

École polytechnique de Louvain

Conducted disturbances propagation between 2 and 150 kHz in the low voltage distribution network

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Introduction

The low voltage distribution network has evolved these last decades due to two main factors. Firstly, technologies which use increasing more power electronics have been developed. Secondly, energy saving and renewable energy devices are emerging. Power electronics allow to achieve a better efficiency by working at high frequencies and renewable energy needs power electronics converters to transmit energy to the grid. These technologies often work at the frequency range between 2 and 150 kHz and send conducted disturbances (CD) to the grid.

On the other hand, with the arrival of renewable energies, the grid has to be managed differently with the aid of communication systems. Communication may be wireless, or via fixed wired connections such as powerline communication (PLC) which uses the low voltage distribution network as a path of communication.

The signals sent by power electronics and communication systems can cause undesirable effects to devices connected to the grid. Moreover, these disturbances can weaken or even disrupt the communication of intentional signals. Furthermore, power electronics filters may attenuate intentional communication signals because they are a low impedance path for high frequency signals.

The undesirable effects of disturbances are amplified by the lack of standardisation at the frequency range of 2 and 150 kHz. Power electronics are designed to satisfy power quality standards below 2 kHz and electromagnetic compatibility above 150 kHz. Naturally, they work in between these frequencies. With the increasing number of power electronics, emissions at this frequency range are becoming an issue.

From the perspective of proposing more standardisation between 2 and 150 kHz, several researches have to be conducted. The goal of this master thesis is to attain a better understanding on how the signals sent by power electronics propagate through the grid. Particularly, the resonance phenomena through the grid is studied in-depth in order to understand if resonance can lead to issues in terms of disturbance voltage magnitude.

This work is organised in six chapters.

The first one gives an overview of CD issues between 2 and 150 kHz. It explains the smart grid principle and how it communicates through the low voltage distribution network. Then, it lists sources, victims and undesirable effects of CD. Afterwards, standardisation basis are given followed by actual existing standards. Eventually, the objectives of this work are defined.

The goal of this work is to study the propagation of the CD through the grid. Therefore, the second chapter elaborates a model for low voltage distribution cables. At the end, it provides a three-phase cable model and a single-phase equivalent cable model which will be used in the next chapters.

By using the models developed in the previous chapter, the third chapter studies low voltage cable frequency behaviour. This enables better understanding of resonance phenomena and the influence of the skin effect (increase of the resistance value with the frequency).

Chapter four explains the working principle of the main CD sources and provides a simple model for them. Since a filter is always connected between power electronics and the grid, its design is developed. At the end, a CD model with its filter is usable.

Then, chapter five presents a method to study the propagation of CD using the symmetrical components previously developed in the second chapter.

Finally, the last chapter uses the method of chapter five to simulate the propagation of CD when one CD source is connected to the grid. The CD source model used for simulations is provided in the fourth chapter. The results of the third chapter will be used to better understand the CD propagation outcomes from simulations.

Context

In the past, the electrical grid was only used to transport electricity from the producer to the consumer. Nowadays, in the context of global warming, the need for renewable energy is growing. They are increasingly emerging on the grid with PV panels at the consumer scale or wind turbine in the medium voltage. In this context, the consumer can also be the producer which involves a change in the power flow direction.

The grid operator must keep the balance on the grid between the produced energy and the consumed energy. If there is a great unbalance, incidents such as power failure or blackouts can occur. With the emergence of renewable energy, keeping this balance is more difficult, particularly since the energy produced by the renewable energy is time variable.

In this context, the smart grid using the LV distribution network or wireless to communicate is a solution to manage the grid more efficiently and safely. Unfortunately, the grid is increasingly polluted with signals in the frequency range used by smart meter PLC. This causes interference and can lead to a loss of communication. Moreover, the interference in the LV grid can have several consequences in addition to disrupt smart meters communication.

In this chapter, smart grid and smart meters are first developed. Then, the victims and the sources of CD are listed as well as some of the undesirable effects. Afterwards, basis for the standardisation is provided and the existing standards between 2 and 150 kHz are given. Finally, the objectives of this master thesis in the context of CD in this frequency range are given.

1.1 Electromagnetic interference

One term is widely used in this work: **conducted disturbances** (CD). Before going further in the conducted disturbances topic, this term must be defined. Electromagnetic interference (EMI) is explained first and then CD are developed.

EMI is caused by one electrical or electronic device to another by the electromagnetic fields set up by its operation [1]. It is an unwanted signal at the signal receiver. There are three types of EMI [2] (represented in Figure 1.1). The first one is the radiated one. It occurs when a signal propagates into space as electromagnetic radiation. Indeed, every conductor is an antenna that is capable of both transmitting and receiving signals. The second type of EMI is the conducted one. It concerns

interference that travels through a conductive path instead of the air. The last type is the coupled EMI. It can be a capacitive or magnetic coupling.

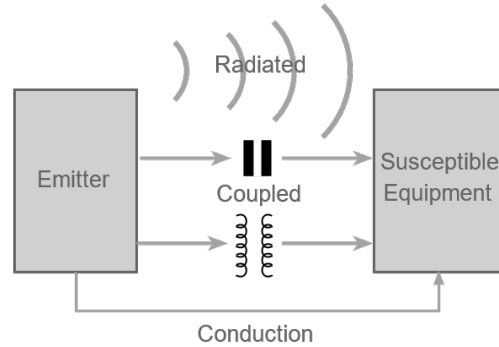


Figure 1.1: Types of EMI [1]

In this work, only the conducted EMI is considered. Indeed, radiated EMI occurs above 30 MHz and conducted EMI occurs between 9 kHz and 30 MHz according to [3]. Moreover, the communication path of the PLC is the grid which is a conductive one. In addition, communication takes place between 3 and 148.5 kHz. Therefore, only the conducted disturbances are involved since they flow through the grid between 2 and 150 kHz.

1.2 Smart grid

Conventionally, the grid is fitted with sensors which transmit data to the grid operator who manages the energy flow remotely. The smart grid consists of using digital technology that allows two-way communication between the utility and its customers to control and responds quickly to changes in the electric demand[4]. The technology allowing this communication is the smart meter. It is able to turn on consumers' home appliance in order to use them when the electricity production is high and the prices are low.

There are four features attributed to the smart grid. Firstly, its flexibility makes managing the variation in electricity generation and consumption easier. Then, it sends information in real time which makes the grid more reliable since it reduces failure and incident risks. Furthermore, it enables integration of the renewable energy into the grid. Eventually, better management of energy reduces the costs and allows money saving[5].

1.2.1 Smart metering

Smart metering is key in smart grid communication. It records the electrical power used and the quantities consumed in its memory at different times of day depending on the defined protocol. This information is sent to the grid operator. The difference with the electronic meter is that the smart meter allows two-way communication, while the electronic meter only sends information from the consumer to the grid operator [6]. Communications from the meter to the network may be wireless,

or via fixed wired connections such as PLC[7].

To have an idea how this technology is spread, 32M meters were installed in Italy and 0.6M in Sweden in 2014[8].

There are some obstacles to the smart metering development. First of all, it has a cost and its installation is mainly a political decision. Then, to allow a good communication, the meters must be widely spread. Indeed, each one amplifies the signals of the others. If there are not enough smart meters in an area, the communication is not possible because the signal is too attenuated. Eventually, the bandwidth of 3 to 148.5 kHz can suffer from CD which can inhibit the communication.

The PLC needs a certain signal level to assure its functioning. They are shown in Figure 1.2 in function of the frame error rate (FER). The different signal levels explanation are listed below beginning from the top to the bottom of the power level.

- The maximum PLC signal level corresponds to the maximum output level of the transmitter
- The minimum PLC signal level without errors is the minimum level required by the receiver such as no communication errors occur for a given noise level ($0\% < \text{FER} < 5\%$)
- PLC link breaking level is reached when no communication is possible for a given noise ($\text{FER}=100\%$)
- The noise level is the noise measured at the receiver

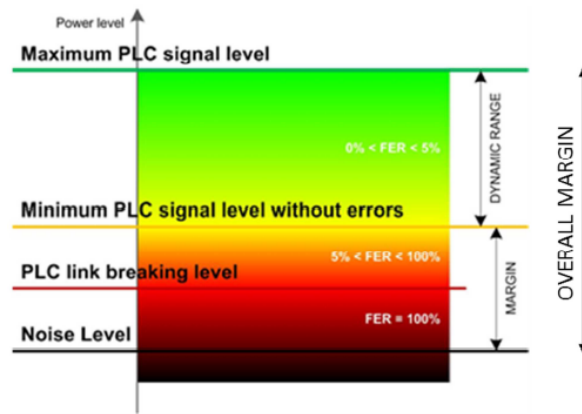


Figure 1.2: Signal levels for proper PLC functioning

1.3 Sources and victims of conducted disturbances

The smart grid was previously developed to introduce the issue of CD between 2 and 150 kHz. However, it is not the only device which uses this frequency range. More generally, there are several victims and sources of CD between 2 and 150 kHz. In this section, the main groups of CD effects are presented. Then, the sources and the victims of CD are listed. Eventually, the consequences caused by these CD on their victims are given.

1.3.1 Conducted disturbances effect groups

The effects of CD are gathered in four different groups. In this section, the mains communication systems (MCS) are used to characterise communication systems such as PLC. These effect groups are listed below [8].

- Non-intentional emissions from network users' equipment interfering with the MCS signals leading to disturbances, loss or failure of the communication.
- Distortion of the supply voltage due to non-intentional emissions from network users' equipment or from the MCS signals which leads to degraded performance or maloperation of network users' equipment.
- Network users' equipment representing a low-impedance path at frequencies used for MCS lead to an attenuation of the intentional MCS signal which might disturb or interrupt the communication.
- Non-intentional (network users' equipment) or intentional (MCS) emissions may result in somehow higher current, leading to overheating and accelerating ageing of components in network users' equipment.

1.3.2 Conducted disturbances sources

Some examples of CD sources are listed below [8]. One can observe the PLC is a source of disturbances even if their emissions are intentional.

- Inverter (photovoltaic, drives for elevator, ...) and variable speed drive (heating system circulation pumps, ventilation,...)
- Switched-mode power supplies (charging devices for electric vehicles, ...)
- Lighting equipment (CFL, LED lighting equipment, ...)
- Household equipment (induction cookers, washing machines, ...)
- Active filter
- Portable mains operated tools
- Automated Meter Reading system using PLC (AMR-PLC)

1.3.3 Conducted disturbances victims

Some of the equipment victims are listed below.

- AMR-PLC (victim and source at the same time)
- Solid state meters
- Electronic control (touch dimmer lamp (TDL), alarm systems, traffic control systems, traffic lights,...)
- Communication systems (Ethernet-systems, routers, ADSL-modems, ...)
- Earth leakage circuit breaker
- Contactless magnetic card reader
- TV and radio receiver

1.3.4 Conducted disturbances consequences on equipment in the frequency range between 2 and 150 kHz

There are several consequences due to the CD in the frequency range from 2 to 150 kHz which have been identified. Just a few are cited here, others part shown in Annex A.

CD can cause unintentional switch-on and -off of street lighting, malfunctioning of traffic lights, unintentional switching between light step of a TDL, audible noise in induction cookers, loss of PLC communication and so on.

These effects are very disruptive and can not be ignored. Therefore, lots of studies and research have been done in this context. A solution to limit the effects of the CD is setting stricter standards. Standard definition and actual standardisation existing between 2 and 150 kHz are provided in Section 1.4.

1.4 Standardisation

1.4.1 Definition

Standards are voluntary agreements, made by stakeholders concerning a product, a service or a process. They are part of the knowledge economy that underpins European industry and society. They facilitate innovation, promote the adoption of new technologies and facilitate cross-border trade. Also, *standards can be used to improve safety and performance, raise levels of energy efficiency, and protect consumers, workers and the environment.*

Standards are developed on the global, European and national level. On the European level, standards are developed by so-called technical committees, which are facilitated by the European Standards Organisations (ESOs) CEN and CENELEC and their national member bodies. Standards are drafted by experts, representing all types of stakeholders. The standardisation process is

characterized by its transparency, consensus-based decision making and the fact that all interest parties can join the process[9].

1.4.2 Electromagnetic compatibility

Electromagnetic compatibility (EMC) is the key for setting standards in the frequency range between 2 and 150 kHz. Therefore, the bases are explained before going further with standards.

According to [10], EMC is the ability of equipment or a system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

EMC covers different terms which set different limits to avoid disturbances. These limits are depicted in Figure 1.3. Each term on this figure are defined beginning from the bottom to the top of the disturbance level (definitions taken from from [10]).

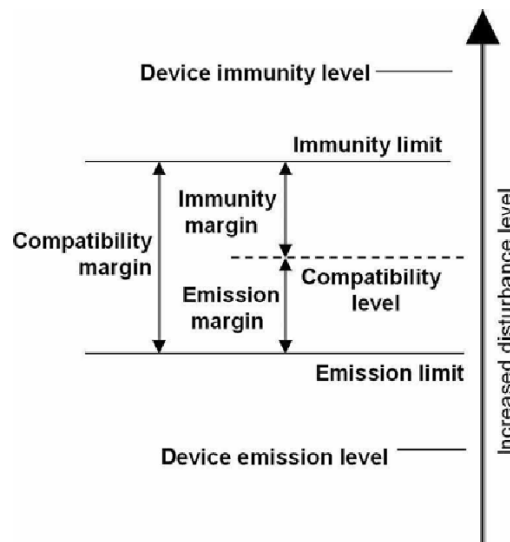


Figure 1.3: Various levels, limits, and margins used in EMC standards [11]

The **emission level** of a device (or a disturbing source) is the level of a given electromagnetic disturbance emitted from a particular device, equipment or system. The **emission limit** from a disturbing source is the specified maximum emission level of a source of electromagnetic disturbance.

The **immunity level** is the maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance. The **immunity limit** is the specified minimum immunity level. The **compatibility level** is the specified electromagnetic disturbance level used as a reference level for co-ordination in the setting of emission and immunity limits.

By convention, the compatibility level is chosen so that there is only a small probability that it will be exceeded by the actual disturbance level. However electromagnetic compatibility is achieved only if emission and immunity levels are controlled such that, at each location, the disturbance level

resulting from the cumulative emissions is lower than the immunity level for each device, equipment and system situated at this same location.

The **emission margin** is the ratio of the electromagnetic compatibility level to the emission limit. The **immunity margin** is the ratio of the immunity limit to the electromagnetic compatibility level. Finally, the **compatibility margin** is the ratio of the immunity limit to the emission limit.

1.4.3 Compatibility limit

In the frequency range between 2 and 150 kHz, only one standard proposes compatibility level. This standard is provided by the International Electrotechnical Commission (IEC).

As mentioned in Section 1.4.2, compatibility level specifies disturbance level as a reference level for co-ordination in the setting of emission and immunity limits. Therefore, one can consider this standard as a first step towards in-depth standardisation between 2 and 150 kHz.

The compatibility level set by standard IEC 61000-2-2, between 2 and 9 kHz is expressed in percentage of the fundamental and is based on the RMS value. Between 9 and 150 kHz, the compatibility level is expressed in dB μ V and is expressed in quasi-peak value. These compatibility limits are depicted in Figure 1.4.

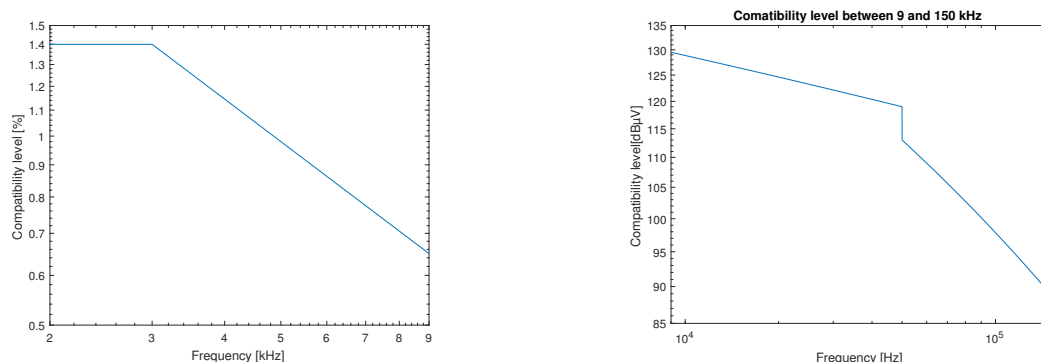


Figure 1.4: Compatibility level between 2 and 150 kHz according to IEC 61000-2-2 1.4

1.4.4 Voltage characteristics

Voltage characteristics are quasi-guaranteed limits covering the LV and MV grid. These limits are equal or a bit above the compatibility levels. Its evaluation is based on a temporal statistic. For a week, 95 % of the RMS value on 10 minutes time span must be below the limit [12].

These characteristics are provided by EN50160 between 100 Hz and 100 kHz. They are depicted in Figure 1.5

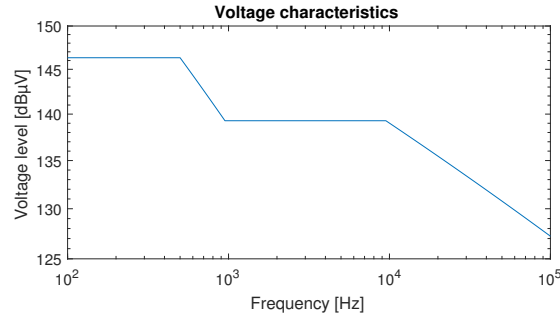


Figure 1.5: Voltage characteristics provided by EN50160 [13]

1.4.5 Emission limit

The emission limit from a disturbing source is the specified maximum emission level of a source of electromagnetic disturbance. In this section, standards which limit intentional and non-intentional emission limits between 2 and 150 kHz are given.

Band limitation

Standard EN 50065 fixes frequency bands between 3 and 148.5 kHz used by main communication systems. This band is separated into 2 bands as shown in Table 1.1. The first one is dedicated to the grid operator, therefore, communication from smart meters takes place in this frequency range. The second band is devoted to consumers and required a specific protocol to be able to use it.

Frequency range in kHz			
[3 95]		[95 148.5]	
Grid operator and license owner		Consumer band	
	[95 125]	[125 140]	[140 148.5]
	Access protocol required		

Table 1.1: Classification of frequency bands between 3 and 148.5 kHz according to [14]

Intentional emission

Intentional emissions are signals used by MCS. The emission limits are fixed by EN50065 between 3 and 148.5 kHz. These limits are presented in Figure 1.6. Between 9 and 95 kHz, standard EN60065 specifies different limits depending on whether the communication is narrowband or broadband. Between 95 and 148.5 kHz, the limit depends on the apparatus class (122 or 134).

Non-intentional emission

CISPR 14 provides emission limits for household appliances, electric tools and similar apparatus. CISPR 15 fixes emission limits for radio disturbance characteristics of electrical lighting and similar

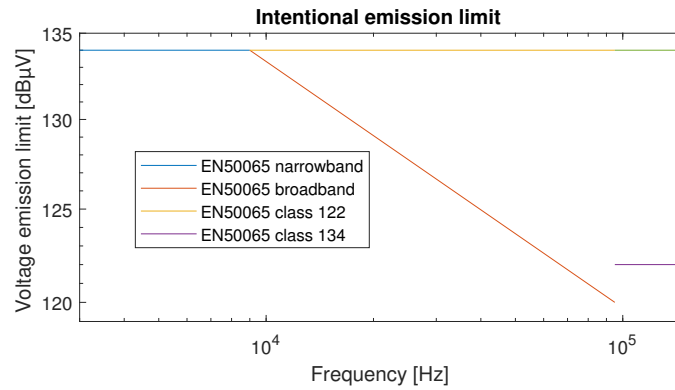


Figure 1.6: Intentional emission limit provided by EN50065 [14]

equipment. EN50065 provides limits for out-of-band communication signals. These limitations are depicted in Figure 1.7.

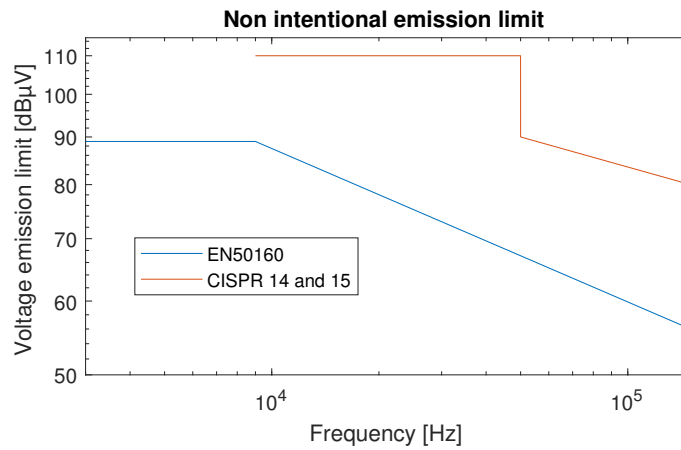


Figure 1.7: Non intentional emission limit fixed by EN50065 [14] and CISPR 14 and 15 [15]

1.4.6 Additional standard information

In addition to compatibility level and emission limit standards, measurement and immunity test level standards exist.

In [16], the author explains that the immunity levels test standards are well defined but immunity limits standards do not exist at this time. However, it has to be noted that at the end of the immunity test levels, the results could be used as a guide in formulating performance criteria for immunity limit standards.

Also from [16], the apparatus emission measurements are well defined but the measurement preconditions raise some open questions since the results differ from one precondition to another. Some work has to be done in this field [15].

In summary, current standards provide compatibility level and emission limits between 2 and 150 kHz. However, the standardisation is not complete, particularly in term of immunity limit.

Furthermore, the measurement preconditions are not well defined and results vary depending on them. In-depth studies have to be conducted to fill the gap of standardisation between 2 and 150 kHz in order to protect equipment from undesirable effects of CD in this frequency range.

1.5 Objectives

In this chapter, the lack of standardisation between 2 and 150 kHz was highlighted. Several works are performed to allow better understanding of CD sources, propagation and their undesirable effects. Particularly, this work will further use the results of [15] which models the CD sources.

Power electronics are always equipped with a filter to satisfy standards above 150 kHz. These filters are low impedance path for signals between 2 and 150 kHz. Moreover, the combination of filters and grid impedance can lead to resonance phenomena. Further research is required to determine if amplification of emission due to resonances in the low-voltage grid is a concern.

The goal of this master thesis is studying CD propagation between 2 and 150 kHz through the low voltage distribution network. Especially, distribution grid models will be developed to simplify the simulations. At the end, these models will be used to simulate a realistic situation with one CD source and to understand how they propagate through the grid.

Low voltage cable modelling

In order to study CD at the frequency range between 2 and 150 kHz, a model for the low voltage distribution grid has to be found. Indeed, since these CD propagate through the grid, its modelling is the key to understand their propagation.

In this chapter, the most common used type of cables are listed. Then, the power line theory is developed. Using this theory, a model for low voltage distribution cables is proposed. The equations to calculate the resistance in function of the frequency are given. After that, the primary parameters of each cable are listed. Then, the positive/negative and zero sequence single-phase equivalent model is presented. Finally, a frequency variable model which fits the skin effect is proposed. This model will not be used in the rest of this work for reasons explained at the end of this chapter.

2.1 Low voltage cable characteristics

We focus on low voltage (LV) Belgian power and connection cables. Power cables transport electricity. They are characterised by a higher cross section and a lower impedance limiting the losses and allowing a higher current flowing through them than the connection cables. Connection cables are smaller cables that are connected between the load (house, PV panels, small wind turbines,...) and the power cable. The connection cables which are smaller have a bigger impedance.

Low voltage cables are separated into two kinds of cable configurations : overhead and underground cables. The two voltages mostly found in low voltage network is $3 \times 230V$ or $3 \times 400V + \text{neutral}$. Table 2.1 depicts the main different cables used in Belgium.

Two conductive materials are used : aluminium and copper. Copper has a smaller linear resistance per unit length than aluminium. However, copper cables have the tendency to be stolen. Furthermore, aluminium is lighter, more flexible and cheaper. For this reason, aluminium cables are becoming more present on the grid.

An explanation of the meaning of each letter constituting the cable notation is given in Annex C.

Cable	Type	Cross section mm^2
Overhead	BAXB power cable	$3 * 95 + 1 * 54.6 + 2 * 16$
	BAXB connection	$4 * 16$
		$4 * 25$
Underground	EAXeVB power cable	$4 * 95$
		$4 * 150$
	EXVB connection	$4 * 16$
		$4 * 25$
		$4 * 35$
	XVB connection	$2 * 1.5$
		$4 * 1.5$
		$3 * 2.5$
		$4 * 2.5$
		$4 * 6$

Table 2.1: Main low voltage cables in Belgium. Source [17]

2.2 Power line theory

Knowing which cables are used in low voltage distribution grid, a model for cables has to be determined in order to study the propagation of CD. A differential line segment of length Δx is presented in Figure 2.1. It shows the phase-to-neutral equivalent representation. This model is the distributed parameters model and its parameters (R' , L' , C' and G') are the primary parameters of the line expressed per unit length.

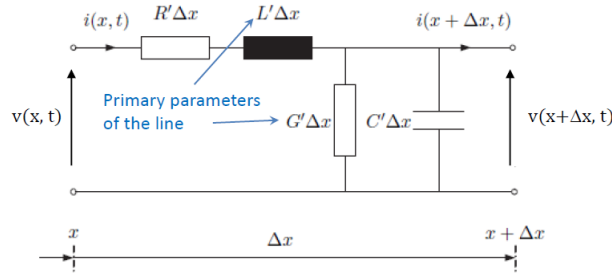


Figure 2.1: Differential line segment [18]

Assuming the sinusoidal steady-state approximation[18], the secondary parameters of the line can be calculated. Taken R' , L' , C' and G' the primary parameters of the line and L the length of the line, the series impedance is given by Equation 2.1 and the line shunt admittance by Equation 2.2, with $\bar{Y}'$ and $\bar{Z}'$ expressed per unit length.

$$\bar{Z} = \bar{Z}'L = R'L + j\omega L'L \quad (2.1)$$

$$\bar{Y} = \bar{Y}'L = G'L + j\omega C'L \quad (2.2)$$

In this work, the conductance G is neglected. The secondary parameters of the line are the characteristic impedance and the propagation exponent, respectively :

$$Z_c = \sqrt{\frac{\bar{Z}}{\bar{Y}}} \quad (2.3)$$

$$\gamma = \sqrt{\bar{Z}\bar{Y}} \quad (2.4)$$

The characteristic impedance of a transmission line is defined as the impedance looking into an infinitely long line. If the line impedance is equal to the characteristic impedance, thus the reflected wave is zero. The propagation exponent represents how the propagation takes place along the line. It gives the voltage after a distance x as in Equation 2.5 [19].

$$V_x = V_i e^{-\gamma x} \quad (2.5)$$

These parameters can be used to calculate the chain matrix of a line. Indeed, this matrix links the parameters of one side of a two-port network to the other side. For example, if we know the voltage and the current on side 2 of Figure 2.2, this matrix can give us the voltage and the current on side 1.

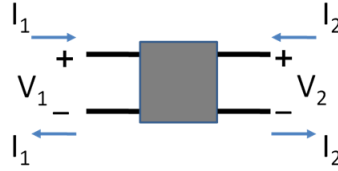


Figure 2.2: Two-port network [20]

Generally and with Figure 2.2 notations, the chain matrix is given by Equation 2.6

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (2.6)$$

Using the secondary parameters of the line, the A , B , C and D matrix components can be calculated. If l is the length of the line, the chain matrix becomes :

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & \bar{Z}_C \sinh \gamma l \\ \bar{Y}_C \sinh \gamma l & \cosh \gamma l \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (2.7)$$

The chain matrix components calculated with the secondary parameters can be used to know

the π lumped parameters. These parameters are depicted in Figure 2.3.

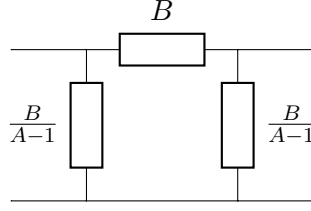


Figure 2.3: Lumped π equivalent circuit with secondary parameters of the line

The lumped parameters model is valid if the short line approximation can be applied. In this case, the CD wavelength must be higher than the cable length. Mathematically, the condition to apply the short line approximation is given in Equation 2.8.

$$\lambda_{CD} > L_{cable} \quad (2.8)$$

In this case, the chain matrix parameters can be written with the primary parameters of the line as done in Equations 2.9 and 2.10.

$$B = \bar{Z}' L \quad (2.9)$$

$$\frac{B}{A-1} = \frac{1}{\frac{\bar{Y}' L}{2}} \quad (2.10)$$

If the wavelength is smaller than the cable length, the long line approximation is more appropriate. Thus, the parameters are distributed through the cable into differential segments. This model is depicted in Figure 2.1.

To choose the appropriate approximation, the wavelength must be calculated with Equation 2.11. v is the wave propagation speed and f is the wave frequency.

$$\lambda = \frac{v}{f} \quad (2.11)$$

If c is the light speed ($c = 3 \cdot 10^8 [\frac{m}{s}]$), ϵ_r the relative permittivity of insulation material and μ_r the relative permeability of the conductor, the propagation speed is given by Equation 2.12 [21]. The wavelength is eventually computed with Equation 2.13.

$$v = \frac{c}{\sqrt{\mu_r \epsilon_r}} \quad (2.12)$$

$$\lambda = \frac{c}{f \sqrt{\epsilon_r \mu_r}} \quad (2.13)$$

The cables we are working with are made of XLPE insulator, with a relative permittivity of $\epsilon_r = 2.25$. The conductors are copper or aluminium made, thus their permeability are almost equal to one, i.e. $\mu_r \simeq 1$.

Since CD in the frequency range between 2 and 150 kHz are studied, the wavelengths associated to these frequencies are standing between 1.33 km and 100 km. In low voltage distribution grid, the cable length are not longer than 1 km, otherwise the voltage drop through them is too large. Therefore, the short-line approximation is valid since the CD wavelength is larger than the cable length.

Two cable models can be used with the short line approximation : the π and the T models. They are represented in Figure 2.4.



Figure 2.4: Pi and T model

The chain matrix enable prediction of the CD propagation through the cable and does not claim any simulation with Simulink, only computer calculations. In chapter three, it will be used to study the frequency response of the cables.

With the short line approximation, the chain matrix of Equation 2.7 can be simplified and is given by Equation 2.14 for the T model.

$$\begin{aligned} A &= 1 + \bar{Y} \frac{\bar{Z}}{2} = D \\ B &= \frac{\bar{Z}(4 + \bar{Y}\bar{Z})}{4} \\ C &= \bar{Y} \end{aligned} \tag{2.14}$$

For the π model, components of Equation 2.7 can be written with the primary parameters of the line with Equation 2.15.

$$\begin{aligned} A &= 1 + \frac{\bar{Y}}{2} \bar{Z} = D \\ B &= \bar{Z} \\ C &= \frac{\bar{Y}(4 + \bar{Y}\bar{Z})}{4} \end{aligned} \tag{2.15}$$

2.3 Primary line parameters

The theoretical resistance of the cables is computed in order to compare it with cable manufacturer resistance values. For low voltage cables, formulas are not precise enough to calculate the inductance and the capacitance. Therefore, only manufacturer values will be taken into account.

2.3.1 Resistance calculation

In low frequency, the resistance can be calculated by Equation 2.16 with l the length of the cable [m], ρ the resistivity [Ωm] and A the cross section of the cable (as depicted in Figure 2.5).

$$R_{DC} = \frac{l\rho}{A} [\Omega] \quad (2.16)$$

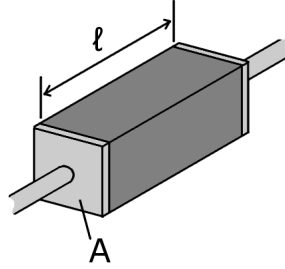


Figure 2.5: Schematic to compute resistance [22]

The resistivity, ρ , increases with the temperature according to Equation 2.17.

$$\rho(T) = \rho(T_0)(1 + \alpha_{conductor}(T - T_0)) \quad (2.17)$$

With Equation 2.16 and 2.17, the DC resistance in function of the temperature can be calculated with Equation 2.18.

$$R_{DC}(T) = \frac{l\rho(T_0)(1 + \alpha_{conductor}(T - T_0))}{A} [\Omega] \quad (2.18)$$

The literature gives values of resistance at 90°C. As resistance values are going to be compared each other, this temperature will be chosen as the reference temperature. In other words, all resistance values are calculated at 90°C.

Equation 2.18 is limited in low frequencies by the skin effect. Indeed, when the frequency increases, the alternating current has the tendency to be distributed near the outer diameter of the conductor in a distance θ . θ , the skin depth, is represented in Figure 2.6. This distribution causes the resistance value to increase with the frequency and is called the skin effect.

If the current is distributed in the outer diameter and if $D \gg \theta$, one can assume that the cross

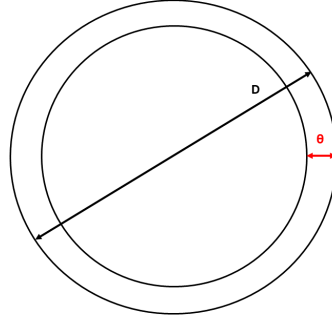


Figure 2.6: Alternative current distribution due to the skin effect

section can be approximated by Equation 2.19.

$$A \approx \theta \pi D \quad (2.19)$$

Replacing Equation 2.19 in 2.16, the resistance in high frequencies is given by Equation 2.20.

$$R_{AC} = \frac{\rho l}{\theta \pi D} [\Omega] \quad (2.20)$$

If $\theta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{\rho}{\pi f\mu}}$ (with μ the material permeability) is replaced in Equation 2.20, the AC resistance is computed with Equation 2.21.

$$R_{AC} = \frac{l}{D} \sqrt{\frac{\rho \mu f}{\pi}} [\Omega] \quad (2.21)$$

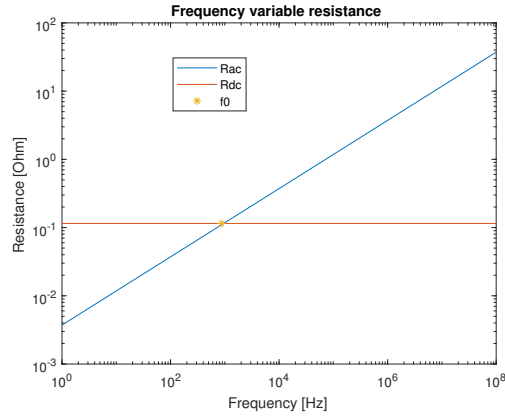
Eventually, when introducing the temperature variable resistivity of Equation 2.17 in Equation 2.21, we end up for the AC resistance with Equation 2.22.

$$R_{AC} = \frac{l}{D} \sqrt{\frac{\rho(T_0)(1 + \alpha_{conductor}(T - T_0)) \mu f}{\pi}} [\Omega] \quad (2.22)$$

If f_0 is the frequency when $R_{DC} = R_{AC}$, the frequency dependent resistance is given by Equation 2.23. The variable resistance is depicted in function of the frequency in Figure 2.7

$$\begin{cases} R(f) = \frac{l}{A} \rho(T_0)(1 + \alpha_{conductor}(T - T_0)) & [\Omega] & f < f_0 \\ R(f) = \frac{l}{D} \sqrt{\frac{\rho(T_0)(1 + \alpha_{conductor}(T - T_0)) \mu f}{\pi}} & [\Omega] & f > f_0 \end{cases} \quad (2.23)$$

For calculation, values of Table 2.2 are used.

Figure 2.7: Frequency variable resistance for a 500-meter long EAXeVB 150² cable

	$\rho(20^{\circ}C) [n\Omega m]$	$\mu [\frac{H}{m}]$	$\alpha [\frac{1}{K}]$
Copper	17.5	1.2566×10^{-6}	3.93×10^{-3}
Aluminium	26.5	1.2566×10^{-6}	3.93×10^{-3}

Table 2.2: Values attributed to aluminium and copper

2.3.2 Low voltage distribution cables

The primary parameters of the cables are listed in Tables 2.3, 2.4, 2.5 and 2.6. The resistance values given by cable manufacturers are compared to the resistance values calculated with Equation 2.23.

Several manufacturers values are listed in order to compare them. Indeed, if two different manufacturers give almost the same primary parameter value, one can assume this value to be reliable.

	Source	EAXeVB 95 ²	EAXeVB 150 ²	Unit
AC resistance at 50Hz	b-cables	0.4109	0.2651	$\frac{\Omega}{km}$
	Cablerie d'Eupen	0.411	0.265	
	Calculated	0.4289	0.2824	
Capacitance	b-cables	$0.446 \cdot 10^{-6}$	$1.698 \cdot 10^{-6}$	$\frac{F}{km}$
Inductance	b-cable	$2.19 \cdot 10^{-4}$	$2.19 \cdot 10^{-4}$	$\frac{H}{km}$
	Cablerie d'Eupen	$2.48 \cdot 10^{-4}$	$2.48 \cdot 10^{-4}$	
Max current	Cablerie d'Eupen	245	315	A

Table 2.3: EAXeVB power cable characteristics. Source [23]

	Source	EXVB 10 ²	EXVB 16 ²	EXVB 25 ²	Unit
AC resistance at 50 Hz	Nexans	2.3335	1.4665	0.9273	$\frac{\Omega}{km}$
	Cablerie d'Eupen	2.34	1.47	0.931	
	Calculated	2.3972	1.53	1	
Inductance	Nexans	$2.98 \cdot 10^{-4}$	$2.58 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$	$\frac{H}{km}$
	Cablerie d'Eupen	$2.73 \cdot 10^{-4}$	$2.64 \cdot 10^{-4}$	$2.65 \cdot 10^{-4}$	
Max current	Cablerie d'Eupen	90	120	150	A

Table 2.4: EXVB connection cable characteristics. Source [24] [25] [26]

	Source	BAXB 16 ²	BAXB 25 ²	BAXB 95 ²	Unit
AC resistance AT 50 Hz	Cablerie d'Eupen	2.45	1.11	0.410	$\frac{\Omega}{km}$
	Calculated	2.16	1.38	0.37	
Inductance	Cablerie d'Eupen	2.71 10 ⁻⁴	2.66 10 ⁻⁴	2.43 10 ⁻⁴	$\frac{H}{km}$
Max current	Cablerie d'Eupen	75	105	255	A

Table 2.5: BAXB connection (16² and 25²) and power cable (95²) characteristics. Source [26]

	Source	XVB 1.5 ²	XVB 2.5 ²	XVB 6 ²	Unit
AC resistance at 50 Hz	Cablerie d'eupen	15.5	9.49	3.94	$\frac{\Omega}{km}$
	Nexans	15.43	9.4485	3.93	
	Calculated	15.30	9.26	3.93	
Capacitance	[27]			8.46 10 ⁻⁸	$\frac{F}{km}$
Inductance	Cablerie d'Eupen	3.23 10 ⁻⁴	3.32 10 ⁻⁴	2.94 10 ⁻⁴	$\frac{H}{km}$
	Nexans	3.52 10 ⁻⁴	3.32 10 ⁻⁴	3.04 10 ⁻⁴	
Max current	Cablerie d'Eupen	30	40	50	A

Table 2.6: XVB connection cable characteristics. Source [26] [25]

When comparing manufacturer and calculated resistance values for each cable, they are very close to each other. Therefore, one can assume the resistance formula to be accurate enough to be used in further simulations. Moreover, the inductance values are almost the same for different manufacturers. One can rely on these values since they have been measured independently.

2.3.3 Capacitance approximation

The cable model contains a capacitance. To know the capacitance value of small cross section cables, measurements have to be performed. Indeed, manufacturers do not provide these values. Unfortunately, capacitance value measurement is not done in this work. Therefore, approximation for these capacitances has to be made.

In [27], the author has measured the capacitance value of XVB 6², 10² and 15² cables. These capacitance values are 8.46 10⁻¹¹ $\frac{F}{m}$ for the XVB 6² and 10² cables and 5.19 10⁻¹¹ $\frac{F}{m}$ for the XVB 15² cable. In this work, only the XVB 6² cable is used.

The XVB 6² capacitance value is 5 times smaller than the capacitance value of an EAXeVB 95² cable (4.46 10⁻¹⁰ $\frac{F}{m}$). Therefore, it can not be neglected. Since we do not have more capacitance values, the XVB 6² capacitance value will be used for cables in which the capacitance value is not provided.

2.3.4 Primary parameters summary

In this work, the manufacturer's values are used as primary parameters of the cables. The values between different manufacturers are very close. Arbitrarily, the first one given in the tables is chosen.

Furthermore, the skin effect must be taken into account. Equation 2.23 is used to calculate the

resistance value in function of frequency.

Eventually, when capacitance value is not provided, the capacitance value of the XVB 6² cable is used (measured value). Even if it will cause inaccuracy, the general frequency behaviour of the cables will be respected.

2.4 Three-phase cable model

The whole distribution grid model is almost built. Indeed, with the short line approximation, the T and the π lumped model can be used. Furthermore, the primary parameters of the cables are provided. With these elements, the three-phase cable model can be elaborated. But first, a choice has to be made between the T and the π model. Arbitrarily, the T model is chosen.

The three-phase T model with the three conductors and a neutral is depicted in Figure 2.8.

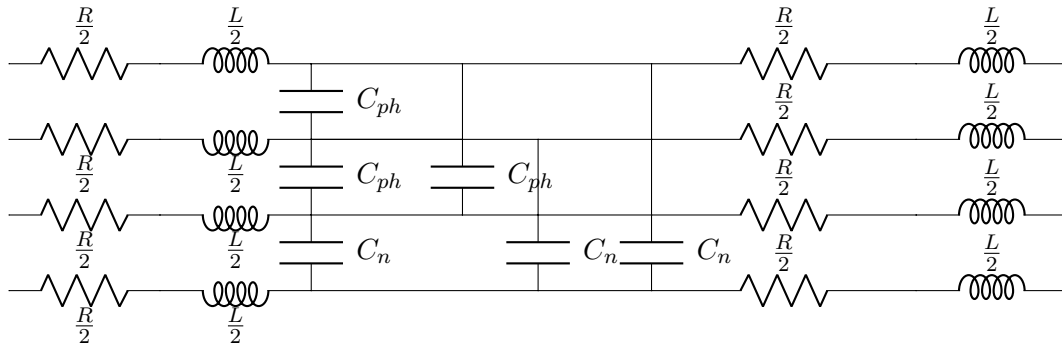


Figure 2.8: T distribution three-phase plus neutral cable model

The main difference between the single-phase model and the three-phase model is that the equivalent capacitance is split into the phase-to-neutral capacitance (C_n) and the phase-to-phase capacitance (C_{ph}) in the three-phase cable model. From values found in [28], the relation between the phase-to-neutral and the phase-to-phase capacitance value is given in Equation 2.24.

$$C_n = 10C_{ph} \quad (2.24)$$

Furthermore, when manufacturers give the capacitance per unit length of a cable, this capacitance is the equivalent capacitance. It combines the two previous ones with this relation of Equation 2.25.

$$C_{equ} = C_n + 3C_{ph} \quad (2.25)$$

Gathering Equations 2.24 and 2.25, one can obtain the two capacitance values with Equation

2.26.

$$\begin{aligned} C_n &= \frac{10}{13} C_{equ} \\ C_{ph} &= \frac{1}{13} C_{equ} \end{aligned} \quad (2.26)$$

2.5 Positive, negative and zero sequence models

The three-phase T equivalent model of Figure 2.8 will be simplified into a single-phase equivalent model in this section. This equivalent model will depend on the sequence of the CD (positive, negative or zero sequence).

Two cases are covered : the positive/negative sequence and the zero sequence. The positive/negative sequence occurs when the three phases are fed with phasors having a phase shift of 120 °and 240 °and the same magnitude. The zero sequence happens when all the phasors have the same magnitude and the same phase.

2.5.1 Symmetrical components basis

Let's make a brief summary about the symmetrical components. A system of three unbalanced phasors can be resolved in the following three symmetrical components :

- Positive sequence : a balanced three-phase system with the same phase sequence as the original sequence.
- Negative sequence : a balanced three-phase system with the opposite phase sequence as the original sequence.
- Zero sequence : three phasors that are equal in magnitude and phase.

Defining $a = e^{j\frac{2\pi}{3}}$, Figure 2.9 depicts the positive sequence conformed to Equation 2.27.

$$\begin{cases} V_a = V_{a1} \\ V_b = a^2 V_{a1} \\ V_c = a V_{a1} \end{cases} \quad (2.27)$$

Figure 2.10 depicts the negative sequence of Equation 2.28.

$$\begin{cases} V_a = V_{a2} \\ V_b = a V_{a2} \\ V_c = a^2 V_{a2} \end{cases} \quad (2.28)$$

Figure 2.11 gives the zero sequence given in Equation 2.29.

$$\begin{cases} V_a = V_{a0} \\ V_b = V_{a0} \\ V_c = V_{a0} \end{cases} \quad (2.29)$$

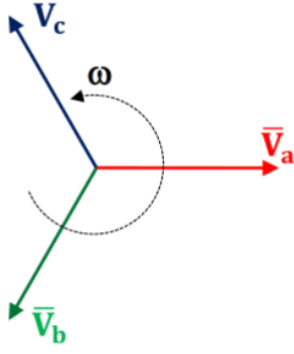


Figure 2.9: Positive sequence [29]

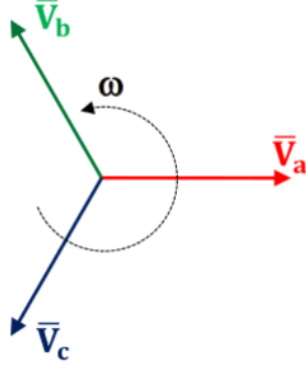


Figure 2.10: Negative sequence [29]

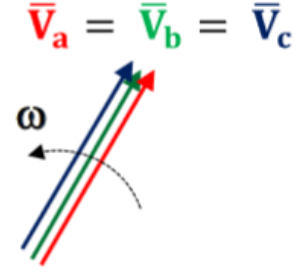


Figure 2.11: Zero sequence [29]

Equation 2.30 represents a balanced three-phase harmonics sequencing.

$$\begin{cases} I_{ah} = \sqrt{2}I_h \cos[h(\omega_g t - \phi_h)] \\ \quad = \sqrt{2}I_h \cos[h(\omega_g t - \phi_h) + \alpha_h] \\ I_{bh} = \sqrt{2}I_h \cos[h(\omega_g t - \phi_h - \frac{2\pi}{3})] \\ \quad = \sqrt{2}I_h \cos[h(\omega_g t - \phi_h) + \beta_h] \\ I_{ch} = \sqrt{2}I_h \cos[h(\omega_g t - \phi_h - \frac{4\pi}{3})] \\ \quad = \sqrt{2}I_h \cos[h(\omega_g t - \phi_h) + \gamma_h] \end{cases} \quad (2.30)$$

Three cases are possible considering $n \in \mathbb{N}$:

$$\begin{cases} h = 3n + 1 & (4, 7, 10, \dots) \\ h = 3n & (3, 6, 9, \dots) \\ h = 3n - 1 & (2, 5, 8, \dots) \end{cases} \quad (2.31)$$

Let's analyse each case separately.

- For $h = 3n+1$:

$$\begin{cases} \alpha_{3n+1} = 0 = 0 \\ \beta_{3n+1} = -(3n+1)\frac{2\pi}{3} = -\frac{2\pi}{3} \\ \gamma_{3n+1} = -(3n+1)\frac{4\pi}{3} = -\frac{4\pi}{3} \end{cases} \quad (2.32)$$

$h = 3n+1$ corresponds to the positive sequence.

- For $h = 3n-1$:

$$\begin{cases} \alpha_{3n-1} = 0 = 0 \\ \beta_{3n-1} = -(3n-1)\frac{2\pi}{3} = -\frac{4\pi}{3} \\ \gamma_{3n-1} = -(3n-1)\frac{4\pi}{3} = -\frac{2\pi}{3} \end{cases} \quad (2.33)$$

$h = 3n-1$ corresponds to the negative sequence.

- For $h = 3n$:

$$\begin{cases} \alpha_{3n} = 0 = 0 \\ \beta_{3n} = -(3n)\frac{2\pi}{3} = 0 \\ \gamma_{3n} = -(3n)\frac{4\pi}{3} = 0 \end{cases} \quad (2.34)$$

$h = 3n$ corresponds to the zero sequence.

Now that the positive, negative and zero sequences have been determined, this concept is used to pass from a three-phase equivalent model to a single-phase equivalent model.

2.5.2 Positive and negative sequences

The three-phase equivalent model shown in Figure 2.8 is simplified into a single-phase equivalent model for positive and negative sequence disturbances. The system with these two sequences is three-phase 120°shifted with equal magnitude.

As a reminder of Equation 2.25, the equivalent impedance for the positive/negative is rewritten in Equation 2.35. In Positive and negative sequences, the star connected capacitance value stays constant (C_n) while the delta connected capacitance value (C_{ph}) is three times larger. The equivalent capacitance value is found by summing these capacitances as in Equation 2.35.

$$C_{equ} = C_n + 3C_{ph} \quad (2.35)$$

The equivalent capacitance being determined, the resistance and the inductance value of the single-phase equivalent model must also be fixed. The sum of the currents flowing through the neutral capacitance is null since they are shifted by 120 °each other.

Therefore, no current flows in the neutral impedance. Consequently, this impedance can be represented in positive/negative sequence by a short circuit. More generally, the neutral series impedance always disappears [29] in positive/negative sequence. Eventually, in positive/negative sequence, the phase series impedance has the same value than in the three-phase equivalent model.

The complete positive and negative sequence single-phase equivalent model is represented in Figure 2.12.

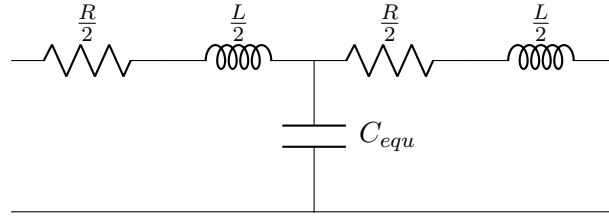


Figure 2.12: Single-phase positive and negative sequence equivalent model

2.5.3 Zero sequence

In zero sequence, the system has the same magnitude and the same phase. Consequently, the voltage drop through the phase capacitance (C_{ph} in Figure 2.8) is null ; no current flows through them. Therefore, this capacitance disappears in the single-phase zero sequence model. More generally, in delta connection configuration, there is no zero sequence component. The equivalent capacitance in zero sequence is given by Equation 2.36

$$C_{equ} = C_n \quad (2.36)$$

Moreover, when star connected, the zero sequence impedance using Figure 2.13 notations is calculated with Equation 2.37. More intuitively, one can understand that the current flowing through the neutral impedance (Z_N) is three times smaller in the single-phase equivalent model than in the three-phase model. Therefore, to conserve the same voltage drop through the neutral impedance, the neutral zero sequence impedance must be three times higher. More generally, the star connected impedance stays constant in zero sequence (Z_Y) and the neutral impedance is multiplied by three.

$$Z_0 = Z_Y + 3Z_N \quad (2.37)$$

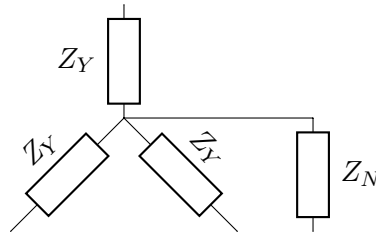


Figure 2.13: Three-phase star connection configuration

Using the notation of Figure 2.8, the zero sequence neutral impedance is calculated with Equation 2.38 (index '0' means zero sequence).

$$\frac{Z_{n,0}}{2} = 3\left(\frac{R}{2} + j\omega\frac{L}{2}\right) \quad (2.38)$$

Figure 2.14 shows the equivalent zero sequence single-phase model. The equivalent capacitance

is the neutral capacitance. The neutral impedance is multiplied by three. Eventually, the phase impedance remains the same as in the three-phase cable model.

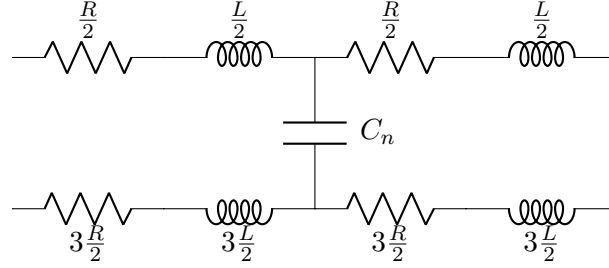


Figure 2.14: Single-phase zero sequence equivalent model

For simplification, Figure 2.15 is equivalent to Figure 2.14.

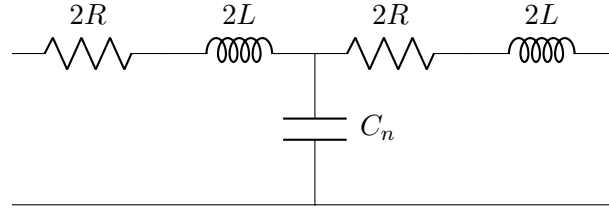


Figure 2.15: Single-phase zero sequence simplified equivalent model

2.5.4 Three-phase to single-phase equivalent model summary

The CD can take three forms : positive, negative and zero sequence form. The single-phase equivalent model depends on the sequence of the CD.

For the positive and the negative sequences, the equivalent capacitance is $C_{equ} = C_n + 3C_{ph}$ and the neutral impedance is a short circuit. For the zero sequence, the equivalent capacitance is $C_{equ} = C_n$ and the neutral impedance is three times higher than in the three-phase model.

Passing from a three-phase model to a single-phase model depending on the sequence enables calculation of the chain matrices of the cables. These matrices will be used in Chapter 3 to study the frequency response of the distribution cable. Furthermore, these sequence single-phase equivalent models will be used in Chapter 5 to study unbalanced disturbances.

2.6 Skin effect modelling

2.6.1 Skin effect model principle

As mentioned in section 2.3, the skin effect increases the resistance value with the frequency. As CD in the frequency range between 2 and 150 kHz are studied, the skin effect can not be neglected since these frequencies are high. Therefore, a further investigation of this phenomena is worthwhile.

Moreover, in Simulink, the resistance is not variable. In order to use this tool and to be the most accurate as possible, a model of the skin effect is elaborated. Figure 2.16 shows how the resistance behaves in the frequency domain. These curves are following the skin effect equations seen in section 2.3 (Equation 2.23) :

$$\begin{cases} R(f) = \frac{l}{A} \rho(T_0)(1 + \alpha_{conductor}(T - T_0)) & [\Omega] \quad f < f_0 \\ R(f) = \frac{l}{D} \sqrt{\frac{\rho(T_0)(1 + \alpha_{conductor}(T - T_0)) \mu f}{\pi}} & [\Omega] \quad f > f_0 \end{cases}$$

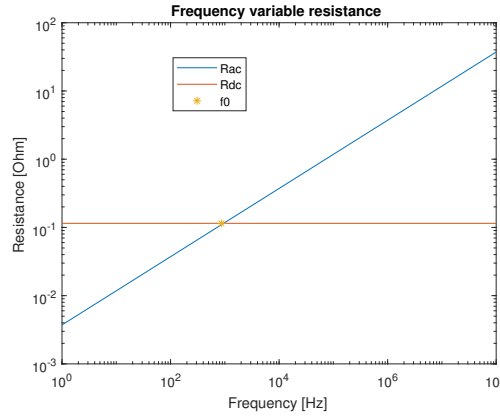


Figure 2.16: Frequency variable resistance for a 500-meter long EAXeVB 150² cable

In a few words, to fit the skin effect, the ladder circuit represented in Figure 2.17 is used. The resistances and the inductances are placed in a ladder configuration with specific values which causes the total impedance increasing with the frequency. The impedance is the equivalent impedance calculated between point A and point B of Figure 2.17.

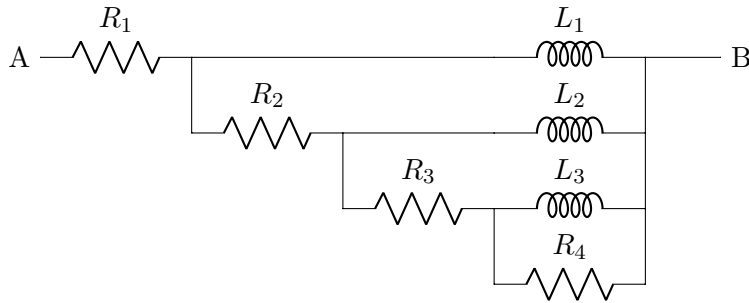


Figure 2.17: Ladder used to model the skin effect

To find the resistance and the inductance values, the equivalent impedance of the ladder is analytically calculated with resistance and the inductance values the unknowns. Their values are found using the curve fitting. The computer tries to find with which values of the resistances and the inductances, the equivalent impedance fits optimally the resistance value calculated with the skin effect equations. The whole approach leading to this model is explained in details in Annex D.1.

For an EAXeVB 150² cable of 500 meters, the resistance and the inductance values are listed in Table 2.7.

Resistance	Ω	Inductance	Henry
R_1	0.1164	L_1	5.7403e-5
R_2	0.1933	L_2	5.254e-6
R_3	0.6497	L_3	5.577e-7
R_4	2.1045		

Table 2.7: Skin effect model parameters for an EAXeVB 150² cable of 500 meters

Figure 2.18 supports that the skin effect model fits well the resistance value (with the skin effect) between 2 and 150 kHz. Indeed, the magnitude and the phase of the equivalent impedance of the model of Figure 2.17 with values of Table 2.7 are illustrated on this figure. On the left-hand side, the graphic shows the impedance magnitude of the model (in orange) compared to resistance magnitude when following the skin effect equations (in blue). The right-hand side graphic depicts the phase induced by the model in the frequency domain. Unfortunately, since there are inductances in the model, phase shift is unavoidable. In reality, the skin effect does not induce any phase shift. Therefore, the model brings inaccuracy in simulations. The consequences implied by the skin effect model phase shift are studied in-depth in Annex D.1.

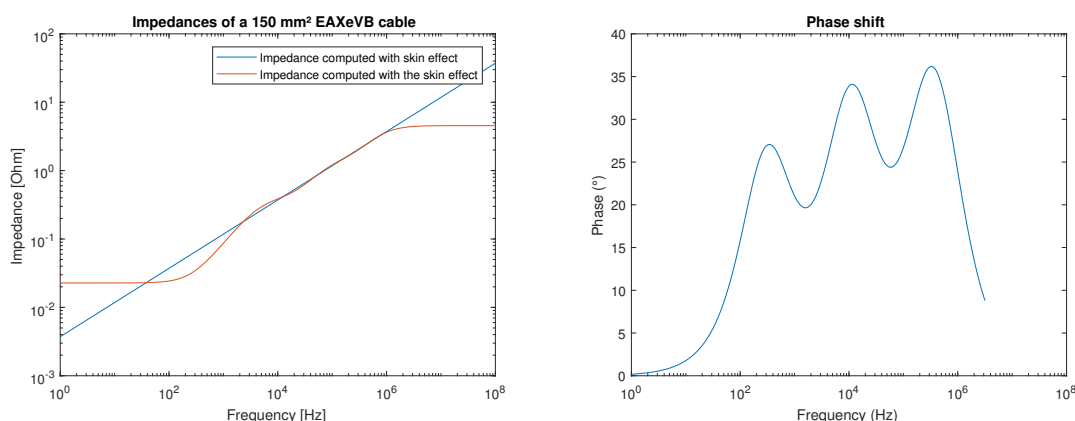


Figure 2.18: Magnitude and phase of the ladder skin effect model

2.6.2 Rejection of the skin effect model

For the rest of this work, the skin effect model will not be used. The main reason is that this model introduces a phase shift exactly around the peak resonance area of the cable frequency response (explained in Annex D.2). Since this zone is the most important (it amplifies the CD), phase shift inaccuracies can not be tolerated. Furthermore, the resistance value when working around the resonance frequency can be replaced by a resistance value calculated at this frequency (explained in Annex D.2).

In a few words, the skin effect model is rejected because of its phase inaccuracy and since there is an alternative : replacing the resistance value by the one calculated at the critical frequency. A whole methodical approach to support the choice of not using the skin effect model is explained in Annex D.2.

2.7 Conclusion

The goal of this chapter was elaborating a model for low voltage distribution cables. Since CD are flowing through the cables, it is relevant to use an accurate cable model. The approach to build this model is explained below in a few words.

Foremost, the main cables used in the Belgian low voltage network are inventoried. A model for the long line and the short line approximation is given. For long line approximation, the distributed parameters model is more suitable. In short line approximation, the lumped parameters model is the most appropriate. In the frequency range between 2 and 150 kHz, the short line approximation is used. Therefore, the T and the π model can be chosen. The chain matrix of these two models is calculated in order to study the frequency response of the cables later. Afterwards, the skin effect equations for the resistance value in high frequencies are given. Then, the primary parameters (R, L and C) given by the manufacturers are listed. A comparison between calculated and manufacturers resistance values is made. These values were very close, leading us to the conclusion that the resistance formula is reliable. Moreover, the inductance values given by different manufacturers were really close to each other, meaning that these values are also reliable. Unfortunately, there is a lack in capacitance value which led to take one capacitance value for cables where this value is not provided.

Then, the three-phase cable model is established. The primary parameters of this model vary depending on the cable type and the cable length. A method to pass from a three-phase to a single-phase model is presented depending on the type of disturbance applied to the cable. This model is the same for the positive and the negative sequence, and is different for the zero sequence.

Eventually, a model fitting the skin effect is developed. It is made of inductances and resistances placed in a ladder configuration. The equivalent impedance of this model increases with the frequency. The idea was to replace the resistance of the three-phase equivalent model by the skin effect model. Unfortunately, this model introduces a phase shift which brings too much inaccuracies. Therefore, it will no longer be used in this work.

As a summary, this chapter proposes a model of distribution cables in which the CD are flowing through.

Frequency behaviour of typical low voltage cables

In this chapter the chain matrix components are used to study the frequency behaviour of the cables. As seen in Chapter 2, there are two types of low voltage distribution cables: the underground and the overhead cables. For each of these two categories, the cables can be for connection or for power transportation. Unfortunately, due to the difficulty in measuring the capacitance of low voltage distribution cables, we had only the capacitance value of the EAXeVB cables (underground power cables) and the XVB 6² underground distribution cable. Therefore, only these cable frequency responses are deeply investigated.

First of all, a reminder on the chain matrix is given. Then, the frequency behaviour of EAXeVB cables and the influence of the length is presented. The same approach is used for the XVB 6² cable. Finally, the skin effect influence on the cable frequency response is examined. To achieve that, the resistance value is calculated in function of the frequency and is included in the cable model. Then, the frequency response with and without the skin effect resistance value is computed.

3.1 Reminder on the chain matrix

To study the frequency response of the cables, the chain matrix is used. The different components of this matrix are studied one by one in this chapter. This matrix is built using the secondary parameters of the line as saw in Section 2.2. Then, with the short line approximation, the chain matrix represented in Equation 3.1 is calculated with the primary parameters of the line.

$$\begin{bmatrix} \overline{V_1} \\ \overline{I_1} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \overline{V_2} \\ -\overline{I_2} \end{bmatrix} \quad (3.1)$$

The different components of the chain matrix allow studying the frequency behaviour of the cables under specific conditions. A gives the transfer function of $\frac{V_1}{V_2}$ when $I_2 = 0$, B gives $\frac{V_1}{-I_2}$ when $V_2 = 0$, C gives $\frac{I_1}{V_2}$ when $I_2 = 0$ and D gives $\frac{I_1}{-I_2}$ when $V_2 = 0$.

The A, B, C and D chain matrix components are computed with the parameters of Figure 3.1

with Equation 3.2 as deeper explained in Section 2.2.

$$\begin{aligned}
 A &= 1 + \frac{\overline{Y}\overline{Z}}{2} = D \\
 B &= \frac{\overline{Z}(4 + \overline{Y}\overline{Z})}{4} \\
 C &= \overline{Y}
 \end{aligned} \tag{3.2}$$

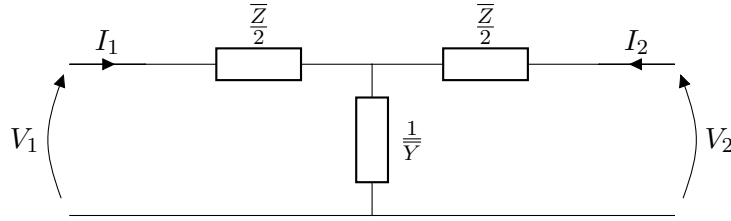


Figure 3.1: T single-phase equivalent model

In Section 2.5, the positive, negative and zero sequence single-phase equivalent circuit were developed. For the positive and the negative sequence, the primary parameters of the cable are given by Equation 3.3. With these parameters, the positive/negative sequence chain matrix components are computed with Equation 3.4.

$$\begin{aligned}
 \overline{Z} &= R + j\omega L \\
 \overline{Y} &= j\omega C_{equ}
 \end{aligned} \tag{3.3}$$

$$\begin{aligned}
 A &= 1 + j\omega C_{equ} \frac{(R + j\omega L)}{2} = D \\
 B &= (R + j\omega L) \frac{4 + j\omega C_{equ}(R + j\omega L)}{4} \\
 C &= j\omega C_{equ}
 \end{aligned} \tag{3.4}$$

For the zero sequence, the primary parameters are shown in Equation 3.5. With these parameters, the chain matrix components of the zero sequence are calculated with Equation 3.6.

$$\begin{aligned}
 \overline{Z} &= 4R + 4j\omega L \\
 \overline{Y} &= j\omega C_n
 \end{aligned} \tag{3.5}$$

$$\begin{aligned}
A &= 1 + j\omega C_n(2R + 2j\omega L) = D \\
B &= (R + j\omega L) \left(4 + j\omega C_n(4R + 4j\omega L) \right) \\
C &= j\omega C_n
\end{aligned} \tag{3.6}$$

3.2 Frequency response of the cables

Having reminded the usefulness and the calculation of the chain matrix components, let's use them to understand the frequency response of the cables. The approach to study the frequency response of cables is the following. First of all, the length of the cable is fixed at 100 meters and the chain matrix components A, B and C are examined in the frequency domain for the positive/negative and the zero sequence. After that, frequency response of the cables is studied for different cable lengths to study their impact.

The chain matrix components are investigated in this section for EAXeVB and XVB cables. Let's keep in mind for the rest of this chapter that:

- $A = \frac{\bar{V}_1}{\bar{V}_2}$ when $\bar{I}_2 = 0$
- $B = \frac{\bar{V}_1}{-\bar{I}_2}$ when $\bar{V}_2 = 0$
- $C = \frac{\bar{I}_1}{\bar{V}_2}$ when $\bar{I}_2 = 0$

The frequency response of D is not investigated because it has exactly the same value as A.

3.2.1 EAXeVB power cable

Chain matrix component frequency responses

In Figure 3.2, the A, B and C chain matrix components are represented for a 100-meter long for an EAXeVB 95² and 150² cables in positive/negative and zero sequence. The A, B and C chain matrix component frequency responses are analysed.

First of all, A and B frequency response is studied. The magnitude of A stays constant before the resonance frequency and increases after the resonance frequency. The B frequency response follows the same behaviour but with a higher resonance frequency than A. For A and B, the zero sequence resonance frequency appears before the positive/negative sequence resonance frequency. Moreover, the EAXeVB 150² cable has a smaller resonance frequency than the EAXeVB 95².

The resonance frequency of A is the resonance frequency when the cable is in open circuit. For B, it is the resonance frequency when the cable is in short circuit. These are two limit cases ; therefore, the resonance frequency of the cable always stays between these two frequencies depending on what

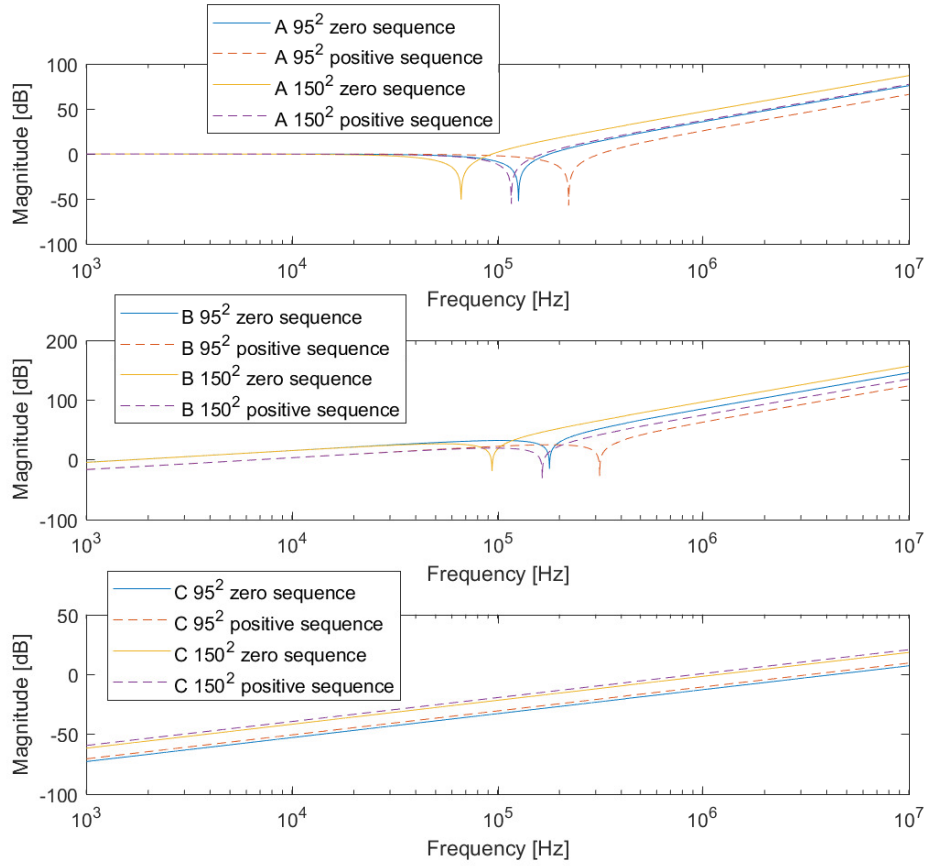


Figure 3.2: Chain matrix components for EAXeVB cables of 100 meters long

is connected to the cable. For example, the more impedance value connected to the cable, the more the resonance frequency will be close to the open circuit resonance frequency and inversely if the cable is connected to a low impedance.

Eventually, the frequency response of C is investigated. It does not have resonance frequency and increases constantly with the frequency in a logarithmic scale. The magnitude is higher for the EAXeVB 150² because its capacitance value is higher than the EAXeVB 95². Indeed, C is proportional to the shunt capacitance. Furthermore, the magnitude is also a bit higher for the positive/negative sequence than the zero sequence. It is due to the higher capacitance value in the positive/negative sequence than for the zero sequence.

Cable length influence

The influence of the cable length on the resonance frequency is first investigated for A and B (not for C since it does not have resonance frequency). Then, the impact of the cable length on the magnitude of B and C at 10 kHz is studied (not for A because its magnitude stays constant at this frequency). 10 kHz is taken as a reference because it is always smaller than the resonance frequency of the cable we are working with and it is a typical switching frequency value.

As one can observe in Figure 3.3, the resonance frequency of A decreases with the cable length. The influence of the cable length on the resonance frequency of B is shown in Figure 3.4. As for A, the resonance frequency decreases with the cable length.

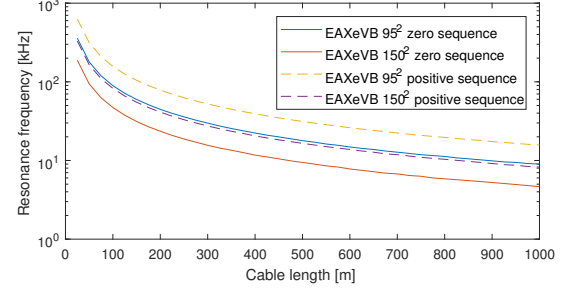
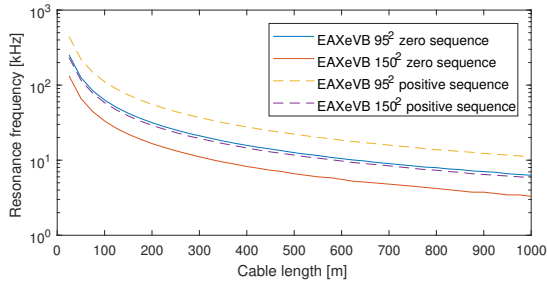


Figure 3.3: Resonance frequency of an EAXeVB in function of its length for the A chain matrix component

Figure 3.4: Resonance frequency of an EAXeVB in function of its length for the B chain matrix component

The B magnitude at 10 kHz is depicted in Figure 3.5. A larger cable length increases the magnitude of the frequency response at 10 kHz. Moreover, the zero sequence has a larger magnitude than the positive/negative sequence.

The cable length impact on the magnitude of C is shown in Figure 3.6. As for B, a larger cable length increases the magnitude of the frequency response at 10 kHz.

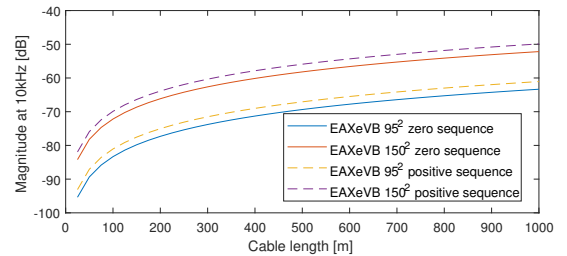
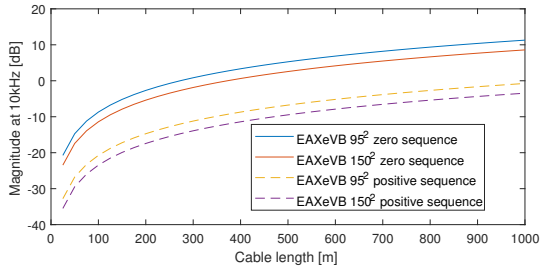


Figure 3.5: Magnitude at 10 kHz of EAXeVB in function of its length for the B chain matrix component

Figure 3.6: Magnitude at 10 kHz of EAXeVB in function of its length for the C chain matrix component

3.2.2 XVB cable

Chain matrix component frequency responses

The last cable for which all the primary parameters are known is the XVB 6² cable. Its chain matrix frequency response components are shown in Figure 3.7. The behaviour of the cable in the frequency domain is the same as for the EAXeVB underground power cable studied in Section 3.2.1.

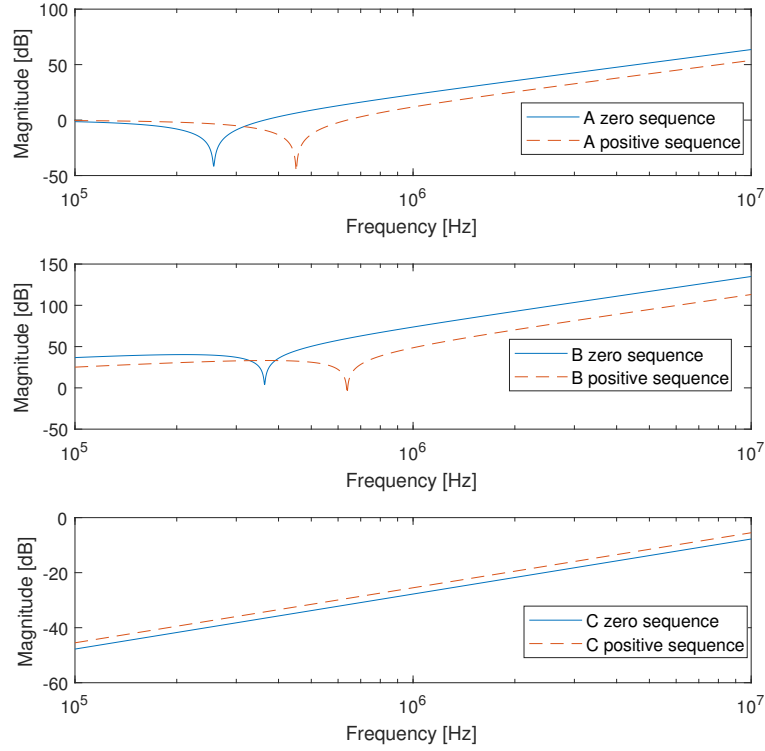


Figure 3.7: A, B and C frequency response for a XVB 6² cable of : long

Cable length influence

The influence of the cable length is not investigated for the XVB cable. Indeed, the magnitude value is different than for the EAXeVB cables but the global behaviour remains the same. Therefore, it is not interesting to burden this chapter with the same type of graphs.

3.2.3 EAXeVB and XVB frequency response comparison

For the same length, the frequency response of an EAXeVB cable is compared to the one of a XVB cable. To have a more clear graph, only the EAXeVB 95² cable is compared with the XVB 6². Moreover, only the positive sequence frequency response is shown also in a purpose of simplification.

In Figure 3.8, the magnitude of the A, B and C frequency response is depicted. The XVB cable resonance frequencies are higher than the EAXeVB cable resonance frequencies. Eventually, the C magnitude of the EAXeVB power cable is higher than the C magnitude of the XVB connection cable magnitude.

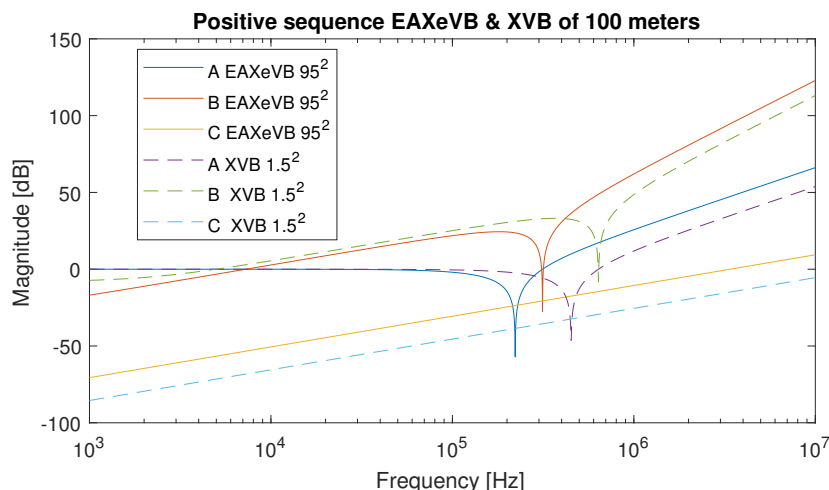


Figure 3.8: A, B and C frequency response for an EAXeVB 95^2 and a XVB 6^2 of 100 meters long in positive sequence

3.2.4 Cable frequency response summary

Global result conclusion can be made about the frequency response of the cables.

First of all, the frequency response of A has a smaller resonance frequency than B. Moreover, the zero sequence resonance frequency is smaller than the positive/negative sequence one. The C frequency response is proportional to the capacitance value and thus its magnitude is higher for the positive/negative sequence than for the zero sequence.

Then, the XVB cable resonance frequency is higher than the EAXeVB cables resonance frequency for the same cable length. In reality, the connection cable (XVB) length is smaller than the power cable (EAXeVB) length. Therefore, the resonance frequency of the connection cable is always higher than the power cable one.

Eventually, the magnitude of B and C before the resonance frequency (at 10 kHz in our example) increases with the cable length. Rather, the resonance frequency of A and B decreases with the cable length.

3.3 Skin effect resistance value

Now that we understand well the frequency response of the cables, it is interesting to know more about the influence of the skin effect. The aim of this section is to know the impact of the skin effect.

To achieve that, the A and B frequency responses are analysed for a cable with a fixed resistance value (taken at 50 Hz) and for a cable with frequency variable resistance value (based on skin effect equations). The frequency response of C is not investigated with the skin effect because it has absolutely no impact on it. Indeed, C depends only on the capacitance value of the cable.

Then, the difference between voltage transfer function with a fixed and a variable resistance value is calculated. To lighten this section, only the EAXeVB 150² is taken. Indeed, the results found with this cable is applicable for all types of cables.

In Figure 3.9, one can observe that the skin effect decreases the resonance peak magnitude and conserves the resonance frequency. Furthermore, it has no impact outside the resonance peak area. Indeed, the transfer function varies only around the resonance frequency area. Outside this area, it remains the same with or without the frequency variable resistance.

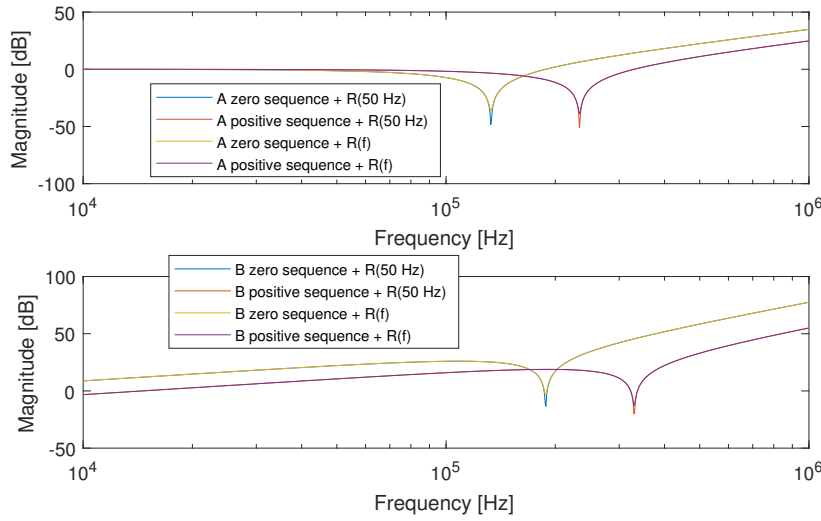


Figure 3.9: A and B frequency response for an EAXeVB 150² with and without variable resistance value

Figure 3.10 shows the attenuation in percent between the voltage magnitude with and without frequency variable resistance value. Mathematically the graph shows:

$$\frac{\Delta V_1(f)}{V_1(R_{constant,50Hz})} = \frac{V_1(R_{constant,50Hz}) - V_1(R(f))}{V_1(R_{constant,50Hz})} \quad (3.7)$$

One can observe from Figure 3.10 that outside the resonance frequency, the voltage with a fixed resistance and a frequency variable resistance value is almost not attenuated. Inversely, close to the resonance peak, the voltage difference when using a variable resistance value is not negligible and rises up to 800 %.

In Figure 3.11, the resonance peak attenuation is represented in function of the cable length. The attenuation decreases with the cable length because when the cable length increases, its resonance frequency decreases. When the frequency decreases, the voltage attenuation between the resistance value at 50 Hz and the resistance value calculated at a certain frequency also decreases (because the resistance value is proportional to the frequency). Therefore, when the resonance frequency decreases, the peak magnitude is less attenuated with the skin effect.

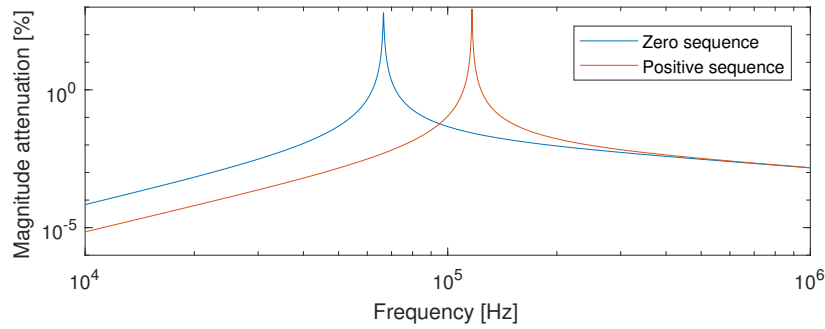


Figure 3.10: Percentage of magnitude attenuation when using a fixed resistance or variable resistance value for an EAXeVB 150² of 100 meters long

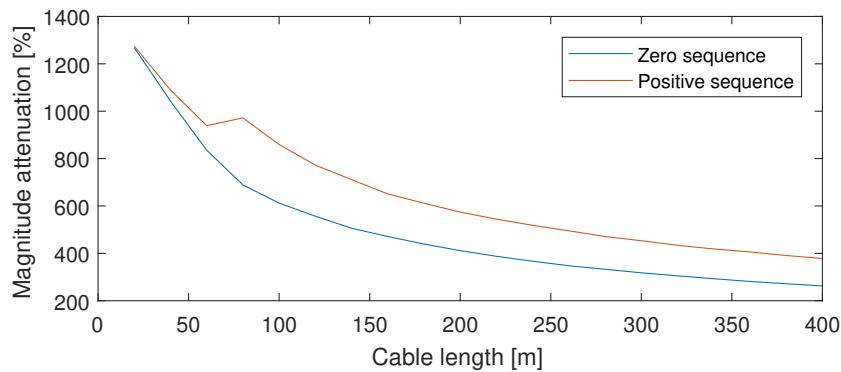


Figure 3.11: Attenuation in percent of the resonance peak for an EAXeVB 150² cable of 100 meters long

3.3.1 Skin effect resistance value summary

Section 3.3 highlights the influence of the skin effect on cable frequency response. Two main results are relevant.

Firstly, the skin effect has a significant impact on the resonance peak magnitude. Its attenuation increases with the resonance frequency. It is due to the increment of the resistance value with the frequency due to the skin effect. Secondly, using a fixed resistance value at 50 Hz or a frequency variable resistance has almost no impact on the magnitude outside the resonance frequency area.

3.4 Cable frequency behaviour summary

The frequency response of the cable analysis is useful to understand the CD propagation. One can imagine a voltage disturbance on one side of a cable, its response on the other side can be calculated thanks to this analysis.

First of all, the A and B chain matrix components frequency response is characterised by a resonance frequency on which the signal is amplified. Their resonance frequencies decrease with the cable length. Furthermore, the zero sequence disturbances have a smaller resonance frequency

than a positive/negative sequence one.

Afterwards, for B and C, the positive/negative sequence magnitude at 10 kHz is higher than the zero sequence magnitude.

Then, the skin effect has no impact on the resonance frequency but only decreases its peak magnitude. Moreover, the attenuation decreases with the cable length. Eventually, it almost does not have any impact on the magnitude outside the resonance frequency area.

Main sources of conducted disturbances between 2 and 150 kHz

In the context of climate change, new energy sources and energy saving devices are emerging. PV panels, CFL, small wind turbines are some examples of what is going to be more present on the grid. All these devices use power electronics send CD on the grid. According to [15], it can be modelled by a voltage or a current source followed by a filter. The CD sources can be separated into three categories.

- The single-phase active inverter (two-level and three-level)
- The three-phase active inverter
- The diode rectifier followed by an APFC (active power factor correction)

In this chapter, the operation explanation of an active inverter and a diode rectifier followed by an APFC is given. The origin of the CD coming from these power electronics devices is explained. Furthermore, a simplified model of these disturbances sources is proposed from [15].

For the inverters, three filters are studied: L, LC and LCL filters. Their design is made as well as their performance comparison. For the APFC followed by a diode rectifier, an EMI filter is also designed. The difference between them is that the inverter filter is designed for blocking frequency components above 50 Hz and the APFC followed by a diode rectifier is designed for blocking frequency components above 150 kHz.

4.1 Self-commutated inverters

The power electronics are responsible for sending the CD on the grid. The working principle of these devices is explained in order to understand how these disturbances are created.

An inverter is a circuit which converts a DC power into an AC power at desired output voltage or current and frequency. It is constituted by switches made of a bipolar transistor in parallel with a diode. When the transistor conducts, the voltage across the diode is null. Otherwise, the voltage across the diode is positive. The modulation controls the opening and closing of these switches.

The active modulation used to control the switches is the Pulse Width Modulation (PWM). It works with two signals. The first one is a saw tooth signal with a carrier frequency. The second one is a sinewave signal with the modulation frequency equal to the grid frequency when the device is connected to the grid. These two signals are shown in Figure 4.1. Every time the modulation wave crosses the triangular signal, the switching mode changes (from on to off and vice versa).

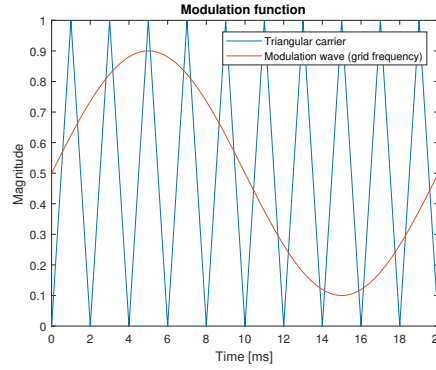


Figure 4.1: PWM signals

4.1.1 Single-phase active inverter

The single-phase active inverter can be made of two configurations: the half-bridge (two-level single-phase active inverter) and the full-bridge (three-level single-phase active inverter) configurations. These two circuits are respectively shown in Figure 4.2. The second one is the most common one. The half-bridge output voltage V_s stands between 0 and E and the full-bridge output voltage varies between $-E$ and E .

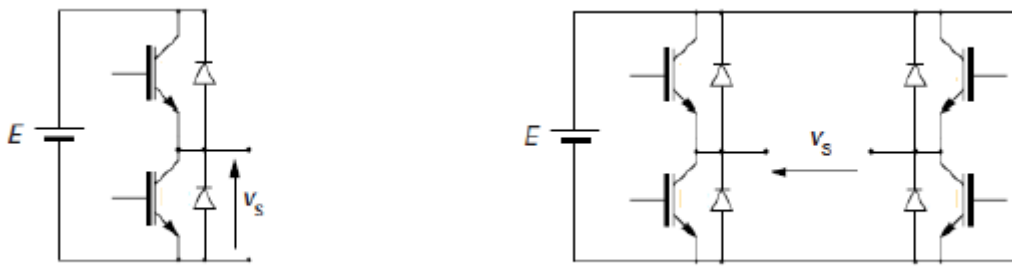


Figure 4.2: Single-phase active inverter circuits [30]

The disturbance frequencies sent by the inverter depend on its parameters. These parameters are listed on Table 4.1. They allow us to know the amplitude, the phase and the frequency components of the signal sent to the grid by the inverter. For each configuration, a double Fourier series is made to obtain the output voltage of the inverter since the PWM uses two signals. It allows calculation of the output voltage as done in [15].

For the **two-level single-phase active inverter**, the output voltage is given by Equation 4.1

ω_c	Carrier frequency
ω_s	Modulation frequency
ϕ	Modulation phase
$k = \frac{\omega_c}{\omega_s}$	Frequency ratio
r	Modulation wave magnitude
V_{in}	Input DC voltage

Table 4.1: Inverter parameters

[15].

$$\begin{aligned}
v_{out}(t) = & rV_{in}\sin(\omega_s t + \phi) + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \\
& \left(\frac{2(1 + (-1)^n)}{\pi m} \sin\left(\frac{m\pi}{2}\right) V_{in} J_n\left(mr\frac{\pi}{2}\right) \cos\left((mk + n)\omega_s t + \phi\right) + \right. \\
& \left. \frac{2(1 - (-1)^n)}{\pi m} \cos\left(\frac{m\pi}{2}\right) V_{in} J_n\left(mr\frac{\pi}{2}\right) \sin\left((mk + n)\omega_s t + \phi\right) \right)
\end{aligned} \tag{4.1}$$

Thanks to equation 4.1, one can find the output frequency components sent by the two-level inverter. They are given in Equation 4.2 if Equation 4.3 is respected. The parameters m and n are positive integers.

$$f_{mn} = (mk \pm n)\omega_s \tag{4.2}$$

$$\begin{cases} n \text{ odd} \rightarrow m \text{ even} & (\text{example : } n = 1 \rightarrow m = 0, 2, 4, \dots) \\ n \text{ even} \rightarrow m \text{ odd} & (\text{example : } n = 2 \rightarrow m = 1, 2, 3, \dots) \end{cases} \tag{4.3}$$

The output voltage of the **three-level single-phase active inverter** is given by Equation 4.4 [15].

$$\begin{aligned}
v_{out}(t) = & rV_{in}\sin(\omega_s t + \phi) + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \\
& \left(\frac{2(1 - (-1)^n)}{\pi m} \cos\left(\frac{m\pi}{2}\right) V_{in} J_n\left(mr\frac{\pi}{2}\right) \sin\left((mk + n)\omega_s t + \phi\right) \right)
\end{aligned} \tag{4.4}$$

The frequency components are given by Equation 4.5. The parameter m is a positive even integer and the parameter n is a positive odd integer.

$$f_{mn} = (mk \pm n)\omega_s \tag{4.5}$$

4.1.2 Three-phase active inverter

The three-phase active inverter convert a DC voltage into a three-phase AC voltage. The output phase-to-neutral voltage stands between $-E$, 0 and $+E$ with a phase shift of 120° between signals. The phase voltage can take the values of 0 , $\pm \frac{E}{3}$ and $\pm \frac{2E}{3}$.

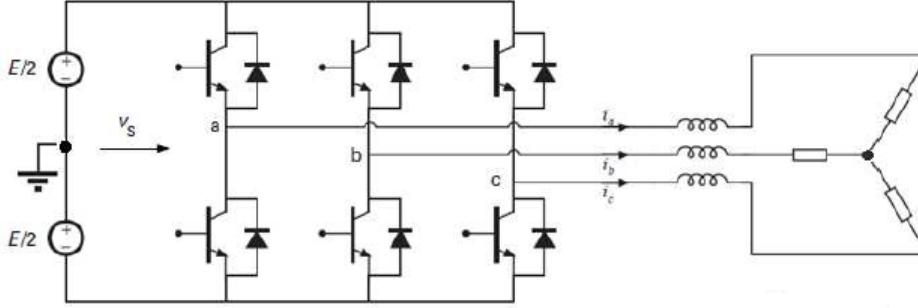


Figure 4.3: Three-phase active inverter circuit [30]

According to [15], the **three-phase active inverter** phase voltage is given in Equation 4.6.

$$\begin{aligned}
 v_{AB}(t) = & \frac{\sqrt{3}rV_{in}}{2} \sin(\omega_s t + \phi - \frac{\pi}{3}) + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \\
 & \left(\frac{-2(1 + (-1)^n)V_{in}}{\pi m} \sin(\frac{m\pi}{2}) \sin(\frac{n\pi}{3}) J_n(mr\frac{\pi}{2}) \right. \\
 & \cos\left((mk + n)\omega_s t + n\phi - \frac{n\pi}{3}\right) + \frac{2(1 - (-1)^n)V_{in}}{\pi m} \\
 & \left. \cos(\frac{m\pi}{2}) \sin(\frac{n\pi}{3}) J_n(mr\frac{\pi}{2}) \sin\left((mk + n)\omega_s t + n\phi - \frac{n\pi}{3}\right) \right)
 \end{aligned} \tag{4.6}$$

The phase-to-neutral voltage is calculated with Equation 4.7.

$$\begin{aligned}
 v_{An}(t) = & \frac{rV_{in}}{2} \sin(\omega_s t + \phi) + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \\
 & \left(\frac{-4(1 + (-1)^n)V_{in}}{3\pi m} \sin(\frac{m\pi}{2}) \sin^2(\frac{n\pi}{3}) J_n(mr\frac{\pi}{2}) \cos\left((mk + n)\omega_s t + n\phi\right) + \right. \\
 & \left. \frac{4(1 - (-1)^n)V_{in}}{3\pi m} \cos(\frac{m\pi}{2}) \sin^2(\frac{n\pi}{3}) J_n(mr\frac{\pi}{2}) \sin\left((mk + n)\omega_s t + n\phi\right) \right)
 \end{aligned} \tag{4.7}$$

The frequency components are given by Equation 4.8 when conditions of Equation 4.9 are

respected. The parameters m and n are positive integers.

$$f_{mn} = (mk \pm n)\omega_s \quad (4.8)$$

$$\begin{cases} n & \neq \text{multiple of } 3 & (n \neq 3, 6, 9, \dots) \\ m \text{ odd} \rightarrow & n \text{ even} & (\text{example : } m = 1 \rightarrow n = 0, 2, 4, 8, \dots) \\ m \text{ even} \rightarrow & n \text{ odd} & (\text{example : } m = 2 \rightarrow h = 1, 5, 7, 11, \dots) \end{cases} \quad (4.9)$$

The frequency components of the three line-to-neutral voltages have the same magnitude. Their phases are the same if n is a multiple of 3 but in this case, their magnitude is zero. Therefore, there is no zero sequence component. With k a positive integer going from zero to infinity, the voltages are positive sequence voltages if $n = 3k+1$ and they are negative sequence voltages if $n = 3k-1$ (Section 2.5.1).

4.1.3 Inverter filter design

The signal at the end of the inverter is made up of several different frequencies and does not look like a 50 Hz sinus. It is needed to add a filter between the inverter and the grid.

According to [31], three different filters can be used to attenuate CD due to power electronics: L, LC and LCL filters. Their transfer functions are depicted in Figure 4.4. All these filters have the same behaviour; they are low pass filters.

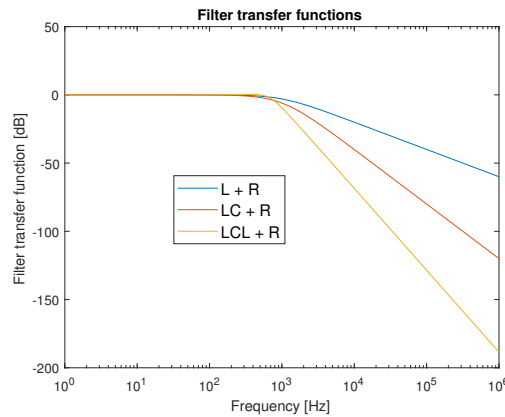


Figure 4.4: Typical transfer function of L, LC and LCL filters when they are connected to a resistance

Without connection to the grid, the theoretical attenuation for each filter is given in Table 4.2.

L	20 dB/decade
LC	40 dB/decade
LCL	60 dB/decade

Table 4.2: Ideal filter attenuation

In reality, the grid impedance has an impact on the filter transfer function. Figure 4.5 shows the transfer function for a filter connected to an EAXeVB 95² cable of 1 km and a damping resistance. With the low voltage grid cable, the transfer function of Figure 4.5 behaves differently from the one of Figure 4.4.

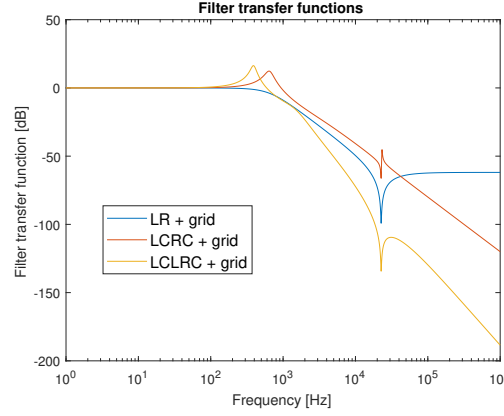


Figure 4.5: L, LC and LCL filter transfer function when they are connected to the grid

In this section, the L, LC and LCL filters are designed to ensure a good filtering when it is connected to a LV distribution cable. All the simulations are performed for a two-level single-phase active inverter with a switching frequency of 17.5 kHz.

L filter

The L filter is the most simple filter. It is made of an inductance. A simple way to design this filter is to connect a load modelled as a resistance as in Figure 4.6. The problem with this method is that we do not connect a resistance in reality but a cable. In high frequencies, the cable inductive reactance is not negligible. This configuration is depicted in Figure 4.7. In the last configuration (Figure 4.8), a resistance is added in series with inductance to damp the filter.

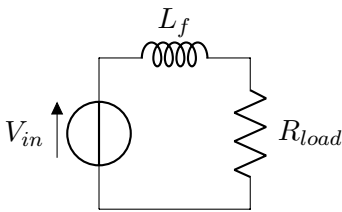


Figure 4.6: L + R

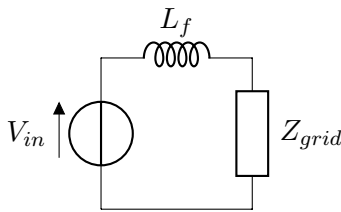


Figure 4.7: L + grid

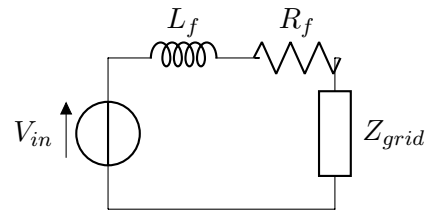


Figure 4.8: LR + grid

Figure 4.9 shows the transfer functions of these three configurations.

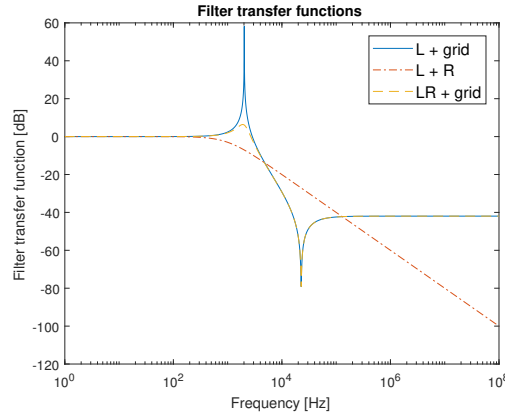


Figure 4.9: L filter transfer functions

If the filter is connected to a load, its transfer function is calculated with Equation 4.10.

$$\frac{V_{out}}{V_{in}} = \frac{R_{load}}{R_{load} + j\omega L_f} = \frac{1}{1 + j\omega \frac{L_f}{R_{load}}} = \frac{1}{1 + j\frac{\omega}{\omega_0}} \quad (4.10)$$

The cutoff frequency is expressed in function of the filter inductance and the load resistance according to Equation 4.11

$$f_0 = \frac{R_{load}}{2\pi L_f} \quad (4.11)$$

To design this filter, the cutoff frequency is chosen to be between the grid frequency and the PWM carrier frequency. The load resistance is fixed and therefore the filter inductance can be calculated.

If the filter is connected to the grid and if it is damped, the transfer function becomes :

$$\frac{V_{out}}{V_{in}} = \frac{Z_{grid}}{Z_{grid} + R_f + j\omega L_f} \quad (4.12)$$

Z_{grid} being variable depending on the grid impedance, the filter is not designed in function of this parameter.

The inductance value is chosen to limit the output current ripple by 10 % of the nominal current amplitude. It can be calculated according to the Equations 4.13 and 4.14 derived from [31] with parameters listed in Table 4.3.

$$L_f = \frac{\sqrt{3}U_n}{16f_{sw}\Delta I_{L,f,max}} \quad (4.13)$$

$$\Delta I_{L,f,max} = 0.1 \frac{\sqrt{2}P_n}{U_n} \quad (4.14)$$

U_n	Nominal grid voltage	230	V
f_{sw}	Switching frequency	17.5	kHz
P_n	Nominal inverter power	3100[32]	W
f_0	Cutoff frequency	1	kHz

Table 4.3: Values of the equation 4.13 and equation 4.14

Then, the resistance value is found with the cutoff frequency. Indeed, the resistance is chosen to dominate the impedance until the cutoff frequency where the inductance reactance is getting more significant. This rule is used to let the resistance damping the peak at the resonant frequency. Mathematically, we calculate the resistance with Equation 4.15.

$$R_f = 2\pi f_0 L_f \quad (4.15)$$

With the values given in Table 4.3, the filter inductance value is $L_f = 13$ mH. The cutoff frequency $f_0 = 1$ kHz and the resistance is $R = 82 \Omega$. Voltage frequency components values obtained from simulations are listed in Table 4.4.

Frequency [Hz]	$V_{inverter}$ [Volt]	V_{grid} [Volt]
17400	97.18	1.33
17500	255	3.45
17400	97.19	1.3
$I_{R,50Hz}$	0.034	A
THD_{out}	1.23	%

Table 4.4: Values obtained with L filtering

With this filter, CD are very well attenuated (98.65 % for the switching frequency component). Furthermore, the power dissipated in the resistance is $P_R = 82 \times 0.034^2 = 94.8mW$, which is negligible considering the inverter power of 3.1 kW.

LC filter

The LC filter connected to a load is depicted in Figure 4.10. In Figure 4.11, the filter is connected to the grid. The problem with this configuration is the resonance caused by the capacitance and the inductance. The solution is to add a resistance in parallel. To limit losses in the resistance ($P_{loss} = \frac{V^2}{R} > P_{inverter}$), a capacitance is added in series with the resistance as in Figure 4.12 to limit the current in the resistance. Figure 4.13 shows the transfer function for these three configurations.

Without any connection, the LC filter transfer function is given in Equation 4.16.

$$\frac{V_{out}}{V_{in}} = \frac{1}{(j\omega)^2 L_f C_f + 1} \quad (4.16)$$

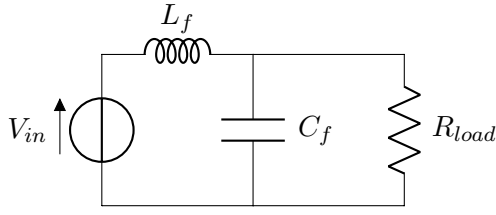


Figure 4.10: LC + R

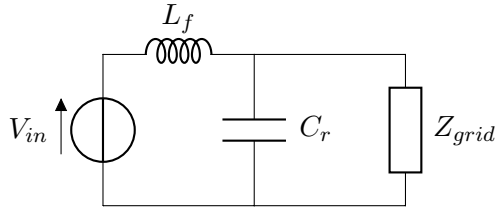


Figure 4.11: LC + grid

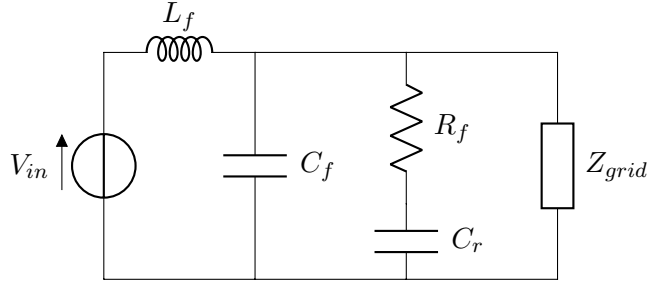


Figure 4.12: LCLRC + grid

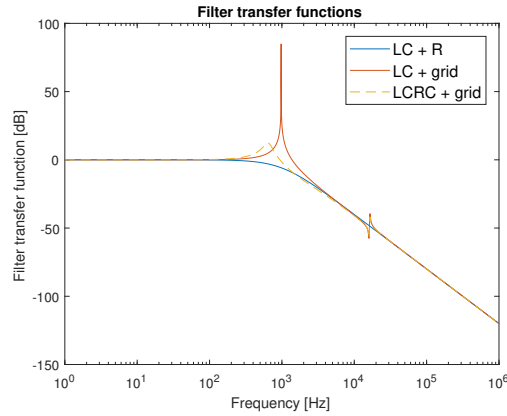


Figure 4.13: LC filter transfer functions

With the Equation 4.16, the cutoff frequency is calculated with Equation 4.17.

$$f_0 = \frac{1}{2\pi} \frac{1}{\sqrt{L_f C_f}} \quad (4.17)$$

To design this filter, L_f and C_f must be calculated. In [31], they firstly determine the value of C_f by imposing it at 5 % the base capacitance value ($C_f = 0.05 C_b$ ¹). This value comes from the fact that the maximum power factor variation for the grid is 5 %. With the values of Table 4.5, the filter capacitance value is $C_f = 9.33 \mu F$. Therefore, one can compute the filter inductance value $L_f = 2.7 mH$ with the cutoff frequency.

Eventually, the damping resistance must be calculated. To do that, the capacitance in series

¹ $Z_B = \frac{U_b^2}{S_n}$ and $C_b = \frac{1}{\omega_b Z_b}$

with the resistance is neglected. With this approximation, the filter transfer function is given by Equation 4.18.

$$\frac{V_{out}}{V_{in}} = \frac{1}{L_f C_f} \frac{1}{(j\omega)^2 + j\omega \frac{1}{R_f C_f} + \frac{1}{L_f C_f}} = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{r} s + \omega_0^2} \quad (4.18)$$

With $\omega_0 = \frac{1}{\sqrt{L_f C_f}}$, the resistance value is computed with Equation 4.19.

$$R_f = Q \sqrt{\frac{L_f}{C_f}} \quad (4.19)$$

Q is the quality factor, its value is $Q=0.5$ to damp critically the peak.

The impedance of C_r at the resonance frequency must be smaller than the resistance R_f to allow the damping. Mathematically, this condition gives:

$$R \geq \frac{1}{2\pi f_0 C_r} \quad (4.20)$$

If $k \leq 1$, the filter capacitance in series with resistance is given by Equation 4.21.

$$C_r = \frac{k}{2\pi f_0 R} \quad (4.21)$$

k is chosen to be sufficiently high to limit the current flowing through the resistance and decrease the losses in the the resistance. But if it is too small, the resonance peak is not sufficiently damped. The purpose here is to find a trade-off between a high k which damps the resonance peak and a high k which decreases the Joule losses in the resistance.

U_b	Base grid rms voltage	230	Volt
S_b	Base inverter apparent power	3100 [32]	VA
$Z_b = \frac{U_b^2}{S_b}$	Base impedance	17	Ω
f_{grid}	Grid frequency	50	Hz
$C_b = \frac{1}{2\pi f_{grid} Z_b}$	Base capacitance	186	μF
f_0	Filter cutoff frequency	1	kHz
Q	Q factor	0.5	[-]
k	$k = \frac{2\pi f_0 C_r}{R}$	0.01	[-]

Table 4.5: Values used to design the LC filter

The values of the filters parameters calculated using Table 4.5 values are listed in Table 4.6.

Values obtained from simulations are listed in Table 4.7.

The switching frequency component is attenuated by 99.29%. The power dissipated into the

L_f	2.7	mH
C_f	9.33	μF
R_f	8.53	Ω
C_r	13.6	μF

Table 4.6: LCRC filter parameter values

Frequency [Hz]	$V_{inverter}$ [Volt]	V_{grid} [Volt]
17400	97.18	0.69
17500	255	1.82
17600	97.19	0.7
$I_{R,50Hz}$	0.98	A
THD_{out}	0.64	%

Table 4.7: Values obtained with LC filtering

resistance and the capacitance is calculated in Equation 4.22.

$$S_r = \frac{U^2}{R + \frac{1}{j\omega C_r}} = 8.23 + j225.7 \text{ VA} \quad (4.22)$$

LCL filter

The LCL filter connected to a load is depicted in Figure 4.14, the same filter connected to the grid is shown in Figure 4.15 and eventually the LCL filter damped and connected to the grid is depicted in Figure 4.16. Figure 4.17 shows the filter transfers function for these three filter configurations.

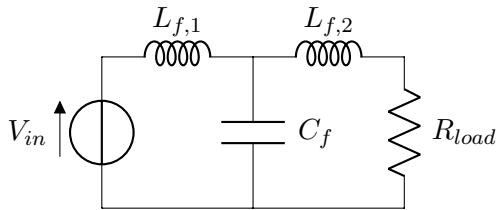


Figure 4.14: LCL + R

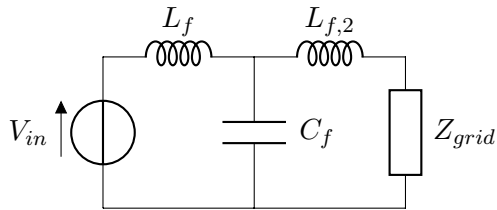


Figure 4.15: LCL + grid

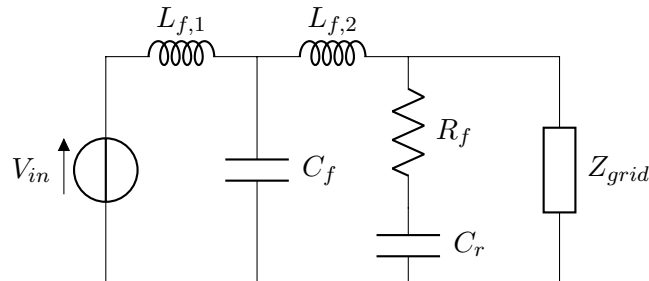


Figure 4.16: LCLR filter

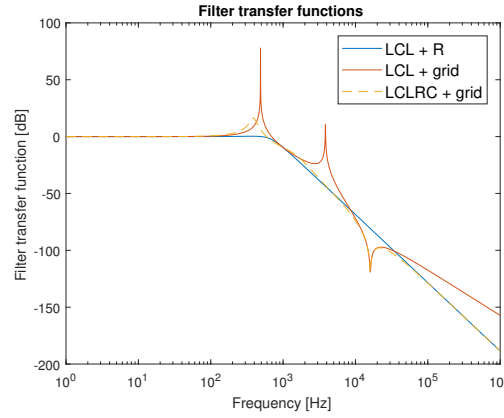


Figure 4.17: LCL filter transfer functions

The transfer function of a LCL filter alone when the output voltage is null (the output is in short circuit) is given in Equation 4.23.

$$\frac{i_{out}}{V_{in}} = \frac{1}{(j\omega)^3 L_{f,1} L_{f,2} C_f + j\omega(L_{f,1} + L_{f,2})} \quad (4.23)$$

The cutoff frequency f_0 is calculated with Equation 4.24.

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{L_{f,1} + L_{f,2}}{L_{f,1} L_{f,2} C_f}} \quad (4.24)$$

The design of this filter is similar to the LC filter design. The filter capacitance is calculated exactly in the same manner and has the same value ($C_f = 9.33\mu F$).

Afterwards, the relation between the two inductance values is shown in Equation 4.25. In [31], they choose the value of r equal to $\frac{1}{3}$.

$$L_{f,2} = r L_{f,1} \quad (4.25)$$

The inductance values are found by solving the cutoff frequency Equation 4.24 with Equation 4.25. Calculated values are : $L_{f,1} = 10.86mH$ and $L_{f,2} = 3.62mH$ for a cutoff frequency of 1kHz.

The resistance is calculated to have a critical damping ($Q=0.5$) according to Equation 4.26.

$$R_f = \frac{1}{Q} \sqrt{\frac{L_{f,1} L_{f,2}}{C_f (L_{f,1} + L_{f,2})}} \quad (4.26)$$

With previous parameters we find $R_f = 34.13\Omega$.

Finally, as done for the LC filter, the impedance of C_r at the resonant frequency must be smaller

than the resistance R_f to allow the damping.

$$C_r = \frac{k}{2\pi f_0 R} \quad (4.27)$$

For the LCL filter, the value of $k=0.001$ is used. This value results from a trade-off as explained for the LC filter.

The values of the filters parameters calculated using Table 4.5 values are listed in Table 4.8.

$L_{f,1}$	10.86	mH
$L_{f,2}$	3.62	mH
C_f	9.33	μF
R_f	34.13	Ω
C_r	5.4	μF

Table 4.8: LCLRC filter parameter values

The frequency component values obtained from simulations are listed in Table 4.9.

Frequency [Hz]	$V_{inverter}$ [Volt]	V_{grid} [Volt]
17400	97.18	0.004
17500	255	0.01
17600	97.19	0.004
$I_{R,50Hz}$	0.4	A
THD_{out}	0.54	%

Table 4.9: Values obtained with LCL filtering

The switching frequency component is attenuated by 99.996 %. The power dissipated into the resistance and the capacitance is given by Equation 4.28.

$$S_r = \frac{U^2}{R + \frac{1}{j\omega C_r}} = 5.18 + j89.44 \text{ VA} \quad (4.28)$$

Inverter filter conclusion

Three filters were studied : L, LC and LCL filter. Their behaviour and their design were deepened.

First of all, we learnt that adding a resistance in parallel enable to damp the signal. To avoid losses, a capacitance is put in series with this resistance. Indeed, the current flowing through the resistance decreases with the capacitance value. Then, the L filter is more sensitive to the grid impedance, causing its transfer function to remain constant after the second resonance. Eventually, the LCL dissipated power, switching frequency component attenuation and total harmonics distortion are lower than the LC filter. For these reasons, the LCL filter is the best filter.

However, when performing simulations, the attenuation of the LCL filter is very high. The signal values after the cutoff frequency are so small that the voltage transfer between cable are wrong

with Simulink. Therefore, in this work, the LC filter will be used.

4.2 Diode rectifier followed by an APFC

4.2.1 Current source model

In the previous section, inverter working principle and modelling is developed. Inverter family constitutes the first main CD source category. A second main source of CD category in power electronics is the combination of a rectifier and an APFC.

The diode rectifier alone is not a source of disturbances between 2 and 150 kHz. Indeed, it generates harmonics but below 2 kHz. However, its capacitance is victim a of CD [33].

An APFC followed by a diode rectifier is a source of CD. The disturbances sent by the APFC propagate through the diode rectifier to the grid. In this section, these two circuits role is explained. Moreover, a simplified model of this circuit combination is given.

The rectifier is used to convert an AC power into DC one. One popular configuration is the four-diode bridge configuration. This circuit is represented in Figure 4.18, with V_{rect} the output voltage rectified by the circuit. Without any filtering element, this voltage is equal to $V_{rect} = V_{peak,AC}|\sin(\omega_g t)|$, ω_g is the grid angular frequency, $V_{peak,AC}$ the grid peak voltage and V_{AC} the grid voltage.

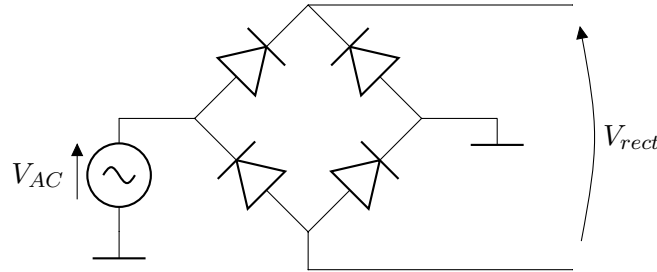


Figure 4.18: Full-wave bridge diode rectifier

The most common circuit used as APFC is the boost converter [34]. This circuit is depicted in Figure 4.19. This converter provides stable DC voltage at the output with good input power factor. It is used to meet the need of good power quality which satisfy standards [35].

The duty cycle of the boost θ is controlled in order to keep the output voltage V_{DC} constant and to provide a constant ratio between the instantaneous value of the inductance current and of the rectified voltage [36]. With R_{equ} a constant, this relation is given by Equation 4.29.

$$\frac{V_{rect}}{i_L} = R_{equ} \quad (4.29)$$

The combination of the rectifier and the APFC can be modelled with a current source. This

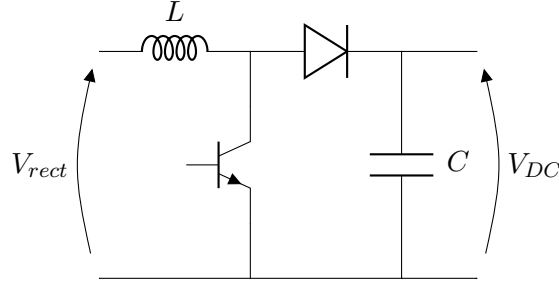


Figure 4.19: APFC boost rectifier

current source is controlled by Equation 4.30 [36]. In order to lighten this section, all the parameters of this equation are developed in Annex F.

$$\begin{aligned}
 i_g(t) = \frac{v_g}{R_{eq}} + \sum_{m=1}^{\infty} \sum_{\alpha=-\infty}^{\infty} \sum_{h=1}^{\infty} \frac{2}{\pi} \times & \left[\left(\frac{I_{m(\alpha+h)}}{h} \cos(\psi_{m(\alpha+h)}) \right. \right. \\
 & - \left. \frac{I_{m(\alpha-h)}}{h} \cos(\psi_{m(\alpha-h)}) \right) \times \cos(m\omega_{sw}t + \alpha\omega_g t) - \left(\frac{I_{m(\alpha+h)}}{h} \sin(\psi_{m(\alpha+h)}) \right. \\
 & \left. \left. - \frac{I_{m(\alpha-h)}}{h} \sin(\psi_{m(\alpha-h)}) \right) \times \sin(m\omega_{sw}t + \alpha\omega_g t) \right] \quad (4.30)
 \end{aligned}$$

The frequency components are given by Equation 4.31. In this equation, m is a positive non-zero integer and α is an odd integer.

$$f_{m,\alpha} = m f_{sw} + \alpha f_{grid} \quad (4.31)$$

4.2.2 EMI filter design

This current source is always followed by an EMI filter. Indeed, disturbances must stand below the limit imposed by standards above 150 kHz. Therefore, a filter is required between the current source and the grid.

The filter design is presented in this section. It must satisfy the CISPR22 standard which specifies the quasi-peak voltage limit between 150 kHz and 30 MHz for CD [37].

Figure 4.20 shows the quasi-peak voltage limitations between 150 and 750 kHz. This voltage limitation in function of the frequency is given by Equation 4.32 between 150 and 500 kHz.

$$v_{limit}(f) = -2.857 \times 10^{-5} f + 70.28 \text{ [dB}\mu\text{V]} \quad (4.32)$$

To design an appropriate EMI filter, the first component appearing after 150 kHz f_1 must be determined. It can be calculated thanks to Equation 4.30. The filter is a LC filter (depicted in Figure 4.21). Its transfer function magnitude decreases by 40 decibels per decade after the cutoff

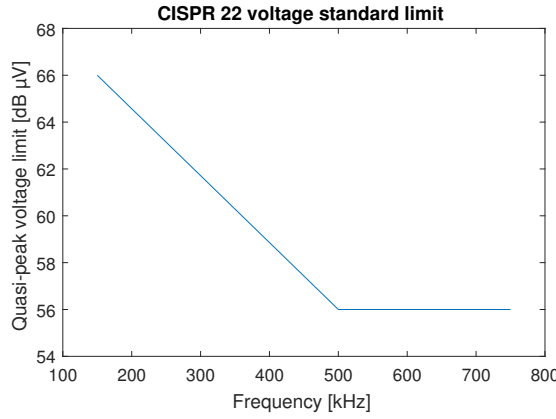


Figure 4.20: Voltage limit of the CISPR 22 standard

frequency f_0 (Figure 4.22). This cutoff frequency is computed for an LC filter with the capacitance and the inductance value using Equation 4.33.

$$f_0 = \frac{1}{2\pi\sqrt{L_f C_f}} \quad (4.33)$$

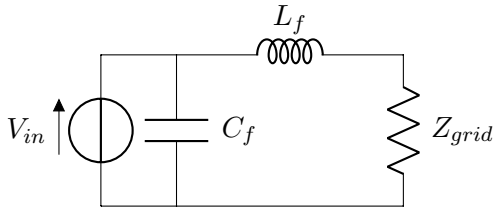


Figure 4.21: LC filter

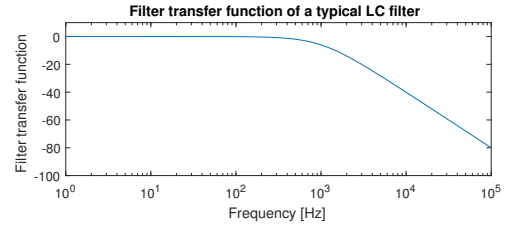


Figure 4.22: LC filter transfer function

The magnitude of the first component sent by the combination of the rectifier and the APFC after 150 kHz is called $v_{disturbance,f1}$. The quasi-peak voltage limitation at this frequency is denoted by $v_{limit,f1}$. A certain margin between these two magnitudes of $\Delta v_{threshold} = 3 \text{ dB}$ is chosen. Therefore, the attenuation that the filter must achieve at f_1 is calculated with Equation 4.34.

$$\Delta v = v_{disturbance,f1} - v_{limit,f1} + \Delta v_{threshold}^2 \quad (4.34)$$

Since the attenuation is 40 decibels per decade, the cutoff frequency of the filter is computed thanks to Equation 4.35.

$$f_0 = \frac{f_1}{10^{\frac{\Delta v}{40}}} \quad (4.35)$$

The design of a LC filter in function of the cutoff frequency is presented in Section 4.1.3. This method will be used to calculate the parameters of the EMI filter in function of the cutoff frequency

²[dBμV] - [dBμV] = [dB]

calculated with Equation 4.35.

4.2.3 Rectifier and APFC combination summary

As a short summary, the combination of a rectifier and an APFC is a source of CD between 2 and 150 kHz. This combination can be modelled by a current source in parallel with an EMI filter. The current source is controlled by Equation 4.30. The EMI filter is made of an inductance and a capacitance. Its design is made to satisfy CISPR22 standard which limits CD above 150 kHz. Its design is developed in Section 4.2.2.

Method to study the conducted disturbances propagation

Up to now, a complete distribution cable model has been elaborated. Next, the frequency response of the cables have been studied to better understand their frequency response in positive/negative and zero sequences. After that, CD source models have been proposed. Now, let's develop a method to study the CD propagation.

The CD source is connected to a simple realistic grid. Furthermore, the CD source is assumed to be the only source of disturbance on the grid. The grid consists on a connection cable connected to a power cable, a transformer and a MV source. The schematic of this configuration is represented in Figure 5.1.

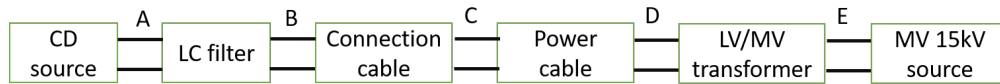


Figure 5.1: Simple grid diagram

In this chapter, a method using the symmetrical components to study the CD propagation is presented. These components were previously developed in Section 2.5.1 for the cables. To be complete, the symmetrical components of the other elements of the grid are given in the first section of this chapter.

The method of symmetrical components is widely used by the grid operator to simplify fault analysis. In this work, the CD voltage or current sources are handled as "fault". As an example, for single-phase-to-neutral fault, the fault impedance is replaced by the CD voltage source (or the CD current) as depicted in Figures 5.2 and 5.3.

Three different disturbances are studied in this chapter. The first one occurs when the three phases of a cable are connected to a balanced CD source (that's the case with a three-phase active inverter). The second case happens when the CD source is connected between one phase and the neutral of a cable. For example with a single-phase active inverter or an APFC followed by a diode rectifier. Eventually, the last case is when the CD source is connected between two phases of a cable (when the cable has only three conductors and no neutral).

One assumption is made in this chapter. The left-hand side seen from the CD source is not

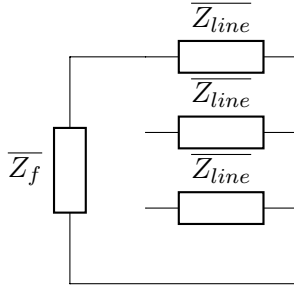


Figure 5.2: Single-phase-to-neutral fault

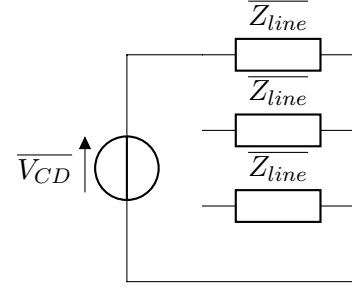


Figure 5.3: Single-phase-to-neutral disturbance

connected to any other devices, cable or load while the right-hand side is connected to the grid. This hypothesis is required to build the symmetrical component circuit.

First of all, a reminder of the symmetrical component is given. Then, the positive, negative and zero sequence schematic of the other grid elements are presented. Afterwards, the three disturbance cases are developed.

5.1 Reminder about the symmetrical components

The method of the symmetrical components is based on the fact that any set of quantities can be converted into symmetrical components with the Fortescue matrix. Setting $a = e^{j\frac{2}{3}\pi}$, the transformation is given by Equations 5.1 and 5.2 to convert ABC unbalanced phasors into symmetrical ones. Index zero corresponds to the zero sequence, index 1 to the positive sequence and index 2 to the negative sequence.

$$\begin{bmatrix} \overline{V}_0 \\ \overline{V}_1 \\ \overline{V}_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \overline{V}_a \\ \overline{V}_b \\ \overline{V}_c \end{bmatrix} \quad (5.1)$$

$$\begin{bmatrix} \overline{I}_0 \\ \overline{I}_1 \\ \overline{I}_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \overline{I}_a \\ \overline{I}_b \\ \overline{I}_c \end{bmatrix} \quad (5.2)$$

Inversely, the symmetrical components can be converted into ABC unbalanced phasors with Equations 5.3 and 5.4.

$$\begin{bmatrix} \overline{V}_a \\ \overline{V}_b \\ \overline{V}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} \overline{V}_0 \\ \overline{V}_1 \\ \overline{V}_2 \end{bmatrix} \quad (5.3)$$

$$\begin{bmatrix} \overline{I}_a \\ \overline{I}_b \\ \overline{I}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} \overline{I}_0 \\ \overline{I}_1 \\ \overline{I}_2 \end{bmatrix} \quad (5.4)$$

These transformations will be used in Section 5.3, 5.4 and 5.5. Before using them, the positive, negative and zero sequence single-phase equivalent circuits of the grid elements are given to allow simulations of a realistic grid.

5.2 Grid elements symmetrical components

Each element on the grid can be represented by a two-port network. In Section 2.5.1, the positive, negative and zero sequence two-port networks were developed for three-phase plus neutral cables.

A distribution network is constituted by cables, load and transformer. To be more complete, medium voltage source is added in the medium voltage side of the grid. In this section, the equivalent positive, negative and zero sequences of the two-port network are given for a transformer and a non-ideal MV source.

5.2.1 Transformer

The single-phase equivalent circuit of a non-ideal transformer is given in Figure 5.4. Its parameters are listed in Table 5.1. The primary side is the LV side.

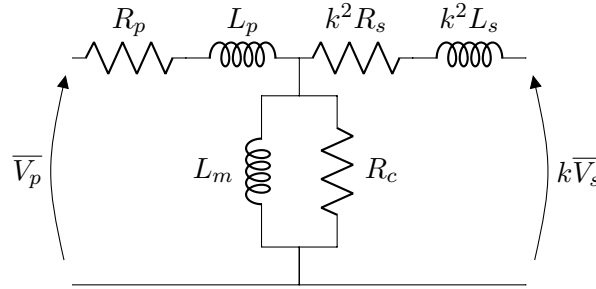


Figure 5.4: Equivalent non-ideal circuit of a transformer

R_p	Primary resistance
R_s	Secondary resistance
L_p	Primary leakage inductance
L_s	Secondary leakage inductance
k	Turn ratio
L_m	Magnetizing inductance
R_c	Core losses

Table 5.1: Equivalent non-ideal transformer parameters

In this work, the magnetizing inductance and the core resistance are assumed to be very high meaning that they are neglected and considered in open circuit. The LV transformer side is star connected with grounded neutral and delta connected in the MV side. The positive, negative and zero sequences are represented in Figures 5.5 and 5.6 for these three-phase connections.

$$\begin{aligned}
 R &= R_p + k^2 R_s \\
 L &= L_p + k^2 L_s
 \end{aligned}
 \tag{5.5}$$

The chain matrices associated to the symmetrical component of the transformer are given in

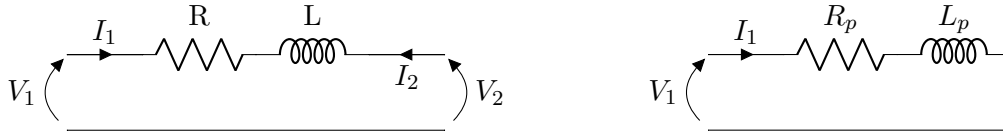


Figure 5.5: Positive/negative sequence of a transformer
Figure 5.6: Zero sequence of a transformer Yg/D1

Equation 5.6 for the positive and the negative sequences. Equation 5.7 gives the relation between $\overline{V}_1$ and $\overline{I}_1$ in zero sequence.

$$\begin{bmatrix} \overline{V}_1 \\ \overline{I}_1 \end{bmatrix} = \begin{bmatrix} 1 & R + j\omega L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{V}_2 \\ -\overline{I}_2 \end{bmatrix} \quad (5.6)$$

$$\overline{V}_1 = \overline{I}_1 (R_p + j\omega L_p) \quad (5.7)$$

5.2.2 Medium voltage three-phase source

The medium non-ideal voltage source is represented in Figure 5.7 with R_{source} its internal resistance and L_{source} its internal inductance. The voltage source is replaced by a short circuit because its 50 Hz component does not play a role in the CD propagation study.

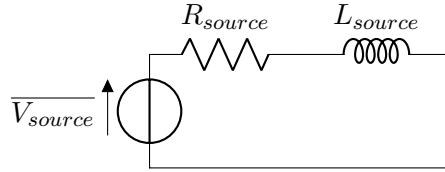


Figure 5.7: Non-ideal voltage source equivalent circuit

The ratio between the low and the medium voltages $k = \frac{400}{15000}$ is used to bring the parameters of the voltage source back in the primary LV side of the transformer. The positive, negative sequence circuits are represented in Figures 5.8.

The zero sequence equivalent circuit is the same as in Figure 5.8 if the voltage source is grounded. It is in open circuit if the voltage source is not grounded. The transformer is delta connected on its secondary side, therefore the zero sequence components of the secondary side do not flow to the primary side. Consequently, the zero sequence circuit will not be used in our case.

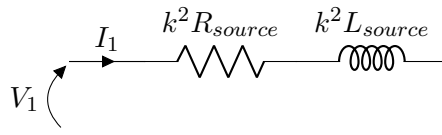


Figure 5.8: Positive and negative sequences of a non-ideal voltage source

The voltage of Figures 5.8 is calculated with Equation 5.8.

$$\overline{V}_1 = \overline{I}_1 (k^2 R_{source} + j\omega k^2 L_{source}) \quad (5.8)$$

5.3 Three-phase disturbance

A balanced phase-to-phase disturbance is presented in Figure 5.9. With this disturbance, the three voltage sources are balanced and not connected to the neutral. This disturbance corresponds to a three-phase active inverter connected to the three phases of a cable. As explained in Section 4.1.2, the three-phase active inverter only sends positive and negative sequence disturbances to the grid. Therefore, the disturbances can be either positive or negative sequence.

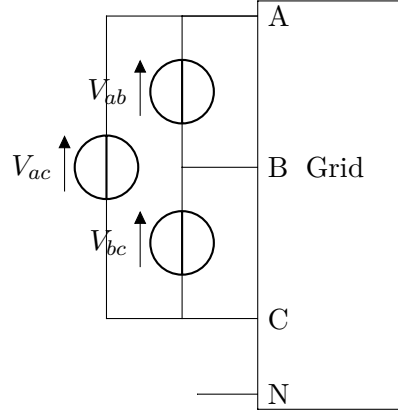


Figure 5.9: Three-phase disturbance

5.3.1 Theoretical approach

For the three-phase disturbance produced by a three-phase active inverter, a positive or a negative sequence voltage is applied on the three phases. The phase voltages are given in Equation 5.9 for the positive sequence and in Equation 5.10 for the negative sequence.

$$\begin{aligned}\overline{V_a} &= \overline{V_{a1}} \\ \overline{V_b} &= a^2 \overline{V_{a1}} \\ \overline{V_c} &= a \overline{V_{a1}}\end{aligned}\quad (5.9)$$

$$\begin{aligned}\overline{V_a} &= \overline{V_{a1}} \\ \overline{V_b} &= a \overline{V_{a1}} \\ \overline{V_c} &= a^2 \overline{V_{a1}}\end{aligned}\quad (5.10)$$

With the transformation of Equation 5.3, the symmetrical voltages are given by Equation 5.11 for a positive sequence disturbance and Equation 5.12 for a negative sequence disturbance. The simplification is done according to the following relation: $1 + a + a^2 = 0$.

$$\begin{aligned}\overline{V_0} &= \frac{1}{3}(\overline{V_a} + \overline{V_b} + \overline{V_c}) = \frac{1}{3}(\overline{V_a}(1 + a^2 + a)) = 0 \\ \overline{V_1} &= \frac{1}{3}(\overline{V_a} + a \overline{V_b} + a^2 \overline{V_c}) = \overline{V_a} \\ \overline{V_2} &= \frac{1}{3}(\overline{V_a} + a^2 \overline{V_b} + a \overline{V_c}) = \frac{1}{3}(\overline{V_a}(1 + a + a^2)) = 0\end{aligned}\quad (5.11)$$

$$\begin{aligned}
\overline{V}_0 &= \frac{1}{3}(\overline{V}_a + \overline{V}_b + \overline{V}_c) = \frac{1}{3}(\overline{V}_a(1 + a + a^2)) = 0 \\
\overline{V}_1 &= \frac{1}{3}(\overline{V}_a + a\overline{V}_b + a^2\overline{V}_c) = \frac{1}{3}(\overline{V}_a(1 + a^2 + a)) = 0 \\
\overline{V}_2 &= \frac{1}{3}(\overline{V}_a + a^2\overline{V}_b + a\overline{V}_c) = \overline{V}_a
\end{aligned} \tag{5.12}$$

With the same reasoning, the symmetrical currents can be calculated. Their values are given in Equation 5.13 for a positive sequence disturbance and in Equation 5.14 for a negative sequence disturbance.

$$\begin{aligned}
\overline{I}_a &= \overline{I}_1 \\
\overline{I}_0 &= \overline{I}_2 = 0
\end{aligned} \tag{5.13}$$

$$\begin{aligned}
\overline{I}_a &= \overline{I}_2 \\
\overline{I}_0 &= \overline{I}_1 = 0
\end{aligned} \tag{5.14}$$

With a positive sequence disturbance, the negative and the zero sequence current are null, therefore, only the positive sequence circuit is represented in the symmetrical circuit. This representation is shown in Figure 5.10. Since the positive and the negative sequence circuits are the same, Figure 5.10 is also available for a negative sequence disturbance.

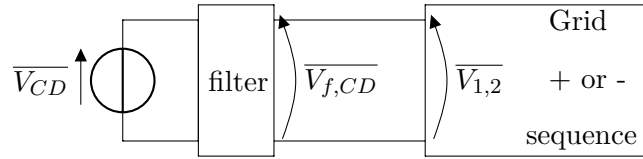


Figure 5.10: Positive or negative sequence of a balanced phase-to-phase disturbance

5.3.2 Computational method

To compute the CD propagation, the chain matrices of each element of the grid can be multiplied. Indeed, when two-port networks are put in series, their chain matrix can simply be multiplied to create a new two-port network chain matrix. This property is demonstrated in Annex B.

As a reminder, the chain matrix is given by Equation 5.15. The notations of the voltage and the current of the chain matrix has been modified to avoid the confusion between the chain matrix indexes and the symmetrical component ones.

$$\begin{bmatrix} \overline{V}_{in} \\ \overline{I}_{in} \end{bmatrix} = \begin{bmatrix} \overline{A} & \overline{B} \\ \overline{C} & \overline{D} \end{bmatrix} \begin{bmatrix} \overline{V}_{out} \\ -\overline{I}_{out} \end{bmatrix} \tag{5.15}$$

The phase voltages are computed respectively with Equation 5.16 and 5.17 for a positive and negative sequence disturbance.

$$\begin{aligned}\overline{V}_a &= \overline{V}_1 \\ \overline{V}_b &= a^2 \overline{V}_1 \\ \overline{V}_c &= a \overline{V}_1\end{aligned}\quad (5.16)$$

$$\begin{aligned}\overline{V}_a &= \overline{V}_2 \\ \overline{V}_b &= a \overline{V}_2 \\ \overline{V}_c &= a^2 \overline{V}_2\end{aligned}\quad (5.17)$$

To compute the current in each phase, the positive/negative sequence current must be calculated since $\overline{I}_{1,2} = \overline{I}_a$. The positive/negative sequence current is the positive/negative sequence voltage divided by the positive/negative sequence impedance as in Equation 5.18.

$$\overline{I}_{1,2} = \frac{\overline{V}_{1,2}}{\overline{Z}_{1,2}} \quad (5.18)$$

If the output side of the positive/negative sequence is left in open circuit, the output current is null. Therefore, the impedance seen by positive/negative sequence voltage is given by Equation 5.19.

$$\overline{Z}_{oc} = \frac{\overline{A}}{\overline{C}} \quad (5.19)$$

If the output side of the positive/negative sequence circuit is short circuited, the impedance seen by the positive/negative sequence voltage is calculated with Equation 5.20 since the output voltage is null.

$$\overline{Z}_{sc} = \frac{\overline{B}}{\overline{D}} \quad (5.20)$$

Eventually, with the positive/negative sequence current, the currents in each phase can be calculated with Equation 5.21 if the disturbance is a positive sequence and with Equation 5.22 if it is a negative sequence.

$$\begin{aligned}\overline{I}_a &= \overline{I}_1 \\ \overline{I}_b &= a^2 \overline{I}_1 \\ \overline{I}_c &= a \overline{I}_1\end{aligned}\quad (5.21)$$

$$\begin{aligned}\overline{I}_a &= \overline{I}_2 \\ \overline{I}_b &= a \overline{I}_2 \\ \overline{I}_c &= a^2 \overline{I}_2\end{aligned}\quad (5.22)$$

With these equations and the chain matrix of each grid element, the voltage and the current in each phases can be calculated analytically.

5.3.3 Simulation method and application case

After proposing an analytical calculation method for the voltages and the currents, the simulation approach is investigated. It uses positive, negative and zero sequence circuit to simulate the symmetrical component with a simulation tool.

The positive sequence circuit with the grid is depicted in Figure 5.11. It is made of a connection cable, a power cable, a transformer and a medium voltage source. The filter is the one calculated in Section 4.1.3.

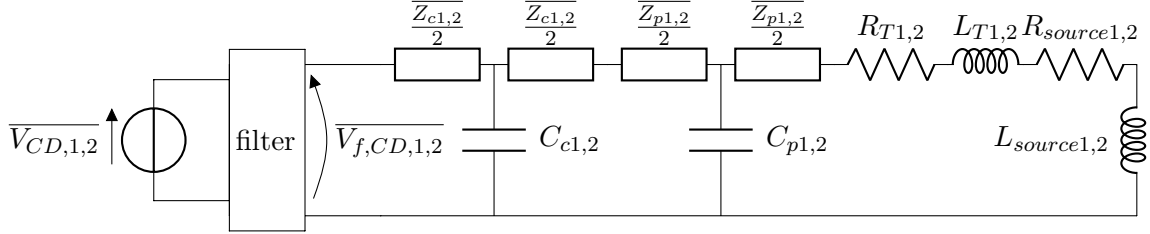


Figure 5.11: Positive sequence circuit of the phase-to-phase disturbance with the considered grid

The parameters appearing in Figure 5.11 are listed in Table 5.2.

$\overline{Z_c}$	Series impedance of the connection cable
$\overline{Z_p}$	Series impedance of the power cable
C_c	Equivalent impedance of the connection cable
C_p	Equivalent impedance of the power cable
R_T	Transformer resistance
L_T	Transformer leakage inductance
R_{source}	Non-ideal source resistance
L_{source}	Non-ideal source inductance

Table 5.2: Parameters corresponding to Figure 5.11

5.4 Single-phase-to-neutral disturbance

The second type of disturbance is the single-phase-to-neutral when a CD source is connected between one phase and the neutral. This case is represented in Figure 5.12.

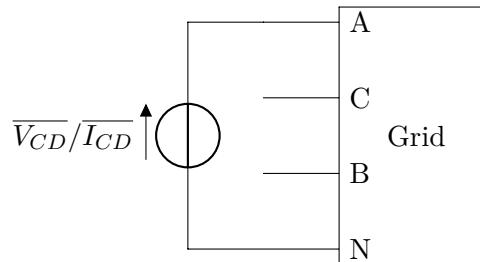


Figure 5.12: Single-phase-to-neutral disturbance

5.4.1 Theoretical approach

When analysing Figure 5.12, the phase currents can be written with Equation 5.23.

$$\begin{aligned}\overline{I}_a &\neq 0 \\ \overline{I}_b &= \overline{I}_c = 0\end{aligned}\tag{5.23}$$

With the transformation of Equation 5.4, the symmetrical currents are calculated in Equation 5.24.

$$\begin{aligned}\overline{I}_0 &= \frac{1}{3}(\overline{I}_a + \overline{I}_b + \overline{I}_c) = \frac{1}{3}\overline{I}_a \\ \overline{I}_0 &= \overline{I}_1 = \overline{I}_2 = \frac{1}{3}\overline{I}_a\end{aligned}\tag{5.24}$$

Since the symmetrical currents are equals, the positive, negative and zero sequence single-phase equivalent circuits are put in series. This configuration is shown in Figure 5.13.

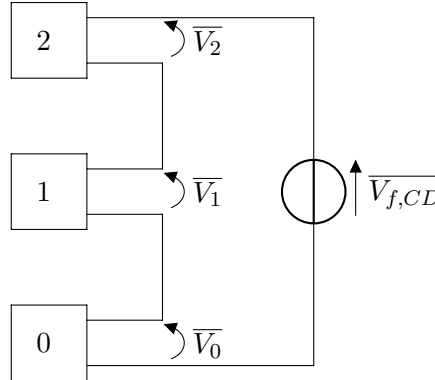


Figure 5.13: Phase-to-neutral positive, negative and zero sequence connection

The current in phase A is given by Equation 5.25. It is three times higher than the symmetrical currents.

$$\overline{I}_a = 3\overline{I}_0\tag{5.25}$$

5.4.2 Filter

Any CD source (inverter or APFC followed by a diode rectifier) is modelled with a filter in parallel. In the previous case (i.e. the three-phase disturbance), the filter in ABC and 012 system is the same because in these two representations, the filter sees the same current and voltage (i.e. the same impedance). Here, with a phase-to-neutral disturbance, the current seen by the filter in

the symmetrical representation is three times smaller than in the ABC system (Equation 5.25). Therefore, the filter sees a different impedance in the symmetrical system than in the ABC system. Consequently, its filter configuration must be modified in the 012 system.

The filter in the symmetrical system is different if the disturbance is a voltage source or a current source. These two filter configurations are given below.

Voltage source

If the CD is modelled as a voltage source, the filter configuration in the symmetrical system is depicted in Figure 5.14. The approach to find it is developed in Annex G.1.

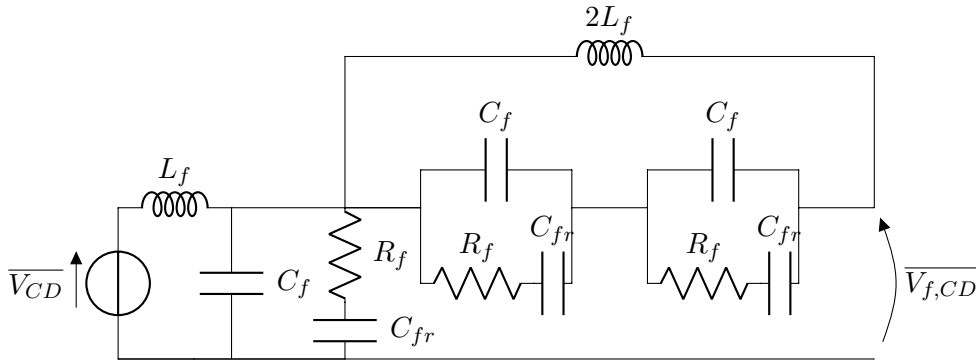


Figure 5.14: Equivalent filter in the symmetrical system for the phase-to-neutral disturbance voltage source

Current source

The filter in the symmetrical system when the filter is designed for a CD current source is shown in Figure 5.15. The parameter Z_N is the Norton equivalent impedance seen in the ABC system. This impedance is depicted in Figure 5.16 and just have to be replaced in the circuit of Figure 5.15. The approach to find this configuration is developed in Annex G.2.

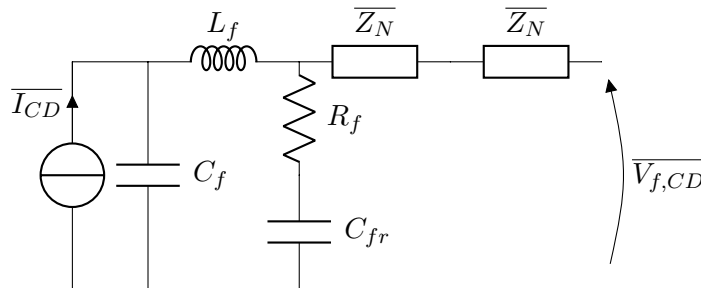
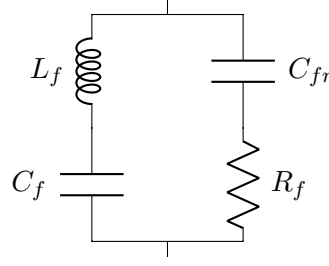


Figure 5.15: Equivalent filter in the symmetrical system for the phase-to-neutral disturbance current source

Figure 5.16: $\overline{Z}_N$ with a current disturbance source

5.4.3 Computational method

The principle of voltage divider is used to know the voltage V_0 , V_1 and V_2 . To do that, the impedance seen by each symmetrical voltage must be calculated. As done for the three-phase disturbance, for each sequence, the chain matrices can be multiplied to end up with only one chain matrix combining each element of the grid. If the sequence is left in open circuit, the current at its output is null. Therefore, the impedance seen by the voltage is given by Equation 5.26.

$$\overline{Z}_{oc} = \frac{\overline{A}}{\overline{C}} \quad (5.26)$$

If the output side of the sequence is in short-circuit, the output voltage of the two-port network is null. In this case, the impedance seen by the symmetrical voltage is calculated with Equation 5.27.

$$\overline{Z}_{sc} = \frac{\overline{B}}{\overline{D}} \quad (5.27)$$

The symmetrical voltage components are given by Equation 5.28.

$$\begin{aligned} \overline{V}_0 &= \overline{V_{f,CD}} \frac{\overline{Z}_0}{\overline{Z}_0 + \overline{Z}_1 + \overline{Z}_2} \\ \overline{V}_1 &= \overline{V_{f,CD}} \frac{\overline{Z}_1}{\overline{Z}_0 + \overline{Z}_1 + \overline{Z}_2} \\ \overline{V}_2 &= \overline{V_{f,CD}} \frac{\overline{Z}_2}{\overline{Z}_0 + \overline{Z}_1 + \overline{Z}_2} \end{aligned} \quad (5.28)$$

Eventually, the current flowing in phase A is calculated with Equation 5.29.

$$\overline{I}_a = 3\overline{I}_0 = 3 \frac{\overline{V_{f,CD}}}{\overline{Z}_0 + \overline{Z}_1 + \overline{Z}_2} \quad (5.29)$$

With this method, the symmetrical voltage components can be calculated analytically. Finally, A, B and C voltage are calculated using the transformation of Equation 5.3.

5.4.4 Simulation method and application case

As in Section 5.3, the simulated grid is constituted by a connection cable, a power cable, a transformer and a MV source. The positive and negative sequences are depicted in Figure 5.17 and the zero sequence single-phase circuit is shown in Figure 5.18. The parameters are the same as those used in Section 5.3.

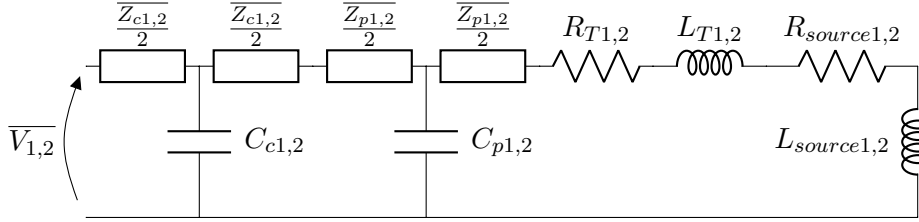


Figure 5.17: Positive and negative sequences for a phase-to-neutral disturbance

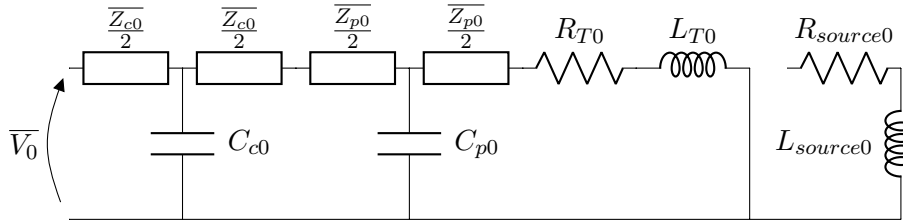


Figure 5.18: Zero sequence for a phase-to-neutral disturbance

These circuits have just to be connected like in Figure 5.13 and then the symmetrical equivalent circuit can be simulated.

5.5 Unbalanced phase-to-phase disturbance

The last type of disturbance occurs when a source of CD source is connected between two phases of a cable. That's the case when a cable has three conductors and no neutral. This type of connection is less common because the grid operator has decided to use mainly cable with three phases and one neutral. However, there are still cables like this in the actual grid.

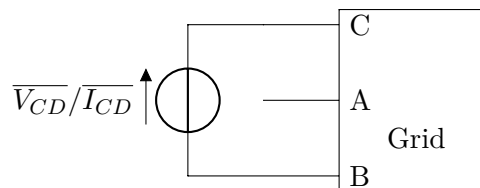


Figure 5.19: Unbalanced phase-to-phase disturbance

5.5.1 Theoretical approach

According to Figure 5.19, the currents can be written with Equation 5.30.

$$\begin{aligned}\overline{I_a} &= 0 \\ \overline{I_b} &= -\overline{I_c}\end{aligned}\tag{5.30}$$

With Equation 5.4, the symmetrical currents are given by Equation 5.31.

$$\begin{aligned}\overline{I_0} &= \frac{1}{3}(\overline{I_b} + \overline{I_c}) = 0 \\ \overline{I_1} &= \frac{1}{3}(a\overline{I_b} + a^2\overline{I_c}) = \frac{1}{3}\overline{I_b}(a - a^2) \\ \overline{I_2} &= \frac{1}{3}(a^2\overline{I_b} + a\overline{I_c}) = \frac{1}{3}\overline{I_b}(a^2 - a)\end{aligned}\tag{5.31}$$

With Equation 5.31, the symmetrical current components are simplified by Equation 5.32.

$$\begin{aligned}\overline{I_1} &= -\overline{I_2} \\ \overline{I_0} &= 0\end{aligned}\tag{5.32}$$

Thanks to Equation 5.32, the symmetrical component circuit can be represented in Figure 5.20.

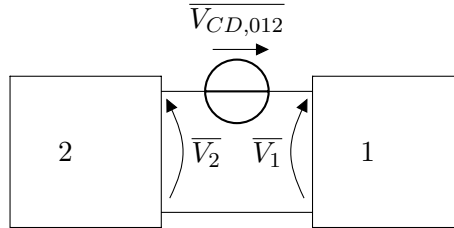


Figure 5.20: Symmetrical representation of a phase-to-phase disturbance

The voltage $\overline{V_{CD,012}}$ of Figure 5.20 must be determined. Firstly, the phase voltages are computed with the transformation of Equation 5.3 in Equation 5.33.

$$\begin{aligned}\overline{V_A} &= \overline{V_1} + \overline{V_2} \\ \overline{V_B} &= a^2\overline{V_1} + a\overline{V_2} \\ \overline{V_C} &= a\overline{V_1} + a^2\overline{V_2}\end{aligned}\tag{5.33}$$

The voltage difference between C and B can be expressed by Equation 5.34 according to Figure

5.19 and Equation 5.33.

$$\begin{aligned}\overline{V_{f,CD}} &= \overline{V_C} - \overline{V_B} \\ \overline{V_{f,CD}} &= (\overline{V_1} - \overline{V_2})(a^2 - a)\end{aligned}\tag{5.34}$$

In equation 5.35, the voltage $\overline{V_{CD,012}}$ is expressed in function of the voltage $\overline{V_{f,CD}}$ from the ABC system.

$$\begin{aligned}\overline{V_1} - \overline{V_2} &= \overline{V_{CD,012}} \\ \overline{V_{CD,012}} &= \frac{\overline{V_{f,CD}}}{(a^2 - a)} = \frac{\overline{V_{f,CD}}}{-j\sqrt{3}}\end{aligned}\tag{5.35}$$

Eventually, the current in phase B is calculated with the positive sequence current in Equation 5.36 using Equation 5.31.

$$\begin{aligned}\overline{I_1} &= \frac{\overline{V_1}}{\overline{Z_1}} \\ \overline{I_1} &= \frac{1}{3}(a - a^2)\overline{I_b} \\ \overline{I_b} &= 3\frac{\overline{I_1}}{(a - a^2)} \\ \overline{I_b} &= 3\frac{\overline{V_1}}{-j\sqrt{3}\overline{Z_1}}\end{aligned}\tag{5.36}$$

This type of disturbance will not be further developed in this work because it is more difficult to implement and less often occurs in the grid since the most of the cables are three-phase plus neutral configured.

5.6 Summary

The method of the symmetrical component can be used to study the CD propagation. Commonly, this method is used to calculate the short circuit current in case of fault. In our case, the disturbance connected to the cable is seen as a fault.

This method is built for three different disturbances. The first one is the three-phase disturbance occurring when a three-phase rectifier is connected to the grid. Then, the phase-to-neutral disturbance is investigated. It corresponds to the connection of a device between one phase and the neutral. Eventually, the connection of a disturbance between two phases is studied.

The simulation times in the ABC and the 012 systems have been compared. They are listed in Table 5.3. The conditions for each simulation are the following:

- No measurement block connected
- Switching frequency of 10 kHz
- Simulated time of 0.5 seconds
- Same grid configuration of Figure 5.1
- CD source parameters listed in Annex F, E.2 and E.1

	ABC simulation time [s]	012 simulation time [s]
Three-phase inverter	25.27	0.47
Single-phase inverter	16.7	0.58
APFC + diode rectifier	81.42	0.84

Table 5.3: Simulation times in ABC and 012 systems

The symmetrical method to study CD has two main advantages. Firstly, it enable calculation of the positive, negative and zero sequence components analytically. In this work, only the case where two cables are connected in series is studied. However, if the cables are connected in parallel/parallel or in series/parallel, the chain matrix properties also allow calculation of one chain matrix for different two-port networks connected to each other. Secondly, the simulations performed in the symmetrical system are significantly quicker than in the ABC system.

Study of conducted disturbances propagation in the low voltage distribution grid through simulations

This last chapter uses the method developed in Chapter 5 to study the CD propagation through simulations. First of all, the three-phase disturbance is investigated. This case occurs when a three-phase active inverter is connected between the three phases of a cable. Then, the unbalanced phase-to-neutral disturbance is simulated. This case corresponds to a CD source connected between one phase and the neutral. Such devices can be modelled as a voltage source such as the single-phase active inverter or a current source such as the APFC.

The grid which will be simulated is constituted by a connection cable, a power cable, a transformer and a MV source. This configuration is shown in Figure 6.1. The different letters on this diagram correspond to the reference where the voltage will be calculated in the rest of this chapter.

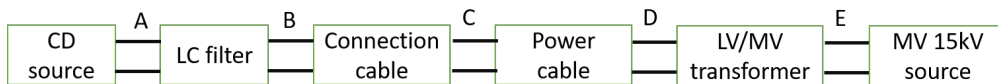


Figure 6.1: Grid diagram with connection points

In this chapter, the EAXeVB 150² cable of 500 meters and the XVB 1.5² cable of 10 meters are used for the majority of the simulations. However, the cable length will vary when its impact on the CD is studied.

In the majority of the figures in the chapter, the compatibility level proposed by standard IEC 6100-2-2 is represented to give a reference. The compatibility level is normally expressed in RMS value between 2 and 9 kHz and in peak value between 9 and 150 kHz. All the voltage magnitude calculated in this chapter are expressed in peak values. Therefore, the compatibility level between 2 and 9 kHz is expressed in peak value to allow the comparison even if it is expressed in RMS value in the standards.

6.1 Three-phase disturbance

Let's begin this chapter by studying how the CD coming from a three-phase active inverter propagate. That corresponds to the three-phase disturbance studied in Chapter 5. In this case, the positive/negative sequence circuit is put in parallel with the CD voltage source and its filter. The frequency components sent by the three-phase active inverter are given by Equation 6.1 (Section 4.1) with n different from a multiple of three ($n \neq 0, 3, 6, \dots$). If $n = 1, 4, 7, \dots$ the disturbance is a positive sequence and if $n = 2, 5, 8, \dots$ the disturbance is a negative sequence (Section 2.5.1). The same simulation is performed to simulated positive and negative sequence since their symmetrical single-phase equivalent models are the same.

$$f_{mn} = (mk \pm n)\omega_s \quad (6.1)$$

The parameter values used to simulate the three-phase active inverter are listed in Annex E.2.

This section is separated in four parts. Firstly, propagation through the grid is investigated by calculating the voltage in the frequency domain at different points of the grid. Then, the impedance seen by the disturbance is computed in order to better understand the frequency response. Afterwards, the skin effect impact on the voltage magnitude is examined. Eventually, the frequency response with different cable lengths is calculated to study the cable length impact on CD propagation

The spectrum of the signal sent by a three-phase active inverter is presented in Figure 6.2. The first frequency component above the grid frequency component with the highest magnitude is $\omega_{sw} \pm 2\omega_{grid}$ ($m = 1$ and $n = 2$ regarding Equation 6.1). This frequency component is equal to 10000 ± 100 Hz with a switching frequency of 10 kHz. This frequency component has the highest magnitude, however, the other frequency components around multiples of the switching frequency are not negligible. Therefore, the frequency response between 2 and 100 kHz will be studied to understand the frequency response of the grid at these frequencies.

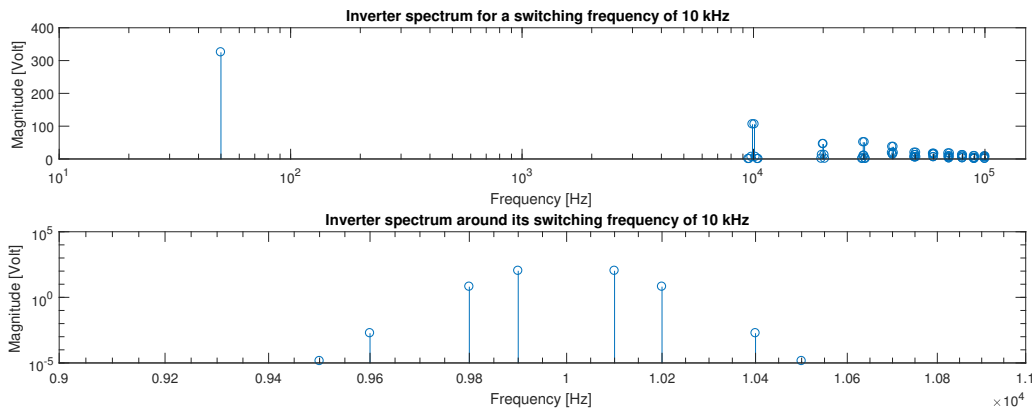


Figure 6.2: Voltage spectrum of a three-phase active inverter with a switching frequency of 10 kHz

Frequency response at different point of the grid

In Figure 6.3, the voltage at point A, B, C and D (point represented in Figure 6.1) are shown in function of the switching frequency of the inverter.

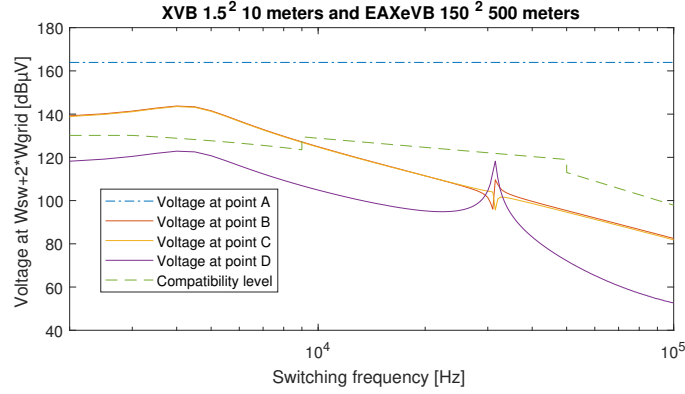


Figure 6.3: Voltage at point A, B, C and D for the frequency component of $\omega_{sw} + 2\omega_{grid}$

Firstly, the voltages at point B and C are almost the same. The connection cable between these two voltages is only 10 meters long, which explains why the voltages are almost the same.

Secondly, before 10 kHz, the voltage is a bit amplified. It is due to the cutoff frequency of the filter which has an amplification at this frequency. The voltage is higher than the compatibility level because the filter was not designed for such lower frequencies. The compatibility level is shown only to give a reference.

Finally, the voltage magnitude at point D is below the voltage magnitude at point B outside the resonance. They are separated by about 20 dB. However, at the resonance frequency, the voltage at D is above the voltage at B. In other words, after 500 meters of power cable and at the resonance frequency, the CD magnitude is higher than at the CD source.

Impedance calculation

In Figure 6.4, the voltage source, the filter and the positive sequence grid impedance are represented. The total filter capacitance value is approximated by the sum of the two capacitances in parallel within the filter (i.e. $C_{f,tot} = C_f + C_{fr}$). The filter parameter values are calculated in Section 4.1.3.

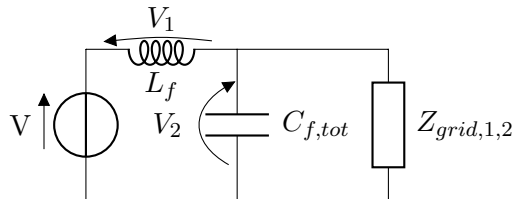


Figure 6.4: Voltage divider seen from the CD source

To understand how the CD propagate, the positive/negative sequence impedance seen by V_2 in

Figure 6.4 is calculated in Figure 6.5.

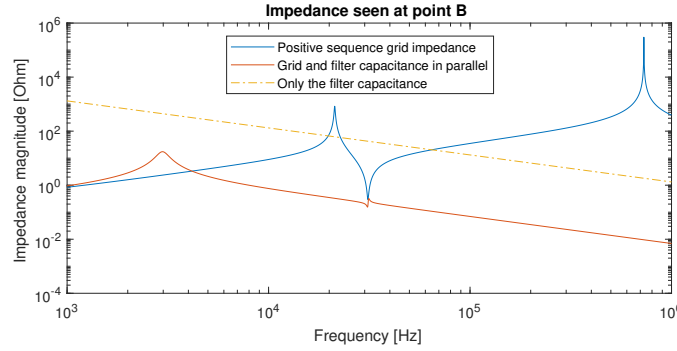


Figure 6.5: Positive/negative sequence impedance seen from the filter (grid impedance), impedance seen by V_2 (grid + capacitance in parallel) and capacitive reactance (only the filter capacitance)

The power cable resonance frequency is 27 kHz. The filter capacitive reactance magnitude decreases linearly with the frequency. When combining the capacitance and the positive/negative sequence grid impedance, the resonance frequency of the power cable remains present even with the filter capacitance. The power cable resonance causes the voltage peak of Figure 6.3.

Skin effect

In Figure 6.6, a zoom around the resonance frequency is done to highlight the impact of the skin effect on the CD magnitude. The skin effect influence is significant around the resonance frequency since it decreases the resonance peak by a few dB. After the resonance frequency, the voltage magnitude decreases less quickly with the skin effect than with a fixed resistance value.

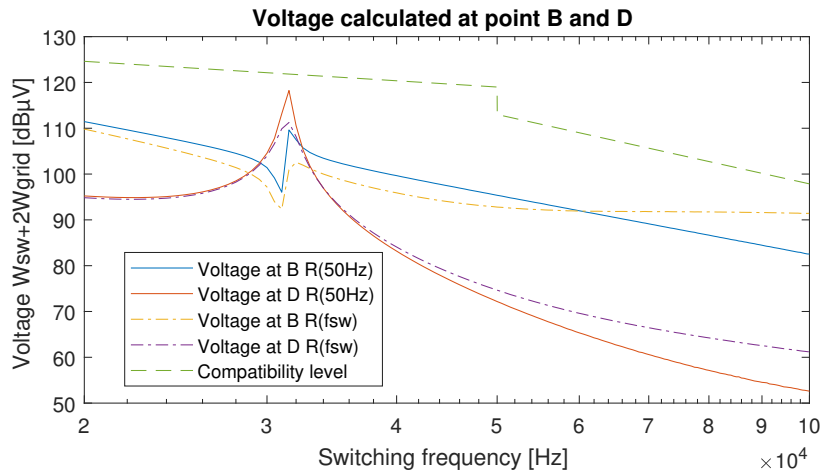


Figure 6.6: Voltage magnitude with and without the skin effect

Cable length

Now that the propagation of the CD in function of the switching frequency is better understood, let's study the influence of the cable length on the CD propagation.

In Figure 6.7, the voltage was calculated at point C and D for three different EAXeVB 150² cable lengths (and a fixed XVB 1.5² cable length). The resonance frequency decreases when the cable length increases as predicted in Chapter 6.7. The impact of the resonance frequency is less significant at point B than at point D. Moreover, when the cable length decreases, the filter cutoff frequency increases. Therefore, for a fixed frequency, the magnitude can increase significantly when the power cable length decreases.

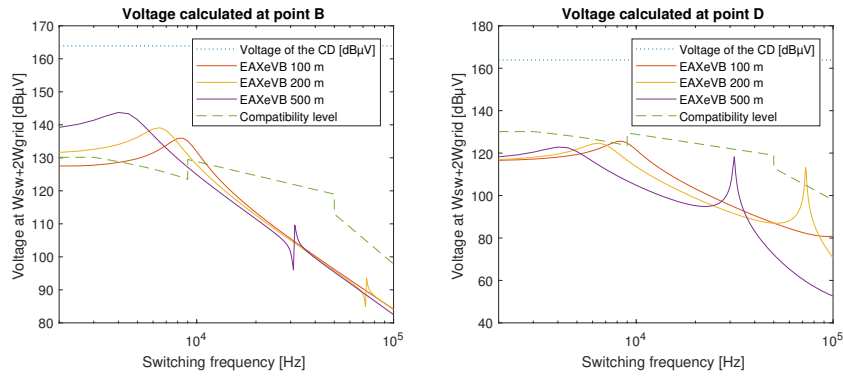


Figure 6.7: Voltage magnitude at B and D for different power cable length

In Figure 6.8, the voltage is calculated at point B and D for three different XVB 1.5² cable lengths (with a fixed EAXeVB 150² cable length). When the connection cable length increases, the resonance frequency of the power cable decreases as well as the resonance peak magnitude at point D. The resonance frequency of the power cable gets closer to its resonance frequency in open circuit since it is connected to a higher impedance magnitude.

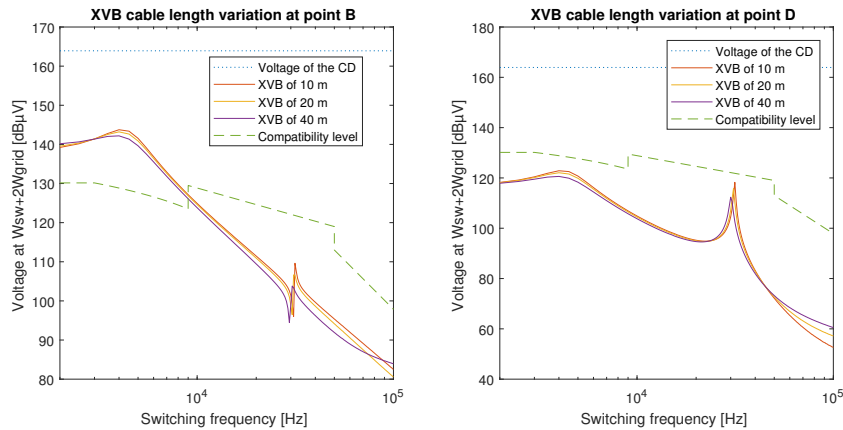


Figure 6.8: Voltage magnitude at B and D for different connection cable length

6.1.1 Summary

Let's summarise what has been learnt in this section which has been studied the three-phase disturbance.

First of all, the voltage magnitude on each phase is very sensitive to the resonance frequency of the power cable. The voltage magnitude at point D is below the voltage magnitude at point B

everywhere except at the resonance frequency. Therefore, it is not because a device is not close to a disturbance source that the voltage magnitude away from this disturbance source is lower than at the source.

Then, the frequency voltage behaviour is directly linked to the positive sequence impedance of the grid. Therefore, one can estimate the resonance frequency values by calculating it with the positive sequence grid impedance.

The skin effect decreases the magnitude of the voltage peak at the resonance frequency. After the resonance, the voltage magnitude decreases less quickly with the skin effect.

Eventually, an increment in the power cable length decreases the resonance frequency of the system by several kilos Hertz. Then, an increase of the connection cable length decreases the peak magnitude of the resonance and the resonance frequency value by several hundreds of Hertz.

6.2 Single-phase-to-neutral disturbance

The second disturbance studied is the single-phase-to-neutral one. The disturbance can be a voltage source or a current source. The voltage source models a single-phase active inverter and the current source models a diode rectifier followed by an APFC.

In this section, the single-phase active rectifier is first simulated and then the APFC followed by a diode rectifier too. Their frequency responses are calculated. The parameter values used to simulate the single-phase active inverter and the APFC followed by a diode rectifier are listed in Annex E.1 and Annex E.3 respectively.

For each source of disturbance (current or voltage source), the section is organised in five parts.

Firstly, the voltage on phase A and B is shown in function of the frequency at point B. The disturbance is applied only between phase A and the neutral. Calculating the voltage in phase A and B shows the impact of a disturbance applied in phase A on the other phases. The voltage on phase C will not be represented because it has the same magnitude as in phase B (as demonstrated in Section 5.4).

Then, the impedance of the grid seen by the disturbance is calculated. Since the voltage or the current are fixed by the disturbance, the impedance is the key to understand their frequency behaviour.

After that, the frequency response on phase A and B is depicted at point B and point D in order to figure out how the CD propagate through the grid.

As done in Section 6.1, the frequency response is calculated with and without the skin effect to see its impact on the voltage magnitude.

Eventually, the frequency response is computed for different cable lengths. This enables to show the effect of the power and the connection cable length on the frequency response.

6.2.1 Single-phase active inverter

The first CD sent by the single-phase two-level active inverter above the grid frequency is at $\omega_{switching}$. For the single-phase three-level active inverter, the frequency component above the grid frequency is at $2\omega_{switching} - \omega_{grid}$ (as explained in Section 4.1). Only the single-phase two-level active inverter is simulated and not the single-phase three-level active inverter for the purpose of simplification.

The single-phase two-level active inverter voltage spectrum is depicted in Figure 6.9 for a switching frequency of 10 kHz. As for the three-phase active inverter of Figure 6.2 in Section 6.1, the highest frequency component magnitude above the grid frequency component is at the switching frequency. Also as in Section 6.1, the other multiples of the switching frequency components are not negligible, therefore, the frequency response between 2 and 100 kHz is studied. Furthermore, simulating the same frequency range as done in Section 6.1 will allow us to compare the frequency response between each other.

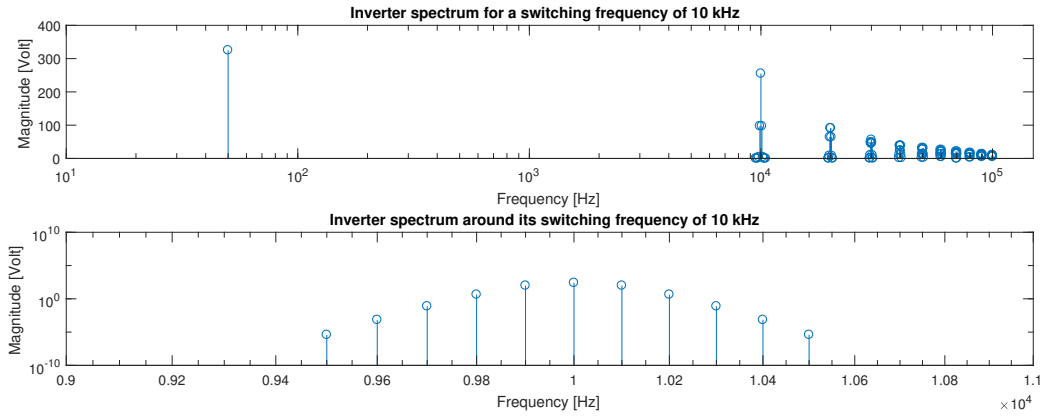


Figure 6.9: Single-phase two-level active inverter voltage spectrum for a switching frequency of 10 kHz

As a reminder, the parameters of the LC filter in parallel with the single-phase active inverter are listed in Table 6.1.

f_{cutoff}	1	kHz
C_f	9.33	μF
C_{fr}	13.6	μF
R_f	8.53	Ω
L_f	2.7	mH

Table 6.1: EMI filter values

Frequency response in phase A and B

The frequency response after the filter for phase A and phase B is shown in Figure 6.10 when the CD voltage source and its filter are connected between the phase A and the neutral.

Firstly, voltage in phase B is not negligible compared to the voltage in phase A. Therefore, even if the disturbance is applied to phase A, it has a significant impact on phase B (and C since $\overline{V_B} = \overline{V_C}$).

Then, the magnitude of the voltage on phase B is always below the magnitude on phase A.

Eventually, the resonance has an important impact on the magnitude in the two phases. In phase A, the voltage magnitude crosses the compatibility level which it would not have crossed without the resonance.

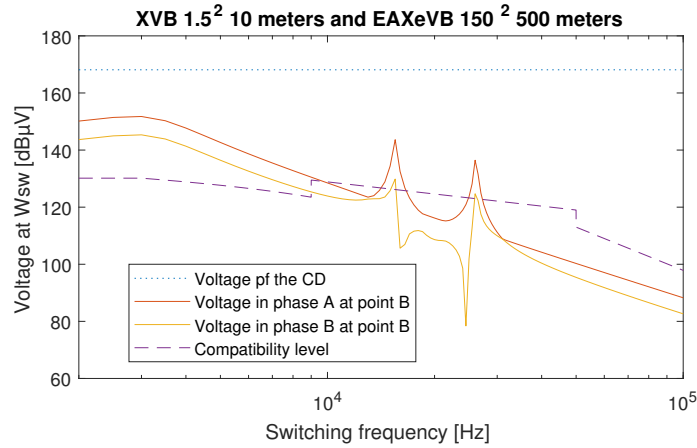


Figure 6.10: Frequency response of phase A and B calculated at point B

Impedance calculation

In Figure 6.11, the impedance seen by the filter in the symmetrical system is depicted with and without the filter capacitance in parallel. This impedance calculation enables understanding of the frequency behaviour of Figure 6.10 because the frequency behaviour of the CD is directly proportional to the grid impedance.

This impedance is a combination between the positive, the negative and the zero sequence impedance. The first impedance magnitude drop is due to the zero sequence power cable resonance frequency and the second impedance drop is due to the combination of the positive and the negative sequence power cable resonance frequency.

The power cable resonance frequencies remain constant with the filter capacitance but the resonance peak (local maximums) are shifted in lower frequencies. The two power cable resonance frequencies cause the two peaks on phase A in Figure 6.10.

Frequency response at different point of the grid

In Figure 6.12, the voltage is calculated in the frequency domain at point B and D for the phase A and the phase B. It enables understanding of how the CD propagate through the grid.

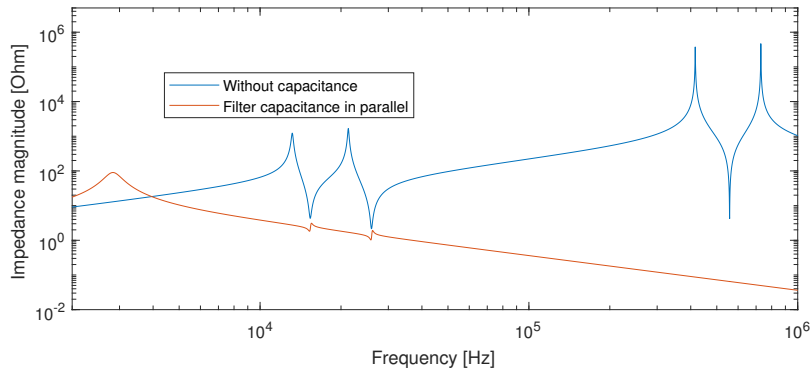


Figure 6.11: Impedance seen by the filter in the symmetrical system with and without the filter capacitance in parallel

Firstly, outside the resonance frequency area, the voltage is attenuated by approximately 35 dB between point B and point D.

Secondly, at the resonance frequencies, the voltage at point D is less attenuated than outside the resonance frequency area.

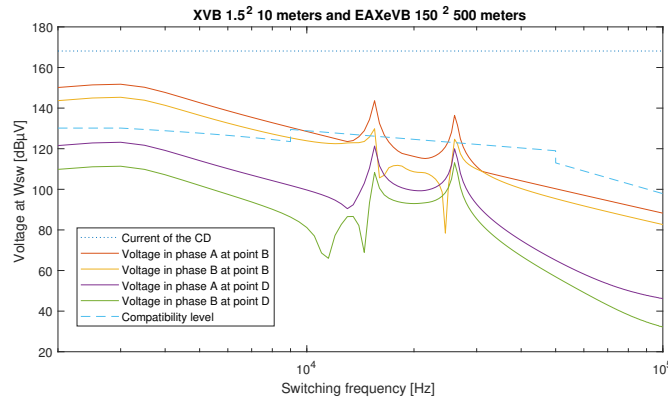


Figure 6.12: Voltage of phase A and B calculated at point B and D

Skin effect

In Figure 6.13, the frequency response of phase A and B is calculated with the resistance value given by the cable manufacturer and with the resistance value calculated at the switching frequency of the disturbance to take into account the skin effect.

Firstly, the skin effect has a smaller impact on the voltage magnitude than with the three-phase disturbance studied in Section 6.1. In the case of a single-phase-to-neutral voltage disturbance, the skin effect only damps the peaks.

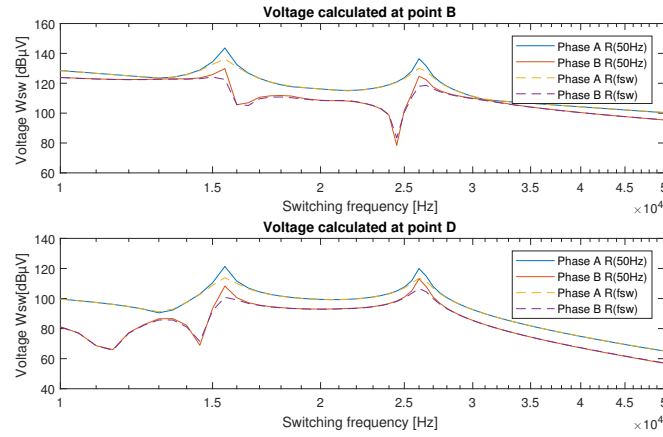


Figure 6.13: Frequency response of phase A and B at point B with and without the skin effect

Cable length

Eventually, the impact of the cable length is examined. Firstly the power cable length impact is studied and then the connection cable length too.

As the power cable resonance frequency increases when the cable length decreases, all the frequency behaviour shape is shifted on higher frequencies when the cable length decreases as depicted in Figure 6.14.

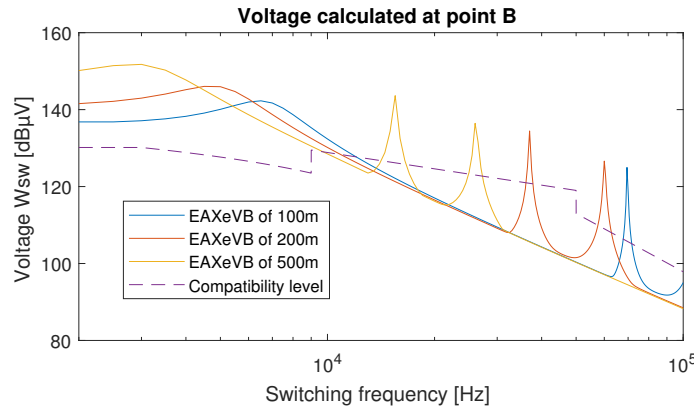


Figure 6.14: Frequency response of phase A at point B for different power cable lengths

Figure 6.15 shows the frequency voltage behaviour at point B for different connection cable lengths.

When the connection cable length increases, the resonance frequency decreases by several hundred Hertz. The resonance frequencies of the power cable are staying between the resonance frequency it has in open circuit and in short circuit. When the connection cable length increases, the power cable resonance frequencies are closer to the open circuit resonance frequency since the impedance in which it is connected is higher. Therefore, its resonance frequency decreases. Moreover, a higher connection cable length damps the resonance peak. It is due to its higher resistance value which is proportional to the cable length.

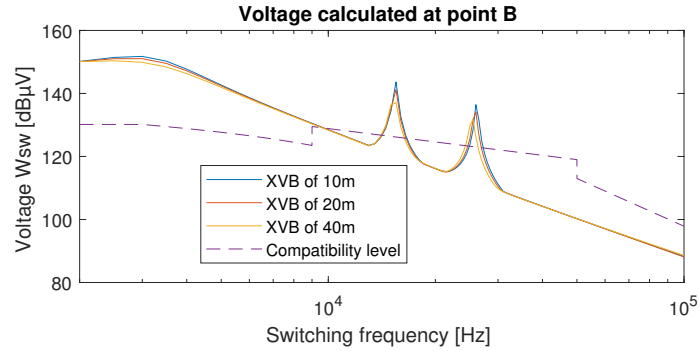


Figure 6.15: Frequency response of phase A at point B for different connection cable lengths

Voltage source disturbance summary

First of all, we learnt that the voltage in phase B is significantly impacted by a CD voltage applied on phase A. Furthermore, the frequency behaviour of the CD for a single-phase-to-neutral voltage source has two resonance peaks. These peaks are linked to the positive/negative and zero sequence resonance frequencies of the power cable.

Then, the amplitude of the phase voltage at point D is smaller than at point B, meaning that the voltage is attenuated when moving away from the CD source.

Afterwards, the skin effect only damps the peaks when it is taken into account. Its effect on the magnitude is less significant than with a three-phase disturbance.

Eventually, the power cable length sets the resonance frequencies of the system. Moreover, a higher connection cable length decreases by several Hertz the resonance frequencies and damps the resonance peaks.

6.2.2 APFC followed by a diode rectifier

The second source of CD is the APFC combined with a diode rectifier. It is modelled with a current source in parallel with an EMI filter. The CD source studied before were modelled as voltage sources. Now, the CD source is a current source with different filter parameters.

An APFC combined with a diode rectifier current spectrum is depicted in Figure 6.16 for a switching frequency of 10 kHz. The highest frequency component magnitude is at $\omega_{sw} \pm \omega_{grid}$ as explained in Section 4.2.1. The switching frequencies of the APFC are standing between 40 and 50 kHz as explained in Annex E.3. However, the frequency response between 2 and 100 kHz is studied to allow the comparison with the disturbances sent by a three-phase and a single-phase active inverter.

To be more accurate, the EMI filter parameters should be calculated for each switching frequency. However, for a purpose of simplification and better understanding, one filter is used with fixed parameters. Otherwise, the frequency response is changing at each switching frequency and it is

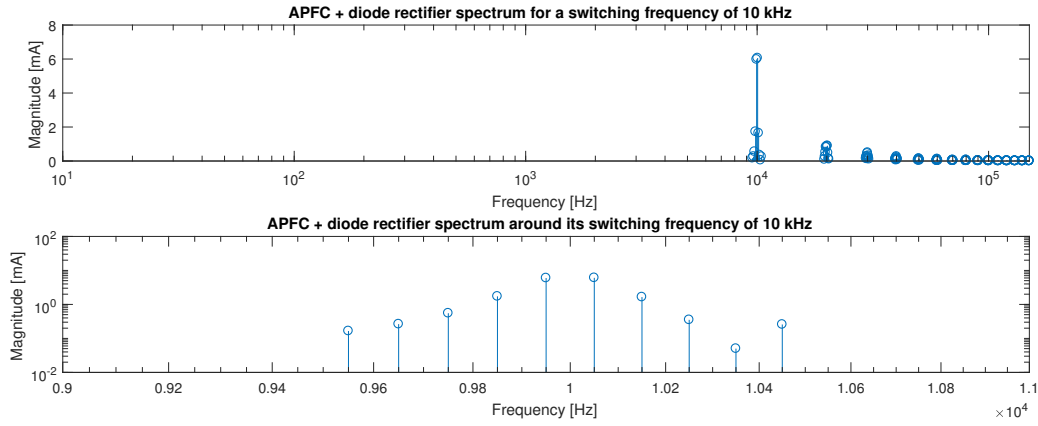


Figure 6.16: APFC followed by a diode rectifier current spectrum for a switching frequency of 10 kHz

more difficult to understand the propagation behaviour of the disturbances. The EMI filter is designed for a switching frequency of 15 kHz with parameters listed in Table 6.2.

f_{sw}	15	kHz
f_0	119.95	kHz
C_f	90.26	nF
C_{fr}	97.52	nF
R_f	7.35	Ω
L_f	19.5	μH

Table 6.2: EMI filter values

Frequency response in phase A and B

In Figure 6.17, the frequency response of the voltage in phase A and phase B is shown when the CD source and its EMI filter are connected between the phase A and the neutral at point B.

As in Section 6.2.1, the voltage in phase B is not negligible compared to the voltage in phase A where the disturbance is connected. Moreover, the peak magnitudes reach the compatibility level which means that these disturbances could be harmful for the surrounding devices. Furthermore, the frequency behaviour has three resonance frequencies instead of two for the single-phase active inverter. After the last resonance, the voltage magnitude decreases.

Impedance calculation

In Figure 6.18, the impedance seen by the filter in the symmetrical system is depicted with and without the filter capacitance in parallel. This impedance calculation enable understanding of the frequency behaviour of Figure 6.17.

As for the single-phase active inverter, the power cable resonance frequencies (impedance mag-

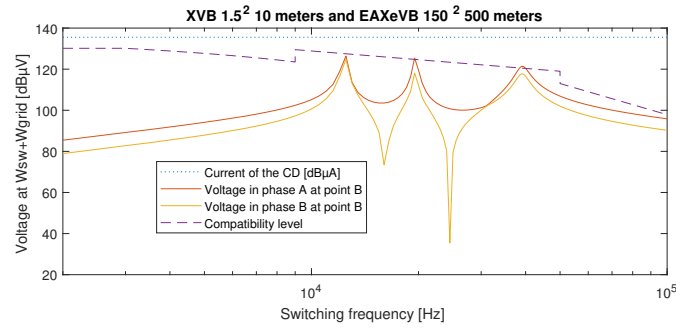


Figure 6.17: Frequency response of phase A and B with a CD current source connected between phase A and neutral

nitude drop) remain constant with the filter capacitance but the resonance peaks (local maximums) are shifted in the lower frequencies. However, due to a smaller filter capacitance value than with the single-phase active inverter, the first resonance peak is less shifted in low frequencies. That explains why there are three resonance peaks with the APFC instead of two with the single-phase active inverter.

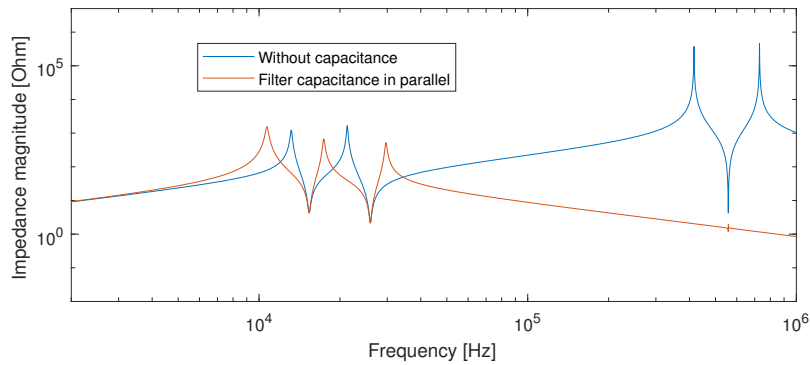


Figure 6.18: Impedance seen by the filter in the symmetrical system with and without the filter capacitance in parallel

Frequency response at different point of the grid

To understand how the CD propagate through the cables, the voltage at point B and D is calculated. The frequency behaviour at these two points is depicted in Figure 6.19. Outside the resonance frequency, between point B and point D, the voltage is attenuated by about 35 dB. At the second resonance frequency, the voltage is less attenuated. The voltage magnitude at point D is always below the magnitude at point B. Therefore, the CD voltage magnitude decreases when moving away from the disturbance source.

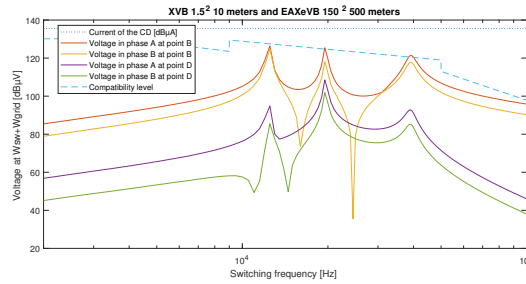


Figure 6.19: Voltage of phase A and B at point B and D

Skin effect

In Figure 6.20, the voltage magnitude is calculated in phase A and B at point B and D with the resistance value given by the cable manufacturers and with the resistance value calculated at the switching frequency. One can observe that the skin effect has almost no impact on the voltage magnitude. However, at the resonance frequencies, it damps the peak magnitude.

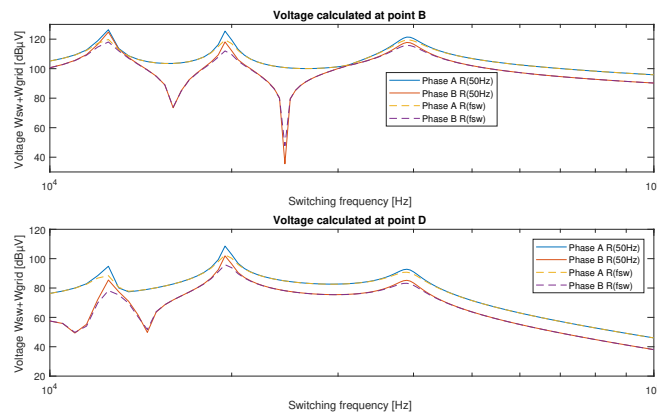


Figure 6.20: Frequency response of phase A and B at point B and D with and without the skin effect

Cable length

The influence of the power cable length is highlighted in Figure 6.21. The frequency response is calculated for different power cable length. When the cable length increases, its resonance frequency decreases. Here, when its length increases, all the frequency behaviour shape is shifted in lower frequencies.

Eventually, the influence of the connection cable length is depicted in Figure 6.22. The third resonance frequency decreases by several kilo Hertz when the connection cable length increases. This is because a higher connection cable length decreases the power cable resonance frequency.

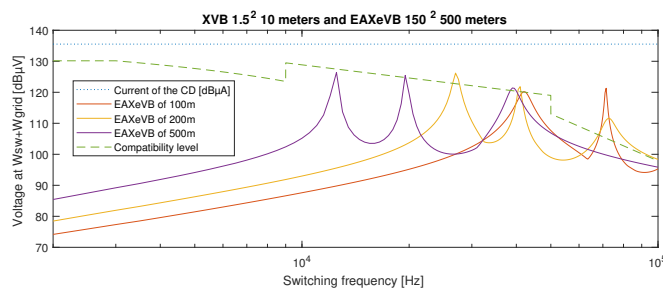


Figure 6.21: Frequency response of phase A at point B for different EAXeVB 150² cable lengths

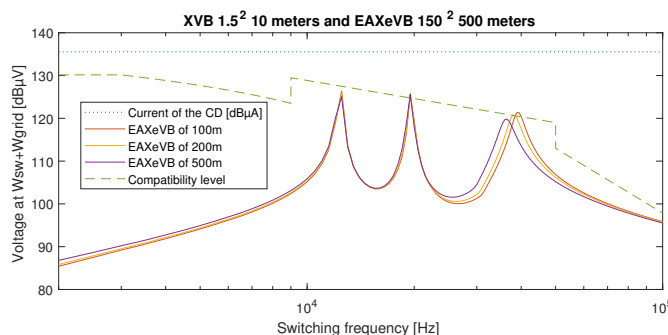


Figure 6.22: Frequency response of phase A at point B for different XVB 1.5² cable lengths

Current source disturbance summary

The conclusions are almost the same as for the CD voltage source of Section 6.2.1. The power cable sets the resonance frequencies of the system, the phase B is significantly impacted by a disturbance in phase A and the skin effect damps the resonance peak magnitude.

However, two things are different compared to the single-phase active inverter. Firstly, the magnitude of the CD are different because they depend on the parameters simulated and the type of CD source. Then, the frequency behaviour has three resonance frequencies instead of two in Section 6.2.1. This comes from the smaller filter capacitance value which makes the impedance magnitude quite different.

6.3 Conclusions

A summary of this chapter is presented in Table 6.3 where the main characteristics are compared between the different type of disturbances.

Type of disturbance	Balanced phase-to-phase disturbance	Single-phase-to-neutral disturbance	
Propagation characteristics	Three-phase active inverter	Single-phase active inverter	APFC + diode rectifier
Number of resonance peaks	1	2	3
Phase voltage magnitude	Same voltage magnitude on each phase	Voltage on phase B and C significantly impacted by the disturbance on phase A	
Voltage at point D compared to point B	Attenuated except at the power cable resonance	Attenuated	
Skin effect impact at the resonance frequency(ies)	Resonance peak magnitude damped	Resonance peak magnitude damped	
Skin effect outside the resonance frequency(ies)	Voltage at point B and D decreases less quickly after the resonance frequency	No effect	
Increase of the power cable length	Frequency behaviour shifted in lower frequencies		
Increase of the connection cable length	Small decrease of the resonance frequency and the peak magnitude	Small decrease of the last resonance frequency and its peak magnitude	

Table 6.3: Chapter 6 summary

Conclusion and future perspectives

Due to the lack of standardisation between 2 and 150 kHz, conducted disturbances in this frequency range are becoming an issue since an increasing number of power electronics are connected to the grid. In this context, this master thesis studies CD propagation through the grid in order to help establishment of standards. This thesis is divided in three parts.

The first one focuses on the grid modelling. First of all, the three-phase cable model is elaborated. Then, the positive, negative and zero sequence single-phase equivalent circuits are developed. These models allow us to study the frequency behaviour of the cables.

The second part proposes a simplified model for the three type of CD source studied in this thesis. Then, filter design is developed and their parameter values are calculated.

The last part uses the cable models of the first part and the CD source models of the second part to simulate CD propagation in a simple LV grid. Through these simulations, some results are highlighted.

This master thesis has led us to two main learnings.

Firstly, a method to study a three-phase, the phase-to-neutral and a phase-to-phase disturbance is proposed. This method can resolved CD propagation study analytically or through simulations. It is a key to a better understand of the grid frequency response with regard to the type of disturbance.

Secondly, through simulations, three mains results are highlighted. First of all, in the frequency range of 2 and 150 kHz, the three-phase active inverter has one resonance frequency, the single-phase active inverter has two resonance frequencies and the APFC followed by a diode rectifier has three resonances frequencies. These resonance frequencies lead to significant peak magnitudes which can reach compatibility level. Then, the voltage magnitude distant from the CD source is attenuated except at the resonance frequency of a three-phase disturbance. Eventually, the resonance frequency decreases when the power cable length increases, therefore, smaller power cable length can shift the resonance frequency above 150 kHz.

Further in-depth research into the propagation of CD should be performed. Firstly, the case when several CD sources are connected to the grid should be investigated to highlight their interaction between each other and to study the EMI filter low impedance path impact. Then, a thorough grid impedance calculation should be evaluated since they are needed to implement standards. Next, simulations with several cables in series and in parallel should be done to be closer to a realistic LV grid configuration. Eventually, experimental research should be conducted in order to validate and/or rectify some theoretical results.

EMI effects

Some examples of EMI effects on equipment are listed in Table A.1.

Equipment	Effect
TDLs	Unintentional switching between light step (ON and OFF)
Street lighting	Unintentional switch-on and -off
Traffic lights	Malfunction
Solid state meters	Displaying wrong meter register values
MCS	Temporary or quasi-permanent loss of communication
Contactless magnetic card reader	Malfunction of reading function
Home telephone	Malfunction of ringing
Heating systems	Incorrect alarms due to sensor faults
ADSL modem	Loss of link
Coffee cooker	Incorrect control lamp function and malfunction
Steam irons	Insufficient heat, water loss, incorrect lamp blinking
Washing machines	Self-restart after end of operation phase
Induction cookers	Audible noise
PCs and Lamps	Audible noise
TV and radio receiver	Audible noise (up to 20 kHz)
Automatic urinal water control	Switching to permanent operation

Table A.1: Effects of EMI on equipment [8]

Chain matrix property

When two cables are connected in series (situation depicted in Figure B.1), their chain matrices can be multiplied. This property is demonstrated in this appendix.

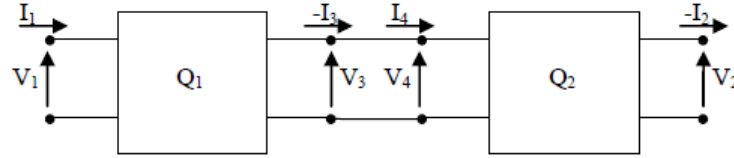


Figure B.1: Two two-terminal-pair networks in series [38]

The two-terminal-pair network Q1 and Q2 chain matrices are respectively represented in Equations B.1 and B.2.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} V_3 \\ -I_3 \end{bmatrix} \quad (\text{B.1})$$

$$\begin{bmatrix} V_4 \\ I_4 \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (\text{B.2})$$

Since $V_3 = V_4$ and $-I_3 = I_4$, one can obtain Equation B.3.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (\text{B.3})$$

When multiplying the two chain matrices a new chain matrix is available in Equation B.4

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (\text{B.4})$$

Cable notation

The notation of the cables is depicted in Table C.2 with number corresponding to Table C.1.

1	2	3	4	5	6
E					B

Table C.1: Cable notation

E	1. Utilisation type Energy	A	4. Internal protection Underground utilisation
	2. Conductor core Copper Aluminium	C	Peripheral neutral
	3. Conductor isolation Impregnated paper Mineral Paper without impregnation PVC PE XLPE	D	Deployable neutral
I		F	Light screen armour
M		e	Longitudinal sealing
P		J	5. Shell Jute
V		V	Polychloride sheathed
W		W	Polyethylene sheathed
(X)		B	6. Type of normalisation Belgian

Table C.2: Cable notation [39]

Skin Effect

D.1 Skin effect modelling

In this section, an EAXeVB 150² cable of 500-meters long is considered.

Modelling methods

The two methods [40] [41] which model the skin effect are illustrated in Figure D.1. Both methods consist on increasing the impedance in the frequency domain. It involves that the phase is also going to change, the purpose will be to minimise this phase and the error between the impedance approximated and computed analytically.

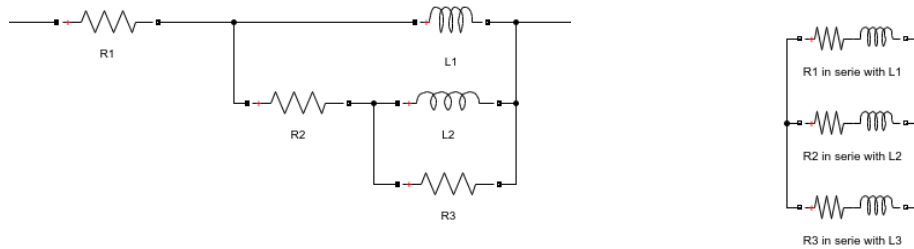


Figure D.1: Ladder method and parallel method

Curve fitting

When using the curve fitting with Matlab, we have obtained the parameters of table D.1

Rank	Ladder method		Parallel method	
	Magnitude error max [%]	Phase max [°]	Magnitude error max [%]	Phase max [°]
1	32.17	40.03	75	59
2	51.64	52.3	36.57	46
3	26.4	42	19.47	44.91
4	47.83	49	70.6	54.87

Table D.1: Curve fitting skin effect model parameters

Non linear solver

With the matlab function `lsqnonlin`, we can solve non-linear least-squares problems with several functions. With this method, we have compared values when we have just the absolute value of the impedance to approximate and when we have amplitude and phase (which is zero with the skin effect). The values are listed in Table D.2.

	Ladder method			
	Without phase approximation		With phase approximation	
Rank	Error max [%]	Phase max [°]	Error max [%]	Phase max [°]
1	116	62.47	338	48.49
2	25.35	37.7	61.44	39.61
3	26.4	41.93	208	25.89
4	14	40	193	34
5	8.41	41.23	198	31
	Parallel Method			
	Without phase approximation		With phase approximation	
Rank	Error max [%]	Phase max [°]	Error max [%]	Phase max [°]
1	75	59	338	48
2	36.57	46	337	48
3	19.37	45	194	38
4	55	52	338	48

Table D.2: Non-linear solver skin effect model parameters

Method and parameters choice

The nonlinear solver with rank 3 ladder is chosen because it is the best trade-off between amplitude error, phase and model complexity. Amplitude and phase are shown in Figure D.2

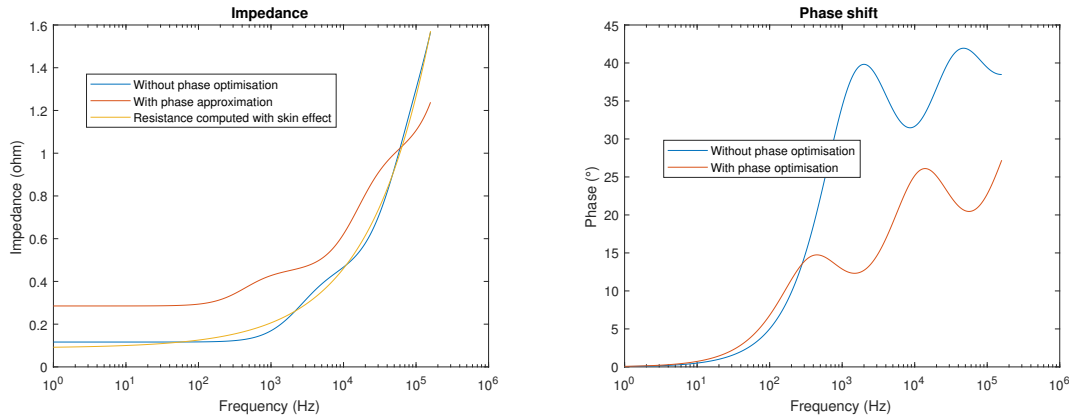


Figure D.2: Amplitude and phase of impedance with ladder method of rank 3

We have tried to find a compromise between the two results depicted in Figure D.2 (i.e. with and without phase optimisation) by imposing $R_1 = R_{dc}$ with other parameters found with phase approximation. Table D.3 gives parameters obtained with a trade-off between the two previous

curves. The maximum error with this model is 31.4 % and the maximum phase is 34.09°(before 150 kHz). The final resistance model impedance magnitude and phase are depicted in Figure D.3.

Resistance	Ω	Inductance	Henry
R_1	0.1164	L_1	5.7403e-5
R_2	0.1933	L_2	5.254e-6
R_3	0.6497	L_3	5.577e-7
R_4	2.1045		

Table D.3: Final parameters obtained for the skin effect approximation

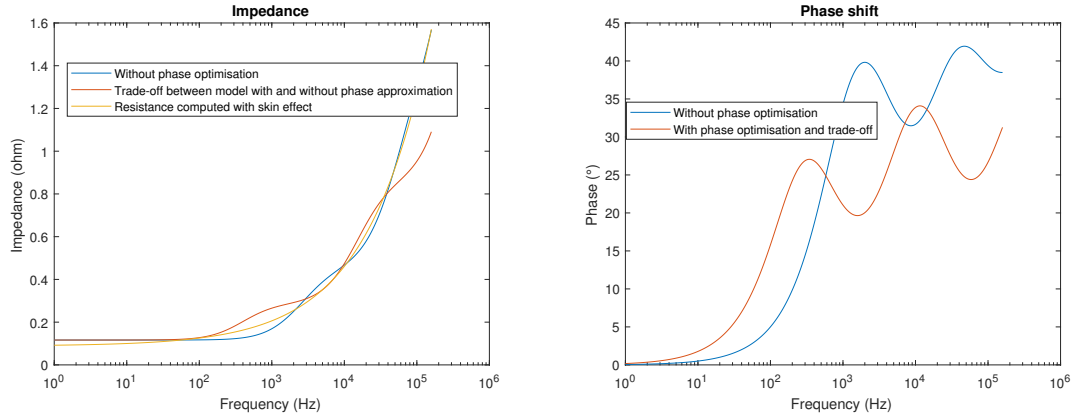


Figure D.3: Amplitude and phase of impedance with ladder method of rank 3 with trade-off

D.2 Rejection choice of the skin effect model

D.2.1 Skin effect model

It was proved in Section 2.3.1 that the skin effect has an impact near the resonance area. The skin effect model increases the equivalent impedance in the frequency domain but unfortunately induces a phase shift. In order to know if using the skin effect model is appropriated, the skin effect model consequences are studied in-depth.

Alone, the skin effect model have a maximum phase shift at 48.24 kHz of 40.66°(for an EAXeVB 150² of 500-meters long). However, this phase shift is not appearing when the skin effect model is introduced in the entire three-phase cable model.

This result leads to figure out that the only phase shift between the signal with a fixed resistance value and the signal with skin effect model as resistance only appears in the resonance peak area. To prove that, some signals at different frequencies are simulated. For each frequencies, the phase shift between the signal with fixed resistance value and the signal with the skin effect model replacing the resistance is calculated.

In Figure D.4, these phase shifts are depicted in function of the frequency. We clearly see that the maximum phase shift is appearing at the resonance frequency of the cable. Unfortunately, since

the CD propagation is studied, we are particularly interested by this resonance area. Therefore, this phase shift can cause error in simulation and wrong interpretation of the results.

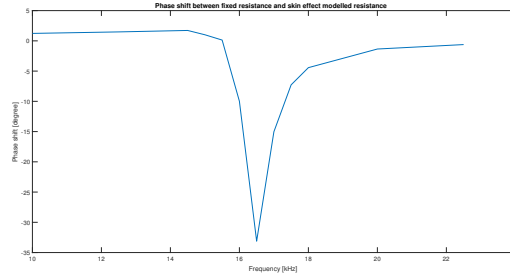


Figure D.4: Phase shift between fixed resistance and skin effect modelled resistance

D.2.2 Skin effect model rejection

We have learnt three major things up to now. First of all, every cable has the resonance frequency dependent on the cable length and the type of cable. Afterwards, the skin effect decreases the magnitude of the resonance peak and does not come into play outside the resonance area (these results come from Chapter 3). Eventually, the skin effect model induces a phase shift up to 33 ° around the resonance frequency area. Outside this area, the model does not induce any phase shift.

If CD are not standing in the resonance peak area, it is not worth to use variable frequency resistance because the skin effect only plays the role of decreasing the resonance peak magnitude. Furthermore, if CD are appearing in the resonance peak area, there are two options. The first one is to use the skin effect model but it will induce phase shift. The second one is to replace the value of the resistance by the resistance value calculated at the resonance frequency.

The phase of each CD components is very important because CD shifted by 180 ° are cancelling each other. We saw before that the skin effect model could introduce for an EAXeVB 150² cable of 500 meters a phase shift of 33 ° which is not negligible. Therefore, the choice to not use this model in this work is adopted. The alternative will be to calculate the resistance value at a certain frequency to simulate the skin effect.

Device parameters

E.1 PV panels

PV panels convert solar energy into electrical energy. The voltage supplied by the PV panels is a DC voltage. To transmit it to the grid, a DC/AC converter is placed between the PV panels and the grid. To satisfy standards, a CD filter is connected between the converter and the grid.

Furthermore, to allow the system to work in Maximum Power Point Tracking (MPPT) mode, a boost converter is placed between the PV panels and the DC/AC inverter. The MPPT is an algorithm that included in charge controllers used for extracting maximum available power from PV module under certain conditions. The boost also sends CD between 2 and 150 kHz but they are attenuated and are negligible compared to the CD sent by the inverter. Therefore, this block is neglected.



Figure E.1: PV panel to grid schematic

For house scale PV panel installations, the converter is a single-phase active inverter. This device is connected between on phase of the cable and the neutral. For bigger PV panels installation ($P > 5kW$), a three-phase active inverter is used.

From [28], the parameters for PV panels installation are given in Table E.1. The formulas of r and ϕ come from [42]. X_{filter} is the filter reactance calculated in Section 4.1.3. The value of θ_0 is calculated during simulations.

E.2 Small wind turbines

Small wind turbines are connected directly to the low voltage distribution grid. Their power is generally higher than the PV panels. Since it is higher than 5kW, the three-phase active inverter

Characteristic	Range	Value used for simulations	Unit
$V_{in} = V_{DC}$	[175 560]	360	Volt
$\omega_c = k\omega_s$	[15 20]	17.5	kHz
$P_{inverter}$ [32]	[3 5]	3.1	kW
$r = \frac{\sqrt{2}X_{filter}}{F_{grid}V_{DC}} \sqrt{P_{inverter}^2 + \frac{V_{grid}^4}{X_{filter}^2}}$	[0 1]	0.9047	[-]
$\phi = \tan^{-1}\left(\frac{X_{filter}P_{DC}}{V_{grid}^2}\right) + \theta_0$		9.18 + 37	°

Table E.1: PV panel characteristics

is used instead of the single-phase active inverter as for PV panels.

Small wind turbine power converting chain is depicted in Figure E.2. It is made of a Permanent Magnet Synchronous Generator(PMSG). This generator is followed by a AC/DC rectifier which is also followed by an DC/AC three-phase inverter. Finally, an EMI filter is placed before the grid to limit CD to flow through the grid.

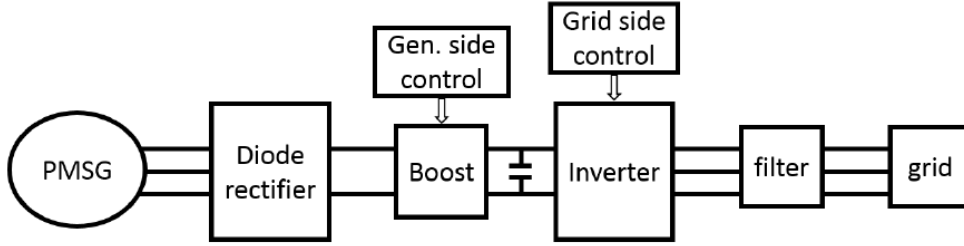


Figure E.2: Small wind turbine model [43]

The small wind turbine parameters are listed in Table E.2. They are used to simulate the three-phase active inverter in this work. As for the PV panels, the formulas of r and ϕ come from [42]. X_{filter} is the filter reactance calculated in Section 4.1.3. The value of θ_0 is calculated from simulations.

Characteristic	Range	Value used for simulations	Unit
$V_{in} = V_{DC}$	[650 800]	800	Volt
$\omega_c = k\omega_s$	[3 30]	3	kHz
$P_{inverter}$ [32]	[3 20]	10	kW
$r = \frac{2\sqrt{2}X_{filter}}{V_{grid}V_{DC}} \sqrt{\frac{P_{inverter}^2}{9} + \frac{V_{grid}^4}{X_F^2}}$	[0 1]	0.814	[-]
$\phi = \tan^{-1}\left(\frac{X_{filter}P_{DC}}{3V_{grid}^2}\right) + \theta_0$		3.08 + 37	°

Table E.2: Small wind turbine characteristics

E.3 CFL

Compact fluorescent lamp (CFL) is an energy-saving device which uses less electrical power and has a larger life-span than other traditional lamp [44]. Its complete model is depicted in Figure

E.3. The EMI filter is used to attenuate frequencies above 150 kHz as defined in CISPR standard. The rectifier converts an AC voltage into a DC one. The APFC keeps the power factor as close to the unity as possible. Finally, a half-bridge and a tank circuit are used to obtain a high-frequency current needed to feed properly the lamp[36].



Figure E.3: Complete model of a CFL [36]

According to [36], CFLs send CD due to the combination of a diode rectifier and an APFC present in their complete model. The complete chain between the grid and the lamp can be modelled with a current source in parallel with an EMI filter. Generally, all devices which have a rectifier followed by an APFC are CD sources. CFL is taken as an example because this device is widely used in a household scale.

In Table E.3, the CFL specific characteristics are listed. The DC voltage V_{DC} is the value of the voltage at the output side of the APFC. The switching angular frequency ω_{sw} is the angular frequency of the saw tooth signal used to control the transistor of the APFC. Eventually, the active power of the lamp is relevant because it influences some parameters used to calculate the value of the current source.

Characteristic	Range	Value used for simulations	Unit
V_{DC}	400 & 700	700	Volt
ω_{sw}	[40 50]	45	kHz
P_{lamp}	[8 30]	30	W

Table E.3: CFL characteristics

E.4 Transformer and MV source parameters

The parameters used in simulations for the transformer are listed in Table E.4. The Simulink block used is the "three-phase transformer two windings". The primary is Yg connected and the secondary is delta connected.

Nominal power	250	kVA
Primary voltage	400	V
Primary resistance	0.002	pu
Primary inductance	0.02	pu
Secondary voltage	15	kV
Secondary resistance	0.002	pu
Secondary inductance	0.02	pu

Table E.4: Transformer parameters

Table E.5 lists the parameters used to simulate the blocs "Three-Phase voltage source" in Simulink.

Phase-to-phase voltage	15	kV [V_{rms}]
Three-phase short-circuit level at base voltage	200	MVA
Base voltage phase-to-phase	15	kV [V_{rms}]
X/R ratio	1	

Table E.5: MV source parameters

CFL equations

CFLs can be modelled with a current source controlled with Equation F.1 (with α and h odd integers). All the parameters of this equation are developed below.

$$\begin{aligned}
 i_g(t) = & \frac{v_g}{R_{eq}} + \sum_{m=1}^{\infty} \sum_{\alpha=-\infty}^{\infty} \sum_{h=1}^{\infty} \frac{2}{\pi} \times \\
 & \left[\left(\frac{I_{m(\alpha+h)}}{h} \cos(\psi_{m(\alpha+h)}) - \frac{I_{m(\alpha-h)}}{h} \cos(\psi_{m(\alpha-h)}) \right) \times \right. \\
 & \cos(m\omega_c t + \alpha\omega_g t) \\
 & - \left(\frac{I_{m(\alpha+h)}}{h} \sin(\psi_{m(\alpha+h)}) - \frac{I_{m(\alpha-h)}}{h} \sin(\psi_{m(\alpha-h)}) \right) \times \\
 & \left. \sin(m\omega_c t + \alpha\omega_g t) \right]
 \end{aligned} \tag{F.1}$$

$$I_{mn} = \frac{\sqrt{A_{mn}^2 + B_{mn}^2} V_{DC}}{(m\omega_c + n\omega_g)L} \tag{F.2}$$

$$\psi_{mn} = n\phi + \tan^{-1}\left(\frac{A_{mn}}{B_{mn}}\right) - \frac{\pi}{2} \tag{F.3}$$

$$A_{mn} = \frac{1}{m\pi^2} \int_{\phi}^{\pi+\phi} \sin(-mr2\pi\sin(y) + ny) dy \tag{F.4}$$

$$B_{mn} = \frac{-1}{m\pi^2} \int_{\phi}^{\pi+\phi} \cos(-mr2\pi\sin(y) + ny) dy \tag{F.5}$$

$$B_{m0} = \frac{1}{m\pi} - \frac{1}{m\pi^2} \int_{\phi}^{\pi+\phi} \cos(mr2\pi\sin(y)) dy \tag{F.6}$$

$$r = \frac{V_{peak}}{V_{DC}} \sqrt{1 + \left(\frac{L\omega_g}{R_{eq}}\right)^2} \tag{F.7}$$

$$\phi = \tan^{-1}\left(\frac{-L\omega_g}{R_{eq}}\right) \quad (\text{F.8})$$

$$L = \frac{V_{peak}\theta_{min}}{\Delta i_{max}f_c} \quad (\text{F.9})$$

$$\theta_{min} = \frac{V_{DC} - V_{peak}}{V_{DC}} \quad (\text{F.10})$$

$$R_{eq} = \frac{V_{peak}^2}{2P_{lamp}} \quad (\text{F.11})$$

Phase-to-neutral disturbance filter

G.1 Voltage source filter

The phase-to-neutral disturbance is represented in Figure G.1 when the disturbance is a voltage source. For this type of disturbance it was saw in Chapter 5 that :

$$\begin{aligned}
 \overline{I_b} &= \overline{I_c} = 0 \\
 \overline{I_a} &= 3\overline{I_1} = 3\overline{I_2} = 3\overline{I_0} \\
 \overline{V_A} &= \overline{V_0} + \overline{V_1} + \overline{V_2}
 \end{aligned} \tag{G.1}$$

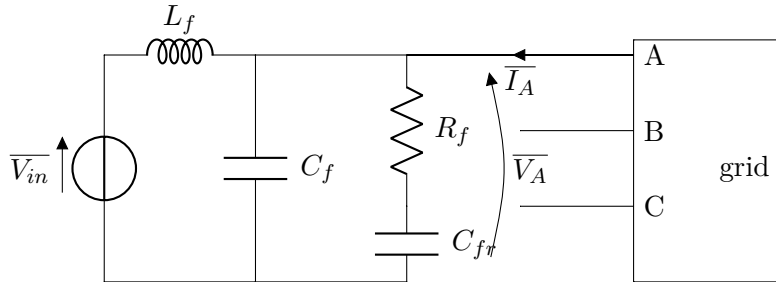


Figure G.1: Phase-to-neutral disturbance

In Figure G.2, a simplification of Figure G.1 is represented.

$$\begin{aligned}
 \overline{Z_1} &= j\omega L_f \\
 \overline{Z_2} &= \left(j\omega C_f + \frac{j\omega C_{fr}}{1 + j\omega C_{fr} R_f} \right)^{-1}
 \end{aligned} \tag{G.2}$$

With this simplification, the Thevenin equivalent circuit is built in Figure G.3.

$$\begin{aligned}\overline{V_{th}} &= \overline{V_{in}} \frac{\overline{Z_2}}{\overline{Z_2} + \overline{Z_1}} \\ \overline{Z_{th}} &= \overline{Z_1} // \overline{Z_2} = \frac{\overline{Z_1} \overline{Z_2}}{\overline{Z_1} + \overline{Z_2}}\end{aligned}\tag{G.3}$$

The voltage at A is given by Equation G.4

$$\overline{V_a} = \overline{V_{th}} + \overline{Z_{th}} \overline{I_A}\tag{G.4}$$

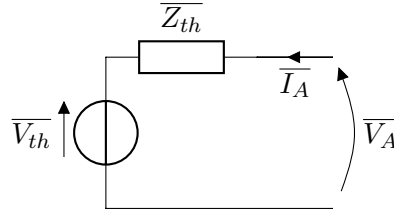
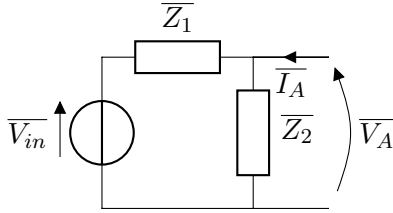


Figure G.2: Equivalent circuit of Figure G.1 Figure G.3: Thevenin equivalent of Figure G.2

If Equation G.1 is introduced in Equation ??, $\overline{V_a}$ is calculated with Equation G.5.

$$\begin{aligned}\overline{V_a} &= \overline{V_0} + \overline{V_1} + \overline{V_2} \\ &= \overline{V_{th}} + 3\overline{Z_{th}} \overline{I_1}\end{aligned}\tag{G.5}$$

Figure G.4 is built with Equation G.5.

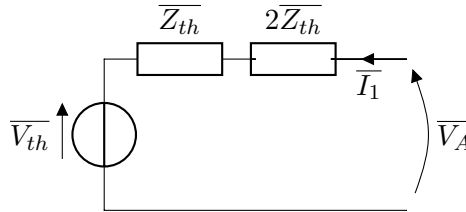


Figure G.4: Thevenin equivalent in the symmetrical coordinates

Figure G.5 is built by replacing the Thevenin equivalent circuit by the initial circuit.

G.2 Current source filter

The phase-to-neutral disturbance is represented in Figure G.6 when the disturbance is a current source. According to Chapter 5, the current and the voltage can be expressed by Equation G.6.

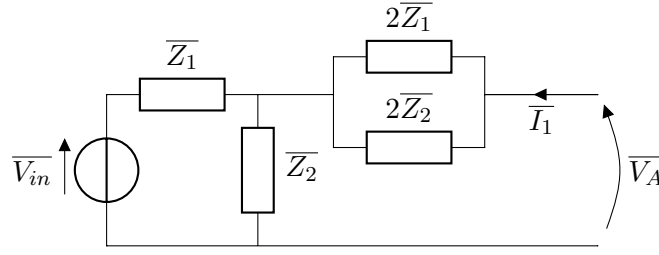


Figure G.5: Equivalent filter in the symmetrical coordinates

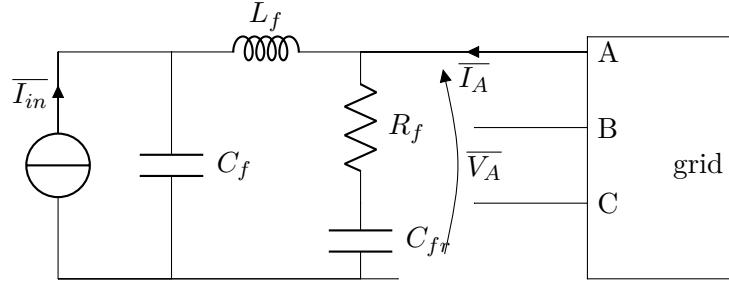


Figure G.6: Phase-to-neutral disturbance circuit without the resistance in parallel imposed by simulink

$$\begin{aligned}
 \bar{I}_b &= \bar{I}_c = 0 \\
 \bar{I}_a &= 3\bar{I}_1 = 3\bar{I}_2 = 3\bar{I}_0 \\
 \bar{V}_A &= \bar{V}_0 + \bar{V}_1 + \bar{V}_2
 \end{aligned} \tag{G.6}$$

Figure G.7 is the Norton equivalent representation of the circuit shown in Figure G.6.

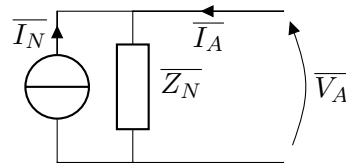


Figure G.7: Norton equivalent circuit of Figure G.6

The voltage in phase A ($\bar{V}_A$) is calculated with Equation G.7.

$$\begin{aligned}
 \bar{V}_A &= \bar{I}_N \bar{Z}_N + \bar{I}_A \bar{Z}_N \\
 &= \bar{I}_N \bar{Z}_N + 3\bar{I}_1 \bar{Z}_N \\
 &= (\bar{I}_N + \bar{I}_1) \bar{Z}_N + 2\bar{I}_1 \bar{Z}_N
 \end{aligned} \tag{G.7}$$

The Norton impedance associated to the filter in the ABC system is shown in Figure G.8. In the symmetrical system, the Norton equivalent circuit is depicted in Figure G.9 according to Equation

G.7.

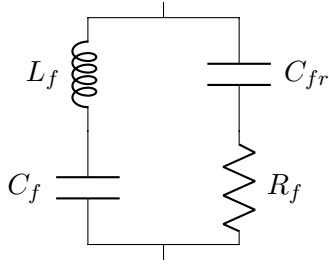


Figure G.8: $\overline{Z}_N$ with a current disturbance source

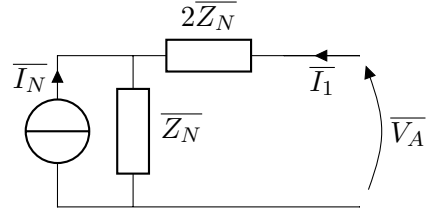


Figure G.9: Norton equivalent in the symmetrical components system

In the symmetrical domain, the Norton current source in parallel with the Norton impedance can be replaced by the filter of the ABC system represented in Figure G.6. Then, the Norton impedance has just to be replaced by the one of Figure G.8 and the circuit is ready to be used in the symmetrical system.

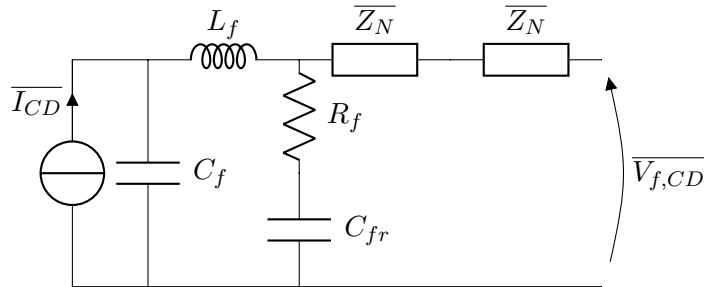


Figure G.10: Equivalent filter in the symmetrical system for the phase-to-neutral disturbance current source

Acronym list

AC	Alternating current
ADSL	Asymmetric digital subscriber line
AMR-PLC	Automated meter reading system using powerline communication
APFC	Active power factor correction
CD	Conducted disturbances
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CFL	Compact fluorescent lamp
CISPR	Comité International Spécial des Perturbations Radioélectriques
DC	Direct current
EM	Electromagnetic
EMI	Electromagnetic interference
EN	European Standard (a verifier)
FER	Frame error rate
IEC	International Electrotechnical Commission
L	Inductance filter
LC	Inductance and capacitance filter
LCL	Two inductances and one capacitance filter
LV	Low voltage
MCS	Main communication systems
MV	Medium voltage
PLC	Powerline communication
PMSG	Permanent-Magnet synchronous generator
PWM	Pulse width modulation
RMS	Root mean square
THD	Total harmonis distortion

Table H.1: Acronym list

Bibliography

- [1] Electronic notes, “Electrical resistivity and conductivity”, in: (2018), URL: https://www.electronics-notes.com/articles/analogue_circuits/emc-emi-electromagnetic-interference-compatibility/what-is-emi-basics-tutorial.php.
- [2] R Keim, “What Is the Difference between Conducted and Radiated EMI?”, in: (2018), URL: <https://www.allaboutcircuits.com/technical-articles/difference-between-conducted-EMI-radiated-EMI-electromagnetic-interference/>.
- [3] Keysight technologies, “Making conducted and radiated emissions measurements”, in: (March 2019), URL: <http://literature.cdn.keysight.com/litweb/pdf/5990-6152EN.pdf>.
- [4] smartgrid.gov, “What is the smart grid?”, in: (2019), URL: https://www.smartgrid.gov/the_smart_grid/smart_grid.html/.
- [5] energuide.be, “What exactly is a smart electricity grid?”, in: (2019), URL: <https://www.energuide.be/en/questions-answers/what-exactly-is-a-smart-electricity-grid/1581/>.
- [6] sibelga.be, “What is a smart meter?”, in: (17 july 2018), URL: <https://www.sibelga.be/en/blog/what-is-a-smart-meter>.
- [7] wikipedia, “Smart meter”, in: (2019), URL: https://en.wikipedia.org/wiki/Smart_meter.
- [8] SC CENELEC, “205A Study Report: October 2015 Electromagnetic Interference between Electrical Equipment”, in: *Systems in the Frequency Range below 150* ().
- [9] Jolien van Zetten, “What is standardisation?”, in: *ResiStand* (), URL: <http://resistand.eu/content/what-standardisation>.
- [10] Electropedia International Electrotechnical Commission, “The World’s Online Electrotechnical Vocabulary”, in: (), URL: www.electropedia.org.
- [11] Malcolm Barnes, “Electromagnetic compatibility (EMC)”, in: 2003.
- [12] A Robert, *Qualité de l’électricité. Notions de base*, Louvain-la-Neuve, Be: Université Catholique de Louvain, 2012.
- [13] E De Jaeger, *LELEC 2520 : EN50160_March2010*, Louvain-la-Neuve, Be: Université Catholique de Louvain, 2018-2019.
- [14] Association Française de Normalisation, *NF EN 50065-1*, Université Catholique de Louvain, 2002.
- [15] C Leroi, *Conducted disturbances in the frequency range 2-150 kHz: Sources, propagation and consequences*, Louvain-la-Neuve, Be: Université Catholique de Louvain, 2018.

- [16] Dr. Ing. Jos Knockaert, *High Frequency Power Quality*, Louvain-la-Neuve, Be: Gent university, LEMCKO, March 2016.
- [17] D Lacave, "Private email", Ores, Nov. 2018.
- [18] E De Jaeger, *Transmission and Distribution Power Lines*, Louvain-la-Neuve, Be: Université Catholique de Louvain, 2018-2019.
- [19] Wikipedia, "Primary line constant", in: (Apr. 2019).
- [20] Wikipedia, "Two-port network", in: (Mar. 2019).
- [21] O Casha B, *Transmission line, RF and Microwave Systems Design*, 2011.
- [22] Wikipedia, "Electrical resistivity and conductivity", in: (2018).
- [23] B-cables, *Caractéristiques du câble*, 2018, URL: <http://www.b-cables.be/site/documenten/25-%201.pdf>.
- [24] *EXVB Eca 1kV*, Nexans, 2018, URL: https://www.nexans.be/eservice/Belgium-en/navigate%5C_346379/EXVB%5C_Eca%5C_1kV.html.
- [25] Van Outryve, "Private email", Nexans, Nov. 2018.
- [26] Cablerie d'Eupen, *Manuel technique*, 11/2016.
- [27] C Wawrzyniak, "Etude de l'impact des systèmes de contrôle du Smart-Grid sur le canal de transmission par courant porteur dans le cas des réseaux BT et MT Doctorat", MA thesis, Université de Mons, 2016.
- [28] C Leroi, "Qualité de la tension et compatibilité électromagnétique : problématique des perturbations conduites dans la bande de 2 kHz à 150 kHz", MA thesis, Louvain-la-Neuve, Be: Université Catholique de Louvain, 2014.
- [29] E De Jaeger, *LELEC 2520 : Symmetrical Components in Three-Phase Systems*, Louvain-la-Neuve, Be: Université Catholique de Louvain, 2018-2019.
- [30] M Bekemans, *LELEC 2660 : DC-AC converter*, Louvain-la-Neuve, Be: Université Catholique de Louvain, 2018-2019.
- [31] L. Hassaine A.E.W.H. Kahlane and M. Kherchi, "LCL filter design for photovoltaic grid connected systems", in: (2014).
- [32] *Sunny Boy data sheet*, SMA, 2019, URL: <https://www.wholesalesolar.com/cms/sma-sunny-boy-5.0-us-inverter-specs-4261801217.2931725.pdf>.
- [33] Jan Meyer, Stephan Haehle, and Peter Schegner, "Impact of higher frequency emission above 2kHz on electronic mass-market equipment", in: (2013).
- [34] David Williams, "How the Boost PFC Converter Circuit Improves Power Quality", in: (Dec. 2016).
- [35] MOHAN.H.R MEGHANA.R.REDDY B.N.SARKAR, "SINGLE PHASE ACTIVE PFC USING BOOST CONVERTER", in: *International Journal of Advanced Computational Engineering and Networking*, ISSN: 2320-2106 1 (July 2013).

- [36] E De Jaeger and C Leroi, “MODELLING OF HARMONICS PRODUCED BY COMPACT FLUORESCENT LAMPS IN THE FREQUENCY RANGE 2-150 KHZ”, in: *25th International Conference on Electricity Distribution* (Madrid, June 2019).
- [37] International special committee on radio interference, “Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement”, in: *International Electrotechnical Commission* (March 2006).
- [38] T Ditchi, *Ligne de transmission*, Sorbonne Universités,
- [39] ORES, “CONSTRUIRE UN RESEAU SOUTERRAIN BASSE TENSION”, Unpublished document.
- [40] C Leroi, “Low voltage cables modelling”, Université Catholique de Louvain, Louvain-la-Neuve, Be, Nov. 2017.
- [41] B.K. Sen and R.L. Wheeler, *skin effects models for transmission line structures using generic spice circuit simulators*.
- [42] C Leroi, “Modelling of disturbances sources in the frequency range 2-150 kHz”, in: *Unpublished document* (May 31, 2019).
- [43] C Leroi, “Small Wind Turbines - Simplified model”, in: (January 30, 2019), Université catholique de Louvain.
- [44] Wikipedia, “Compact fluorescent lamp”, in: (2019).

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