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Chapter 4

Power AC Transmission Lines

The submarine power AC cables have an important role in offshore wind energy. Furthermore, the submarine cables are the main difference between the offshore wind farms transmission system and onshore wind farms transmission system.

Therefore, a proper submarine cable model is crucial to perform accurate evaluations of the offshore wind farms collector and transmission systems. So, in the present chapter the different options to model a submarine cable are evaluated and their accuracy is discussed.

Then based on an accurate and validated submarine cable model, an analysis about the reactive power management in submarine power transmission lines is carried out. Thus, taken into account active power losses, the reactive power generated in the transmission system and the voltage drop for three different reactive power management options, a reactive power compensation option is proposed.

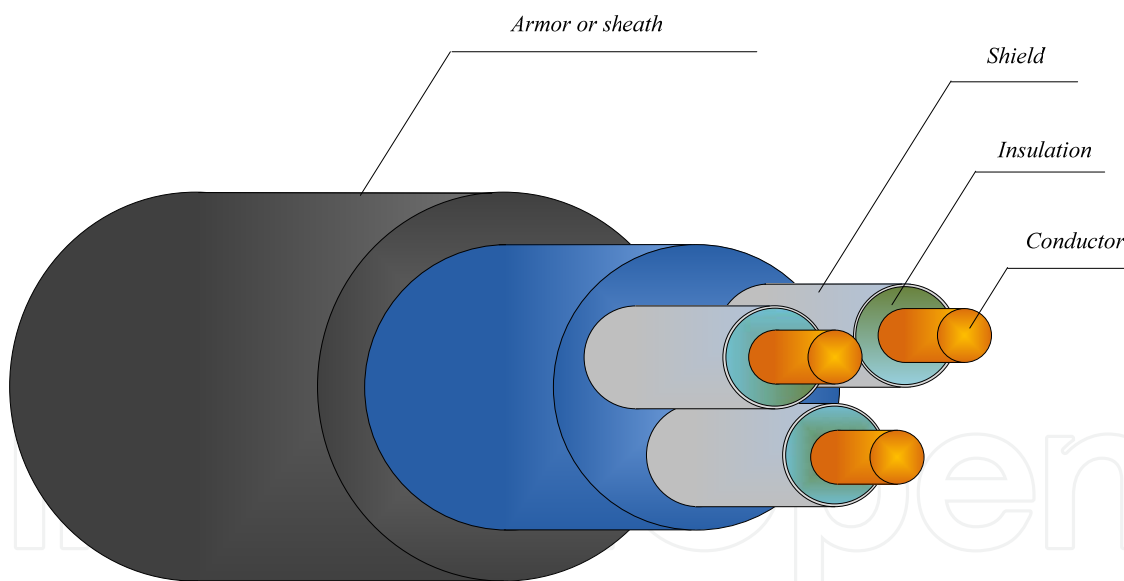


Figure 4.1 Generic representation of a electric power cable.

4.1 Basic components of electric power cables

The purpose of a power cable is to carry electricity safely from the power source to different loads. In order to accomplish this goal, the cable is made up with some components or parts. Figure 4.1 shows a description of the cable components, which are:

Conductor: The conductor is referred to the part or parts of the cable which carry the electric power. Electric cables can be made up by one conductor (mono-phase cables), three (three-phase cables), four, etc.

Insulation: Dielectric material layer with the purpose of insulate conductors of different phases or between phases and ground.

Shield: metal coating, which covers the entire length of the cable. It is used to confine the electric field inside the cable and distribute uniformly this field.

Armor or sheath: Layer of heavy duty material used to protect the components of the cable for the external environment.

4.1.1 Conductor

Some materials, especially metals, have huge numbers of electrons that can move through the material freely. These materials have the capability to carry electricity from one object to another and are called conductors. Thus, conductor is called to the part or parts of the cable which carry electric power.

The conductor may be solid or made up with various strands twisted together. The strand can be concentric, compressed, compacted, segmental, or annular to achieve desired properties of flexibility, diameter, and current density.

The choice of the material as a conductor depends on: its electrical characteristics (capability to carry electricity), mechanical characteristics (resistance to wear, malleability), the specific use of the conductor and its cost.

The classification of electric conductors depends on the way the conductor is made up. As a result, the conductors can be classified as [42]:

4.1.1.1 Classification by construction characteristics

Solid conductor: Conductor made up with only one conductor strand.

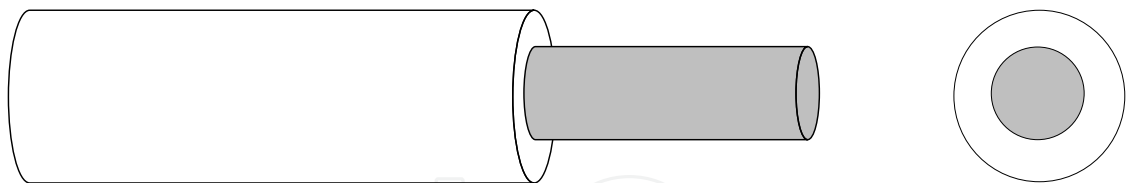


Figure 4.2 Conductor made up with Only one conductor strand.

Strand conductor: Conductor made up with several low section strands twisted together. This kind of conductor has bigger flexibility than solid conductor.

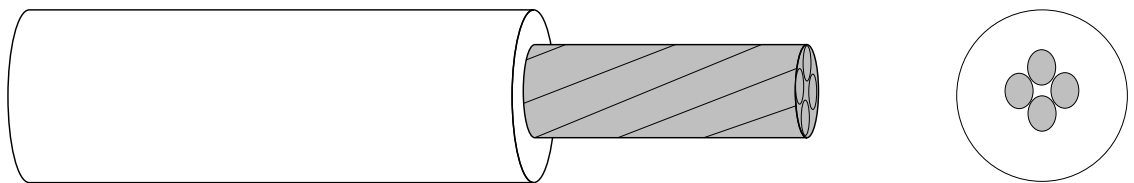


Figure 4.3 Conductor made up with several low section strands twisted together.

4.1.1.2 Classification by the number of conductors

Mono-conductor: Conductor with only one conductive element, with insulation and with or without sheath.

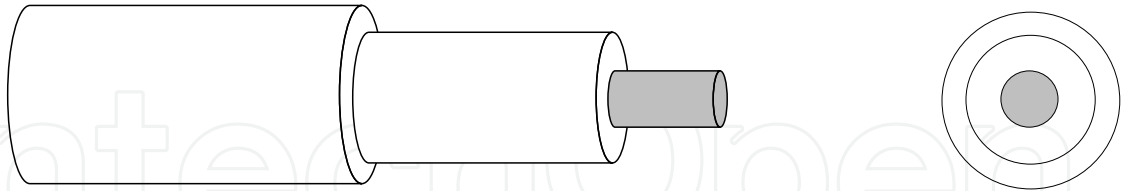


Figure 4.4 Conductor with Only one conductive element.

Multiple-conductor: Conductor with two or more conductive elements, with insulation and with one or more sheaths.

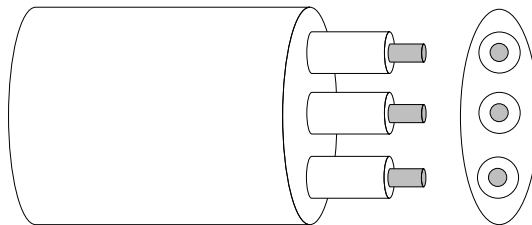


Figure 4.5 Conductor with multiple conductive elements.

4.1.2 Insulation

The purpose of the insulation is to prevent the electricity flow through it. So the insulation is used to avoid the conductor get in touch with people, other conductors with different voltages, objects, artifacts or other items.

4.1.2.1 Air insulated conductors

A metallic conductor suspended from insulating supports, surrounded by air, and carrying electric power may be considered as the simplest case of an insulated conductor [42].

Air is not a very good insulating material since it has lower voltage breakdown strength than many other insulating materials, but it is low in cost if space is not a constraint. On the contrary, if the space is a constraint, the air is replaced as insulation material for another material with higher voltage breakdown strength [42].

The same occurs in environments where isolation by air is not possible like submarine cables. In this case neither is possible isolation by sea water, since it is not an insulating material.

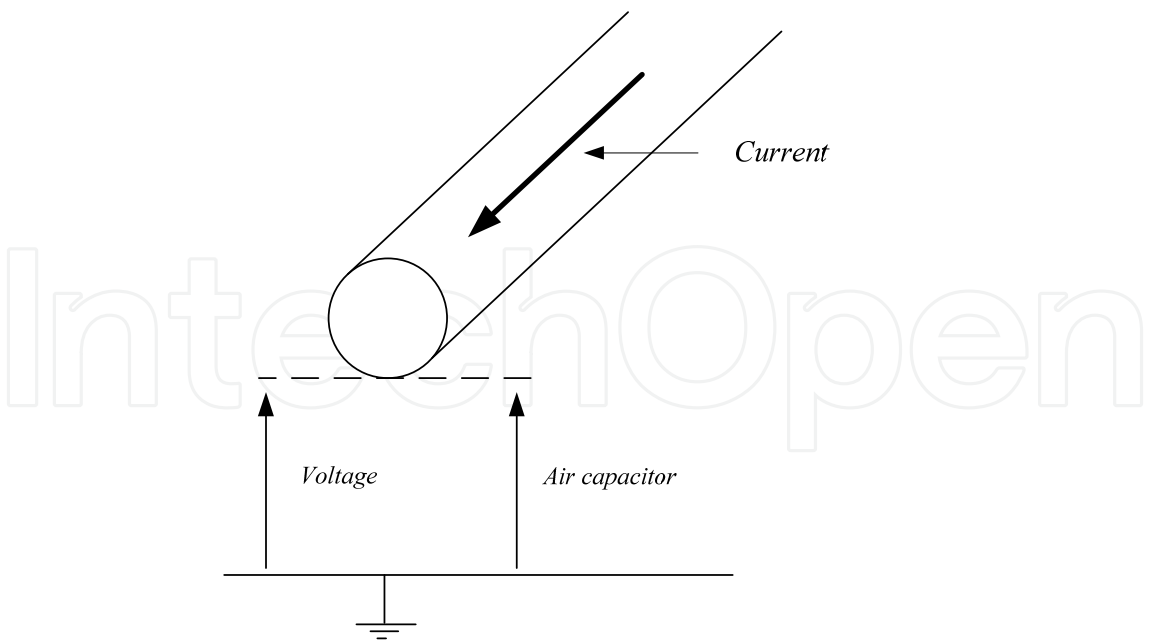


Figure 4.6 Air insulated conductor.

4.1.2.2 Insulation by covering the conductor with a dielectric material

In this type of insulation, the conductor is covered by an insulating material with high voltage breakdown strength (a dielectric), usually a polymer.

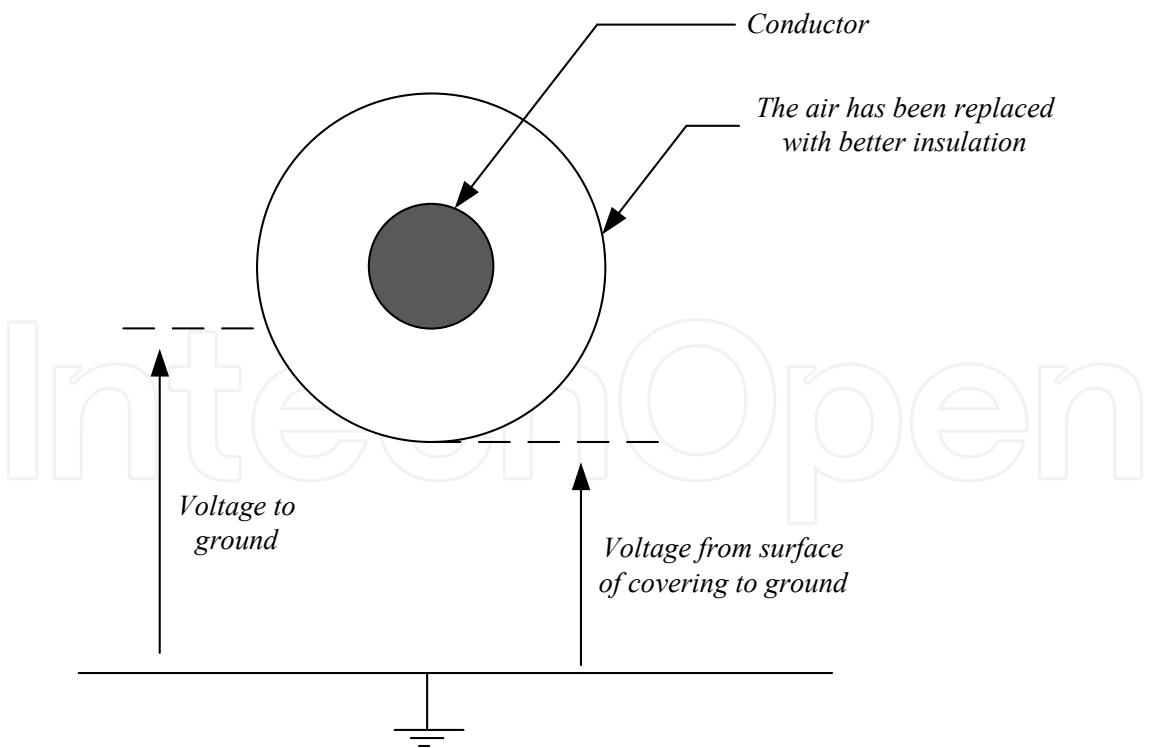


Figure 4.7 Insulation by covering the conductor with a dielectric material.

If the metallic conductor is covered with an insulating material, transmission lines can be placed close to ground or touching the ground. But in this cases when the ground plane is brought close or touches the covering, the electric field lines become increasingly distorted.

Considering the equipotential lines of the electric field, these are bended due to the potential difference on the covering surface. As shown in Figure 4.8.

At low voltages, the effect is negligible. As the voltage increases, the point is reached where the potential gradients are enough to cause current to flow across the surface of the covering. This is commonly known as “tracking.” Even though the currents are small, the high surface resistance causes heating to take place which ultimately damages the covering. If this condition is allowed to continue, eventually the erosion may progress to failure [42].

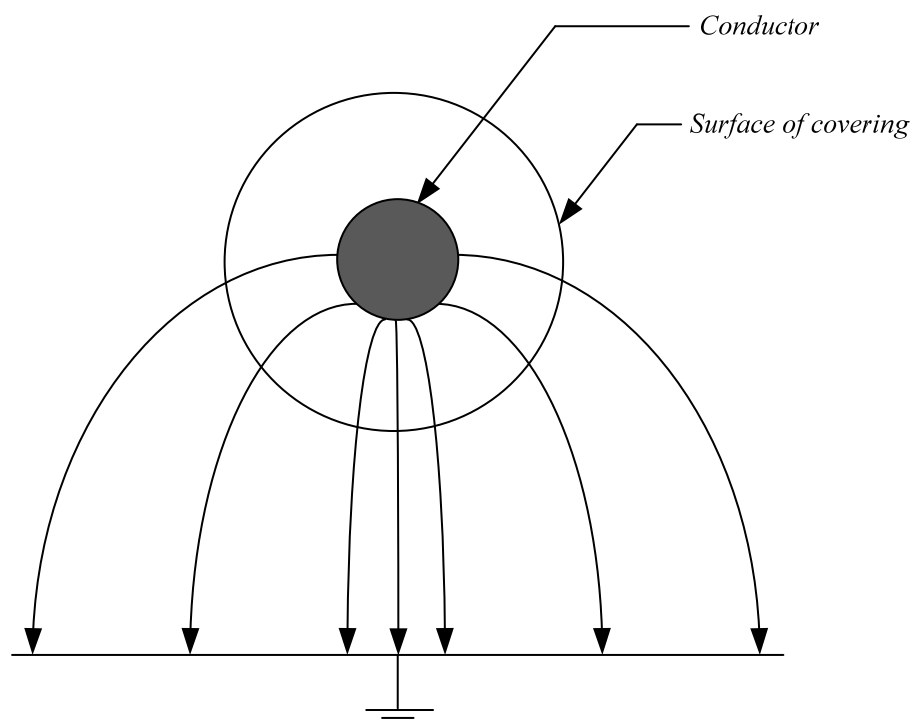


Figure 4.8 Equipotential lines of the conductor's electric field when the transmission line is close to the ground.

Therefore, high voltage power cables close to ground, like submarine cables, are provided with a shield to avoid this effect.

4.1.3 The insulation shield

The shield is a metallic coating over the insulation and connected to ground. The purpose of the shield is to create an equipotential surface concentric with the conductor to avoid the bending of the electric field lines.

The shield is also used to avoid the effects of external electric fields on the cable and as a protection for worker staff, through the effective connection to ground. The main reasons to use a shield are:

- To confine the electric field inside the cable between the conductor and the shield.
- To make equal the efforts inside the insulation, minimizing partial electric discharges

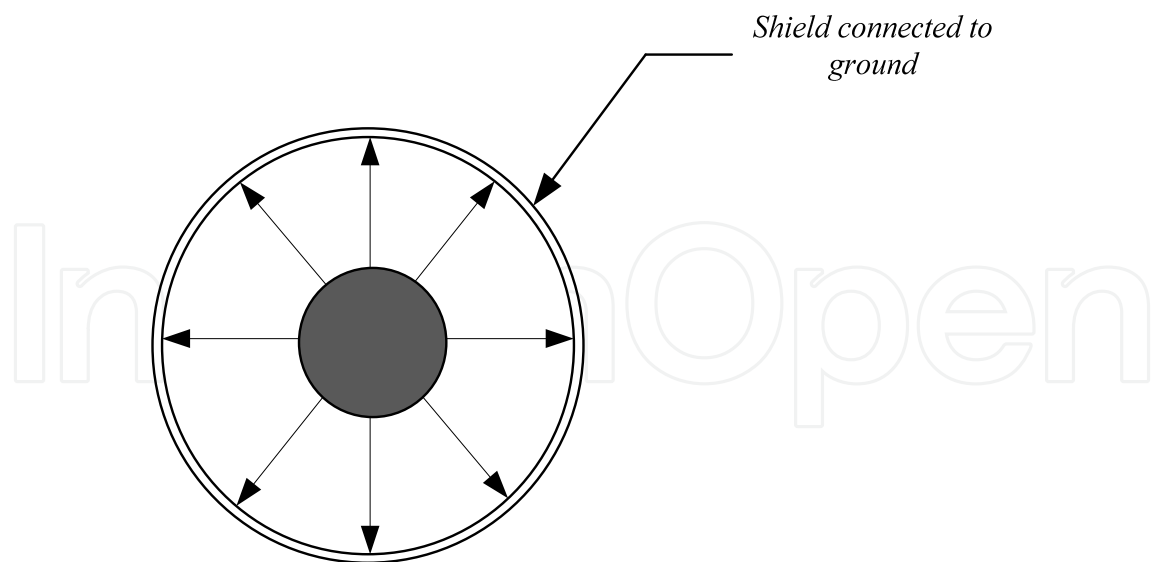


Figure 4.9 Equipotential lines of the conductor's electric field when the transmission line is provided with a shield.

- To protect the cable from induction voltages.
- To avoid electromagnetic or electrostatic interferences.

4.1.4 Armor or sheath

The purpose of this part of the cable is to protect the integrity of the insulation and the conductor from any mechanical damage such as scrapes, bumps, etc.

If mechanical protections are made by steel, brass or other resistant material, this mechanical protection is called as "armor." The "armor" can be composed by strips, strands or plaited strands.

The armor has especial importance in submarine cables, due to this type of cables are under water and the armor provides mechanical protection against to submarine water currents. Therefore, often submarine cables have an armor made up with a crown of steel strands in order to achieve a good mechanical protection [43].

4.2 Power transmission line modeling

4.2.1 Power transmission lines electric representation

A power transmission line presents several phenomena. First of all, the conductor of the cable used in power transmission lines has a small resistivity. Resistivity is the scalar property of an electric circuit which determines, for a given current, the rate of which electric energy is converted into heat or radiant energy. The resistivity of a specific cable is given by equation (18).

$$R = \frac{l}{\sigma \cdot A_c} \quad (\text{ohm}) \quad (18)$$

Where: ' l ' is the length of the cable, σ is the conductivity of the cable and A_c is the conductor area of the cable.

When an electric current flows through a conductor generates a magnetic field around it, which in turn induces an electric field. This field generates a current in the conductor in opposite direction of the original current. This effect is called self-inductance and can be described as [44]:

$$L = \frac{\mu_0}{8\pi} + \frac{\mu_0}{2\pi} \ln\left(\frac{b}{a}\right) \quad \left(\frac{H}{m}\right) \quad (19)$$

$$L = 0.5 + 0.2 \ln\left(\frac{b}{a}\right) \quad \left(\frac{mH}{Km}\right) \quad (20)$$

Where: μ_0 is the magnetic constant or the permeability of the free space and (a , b) are the radius of conductor cylinders (see Figure 4.10).

In case of cables with more than one wire or conducting element, besides the self inductance of each wire, must be also considered the electric field created in other wires. Consequently, the inductance of a multi-conductor cable mainly depends on the thickness of the insulation over the conductors.

Power transmission lines with triangular spatial disposition of the conductors, i.e. with the same separation between the three conductors present a self-inductance given by (21) [45]:

$$L = 0.05 + 0.2 \ln\left(\frac{D}{a}\right) \quad \left(\frac{mH}{Km}\right) \quad (21)$$

Where: D is the distance between conductors and a is the conductor radius

It is important to highlight that the equations are for power lines with triangular spatial disposition. If the spatial disposition is with conductors in line, the value of the self-inductance is altered.

Another effect to be considered to represent a cable is the capacity of the line to ground (which is represented by the capacitor C). The voltage difference from the conductor to ground causes this effect.

In the cases of cables with insulation and placed close to the ground (like underground or subsea cables), they have to be provided with a shield. Thus, this capacity depends on the dielectric (insulation). Due to the fact that this capacitor represents the capacitive behavior performed between the conductor and the shield (a conductor connected to ground). In the most generic case is calculated by the equation (22).

$$C = \frac{Q_{e1}}{V1 - V2} = \frac{Q_{e2}}{V2 - V1} \tag{F} \tag{22}$$

Where: C is the capacity of the cable, V1 is the voltage of the conductor 1, V2 is the voltage of the conductor 2, Q_{e1} is the electric charge stored in the conductor 1 and Q_{e2} is the electric charge stored in the conductor 2.

Simplifying the cable as a cylindrical conductor of radius “a” and a cylindrical surface coaxial with the first of radius “b” (a < b), where the space between them is filled with a dielectric material, Figure 4.10

It is possible to make the assumption that “a” and “b” (cable cross section) are very small in comparison with length (l) of the conductor cylinders (cable). As a result, the length of conductor cylinders (cable) can be considered as infinite, i.e. an ideal cylindrical capacitor. Where its capacity is given by equations (23) and (24) [46]:

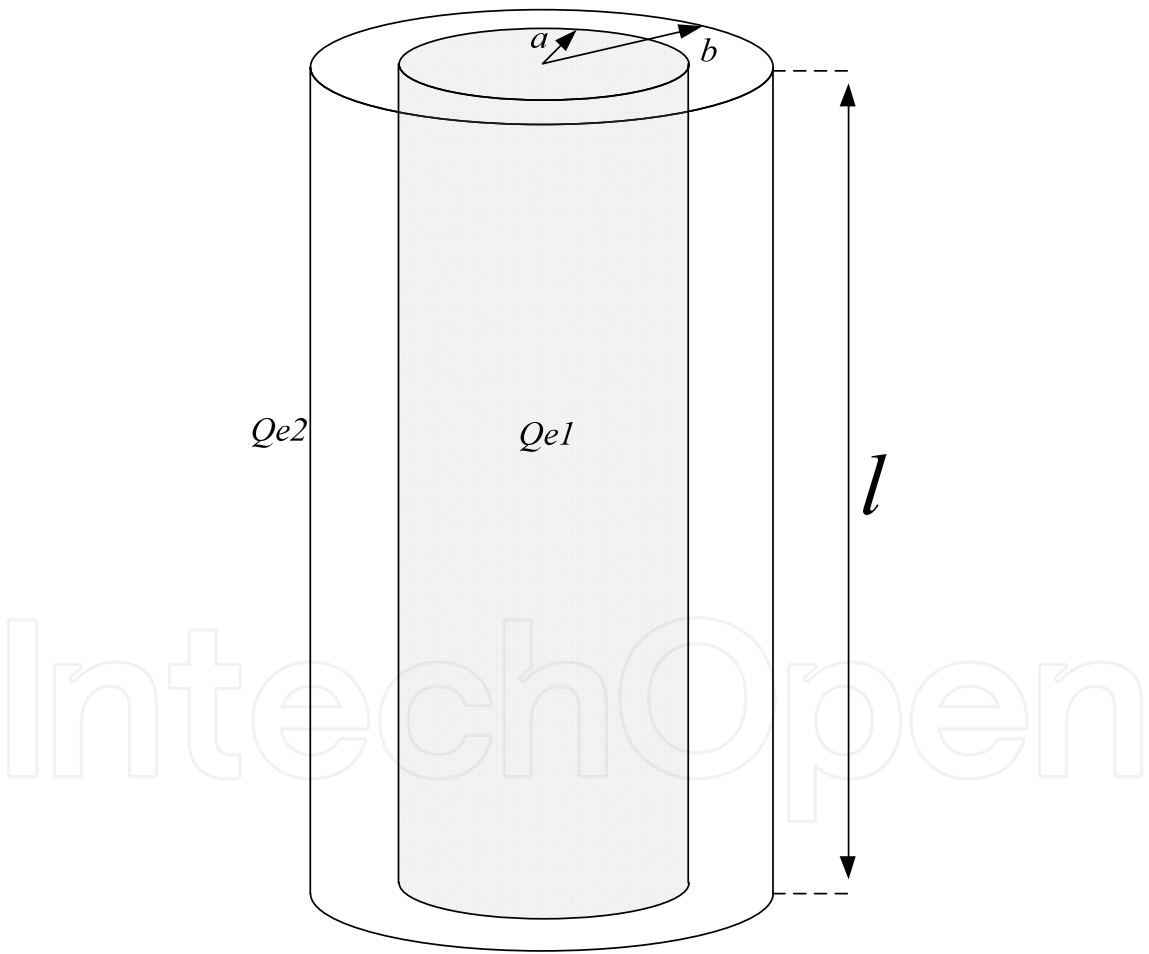


Figure 4.10 Geometrical approximation of the physical form of the cable.

$$C = \frac{2 \cdot \pi \cdot \epsilon_0 \cdot \epsilon_r \cdot l}{\ln\left(\frac{b}{a}\right)} \quad (\text{F}) \quad (23)$$

$$C = \frac{\epsilon_r}{17.97 \cdot \ln\left(\frac{b}{a}\right)} \quad (\mu\text{F/Km}) \quad (24)$$

Where: ϵ_r is the dielectric constant or relative permittivity of the insulating material between conductors, ϵ_0 is the dielectric constant in the vacuum, l is the length of the conductor cylinders and (a, b) are the radius of conductor cylinders.

Finally, the cable has a leakage current from the conductor to ground (represented by a conductance G). The dielectric is a material with low conductivity, but not zero, i.e. the insulation presents high impedance, nevertheless, this does not mean infinite. Thus, the conductance G represents the current generated from the conductor to ground (the shield connected to ground) through the dielectric because the insulation is not ideal.

In short, transmission lines are basically circuits with distributed parameters, i.e. R , L , C and G are distributed along the whole length of line. Where:

- The distributed resistance R of the conductors is represented by a series resistor (expressed in ohms per unit length).
- The distributed inductance L (due to the magnetic field around the wires, self-inductance, etc.) is represented by a series inductor (henries per unit length).
- The capacitance C between the conductor and the shield is represented by a shunt capacitor C (farads per unit length).
- The conductance G of the dielectric material separating two conductors (the shield and the conductor) is represented by a conductance G , shunted between the signal wire and the return wire (Siemens per unit length).

Therefore, a transmission line can be represented electrically per phase for each differential length as in Figure 4.11 [47], [48] y [49].

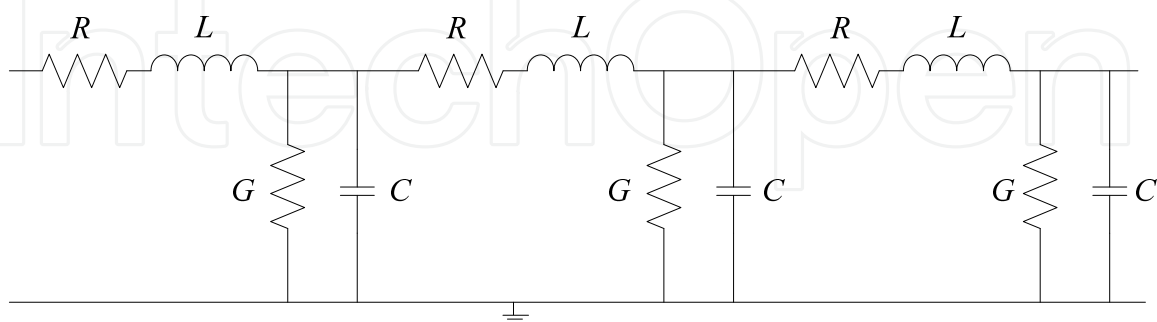


Figure 4.11 Electric representation of the cable per differential length.

In the same way, for three-phase transmission lines, the cable can be represented using three identical schemes per phase as follows, Figure 4.12.

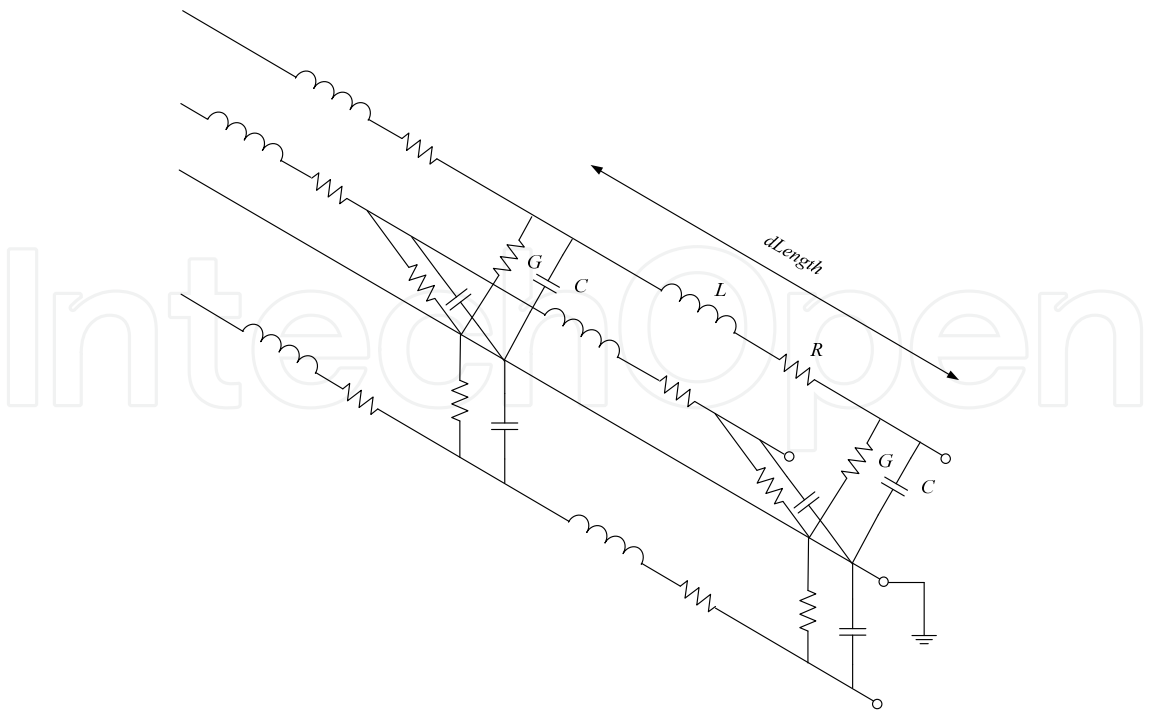


Figure 4.12 Electric representation of the three phase cable per differential length.

4.2.1.1 Skin effect

In DC circuits, the current density is similar in all the cross section of the conductor, but in AC circuits, the current density is greater near the outer surface of the conductor. This effect is called skin effect.

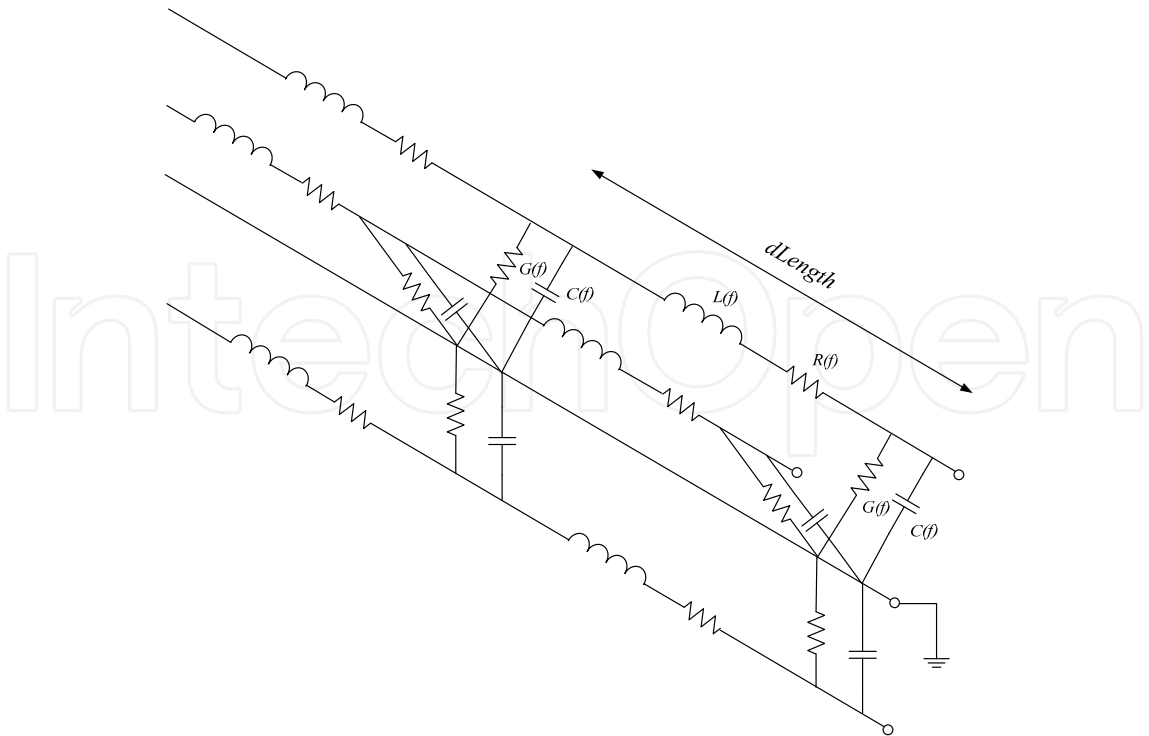


Figure 4.13 Electrical representation of a three-phase cable per differential length with frequency dependent parameters.

Due to this phenomenon, AC resistance of the conductor is greater than DC resistance. Near to the center of the conductor there are more lines of magnetic force than near the rim. This causes an increment in the inductance toward the center and the current tends to crowd toward the outer surface. So at high frequencies the effective cross section area of the conductor decreases and AC resistance increases.

In short, the skin effect causes a variation in the parameters of the cable, due to the non uniform distribution of the current through the cross section of the cable. This variation depends on frequency. Consequently, RGLC parameters are frequency dependent.

If this effect is taken into account the electric representation of the cable for each differential length is represented as shown in Figure 4.13.

4.2.2 Power transmission line modeling options

Based on the electric representation of the cables and depending on the cable model requirements, it is possible to perform more or less simplifications, in order to maintain the accuracy of the model and reduce its complexity. Thus, there are several ways for modeling a cable; these models can be classified as follows [50].

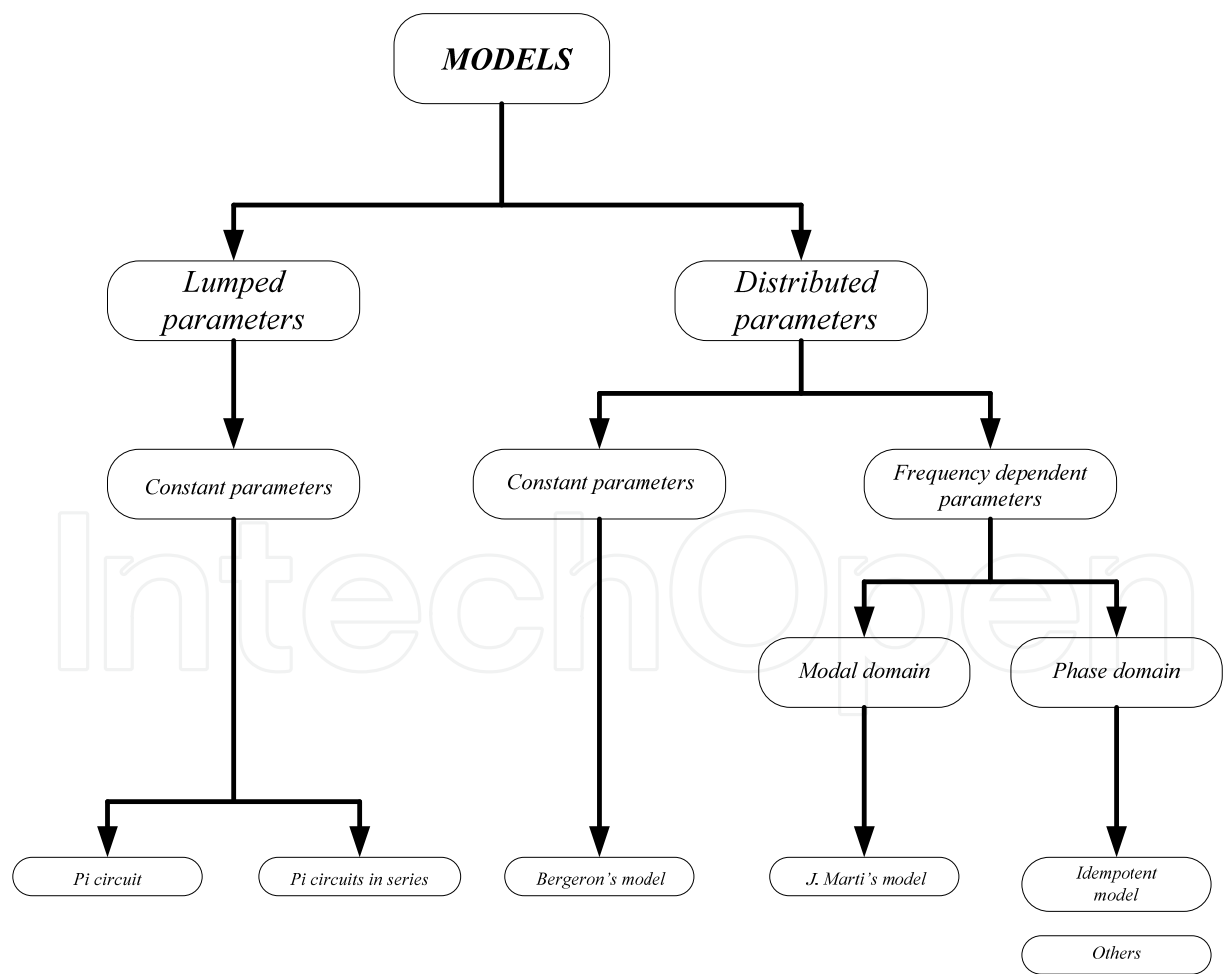


Figure 4.14 Classification of the different types of cable models.

In the present work, these models are divided into models based on constant parameters and models based on frequency dependent parameters. This division is made, because these two groups are based on different electrical representations, Figure 4.12 and Figure 4.13.

Thus, according to [51] for modeling the transmission lines with constant parameters there are the following options:

- Bergeron's traveling wave.
- Standard short, medium and long line models for phasor domain. If only care about 50-60Hz.
- Sequence of single phase "π" segments. In order to model the transients in easy way.

If the objective is the analysis of a wide frequency spectrum accurately, a more accurate model of a line can be developed considering the RGLC parameters distributed and frequency dependent. So, in this report, the following frequency dependent cable models are considered:

- Frequency dependent model in modal domain (J. Marti).
- Frequency dependent model in phase domain (Idempotent model)

4.2.2.1 Constant parameter models

All the mathematical analysis of the evolution of the current and voltage to develop constant parameter models are based on a generic segment of the cable with length (Δx). Therefore, these models are developed starting from the electrical representation of Figure 4.11

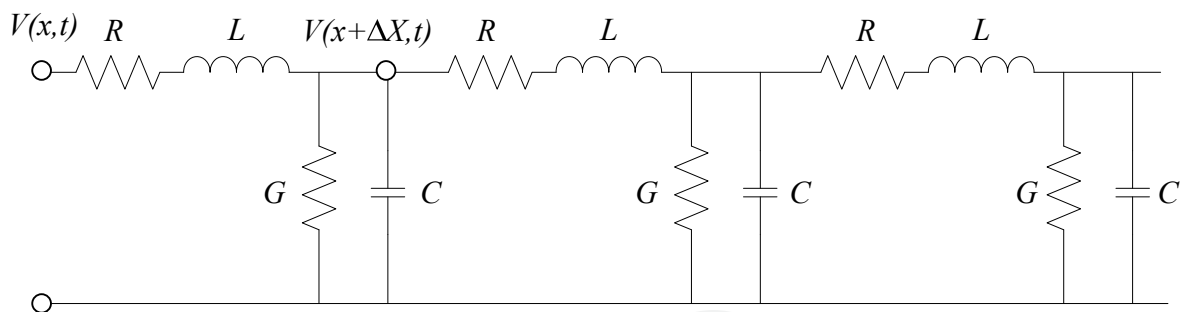


Figure 4.15 Electrical representation of a generic cable segment with constant parameters.

Where: $V(x,t)$ and $V(x+\Delta x,t)$ are instantaneous voltages on x and $x+\Delta x$ respectively and $I(x,t)$ and $I(x+\Delta x,t)$ instantaneous current on x and $x+\Delta x$.

Applying Kirchoff's laws to this circuit, it is possible to obtain the following equations to describe the behavior of the circuit:

$$V(x,t) - V(x + \Delta x,t) = \Delta V \quad (25)$$

$$\Delta V = -(RI(x,t) + L \frac{\partial I}{\partial t}) \Delta x \quad (26)$$

$$I(x,t) - I(x + \Delta x,t) = \Delta I \quad (27)$$

$$\Delta I = -(GV(x,t) + C \frac{\partial V}{\partial t}) \Delta x \quad (28)$$

In the limit $\Delta x \rightarrow 0$, these equations ((26) and (28)) can be expressed as follows:

$$-\frac{\partial V}{\partial x} = RI + L \frac{\partial I}{\partial t} \quad (29)$$

$$-\frac{\partial I}{\partial x} = GV + C \frac{\partial V}{\partial t} \quad (30)$$

The equations (29) and (30) are called the general equations of the transmission lines and all the constant parameter models are based on these equations.

4.2.2.2 Standard short, medium and long line models for phasor domain

Taking the derivative of equations (29) - (30), it is possible to obtain the following second-degree ordinary differential equations of the transmission line for voltage and current.

$$\frac{\partial^2 V}{\partial x^2} = \gamma^2 \frac{\partial V}{\partial t} \quad (31)$$

$$\frac{\partial^2 I}{\partial x^2} = \gamma^2 \frac{\partial I}{\partial t} \quad (32)$$

$$\gamma = \alpha_\gamma + i\beta_\gamma = \sqrt{(R + i\omega L)(G + i\omega C)} \quad (33)$$

Where: γ is the wave propagation constant, α_γ is the real part of the propagation constant which represents the attenuation (Np/m) and β_γ is the imaginary part of the propagation constant which represents phase velocity (rad/m).

Applying D'Alenbert to the second-degree differential equations, it is possible to obtain the general solution of the equations. This solution consists of two traveling waves that propagate through the line, one from left to right and the other one in reverse.

A simple way to work with traveling voltage waves is representing the system as a two ports network or a quadripole. Moreover, the standard model (for short, medium and large lines) is focused to represent only the steady state of the transmission lines (50-60Hz). Consequently, is possible to use a lumped parameters quadripole.

If the length of the transmission line is small in comparison with the traveling wave length, equation (34). The traveling time of the electromagnetic waves can be neglected, allowing the representation of the transmission system by lumped parameters.

$$\lambda = \frac{v_e}{f_e} = \frac{1}{\sqrt{LC}f_e} \quad (34)$$

Where: v_e is the propagation speed of the traveling wave and f_e is the frequency of the analyzed transient phenomenon

In equation (34) the frequency is inversely proportional to the traveling wave length. As a result, for low frequencies the wave length is large in comparison with the length of the transmission line, i.e. the traveling wave that goes from one node to the other node appears instantly in the second node with virtually no time delay.

Therefore, to obtain the equations of the transmission line for the standard model (50-60Hz) the transmission parameters (also called ABCD-parameters) are used.

On the contrary, if the required frequency for the analysis is high, the traveling wave length is less than the length of the transmission line. As a result, it is not possible to neglect the delay in the wave between the two ends of the cable. In these cases, models based on traveling waves are more accurate [50].

ABCD parameters

These parameters are based on a lumped parameter two port network or quadripole, Figure 4.16 Each parameter of the ABDC parameters of the two-port network represents:

- (A) the voltage relation between the two ports in open circuit.
- (B) the negative transference impedance in short circuit.
- (C) the transference admittance in open circuit.
- (D) the negative current relation between the two ports in short circuit.

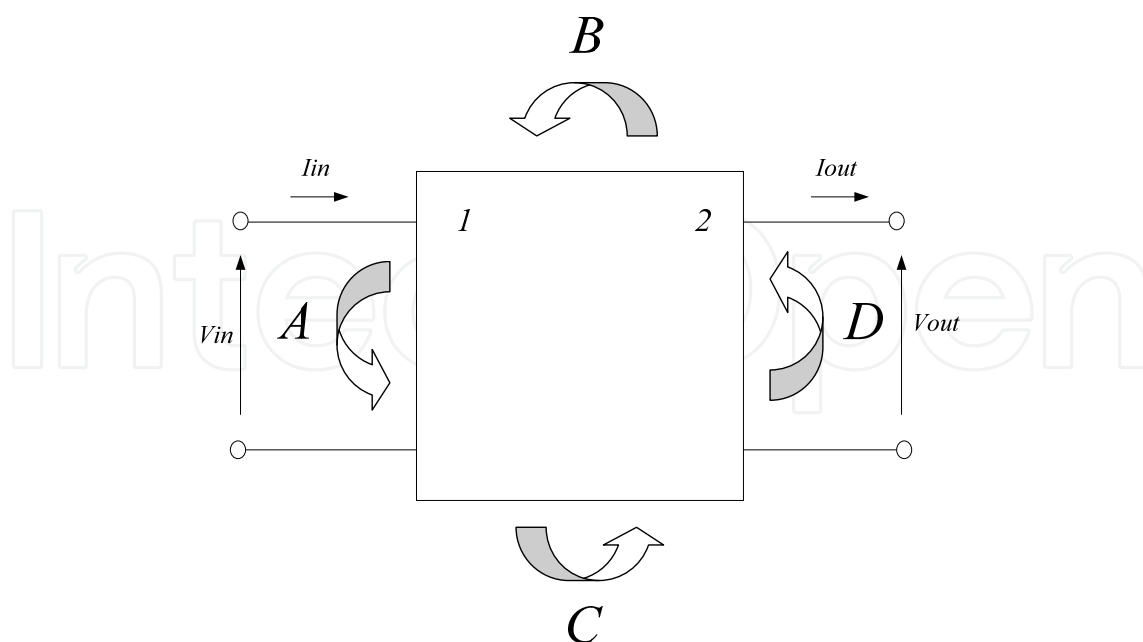


Figure 4.16 Two port system or qudrupole oriented to a transmission line in phasor domain.

Thus, the currents and voltages on both sides of this generic system are related by equations (35)-(37):

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_{out} \\ I_{out} \end{bmatrix} \quad (35)$$

$$V_{in} = A \cdot V_r + B \cdot I_{out} \quad (36)$$

$$I_{in} = C \cdot V_r + D \cdot I_{out} \quad (37)$$

Standard models for phasor domain are developed starting from these general equations (36)-(37). Depending on the physical phenomena that are considered (section 4.2), transmission lines can be simplified in one way or in another. The consideration or not of all these physical phenomena depends on the cable length. So, depending on the cable length, there are three general models for overhead transmission lines: short (< 80 km), medium (80 Km to 240 Km) and long (more than 240 Km) [47].

4.2.2.2.1 Standard short line models for phasor domain (<80 Km)

The capacitive component of the cable increases with its length (equation (23)), so for short overhead cables, the capacitive component is generally small. In the same way, the admittance G represents a leakage current, which depends on the insulation material's conductivity. Usually this material has a low conductivity and the associated resistivity is very high. Therefore, for short lines with very low capacitive component, the capacitive component and the admittance (a high resistivity in parallel) of the line can be neglected [51].

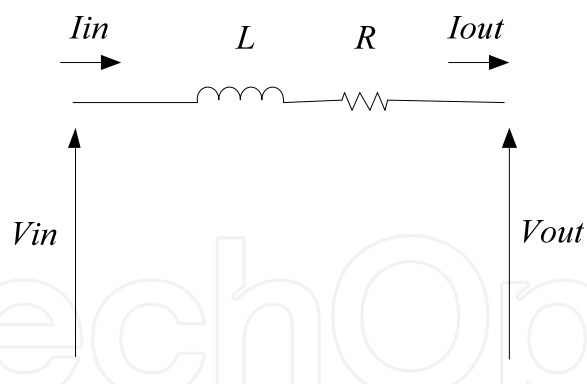


Figure 4.17 Standard cable model for short lengths.

Where: L represents the phenomenon of the self inductance and R is the resistance of the cable.

The ABDC parameters taken into account these simplifications are:

$$A=1 ; B=Z ; C=0 ; D=1 \quad (38)$$

Where: Z is the total series impedance.

If these constants are replaced in the general equation of the standard model (equation (35)) is possible to obtain the general equations of the model for short lines.

4.2.2.2.2 Standard medium line models for phasor domain (80Km<length< 240Km)

In cables of medium length, the capacitive component is bigger than in the case before (short lines). So, for lines with this length, the capacitive component has to be considered to obtain an accurate cable model. Therefore, in this case, as the cable model the so called nominal "π" circuit is used, Figure 4.18.

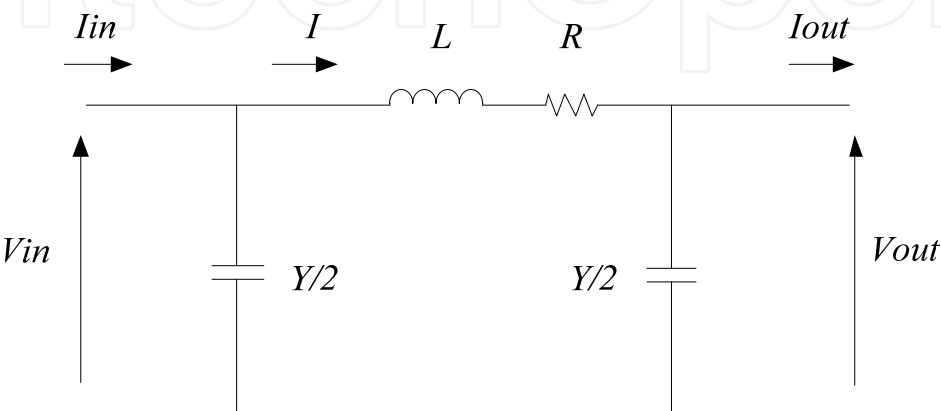


Figure 4.18 Standard cable model for medium cable lengths. Nominal-π circuit.

From this model, it is possible to obtain the following equations to relate Vs, Vr, Ir and Is:

$$V_{in} = V_{out} + IZ \tag{39}$$

$$I = I_{out} + V_{out} \cdot \frac{Y}{2} \tag{40}$$

$$I_{in} = I_{out} + V_{in} \cdot \frac{Y}{2} \tag{41}$$

Based on these equations, the complex constants A, B, C and D have the following expressions:

$$A = D = 1 + \frac{ZY}{2} \tag{42}$$

$$B = Z \tag{43}$$

$$C = \left(1 + \frac{ZY}{4}\right) \tag{44}$$

Where: Y is the total shunt admittance and Z is the total series impedance.

As in the previous case, if these constants are replaced in the general equation of the standard model (equation (35)) is possible to obtain the general equations of the model for medium lines.

4.2.2.2.3 Standard long line models for phasor domain (> 240Km)

In this case, the evolution of the traveling waves and the refraction at the end of the line must be taken into account. So, this model has the general equations shown in (45) - (48).

Usually the conditions of the current and voltage are required at the end of the line (when $x = l$, length of the line). Thus, the general equations of the system are simplified:

$$V_{out} = V_{in} \cdot \cosh(\gamma l) - I_{in} \cdot Z_c \cdot \sinh(\gamma l) \quad (45)$$

$$I_{out} = I_{in} \cdot \cosh(\gamma l) - \frac{V_{in}}{Z_c} \cdot \sinh(\gamma l) \quad (46)$$

$$V_{in} = V_{out} \cdot \cosh(\gamma l) - I_{out} \cdot Z_c \cdot \sinh(\gamma l) \quad (47)$$

$$I_{in} = \frac{V_{out}}{Z_c} \cdot \sinh(\gamma l) + I_{out} \cdot \cosh(\gamma l) \quad (48)$$

Where:

$$\cosh(\gamma l) = \left(\frac{e^{\gamma l} + e^{-\gamma l}}{2} \right) \quad (49)$$

$$\sinh(\gamma l) = \left(\frac{e^{\gamma l} - e^{-\gamma l}}{2} \right) \quad (50)$$

$$Z_c = \sqrt{\frac{L}{C}} \quad (51)$$

In this way, the ABCD constants or the quadripole constants have the following expressions:

$$A = D = \cosh(\sqrt{ZY}) \quad (52)$$

$$B = \sqrt{\frac{Z}{Y}} \cosh(\sqrt{ZY}) \quad (53)$$

$$C = \sqrt{\frac{Y}{Z}} \cosh(\sqrt{ZY}) \quad (54)$$

However, it is possible to simplify even more those expressions by using equivalent mathematical series instead of the hyperbolic functions:

$$A = D = \cosh(\sqrt{ZY}) = 1 + \frac{YZ}{2} + \frac{Y^2Z^2}{24} + \frac{Y^3Z^3}{720} + \dots \tag{55}$$

$$B = Z \cdot \left(1 + \frac{YZ}{6} + \frac{Y^2Z^2}{120} + \frac{Y^3Z^3}{540} + \dots \right) \tag{56}$$

$$C = Y \cdot \left(1 + \frac{YZ}{6} + \frac{Y^2Z^2}{120} + \frac{Y^3Z^3}{540} + \dots \right) \tag{57}$$

Usually three terms of the series are enough to model overhead transmission lines with less than 500 km, nevertheless, the first two terms are enough in most cases. Consequently, the equivalent circuit for long transmission lines is an equivalent "π" circuit that can be expressed as follows:

$$\frac{A-1}{B} = \frac{Y}{2} \tag{58}$$

$$B = Z \tag{59}$$

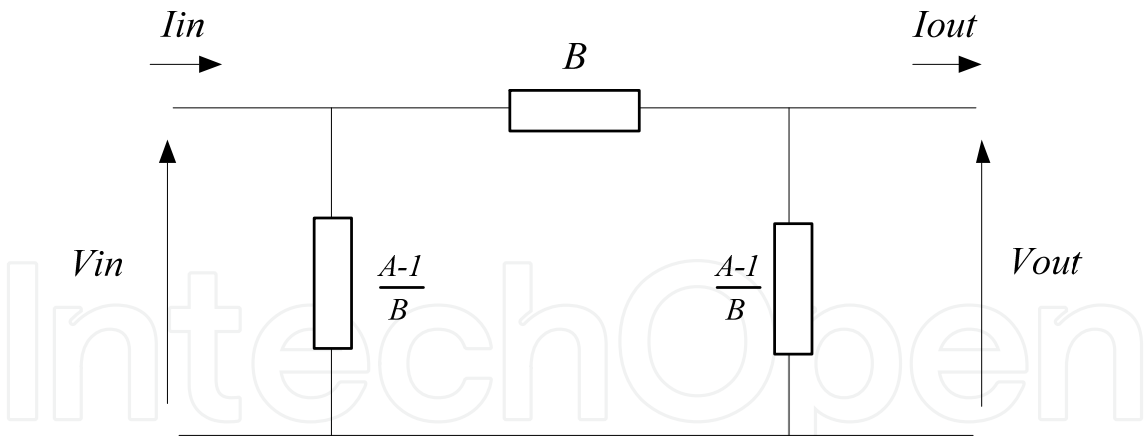


Figure 4.19 Standard cable model for long cable lengths. Equivalent π circuit.

As is distinguished in the beginning of this section, the cable model developed in the present section, depicted in Figure 4.19, only represents the cable for the conditions at the ends of the line. If the results in the intermediate points of the cable are required, the equations (45) - (48) must be considered. Another option is the use of several equivalent π circuits.

4.2.2.2.4 Sequence of single phase “π” segments

If the cable model has to represent the cable in a frequency range bigger than the fundamental frequency (50-60Hz), one option can be the use of several single phase "π" segments in series.

Cascading several identical "π" sections or circuits, as shown in Figure 4.20, it is possible to obtain a lumped parameters model which is an approximation of a distributed parameters model.

Cable models based on distributed parameters have an infinite number of states, but models based on “π” sections have a finite number of states, as many as “π” sections. Therefore, depending on the number of “π” sections used to model the cable, the model is more similar to a distributed parameters model and as a result, the model is able to represent the cable in a bigger frequency range.

Thus, the required number of "π" sections for a specific model depends on the required frequency range and the length of the line. In Figure 4.20 are represented N "π-nominal" circuits in cascade (from now only "π") [52]:

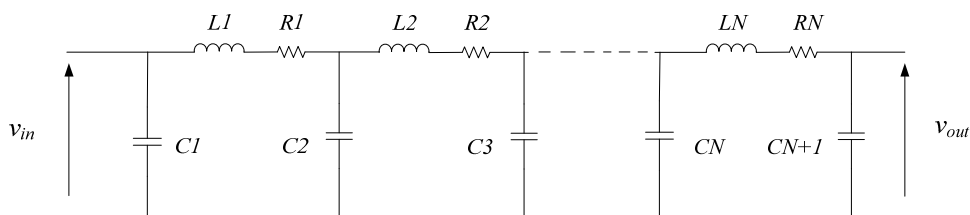


Figure 4.20 Submarine cable modeled as N “π” circuits.

To obtain the relation between the input variables and the output variables, the system is represented as several two-port networks (quadrupoles) with several ABDC parameters Figure 4.21

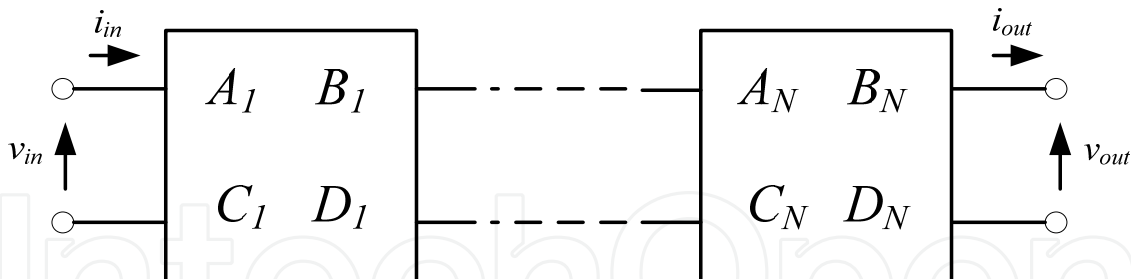


Figure 4.21 N quadrupoles in series.

It is important to keep in mind that each section is a part of the same cable, thus the output impedance of any cable section and the input impedance of the next section are the same. Consequently, there are not refractions between sections.

Moreover, if all the sections have the same length, as is usual, their associated "π" circuits are the same. The cable model can be represented with equation (60) [50].

$$\begin{bmatrix} v_{in} \\ i_{in} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^N \cdot \begin{bmatrix} v_{out} \\ i_{out} \end{bmatrix}$$

(60)

So, the equivalent ABDC parameters for several " π " circuit is the product of all the matrixes of all two port sections.

The number of " π " circuits in series for a correct representation of the transmission line depends mainly on the required frequency for the analysis [53]. Thus, for a specific maximum frequency, the maximum length that can be represented by each " π " circuit is limited by equation (61).

$$l_{\max} \leq \frac{v_e}{5f_{\max}} \quad (61)$$

Where: v_e is the propagation velocity of the traveling wave, $l_{\max}$ is the maximum length that can be represented by each " π " section and $f_{\max}$ the maximum frequency.

Another way to obtain the number of " π " circuits in series for a correct representation of the transmission line is used in [54]. As [54] a pretty good approximation to determine the number of required " π " circuits is given by the equation (62), which depends on the following parameters.

- The travelling time (τ) or the propagation velocity.
- The maximum required frequency for the simulation model.
- The length of the line (l).

$$f_{\max} = \frac{Nv_e}{8l} \quad (62)$$

Where: N is the number of required " π " circuits, v_e is the propagation velocity of the traveling wave, l is the length and $f_{\max}$ the maximum required frequency.

4.2.2.2.5 Bergeron's traveling wave

To perform a accurate analysis of a cable based on constant and distributed parameters, the Bergeron's travelling wave method is used [55], [56] and [57]. This method is based on the way that the travelling wave is propagated and its refraction at the end of the line.

The bergeron's travelling wave model is developed starting from the general equations of transmission lines (29)-(30), but in this case the series resistance and the admittance are neglected. So the transmission line is considered as a lossless line and all the global losses are considered at both ends of the line.

In this way the general equations of the transmission lines can be simplified into:

$$\frac{\partial V}{\partial x} = -L \frac{\partial I}{\partial t} \quad (63)$$

$$\frac{\partial I}{\partial x} = -C \frac{\partial V}{\partial t} \quad (64)$$

Then, if another partial derivative is performed on these equations, the following second degree lineal differential equation is obtained.

$$\frac{\partial^2 I}{\partial x^2} = LC \frac{\partial^2 I}{\partial t^2} \quad (65)$$

Applying D'Alenbert on equation (65), it is possible to obtain the generic expressions for voltage and current:

$$I(x, t) = f_1(x - v_e t) + f_2(x + v_e t) \quad (66)$$

$$V(x, t) = Z_c [f_1(x - v_e t) + f_2(x + v_e t)] \quad (67)$$

Find the particular solution of these equations ((66) and (67)) is very complex. Therefore, for work with them computational models in EMTP (Electro Magnetic transients program) are used. So, the model is adapted to EMTP.

Usually the conditions of the current and voltage are required at the end of the line, i.e. when $x = l$. Thus, this model for EMTP is only valid for results at the end of the lines.

However, if results on an intermediate point of the line are required, it is possible to obtain those by using several Bergeron's travelling wave models in series, i.e. dividing the cable in several sections and modeling each one with traveling wave model. In this case also, due to the fact that those sections are sections of the same cable (the same input impedance), there are not refractions between sections.

The traveling wave does not appear in the other end of the cable instantly. Therefore, the ends of the cable are decoupled with a time constant and there are not any changes in the voltage and current values until expires the period of time necessary for the wave to cross the line (τ). The generic equivalent circuit of the model is shown in Figure 4.22.

$$\tau = \frac{l}{v_e} = l\sqrt{LC} \quad (68)$$

The general equations of the model are:

$$e_k(t) + Z_c i_{km} = e_m(t - \tau) + Z_c (-i_{mk}(t + \tau)) \quad (69)$$

Where the current sources represents the time delay:

$$I_k(t - \tau) = -\frac{1}{Z_c} (e_m(t - \tau)) - i_{mk}(t + \tau) \quad (70)$$

$$I_m(t - \tau) = -\frac{1}{Z_c} (e_k(t - \tau)) - i_{km}(t + \tau) \quad (71)$$

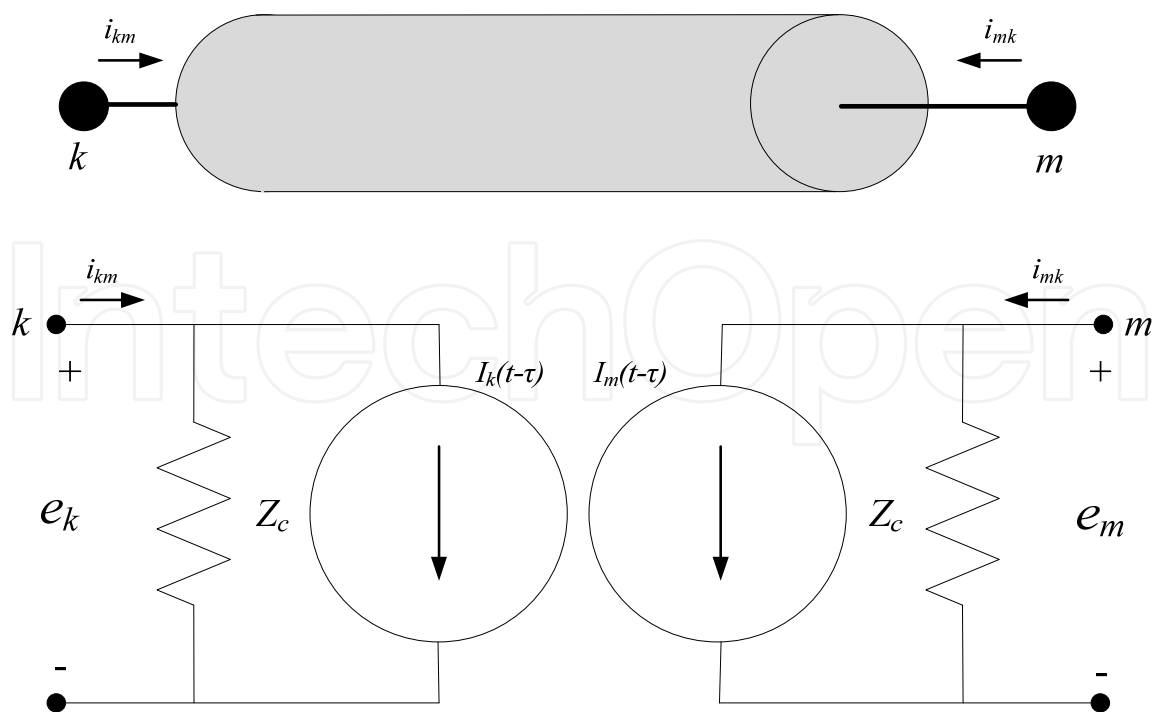


Figure 4.22 Equivalent model for Bergeron’s travelling wave.

4.2.2.3 Frequency dependent models

If a very accurate analysis is required, the variation of the parameters with the frequency variation must be taken into account. Due to the fact that, the skin effect of the transmission lines affects significantly to the system resonances [58].

The resistive component of a transmission line is only a little part of the total impedance when the system is not in resonance. However, this series resistance is very important when the system is in resonance. If the circuit is in resonance, the imaginary components of the impedance are balanced, so the resistive component determines the total impedance.

Therefore, if the required frequency range for the model is wide, several times bigger than the fundamental frequency (the frequency used to estimate the electrical parameters of the model), these variations have to be taken into account, to obtain accurate results,

4.2.2.3.1 Frequency dependent model in modal domain (J. Marti)

One way to obtain more accurate models is developing the transmission line equations in frequency domain considering distributed parameters, due to the distributed nature of the losses and frequency dependent parameters.

In these two fundamentals is developed the model of J. Marti [50] and [59]. The equivalent circuit of this model is based in voltage sources, not like Bergeron’s model which is based on current sources, as can be seen in Figure 4.23. Another difference with the Bergeron’s model are the losses, in this case, the losses are represented by impedances in series.

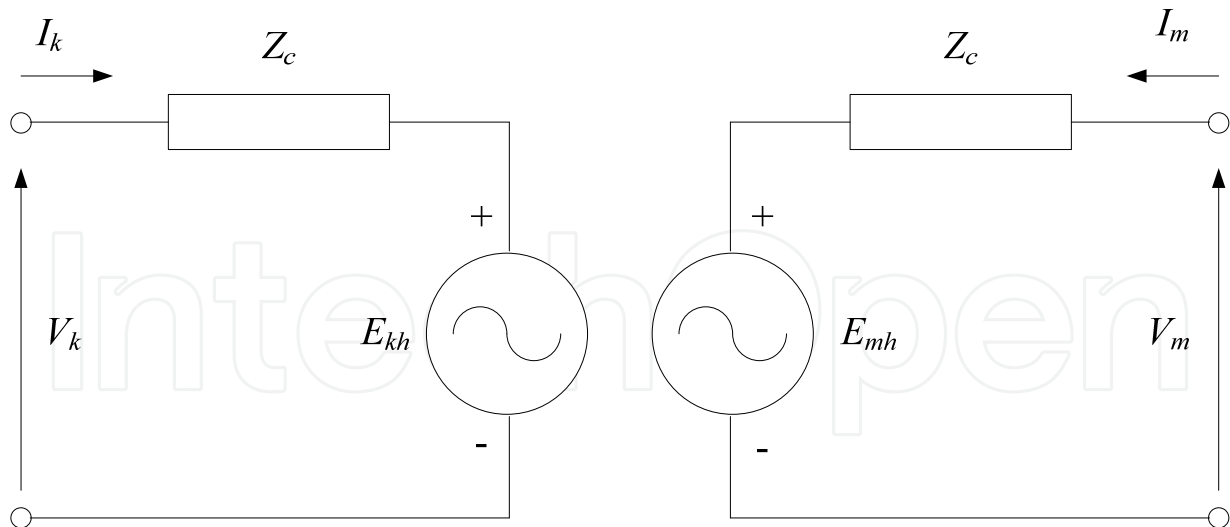


Figure 4.23 Equivalent circuit for J. Marti model in frequency domain.

The general equations of this model, i.e. the equations used to describe the behaviour of the system are (72) and (73):

$$V_k(\omega) = Z_c(\omega) \cdot I_k(\omega) + E_{mh}(\omega) \quad (72)$$

$$V_m(\omega) = Z_c(\omega) \cdot I_m(\omega) + E_{kh}(\omega) \quad (73)$$

Where:

$$E_{mh}(\omega) = A(\omega) \cdot F_{pk} = [V_k(\omega) + Z_c(\omega)I_k(\omega)]e^{-\gamma\omega l} \quad (74)$$

$$E_{kh}(\omega) = A(\omega) \cdot F_{pm} = [V_m(\omega) + Z_c(\omega)I_m(\omega)]e^{-\gamma\omega l} \quad (75)$$

This model is frequency dependent, in both, in the characteristic impedance (equation (76)) and in propagation constant (equation (77)).

$$Z_c(\omega) = \sqrt{\frac{R'(\omega) + i\omega L'(\omega)}{G'(\omega) + i\omega C'(\omega)}} \quad (76)$$

$$\gamma(\omega) = \sqrt{(R'(\omega) + i\omega L'(\omega))(G'(\omega) + i\omega C'(\omega))} \quad (77)$$

The J. Marti model it is not very accurate at low frequencies and for very short lines, due to the imperfections of the system in time domain [60].

4.2.2.3.2 Frequency dependent model in phase domain (Idempotent model)

As a example of this kind of models, the Idempotent model is analyzed [50], [61] and [62]. This model and the J. Marti model have similar fundamentals, but this model solves the problem of J. Marti's model with frequency dependent modal transformation matrixes. This problem is solved because the propagation wave is represented in phase domain.

The equivalent circuit of this transmission line model (the idempotent model) is depicted in Figure 4.24.

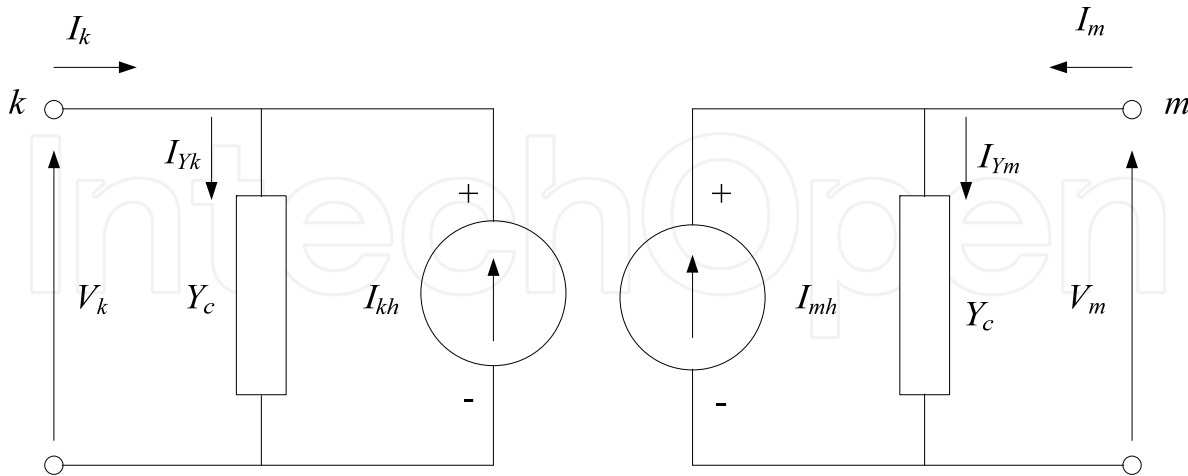


Figure 4.24 Equivalent circuit for the idempotent model.

The general equations of this model are (78) and (79):

$$[Y_c][V_m] - [I_m] = ([Y_c][V_k] + [I_k])e^{-[\gamma]l} = [A][F_{pk}] \quad (78)$$

$$[Y_c][V_k] - [I_k] = ([Y_c][V_m] + [I_m])e^{-[\gamma]l} = [A][F_{pm}] \quad (79)$$

Where:

$$[I_{mh}] = ([Y_c][V_k] + [I_k])[A] \quad (80)$$

$$[I_{kh}] = ([Y_c][V_m] + [I_m])[A] \quad (81)$$

The idempotent model with some changes / improvements detailed in [63] is used in PSCAD as the most accurate model. Moreover, the PSCAD user's guide guaranties that its cable model, frequency dependent in phase domain is very accurate [64].

4.2.3 Verification of cable models

The complexity and the accuracy are two concerns to be considered to select a cable model. Depending on the required accuracy, the used cable model can be less complex. In some cases, like in cases where the steady state is the analyzed field, the use of complex models does not improve significantly the accuracy of the model. So, there must be a balance between the complexity of the model and required accuracy. In short, depending on the requirements of the analysis, one model or another can be used.

In the present section, to carry out this evaluation of how accurate the considered cable models are and under what conditions can represent the behavior of the transmission line, the PSCAD software is used, software oriented to power electric systems.

PSCAD provides three different cable models with distributed parameters in its standard library: The Bergeron's traveling wave model, the frequency dependent model in modal

domain (J. Marti) and frequency dependent model in phase domain [64]. However, for lumped parameter models, like a " π " circuit, there is not any specific cable model. So to represent this kind of models, resistors, capacitors and inductors have to be used.

In the present work, two of the cable models analyzed in the previous section are considered to evaluate their accuracy (Bergeron's travelling wave model and a " π " circuits). In this way, to evaluate their accuracy, the simulation results of the considered two models are compared with the frequency dependent model in phase domain used by PSCAD that has been successfully validated experimentally in [65] and [66].

To work with those distributed parameter models, PSCAD calculates the RGLC parameters for the electric representation of the line by its own, based on physical parameters of the cable.

The basic geometry used by PSCAD to represent the cable is made up by concentric and homogeneous conductor and insulation layers. This approximation of the cable used by PSCAD has even more layers than the example analyzed in section 3.2.1, i.e. presents more conductor and insulation layers. But, a real cable has more layers than the approximation used by PSCAD and even parts that cannot be represented in this approximation. Therefore, to represent correctly a specific cable in PSCAD, some physical parameters of the cable have to be corrected before to fill into the PSCAD template [65].

However, to carry out this comparison, the correction of the physical parameters of the cable does not make any sense, because the physical parameter correction only affects to the electric representation, i.e. to the estimation of the RGLC parameters performed by PSCAD and all the compared models in the present section are based on the same electric representation. Therefore, the parameter correction is explained in section 4.2.4.).

4.2.3.1 Comparative of transient response for different cable models

In this section two cable models are compared with the validated model, in order to know how accurate are and in which cases are valid, starting from the simplest (unique " π " circuit) to Bergeron's model (the simplest model considering distributed parameters).

With a sharp voltage variation like a step or pulse, the most frequencies of the spectrum are excited. Thus, it is possible to compare the results and determine if the frequency responses are similar or not. This is the way used by [65] and [66] to determined the PSCAD frequency dependent model in the phase domain as a valid one.

In [65] and [66] to carry out the validation of the cable model, the results obtained by applying a voltage step to a 20kV XLPE cable are compared with the simulation results obtained in PSCAD by applying the same voltage step.

In this section the same procedure is used. Therefore, using the simulation scenario depicted in Figure 4.25, the transient responses for a voltage step for different models are obtained, in order to compare the results and evaluate their similarity.

In this case, instead of a DC voltage step, is used an AC voltage step, i.e. the AC voltage source is suddenly connected to the cable. To carry out this analysis, the breaker is connected in the worst case, when the AC voltage has the maximum value.

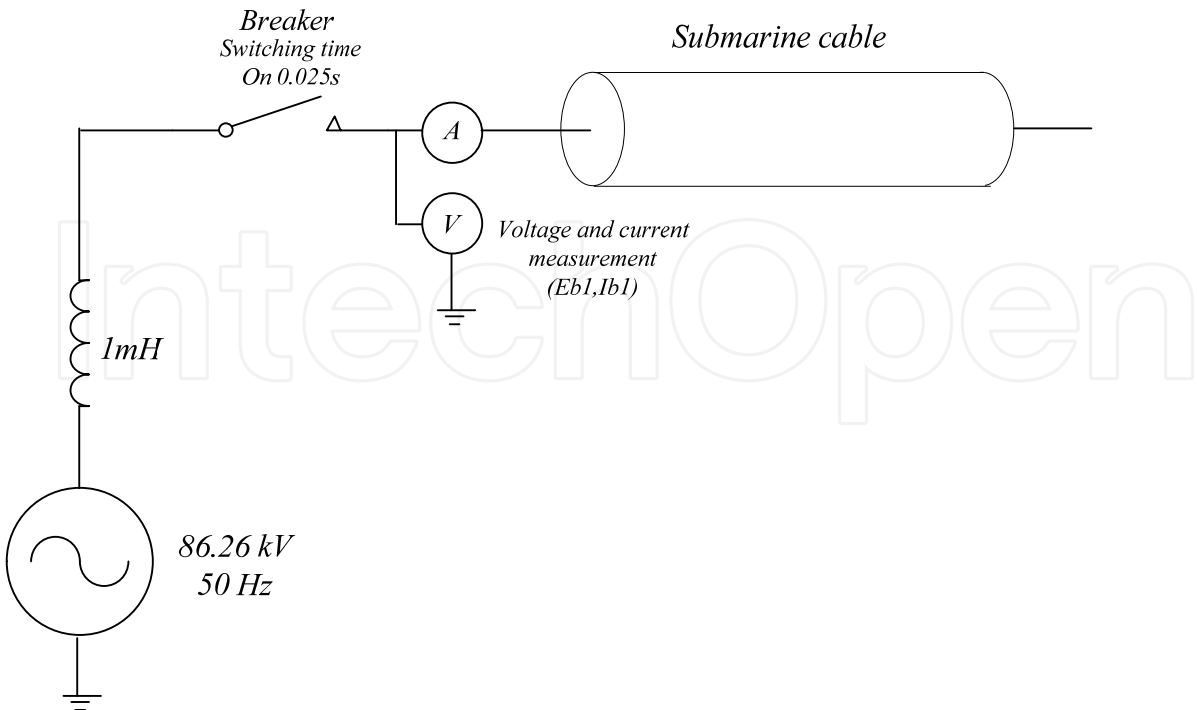


Figure 4.25 Simulation scenario in PSCAD for the verification of cable models.

The simulations are based on a cable of 150kV – 1088 A (courtesy by General Cable) with 50 Km length. The characteristics of this cable are shown in Figure 4.26.

Conductor	Radius	21.75 mm
	Conductivity of the material	(Copper) 1.7 e-8
	Magnetic permeability	1
Insulation	thickness	10 mm
	Relative permittivity	2.3
	Magnetic permeability	1
Shield	thickness	0.8 mm
	Conductivity of the material	(Copper) 1.7 e-8
	Magnetic permeability	1
Sheath	thickness	42.3 mm
	Relative permittivity	2.3
	Magnetic permeability	1

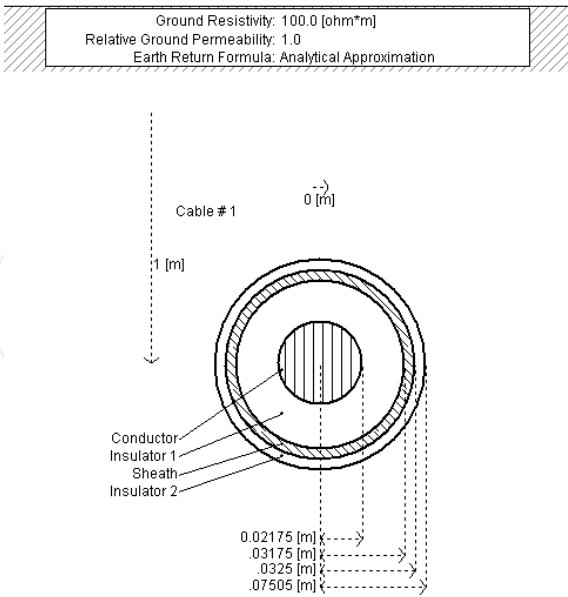


Figure 4.26 Graphic representation of the cable in PSCAD and its parameters.

From the physical characteristics of Figure 4.26, PSCAD solves / estimates the equivalent impedances (RLGC parameters) for the electric representation of the cable (Figure 4.11 for constant parameter models and Figure 4.13 for frequency dependent models). Upon this electric representation, the considered models (described in section 4.2.2.) are developed, unless for the unique “ π ” circuit model, i.e. to the Bergeon’s travelling wave model and frequency dependent model in phase domain.

As is distinguished at the beginning of this section, for lumped parameter models PSCAD does not provides any specific cable model. So, the unique “ π ” circuit model is defined directly by its RLC parameters. Thus, the cable with the physical parameters described in Figure 4.26 can be defined electrically at 50 Hz with the RLC parameters depicted in Table 4.1.

50 Km	Resistivity (ohm)	Inductivity (mH)	Capacitance (uF)
“ π ” Parameters (50 Hz)	6.09	8.8	16.92

Table 4.1 RLC parameters for the equivalent “ π ” circuit which models the 50Km cable for 50Hz.

4.2.3.1.1 Comparative of transient responses for the “ π ” circuit model

Firstly, the comparison of the unique “ π ” circuit model and the PSCAD frequency dependent model in phase domain is carried out. To this end, the procedure described in the previous section 4.2.3.1 is used.

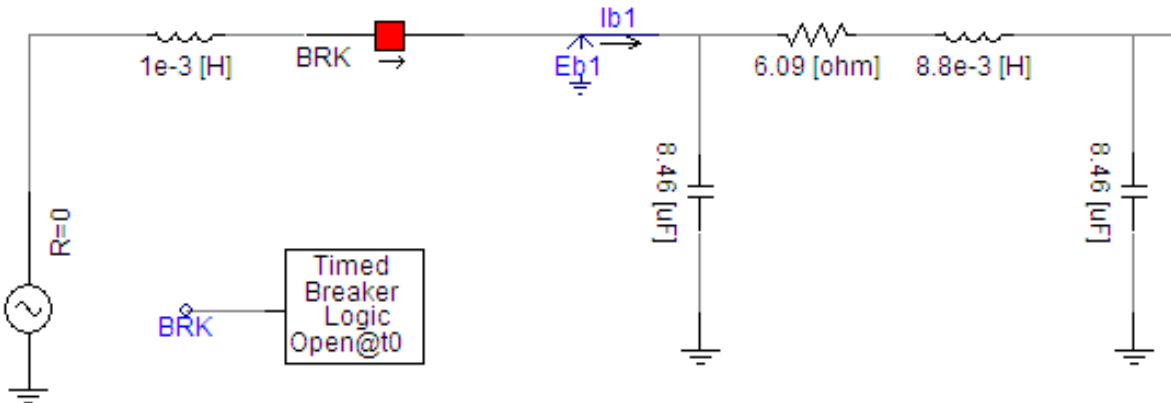


Figure 4.27 Simulation scenario in PSCAD for the “ π ” circuit.

The simulation results of the submarine cable modeled as a unique “ π ” circuit and the validated frequency dependent model in phase domain upon a AC step are shown in Figure 4.28 and Figure 4.29. It is easy to observe on these results, that only one “ π ” circuit is not enough to represent adequately the transient response of the transmission line. The current peak immediately subsequent to the close of the breaker is more than the double compared to the validated model. Moreover, the oscillation frequencies and the duration of the transients are substantially different.

However, it is important highlight that the mean values after the transient of the two models are very similar. So, despite its simplicity, for the steady state, this model can be a reasonably good approximation.

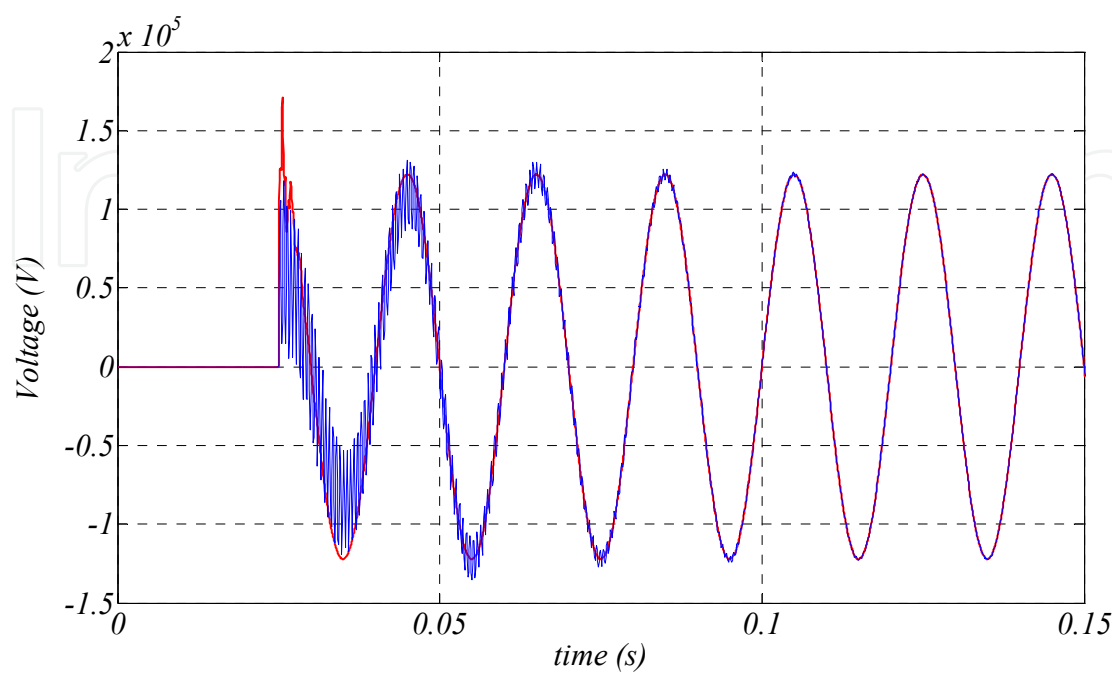


Figure 4.28 Comparison of the input voltages of the cable (Eb1): (blue) for the "π" circuit and (red) for the frequency-dependent model in phase domain of PSCAD.

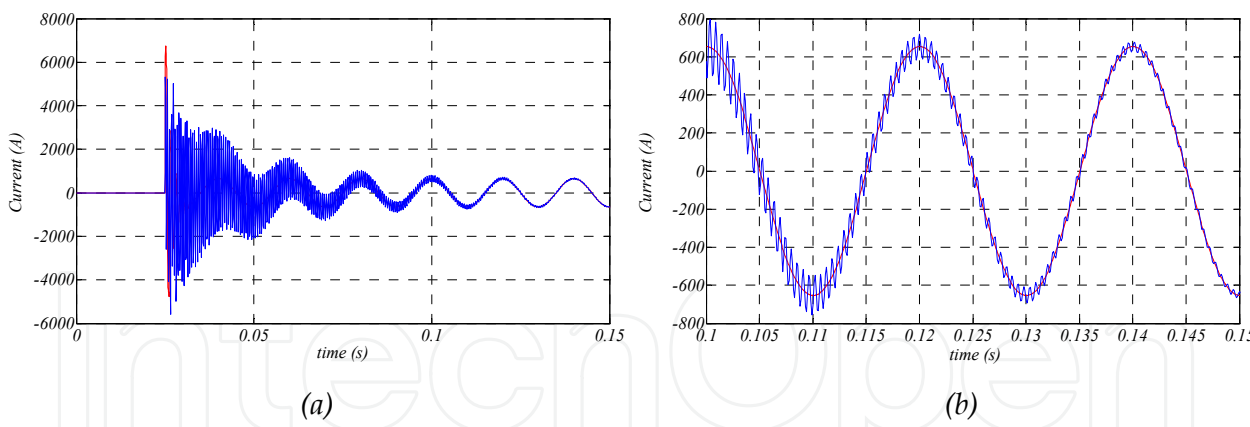


Figure 4.29 Comparison of the input current of the cable (Ib1): (blue) for the "π" circuit and (red) for the frequency-dependent model in phase domain of PSCAD.

4.2.3.1.2 Comparative of transients for the Bergeron’s travelling wave model

The next model to analyze is Bergeron’s travelling wave model. The Bergeron’s travelling wave model is based on a distributed parameters representation of the transmission line.

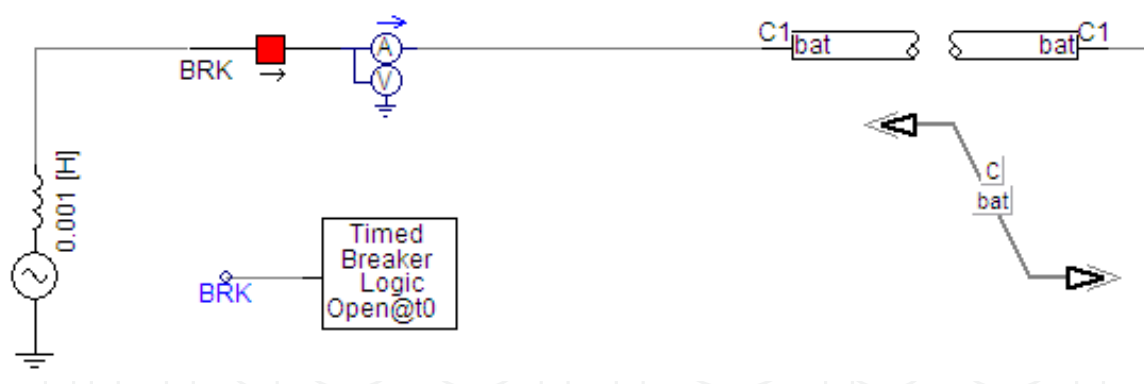


Figure 4.30 Simulation scenario in PSCAD for the Bergeron’s travelling wave model. The simulation results of the scenario depicted in Figure 4.30 are shown in Figure 4.31 and Figure 4.32. In this second case, the transient responses of those models are more similar than in the first case. The first voltage peak, when the breaker is activated, is only a little bit smaller with this model. In the same way, the oscillation frequencies of the transient responses are similar.

With regards to the current, it is possible to see the same behavior pattern. The transient response is a little bit larger in time with Bergeron’s travelling wave model and also has more high frequencies.

One reason for this could be the way that the electric parameters (RGLC) are calculated. Bergeron’s model is based in an electric representation with constant parameters, so for frequencies far away for the frequency used to calculate those parameters, because of the skin effect (see 4.2.1.1), they cannot represent well the cable. The skin effect increases the resistive component of the cable depending on the frequency and as a result, causes the attenuation of high frequencies.

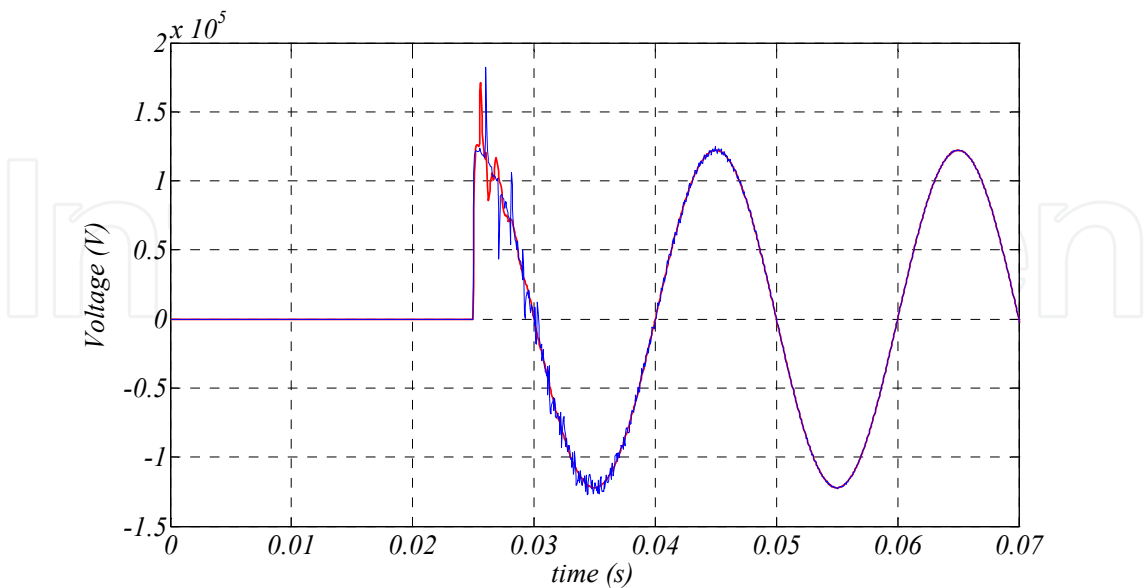


Figure 4.31 Comparison of the input voltages of the cable (Eb1): (blue) for the Bergeron’s travelling wave model and (red) for the frequency-dependent model in phase domain of PSCAD.

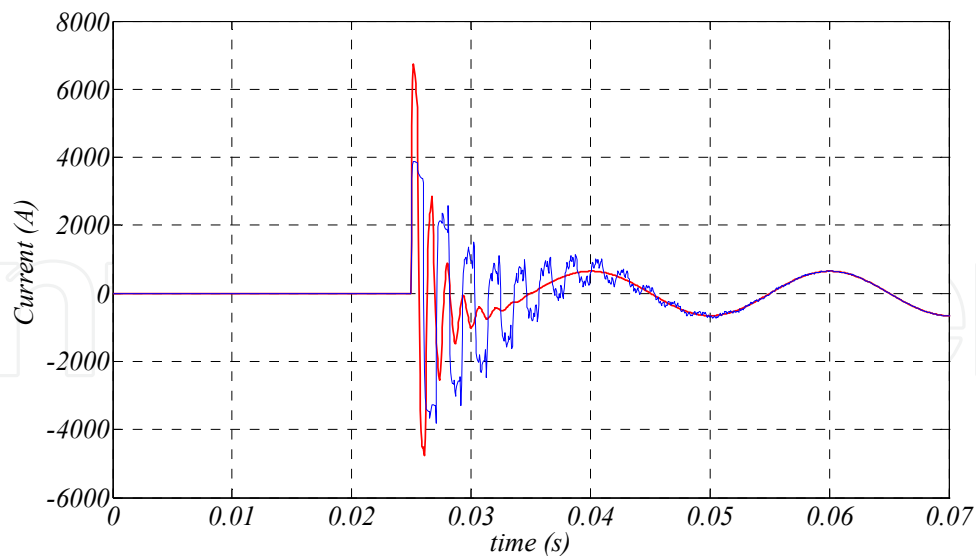


Figure 4.32 Comparison of the input current of the cable (I_{b1}): (blue) for the Bergeron's travelling wave model and (red) for the frequency-dependent model in phase domain of PSCAD.

In conclusion, this model is accurate for frequencies close to 50Hz (or 60Hz), the frequency usually used to calculate the electric parameters, i.e. it can represent the steady state and low frequencies. Starting from its nominal frequency, if the bigger is the frequency variation, the bigger is the deviation in the frequency response of the system (less accuracy).

4.2.4 Cable parameter adaptation for PSCAD

Based on the physical characteristics of Figure 4.26, PSCAD solves / estimates the equivalent impedances (RLGC parameters) for the electric representation of the cable. Thus, for complex models, where are required a lot of parameters and detailed electric specifications, the definition of the cable is more simple. However, this way has a drawback, as is explained in section 4.2.3, the template provided by PSCAD is an approximation and it cannot represent complex cable structures.

The PSCAD template has concentric, circular and homogeneous layers to introduce the data of the cable. Even though, some subsea cables are made up with other physic characteristics, such as: semiconductor layers, conductors made up by a crown of strands, the fill between conductors or other non concentric elements.

Due to the impossibility to fill in correctly the data of the cable to the PSCAD software, the physic parameters of the cable have to be corrected. The purpose of this correction is to achieve the same value for the electric parameters estimated by PSCAD and the parameters measured by the cable manufacturer. Therefore, some parameters of the conductor, shield and insulation are corrected.

The physic characteristics of the cable provided by the manufacturer (Courtesy by General Cable) are shown in Table 4.2

Parameter	Value
Rated voltage	87 / 150kV
Rated current	1088 A
Conductors cross section:	1.200 mm ²
Separation between conductors:	97.839996 mm
Buried depth	1 m
Shields cross section	30 mm ²
Shield type:	Metallic strip
Armor type:	Strands crown
Diameter of conductor	43,5 mm
Insulation thickness	20 mm
Diameter upon the insulation	88,5 mm
Diameter down the sheath:	215,6 mm
Diameter down the armor:	226,7 mm
Sheath thickness:	8,9 mm
External diameter:	244,5 mm
Relative dielectric constant:	2,50
Resistivity of the conductor d.c. at 20°C:	0,0151 Ohm/km
Resistivity of the conductor a.c.	0,0205 Ohm/km
Resistivity of the shield d.c. at 20°C:	0,6264 Ohm/km
Nominal capacitance of the cable:	0,233 μF/km
Inductance of the cable:	0,352 mH/km

Table 4.2 Cable characteristics provided by General Cable.

4.2.4.1 Conductor

Looking at Table 4.2, the conductor has a 43.5 mm diameter and also an effective cross section of 1200 mm². If the conductor is considered as solid core, homogenous and circular (as the template does), the cross section for this diameter (equation (65)) it is not the same.

$$A_c = \pi \cdot r_c^2 = \pi \cdot 21.75^2 = 1486.17mm^2$$

(82)

If the conductor is considered as solid core, homogenous and circular, the effective cross section is 1486.17 mm². Therefore, to solve this difference it is necessary to correct the resistivity of the conductor ρ .

Like first step, the real resistivity of the conductor (based on the data of the cable given by the manufacturer) is calculated, equations (83) - (84).

$$R_{DC} = \frac{\rho_c \cdot l}{A_c} = 0.0151 \text{ ohm/Km}$$

(83)

$$\rho_c = \frac{R \cdot A_c}{l} = 1.812 \cdot 10^{-8}$$

(84)

Where: ρ_c is the resistivity, l is the length of the cable and A_c is the effective cross section of the conductor (1200 mm²).

Then, the correction is applied to the resistivity of the conductor's material, i.e. the resistivity data to fill into the PSCAD template is changed to maintain the same absolute resistance of the conductor. So, the corrected resistivity depends on the effective cross section and the real cross section [65].

$$\rho_c' = \rho_c \frac{\pi \cdot r_c^2}{A_c} = 2.24412 \cdot 10^{-8} \quad (85)$$

To verify this estimation, the absolute resistance of the conductor in two cases is calculated, for 50 Hz and for direct current. In this way, these results can be compared with the characteristics provided by the manufacturer (Table 4.2).

$$R_{a.c.}(50) = \frac{\rho_c}{\delta_{50}} \cdot \frac{l}{\pi(D - \delta_{50})} = \frac{2.244 \cdot 10^{-8}}{0.010662} \cdot \frac{1000}{\pi(0.0435 - 0.010662)} = 0.0204 \text{ ohm/Km} \quad (86)$$

$$\delta_{50} = \sqrt{\frac{2 \cdot \rho_c}{\omega \cdot \mu}} = \sqrt{\frac{2 \cdot 2.244 \cdot 10^{-8}}{2 \cdot \pi \cdot 50 \cdot 4 \cdot \pi \cdot 10^{-7}}} = 0.010662 \quad (87)$$

Where: l is the length of the cable, D is the diameter of the conductor, ρ_c is the resistivity, ω is the angular speed of the current ($2\pi f$), μ is the absolute magnetic permeability of the conductor ($\mu_0 \mu_r$), μ_0 is the magnetic constant or the permeability of the free space ($4\pi \times 10^{-7} \text{ N/A}^2$) and μ_r is the relative magnetic permeability.

Comparing the results obtained in equations (86) with the data given by the manufacturer (Table 4.2.), it is possible to observe practically the same values. Consequently, the correction performed to the resistivity of the conductor is reasonable accurate.

4.2.4.2 Shield

The shield is something more than only a metallic strip, the shield can be made up with multiple layers. Looking at Table 4.2, the conductor has a 43.5 mm diameter and the insulation has a thickness of 20 mm. However, the diameter upon the insulation is 88.5mm. So, there is an undefined layer of 2.5 mm.

Considering from the data provided by the manufacturer that the shield has only 30mm² of cross section. It is possible to deduce that one of them: the shield or the insulation has more complex structure than the PSCAD template.

Therefore, in order to maintain the shield with a 30 mm² thickness and the same capacitive component for the cable, the diameter of the insulation and its relative permeability has to be changed.

Assuming that the outer diameter of the shield's conductor layer is 88.5 mm, it is possible to obtain the inner diameter of the shield, equations (88) - (90).

$$A_s = R_s^2 - r_s^2 \quad (88)$$

$$30\text{mm}^2 = 44.45^2 - r_s^2 \quad (89)$$

$$r_s = \sqrt{44.25^2 - 30} = 43.9mm \tag{90}$$

In the present analysis the Shield of the cable is metal strip kind. However, there are also other types of shields, like strands crown kind. In these cases it is necessary to carry out another correction [65].

4.2.4.3 Insulation

To correct the area of the shield, the radius of the insulation is modified. So, the value of the capacitive component using the radius calculated in the equation (90) is not the same of the characteristic provided by the manufactures, equation (91).

$$C = \frac{\epsilon_r}{17.97 \cdot \ln(b/a)} = \frac{2.5}{17.97 \cdot \ln(43.9/21.75)} = 0.198 \text{ }\mu F / Km \tag{91}$$

Therefore, to represent correctly in PSCAD the capacitive component of the submarine cable, the dielectric constant has to be corrected, equations (92) - (93).

$$\epsilon_r = 0.233 \cdot 17.97 \cdot \ln(43.9/21.75) = 2.94 \tag{92}$$

$$C = \frac{\epsilon_r}{17.97 \cdot \ln(b/a)} = \frac{2.94}{17.97 \cdot \ln(43.9/21.75)} = 0.233 \text{ }\mu F / Km \tag{93}$$

4.2.4.4 Measure with PSCAD the adapted parameters

To validate the parameters correction carried out in the preceding sections, a equivalent submarine cable in PSCAD (Figure 4.33) based on the physic data of the cable shown in Table 4.3. is defined. In this way, it is possible to obtain the electric parameters via PSCAD to compare them with the electric data provided by the manufacturer.

Table shows the parameters of the transmission line solved by PSCAD based on the physical parameters of Figure 4.33.

	Resistivity Seq +	Inductivity Seq +	Capacitance Seq +
Electric parameters (50 Hz)	0.0311* Ohm/km	0.334 mH/km	0.233 μF/km
*Resistivity without taking into account the shield, conductor only 0.0190 Ohm/km			

Table 4.3 RGLC electrical parameters calculated by PSCAD based on the physical dimensions and characteristics.

As a conclusion, the electrical parameters calculated by PSCAD (Table 4.3) in comparison with the parameters specified by the manufacturer are substantially similar.

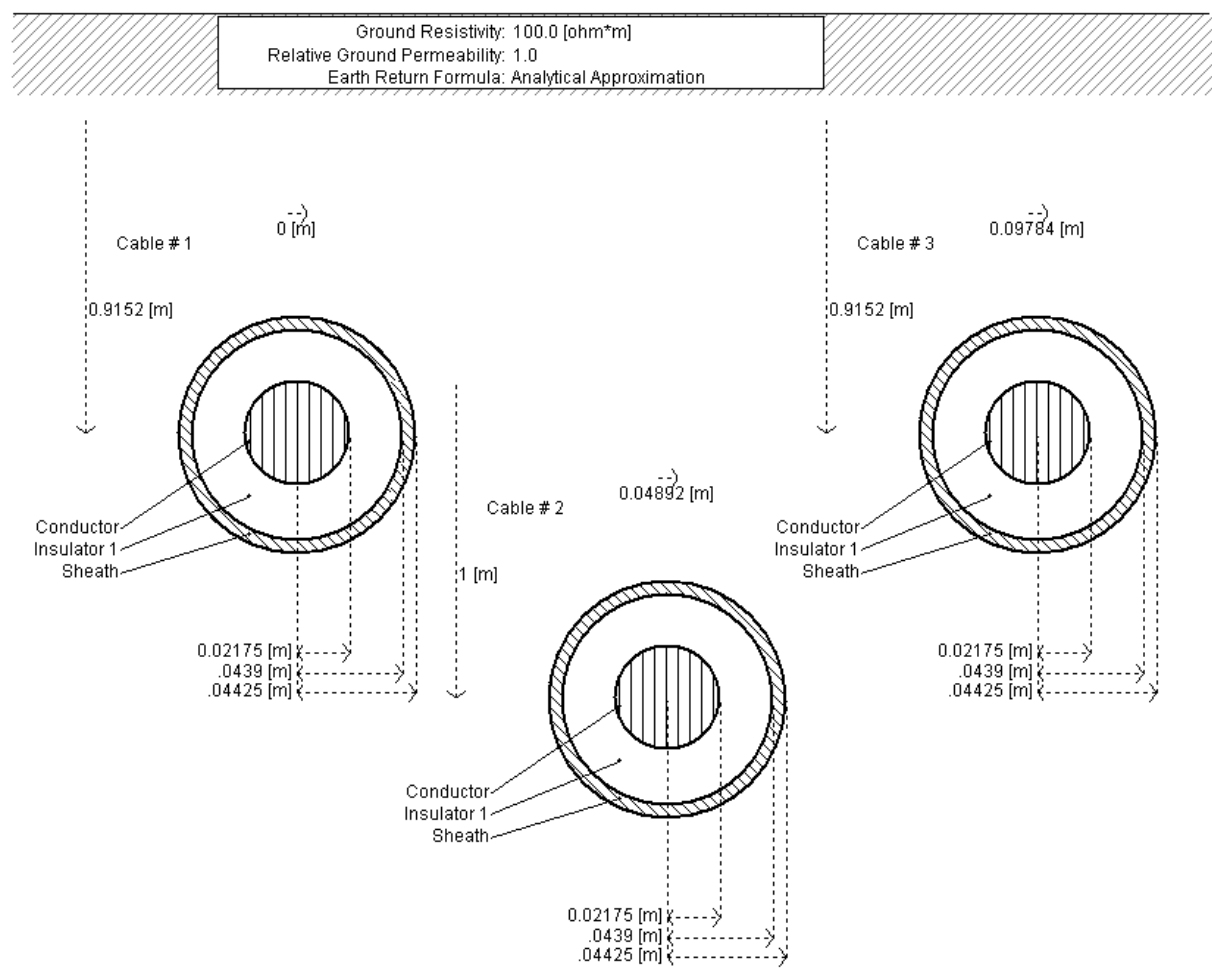


Figure 4.33 Graphic representation in PSCAD of the three-phase cable.

4.3 Reactive power Management in subsea power cables

4.3.1 Introduction

For the construction of the onshore high voltage transmission lines, almost exclusively air insulated conductors are used. However, the submarine cables are placed in very different environment which requires other kind of insulation.

Therefore, due to their construction characteristics (conductor, insulation, shield and armor), the submarine cables have a high capacitive component (see section 4.2). As a consequence, the transmission of the energy through these cables in AC provokes charge / discharge currents. This current causes a reactive power.

The maximum current capable to transfer a cable is determined by its construction characteristics (cross section of the conductor and its thermal characteristics). Thus, the active current capable to carry a cable is limited by charge / discharge current (reactive current) flowing through the cable (equation (94)).

$$|I| = \sqrt{I_{active}^2 + I_{reactive}^2} \tag{94}$$

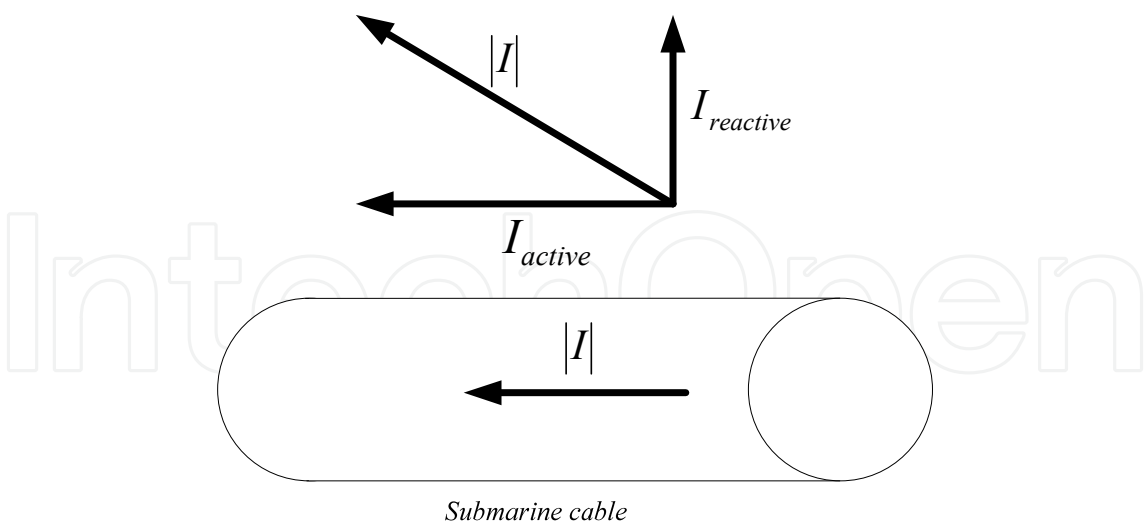


Figure 4.34 Graphic representation of the current through the cable.

Moreover, the capacitive component of the cable increases with the length of the cable (equation (23)). So, there is a specific length for each voltage level where the reactive current generated in the cable is the same of the rated current. This limit depends on the cable voltage and capacitive component (length).

Considering the transmission frequency constant (50Hz-60Hz), the expression of the reactive current is shown in equations (95) - (97).

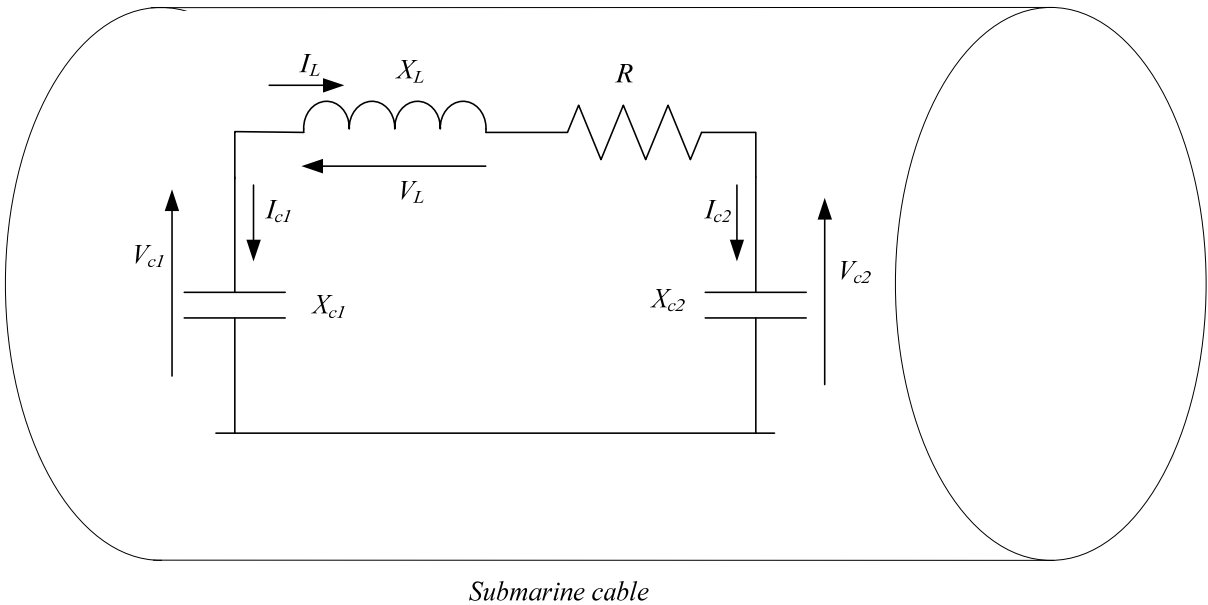


Figure 4.35 Simplified phase to neutral point (not physical) representation of a mono-phase submarine cable using a “π” model.

$$I_{c1} = \frac{|V_{c1}|}{|X_{c1}|} \approx I_{c2} = \frac{|V_{c2}|}{|X_{c2}|} \tag{95}$$

$$|X_{c1}| = |X_{c2}| = \frac{1}{\omega C_2} = \frac{1}{\omega C_1} \tag{96}$$

$$I_{c1} = |V_{c1}| \cdot \omega \cdot C_1 \approx I_{c2} = |V_{c2}| \cdot \omega \cdot C_2 \tag{97}$$

Where: I_{C1} and I_{C2} are the reactive currents, $|V_{C1}|$ and $|V_{C2}|$ are the magnitude of the applied voltage, ω is the pulsation and C_1 and C_2 represents the capacitive component of the cable.

So, if the reactive current reaches the rated current of the cable, this cable cannot transfer any active power.

To understand better this problem, the reactive power generated in the cable (caused by reactive current) for three examples is calculated, Table 4.5 Examples with different voltages and rated powers, the electrical characteristics of the cables used in those examples are depicted in Table 4.4

Cable	Vn (kV)	In(A)	Rac(Ω/Km)	L (mH/Km)	C (μF/Km)
A	36	911	0.0341	0.294	0.331
B	150	1088	0.0205	0.352	0.233
C	220	1055	0.048	0.37	0.18

Table 4.4 Characteristics of the submarine cables.

Cable	Vn (kV-50Hz)	Reactive current (A/Km)	Reactive power (MVAR/Km)
A	36	2.2	0.134
B	150	6.33	1.6455
C	220	7.18	2.736

Table 4.5 Reactive power generated in the submarine cables.

Therefore, to make more efficient the power transmission system, it is necessary to minimize the reactive current flowing through the cable by managing the reactive current. This management of the reactive power has to be oriented to increase the active power transmission capability of the transmission lines and to reduce the conduction losses.

4.3.2Types of reactive power management

With low power factors, the conduction losses in the cable are higher and the required conductor size is higher. Therefore, most of the grid codes for wind farms have as a requirement a power factor close to unit at the point of common coupling (see Appendix B: Power Factor Requirements at the Point of Common Coupling). Consequently, the reactive power compensation is necessary at least at the PCC.

If the reactive power flowing through the transmission system is managed in addition to the compensation at the PCC, makes the transmission system more efficient. With regards to the reactive power management classification, these can be classified by two parameters:

- The location of the compensation: at one end only or in both ends.
- The characteristics of the compensation: static or dynamic. The compensation device can compensate always the same reactive power at the same voltage or on the contrary depending on the requirements.

4.3.2.1 Reactive power compensation at one end or in both ends

In the first case, the reactive power compensation at one end is evaluated. This reactive power compensation is made by injecting reactive current in one end only, at the onshore side. So, there is not a reactive power management of the transmission line.

Basically, the energy is generated with a unitary power factor. This energy is transmitted through the submarine cables to the onshore substation, where the reactive power generated in the cable is compensated to integrate the energy in the main grid, Figure 4.36 (a).

The best option to minimize the reactive current as much as possible is the compensation of the reactive power generated in the cable along all its length. This option, allows the use of the cable without length limit and the reduction of the conduction losses to the minimum. But this option is not easy to carry out, due to the fact that the cables are placed in the seabed.

Therefore, if it is not possible to place reactive power compensation at intermediate points of the cable, the next best option is the compensation of the reactive power of the cable at both ends [9].

In this kind of reactive power management, an inductive reactive current is injected at the offshore end of the submarine cable, thus, due to the capacitive and distributed nature of the submarine cable, this inductive reactive current is neutralized along the length of the submarine cable.

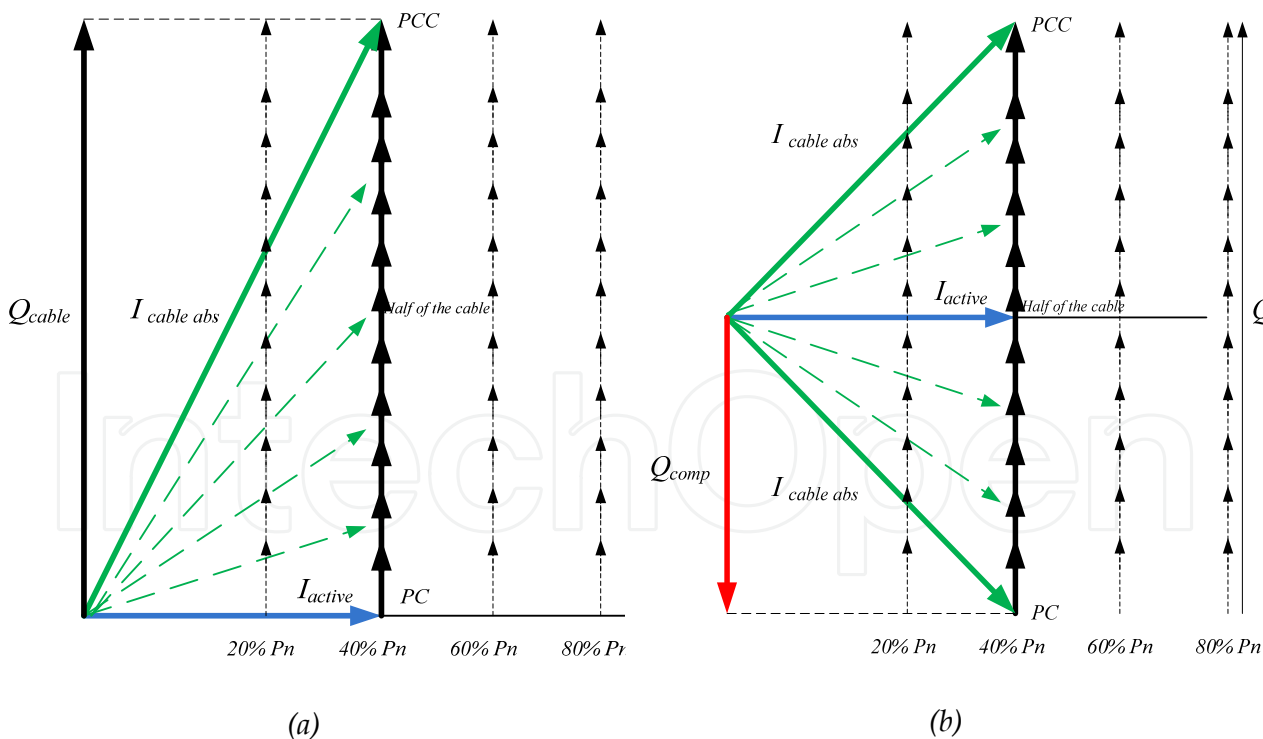


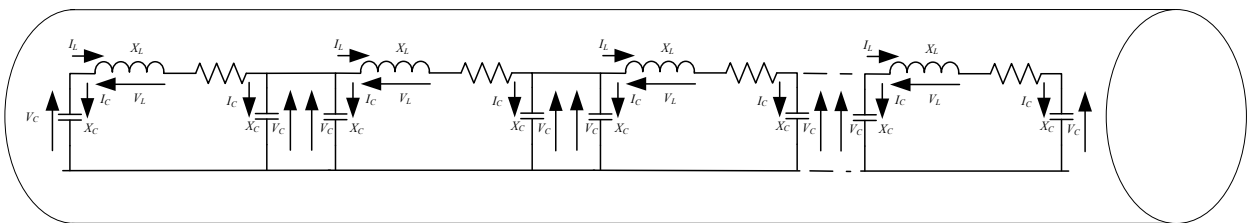
Figure 4.36 Representation of the current through the transmission line for two ways of the reactive power management: (a) reactive power compensation at one end and (b) reactive power compensation in both ends.

So, if this injected inductive current is exactly the half of the total capacitive reactive current generated by the cable, the inductive current is neutralized along the cable length until the middle of the cable. At this point, the inductive reactive current injected in the offshore end is completely neutralized and the power factor is unitary. Consequently, at the other end of the cable only appears the reactive power generated by the half of the cable, i.e. only the half amount of the capacitive reactive power generated in the cable, which is compensated by the compensation device at this end (onshore).

In this way, it is possible to minimize the maximum current flowing through the cable as well as the conductive losses, Figure 4.36 (b).

To compare these two different ways to manage the reactive power, an example is defined. This example is based on the cable “B” (Table 4.4) of 50 Km. With regards to the cable model, several “ π ” circuits in series are used (see section 4.2.2.2.4).

The analysis uses this cable model, because despite its simplicity, it is possible to obtain accurate results for the steady state and allows the measure of the results at intermediate points of the cable. More specifically, one “ π ” circuit for each kilometer is used.



Submarine cable

Figure 4.37 Simplified phase to neutral point (not physical) representation of a mono-phase submarine cable using N “ π ” circuits in series.

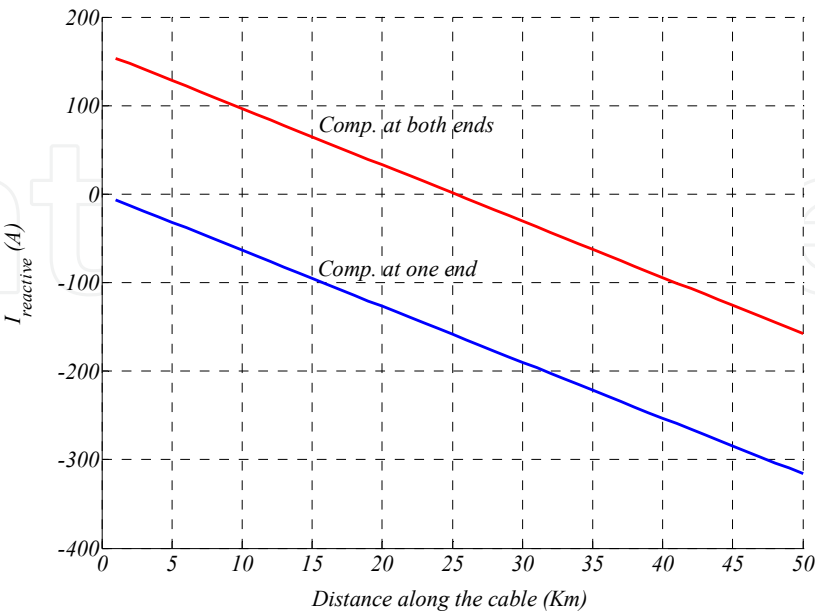


Figure 4.38 Reactive current through the cable, (red) reactive power compensation at both ends and (blue) reactive power compensation at one end only. For the cable B (150kV) and 50 Km.

Therefore, as can be seen at Figure 4.38, using the reactive power management which compensate the reactive power at both ends, the maximum current value decreases in comparison with the management way which injects the reactive power in one end only. As a result, the capability of the cable to carry active power increases. In the same way, the conduction losses are reduced.

Going more depth into the analysis, a more detailed comparison is carried out. In this second case, more cable lengths, different voltages and several transmitted active power levels are considered.

For that purpose, two cables are considered: the cables “A” and “B” of Table 4.4. As in the case before, there are modeled like several “ π ” circuits in series.

Based on these two cables, the total current along the line is obtained, for these two ways of the reactive management. In this case, two main scenarios are considered: 30 MW of transmitted active power with 36 kV of transmission voltage and 150 MW of transmitted active power with 150 kV of transmission voltage.

In each one of those scenarios, four cable lengths are considered: 50Km, 100Km, 150Km and 200Km. The results of the total current along the line for these configurations are depicted in Figure 4.39.

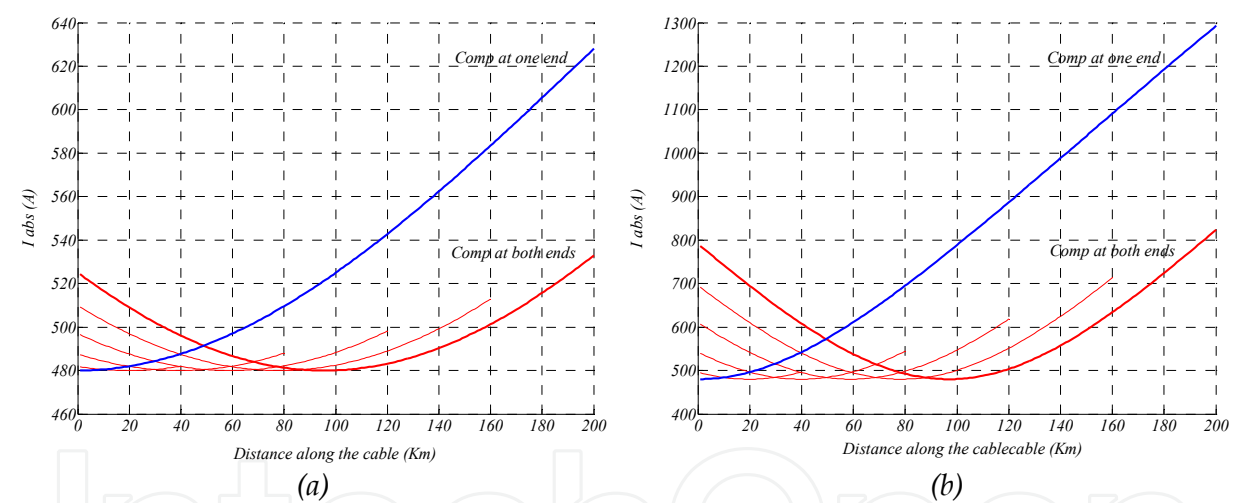


Figure 4.39 Total current along the submarine cable depending on cable length, compensation at both ends (red) and onshore compensation only (blue). (a) 30MW-36kV configuration and (b) 150MW-150kV.

Figure 4.39 shows the current along the cable for different lengths. For the case of the only onshore compensation, for different cable lengths, circulates the same current at the same length. On the contrary, with a compensation of 50% of the reactive power at each ends, the minimum current appears in the middle of the cable and the maximum currents at both ends.

This reduction and current distribution pattern along the cable happens for all the cable lengths and all the configurations. The different configurations and the different cable properties only affects on the amount of the generated reactive power, not in this maximum current reduction or in the shape of the current along the cable.

The management of the reactive power through the cable is determinant for long distances, because without the proper reactive power compensation, the cable may not be capable to transmit the required energy.

For example, the scenario with 150MW-150kV (using the cable “B” of Table 4.4) has a rated current of 1088A. But, as can be seen in Figure 4.39, for cable lengths longer than 150Km the required total current is bigger. Therefore, if a reactive power compensation at both ends is not performed, the cable cannot be capable to transmit the required active current.

4.3.2.2 Reactive power compensation: fixed or variable

Before to perform the analysis about the compensation characteristic fixed or variable, it is important to know how is generated the reactive power in the cable in more detail.

In addition to the capacitive component; the cable also has an inductive component. So, the reactive power generated in the cable is not constant at a specific voltage, depends on the transmitted power.

The capacitive reactive power generated in a specific cable (specific capacitive component) is determined by the applied voltage; due to this component is a “shunt” impedance. However, the inductive reactive power generated by the cable depends on the amount of active current flowing through the cable (transmitted active power), Figure 4.35. As a consequence, the amount of the reactive power generated by the cable varies.

$$Q_C = \frac{|V_C|^2}{|X_C|} \quad (98)$$

$$Q_L = |I_L|^2 \cdot |X_L| \quad (99)$$

Where: Q_C is the capacitive reactive power per phase, $|V_C|$ is the module of the voltage applied to the capacitive component, Q_L is the inductive reactive power per phase, $|I_L|$ is the module of the current through the inductive component, $|X_L|$ is the module of the inductive impedance and $|X_C|$ is the module of the capacitive impedance.

The philosophy of the reactive power management is the minimization of the total current flowing through the cable by reducing the reactive current flowing through the cable as much as possible.

Thus, to reduce to the minimum the reactive current flowing through the cable by the injection of the inductive current at both ends, it is necessary to inject exactly the half of the capacitive reactive current generated by the cable.

Therefore, because of the variation in the reactive current generated by the cable, the half of this reactive current needed for the optimum reactive power management varies too. This variation at each end is exactly the half of the total variation of the cable.

However, considering the total capacitive reactive current generated by the cable, this variation is quite little. So, the use of big inductances to perform the reactive power compensation is an economic option.

Regarding to the characteristics of those inductances, their inductivity depends on the reactive power generated by the submarine cable: The capacitive reactive power (equation (98)) minus the inductive reactive power (equation (99)), this last one, depending on the transmitted active power. So, the inductivity of those inductances has to be adjusted for a specific transmitted active power.

The best option, the option which reduces to the minimum the required maximum current of the cable, can be achieved adjusting the inductivity for the worst case. The case when the line is transmitting the rated active power. When the cable is transmitting the rated power, the maximum active current is flowing through the cable, so, if the reactive current flowing through the cable is optimized (reduced to the minimum) for this case, the required rated current of the cables is reduced.

The expression of the generated inductive reactive current / power at these inductances is shown in equations (100) and (101).

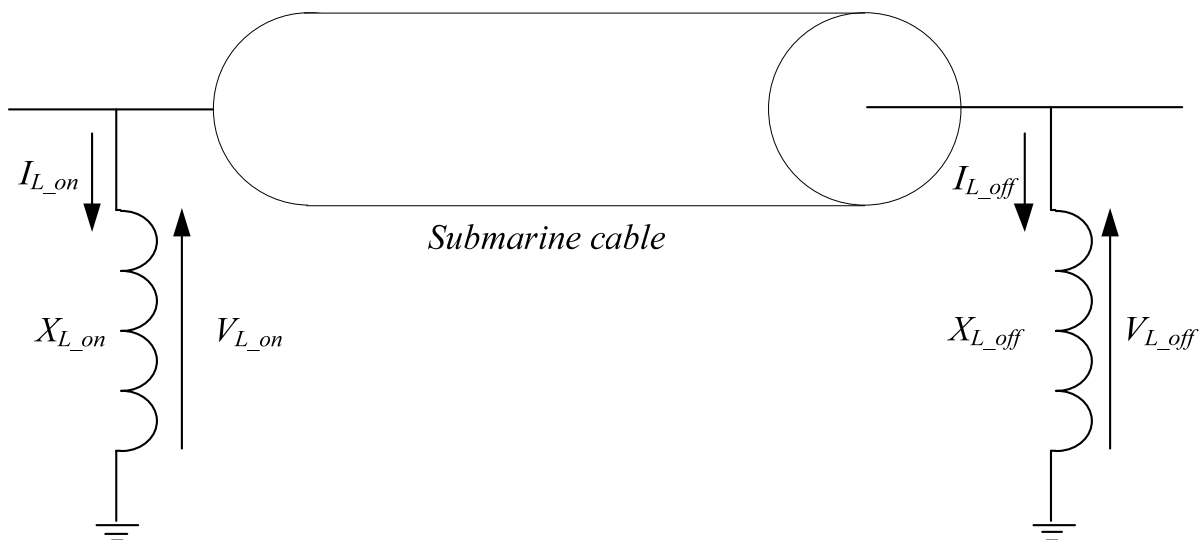


Figure 4.40 Graphic representation of a submarine cable (mono-phase) with inductances at both ends.

$$Q_{Lcomp_on} = \frac{|V_{L_on}|^2}{|X_{L_on}|} = \frac{|V_{L_on}|^2}{\omega \cdot L_on} \quad (100)$$

$$L_on = \frac{|V_{L_on}|^2}{\omega \cdot Q_{Lcomp_on}} \quad (101)$$

Where: Q_{Lcomp} is the module of the inductive reactive power and $|V_L|$ is the module of the applied voltage in the inductance.

4.3.3 Comparative of different types of reactive power compensation for a specific scenario in PSCAD

Any change in the power characteristics at the onshore substation, affects only to the circuit which is after this point, i.e. any change in the power factor at this point (PCC), only affects to the characteristics of the power injected in the main grid.

Nevertheless, controlling the power factor at the collector point of the offshore wind farm (the offshore end of the transmission cable), it is possible to control the active and reactive current relation through the transmission line. Due to the fact that this point is the energy “emitter” point. Thus, to carry out the management of the reactive power flowing through the transmission line, the main point to control the reactive power is the collector point.

Therefore, to perform the management of the reactive power flowing through the transmission line, there are three different options:

- Option 1: Without a reactive power management through the cable. The energy is generated with a unitary power factor in the wind farm, i.e. P.F. ≈ 1 in the “emitter” end of the cable and then transmitted through the submarine cables to the onshore substation. At this point, the reactive power generated in the cable is compensated to integrate the energy into the main grid.
- Option 2: With a rough reactive power management. The inductive reactive power is injected at both ends, but via inductances, always the same quantity for the same voltage.
- Option 3: With an adjusted reactive power management. The inductive reactive power is adjusted dynamically to obtain the same current module at both ends, i.e. the reactive power is injected depending on transmitted active power.

In the present section, a comparative of these three different options is carried out. For this purpose, a scenario using the cable model validated in the previous section is developed. This scenario has a 150 MW rated power, with a transmission voltage of 150 kV and 50 Km submarine cable length.

The objective is to obtain the main parameters of the transmission system upon this scenario for each one of those three management options. The parameters taken into account are: Active power losses, the reactive power generated in the transmission system and the voltage drop.

The analysis is focused exclusively in the transmission line and in the steady state, so, the wind farm is considered as a controlled P,Q source (see Figure 4.41).

The reactive power generated by the submarine cables varies with the amount of the transmitted active power, thus, a range of the transmitted active power is defined. This range is calculated, considering that the wind turbines generate energy with wind speeds between 3.5-30m/s. If the wind farm has 30 wind turbines of 5 MW, depending on the equation (102) explained in section 2.2.3, the range of the generated active power of a wind farm is approximately 5MW to 150 MW.

$$P_t(v) = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot V_{wind}^3 \cdot C_p \quad (102)$$

Where: $P_t(v)$ is the output power depending on the wind in Watts, ρ is the density of air (1.225 measured in kg/m^3 at average atmospheric pressure at sea level at 15°C), r = the radius of the rotor measured in meters (63m), V_{wind} = the velocity of the wind measured in m/s and C_p = the power coefficient (0.44).

4.3.3.1 Option 1: Without reactive power management
(reactive power compensation at one end)

In this first case, the first of the three considered reactive power management options is analyzed. To this end, the scenario illustrated in Figure 4.41 is simulated.

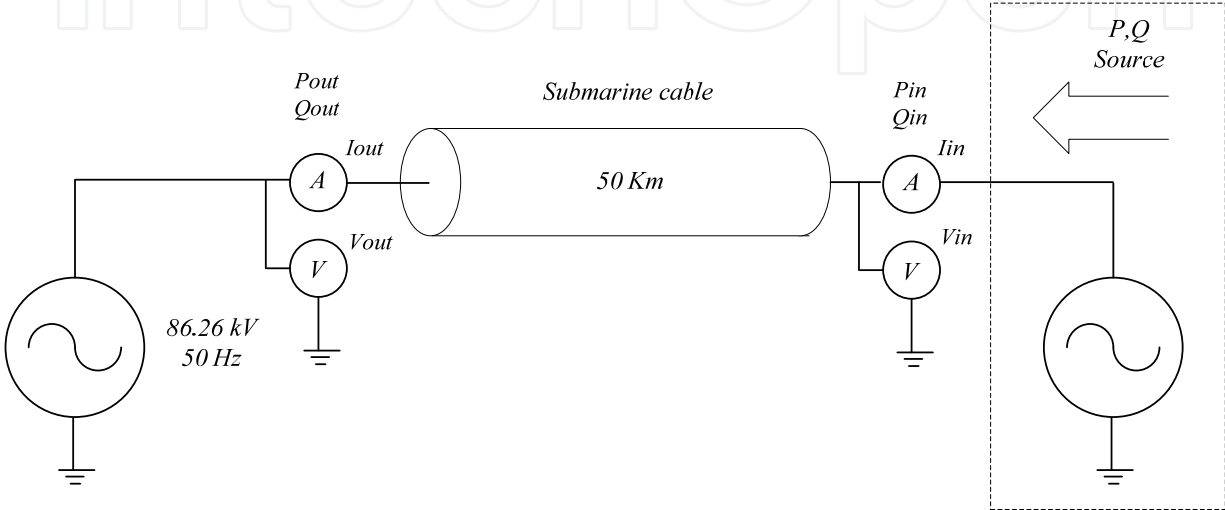


Figure 4.41 Diagram of the first simulation scenario, submarine cable without reactive power management.

In Table 4.6, the simulation results of the transmission system depicted in Figure 4.41 are summarized. These results are obtained in the active power range of the offshore wind farm (5-150MW).

P_{in} MW (FP=1)	Generated Q ($Q_{out}-Q_{in}$)	P losses ($P_{in}-P_{out}$)	ΔV (kV) ($V_{out}-V_{in}$)	I_{in}	I_{out}
5	83.07 MVAR	0.237 MW	1.22	21 A	318 A
15	83.07 MVAR	0.251 MW	1.31	58 A	323 A
25	83.05 MVAR	0.284 MW	1.425	99 A	333 A
40	82.9 MVAR	0.344 MW	1.5	153 A	357 A
60	82.55 MVAR	0.488 MW	1.7	234 A	392 A
80	82.01 MVAR	0.683 MW	1.87	312 A	440 A
100	81.32 MVAR	0.915 MW	2.03	385 A	495 A
120	80.4 MVAR	1.22 MW	2.18	459 A	555 A
150	78.75 MVAR	1.76 MW	2.38	575 A	648 A

Table 4.6 Simulation results for the first scenario. Reactive power generated in the cable, active power losses and voltage drop.

As can be seen in Table 4.6, the capacitive reactive power generated in the transmission line is about 83 MVAR. This value is in concordance with the estimation in a simply way of the equation (103) explained in section 4.3.2.2.

$$Q_C = 3 \cdot \frac{|V_C|^2}{|X_C|} = \frac{86.6^2}{273.22} = 82.3\text{MVAR} \tag{103}$$

Where: Q_C is the capacitive reactive power for the three phases, $|V_C|$ is the module of the applied voltage to the capacitive component and $|X_C|$ is the module of the capacitive impedance.

4.3.3.2 Option 2: Transmission system with fixed reactive power compensation (at both ends)

In the second case, the management of the reactive power flowing through the transmission line is made via inductive impedances at both ends of the line, (Figure 4.42). The value of the inductance is calculated to compensate exactly the reactive power generated in the cable when this is carrying the rated active power, equations (100) and (101).

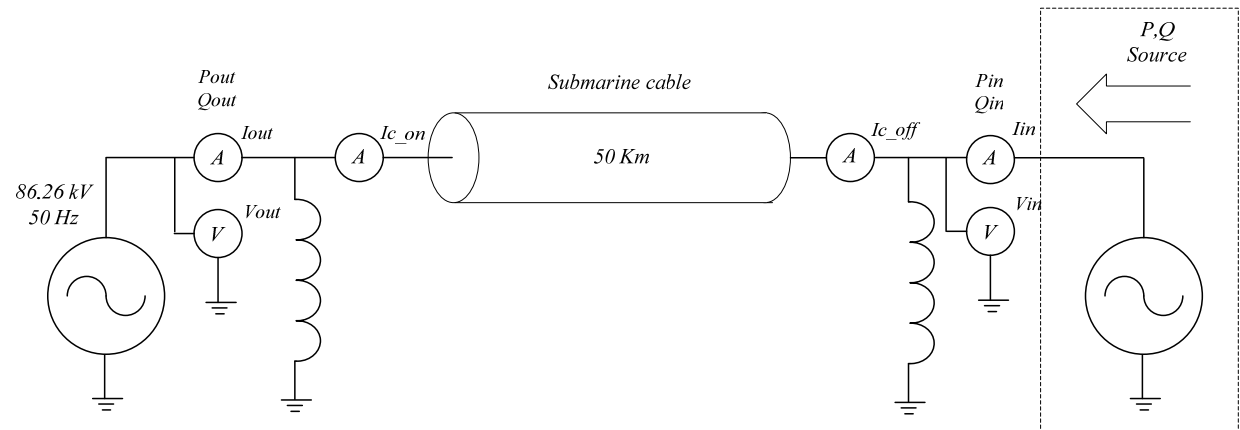


Figure 4.42 Diagram of the second simulation scenario, submarine cable with fixed inductances at both ends.

The results, obtained by the simulation of the defined scenario with the second option for the reactive power management, are depicted in Table 4.7.

Comparing the results in Table 4.6 with the results on Table 4.7, can be seen how the reactive power management reduces significantly the voltage drop in the line. In the same way, with this kind of reactive power management, the active power losses have an important decrement. Especially, in cases when the transmitted active power through the line is less than the 50% of the rated power.

In the considered range of the active power generated for the offshore wind farm (5-150MW), the variation of the reactive power generated in the line is about 4.8 MVAR, i.e. the submarine cables in combination with the inductances have a 4.8 MVAR variation. This value is significantly low in comparison with the reactive power generated in the submarine cables 83 MVAR, approximately the 5%.

<i>P_{in}</i> <i>MW</i> (<i>FP=1</i>)	Generated <i>Q</i> (<i>Q_{out}-Q_{in}</i>)	<i>P</i> losses (<i>P_{in}-P_{out}</i>)	ΔV (kV) (<i>V_{out}-V_{in}</i>)	<i>I_{lin}</i>	<i>I_{c_off}</i>	<i>I_{c_on}</i>	<i>I_{out}</i>
5	4.92 MVAR	0.12 MW	0.106	17 A	151 A	171 A	26 A
15	4.88 MVAR	0.13 MW	0.19	55 A	162 A	174 A	60 A
25	4.8 MVAR	0.16 MW	0.27	95 A	178 A	193 A	99 A
40	4.58 MVAR	0.22 MW	0.41	151 A	217 A	230 A	153 A
60	4.12 MVAR	0.365 MW	0.596	234 A	274 A	280 A	238 A
80	3.46 MVAR	0.56 MW	0.75	310 A	342 A	351 A	314 A
100	2.67 MVAR	0.79 MW	0.89	380 A	411 A	416 A	382 A
120	1.66 MVAR	1.1 MW	1.03	458 A	482 A	485 A	460 A
150	0.16 MVAR	1.65 MW	1.24	572 A	590 A	591 A	572 A

Table 4.7 Simulation results for the second scenario. Reactive power generated in the transmission system (cable + inductances), active power losses and voltage drop.

This value, the reactive power variation of the cables depending on the transmitted power, is in concordance with the estimation in a simply way of the equation (104) explained in section 4.3.2.2.

$$Q_L = 3 \cdot I_L^2 \cdot |X_L| = 3 \cdot 577^2 \cdot 5.246 = 5.23 MVAR$$

(104)

$$I_L = \frac{P}{3 \cdot V_{\phi n}} = \frac{150 MW}{3 \cdot 86.6 kV} = 577 A$$

(105)

Where: Q_L is the inductive reactive power for the three phases, $|I_L|$ is the module of the current through the inductive component, $|X_L|$ is the module of the inductive impedance, P is the transmitted power through the transmission line and $V_{\phi n}$ is the rated voltage per phase of the transmission system.

4.3.3.3 Option 3: Transmission system with variable reactive power compensation (at both ends)

In the third and last case, to achieve the optimum reactive power management, the inductive reactive current is injected at both ends of the cable depending on the transmitted amount of the active power.

As is estimated in the case before, the variation of the reactive power generated in the line (cable + inductances) is about the 5%. So, in this third case, the effect of this variation in the transmission system parameters is analyzed. For this purpose, the simulation of the scenario shows in Figure 4.43 is carried out.

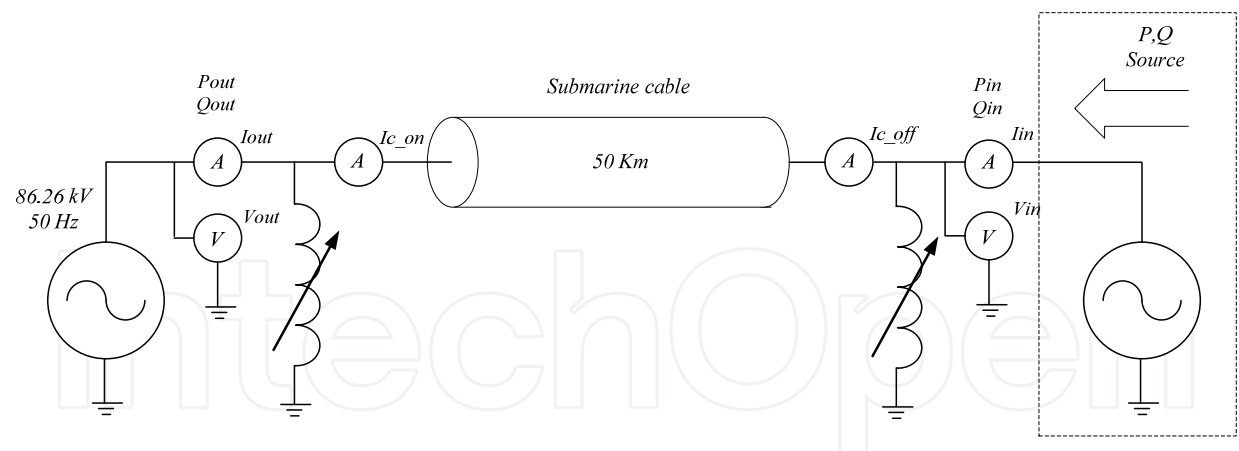


Figure 4.43 Diagram of the third simulation scenario, submarine cable with the injection of the inductive reactive power at both ends depending on the requirements.

The simulation results of the defined scenario (Figure 4.43), for the considered active power range of the offshore wind farm (5-150MW) are summarized in Table 4.8. Notice that in the results of Table 4.8, there are not shown the results of the reactive power generated in the transmission line, because the reactive power of the cable is totally compensated at both ends.

<i>P_{in}</i> MW (FP=1)	<i>P</i> losses (<i>P_{in}</i> - <i>P_{out}</i>)	ΔV (kV) (<i>V_{out}</i> - <i>V_{in}</i>)	<i>I_{in}</i> = <i>I_{out}</i>	<i>I_{c_on}</i> = <i>I_{c_off}</i>
5	0.118 MW	0.035	17 A	160 A
15	0.13 MW	0.12	55 A	167 A
25	0.16 MW	0.2	95 A	185 A
40	0.22 MW	0.345	151 A	223 A
60	0.36 MW	0.536	234 A	277 A
80	0.56 MW	0.7	310 A	347 A
100	0.79 MW	0.855	380 A	413 A
120	1.1 MW	1.01	458 A	483 A
150	1.65 MW	1.24	572 A	590 A

Table 4.8 Simulation results for the second scenario. Active power losses and voltage drop.

Comparing the results on Table 4.8, with the results on Table 4.7, it can be seen how the active power losses have not a significantly reduction. With regards to the voltage drop, this has a little reduction only in cases when the transmitted active power through the line is less than the 50% of the rated power.

The fixed inductances at both ends of the cable are fit to achieve the optimum reactive power management with rated active power. So, in cases when the transmitted active power is close to the rated power, with both ways: with fixed inductances and with variable injection of the reactive power, similar results are obtained.

4.3.3.4The effect of the cable length

The reactive power generated in the submarine cables depends on the cable length (Table 4.5), thus, as the length affects to the amount of reactive power to compensate, this aspect has to be analyzed.

In this way, with the increase of the reactive current through the line, the current limit of the cable (1088A in the present case, Table 4.4) has to be taken into account. If the required active current to transmit the rated power of the wind farm is close to the rated current of the cable or the transmission cable is too long, it is possible that without the proper compensation, the cable would not be capable to transmit the required power.

In Table 4.9, the results of the three types of reactive power management (explained in the previous sections) for two cable lengths 50 Km and 150Km are summarized.

<i>Transmitted active power</i> MW (P.F.=1)		<i>50 Km cable length</i>			
		ΔQ (MVAR)	ΔP (MW)	ΔV (kV)	I_{max} (A)
5 MW	<i>Option 1</i>	83.07	0.237	1.22	318
	<i>Option 2</i>	4.92	0.12	0.106	169
	<i>Option 3</i>	-	0.118	0.035	160
150 MW	<i>Option 1</i>	78.75	1.76	2.38	648
	<i>Option 2</i>	-	1.65	1.24	592
	<i>Option 3</i>	-	1.65	1.24	592
		<i>150 Km cable length</i>			
		ΔQ (MVAR)	ΔP (MW)	ΔV (kV)	I_{max} (A)
5 MW	<i>Option 1</i>	262.4	4.73	11.47	1012
	<i>Option 2</i>	11.9	1.05	0.61	504
	<i>Option 3</i>	-	1	0.075	482
150 MW	<i>Option 1</i>	256.9	8.4	14.6	1130
	<i>Option 2</i>	-	5.1	3.4	728
	<i>Option 3</i>	-	5.1	3.4	728

Table 4.9 Simulation results for different kind of reactive power management, for two cable lengths 50Km and 150Km.

Notice that without the proper reactive power management, it is impossible to transmit the rated power with the selected cable to 150Km away, because the required current for that purpose is higher than the current limit of the cable.

For cases with a submarine cables of 150Km or longer, providing the transmission system with reactive power management, it is possible to see a higher reduction in the voltage drop and active power losses. Making clear that, the more is the reactive power generated in the cable, the more important is a correct reactive power management.

4.4 Chapter conclusions

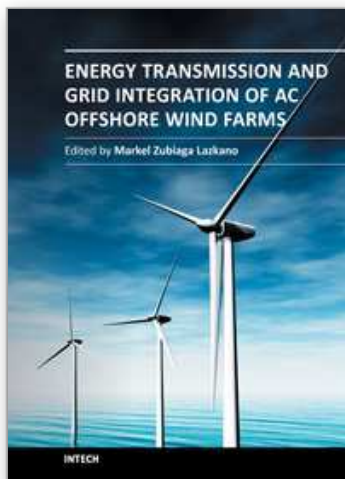
In this chapter, the main characteristics of the submarine cables are analyzed, such as: their physical structure, the way to represent them electrically or different ways to model it, from the most simply to more complex models. Then, based on a validated cable model several electric aspects of the transmission lines are evaluated.

In this way, from the analysis carried out in this chapter is clear that the transmission of the 150 MW at 150kV to 50Km away is perfectly possible. At least if it is performed with the cable considered in this chapter. Using this cable, the voltage drop of the transmission line is less than 5% and the active power losses are not too high. In the same way, the current limit of the cable is enough to carry the rated active power at any circumstance. So, this scenario is perfectly valid and feasible.

The reactive power management of the submarine cable reduces significantly the active power losses and the voltage drop. This reduction is more obvious, in cases where the transmitted active power is less than the 50% and for long submarine cables (big amount of generated reactive power), i.e. this reduction is more obvious, in cases when the reactive current is high in relation to the active current.

The reactive power management, based on fixed inductances at both ends of the line has similar improvements in comparison with the variable compensation at both ends. Moreover, if those inductances are adjusted for the worst case, using fixed inductances, the maximum voltage drop, the maximum active power losses and the required maximum current for the cable are exactly the same. So, this option is simply and enough for a good reactive power management.

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Edited by MSc Markel Zubiaga

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This book analyses the key issues of the offshore wind farm's energy transmission and grid integration infrastructure. But, for this purpose, there are not evaluated all the electric configurations. In the present book is deeply evaluated a representative case. This representative case is built starting from three generic characteristics of an offshore wind farm: the rated power, the distance to shore and the average wind speed of the location. Thus, after a brief description of concepts related to wind power and several subsea cable modeling options, an offshore wind farm is modeled and its parameters defined to use as a base case. Upon this base case, several analyses of the key aspects of the connection infrastructure are performed. The first aspect to analyze is the management of the reactive power flowing through the submarine cable. Then, the undesired harmonic amplifications in the offshore wind farms due to the resonances and after this, transient over-voltage problems in the electric infrastructure are characterized. Finally, an offshore wind farm connection infrastructure is proposed in order to achieve the grid code requirements for a specific system operator, but not as a close solution, as a result of a methodology based on analyses and simulations to define the most suitable layout depending on the size and location of each offshore wind farm.

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