto degli schermi aggiunto dopo

%% tubo

roc=Rc/deltac; % resistività rivestimento [Ohm*m]
z=ZserieTUBO(f,ro,rop,mu0,mur,Dt); % z[Ohm/m]
y=yTUBO(f,Dt,roc,deltac,eps0,epsr); % y [S/m]
Zc= (z/y)^0.5; % Zc [Ohm]
gamma= (z*y)^0.5; % gamma [m^-1]

%% linea aerea
if linea==1
    % COND [ dcond [m],Rii[Ohm/km]]
    COND=[...
        Daerea Rkm380 % % d1 fase 1 destra
        Daerea Rkm380 % % d2 tolgo questi se caso guasto
        Daerea Rkm380 % % d3 tolgo questi se caso guasto
        Daerea Rkm380 % % s1 fase 1 sinistra - tolgo questi se singola
terna
        Daerea Rkm380 % % s2 tolgo questi se singola terna
        Daerea Rkm380 % % s3 tolgo questi se singola terna
        diamfg rfg % % fune di g - sinistra - f4
        diamfg rfg % % f5 tolgo questa se 1 fune (comando seguente)
        Dt real(z)*1000]; % % pipe sono valori non utilizzati, ma è
importante che siano presenti

if regime==1; %regime
    if tipoterna==3; % doppia terna simmetrica
        I_=[...
            (Ifase380/2)*exp(0*1i) % terna di destra

```

```

                (Ifase380/2)*exp(sqz*2/3*pi*1i)
                (Ifase380/2)*exp(sqz*4/3*pi*1i)
                (Ifase380/2)*exp(0*1i)           % terna di sinistra
                (Ifase380/2)*exp(sqz*2/3*pi*1i)
                (Ifase380/2)*exp(sqz*4/3*pi*1i)];

elseif tipoterna==2; % doppia terna ottimizzata (antisimmetrica)
    I_=[...
        (Ifase380/2)*exp(0*1i)           % terna di destra
        (Ifase380/2)*exp(sqz*2/3*pi*1i)
        (Ifase380/2)*exp(sqz*4/3*pi*1i)
        (Ifase380/2)*exp(sqz*4/3*pi*1i)           % terna di sinistra
        (Ifase380/2)*exp(sqz*2/3*pi*1i)
        (Ifase380/2)*exp(0*1i)];

elseif tipoterna==1; %terna singola
    I_=[...
        Ifase380*exp(0*pi*1i)
        Ifase380*exp(sqz*2/3*pi*1i)
        Ifase380*exp(sqz*4/3*pi*1i)];

    COND_(4,:)=[]; % terna singola a regime, tolgo una terna
    COND_(4,:)=[];
    COND_(4,:)=[];

end

numfasi=length(I_); % numero fasi

elseif regime==2; % guasto
    I_=[...
        Iguasto380*exp(-2/3*pi*1i)]; % Icc

    numfasi=length(I_); % numero fasi

    COND_(2,:)=[]; % tolgo conduttori di fase non coinvolti nel guasto
    COND_(2,:)=[];
    COND_(2,:)=[];
    COND_(2,:)=[];
    COND_(2,:)=[];

end

if numfuni==1;
    COND_(end-1,:)=[]; % tolgo la seconda fune
    %Df1f2=0;
end
if numfuni==0;
    COND_(end-1,:)=[]; % tolgo la seconda fune
    COND_(end-1,:)=[]; % tolgo la terza fune
    Df1f2=0;
end

%% cavo
elseif linea==2
    % COND [ dcond [m],Rii[Ohm/km]]
    COND_=[...
        diam_condutt 1.28*r20cavo % d1 fase 1 (90°C in esercizio)
        diam_condutt 1.28*r20cavo % d2
        diam_condutt 1.28*r20cavo % d3
        Dt real(z)*1000];

    if regime==1; % regime normale
        I_=[... %
            Ifase220*exp(0*1i)
            Ifase220*exp(2/3*pi*1i)
            Ifase220*exp(4/3*pi*1i)];
        numfasi=length(I_);
    %COND_(4,:)=[]; % tolgo lo schermo
    elseif regime==2; % guasto
        I_=[...
            Iguasto220*exp(0*1i)];
        numfasi=length(I_);
    end
end

```

```

        % tolgo i valori che non ci sono in caso di corto
        % presente solo cond 1 e schermo 1
        COND_(2,:)=[];           % tolgo secondo conduttore
        COND_(3,:)=[];           % tolgo terzo conduttore

    end
end

alfa=(w(f)*mu0/ro)^0.5;

%% calcolo FEM

for index=1:length(deq);        % ATTENZIONE Ifune(:,end) per alleggerire il
    calcolo tanto sono tutti uguali

    [E(index),Ifune(index,:),Ec(index),E0(index)]=femAereaNEW(f,ro,numfasi_,I_,num
    funi,COND_,deq(index),h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,hpipe,ICarson);

end
Ifune=Ifune(end,:); % tanto sono tutti uguali

function
[E,Ifune,Ec,E0]=femAereaNEW(f,ro,numfasi,I,numfuni,mat_cond,deqsez,h1,h2,h3,hf
,Df1f2,sb1,sb2,sb3,hpipe,ICarson)

%
% discr= discretizzazione [m]
% deqsez distanza di questa sezione
% bisogna fare E per tutte le deq=[deqsez1,deqsez2,...] di una linea
% inducente!!!! (poi si somma vettorialmente le E )
% h1, h cond basso
% hr = dist assiale tra cond
% Df1f2= dist tra funi (0 se una fune)
% sb1,sb2,sb3 sbracci rispetto all'asse del palo
% hpipe = profondità asse tubo CON SEGNO
% dpt = profondità posa tubo
% COND [ dcond,RiiOhm/km] METTERE I VALORI EFFETTIVI NELL'ORDINE PRESCRITTO

%h2=h1+hr; % h2 altezza cond 2
%h3=h1+2*hr;

% posizioni dei conduttori

posiz=[...
    -sb1+h1*li
    -sb2+h2*li
    -sb3+h3*li
    sb1+h1*li
    sb2+h2*li
    sb3+h3*li
    Df1f2/2+hf*li
    -Df1f2/2+hf*li
    deqsez+hpipe*li]; % posizioni

if numfasi==1;
    posiz(2)=[];
    posiz(2)=[];
    posiz(2)=[];
    posiz(2)=[];
    posiz(2)=[];
elseif numfasi==3;
    posiz(4)=[];
    posiz(4)=[];
    posiz(4)=[];
end

if numfuni==1;
    posiz(end-1)=[];
elseif numfuni==0;

```

## Appendix F

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```

        posiz(end-1)=[];
        posiz(end-1)=[];
end

% diametri e distanze

% for i=1:length(posiz);
%     for j=1:length(posiz);
%         d(i,j)=abs(posiz(i)-posiz(j));
%         %d(i,j)=(posiz(i)-posiz(j));
%     end
% end

% for k=1:length(posiz);
%     d(k,k)=mat_cond(k,1);
% end

% matrice delle impedenze auto e mutue del fascio conduttori

% %Z=eye(length(posiz));

% % for ii=1:length(posiz);
% %     for jj=1:length(posiz);
% %         Z(ii,jj)=Zij(f,ro,abs(d(ii,jj)));
% %     end
% % end
r_c=mat_cond(:,1)./2; % raggi conduttori
mcoef=1;
Rc=mat_cond(:,2); % resistenze chilometriche dei conduttori
%ICarson=1; % switch mode: 1. Carson Clem
%                               4. Carson Series
NCarsonCrTerms= 14; %14; % numero termini della serie di carson

Z=CalcRLC1(posiz, ro, r_c, mcoef, Rc, 0 ,ICarson, NCarsonCrTerms, 1, 0,
1)./1000;

% for q=1:length(posiz);
%     Z(q,q)=Zii(mat_cond(q,2),f,ro,imag(posiz(q)),d(q,q));
% end

% zero funi di guardia

if numfuni==0;
    for fgf=1:length(posiz)-1;
        Ev(fgf)=-Z(end,fgf)*I(fgf);
    end
    E0=sum(Ev); % fem sul tubo
    Ifune=0; % corrente sulla fune

    Ec=0;
    E=Ec+E0;

elseif numfuni==1;

% una fune di guardia
    for fgf=1:length(posiz)-2;
        En(fgf)=-Z(end-1,fgf)*I(fgf);
    end
    Enoto=sum(En); % fem sulla fune 1
    Ifune=Enoto/Z(end-1,end-1); % corrente sulla fune
    for rr=1:length(posiz)-2;
        Ev(rr)=-Z(end,rr)*I(rr);%%%-
    end
    E0=sum(Ev(:)); % fem sul tubo senza fune
    Ec=-Ifune*Z(end,end-1); %%%- % contributo fem dalla fune 1
    %Ec2=0; % contributo fem dalla fune 2
    E=E0+Ec; % fem complessiva
else

% due funi di guardia
    Z1=[...

```

```

Z(end-2,end-2) Z(end-2,end-1) 0
Z(end-1,end-2) Z(end-1,end-1) 0
Z(end,end-2) Z(end,end-1) 1];

for rr=length(posiz)-2:length(posiz);
for col=1:length(posiz)-3;
En(rr,col)=Z(rr,col)*I(col);
end
end

Enoto(1)=-sum(En(length(posiz)-2,:)); % fem sulla fune 1
Enoto(2)=-sum(En(length(posiz)-1,:)); % fem sulla fune 2
Enoto(3)=-sum(En(length(posiz),:)); % fem sul tubo senza fune

I7I8=Z1\'(Enoto');
Ifune=[I7I8(1),I7I8(2)]; % correnti sulle funi
E=I7I8(3); % fem sul tubo con le funi
E0=Enoto(3); % fem sul tubo senza fune
Ec=E-E0; % contributo fem della fune

end

```

## **Induced Voltage Calculation: “Feeder Idrovia Saonara”**

In this section I will show the Main program I used for the analysis of “Feeder Idrovia Saonara”.

### **MAIN PROGRAM**

```

% ANALISI INDUZIONE SU FEEDER IDROVIA SAONARA
%
% inducente linea aerea 380kV doppia terna ottimizzata (dolo camin) e cavo
trifase
%
%
% -ICarson: 1. carson clem, 4. carson series
% -tipoterna: 3. doppia terna simmetrica; 2. doppia terna ottimizzata; 1.
singola terna
% -sb1: [m] sbraccio cond 1 (più basso) positivi se i conduttori
stanno dalla parte del tubo ( in caso di terna singola)
% -sb2: [m] sbraccio cond 2
% -sb3: [m] sbraccio cond 3
% -sqnz: 1. inversa, -1. diretta
% -numfuni: numero duni di guardia 1 o 2
% -h1: [m] altezza MEDIA conduttore più basso
% -h2:
% -h3:
% -linea: 1 - aerea ; 2 _ cavo
% -hf: [m] altezza MEDIA della fune di guardia (delle due se doppie
sullo stesso piano da terra)
%
%
clear

path(path,'tools')
path(path,'tools/Carson')

dati_input
ro=41.86;

% -----
% FEM LINEA AEREA
% -----

% singola terna zero funi
tipoterna=2; % doppia terna ottimizzata

```

## Appendix F

```

numfuni=1; % numero funi
Df1f2=0;

linea=1; % aerea
distanze_equivalenti

sb1=sb1; % [m] sbraccio cond 1 (più basso)
positivi se i conduttori stanno dalla parte del tubo ( in caso di terna
singola)
sb2=sb2; % [m] sbraccio cond 2
sb3=sb3; % [m] sbraccio cond 3
h1=h1; % [m] altezza MEDIA conduttore più
basso
h2=h1+hr ; % [m] altezza MEDIA conduttore
intermedio
h3=h1+2*hr; % [m] altezza MEDIA conduttore più
alto
hf=hf ; % [m] altezza MEDIA della fune di
guardia (delle due se doppie sullo stesso piano da terra)

% CALCOLO FEM LINEA AEREA --regime--
regime=1; %regime

[E1,Ec1,E01,Ifune1]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linea,ICarson
,tipoterna,numfuni,Ifase380,Iguasto380,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,m
ur,epsr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separ
az_cavi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

% CALCOLO FEM LINEA AEREA --guasto--
regime=2; % guasto

[E2,Ec2,E02,Ifune2]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linea,ICarson
,tipoterna,numfuni,Ifase380,Iguasto380,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,m
ur,epsr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separ
az_cavi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

% sezione della linea aerea
figure(1)
xmin=-49.5;
xmax=49.5;
ymin=-10;
ymax=50;
x=xmin:xmax;
y_soil=0*ones(1,length(x));
y_pipe=hpipe*ones(1,length(x));

plot(sb1,h1,'r.',sb2,h2,'g.', sb3, h3,'b.',-sb1,h1,'b.',-sb2,h2,'g.',-
sb3, h3,'r.',0,hf,'k.',x,y_soil,'k-',x,y_pipe,'b-', 'MarkerSize',15)
xlabel('axial distance [m]')
ylabel('height [m]')
legend('R','S','T','T','S','R','earthwire','soil level','pipe
level','Location','Best')
axis([xmin xmax ymin ymax])
axis equal
grid on
title ('HV aerial line')

% -----
% FEM LINEA IN CAVO
% -----

tipoterna=1; % singola terna
numfuni=0; % numero funi sempre zero

linea=2; % cavo
distanze_equivalenti

sb1=-DiamCavo/2; % [m] posizione x conduttore 1
sb2+=DiamCavo/2; % [m] posizione x conduttore 2
sb3=0; % [m] posizione x conduttore 3
h1=(h_cavo+DiamCavo/2); % [m] posizione y conduttore 1
h2= (h_cavo+DiamCavo/2) ; % [m] posizione y conduttore 2
h3=(h_cavo+DiamCavo/2+DiamCavo*sin(pi/3)); % [m] posizione y conduttore 3

```

```

% CALCOLO FEM LINEA IN CAVO --regime--
regime=1; %regime%

[E3, Ec3, E03, Ifune3]=valutazionek_femNEW(deq, f, mu0, eps0, ro, regime, linea, ICarson
, tipoterna, numfuni, Ifase380, Iguasto380, sqnz, Ifase220, Iguasto220, Dt, hpipe, rop, m
ur, epsr, deltac, Rc, Daerea, Rkm380, diamfg, rfg, h1, h2, h3, hf, Df1f2, sb1, sb2, sb3, separ
az_cavi, DiamCavo, h_cavo, raggio_medio_schermo, rs, diam_condutt, r20cavo);

% CALCOLO FEM LINEA IN CAVO --guasto--
regime=2; %guasto%

[E4, Ec4, E04, Ifune4]=valutazionek_femNEW(deq, f, mu0, eps0, ro, regime, linea, ICarson
, tipoterna, numfuni, Ifase380, Iguasto380, sqnz, Ifase220, Iguasto220, Dt, hpipe, rop, m
ur, epsr, deltac, Rc, Daerea, Rkm380, diamfg, rfg, h1, h2, h3, hf, Df1f2, sb1, sb2, sb3, separ
az_cavi, DiamCavo, h_cavo, raggio_medio_schermo, rs, diam_condutt, r20cavo);
k=(rs/1000)/Zii(2, rs, f, ro, 100, 2*raggio_medio_schermo); % coefficiente
correttivo
E4=k.*E04;

figure(2)

y_soil=0*ones(1,length(deq));
y_pipe=hpipe*ones(1,length(deq));
cav_dim=2.5; % dimensione grafico cavo
x=deq;

plot(sb1,h1,'r.',sb2,h2,'g.', sb3,
h3,'b.',x,y_soil,'k-',x,y_pipe,'b-', 'MarkerSize',15)
xlabel('axial distance [m]')
ylabel('height [m]')
legend('R','S','T','soil level','pipe level','Location','NorthEast')
axis equal
axis([-cav_dim cav_dim -cav_dim cav_dim])
grid on
title ('HV cable')

% -----
% MATRICE ALLE IMPEDENZE DELLA TUBAZIONE
% -----

roc=Rc/deltac; % resistività rivestimento [Ohm*m]
z=ZserieTUBO(f,ro,rop,mu0,mur,Dt); % z [Ohm/m]
y=yTUBO(f,Dt,roc,deltac,eps0,epsr); % y [S/m]
Zc= (z/y)^0.5; % Zc [Ohm]
gamma= (z*y)^0.5; % gamma [m^-1]
Li=ones(length(assex),1)*discr;

for Rispp6=1:3

    for Rispp7=1:2

        % Z MONTE

        if Rispp6==1; % SCARICATORE NON ATTIVO (FLOTTANTE)
            % a monte tubo flottante sospeso (isolato da giunto non messo a
            terra)
            z_monte=2/(y*Li(1)); %parallelo lato sx del pi greco con
            aria (flottante)
        elseif Rispp6==2; % SCARICATORE ATTIVO
            %z_monte=2*Zc/(2+y*Li(1)); % tubo infinito
            z_monte=Zc/(2+y*Li(1)); % tubo doppio infinito Zc/2 !!
        elseif Rispp6==3; % MESSA A TERRA
            z_monte=Zterra; % messa a terra
        end

        % Z VALLE

        if Rispp7==1; % SITUAZIONE ATTUALE
            %a valle tubo infinito
            z_valle= 2*Zc/(2+y*Li(length(Li))); %parallelo lato dx del pi
            greco con impedenza caratteristica

```

## Appendix F

```

elseif Risp7==2;    % MESSA A TERRA
    z_valle=Zterra;
end

    for a=1:length(Li)-1;
        yi=y*Li(a);    %ammettenze del tratto considerato
        yipl=y*Li(a+1);    %ammettenze tratto successivo

        diag_sopra = 2/(yi+yipl);
        m_impedenze(a,a+1)= -diag_sopra;    % diagonale sopra
        m_impedenze(a+1,a)= -diag_sopra;    % diagonale sotto
        z_a_terra(a)=diag_sopra;
    end
    %%%%%%%%%% m_impedenze(1,1) e m_impedenze(n,n)%%%%%%%%%
    m_impedenze(1,1)= z_monte+z*Li(1)-m_impedenze(1,2);
    m_impedenze(length(Li),length(Li))= -m_impedenze(end,end-
1)+z*Li(length(Li))+z_valle;

    for b=2:length(Li)-1;
        m_impedenze(b,b)= -m_impedenze(b,b-1)+z*Li(b)-
m_impedenze(b,b+1);
    end

    matr_z_tubo(:, :, Risp6, Risp7)=m_impedenze(:, :);
    z_vs_terra(:, Risp6, Risp7)=z_a_terra(:);
end

end

% -----
% TENSIONI VERSO TERRA A REGIME
% -----
%
%
% FEM LINEA AEREA - E1
% FEM LINEA IN CAVO - E3
%
%
% -----

% E1 - linea aerea REGIME
% (11) SCARICATORE NON ATTIVO SX , DX SITUAZIONE ATTUALE

E=E1*discr;

m_impedenze=matr_z_tubo(:, :, 1, 1);
z_a_terra=z_vs_terra(:, 1, 1);

    %CORRENTI NELLA PIPELINE
    correnti_di_maglia=m_impedenze\('E');
    for k=1:length(Li)-1;
        correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
    end

    correnti_di_maglia(end)=[];

    % TENSIONI VERSO TERRA

    Tensioni=z_a_terra.*correnti_a_terra';

Ipl_11=correnti_di_maglia;
Vpl_11=Tensioni;

% -----

% E3 - linea in cavo REGIME
% (11) SCARICATORE NON ATTIVO SX , DX SITUAZIONE ATTUALE
E=E3*discr;
m_impedenze=matr_z_tubo(:, :, 1, 1);
z_a_terra=z_vs_terra(:, 1, 1);

```



```

%CORRENTI NELLA PIPELINE
correnti_di_maglia=m_impedenze\(E');
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% TENSIONI VERSO TERRA

Tensioni=z_a_terra.*correnti_a_terra';

Ip3_ll=correnti_di_maglia;
Vp3_ll=Tensioni;

% -----

% -----
% TENSIONI VERSO TERRA IN CONDIZIONI DI GUASTO
% -----
% -----
% FEM LINEA AEREA - E2
% FEM LINEA IN CAVO - E4
% -----

% E2 - linea aerea GUASTO
% (11) SCARICATORE NON ATTIVO SX , DX SITUAZIONE ATTUALE

E=E2*discr;

m_impedenze=matr_z_tubo(:, :, 1, 1);
z_a_terra=z_vs_terra(:, 1, 1);

%CORRENTI NELLA PIPELINE
correnti_di_maglia=m_impedenze\(E');
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% TENSIONI VERSO TERRA

Tensioni=z_a_terra.*correnti_a_terra';

Ip2_ll=correnti_di_maglia;
Vp2_ll=Tensioni;

% -----

% E4 - linea in cavo GUASTO
% (11) SCARICATORE NON ATTIVO SX , DX SITUAZIONE ATTUALE

E=E4*discr;

m_impedenze=matr_z_tubo(:, :, 1, 1);
z_a_terra=z_vs_terra(:, 1, 1);

%CORRENTI NELLA PIPELINE
correnti_di_maglia=m_impedenze\(E');
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% TENSIONI VERSO TERRA

```

## Appendix F

---

```
Tensioni=z_a_terra.*correnti_a_terra';

Ip4_11=correnti_di_maglia;
Vp4_11=Tensioni;

% -----
% -----

% E2 - linea aerea GUAUTO
% (21) SCARICATORE ATTIVO SX , DX SITUAZIONE ATTUALE

E=E2*discr;

m_impedenze=matr_z_tubo(:, :, 2, 1);
z_a_terra=z_vs_terra(:, 2, 1);

%CORRENTI NELLA PIPELINE
correnti_di_maglia=m_impedenze\(E');
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% TENSIONI VERSO TERRA

Tensioni=z_a_terra.*correnti_a_terra';

Ip2_21=correnti_di_maglia;
Vp2_21=Tensioni;

% -----

% -----
% MITIGAZIONE (GUAUTO) - scaricatori che intervengono solo in caso di
% guasto
% -----

% E2 - linea aerea GUAUTO
% (22) SCARICATORE DELL'ISOLATORE ON , DX SCARICATORE PER SOVRAT

E=E2*discr;

m_impedenze=matr_z_tubo(:, :, 2, 2);
z_a_terra=z_vs_terra(:, 2, 2);

%CORRENTI NELLA PIPELINE
correnti_di_maglia=m_impedenze\(E');
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% TENSIONI VERSO TERRA

Tensioni=z_a_terra.*correnti_a_terra';

Ip2_22=correnti_di_maglia;
Vp2_22=Tensioni;

% -----

% E2 - linea aerea GUAUTO
% (32) MESSA A TERRA SX , DX MESSA A TERRA
E=E2*discr;

m_impedenze=matr_z_tubo(:, :, 3, 2);
z_a_terra=z_vs_terra(:, 3, 2);

%CORRENTI NELLA PIPELINE
```

```

        correnti_di_maglia=m_impedenze\(E');
        for k=1:length(Li)-1;
            correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
        end

        correnti_di_maglia(end)=[];

        % TENSIONI VERSO TERRA

        Tensioni=z_a_terra.*correnti_a_terra';

Ip2_32=correnti_di_maglia;
Vp2_32=Tensioni;

% -----
% -----

% % E4 - linea in cavo GUASTO
% % (32) MESSA A TERRA SX , DX MESSA A TERRA
%
% E=E4*discr;
%
% m_impedenze=matr_z_tubo(:, :, 3, 2);
% z_a_terra=z_vs_terra(:, 3, 2);
%
%         %CORRENTI NELLA PIPELINE
%         correnti_di_maglia=m_impedenze\(E');
%         for k=1:length(Li)-1;
%             correnti_a_terra(k)=correnti_di_maglia(k)-
correnti_di_maglia(k+1); %perdo l'ultima corrente di maglia
%         end
%
%         correnti_di_maglia(end)=[];
%
%         % TENSIONI VERSO TERRA
%
%         Tensioni=z_a_terra.*correnti_a_terra';
%
% Ip4_32=correnti_di_maglia;
% Vp4_32=Tensioni;

%-----
% GRAFICI
%-----
x=assex;

% EMF
% regime (aerea e cavo)
figure(3)
plot(x,abs(E1),x,abs(E3),x,abs(E1+E3),x,sqrt(abs(E1).^2+abs(E3).^2))
xlabel('Pipeline length [m]')
ylabel('E.m.f [V/m]')
legend('HV line','HV cable','Vectorial sum','Italian standard
sum','Location','Best')
grid on
title('Induced e.m.f. [V/m] on the pipe (Steady state condition)')

% guasto (aerea e cavo)
figure(4)
plot(x,abs(E2),x,abs(E4))
xlabel('Pipeline length [m]')
ylabel('E.m.f [V/m]')
legend('HV line','HV cable','Location','Best')
grid on
title('Induced e.m.f. on the pipe (Fault condition) [V/m]')

x(end)=[];
U_scr=V_scar*ones(1,length(x));
U_reg=V_regime*ones(1,length(x));
U_gst=V_guasto*ones(1,length(x));

% TENSIONI

```

## Appendix F

---

```
% SCARICATORE NON ATTIVO
% regime (aerea e cavo)
figure(5)
plot(x,abs(Vp1_11),x,abs(Vp3_11),x,abs(Vp1_11+Vp3_11),x,sqrt(abs(Vp1_11).^2+abs(Vp3_11).^2))
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
legend('HV line','HV cable','Vectorial sum','Italian standard sum','Location','Best')
grid on
title('Voltage [V] on the pipe (Steady state condition)')

% guasto (aerea e cavo)
figure(6)
plot(x,abs(Vp2_11),x,abs(Vp4_11),x,U_scr,'r',x,U_gst,'m')
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
legend('HV line','HV cable','Joint's discharger limit','Maximum admissible voltage','Location','Best')
grid on
title('Voltage [V] on the pipe (Fault condition) - joint's discharger OFF')

% TENSIONI
% SCARICATORE flangia ATTIVO
% guasto (aerea)
figure(7)
plot(x,abs(Vp2_21),x,U_gst,'m')
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
legend('HV line','Maximum admissible voltage','Location','Best')
grid on
title('Voltage [V] on the pipe (Fault condition) - joint's discharger ON')

% MITIGAZIONE
% guasto (aerea)
% SCARICATORE flangia ATTIVO - SCARICATORE A DESTRA -
figure(8)
plot(x,abs(Vp2_22),x,U_gst,'m')
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
legend('HV line','Maximum admissible voltage','Location','Best')
grid on
title('Voltage [V] (Fault) - joint's discharger ON - downstream discharger ON ')

% guasto (aerea)
% SCARICATORE SINISTRA - SCARICATORE A DESTRA -
figure(9)
plot(x,abs(Vp2_32),x,U_gst,'m')
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
ylim([0 1200])
legend('HV line','Maximum admissible voltage','Location','Best')
grid on
title('Voltage [V] (Fault) - upstream discharger ON - downstream discharger ON ')

%-----
% STAMPA RISULTATI
%-----

cd results/dolo_camin_cable

print(figure(1),'-dpng','aerialSection.png')
print(figure(2),'-dpng','cableSection.png')

print(figure(3),'-dpng','EMFsteadystate.png')
print(figure(4),'-dpng','EMFfault.png')

print(figure(5),'-dpng','Usteadystate.png')
print(figure(6),'-dpng','Ufault_fldisOFF.png')
print(figure(7),'-dpng','Ufault_fldisON.png')
print(figure(8),'-dpng','Ufault_fldisON_dwnstrmON.png')
```

```
print(figure(9), '-dpng', 'Ufault_upstrmON_dwnstrmON.png')

close all
```

## Program for $k_4$ analysis (Appendix B)

This is the program I used for  $k_4$ 's analysis.

```
k4_ok_MAIN.m
% Analisi k4
clear

casi=3;
passo=10;
dmax=200;

h1_v= [15 15 23.5];           %[m] altezza MEDIA conduttore
più basso
s_v = [4.7 6 8.3] ;          %[m] distanza verticale media
tra le fasi
w_v= [3.2 4.5 6.3];          %[m] sbraccio medio
dpt_v=[0.86045 0.86045 0.86045]; %[m] profondità
ASSE del tubo

for tp=1:casi;

    h1 =h1_v(tp);
    s = s_v(tp) ;
    w=w_v(tp);
    dpt= dpt_v(tp);

    h2eq=h1+s+dpt;           % [m] altezza equivalente del baricentro dei
conduttori

    deq=0:passo:dmax;

    for in=1:length(deq); % rigoroso dt, st

        R=(deq(in)^2+h2eq^2)^0.5; % [m] distanza fra baricentro linea e asse
tubo
        phi=pi-atan(deq(in)/h2eq); % [rad] angolo

        A1=1/(R^2);
        A2=(s^3+12*w^2)/(s^2+3*R^2);
        A3=R^4-2*s^2*R^2*cos(2*phi)+s^4;

        k4(in)=A1*(A2*A3)^0.5;

    end

    for in=1:length(deq); % semplificato dt, dt(w=0)
tubo
        R=(deq(in)^2+h2eq^2)^0.5; % [m] distanza fra baricentro linea e asse
        k4a(in)=((s^3+12*w^2)^0.5)*1*(R^2-s^2)/(R^3*sqrt(3));

    end

    diff=(k4-k4a)./k4;

    % for in=1:length(deq);
    %
    % R=(deq(in)^2+h2eq^2)^0.5; % [m] distanza fra baricentro linea e asse
tubo
```

## Appendix F

---

```
% phi=-pi/2+atan(deq(in)/h2eq); % [rad] angolo
%
%
% k4tr(in)=s/(R^3)*sqrt(2)/3*sqrt(s^3+12*w^2)*sqrt(s^6-
2*(R^3)*(s^3)*cos(3*phi)+R^6)/sqrt(s^4+(s^2)*(R^2));
%
% end

K4(:,tp)=k4a(:);
Diff(:,tp)=diff(:)*100;

end

max(Diff)

% pass=10;
% maxlen=100;
% tab=1:pass:maxln;
%
% for tab=1:pass:maxln
%     for nu=1:length(tab)
%         K4tab(:,nu)=K4(:,tab);
%     end
% end
%

% tabella
figure(1)
plot(deq,K4(:,1),deq,K4(:,2),deq,K4(:,3))
xlabel('distance form line axis [m]')
ylabel('k4')
legend('132kV','220kV','380kV')
grid on
title('k4 values')

cd results/k4
xlswrite('k4.xls',K4)
print(figure(1),'-dpng','k4Comparison.png')

cd ../
cd ../

close all
```

## **Program for Comparison of cable's and aerial line's values of induced emf (sections 2.5 – 2.6)**

cable\_lineMAIN.m

```
% confronto cavo -linea aerea
%
% dati di input verranno riscritti:
% -ICarson:      1. carson clem, 4. carson series
% -tipoterna:    3. doppia terna simmetrica; 2. doppia terna ottimizzata; 1.
singola terna
% -sb1:          [m] sbraccio cond 1 (più basso) positivi se i conduttori
stanno dalla parte del tubo ( in caso di terna singola)
% -sb2:          [m] sbraccio cond 2
% -sb3:          [m] sbraccio cond 3
% -sqnz:         1. inversa, -1. diretta
% -numfuni:      numero duni di guardia 1 o 2
% -hl:           [m] altezza MEDIA conduttore più basso
```

```

% -h2:
% -h3:
% -linea: 1 - aerea ; 2 _ cavo
% -hf: [m] altezza MEDIA della fune di guardia (delle due se doppie
sullo stesso piano da terra)
%
%
clear

path(path,'../Multiconductor_s/tools')
path(path,'../Multiconductor_s/tools/Carson')

dati_input
%distanze_equivalenti
deq=-50:50;
ICarson=1;
kal=1;
sqnz=-1;% sequenza diretta
sz=1;

x=deq;
x(1)=-50;
ps=2; % passo dei cerchietti

xmin=-49.5;
xmax=49.5;
ymin=-10;
ymax=50;
y_soil=0*ones(1,length(x));
y_pipe=hpipe*ones(1,length(x));

regime=2;

% singola terna zero funi/una fune guasto
tipoterna=1; % singola terna
numfuni=1; % numero funi
linea=1; %aerea
sb1=4.8; % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
sb2=-4.7; % [m] sbraccio cond 2
sb3=4.6; % [m] sbraccio cond 3
h1=20; % [m] altezza MEDIA conduttore più basso
h2=25 ;
h3=30;
hf=40 ; % [m] altezza MEDIA della fune di guardia (delle due
se doppie sullo stesso piano da terra)
Ifase380=1000;
Iguasto380=10000;
Df1f2=0;

[E1(kal, :,sz),Ec1(kal, :,sz),E01(kal, :,sz),Ifunel(kal, :,sz)]=valutazionek_femNE
W(deq,f,mu0,eps0,ro,regime,linea,ICarson,tipoterna,numfuni,Ifase380,Iguasto380
,sqnz,Ifase220,Iguasto220,Dt,hpipe,rop,mur,epsr,deltac,Rc,Daerea,Rkm380,diamfg
,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separaz_cavi,DiamCavo,h_cavo,raggio_medio_s
chermo,rs,diam_condutt,r20cavo);

plot(sb1,h1,'r.',sb2,h2,'g.', sb3,
h3,'b.',x,y_soil,'k-',x,y_pipe,'b-', 'MarkerSize',15)
xlabel('axial distance [m]')
ylabel('height [m]')
legend('R','S','T','soil level','pipe level','Location','Best')
axis([xmin xmax ymin ymax])
axis equal
grid on
title ('HV aerial line')

cav_dim=2.5;

% cavo (no schermi)
%tipoterna=1; % singola terna

```

## Appendix F

```

numfuni=0;           % numero funi sempre zero
linea=2;           %cavo
sb1=-DiamCavo/2;   % [m] sbraccio cond 1 (più basso) positivi
se i conduttori stanno dalla parte del tubo ( in caso di terna singola)
sb2=+DiamCavo/2;   % [m] sbraccio cond 2
sb3=0;            % [m] sbraccio cond 3
h1=(h_cavo+DiamCavo/2);
h2= (h_cavo+DiamCavo/2) ;
h3=(h_cavo+DiamCavo/2+DiamCavo*sin(pi/3));
Df1f2=DiamCavo; %schermo
hf=h1;
Ifase220=1000;
Iguasto220=10000;

[E2(kal, :,sz),Ec2(kal, :,sz),E02(kal, :,sz),Ifune2(kal, :,sz)]=valutazionek_femNE
W(deq,f,mu0,eps0,ro,regime,linea,ICarson,tipoterna,numfuni,Ifase380,Iguasto380
,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,mur,epsr,deltac,Rc,Daerea,Rkm380,diamfg
,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separaz_cavi,DiamCavo,h_cavo,raggio_medio_s
chermo,rs,diam_condutt,r20cavo);

%Ec2=-
(ZijPOLY(f,ro,raggio_medio_schermo,2)/Zii(2,rs,f,ro,100,2*raggio_medio_schermo
)*ones(1,length(x))).*E02;
k=(rs/1000)/Zii(2,rs,f,ro,100,2*raggio_medio_schermo);
E2=k.*E02;

figure(2)
plot(sb1,h1,'r.',sb2,h2,'g.', sb3,
h3,'b.',x,y_soil,'k-',x,y_pipe,'b-', 'MarkerSize',15)
xlabel('axial distance [m]')
ylabel('height [m]')
legend('R','S','T','soil level','pipe level','Location','NorthEast')
axis equal
axis([-cav_dim cav_dim -cav_dim cav_dim])

grid on
title ('HV cable')

%regime
% figure(3)
% plot(x,abs(E1),x,abs(E2))
% xlim([xmin xmax])
% xlabel('axial distance [m]')
% ylabel('E.m.f [V/m]')
% legend('HV aerial line','HV cable','Location','Best')
% grid on
% title('E.m.f. by HV line and HV trefoil cable')
%
%

% guasto

figure(4)
plot(x,abs(E1), 'r',x,abs(E01), 'r-',x,abs(E2), 'b',x,abs(E02), 'b-.')
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('E.m.f [V/m]')
legend('E HV','E0 HV','E cable','E0 cable','Location','Best')
grid on
title('E.m.f. by HV line and HV trefoil cable')

cd results/cable_aerial
%
% print (figure(1), '-dpng', 'aerialSection.png')
% print (figure(2), '-dpng', 'cableSection.png')
% print (figure(3), '-dpng', 'ComparisonE0.png')
% print (figure(4), '-dpng', 'Comparisonfault.png')%
%close all

```



## Program for testing applicability of expressions in section 2.5.3

```

Eregimelew2ewMAIN.m
% limiti formula 1 ew 2 ew
% confronto per verificare la validità delle formule della guida 1 o 2 funi
% utilizzo quello della singola fune come se fosse doppia fune

clear

path(path,'tools')
path(path,'tools/Carson')

dati_input

I=1000; %corrente

% due funi concentrate su una in mezzo

dmax=500;

for d=1:dmax
    % una fune
    posiz1=[...
        sb1+h1*1i
        sb2+(h1+hr)*1i
        sb3+(h1+2*hr)*1i
        0+hf*1i
        d+hpipe*1i]; % posizioni

    for i=1:length(posiz1);
        for j=1:length(posiz1);
            d_rell1(i,j)=abs(posiz1(i)-posiz1(j));
        end
    end

    Z=ZmF2(f, mu0, hf,diamfg,ro,rfg,d_rell1,1,2,Df1f2);

    E1(d)=Z*I;

end

% due funi vere

for d=1:dmax

    posiz2=[...
        sb1+h1*1i
        sb2+(h1+hr)*1i
        sb3+(h1+2*hr)*1i
        Df1f2/2+hf*1i
        -Df1f2/2+hf*1i
        d+hpipe*1i]; % posizioni

    for i=1:length(posiz2);
        for j=1:length(posiz2);
            d_rell2(i,j)=abs(posiz2(i)-posiz2(j));
        end
    end

    Z=ZmF3(f, mu0,hf,diamfg,ro,rfg,d_rell2,1);
    E2(d)=Z*I;

end

d=1:dmax;

figure(1)

plot(d,abs(E1),d,abs(E2))
legend('simplified expression','rigorous expression','Location','Best')

```

## Appendix F

---

```
xlabel('axial distance [m]')
ylabel('|E| at pipeline level [V/m]')
grid on
title('Comparison between emf expressions')

cd results/emf2ewlew

print(figure(1),'-dpng','emf2ewlewcf.png')

close all
```

## Program for the comparison of emf's expressions in section 2.5

valutazionekMAIN.m

```
% valutazione formule emf
%
%
% -ICarson:      1. carson clem, 4. carson series
% -tipoterna:   3. doppia terna simmetrica; 2. doppia terna ottimizzata; 1.
singola terna
% -sb1:         [m] sbraccio cond 1 (più basso) positivi se i conduttori
stanno dalla parte del tubo ( in caso di terna singola)
% -sb2:         [m] sbraccio cond 2
% -sb3:         [m] sbraccio cond 3
% -sqnz:        1. inversa, -1. diretta
% -numfuni:     numero duni di guardia 1 o 2
% -h1:         [m] altezza MEDIA conduttore più basso
% -hr:         [m] distanza verticale media tra le fasi
% -hf:         [m] altezza MEDIA della fune di guardia (delle due se doppie
sullo stesso piano da terra)
%
%
%
clear

path(path,'../Multiconductor_s/tools')
path(path,'../Multiconductor_s/tools/Carson')

dati_input
%distanze_equivalenti
ro=100;
deq=-200:200;

for kal=1:1
    if kal==1
        ICarson=1; % Carson Clem
    elseif kal==2
        ICarson=4; % Carson Series
    end

    for sz=1:2
        if sz==1
            sqnz=1; % sequenza inversa
        elseif sz==2
            sqnz=-1;
        end

        % doppia terna ottimizzata 2 funi
        tipoterna=2; % doppia terna
        numfuni=2; % numero funi
        sb1=4.8; % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
        sb2=4.7; % [m] sbraccio cond 2
        sb3=4.6; % [m] sbraccio cond 3
        h1=30.76; % [m] altezza MEDIA conduttore più basso
        hr=6.8 ; % [m] distanza verticale media tra le fasi
        hf=56.32 ; % [m] altezza MEDIA della fune di guardia (delle
due se doppie sullo stesso piano da terra)
```

```
[E1(kal, :, sz), Ec1(kal, :, sz), E01(kal, :, sz), Ifune1(kal, :, sz)] = valutazionek_fem(d
eq, discr, f, mu0, eps0, ro, regime, linea, ICarson, Risp6, Risp7, tipoterna, numfuni, Ifas
e380, Iguasto380, sqnz, posa, gestione, Ifase220, Iguasto220, Dt, hpipeline, rop, mur, Zterra
, epsr, deltac, Rc, Daerea, Rkm380, diamfg, rfg, hl, hr, hf, Dflf2, sb1, sb2, sb3, separaz_ca
vi, DiamCavo, h_cavo, raggio_medio_schermo, rs, diam_condutt, r20cavo);
```

```
% doppia terna ottimizzata 1 fune
tipoterna=2; % doppia terna
numfuni=1; % numero funi
sb1=4.8; % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
sb2=4.7; % [m] sbraccio cond 2
sb3=4.6; % [m] sbraccio cond 3
hl=30.76; % [m] altezza MEDIA conduttore più basso
hr=6.8 ; % [m] distanza verticale media tra le fasi
hf=56.32 ; % [m] altezza MEDIA della fune di guardia (delle
due se doppie sullo stesso piano da terra)
Dflf2=0;
```

```
[E2(kal, :, sz), Ec2(kal, :, sz), E02(kal, :, sz), Ifune2(kal, :, sz)] = valutazionek_fem(d
eq, discr, f, mu0, eps0, ro, regime, linea, ICarson, Risp6, Risp7, tipoterna, numfuni, Ifas
e380, Iguasto380, sqnz, posa, gestione, Ifase220, Iguasto220, Dt, hpipeline, rop, mur, Zterra
, epsr, deltac, Rc, Daerea, Rkm380, diamfg, rfg, hl, hr, hf, Dflf2, sb1, sb2, sb3, separaz_ca
vi, DiamCavo, h_cavo, raggio_medio_schermo, rs, diam_condutt, r20cavo);
```

```
% singola terna 2 funi
tipoterna=1; % singola terna
numfuni=2; % numero funi
% sb1=-6; % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
% sb2=0; % [m] sbraccio cond 2
% sb3=6; % [m] sbraccio cond 3
% hl=30.76; % [m] altezza MEDIA conduttore più basso
% hr=0 ; % [m] distanza verticale media tra le fasi
% hf=40 ; % [m] altezza MEDIA della fune di guardia (delle
due se doppie sullo stesso piano da terra)
sb1=0;%4.8; % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
sb2=0;%-4.7; % [m] sbraccio cond 2
sb3=0;%4.6; % [m] sbraccio cond 3
hl=30.76; % [m] altezza MEDIA conduttore più basso
hr=6.8 ; % [m] distanza verticale media tra le fasi
hf=56.32 ; % [m] altezza MEDIA della fune di guardia (delle
due se doppie sullo stesso piano da terra)
```

```
[E3(kal, :, sz), Ec3(kal, :, sz), E03(kal, :, sz), Ifune3(kal, :, sz)] = valutazionek_fem(d
eq, discr, f, mu0, eps0, ro, regime, linea, ICarson, Risp6, Risp7, tipoterna, numfuni, Ifas
e380, Iguasto380, sqnz, posa, gestione, Ifase220, Iguasto220, Dt, hpipeline, rop, mur, Zterra
, epsr, deltac, Rc, Daerea, Rkm380, diamfg, rfg, hl, hr, hf, Dflf2, sb1, sb2, sb3, separaz_ca
vi, DiamCavo, h_cavo, raggio_medio_schermo, rs, diam_condutt, r20cavo);
```

```
% singola terna 1 fune
tipoterna=1; % singola terna
numfuni=1; % numero funi
sb1=0;%4.8; % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
sb2=0;%-4.7; % [m] sbraccio cond 2
sb3=0;%4.6; % [m] sbraccio cond 3
hl=30.76; % [m] altezza MEDIA conduttore più basso
hr=6.8 ; % [m] distanza verticale media tra le fasi
hf=56.32 ; % [m] altezza MEDIA della fune di guardia (delle
due se doppie sullo stesso piano da terra)
Dflf2=0;
```

```
[E4(kal, :, sz), Ec4(kal, :, sz), E04(kal, :, sz), Ifune4(kal, :, sz)] = valutazionek_fem(d
eq, discr, f, mu0, eps0, ro, regime, linea, ICarson, Risp6, Risp7, tipoterna, numfuni, Ifas
e380, Iguasto380, sqnz, posa, gestione, Ifase220, Iguasto220, Dt, hpipeline, rop, mur, Zterra
, epsr, deltac, Rc, Daerea, Rkm380, diamfg, rfg, hl, hr, hf, Dflf2, sb1, sb2, sb3, separaz_ca
```

## Appendix F

```
vi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

    % doppia terna simmetrica 2 funi
    tipoterna=3;          % doppia terna simmetrica
    numfuni=2;           % numero funi
    sbl=4.8;             % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
    sb2=4.7;             % [m] sbraccio cond 2
    sb3=4.6;             % [m] sbraccio cond 3
    hl=30.76;           % [m] altezza MEDIA conduttore più basso
    hr=6.8 ;            % [m] distanza verticale media tra le fasi
    hf=56.32 ;          % [m] altezza MEDIA della fune di guardia (delle
due se doppie sullo stesso piano da terra)

[E5(kal, :,sz),Ec5(kal, :,sz),E05(kal, :,sz),Ifune5(kal, :,sz)]=valutazionek_fem(d
eq,discr,f,mu0,eps0,ro,regime,linea,ICarson,Risp6,Risp7,tipoterna,numfuni,Ifas
e380,Iguasto380,sqnz,posa,gestione,Ifase220,Iguasto220,Dt,hpipe,rop,mur,Zterra
,epsr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,hl,hr,hf,Df1f2,sbl,sb2,sb3,separaz_ca
vi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

    % doppia terna simmetrica 1 fune
    tipoterna=3;          % doppia terna simmetrica
    numfuni=1;           % numero funi
    sbl=4.8;             % [m] sbraccio cond 1 (più basso) positivi se i
conduttori stanno dalla parte del tubo ( in caso di terna singola)
    sb2=4.7;             % [m] sbraccio cond 2
    sb3=4.6;             % [m] sbraccio cond 3
    hl=30.76;           % [m] altezza MEDIA conduttore più basso
    hr=6.8 ;            % [m] distanza verticale media tra le fasi
    hf=56.32 ;          % [m] altezza MEDIA della fune di guardia (delle
due se doppie sullo stesso piano da terra)
    Df1f2=0;

[E6(kal, :,sz),Ec6(kal, :,sz),E06(kal, :,sz),Ifune6(kal, :,sz)]=valutazionek_fem(d
eq,discr,f,mu0,eps0,ro,regime,linea,ICarson,Risp6,Risp7,tipoterna,numfuni,Ifas
e380,Iguasto380,sqnz,posa,gestione,Ifase220,Iguasto220,Dt,hpipe,rop,mur,Zterra
,epsr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,hl,hr,hf,Df1f2,sbl,sb2,sb3,separaz_ca
vi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

end

end

x=deg;
x(1)=-50;
ps=2; % passo dei cerchietti

xmin=-49.5;
xmax=49.5;
ymin=0;
ymax_dt=0.009;
ymax_st=0.13;

for kl=1:1          % kl=1 - Carson Clem, kl=2 - Carson Series
if kl==1
    num=1;          % numerazione da 1 a 4 con Carson Clem
elseif kl==2
    num=7;          % numerazione da 5 a 8 con Carson Series
end

figure(num) % doppia terna LR 2 funi
subplot (2,1,1)
```

```

plot(x,abs(E01(kl,:,1)), 'r',x(1:ps:end),abs(E01(kl,1:ps:end,2)), 'ro',x,abs(Ec1
(kl,:,1)), 'g',x(1:ps:end),abs(Ec1(kl,1:ps:end,2)), 'go',x,abs(E1(kl,:,1)), 'b',x
(1:ps:end),abs(E1(kl,1:ps:end,2)), 'bo', 'MarkerSize', 2);
axis([xmin xmax ymin ymax_dt])
xlabel('axial distance [m]')
ylabel('EMF (modulus) [V/m]')
legend('|E0| inv', '|E0| dir', '|Ec| inv', '|Ec| dir', '|E| inv', '|E|
dir', 'Location', 'EastOutside')
grid on

title ('E.m.f induced on a pipeline by a DCLR power line with two earthwires')

subplot (2,1,2)
plot(x,angle(E01(kl,:,1)).*(180/pi), 'r',x(1:ps:end),angle(E01(kl,1:ps:end,2)).
*(180/pi), 'ro',x,angle(Ec1(kl,:,1)).*(180/pi), 'g',x(1:ps:end),angle(Ec1(kl,1:p
s:end,2)).*(180/pi), 'go',x,angle(E1(kl,:,1)).*(180/pi), 'b',x(1:ps:end),angle(E
1(kl,1:ps:end,2)).*(180/pi), 'bo', 'MarkerSize', 2);
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('phase [°]')
legend('E0 ° inv', 'E0 ° dir', 'Ec ° inv', 'Ec ° dir', 'E ° inv', 'E °
dir', 'Location', 'EastOutside')
grid on

figure(num+1) % doppia terna LR una fune

subplot (2,1,1)
plot(x,abs(E02(kl,:,1)), 'r',x(1:ps:end),abs(E02(kl,1:ps:end,2)), 'ro',x,abs(Ec2
(kl,:,1)), 'g',x(1:ps:end),abs(Ec2(kl,1:ps:end,2)), 'go',x,abs(E2(kl,:,1)), 'b',x
(1:ps:end),abs(E2(kl,1:ps:end,2)), 'bo', 'MarkerSize', 2);
axis([xmin xmax ymin ymax_dt])
xlabel('axial distance [m]')
ylabel('EMF (modulus) [V/m]')
legend('|E0| inv', '|E0| dir', '|Ec| inv', '|Ec| dir', '|E| inv', '|E|
dir', 'Location', 'EastOutside')
grid on

title ('E.m.f induced on a pipeline by a DCLR power line with one earthwire')

subplot (2,1,2)
plot(x,angle(E02(kl,:,1)).*(180/pi), 'r',x(1:ps:end),angle(E02(kl,1:ps:end,2)).
*(180/pi), 'ro',x,angle(Ec2(kl,:,1)).*(180/pi), 'g',x(1:ps:end),angle(Ec2(kl,1:p
s:end,2)).*(180/pi), 'go',x,angle(E2(kl,:,1)).*(180/pi), 'b',x(1:ps:end),angle(E
2(kl,1:ps:end,2)).*(180/pi), 'bo', 'MarkerSize', 2);
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('phase [°]')
legend('E0 ° inv', 'E0 ° dir', 'Ec ° inv', 'Ec ° dir', 'E ° inv', 'E °
dir', 'Location', 'EastOutside')
grid on

figure(num+2) % singola terna 2 funi

subplot (2,1,1)
plot(x,abs(E03(kl,:,1)), 'r',x(1:ps:end),abs(E03(kl,1:ps:end,2)), 'ro',x,abs(Ec3
(kl,:,1)), 'g',x(1:ps:end),abs(Ec3(kl,1:ps:end,2)), 'go',x,abs(E3(kl,:,1)), 'b',x
(1:ps:end),abs(E3(kl,1:ps:end,2)), 'bo', 'MarkerSize', 2);
axis([xmin xmax ymin ymax_st])
xlabel('axial distance [m]')
ylabel('EMF (modulus) [V/m]')
legend('|E0| inv', '|E0| dir', '|Ec| inv', '|Ec| dir', '|E| inv', '|E|
dir', 'Location', 'EastOutside')
grid on

title ('E.m.f induced on a pipeline by a three phase line with two
earthwires')

subplot (2,1,2)
plot(x,angle(E03(kl,:,1)).*(180/pi), 'r',x(1:ps:end),angle(E03(kl,1:ps:end,2)).

```

## Appendix F

---

```
*(180/pi),'ro',x,angle(Ec3(kl,:,1)).*(180/pi),'g',x(1:ps:end),angle(Ec3(kl,1:ps:end,2)).*(180/pi),'go',x,angle(E3(kl,:,1)).*(180/pi),'b',x(1:ps:end),angle(E3(kl,1:ps:end,2)).*(180/pi),'bo','MarkerSize',2);
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('phase [°]')
legend('E0 ° inv','E0 ° dir','Ec ° inv','Ec ° dir','E ° inv','E ° dir','Location','EastOutside')
grid on
```

```
figure(num+3) % singola terna una fune
```

```
subplot (2,1,1)
plot(x,abs(E04(kl,:,1)), 'r',x(1:ps:end),abs(E04(kl,1:ps:end,2)), 'ro',x,abs(Ec4(kl,:,1)), 'g',x(1:ps:end),abs(Ec4(kl,1:ps:end,2)), 'go',x,abs(E4(kl,:,1)), 'b',x(1:ps:end),abs(E4(kl,1:ps:end,2))), 'bo','MarkerSize',2);
axis([xmin xmax ymin ymax_st])
xlabel('axial distance [m]')
ylabel('EMF (modulus) [V/m]')
legend('|E0| inv','|E0| dir','|Ec| inv','|Ec| dir','|E| inv','|E| dir','Location','EastOutside')
grid on
```

```
title ('E.m.f induced on a pipeline by a three phase line with one earthwire')
```

```
subplot (2,1,2)
plot(x,angle(E04(kl,:,1)).*(180/pi), 'r',x(1:ps:end),angle(E04(kl,1:ps:end,2)).*(180/pi), 'ro',x,angle(Ec4(kl,:,1)).*(180/pi), 'g',x(1:ps:end),angle(Ec4(kl,1:ps:end,2)).*(180/pi), 'go',x,angle(E4(kl,:,1)).*(180/pi), 'b',x(1:ps:end),angle(E4(kl,1:ps:end,2)).*(180/pi), 'bo','MarkerSize',2);
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('phase [°]')
legend('E0 ° inv','E0 ° dir','Ec ° inv','Ec ° dir','E ° inv','E ° dir','Location','EastOutside')
grid on
```

```
figure(num+4) % doppia terna SB 2 funi
```

```
subplot (2,1,1)
plot(x,abs(E05(kl,:,1)), 'r',x(1:ps:end),abs(E05(kl,1:ps:end,2)), 'ro',x,abs(Ec5(kl,:,1)), 'g',x(1:ps:end),abs(Ec5(kl,1:ps:end,2)), 'go',x,abs(E5(kl,:,1)), 'b',x(1:ps:end),abs(E5(kl,1:ps:end,2))), 'bo','MarkerSize',2);
axis([xmin xmax ymin ymax_st])
xlabel('axial distance [m]')
ylabel('EMF (modulus) [V/m]')
legend('|E0| inv','|E0| dir','|Ec| inv','|Ec| dir','|E| inv','|E| dir','Location','EastOutside')
grid on
```

```
title ('E.m.f induced on a pipeline by a DCSB power line with two earthwires')
```

```
subplot (2,1,2)
plot(x,angle(E05(kl,:,1)).*(180/pi), 'r',x(1:ps:end),angle(E05(kl,1:ps:end,2)).*(180/pi), 'ro',x,angle(Ec5(kl,:,1)).*(180/pi), 'g',x(1:ps:end),angle(Ec5(kl,1:ps:end,2)).*(180/pi), 'go',x,angle(E5(kl,:,1)).*(180/pi), 'b',x(1:ps:end),angle(E5(kl,1:ps:end,2)).*(180/pi), 'bo','MarkerSize',2);
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('phase [°]')
legend('E0 ° inv','E0 ° dir','Ec ° inv','Ec ° dir','E ° inv','E ° dir','Location','EastOutside')
grid on
```

```
figure(num+5) % doppia terna SB una fune
```

```
subplot (2,1,1)
plot(x,abs(E06(kl,:,1)), 'r',x(1:ps:end),abs(E06(kl,1:ps:end,2)), 'ro',x,abs(Ec6
```

```

(kl,:,1)), 'g', x(1:ps:end), abs(Ec6(kl,1:ps:end,2)), 'go', x, abs(E6(kl,:,1)), 'b', x
(1:ps:end), abs(E6(kl,1:ps:end,2)), 'bo', 'MarkerSize', 2);
axis([xmin xmax ymin ymax_stl])
xlabel('axial distance [m]')
ylabel('EMF (modulus) [V/m]')
legend('|E0| inv', '|E0| dir', '|Ec| inv', '|Ec| dir', '|E| inv', '|E|
dir', 'Location', 'EastOutside')
grid on

title ('E.m.f induced on a pipeline by a DCSB power line with one earthwire')

subplot (2,1,2)
plot(x, angle(E06(kl,:,1)).*(180/pi), 'r', x(1:ps:end), angle(E06(kl,1:ps:end,2)).
*(180/pi), 'ro', x, angle(Ec6(kl,:,1)).*(180/pi), 'g', x(1:ps:end), angle(Ec6(kl,1:p
s:end,2)).*(180/pi), 'go', x, angle(E6(kl,:,1)).*(180/pi), 'b', x(1:ps:end), angle(E
6(kl,1:ps:end,2)).*(180/pi), 'bo', 'MarkerSize', 2);
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('phase [°]')
legend('E0 ° inv', 'E0 ° dir', 'Ec ° inv', 'Ec ° dir', 'E ° inv', 'E °
dir', 'Location', 'EastOutside')
grid on

end

% k4 analitico

sb2=4.7; % [m] sbraccio cond 3
h1=30.76; % [m] altezza MEDIA conduttore più basso
hr=6.8 ; % [m] distanza verticale media tra le fasi
dpt=abs(hpipe);
%dist=-50:1:50;

for ind=1:length(deq)
    posiz=[...
        0+(h1+hr+dpt)*1i
        deq(ind)+0*1i];
    d_bar=abs(posiz(1)-posiz(2));
    k4an(ind)=(sqrt(hr^3+12*sb2^2))*(d_bar^2-hr^2)/(d_bar^3*sb2);
end

E08=k4an.*E04(1,:,2);

figure(7)
plot(x, abs(E02(1,:,2)), x, abs(E04(1,:,2)), x, abs(E06(1,:,2)), x, abs(E08))
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('E.m.f [V/m]')
legend('DCLR', 'SC', 'DCSB', 'DCLR k_4', 'Location', 'EastOutside')
grid on
title('Comparison between line arragments and methods')

figure(8)
plot(x, abs(E02(1,:,2)), x, abs(E04(1,:,2)), x, abs(E06(1,:,2))) %(1:ps*2:end)
xlim([xmin xmax])
xlabel('axial distance [m]')
ylabel('E.m.f [V/m]')
legend('DCLR', 'SC', 'DCSB', 'Location', 'EastOutside')
grid on
title('Comparison between line arragments and methods')

```

## Appendix F

---

```
figure(9)
plot(x,abs(E02(1,:,2)),x,abs(E08)) %(1:ps*2:end)
xlim([0 200])
xlabel('axial distance [m]')
ylabel('E.m.f [V/m]')
legend('DCLR', 'DCLR k_4', 'Location', 'EastOutside')
grid on
title('DCLR emf results')

cd results/complete_comparison

print(figure(1),'-dpng','doppiaternaLR2f_CClem.png')
print(figure(2),'-dpng','doppiaternaLR1f_CClem.png')
print(figure(3),'-dpng','singolaterna2f_CClem.png')
print(figure(4),'-dpng','singolaterna1f_CClem.png')
print(figure(5),'-dpng','doppiaternaSB2f_CClem.png')
print(figure(6),'-dpng','doppiaternaSB1f_CClem.png')
print(figure(7),'-dpng','config_st_dt_k4_noew.png')
print(figure(8),'-dpng','config_st_dt_noew.png')
print(figure(9),'-dpng','k4emfcomp.png')

close all
```

## **Program for assessing the influence of the position of earthwires (Appendix C)**

E\_1fPosizEffect\_MAIN.m

```
%
% effetti della posizione della fune
% simmetria nelle correnti
% dissimmetria geometrica
%
% Df1f2= 2* posizione x della fune con una fune
clear

path(path,'../Multiconductor_s/tools')
path(path,'../Multiconductor_s/tools/Carson')

dati_input
ro=100;
Ifase380=1000;      % [A] corrente per fase singola terna

sb1v=[2.5          2.5          2.5          0
0                -5];
sb2v=[-2.5        -2.5        -2.5          0
0                0];
sb3v=[0           0           0           0
0           5];
h1v= [20          20          20          20
20          20];
h2v= [20          20          20          25
25          20];
h3v= [20+5*cos(pi/6) 20+5*cos(pi/6) 20+5*cos(pi/6) 30
30          20];

xfv= [0           0           5           0
5           0];
hfv= [20+2.5*tan(pi/6) 30          25          35
35          25];

for psx=1:length(sb1v)
```



```

% -----
% FEM LINEA AEREA
% -----

% singola terna zero funi
tipoterna=1; % singola terna
numfuni=1; % numero funi

linea=1; % aerea
deq=-100:100;

sb1=sblv(psx); % [m] sbraccio cond 1
(più basso) positivi se i conduttori stanno dalla parte del tubo ( in caso di
terna singola)
sb2=sb2v(psx); % [m] sbraccio cond 2
sb3=sb3v(psx); % [m] sbraccio cond 3
h1=h1v(psx); % [m] altezza MEDIA
conduttore più basso
h2=h2v(psx); % [m] altezza MEDIA
conduttore intermedio
h3=h3v(psx); % [m] altezza MEDIA
conduttore più alto

hf=hfv(psx); % [m] altezza MEDIA
della fune di guardia (delle due se doppie sullo stesso piano da terra)
xf=xfv(psx); % [m] posizione x della fune
Df1f2=xf*2;

% CALCOLO FEM LINEA AEREA --regime--
regime=1; %regime

[E1,Ec1,E01,Ifunel]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linea,ICarson
,tipoterna,numfuni,Ifase380,Iguasto380,sgnz,Ifase220,Iguasto220,Dt,hpipe,rop,m
ur,epsr,deltac,Rc,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Df1f2,sb1,sb2,sb3,separ
az_cavi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

% sezione della linea aerea
figure(2*psx)
xmin=-20;
xmax=20;
ymin=-5;
ymax=40;
x=xmin:xmax;
y_soil=0*ones(1,length(x));
y_pipe=hpipe*ones(1,length(x));

plot(-sb1,h1,'r.',-sb2,h2,'g.',-sb3,
h3,'b.',xf,hf,'k.',x,y_soil,'k-',x,y_pipe,'b-', 'MarkerSize',15)
xlabel('axial distance [m]')
ylabel('height [m]')
legend('R','S','T','earthwire','soil level','pipe
level','Location','EastOutside')
axis equal
axis([xmin xmax ymin ymax])
grid on
title ('HV aerial line')

div=10;

figure(2*psx+1)
plot([0 Ifase380],[0 0], 'r-', [0 -Ifase380/2],[0 Ifase380*sqrt(3)/2], 'g-',
[0 -Ifase380/2],[0 -Ifase380*sqrt(3)/2], 'b-', [0 real(Ifunel)], [0
imag(Ifunel)], 'k-')

axis equal
axis([-Ifase380/div Ifase380/div -Ifase380/div Ifase380/div])
xlabel('Re')
ylabel('Im')
grid on
legend('R','S','T','earthwire','Location','EastOutside')
title('Currents')

E0(:,psx)=E01(:); %non cambia

```

## Appendix F

---

```
E(:,psx)=E1(:);
Ifune(:,psx)=Ifune1(:);

end

x=deq;

figure(101)
plot(x,abs(E(:,1)),'r-',x,abs(E(:,2)),'g-',x,abs(E(:,3)),'y-',x,abs(E0(:,3)),'b.-','MarkerSize',1)
xlabel('Distance from Line Axis [m]')
ylabel('E.m.f [V/m]')
legend('configuration #1','configuration #2','configuration #3','emf with no earthwires','Location','Best')
grid on
title('Induced e.m.f. [V/m] on the pipe (Steady state condition)')

figure(102)
plot(x,abs(E(:,4)),'r-',x,abs(E(:,5)),'y-',x,abs(E0(:,5)),'b.-','MarkerSize',1)
)
xlabel('Distance from Line Axis [m]')
ylabel('E.m.f [V/m]')
legend('configuration #4','configuration #5','emf with no earthwires','Location','Best')
grid on
title('Induced e.m.f. [V/m] on the pipe (Steady state condition)')

figure(103)
plot(x,abs(E(:,6)),'c-',x,abs(E0(:,6)),'k.-','MarkerSize',1)
xlabel('Distance from Line Axis [m]')
ylabel('E.m.f [V/m]')
legend('configuration #6','emf with no earthwires','Location','Best')
grid on
title('Induced e.m.f. [V/m] on the pipe (Steady state condition)')

cd results/ew_position_effects

print(figure(2),'-dpng','posiz1.png')
print(figure(3),'-dpng','curr_posiz1.png')
print(figure(4),'-dpng','posiz2.png')
print(figure(5),'-dpng','curr_posiz2.png')
print(figure(6),'-dpng','posiz3.png')
print(figure(7),'-dpng','curr_posiz3.png')
print(figure(8),'-dpng','posiz4.png')
print(figure(9),'-dpng','curr_posiz4.png')
print(figure(10),'-dpng','posiz5.png')
print(figure(11),'-dpng','curr_posiz5.png')
print(figure(12),'-dpng','posiz6.png')
print(figure(13),'-dpng','curr_posiz6.png')
print(figure(101),'-dpng','emfpos1_2_3.png')
print(figure(102),'-dpng','emfpos4_5.png')
print(figure(103),'-dpng','emfpos6.png')

close all
```

## **Program for comparison of self and mutual impedance's expressions (section 2.3)**

```
% confronto tra
%
% MUTUE IMPEDENZE(1):
% Carson Clem
% Carson Polinomiale
% Carson Series N=14
%
% MUTUE IMPEDENZE(2):
```

---

```

% Carson Series n-terms 1:50 - VERIFICA IL PESO DEI DELTA E DEL TERMINE LOG
%
% AUTOIMPEDEENZE
% Formula semplificata
% Formula con altezza da terra
%
%
%
%
clear

path(path,'../Multiconductor_s/tools')
path(path,'../Multiconductor_s/tools/Carson')

dati_input
ro=100;
global f

% mat_cond [ dcond [m],Rii[Ohm/km]]
mat_cond=[...
    Daerea Rkm380          % %
    Daerea Rkm380];      % %

r_c=mat_cond(:,1)./2; % raggi conduttori
mcoef=1;
Rc=mat_cond(:,2); % resistenze chilometriche dei conduttori

dmax=5000;

for f_case=1:3

    if f_case==1
        f=50;
    elseif f_case==2;
        f=100;
    elseif f_case==3;
        f=1000;
    end

%% MUTUE IMPEDENZE(1)

for kal=1:2;
    if kal==1
        ICarson=1; % Carson Clem
    %     elseif kal==2
    %         ICarson=2; % Carson polinomiale
    elseif kal==2
        ICarson=4; % Carson Series
    end

    NCarsonCrTerms= 8; %14; % numero termini della serie di carson

    for d=1:dmax
        %     posiz=[...
        %         0+300*1i
        %         d*cos(pi/6)+(-d*sin(pi/6)+300)*1i];
        %     posiz=[...
        %         0+j*10
        %         d+j*10];
        %     posiz=[...
        %         50+0*1i
        %         50+d*1i];

        Z=CalcRLC1(posiz, ro, r_c, mcoef, Rc, 0 ,ICarson, NCarsonCrTerms, 1,
0, 1); % [Ohm/m]
        Zm(kal,d)=Z(2,1)/1000;
        %coordinate(:,d)=posiz;

```

## Appendix F

---

```
        %dis(:, :, d)=dd;
    end
end

d=1:dmax;
for kal=3:4
    if kal==3
        mode=1;
    elseif kal==4
        mode=2;
    end

    for jj=1:length(d)
        Zm(kal, jj)=ZijPOLY(f, ro, d(jj), mode)/1000;
    end
end

d=1:dmax;

Zm_ass=abs(Zm);

figure(2*f_case)
subplot (2,1,1)
plot(d, Zm_ass(1, :), d, Zm_ass(2, :), d(1:200:end), Zm_ass(3, 1:200:end), 'o')
grid on
legend('Carson Clem', 'Carson Series ', 'Carson polynomial', 'Location', 'Best')
title('Carson expressions: comparison')
xlabel('distance between conductors [m]')
ylabel('|Zij| [Ohm/m]')
%xlim([0 200])
subplot (2,1,2)
plot(d, Zm_ass(1, :), d, Zm_ass(2, :), d(1:20:end), Zm_ass(3, 1:20:end), 'o')
grid on
legend('Carson Clem', 'Carson Series ', 'Carson polynomial', 'Location', 'Best')
xlim([0 200])
xlabel('distance between conductors [m] - focus')
ylabel('|Zij| [Ohm/m]')

%% MUTUE IMPEDENZE(2)

% dmax=2000
ICarson=4; % Carson Series
NCarsonCrTerms=[8,14,32]; % 30,40];

for hj=1:length(NCarsonCrTerms)%5; % al variare dei termini di carson
    for d=1:dmax
        posiz=[...
            0+60*1i
            d+60*1i];

%         posiz=[...
%             0+300*1i
%             d*cos(pi/13)+(-d*sin(pi/13)+300)*1i];
%         posiz=[...
%             0+0*1i
%             d*cos(pi/13)+(d*sin(pi/13))*1i];

        [ Zclkm , Zij_ln, Zij_DRDX]=CalcRLC2C(posiz, ro, r_c, mcoef, Rc, 0
, ICarson, NCarsonCrTerms(hj), 1, 0, 1); % [Ohm/m]
        %Zclkm =CalcRLC1(posiz, ro, r_c, mcoef, Rc, 0 , ICarson,
NCarsonCrTerms(hj), 1, 0, 1); % [Ohm/m]

        Zm(hj, d)=Zclkm(1,2)./1000;
        Zijln(hj, d)=Zij_ln(1,2)./1000;
        ZijDRDX(hj, d)=Zij_DRDX(1,2)./1000;
    end
end

d=1:dmax;
dfg=500; %passo
```

```

figure(2*f_case+1)
subplot (3,1,1)
plot(d,abs(Zm(1,:)),d(1:dfg:end),abs(Zm(2,1:dfg:end)), 'x',d(1:dfg/2:end),abs(Z
m(3,1:dfg/2:end)), 'o'),%d,abs(Zm(4,:)),d,abs(Zm(5,:))
grid on
legend('|Zij|          n=8','|Zij|          n=14          ','|Zij|          n=32
','Location','EastOutside')% '|Zij| n=8','|Zij| n=16',
xlabel('distance between conductors [m]')
ylabel('|Zij| [Ohm/m]')

title('Carson Series terms')

subplot (3,1,2)
plot(d,abs(ZijDRDX(1,:)),d(1:dfg:end),abs(ZijDRDX(2,
(1:dfg:end))), 'x',d(1:dfg/2:end),abs(ZijDRDX(3,
(1:dfg/2:end))), 'o',d,abs(Zijln(1,:)))
% ,d,abs(ZijDRDX(4,:)),d,abs(ZijDRDX(5,:))
grid on
legend('2*|DR+jDX| n=8','2*|DR+jDX| n=14','2*|DR+jDX| n=32','|logarithmic
term|','Location','EastOutside')% , '2*|DR+jDX| n=8','2*|DR+jDX| n=16'
xlabel('distance between conductors [m]')
ylabel('Terms of |Zij| [Ohm/m]')

subplot (3,1,3)
plot(d,abs(ZijDRDX(1,:)),d(1:dfg/10:end),abs(ZijDRDX(2,
(1:dfg/10:end))), 'x',d(1:dfg/20:end),abs(ZijDRDX(3,
(1:dfg/20:end))), 'o',d,abs(Zijln(1,:)))
% ,d,abs(ZijDRDX(4,:)),d,abs(ZijDRDX(5,:))
grid on
xlim([0 200])
legend('2*|DR+jDX| n=8','2*|DR+jDX| n=14','2*|DR+jDX| n=32','|logarithmic
term|','Location','EastOutside')% , '2*|DR+jDX| n=8','2*|DR+jDX| n=16'
xlabel('distance between conductors [m] - focus')
ylabel('Terms of |Zij| [Ohm/m]')

end
%% AUTOIMPEDEENZE

%
pass=3;
f_a=[50 100 1000]; % frequenze
h=-10:60; % altezza conduttore dal suolo
for in=1:length(f_a)
    for hi=1:length(h) % altezza conduttore dal suolo

        Z1(in,hi)=Zii(1,Rkm380,f_a(in),ro,h(hi),Daerea); % con h
        Z2(in,hi)=Zii(2,Rkm380,f_a(in),ro,h(hi),Daerea); % semplice

    end
end

h=-10:60;

figure(8)

plot(h,abs(Z1(1,:)),h,abs(Z1(2,:)),h,abs(Z1(3,:)),h(1:pass:end),abs(Z2(1,1:pas
s:end)), 'o',h(1:pass:end),abs(Z2(2,1:pass:end)), 'o',h(1:pass:end),abs(Z2(3,1:p
ass:end)), 'o')
legend('Zii(h) f=50Hz','Zii(h) f=100Hz','Zii(h) f=1000Hz','Zii f=50Hz','Zii
f=100Hz','Zii f=1000Hz','Location','EastOutside')
xlabel('height above soil [m]')
ylabel('|Zii| [Ohm/m]')
grid on
title('Carson''s Self Impedance')

%% Stampa Risultati
cd results/carson_expr_cfr

print(figure(2),'-dpng','CarsonExprf50Hz.png')
print(figure(3),'-dpng','CarsonSeriesComponentsf50Hz.png')
print(figure(4),'-dpng','CarsonExprf100Hz.png')
print(figure(5),'-dpng','CarsonSeriesComponentsf100Hz.png')
print(figure(6),'-dpng','CarsonExprf1000Hz.png')

```

## Appendix F

---

```
print(figure(7),'-dpng','CarsonSeriesComponentsf1000Hz.png')
print(figure(8),'-dpng','SelfImpedanceCFR.png')
```

```
close all
```

### **Program for Conductive Coupling's analysis**

Conduct\_MAIN.m

```
% Calcolo accoppiamento conduttivo

clear

path(path,'tools')

dati

deq=0; %distanza orizzontale

%for i=1:length(deq)

posiz=[...
      sb1+(h1)*li      % conduttore
      0+hf*li         % fune
      hpipe+deq*li]; % tubo

for i=1:length(posiz)
  for j=1:length(posiz)
    dist(i,j)= abs(posiz(i)-posiz(j));
  end
end

Zs=Zii(2,rfg,f,ro,hf,diamfg)*lc; % autoimpedenza fune di guardia lungo una
campata 320m
ZT=0.5*(Zs+sqrt(Zs*(4*Zterra+Zs))); % impedenza fune una campata e
resistenze di terra

% correnti nel terreno

% corrente senza funi
Ie(1)=Iguasto380;

% corrente con una fune
Ie(2)= (ZT/(2*Zterra+ZT))*klfune(f,ro,hf,rfg,diamfg,dist)*Iguasto380;

% corrente con una fune semplificata (1/3 a terra, 2/3 sulle funi)
Ie(3)= Iguasto380/3;

for ii=1:length(Ie)
  Ve(ii)=Zterra*Ie(ii); % tensione di terra sul dispersore senza funi
end

Ie_eff=abs(Ie)
Ve_eff=abs(Ve)

z=ZserieTUBO(f,ro,rop,mu0,mur,Dt); % z [Ohm/m]
y=yTUBO(f,Dt,roc,deltac,eps0,epsr); % y [S/m]
Zc= (z/y)^0.5; % Zc [Ohm]
gamma= (z*y)^0.5; % gamma [m^-1]

x=-500:500;

for in=1:length(Ve);
  for ini=1:length(x);
    Vp(in,ini)=Ve(in).*(exp(-abs(gamma.*x(ini))));
```

```

end
end

figure(1)
plot(x,abs(Vp(1,:)),x,abs(Vp(2,:)),x,abs(Vp(3,:)))
xlabel('Pipeline length [m]')
ylabel('Voltage [V]')
legend('HV line without earthwires','HV line with one e.w. - norm''s
expr.','HV line with one e.w. - simpl. expr.','Location','Best')
grid on
title('Voltage [V/m] on the pipe (Conductive Coupling)')
print(figure(1),'-dpng','Conduct_results.png')

% z_=abs(z*500)
% y_=abs(1/(y*1))
% ZC_=abs(Zc)
%
% ZZ=z*500+1/y+Zc

%R=z*c

al=sqrt((Dt/2)^2+4*(hpipe)^2);
ye=pi*(1/ro+li*2*pi*f*4*eps0)/log(1.12/(gamma*a1));
%yel=1/(ro/4*sqrt(pi/pi));
Zp=[Zc/2 1];
yy=[y 10^40]; % 10^40 - coating damaged

for nn=1:2
    for ss=1:2
        R(ss,nn)=Zp(ss)/(1/yy(nn)+1/ye+Zp(ss));
    end
end
% LL=[40 7 6 36];
%
% for ind=1:4
%     R(ind)=Zp(1)/(1/(ye(1)*LL(ind))+1/(yy*1)+Zp(1));
%
% end

Rl=abs(R);
close all

Vn=[100 450 430 90]; % da relazione

x=-100:100;

for in=1:length(Vn);
    for ini=1:length(x);
        Vpn(in,ini)=Vn(in).*(exp(-abs(gamma.*x(ini))));
    end
end

figure(2)
plot(x,abs(Vpn(1,:)),x,abs(Vpn(2,:)),x,abs(Vpn(3,:)),x,abs(Vpn(4,:)))
xlabel('Pipeline length [m]')
ylabel('Voltage [V]')
legend('tower 37','tower 38','tower 39','tower 40','Location','Best')
ylim([0 500])
grid on
title('Voltage [V/m] on the pipe (Conductive Coupling)')
print(figure(2),'-dpng','Conduct_results2.png')

```

## Program for Cigre Guide's example analysis (Appendix E)

This is the program I used for the analysis of Cigré Guide's example.

Input coordinates must be obtained after pipeline's linearization.

### MAIN PROGRAM

```
% ANALISI INDUZIONE SU Cigre
%
%

clear

path(path,'tools')
path(path,'tools/Carson')

dati_input_Cigre

% -----
% FEM LINEA AEREA
% -----

% singola terna due funi
% aerea

coord_Cigre

assex=coordinate_spezioni(1,1):discr:coordinate_spezioni(end,1);
assey=(interp1(coordinate_spezioni(:,1),coordinate_spezioni(:,2),assex));

for q=2:length(assex);
    %deq(q)=((assey(q))*(assey(q-1)))^0.5;
    deq(q)=((assey(q)+(assey(q-1)))/2);
end

sb1=sb1; % [m] sbraccio cond 1 (più basso)
positivi se i conduttori stanno dalla parte del tubo ( in caso di terna
singola)
sb2=sb2; % [m] sbraccio cond 2
sb3=sb3; % [m] sbraccio cond 3
h1=h1; % [m] altezza MEDIA conduttore più
basso
h2=h1+hr ; % [m] altezza MEDIA conduttore
intermedio
h3=h1+2*hr; % [m] altezza MEDIA conduttore più
alto
hf=hf ; % [m] altezza MEDIA della fune di
guardia (delle due se doppie sullo stesso piano da terra)

% CALCOLO FEM LINEA AEREA --regime--
regime=1; %regime

[E1,Ec1,E01,Ifune1]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linea,ICarson
,tipoterna,numfuni,Ifase380,Iguasto380,sqz,Ifase220,Iguasto220,Dt,hpipe,rop,m
ur,epsr,deltac,RC,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Dflf2,sb1,sb2,sb3,separ
az_cavi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

% CALCOLO FEM LINEA AEREA --guasto--
regime=2; % guasto

[E2,Ec2,E02,Ifune2]=valutazionek_femNEW(deq,f,mu0,eps0,ro,regime,linea,ICarson
,tipoterna,numfuni,Ifase380,Iguasto380,sqz,Ifase220,Iguasto220,Dt,hpipe,rop,m
ur,epsr,deltac,RC,Daerea,Rkm380,diamfg,rfg,h1,h2,h3,hf,Dflf2,sb1,sb2,sb3,separ
az_cavi,DiamCavo,h_cavo,raggio_medio_schermo,rs,diam_condutt,r20cavo);

% sezione della linea aerea
figure(1)
```



```

xmin=-49.5;
xmax=49.5;
ymin=-10;
ymax=50;
x=xmin:xmax;
y_soil=0*ones(1,length(x));
y_pipe=hpipe*ones(1,length(x));

plot(sb1,h1,'r.',sb2,h2,'g.', sb3, h3,'b.',Df1f2/2,hf,'k.',-
Df1f2/2,hf,'k.',x,y_soil,'k-',x,y_pipe,'b-', 'MarkerSize',15)
xlabel('axial distance [m]')
ylabel('height [m]')
legend('R','S','T','earthwire','earthwire','soil level','pipe
level','Location','Best')
axis([xmin xmax ymin ymax])
axis equal
grid on
title ('HV aerial line')

% %lunghezza tratti
for qq=2:length(assey);
Li(qq)= ((assey(qq)-(assey(qq-1)))^2+(assex(qq)-(assex(qq-1)))^2)^0.5;
end
% %lunghezza cumulata tratti
%Li(1)=[];
for hh=2:length(Li)-1;
lung_h_cumulata(1)=Li(1);
lung_h_cumulata(hh)=lung_h_cumulata(hh-1)+Li(hh);
end
%lung_h_cumulata(end)=[];

% -----
% MATRICE ALLE IMPEDENZE DELLA TUBAZIONE
% -----

zpip=[(0.13+1i*0.55)/1000 (0.13+1i*0.55)/1000];
ypip=[(0.94+1i*0.003)/1000 (9.4+1i*3.3)/1000000];

for coat=1:2;

roc=Rc(coat)/deltac; % resistività rivestimento
[Ohm*m]
z=ZserieTUBO(f,ro,rop,mu0,mur,Dt); % z [Ohm/m]
y=yTUBO(f,Dt,roc,deltac,eps0,epsr); % y [S/m]
%z=zpip(coat);
%y=ypip(coat);
Zc= (z/y)^0.5; % Zc [Ohm]
gamma= (z*y)^0.5; % gamma [m^-1]
%Li=ones(length(assex),1)*discr;

% Z MONTE
z_monte=2*Zc/(2+y*Li(1)); % tubo infinito Zc

% Z VALLE
z_valle= 2*Zc/(2+y*Li(length(Li))); %parallelo lato dx del pi greco con
impedenza caratteristica

for a=1:length(Li)-1; %dimensione uguale^2 a quella del
vettore tensioni

%diag_sopra= -(2*Li(a)*Li(a+1)/(z_gamma_y_zc(3)^2))/((Li(a)
+Li(a+1))/z_gamma_y_zc(3));
yi=y*Li(a); %ammettenze del tratto considerato
yipl=y*Li(a+1); %ammettenze tratto successivo

diag_sopra = 2/(yi+yipl);
m_impedenze(a,a+1)= -diag_sopra; % diagonale sopra "-" perché la

```

## Appendix F

---

```
corrente è presa col segno meno)
    m_impedenze(a+1,a)= -diag_sopra;      % diagonale sotto
    z_a_terra(a)=diag_sopra;
end
%%%%%%%%%% m_impedenze(1,1) e m_impedenze(n,n)%%%%%%%%%%
m_impedenze(1,1)= z_monte+z*Li(1)-m_impedenze(1,2);
m_impedenze(length(Li),length(Li))= -m_impedenze(end,end-
1)+z*Li(length(Li))+z_valle;

for b=2:length(Li)-1;
    m_impedenze(b,b)= -m_impedenze(b,b-1)+z*Li(b)-m_impedenze(b,b+1);
end

matr_z_tubo(:, :, coat)=m_impedenze(:, :);
z_vs_terra(:, coat)=z_a_terra(:);

end

% -----
% TENSIONI VERSO TERRA A REGIME
% -----
%
% FEM LINEA AEREA    - E1
%
% ---- BITUMINOSO ----
%
% -----

% E1 - linea aerea REGIME
%

E=E1.*Li;

m_impedenze=matr_z_tubo(:, :, 1);
z_a_terra=z_vs_terra(:, 1);

%CORRENTI NELLA PIPELINE
correnti_di_maglia=m_impedenze\('E');
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% TENSIONI VERSO TERRA

Tensioni=z_a_terra.*correnti_a_terra';

IpR_1=correnti_di_maglia;
VpR_1=Tensioni;

% -----
%
% ---- POLIETILENICO ----
%
%
%
E=E1.*Li;

m_impedenze=matr_z_tubo(:, :, 2);
z_a_terra=z_vs_terra(:, 2);

%CORRENTI NELLA PIPELINE
correnti_di_maglia=m_impedenze\('E');
for k=1:length(Li)-1;
    correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
end

correnti_di_maglia(end)=[];

% TENSIONI VERSO TERRA
```

```

        Tensioni=z_a_terra.*correnti_a_terra';

IpR_2=correnti_di_maglia;
VpR_2=Tensioni;

% -----

% -----
% TENSIONI VERSO TERRA IN CONDIZIONI DI GUASTO
% -----
%
% FEM LINEA AEREA - E2
%
% ----- BITUMINOSO -----
%
% -----

E=E2.*Li;

m_impedenze=matr_z_tubo(:, :, 1);
z_a_terra=z_vs_terra(:, 1);

        %CORRENTI NELLA PIPELINE
        correnti_di_maglia=m_impedenze\(E');
        for k=1:length(Li)-1;
            correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
        end

        correnti_di_maglia(end)=[];

        % TENSIONI VERSO TERRA

        Tensioni=z_a_terra.*correnti_a_terra';

IpG_1=correnti_di_maglia;
VpG_1=Tensioni;

% -----

% -----
% ----- POLIETILENICO -----
% -----
% -----

E=E2.*Li;

m_impedenze=matr_z_tubo(:, :, 2);
z_a_terra=z_vs_terra(:, 2);

        %CORRENTI NELLA PIPELINE
        correnti_di_maglia=m_impedenze\(E');
        for k=1:length(Li)-1;
            correnti_a_terra(k)=correnti_di_maglia(k)-correnti_di_maglia(k+1);
%perdo l'ultima corrente di maglia
        end

        correnti_di_maglia(end)=[];

        % TENSIONI VERSO TERRA

        Tensioni=z_a_terra.*correnti_a_terra';

IpG_2=correnti_di_maglia;
VpG_2=Tensioni;

% -----
% GRAFICI
% -----
x=lungh_cumulata;
%x(end)=[];

```

## Appendix F

---

```
E1s=E1;
E2s=E2;
E1s(end)=[];
E2s(end)=[];
% EMF
% regime (aerea e cavo)
figure(2)
plot(x,abs(E1s))
xlabel('Pipeline length [m]')
ylabel('E.m.f [V/m]')
legend('HV line','Location','Best')
grid on
title('Induced e.m.f. [V/m] on the pipe (Steady state condition)')

% guasto (aerea e cavo)
figure(3)
plot(x,abs(E2s))
xlabel('Pipeline length [m]')
ylabel('E.m.f [V/m]')
legend('HV line','Location','Best')
grid on
title('Induced e.m.f. on the pipe (Fault condition) [V/m]')

x=lungh_cumulata;

% TENSIONI
%
% regime bituminoso - polietilenico
figure(4)
plot(x,abs(VpR_1),x,abs(VpR_2))
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
legend('Bituminous Coating','Polyethylene Coating','Location','Best')
grid on
title('Voltage [V] on the pipe (Steady state condition)')

% guasto BITUMINOSO
figure(5)
plot(x,abs(VpG_1))
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
legend('Bituminous Coating','Location','Best')
grid on
title('Voltage [V] on the pipe (Fault condition)')

% guasto POLIETILENICO
figure(6)
plot(x,abs(VpG_2))
xlabel('Pipeline length [m]')
ylabel('Voltage to ground [V]')
legend('Polyethylene Coating','Location','Best')
grid on
title('Voltage [V] on the pipe (Fault condition)')

%-----
% STAMPA RISULTATI
%-----

cd results/cigre

print(figure(1),'-dpng','aerialSection.png')

print(figure(2),'-dpng','EMFsteadystate.png')
print(figure(3),'-dpng','EMFfault.png')

print(figure(4),'-dpng','Usteadystate.png')
print(figure(5),'-dpng','Ufault_bit.png')
print(figure(6),'-dpng','Ufault_poly.png')

close all
```

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# Acknowledgments

I waited until the last page to thank those who supported me during the development of this work. I am pleased to make these acknowledgements in Italian.

Il primo ringraziamento va al professor Roberto Turri, relatore della mia tesi, per l'aiuto e il sostegno fornitomi durante la stesura del lavoro e per la passione che è riuscito a trasmettermi per la materia.

Un grande ringraziamento va all'ing. Roberto Spezie, correlatore della mia tesi, per avermi dato l'opportunità di svolgere il mio lavoro in azienda e per avermi sostenuto con preziosi consigli per la tesi ma anche per la mia formazione professionale.

La mia gratitudine va inoltre all'unità ING-REA-APRI Nord Est di Terna, guidata dall'ing. Gaetano Paziienza, che mi ha ospitato durante il periodo di stage. In particolare voglio ringraziare l'ing. Steve Scarietto e l'ing. Stefano Bisignano, che hanno sempre trovato il tempo per ascoltarmi e consigliarmi, dandomi preziosi suggerimenti per lo svolgimento del mio lavoro. Voglio ringraziare inoltre il geom. Daniele Sperti, l'ing. Marco Caneva, l'ing. Stefano Salaro, l'ing. Alessio Alban, il geom. Marco Volontieri e tutti i membri dell'unità per l'aiuto, la disponibilità e per avermi insegnato il lavoro in team.

Un doveroso ringraziamento va poi a Vanni Bertanza, per i preziosi consigli, la vicinanza e l'interesse per la buona riuscita del mio lavoro.

Ringrazio inoltre tutti i docenti del corso di laurea in Ingegneria Elettrica dell'Università di Padova, per gli insegnamenti, non solo accademici, ricavati dalle loro lezioni in questi preziosi anni di vita universitaria.

Infine ringrazio di cuore Gloria, la mia famiglia e tutti gli amici che mi sono sempre vicini, e che mi hanno dato gli stimoli per dedicarmi a questo lavoro.

