

École polytechnique de Louvain

Integration of high voltage direct current technologies as alternatives for high voltage alternative current lines in meshed grids

Dynamical aspect: stability, transients

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List of Acronyms

A | D | F | G | H | M | P | S | T

A

AC Alternative Current

D

DC Direct Current

F

FRT Fault Ride-Through

G

GFL Grid-Following

GFM Grid-Forming

H

HV High Voltage

HVAC High Voltage Alternative Current

HVDC High Voltage Direct Current

M

MMC Modular Multilevel Converter

P

P2P Point-to-Point

PCC Point of Common Coupling

PLL Phase-Locked Loop

S

SG Synchronous Generator

T

TSO Transmission System Operator

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Part I

Introduction

Chapter 1

Introduction

At the end of the 19th century, a debate took place in the United States of America as to whether Alternative Current (AC) or Direct Current (DC) technologies should be used for public lighting, also known as the *War of the Currents* [6]. To cut a long story short, the technical difficulties of achieving high voltage with DC technologies made transmission over long distances inefficient compared to AC, where high voltage could be achieved thanks to transformers. That is why today's electrical networks are HVAC networks.

However, with technical breakthrough in power electronics, it is now possible to achieve high voltage with DC technologies [7], and even higher than with HVAC [8]. So, when a Transmission System Operator (TSO) builds a new line, they must compare these two technologies. Here are some of the differences: [9]

1. **Losses:** HVDC technologies require converters, which inevitably create losses. But HVAC require three cables and suffers from the skin effect which increase the ohmic resistance of the lines, whereas HVDC only require 2 cables and do not suffer from the skin effect. Also, corona losses are higher at AC voltages than DC ones [10].
2. **Reactive power:** In AC, power can be divided into two categories: active power and reactive power. Reactive power is the power exchanged between the different elements of the network. Long cables mean high capacitance, and the higher the capacitance, the more reactive power is generated. Also, underground or submarine cables' capacitance is much larger than overhead lines. Therefore, all the current flowing through the line does not take part in the active power, thus reducing the capacity of the line for active power. In DC there is no reactive power and therefore it does not suffer from these

limitations.

3. **Asynchronous Connection:** Connecting the areas with an HVAC line require these two areas to have the exact same frequency. With HVDC technologies, they can be independent as the converters at both ends have only the active power in common.
4. **Power Flow Control:** The amount of power flowing through an HVAC line is imposed by physics laws. The one flowing through an HVDC line is chosen by the operator. This difference is investigated in Chap.3.
5. **System costs:** Because of all these differences, the total system costs vary according to the technology. Mainly due to the losses, beyond a certain distance, called the "break-even distance", and despite the cost of the converters, HVDC is overall cheaper than HVAC as shown in Fig.1.1. The break-even distance is around 1000 km for overhead lines but drops to around 50 km for underground/submarine cables due to their larger capacitance.

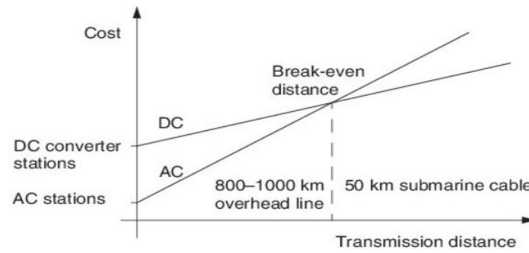


Figure 1.1: Evolution of the total system costs of HVAC or HVDC lines with regards to the transmission distance [8]

In Belgium, the TSO, Elia, considers it necessary to build a new 6 GW line between Mercator and Courcelles for several reasons, the main one being able to cope with the renewable power generation of the off-shore windfarms while respecting to the N-1 criterion [11]. Elia called this project the "Boucle du Hainaut". Indeed, for the time being, the Belgian coast is only connected to the rest of the country via a single corridor, as it can be observed in Fig.1.2

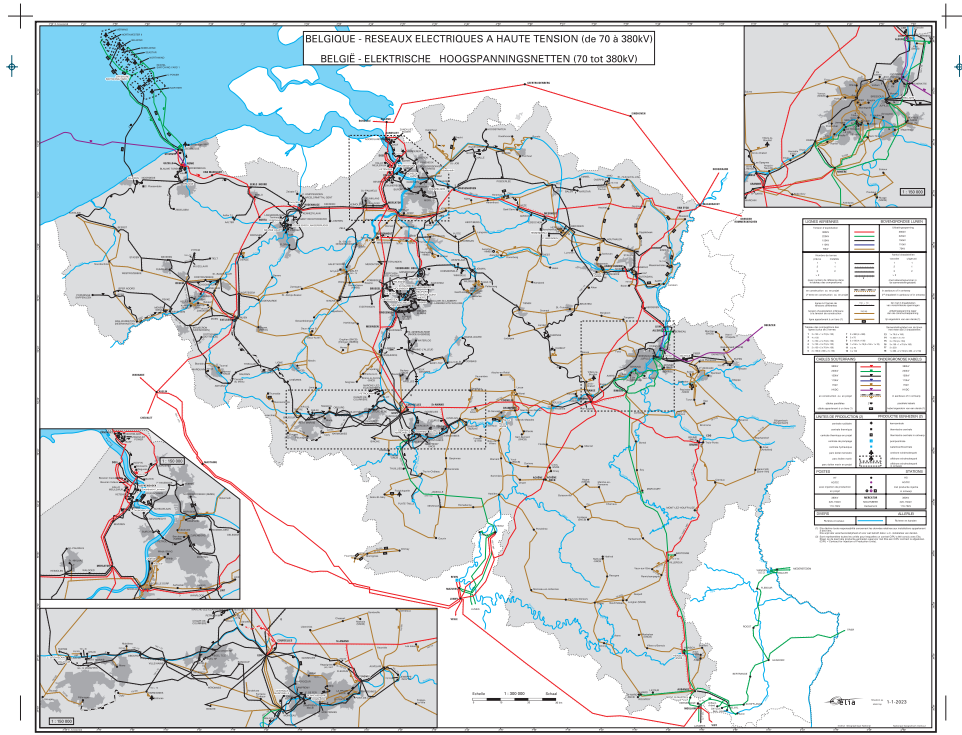


Figure 1.2: Belgian transmission network in 2023 [1]

At the request of some citizens, the possibility of building this new line with HVDC technologies has been investigated [12]. Although the current conclusion is that it is not feasible to build the "Boucle du Hainaut" in a reliable manner with today's HVDC technologies [13] (due to their lack of maturity), it does raise the question of the integration of such technologies in the existing meshed HVAC networks, as does the SuedOstLink project in Germany[14].

This master's thesis aims at giving some parts of answers to this question, mainly focusing on the dynamical aspects. More specifically, the structure is as follow:

Chap.2 introduces the reader to the concept of power system stability.

Chap.3 evaluates the impacts on the load flow of HVAC and HVDC technologies when meshing a radial three-node network.

Chap.4 introduces the reader to the different networks on which simulations will be carried out.

Chap.5, 6 and 7 analyse the effect of varying the active and reactive power control strategies of HVDC converters on the rotor angle stability of the system in a network consisting of 2 nodes connected by an HVAC and an HVDC line for respectively, a topology variation, a load variation and a fault.

Chap.8 analyses the effect of varying the active and reactive power control strategies of HVDC converters on the rotor angle stability of the system in a network consisting of 3 nodes, each of them being connected thanks to HVAC lines and 2 of them being connected by an HVDC line.

Finally, Chap.9 concludes this Master's thesis and point out some improvements to go further.

Chapter 2

Power system stability: the rotor angle stability

This chapter introduces the reader to the concept of power system stability. After a brief overview of the different types of stability, rotor angle stability is introduced in more detail.

In order for a power system to be stable, it must meet a certain number of criteria [15].

1. The frequency must remain within a narrow band around its nominal value. The frequency is an indicator of the well balanced consumption/generation. Indeed, if more power is consumed than produced, the difference will be furnished by releasing some energy stored in the rotating masses of the several generators across the grid. However, as the generators slow down, so does the frequency. Therefore, the frequency is one of the main indicators of the good health of the system.
2. The voltages across the grid must also remain close to their nominal values. Too high voltages could cause, among other unpleasant situations, insulation deterioration and even breakdown which could cause fires [16]. On the other hand, too low voltages could cause motors to stall or increased current in constant power load, which again, could cause fires.

These two quantities are thus of high interest and must be well controlled in steady state as well as after a disturbance. The stability of a power system is the property that allows it to reach an acceptable steady-state following a disturbance [17].

Recovering from a disturbance is important but disturbances can cause the SGs to lose synchronism. This aspect of the power system stability is called the rotor angle stability.

Nowadays, the surge of power electronic devices raises other stability concern such as resonance stability [15]. However, these issues will not be addressed in this master's thesis.

2.1 Rotor angle stability

The rotor angle stability is the *capacity of a set of interconnected synchronous machines to maintain the synchronism after being subjected to a disturbance*[17]. It can be broken down into two different categories: the small disturbance angle stability and the transient stability.

As its name suggests, the small disturbance angle stability is *the system ability to maintain synchronism following “small” disturbances*. Therefore, the system of equations characterizing the network and the SGs can be linearised. Whereas the transient stability is the *system capacity to maintain synchronism following a severe disturbance (e.g. a fault), involving large variations in rotor angles*. [17]

For the following developments, a single SG – infinite bus is assumed.

2.1.1 Small disturbance angle stability

As previously said, under small disturbances, the system can be linearised around its operating point (i.e. around the load angle δ^0 , the field voltage E and the stator voltage V^0). The model obtained is called the Heffron-Phillips model (Fig.2.1).

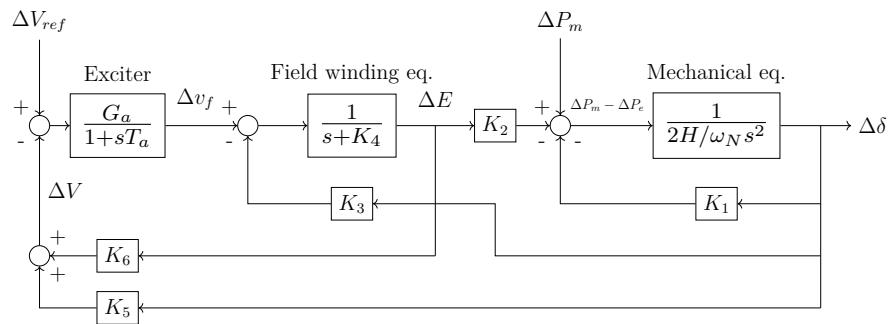


Figure 2.1: The Heffron-Phillips model

With the different constants being:

$$\begin{aligned}
K_1 &= \frac{kV_\infty E}{\omega_N T'_{d0}(X'_d + X_e)} \cos \delta^0 + \frac{(X'_d - X_q)V_\infty^2}{\omega_N(X_q + X_e)(X'_d + X_e)} \cos 2\delta^0 \\
K_2 &= \frac{kV_\infty}{\omega_N T'_{d0}(X'_d + X_e)} \sin \delta^0 \\
K_3 &= \frac{V_\infty(X_d - X'_d)}{k(X'_d + X_e)} \sin \delta^0 \\
K_4 &= \frac{X_d + X_e}{T'_{d0}(X'_d + X_e)} \\
K_5 &= \frac{X_q^2 V_\infty^2 \sin 2\delta^0}{2V^0(X_q + X_e)^2} - \frac{V_\infty X'_d \cos \delta^0 + kX_e \psi_f^0 / T'_{d0}}{V^0(X'_d + X_e)^2} V_\infty X'_d \sin \delta^0 \\
K_6 &= \frac{(V_\infty X'_d \cos \delta^0 + kX_e \psi_f^0 / T'_{d0})X_e}{V^0(X'_d + X_e)^2} \\
k &= \omega_N \frac{L_{fd}}{R_f}
\end{aligned} \tag{2.1}$$

with the parameters ω_N the nominal angular speed, V_∞ the voltage of the infinite grid and X_e the impedance connecting the SG to the infinite grid. The other parameters are those of the SG and are gathered in Tab.4.1.

Despite being linear, this model is still too complex to allow simple interpretations. Therefore, since the time constant of the exciter $T_a = 0.001$ s is small (see Sec.4.1.1), it can be neglected. Furthermore, if the mechanical power P_m remains constant, the model can be simplified as shown in Fig.2.2.

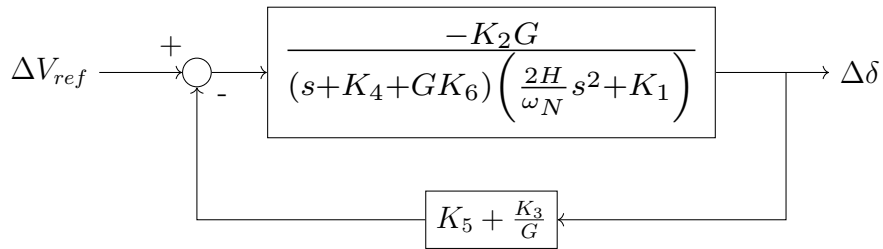


Figure 2.2: The simplified Heffron-Phillips model

Therefore, the transfer function is:

$$\frac{\Delta\delta}{\Delta V_{ref}}(s) = \frac{-GK_2}{\frac{2H}{\omega_N}s^3 + \frac{2H}{\omega_N}(GK_6 + K_4)s^2 + K_1s + K_1(GK_6 + K_4) + K_2(GK_5 + K_3)} \quad (2.2)$$

The poles of this transfer function give information about the stability of the system as its real part gives the damping and its imaginary part gives the frequency of oscillation.

2.1.2 Transient stability

At a fault's location, voltage will drop to 0 pu, resulting in the apparent power $S = VI^*$ to also drop to 0 pu. As the fault is assumed to be quickly cleared, the field winding flux linkage can be assumed to be constant. Therefore, the dynamical behaviour of the SG can be simplified to the swing equation:

$$\frac{2H}{\omega_N} \frac{d^2\theta_m}{dt^2} = P_m - P_e \quad (2.3)$$

Therefore, during a fault, the machine will accelerate as the mechanical power P_m remains constant (at least, in the following simulations) and the electrical power P_e drops due to the fault. In order to allow simple mathematics and thus, a better understanding of what is happening during a fault, a simple lossless machine-infinite bus system will be considered.

As the system is considered lossless, the active power generated by the SG is:

$$P_e = \frac{EV_\infty}{X_e} \sin \theta \quad (2.4)$$

where E is the field voltage, V_∞ the voltage at the infinite bus, X_e the reactance between these two voltages and θ , the rotor angle.

For a given mechanical power, two operating points are theoretically possible, as shown in Fig.2.3. However, only the one having a positive derivative is stable. If this were not the case, an increase in speed would lead to a decrease in electrical power, which would lead to an increase in speed, and so on, until the system collapses. On the other hand, a positive derivative would increase the electrical power as the speed increases, thus stabilising the system.

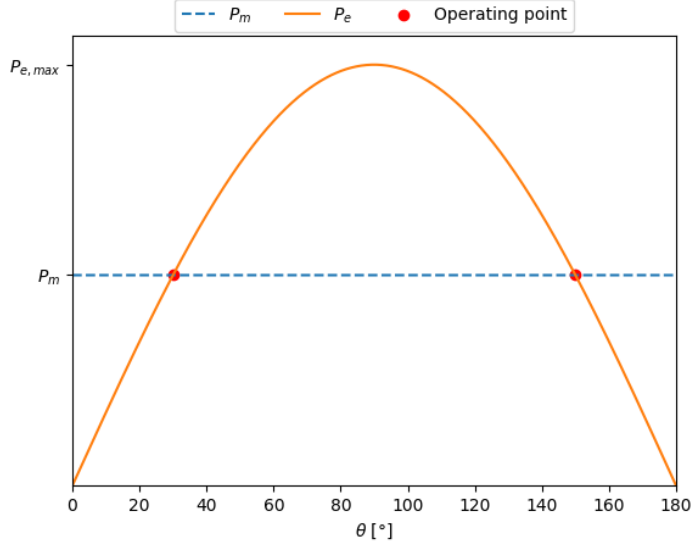


Figure 2.3: The operating points of a SG

During a fault, the electrical power produced will dramatically decrease, and even drop to 0 pu in the case of a lossless grid. Therefore, due to the power imbalance in the SG, the rotor will accelerate and θ will increase. The energy gained during this acceleration is represented by the red area in Fig.2.4.

Once the fault is cleared (by opening the faulted line), the new impedance of the line is greater than the one before the fault (therefore, $P_{after}(\theta) < P_{before}(\theta)$). So P_e is now greater than P_m causing θ to decelerate. The stability limit is such that the electrical power must be greater than the mechanical power throughout the whole deceleration ($\theta < \theta_{max}$), otherwise it would accelerate again and the SG would lose synchronism. The energy lost during this deceleration is represented by the green area in Fig.2.4. This criterion is called the equal area criterion.

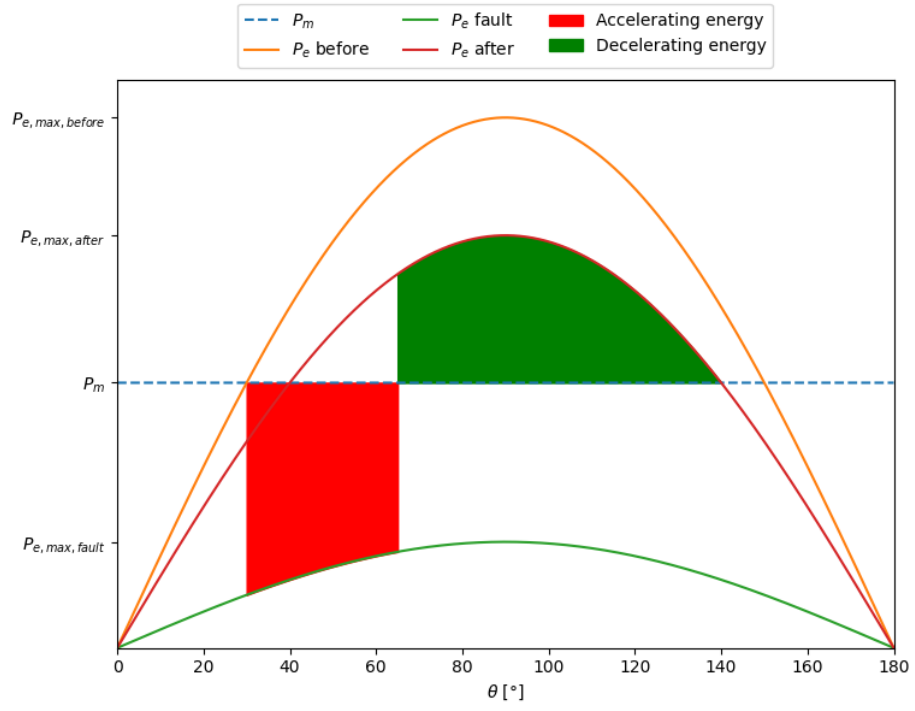


Figure 2.4: Graphical representation of the energy accelerating and decelerating the rotor in the event of a fault

Chapter 3

The differences of the HVAC and HVDC technologies on the power flow

This chapter evaluates the impacts on the load flow of HVAC and HVDC technologies when meshing a radial three-node network. It is shown that an HVDC line allows a wider range of power flows in the system than an HVAC line of the same capacity. Furthermore, the capacity of an HVAC line must be within a certain range, otherwise it would either drastically reduce the set of feasible power flows or be economically inefficient (in normal use). HVDC technologies do not suffer from these limitations.

One of the main differences between an AC system and an HVDC system is the power flow. In a full AC system, it is determined by Ohm's and the current divider laws. In other words, if there are multiple paths for the power to travel from one node to another, it will flow along all of these paths with the intensity of each path being inversely proportional to the impedance of the path. This can produce counterintuitive results.

3.1 General considerations on simplified 3-node network

A 3-node grid where the nodes (X, Y and Z) are connected radially is considered, i.e. X and Y are not connected directly, but only through Z, as displayed in Fig.3.1.

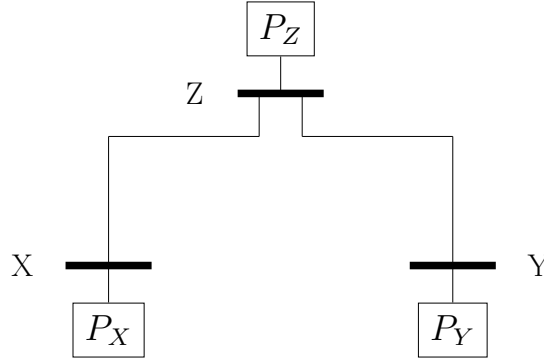


Figure 3.1: Representation of a 3-node grid where nodes X and Y are radially connected via Z

Also, for the sake of simplicity, it is assumed that:

- both lines have the same impedance $\overline{Z}_{XZ} = \overline{Z}_{YZ}$ and their power limits are respectively $P_{max,XZ}$ and $P_{max,YZ}$.
- P_X and P_Y are the powers injected, respectively, at nodes X and Y.
- Node Z is the slack node; therefore, P_Z is such that $P_X + P_Y + P_Z = P_{loss}$

In this configuration, the constraints are :

$$-\begin{bmatrix} P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \leq \begin{bmatrix} P_{XZ} \\ P_{YZ} \end{bmatrix} = \begin{bmatrix} P_X \\ P_Y \end{bmatrix} \leq \begin{bmatrix} P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \quad (3.1)$$

The set of the feasible injections for P_X and P_Y is represented graphically by a rectangle as shown in Fig.3.2.

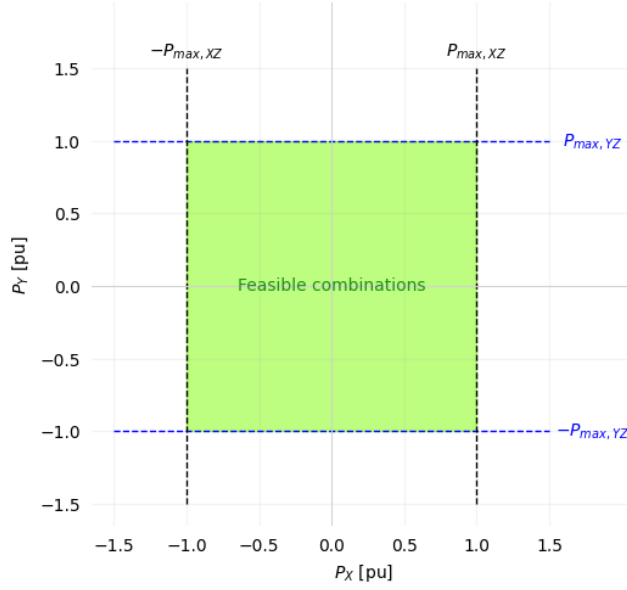


Figure 3.2: Graphical representation of the feasible combinations in a radial 3-node grid where both $P_{max,XZ}$ and $P_{max,YZ}$ are set to 1 pu

Although the set of feasible combinations covers all the needs, it has one major drawback: the unplanned failure of a single component in this network would lead to the outage of a node. Therefore, for redundancy reasons, the network operator would like to build a line to connect nodes X and Y directly.

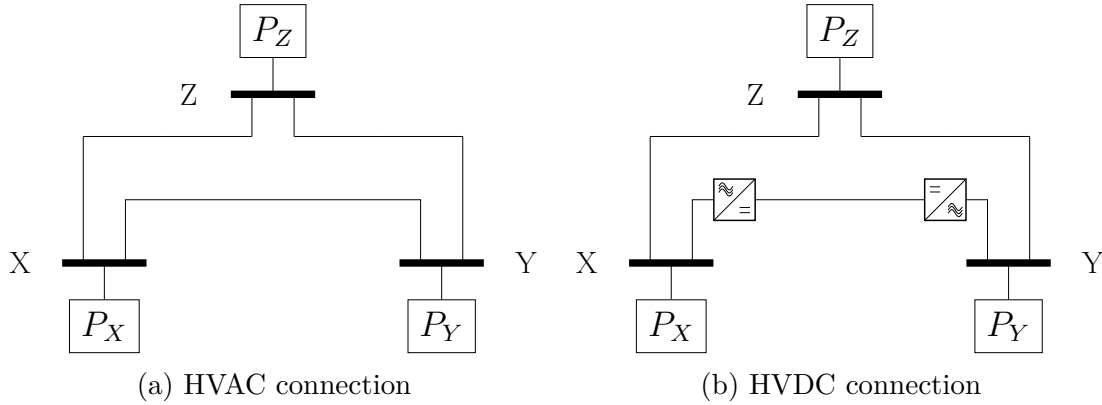


Figure 3.3: Representation of a 3-node grid where node Z is connected to X and Y by HVAC lines and X and Y are connected by an HVAC or HVDC line

3.1.1 Line XY in AC

First, let us consider that this new link will be an AC line, as displayed in Fig.3.3a. What will be the consequences on the load flow? Again, for simplicity, this new line will be assumed to have the same impedance as the already existing ones, and its power limit is $P_{max,XY}$.

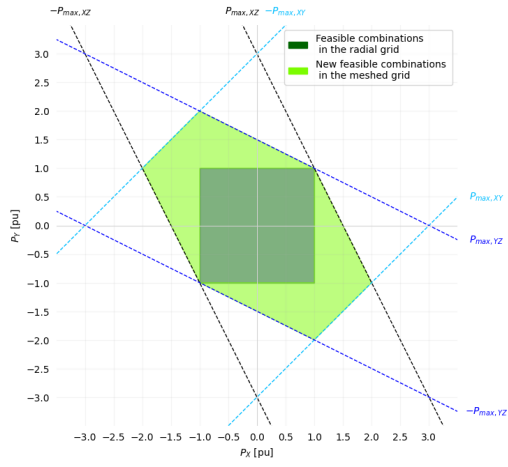
In this configuration, the power flowing through each line is given by the current divider law:

$$\begin{bmatrix} P_{XY} \\ P_{XZ} \\ P_{YZ} \end{bmatrix} = \begin{bmatrix} \frac{Z_{XZ}}{Z_{XY}+Z_{XZ}+Z_{YZ}} & -\frac{Z_{YZ}}{Z_{XY}+Z_{XZ}+Z_{YZ}} \\ \frac{Z_{XY}}{Z_{XY}+Z_{XZ}+Z_{YZ}} & \frac{Z_{YZ}}{Z_{XY}+Z_{XZ}+Z_{YZ}} \\ \frac{Z_{XZ}}{Z_{XY}+Z_{XZ}+Z_{YZ}} & \frac{Z_{XY}}{Z_{XY}+Z_{XZ}+Z_{YZ}} \end{bmatrix} \begin{bmatrix} P_X \\ P_Y \end{bmatrix} = \begin{bmatrix} 1/3 & -1/3 \\ 2/3 & 1/3 \\ 1/3 & 2/3 \end{bmatrix} \begin{bmatrix} P_X \\ P_Y \end{bmatrix} \quad (3.2)$$

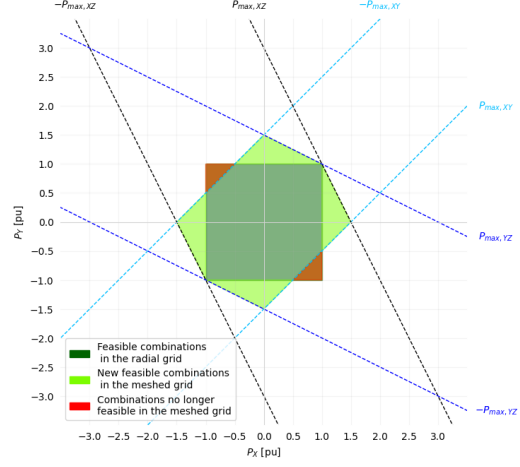
Now, the new constraints are:

$$-\begin{bmatrix} P_{max,XY} \\ P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \leq \begin{bmatrix} P_{XY} \\ P_{XZ} \\ P_{YZ} \end{bmatrix} = \begin{bmatrix} \frac{1}{3}P_X - \frac{1}{3}P_Y \\ \frac{2}{3}P_X + \frac{1}{3}P_Y \\ \frac{1}{3}P_X + \frac{2}{3}P_Y \end{bmatrix} \leq \begin{bmatrix} P_{max,XY} \\ P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \quad (3.3)$$

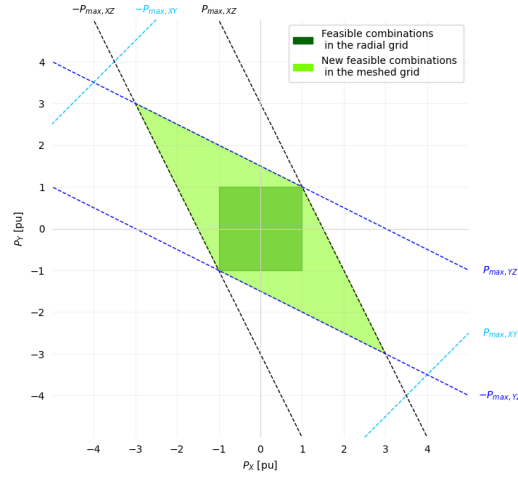
The sets of feasible injections for P_X and P_Y for different values of $P_{max,XY}$ are plotted in Fig.3.4.



(a) $P_{max,XY} = 1.0$ pu



(b) $P_{max,XY} = 0.5$ pu



(c) $P_{max,XY} = 2.5$ pu

Figure 3.4: Graphical representations of the feasible combinations in a meshed AC 3-node grid for different values of $P_{max,XY}$ where $P_{max,XZ} = P_{max,YZ} = 1$ pu

Several observations can be made. First, if the capacity of the new line is the same as the existing ones, the set of feasible combinations increases so that it is now possible to transfer up to 1.5 pu between nodes X and Y if node Z neither generates nor consumes power, and up to 1.0 pu if node Z either generates or consumes 1.0 pu. In comparison, in the radial network, the limits are 1.0 pu in the first case and no power could flow between nodes X and Y in the second case.

However, as the capacity of the new line is reduced, there will come a point where some combinations will no longer be possible. This is because when a certain amount of power flows from one node to another, a certain proportion will flow through the line directly connecting these two nodes and the remainder will flow through the third node (in this case, since all impedances are equal, this proportion is 2/3 and 1/3). It is therefore possible for one line to reach full capacity even though the other lines still have some margin. In this case, $P_{max,XY}$ must be greater than 0.67 pu to ensure that any combination that was feasible in the radial grid will also be feasible in the meshed grid.

To avoid reducing the set of feasible combinations, one might want to build a line with as high a capacity as possible. But for the same reasons, beyond a certain capacity, there would be no new feasible combinations as a result of an increase in capacity. In this case, since at least a third of the power must flow through the existing lines, the limit is 2 pu.

3.1.2 Line XY in DC

If the new connection is a DC line, as displayed in Fig.3.3b, it will have no effect on the AC power flow equations, since the DC system is independent of the AC network. The only difference will be that the sets of feasible combinations for P_X and P_Y will not be centred on (0,0) but on $(P_{HVDC}, -P_{HVDC})$. In other words, it is now possible for no power to flow through the AC network even though P_X and P_Y are non-zero. Therefore, Eq. 3.1 still applies with the slight modification that P_{XZ} is now equal to $P_X - P_{XY}$ and P_{YZ} is equal to $P_Y + P_{XY}$.

$$-\begin{bmatrix} P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \leq \begin{bmatrix} P_{XZ} \\ P_{YZ} \end{bmatrix} = \begin{bmatrix} P_X - P_{XY} \\ P_Y + P_{XY} \end{bmatrix} \leq \begin{bmatrix} P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \quad (3.4)$$

The new graphical representations for the feasible power injections are given in Fig.3.5. This illustrates one of the major advantages of an HVDC line in a meshed network compared to a HVAC system. With an HVDC line, there is no threshold for the capacity of the new line that would make some combinations infeasible or any increase in capacity useless from a power flow perspective. Furthermore, any combination that is feasible in the full AC system is also feasible with the HVDC line.

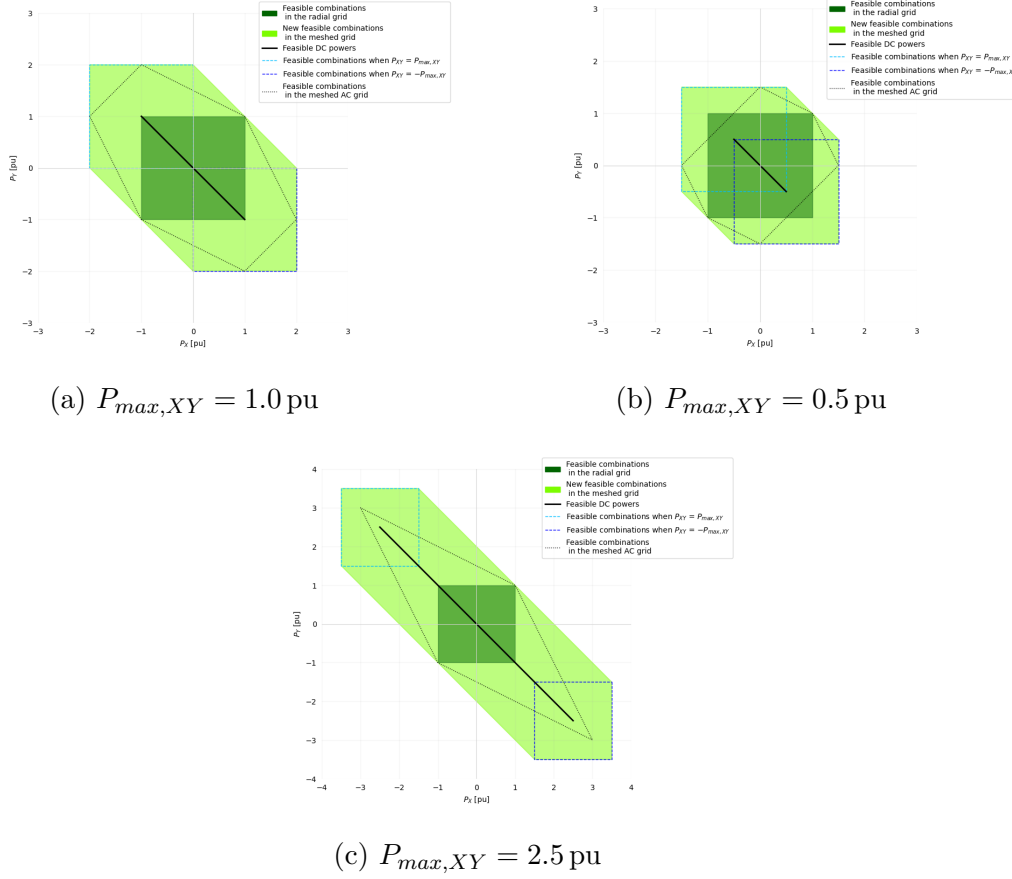


Figure 3.5: Graphical representations of the feasible combinations in a 3-node meshed grid where the XY line is DC and the other two are AC for different values of $P_{max,XY}$ where $P_{max,XZ} = P_{max,YZ} = 1$ pu

3.2 Study case: the "Boucle du Hainaut"

The two provinces of West and East Flanders are connected to the rest of the Belgian grid by a single line between Horta and Mercator (the interconnections are not taken into account). The "Boucle du Hainaut" project therefore aims to mesh the network by linking Avelgem and Courcelles. This section examines the impact of the technology of the line on the possible power flows.

3.2.1 Simplification of the Belgian grid

In 2024, Belgium's 380kV grid consists of 39 nodes and 65 power lines (see Appendix C). In order to represent the feasible power flows in two dimensions, the existing grid must be reduced to a 3-node, 2-line grid.

Avelgem and Courcelles are two obvious choices as the "Boucle du Hainaut" will connect these two nodes. For the third node, Mercator was chosen because it is the connection point between the meshed eastern grid and the radial western grid.

Of the 65 lines, 43 are not part of any path from one of the three selected nodes to another one and are therefore not considered. To simplify the remaining 22 lines into two lines with their equivalent nominal power (i.e. the maximum power without overloading any line) and impedance, simplification rules must be created.

There are two different configurations for lines: in series or in parallel. In series, the equivalent impedance is given by the sum of the impedances and the equivalent rated power is the minimum rated power between the lines. In parallel, the equivalent impedance is the inverse of the sum of the admittances of the lines. The equivalent power requires a little more thought to express.

Consider a given power S flowing through a system of n parallel lines. According to the law of current dividers, the amount of current, and therefore the power, flowing through a given line j is given by the expression:

$$\bar{S}_j = \frac{\bar{Z}_{para}}{\bar{Z}_j} \bar{S} \quad (3.5)$$

where $Z_{para} = 1/(\sum_i 1/Z_i)$ is the equivalent impedance of the system. As all the impedance angles are between 3° and 8° , it can be assumed that the lines' impedance angle are all equal. Therefore, Eq.3.5 becomes:

$$S_j = \frac{Z_{para}}{Z_j} S \quad (3.6)$$

The capacity of the system is the maximal value of S such that the power flowing through each line S_j is inferior to that line's capacity:

$$S_{para,N} = \max \left(\frac{Z_j S_j}{Z_{para}} \right) \quad \text{such that } S_j \leq S_{N,j} \quad \forall j \quad (3.7)$$

As the relationship is first degree in S_j , to maximise $S_{para,N}$, S_j must be maximised and therefore equal to $S_{N,j}$. In physical terms, the capacity of the system is the power that will flow if at least one line is at capacity and no line is overloaded. From Eq.3.6 we can conclude that the line with the smallest product $Z S_N$ will be the first to be fully loaded. Therefore the capacity of the system is given by:

$$S_{para,N} = \frac{\min(Z_j S_{N,j})}{Z_{para}} = \min(Z_j S_{N,j}) \sum_i \frac{1}{Z_i} \quad (3.8)$$

Using these four simplification rules wisely, which are gathered in Tab.3.1, we can simplify the network into a 3-node, 2-line network with the characteristics of the lines given in Tab.3.2.

	$\bar{Z}$	S_N
Series	$\sum_i \bar{Z}_i$	$\min(S_{N,i})$
Parallel	$\frac{1}{\sum_i (1/\bar{Z}_i)}$	$\min(Z_j S_{N,j}) \sum_i \frac{1}{Z_i}$

Table 3.1: Simplification rules

Line	X [Ω]	R [Ω]	S_N [GW]
Avelgem (X) - Mercator (Z)	21.70	2.20	2.24
Mercator (Z) - Courcelles (Y) <i>Brabant</i>	12.88	1.28	2.60
Mercator (Z) - Courcelles (Y) <i>Limburg</i>	73.13	6.94	1.32
Mercator (Z) - Courcelles (Y)	10.95	1.08	3.06

Table 3.2: Characteristics of the equivalent lines of the 3-node/2-line Belgian grid

It can be seen that although the sum of the capacities of both lines (Brabant and Limburg) from Mercator to Courcelles is 3.92 GW, the actual capacity is only 3.06 GW. In other words, although the Limburg line has a capacity of 1.32 GW, only 0.46 is actually used. This is due to the higher impedance, which results in a lower amount flowing through this path. As any other path between these two nodes will be longer than the Belgian ones, they will have a greater impedance and therefore the amount of power flowing through these lines can be neglected in terms of 3.06 GW. Ignoring neighbouring networks will therefore have little effect on the result.

In order to model the non-existing line between Avelgem and Courcelles, some assumptions must be made. First, the Belgian TSO foresees that the capacity of

the line will be 6 GW and its length will be 84.8 km[11]. Secondly, the impedance per unit of length will be considered as the average in the Belgian 380 kV network, which is a resistance of 30.5 mΩ/km and a reactance of 333.8 mΩ/km. Therefore, the resistance and reactance of the line will be assumed to be 2.586 Ω and 28.310 Ω respectively.

3.2.2 Graphical representation

Using Eq. 3.9 for a complete AC grid, Fig.3.6 is obtained.

$$-\begin{bmatrix} P_{max,XY} \\ P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \leq \begin{bmatrix} P_{XY} \\ P_{XZ} \\ P_{YZ} \end{bmatrix} = \begin{bmatrix} \frac{Z_{XZ}}{Z_{XY}+Z_{XZ}+Z_{XY}} & -\frac{Z_{YZ}}{Z_{XY}+Z_{XZ}+Z_{XY}} \\ \frac{Z_{XY}+Z_{XZ}+Z_{XY}}{Z_{XY}+Z_{XZ}+Z_{XY}} & \frac{Z_{YZ}}{Z_{XY}+Z_{XZ}+Z_{XY}} \\ \frac{Z_{XZ}}{Z_{XY}+Z_{XZ}+Z_{XY}} & \frac{Z_{XY}+Z_{XZ}+Z_{XY}}{Z_{XY}+Z_{XZ}+Z_{XY}} \end{bmatrix} \begin{bmatrix} P_X \\ P_Y \end{bmatrix} \leq \begin{bmatrix} P_{max,XY} \\ P_{max,XZ} \\ P_{max,YZ} \end{bmatrix} \quad (3.9)$$

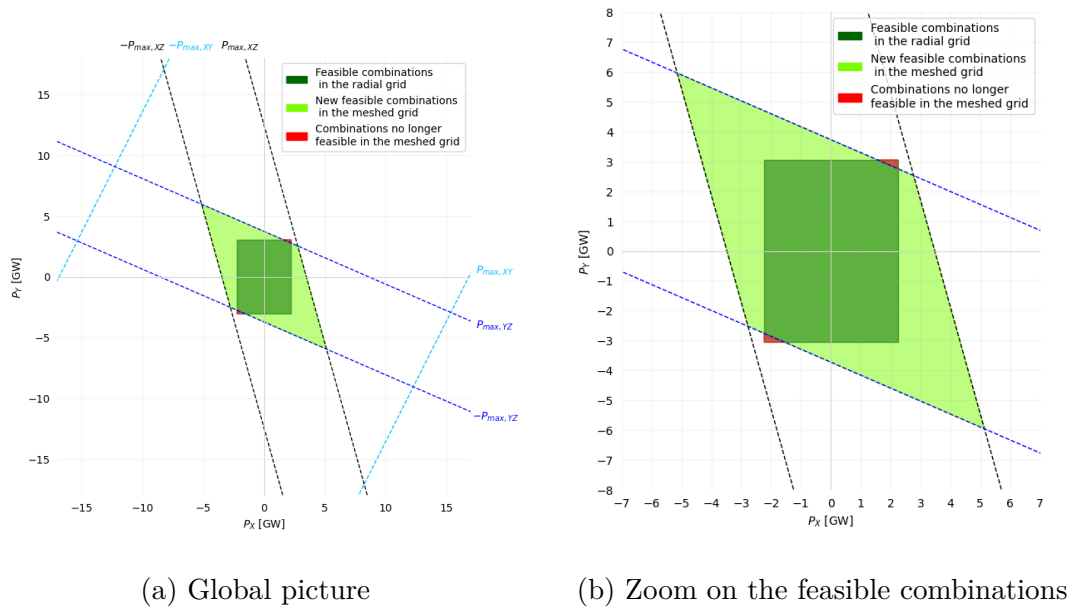


Figure 3.6: Graphical representations of the feasible combinations in a 3-node meshed grid for the study case of the "Boucle du Hainaut" in full AC

It is clear that a 6 GW AC line will make some combinations possible, but will never reach its full capacity. Also, some combinations will become infeasible due

to high supply or demand at nodes X (Avelgem) and Y (Courcelles). The reason for this marginal change is different from that seen on the theoretical network. Here the products ZS of each line are different and therefore the different lines connecting to node Z (Mercator) can no longer reach full capacity at the same time in a meshed network.

With an HVDC line, the picture is different, as shown in Fig.3.7.

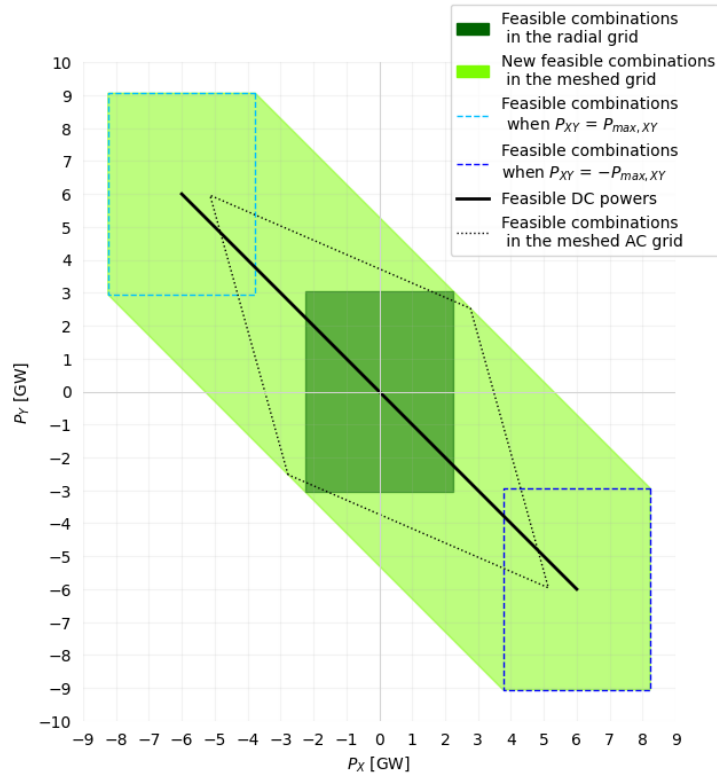


Figure 3.7: Graphical representations of the feasible combinations in a 3-node meshed grid for the study case of the "Boucle du Hainaut" is an HVDC line

As in the theoretical case, combinations that were not possible in the radial grid or in the meshed AC grid are made feasible and the system does not suffer from the threshold on a maximum line capacity.

3.3 Conclusion

There are some obvious advantages to connecting a radial network with an HVDC line rather than a HVAC line from a power flow point of view. In the case of the study, the benefits exceed all expectations.

However, it is important to note that the assumed reactance of the new AC line is likely to be smaller since a 6 GW line will likely result from several lines in parallel. Furthermore, simplifying the Belgian network in three nodes might exacerbate the results as several GW of production or demand at single nodes is unrealistic. However, the conclusion on the benefits of an HVDC line still holds.

Chapter 4

The networks

This chapter introduces the different networks on which the simulations will be carried out to the reader.
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In the following chapters, simulations will be carried out on two different networks: a Point-to-Point (P2P) network and a 3-node mesh network. They are shown in Fig.4.1.

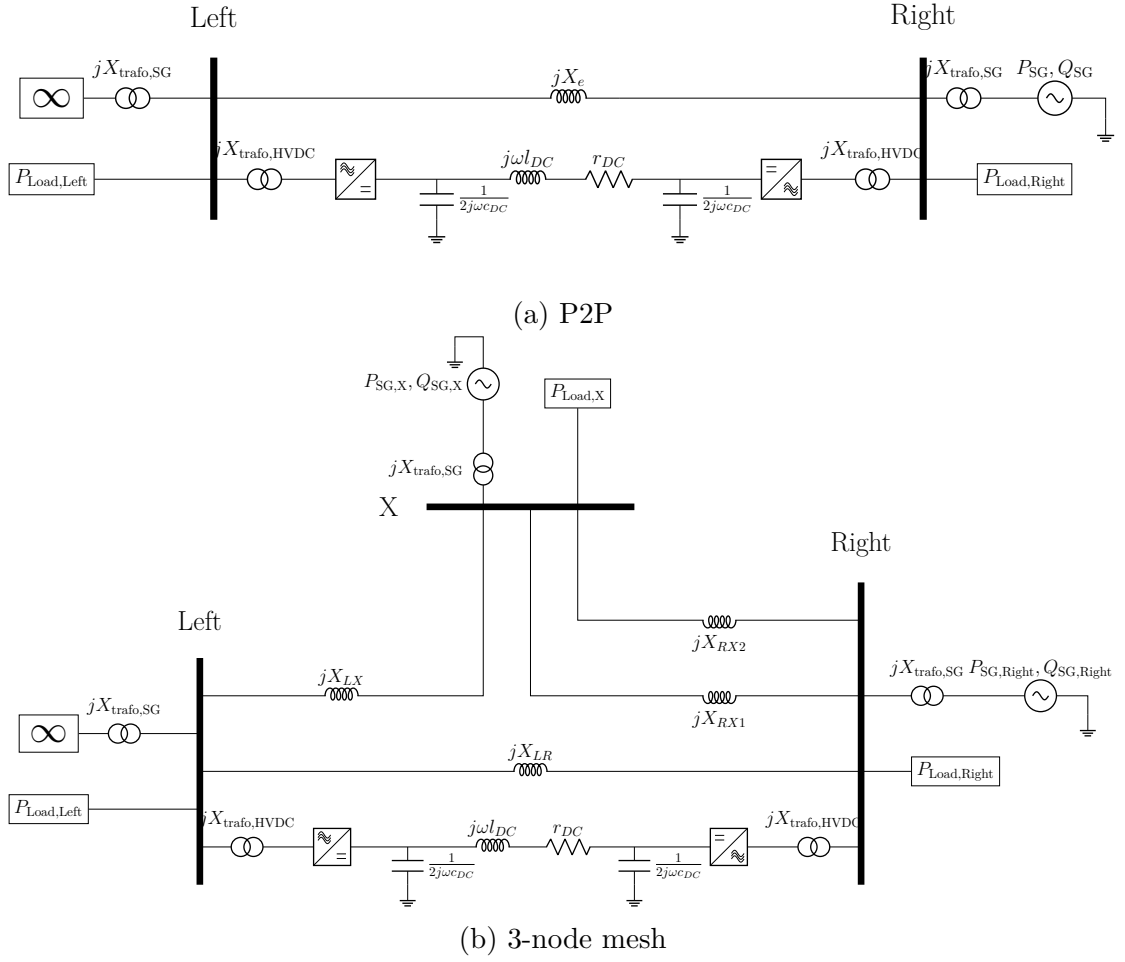


Figure 4.1: Schematics of the networks used for the simulations

The next sections describe the characteristics of the different elements. The basis of the per unit system used are:

- Nominal apparent power $S_N = 1$ GVA
- Nominal voltage $S_N = 380$ kV
- Nominal frequency $f_N = 50$ Hz

4.1 The synchronous generators

The set of parameters used is crucial, as incoherent parameters could cause the system to behave erratically and even collapse. The set of parameters was chosen

from [3]. Unfortunately, key parameters such as the inertia coefficient and the stator resistance were not specified. For the inertia coefficient, a value of 5 s was arbitrarily chosen because it is in the range of common values for this parameter. The stator resistance must also be chosen carefully, because if too high, unrealistic losses will result, and if too low, the machine will lack damping capability. In [2], a 555 MVA machine has a 0.003 pu stator resistance. Although the exercise does not specify whether the values are from a real machine or not, it is assumed that the value is of the correct order of magnitude. To account for the difference in nominal voltages, the value chosen is 0.001 pu. The values are gathered in Tab.4.1.

Parameter name	Symbol	Value	
		P2P	3-node
Nominal power	S_N	2 GVA	5 GVA
d-axis synchronous reactance	x_d	1.89 pu	
d-axis transient reactance	x_d'	0.344 pu	
d-axis subtransient reactance	x_d''	0.267 pu	
d-axis transient short-circuit time constant	T_d'	0.9 s	
d-axis subtransient short-circuit time constant	T_d''	0.0209 s	
q-axis synchronous reactance	x_q	1.80 pu	
q-axis subtransient reactance	x_q''	0.339 pu	
q-axis subtransient short-circuit time constant	T_q''	0.0232 s	
Leakage reactance	x_l	0.2 pu	
Stator resistance	R_s	0.001 pu	
Field inductance resistance ratio	L_{fd}/R_{fd}	275	
Inertia constant	H	5 s	

Table 4.1: Values used to model the synchronous generator [2][3]

4.1.1 Static Excitation

In order for the SG to generate a constant voltage and active power, the value of the mechanical power and the field voltage must be given. While the mechanical power controls the active power generated, the field voltage controls the voltage. As the analysis focus on the first few seconds after a disturbance in the network, the mechanical power is kept constant. However, the field voltage cannot be constant as the voltage would collapse after such events. It is therefore calculated by the ST1A block from *Matlab Simulink*, a static excitation block that aims to keep the voltage constant. A simplified block schematic (i.e. without limiter) can be found in Fig.4.2 (the detailed block schematic can be found in Appendix A).

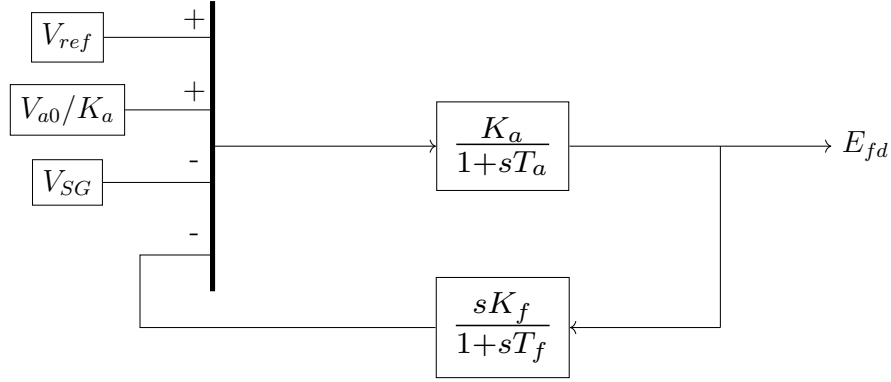


Figure 4.2: Control scheme of the exciter ST1A

The excitation consists of several blocks, each with its own purpose:

1. The main regulator is a low-pass filter with a time constant T_a and a gain K_a .
2. The feedback block is a high pass filter and aims to maintain a smooth output by subtracting the high frequency component of the main regulator output.
3. The purpose of the constant input is to set the excitation voltage E_{fd} to the desired value when $V_{SG} = V_{ref}$, since in steady state:

$$E_{fd} = K_a \left(\frac{V_{a0}}{K_a} + V_{ref,SG} - V_{SG} \right) \quad (4.1)$$

Therefore, the excitation system makes $V_{SG} = V_{ref,SG}$ only when $E_{fd} = V_{a0}/K_a$. Thanks to Simulink's *Load Flow Analyzer* tool, the value of E_{fd} is given in order to have $V_{SG} = V_{ref,SG}$ in the grid (before any event), let's call this value V_{a0} . In order to have V_{a0} as the output of the excitation system, the constant block is set to V_{a0}/K_a . However, when an event occurs, the amount of reactive power consumed by the transformers and the lines will vary. In reaction, V_{SG} will vary, causing the excitation system to adjust E_{fd} in order to keep V_{SG} equal to $V_{ref,SG}$. Moreover, if the system returns to $V_{SG} = V_{ref,SG}$, E_{fd} will return to V_{a0} and the SG will produce the same amount of reactive power as before the event. This will cause a reactive power imbalance in the system. Therefore, the new excitation voltage must be different from E_{fd} and therefore, $V_{SG} \neq V_{ref,SG}$.

There is a trade-off with K_a . Indeed, a larger value for K_a will bring V_{SG} closer to $V_{ref,SG}$ if $E_{fd} \neq V_{a0}$, but will cause larger oscillations, since variations in V_{SG} will cause larger variations in E_{fd} . The values of the different parameters are gathered in Tab.4.2.

Parameter name	Symbol	Value	Unit
Main controller gain	K_a	60	/
Main controller time constant	T_a	0.001	s
Feedback gain	K_f	0.001	/
Feedback time constant	T_f	1	s

Table 4.2: Values used to model the ST1A exciter

4.2 Infinite grid

In order to fix the frequency, as there is no governor for the SG, an infinite grid must be connected to the network. In both networks, it is connected to node Left. In the P2P network, its short-circuit power is 5 GVA and in the 3-node grid, it is 15 GVA. ¹

4.3 The HVAC lines

The most accurate way to model an HVAC line is to solve the Telegrapher's equation [18]. However, in the following simulations, the lines that will be modelled will be shorter than 100km and are thus considered as very short[18]. Furthermore, as the reactance is much larger than the resistance, they will be modelled as a simple reactance. Therefore, the powers flowing through it (where the active power is flowing from 1 to 2) can be expressed as:

$$P_{1 \rightarrow 2} = \frac{V_1 V_2}{X} \sin(\phi_1 - \phi_2) \quad (4.2)$$

$$Q_1 = \frac{V_1}{X} [V_1 - V_2 \cos(\phi_1 - \phi_2)] \quad (4.3)$$

$$Q_2 = \frac{V_2}{X} [V_1 \cos(\phi_1 - \phi_2) - V_2] \quad (4.4)$$

In the P2P network, the nodes are considered to be 84.8km apart (this distance corresponds to the length of the "Boucle du Hainaut" line[11]). Therefore, the value of the reactance per unit of distance is chosen to be the average one on the 380 kV Belgian grid: 4.506 H (334 mΩ/km). Therefore, $X_e = 0.196$ pu (see Appendix.C). It is important to note that this line is actually composed of two branches whose impedance is $2jX_e$.

¹Note that with transformer, the actual short-circuit powers are respectively 2.86 GVA and 4.62 GVA.

In the 3-node grid, the lines have the same impedance as in Sec.3.2 where the line connecting node Left to node Right corresponds to the line connecting Avelgem to Mercator and the ones connecting node Right to node X correspond the lines connecting Courcelles to Mercator. The line Left-Right is the same as in the P2P network. All the data is gathered in Tab.4.3.

Line	Left-Right	Left-X	Right-X1	Right-X2
Impedance (pu)	$j0.196$	$j0.150$	$j0.089$	$j0.506$

Table 4.3: Impedance of the different lines in the 3-node mesh grid

4.4 The transformers

In the networks used for the simulations, there are two types of transformers: the one used to connect the SG to the High Voltage (HV) grid and the one to connect the HVDC converters to the HV grid.

	HVDC	SG
Configuration	Star/Delta	Star/Delta
Nominal power S_N	$S_{N,HVDC}$	$S_{N,SG}$
Nominal low voltage $V_{N,low}$	$V_{N,HVDC} = 26 \text{ kV}$	250 kV
Nominal high voltage $V_{N,high}$	380 kV	380 kV
Series impedance low voltage	$j0.05 \text{ pu}$	$j0.00 \text{ pu}$
Series impedance high voltage	$j0.05 \text{ pu}$	$j0.15 \text{ pu}$

Table 4.4: Characteristics of the transformers

4.5 HVDC converters

For the HVDC converters, the model developed in [19] was used. It is an average-value model of Modular Multilevel Converter (MMC) converters.

An average value model, as explained in [19], models the converters with controlled voltage and current sources so that they behave like real MMC converters. With these simple models we have faster simulations, but we lose some accuracy. Therefore, they are only suitable for studying large disturbances on the AC side.

The MMC is a type of voltage source converter (a technology with power electronics that allows a gate signal to switch them off), made up of several levels of

submodules, which improves the harmonic content of the generated signal [20]. In addition to this advantage, its high efficiency has made it one of the most widely used technologies for this purpose.

In the simulations, the converters will be controlled as Grid-Following (GFL) converters. A GFL converter adjusts its current generation for reaching the targeted powers. In other terms, it can be represented as a controlled current source. Therefore, the converter must track (follow) the voltage at its Point of Common Coupling (PCC). This is done thanks to a Phase-Locked Loop (PLL). However, a PLL requires a strong signal and, in weak or islanded grids, a GFL can be unstable [21].

4.5.1 Power control strategies

Both the active and reactive powers are controlled thanks to PI controller which ensure that the power delivered is the reference power.

Active power

For the active power, the control strategy selected is the constant.

Reactive power

For the reactive power, two cases are analysed:

- The first one is the same as for the active power: a constant amount of power is produced or consumed by each converter.
- The second one is a dynamic droop control strategy: according to the power flow equations, the equation at the node of the converters is:

$$S_{HVDC}^* = j \frac{V_{HVDC}}{X_{trafo,HVDC}} [V_{HVDC} - V_{Right} e^{j(\phi_{Right} - \phi_{HVDC})}] \quad (4.5)$$

The reactive power is the opposite of the imaginary part of this equation:

$$Q_{HVDC} = \frac{V_{HVDC}}{X_{trafo,HVDC}} [V_{Right} \cos(\phi_{Right} - \phi_{HVDC}) - V_{HVDC}] \quad (4.6)$$

In order to keep V_{Right} at 1 pu, the strategy selected is to use the derivative of this expression as the value of a droop strategy:

$$Q_{HVDC,ref} = \frac{dQ_{HVDC}}{dV_{Right}} (V_{ref} - V_{Right}) = \frac{V_{HVDC}}{X_{trafo,HVDC} \sqrt{1 - \left(\frac{|P_{HVDC}| X_{trafo,HVDC}}{V_{HVDC} V_{Right}} \right)^2}} (V_{ref} - V_{Right}) \quad (4.7)$$

One would notice that if the product $V_{HVDC} V_{Right}$ is smaller than the product $|P_{HVDC}| X_{trafo,HVDC}$, infinite values will result. In practice, since $X_{trafo,HVDC} = 0.1$ pu, $|P_{HVDC}| < 1$ pu and $|Q_{HVDC}| < 1$ pu, the limiters will not allow this situation.

Fig.4.3 shows the reactive power generated by the converter if V_{HVDC} is assumed to be equal to V_{Right} and $|P_{HVDC}| = 0$ pu.

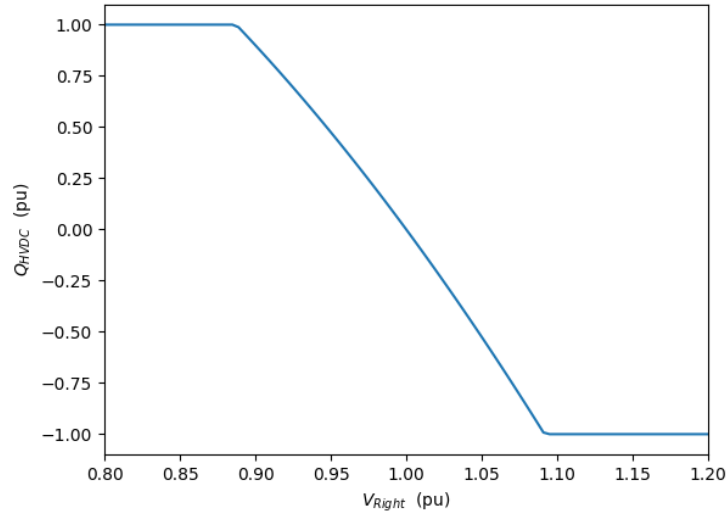


Figure 4.3: Reactive power generated by the converter if V_{HVDC} is assumed to be equal to V_{Right} and $|P_{HVDC}| = 0$ pu

4.6 State of load of the networks

Now that every element of the networks have been characterised, we have to know how much they are loaded.

4.6.1 P2P Network

In this configuration, only the single theoretical state of load presented in Tab.4.5 will be studied.

Node	Generation	Load
Left	$0.6 \text{ pu} + P_{losses}$	1.2 pu
Right	1.1 pu	0.5 pu

Table 4.5: State of load of the P2P Network

As the infinite grid is the slack node, it generates such power that the generation matches the consumption.

4.6.2 3-node mesh Network

As the 3-node grid represent the Belgian 380 kV network, in order to have realistic production and consumption, the country has been divided in three areas. As displayed in Fig.4.4, node X corresponds to Mercator and represents the provinces of Antwerp, Flemish Brabant, Limburg and the Brussels Capital Region. Node Left corresponds to Avelgem and represents the provinces of East and West Flanders. Finally, node Right corresponds to Courcelles and represents the Walloon region (Hainaut, Liège, Luxembourg, Namur and Walloon Brabant).

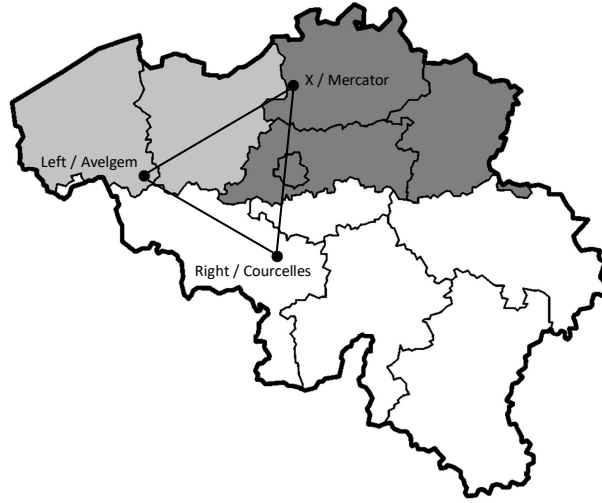


Figure 4.4: Different areas used to model the Belgian grid into a 3-node grid

Therefore, all generating units and loads located in these areas are grouped together as a single SG (whose nominal power is 5 GVA) and load. In order to select plausible ranges of values for loads and generating units, the most important generating units (i.e. nuclear, hydro and gas plants with a capacity greater than 100 MW) are grouped by area in Tab.4.6. Solar farms are not included as they are not connected to the high voltage grid. Onshore wind farms are also excluded as less than 20% of them are connected to the transmission network operated by Elia[22].

Area	Type	Location	Capacity [MW]	Total capacity [MW]
X / Mercator	Nuclear	Doel (Antwerp)	1,916	1,916
	Gas	Zandvliet (Antwerp)	385	845
		Drogenbos (Flemish Brabant)	460	
Left / Avelgem	Gas	Gent-Ham (East Flanders)	126	1,208
		Gent-Ringvaart (East Flanders)	357	
		Knippegroen (East Flanders)	300	
		Herdersbrug (West Flanders)	425	
	Offshore Wind	North sea (West Flanders)	2,261	2,261
Right / Courcelles	Nuclear	Tihange (Liège)	1,992	1,992
	Gas	Amercoeur (Hainaut)	451	1,419
		Saint-Ghislain (Hainaut)	350	
		Angleur (Liège)	158	
		Seraing (Liège)	460	
	Hydro	Plate taille (Hainaut)	173	1,307
		Coo-Trois-Pont (Liège)	1,164	

Table 4.6: The main generation units in Belgium associated to their node in the 3-node Belgian grid [4]

And finally, the interconnections must be modelled. Their capacities are gathered in Tab.4.7.

Area	Country	Line	
		Type	Capacity [MW]
X / Mercator	Netherlands	AC-380 kV	6,044
Left / Avelgem	France	AC-380 kV	1,316
	United Kingdom	DC	1,075
Right / Courcelles	France	AC-220 kV	1,287
	France	AC-380 kV	1,352
	Germany	DC	1,050
	Luxembourg	AC-220 kV	790

Table 4.7: Interconnections capacity gathered by area [5]

Actual data from the Belgian grid was used to determine the operating point of the different grid conditions. The moment when the offshore wind production was at its peak was arbitrarily chosen [23].

High Offshore Wind Generation

On 7 January 2023 at 4:00 am, the Belgian offshore wind reached its peak production of the year with a measured production of 2238 MW (the monitored capacity at the time was 2254 MW). Meanwhile, the Elia grid load was 5592 MW and the physical power flows on the interconnections were such that Belgium was exporting to France (126 MW), Germany (854 MW), Luxembourg (229 MW) and

the Netherlands (1615 MW) and was importing from the UK (974 MW). On aggregate, Belgium was exporting 1850 MW. Since the author did not find all the data necessary to model the grid, the following assumptions have been made:

- The load will be divided proportionally to the population in each area in 2023. Therefore, the load will be assumed to be 2500 MW in area X (44.7%), 1331 MW in area Left (23.8%) and 1761 MW in area Right (31.5%) [24].
- Since France is interconnected to two areas (Left and Right), the assumption of equal loading of the lines is made to divide the flows. Therefore, 97 MW flows from Left and 29 MW from Right.
- Since the nuclear power plants must keep their generation constant, they are assumed to be producing with a capacity factor of 89% (their average capacity factor in 2023 [25]). Therefore, Doel is producing 1700 MW and Tihange 1775 MW.
- Due to the high level of renewable generation, it is assumed that the pumped storage plant does not generate any electricity.
- The gas power plants are assumed to make the balance between the load and the generation. Furthermore, every plants are supposed to have the same capacity factor. Therefore, gas generate 1729 MW: 421 MW, 601 MW and 707 MW in respectively areas X, Left and Right.

Tab.4.8 gathers and summarizes all the information.

Area	X / Mercator	Left / Avelgem	Right / Courcelles
Nuclear generation (MW)	1,700	/	1,775
Gas generation (MW)	421	601	≈ 707
Hydro generation (MW)	/	/	≈ 0
Wind generation (MW)	/	2,238	/
Load (MW)	2,500	1,331	1,761
Exports (MW)	1,615	-877	1,112
Total generation (pu)	0.506	$3.716 + P_{losses}$	1.370
Total load (pu)	2.500	1.331	1.761

Table 4.8: Summary of the generation, loads and exports for the High Offshore Wind Generation state of the grid

4.7 Simulations

In the following chapters all simulations were done using *Matlab Simulink*. Their purpose is to highlight the effect of the control of the active and reactive powers of the HVDC converters.

4.7.1 Control of the active power

In this case, the reactive power is controlled at 0.0 pu and the active power is controlled at different values to see what effect it has on the system.

- In the P2P network, since 0.6 pu must flow from node Right to node Left, the values selected are 0.0, 0.3 and 0.6 pu (a positive value means the power flows from node Right to node Left). Any value smaller than 0.0 or greater than 0.6 would make power to flow round in circles in the network. These situations being largely inefficient, they will not be considered.
- In the 3-node network, the values selected are 0.0, ± 0.45 and ± 0.90 pu. Even though the converters are able to generate/consume up to 1.00 pu of active power, it is important have some reserve for the reactive power. In addition, a network operator will try to avoid using an element at full capacity under normal conditions in order to respect the N-1 criterion.
It is important to note that positive active power references make power to flow round in circles. The purpose of this will be explained in Sec.8.1.

To determine the effect of the presence of the HVDC line, the network is also simulated without it.

4.7.2 Control of the reactive power

In this case, the active power is controlled at 0.0 pu and the reactive power is controlled at different values to see what effect it has on the system. Since the infinite grid is connected to the node Left, varying the reactive power of the converter connected to that node will have no effect. So, only the control of the converter connected to the node Right will be studied.

- In the P2P network, the constant references will be within the range of ± 0.2 pu (± 0.1 pu for the SG). More precisely, the values selected are 0.0, ± 0.1 and ± 0.2 pu
- In the 3-node network, the range is extended to ± 0.4 pu as the SG's nominal power is greater. The values chosen are 0.0 and ± 0.4 pu

The dynamic reactive power control strategy developed in Sec.4.5.1 will also be simulated.

Part II

Simulations on the P2P network

Chapter 5

Topology variation

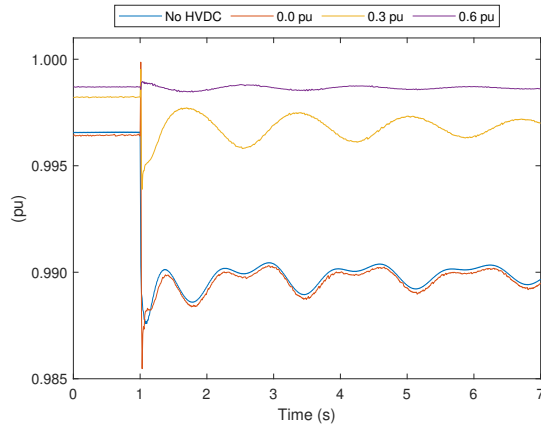
This chapter analyses the effect of varying the active and reactive power control strategies of HVDC converters on the rotor angle stability of the system in the P2P network presented in Chap.4 when the impedance of the line connecting the two nodes is suddenly doubled. It is shown that:

- Transferring active power through the HVDC line instead of the HVAC line attenuates the transient and improves the damping.
- Generating a constant amount of reactive power attenuates the transient and improves the damping. Using dynamic reactive power control gives better results.

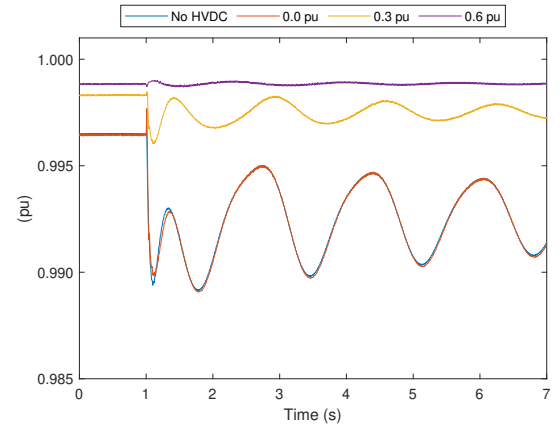
In this scenario, one of the two branches that make up the HVAC line is opened at the time $t_{event} = 1$ s. This will result in the line having instantly an impedance twice as much as before the fault (0.196 pu to 0.392 pu).

5.1 Effect of the active power control of the HVDC converters

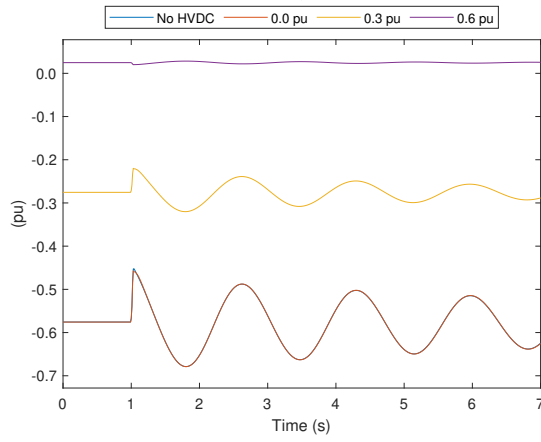
The results of the simulations are displayed in Fig.5.1.



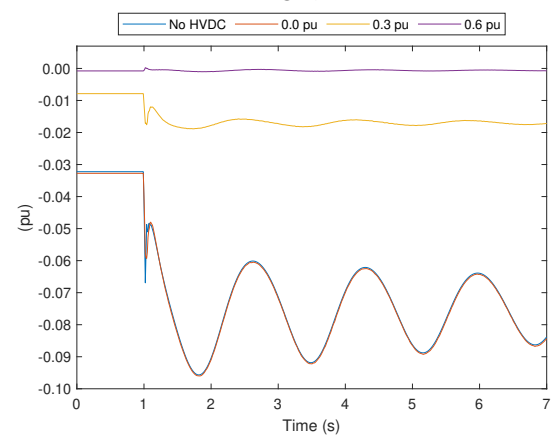
(a) $V_{Left,RMS}$



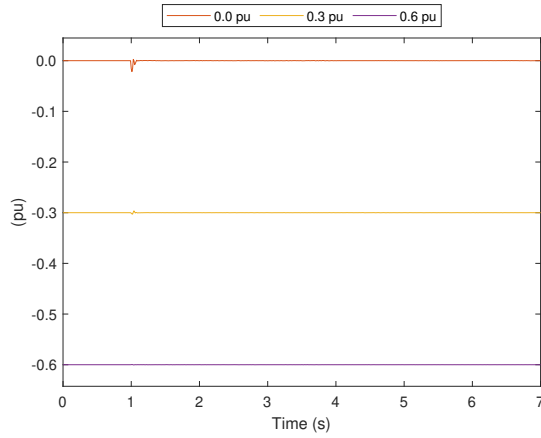
(b) $V_{Right,RMS}$



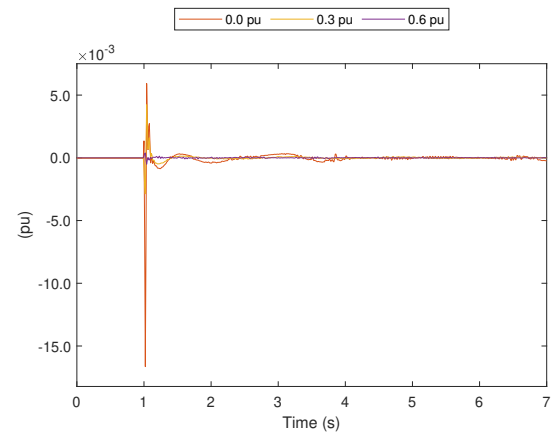
(c) $P_{HVAC,Right}$



(d) $Q_{HVAC,Right}$



(e) $P_{HVDC,Right}$



(f) $Q_{HVDC,Right}$

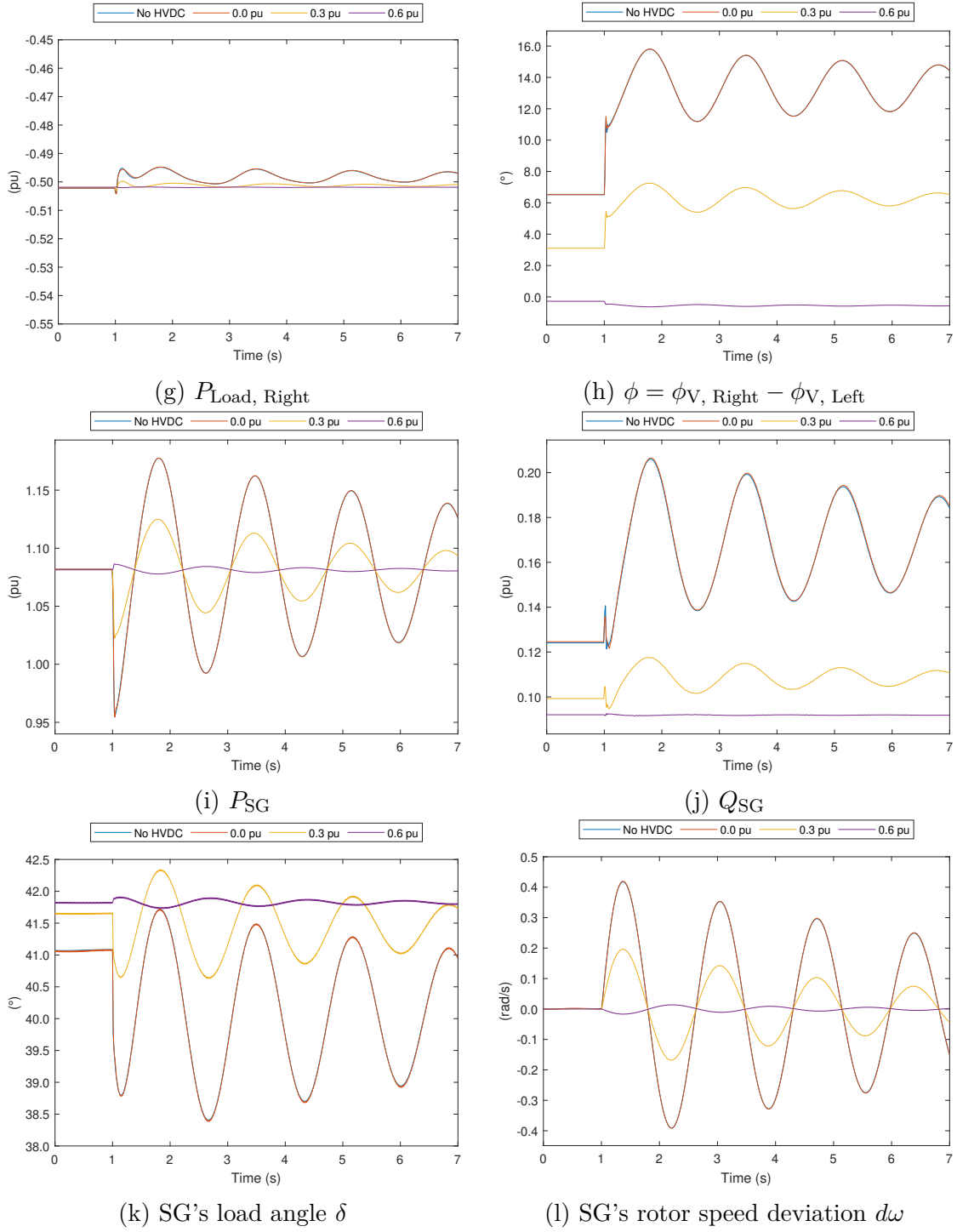


Figure 5.1: Results of the simulations on the effect of the active power control of the HVDC converters for the topology variation scenario

As explained hereabove, the impedance of the line is doubled. According to Eq. 4.2, if no other parameter changes, the amount of active power flowing through the line would be cut by half. However:

1. the load is a pure resistance and thus, consumes $P_{\text{Load, Right}} = V_{\text{Right}}^2 / R_{\text{Load, Right}}$. Since the voltage is controlled by the synchronous generator via its exciter (Sec.4.1.1), it remains constant (Fig.5.1b). Therefore, the power consumed by the load is constant (Fig.5.1g).
2. the HVDC converter (if present) is controlled to consume a given amount of active power, and does so (Fig.5.1e).
3. the mechanical power furnished to the synchronous generator is also constant, leading to a rather constant electrical power production (Fig.5.1i).

For all these reasons, the amount of active power flowing through the line must also be constant (Fig.5.1c).

According to Eq.4.2, because the voltages are both constant as V_{Right} is controlled by the synchronous generator and V_{Left} is connected to the infinite grid (Fig.5.1a), the only way to compensate the decrease of X is by increasing $\sin \phi$ (Fig.5.1h).¹

But changing the amount of active power flowing through the line has an impact on the reactive power flowing through the line (Eq.4.3). As $\sin \phi$ increases, $\cos \phi$ decreases causing $V_{\text{Right}} \cos \phi$ to decrease (as V_{Right} is constant) and thus, causing the amount of reactive power flowing into the line to increase (Fig.5.1d). Since in the power flow equations, the reactive power and the voltage are linked, the exciter of the synchronous machine will increase the excitation voltage in order to maintain the voltage at 1 pu and thus, compensates the increase of consumption of the line (Fig.5.1j). Also, Q_{SG} is greater than $Q_{\text{HVAC, Right}}$ since the SG is connected to node Right via a transformer whose inductance is equal to 0.075 pu and thus, consumes some reactive power. This variation of reactive power is entirely compensated by the machine as the load is a pure resistance, thus neither consuming nor producing reactive power, and the HVDC converter, as for the active power, is controlled to deliver a given amount (in this section, 0 MVar (Fig.5.1f)).

5.1.1 Impact of the HVDC line on the transient

The first and most striking observation is that when $P_{\text{HVDC}} = 0.6$ pu, there is almost no transient whereas when $P_{\text{HVDC}} = 0.0$ pu or 0.3 pu, the transient is clearly

¹There are slight variations in the voltage values which are explained in Sec.5.2. In this section, they are considered constant and equal

noticeable (and is more severe in the case $P_{HVDC} = 0.0$ pu), as shown in Tab.5.1.

Q_{HVDC} (pu)	τ (s)	R^2 (%)	$ \Delta_{max}\delta $ (°)	$ \Delta_{max}d\omega $ (rad/s)
No HVDC	9.4	99.9	2.67	0.42
0.0	9.5	99.9	2.68	0.42
0.3	5.2	99.9	1.03	0.20
0.6	3.9	99.7	0.10	0.02

Table 5.1: Effect of the active power control of the HVDC converters for the topology variation scenario on the damping time constants τ and their R^2 values of the rotor speed deviation and the maximal deviation of the load angle δ et rotor speed deviation $d\omega$

This is because when $P_{HVDC} = 0.6$ pu, all the power flowing from node Right to node Left goes through the HVDC link². Therefore, $\sin \phi \approx 0$ and when the event occurs, $\sin \phi$ must double as X doubles and therefore, it does not vary. When $P_{HVDC} = 0.0$ pu or 0.6 pu, $\sin \phi \neq 0$, thus doubling $\sin \phi$ creates a transient as explained above. Since with $\sin \phi_{0.3} < \sin \phi_{0.6}$, the transient is more severe in the second case. To quantify the severity of the transient, Tab.5.1 gathers the maximal deviation of the SG's load angle δ et rotor speed deviation $d\omega$.

Another point of interest displayed in Tab.5.1 is how damped the oscillations are. As they are of the form $\sin(\omega_{osc}t) \exp(-t/\tau) + B$ where B is a constant, it is relevant to compare the different time constants τ . It was easy to see from the graphs that the more power flowing through the HVDC line, the less severe the transients. What was less obvious is that the damping is also better. Since the R^2 values are close to 1, the assumption of damping of the form $\sin(\omega_{osc}t) \exp(-t/\tau)$ is verified. The time constants can be reduced by a factor of 3, so the damping is 3 times better.

To explain this difference of damping, one must go back to the Heffron-Philipps model and Eq.2.2 to see the effect of the HVDC line on the poles. One obvious difference is the variations of the load angle of the SG. However, as these variations are small, they will be neglected in this part (see Sec.5.2). The other difference is the effect this line has on the load flow. Even though the amount of active power

²In reality, due to some losses in the synchronous generator (mainly the stator resistance $R_s = 0.001$ pu), its net production is slightly inferior to the ideal power flow value and therefore, some power is flowing from node Left to node Right. However, this amount of power an order of magnitude smaller and can be neglected.

flowing from node Right to node Left is constant (around 0.6 pu), the one flowing through the HVAC is not:

$$P_{\text{HVAC}} = P_{\text{RightToLeft}} - P_{\text{HVDC}} = \frac{V_{\text{Right}} V_{\text{Left}}}{X_e} \sin(\phi_{\text{Right}} - \phi_{\text{Left}}) \quad (5.1)$$

So mathematically, $P_{\text{RightToLeft}}$ can be expressed as::

$$P_{\text{RightToLeft}} = \frac{V_{\text{Right}} V_{\text{Left}}}{X_{e,eq}} \sin(\phi_{\text{Right}} - \phi_{\text{Left}}) \approx 0.6 \text{ pu} \quad (5.2)$$

where $X_{e,eq}$ is the equivalent impedance of the line connecting node Left and node Right and therefore, must vary with P_{HVDC} as does $\sin(\phi_{\text{Right}} - \phi_{\text{Left}})$. From these two equations, we have:

$$X_{e,eq} = \frac{P_{\text{RightToLeft}} - P_{\text{HVDC}}}{P_{\text{RightToLeft}}} X_e \quad (5.3)$$

According to this formula, if no power flows through the HVDC line, $X_{e,eq} = X_e$, which makes sense, and if all the power flows in it, $X_{e,eq} = 0$ pu, which makes also sense since both voltage phases are equal despite power flowing from one node to the other.

And if we go back to Eq.2.1, we observe that the constants are function of X_e and therefore, P_{HVDC} will influence the poles. Tab.5.2 shows the evolution of the dominant poles for different values of $X_{e,eq}$ and the estimated parameters of the system.

$X_{e,eq}$	P_{HVDC}	Dominant poles
0.392 pu	0.0 pu	$-1.37 \cdot 10^{-6} \pm j 0.132$
0.196 pu	0.3 pu	$-4.11 \cdot 10^{-6} \pm j 0.136$
0.000 pu	0.6 pu	$-36.36 \cdot 10^{-6} \pm j 0.078$

Table 5.2: Evolution of the dominant poles for different values of $X_{e,eq}$

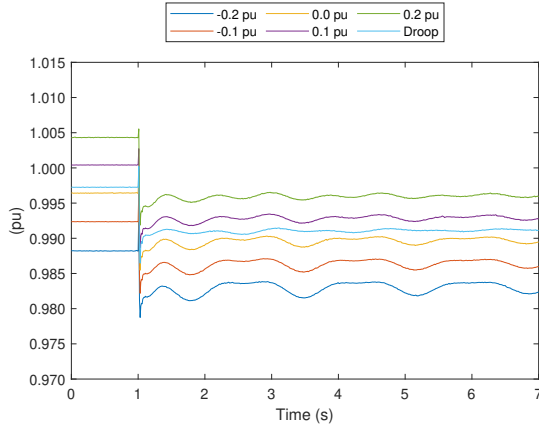
We can clearly observe that a decreasing $X_{e,eq}$ (i.e. an increasing P_{HVDC}) makes the poles more negative and hence, improves the damping. But its rate of change and the variation of the imaginary part are not accurate (in Fig.5.11, we see that there is no variation in the frequency of the oscillations). This is due to the operating point that may be poorly estimated and to the numerous approximations that were explicitly and implicitly made throughout the development:

- The exciter time constant T_a is assumed to be 0.
- The load angle δ of the SG is assumed to be constant.
- The amount of power flowing through $X_{e,eq}$ is assumed to be the same as the one produced by the SG, thus neglecting $P_{\text{Load, Right}}$.
- Node Left is assumed to be the infinite grid but is not. In reality, the infinite grid is the voltage source connected to node Left through the transformer but since $X_{SG} + X_{trafo} + X_{e,eq} \gg X_{trafo} + 1/S_{SSC,\infty}$, variations in ϕ_{Left} are considered small and this assumption can be made.

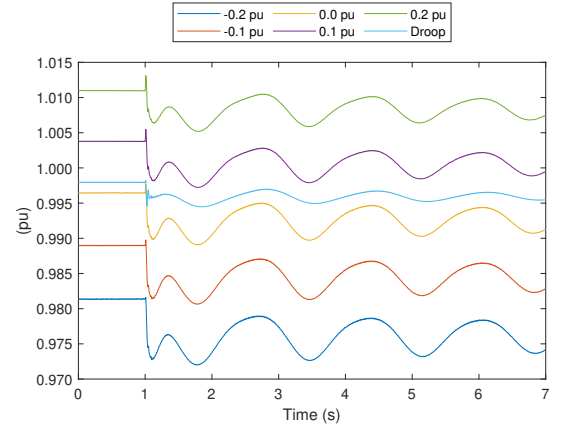
However, this development proves the impact the HVDC line can have on the network.

5.2 Effect of the reactive power control of the HVDC converters

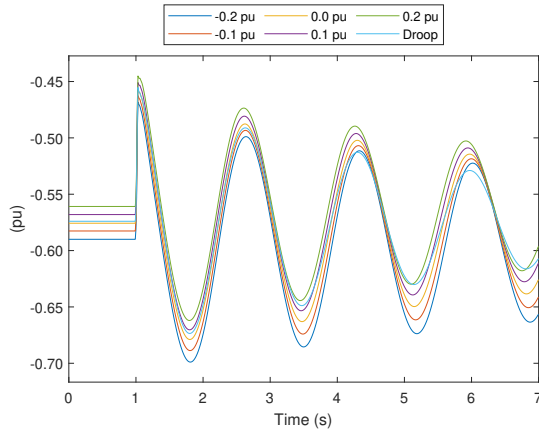
The results of the simulations are displayed in Fig.5.2. For the sake of clarity, the results of the simulation without the HVDC link are not displayed as they are similar to the case $P_{\text{HVDC}} = Q_{\text{HVDC}} = 0$ pu (see Fig.5.1).



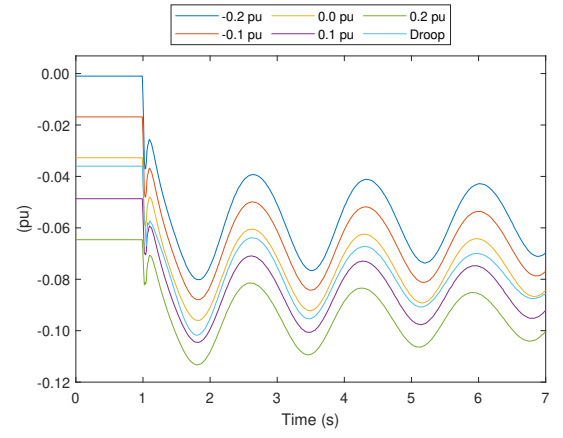
(a) $V_{Left,RMS}$



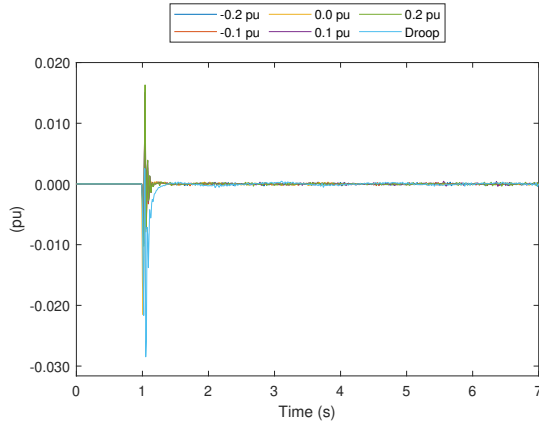
(b) $V_{Right,RMS}$



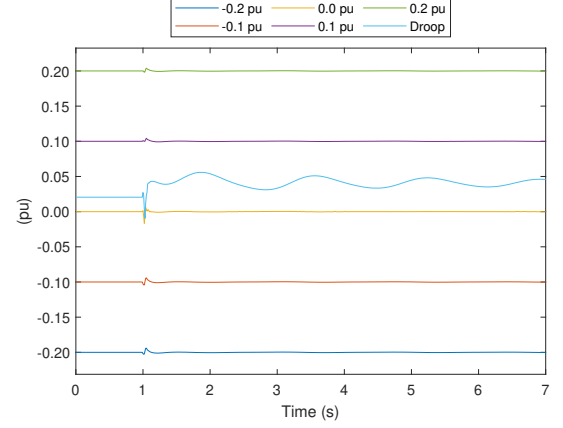
(c) $P_{HVAC,Right}$



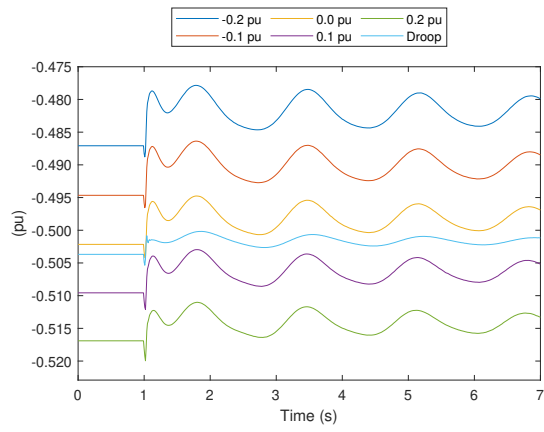
(d) $Q_{HVAC,Right}$



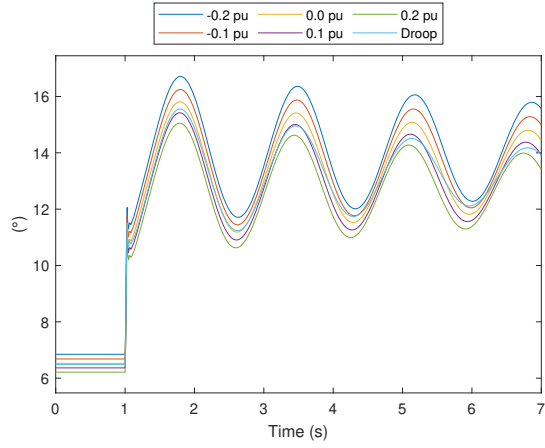
(e) $P_{HVDC,Right}$



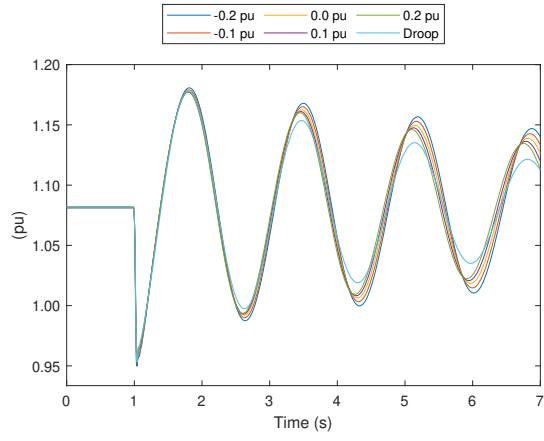
(f) $Q_{HVDC,Right}$



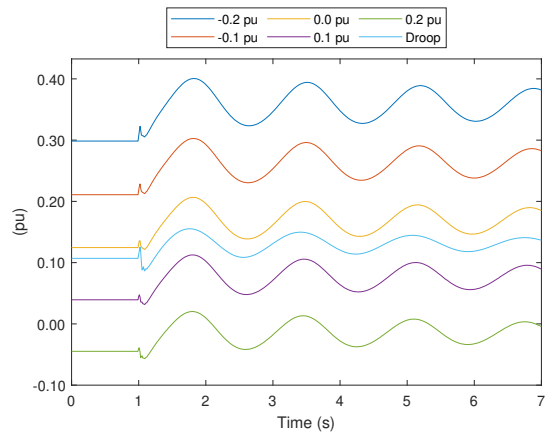
(g) $P_{\text{Load, Right}}$



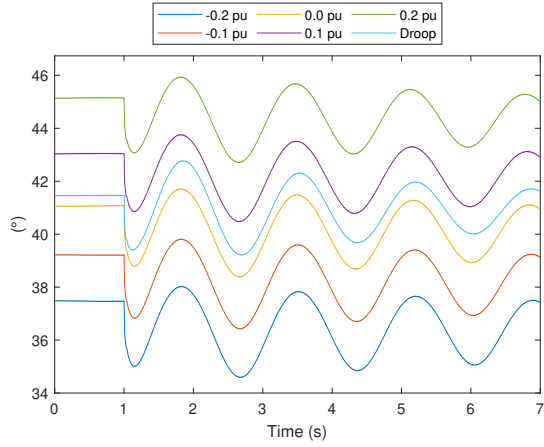
(h) $\phi = \phi_V, \text{Right} - \phi_V, \text{Left}$



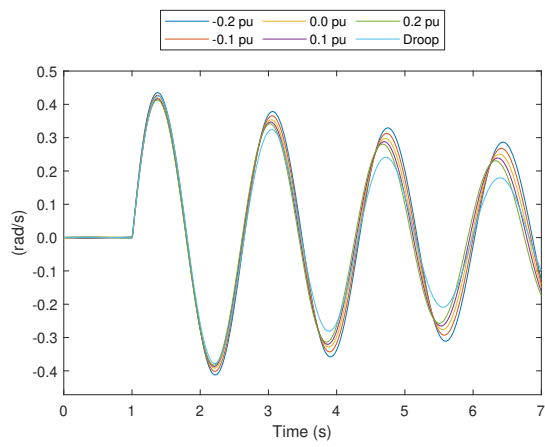
(i) P_{SG}



(j) Q_{SG}



(k) SG's load angle δ



(l) SG's rotor speed deviation $d\omega$

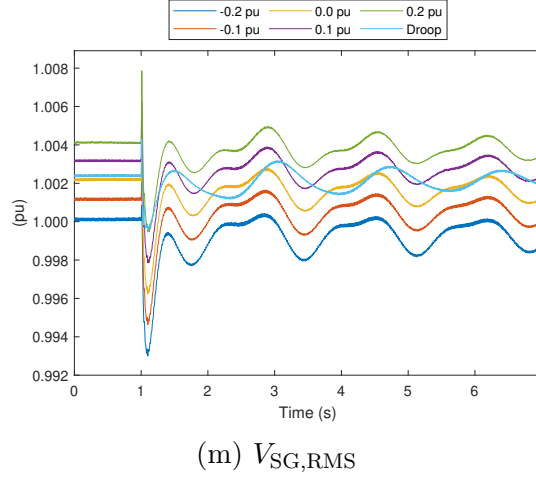


Figure 5.2: Results of the simulations on the effect of the reactive power control of the HVDC converters for the topology variation scenario

5.2.1 Impact of the HVDC line on the steady state operation

First, only the constant reactive power cases are considered. With the reactive power control, the reactive power consumption or production of the HVDC converters is different than when it is controlled to 0.0 pu. In a first time, this variation of reactive power must be absorbed by the SG (Fig.5.2j), which will cause the voltage at the SG terminals to change and thus, the exciter will adjust the excitation voltage as it controls this voltage. But as explained in Sec.4.1.1, the voltages will be slightly different in every case (Fig.5.2m). Because of this and because the amount of reactive power flowing through the transformer connecting node Right to the SG is different while the amount of active power remains constant (Fig.5.2i), the voltage at node Right will also be slightly different in every case (Fig.5.2b). Therefore, the power consumed by the load also varies (Fig.5.2g) leading to a different amount of active power flowing through the HVAC line (Fig.5.2c) as the active power produced by the SG and consumed by the the HVDC converter (Fig.5.2e) remain constant. All of this, explains why the variation of production of reactive power by the SG does not match entirely the variation of production of reactive power by the HVDC converters.

If the reactive power of the HVDC converters is controlled according to the Droop strategy, since $V_{Right,RMS} \approx 1$ pu, almost no reactive power is neither produced nor consumed by the HVDC converter. Therefore, the results in steady state are pretty similar to the case where $Q_{HVDC} \approx 0.0$ pu.

5.2.2 Impact of the HVDC line on the transient

The values of the maximal deviation and the damping time constant are gathered in Tab.5.3

Q_{HVDC} (pu)	τ (s)	R^2 (%)	$ \Delta_{max}\delta $ (°)	$ \Delta_{max}d\omega $ (rad/s)
-0.2	11.8	99.5	2.91	0.44
-0.1	10.5	99.7	2.81	0.43
0.0	9.5	99.9	2.68	0.42
0.1	8.7	99.7	2.58	0.42
0.2	8.3	99.9	2.45	0.41
Droop	5.7	99.9	2.26	0.43

Table 5.3: Effect of the active power control of the HVDC converters for the topology variation scenario on the damping time constants τ and their R^2 values of the rotor speed deviation and the maximal deviation of the load angle δ et rotor speed deviation $d\omega$

As for the active power, the variation in the damping is explained by the Heffron-Philippis model but here, X_e remain constant but the load angle of the SG vary. Tab.5.4 shows the evolution of the dominant poles for different values of δ and the estimated parameters of the system.

δ	Q_{HVDC}	Dominant poles
37°	-0.2 pu	$-1.13 \cdot 10^{-6} \pm j 0.141$
41°	0.0 pu	$-1.34 \cdot 10^{-6} \pm j 0.133$
45°	0.2 pu	$-1.56 \cdot 10^{-6} \pm j 0.124$

Table 5.4: Evolution of the dominant poles for different values of the load angle δ

For the Droop case, the damping is better since the converter injects some reactive power when $V_{Right} < V_{Ref}$ and retrieves some in the opposite case. Therefore, it acts as a proportional controller, enhancing the system's damping.

Chapter 6

Load variation

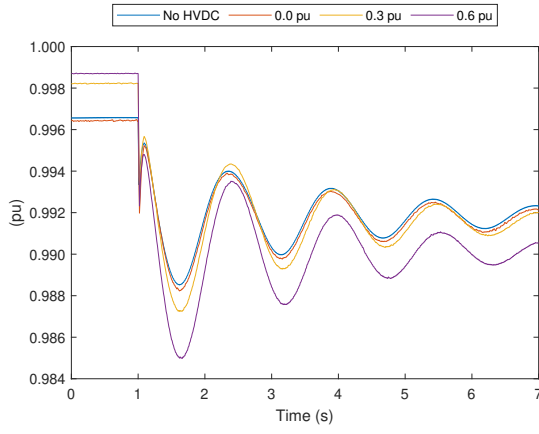
This chapter analyses the effect of varying the active and reactive power control strategies of HVDC converters on the rotor angle stability of the system in the P2P network presented in Chap.4 when the load at node Right suddenly increases by 0.2 pu. It is shown that:

- Transferring active power through the HVDC line instead of the HVAC improves the damping but creates slightly larger deviations.
- Generating a constant amount of reactive power attenuates the transient and improves the damping. Using dynamic reactive power control reduces the deviation but does not improve the damping.

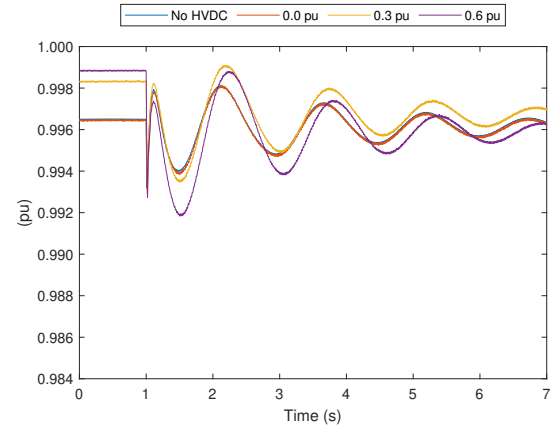
In this scenario, the load connected to node Right increases by 0.2 pu, going from 0.5 pu to 0.7 pu, at $t_{event} = 1$ s.

6.1 Effect of the active power control of the HVDC converters

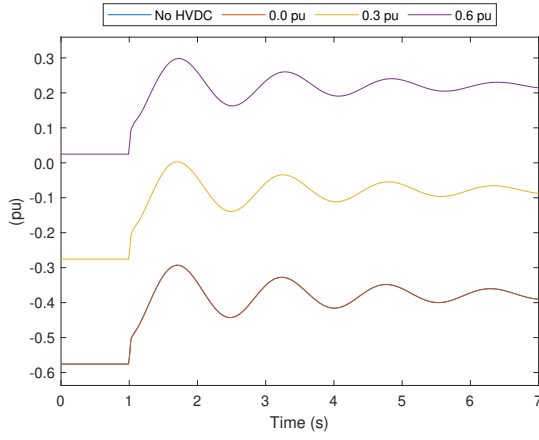
The results of the simulations are displayed in Fig.6.1.



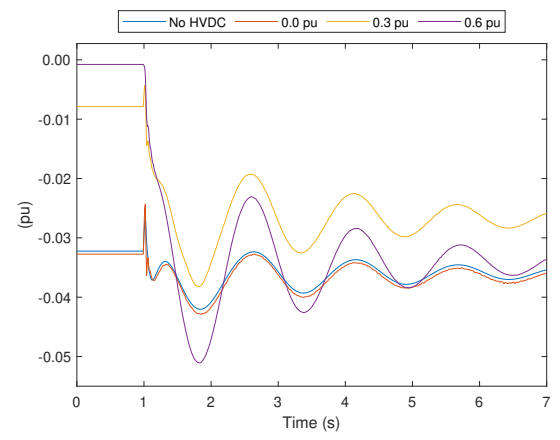
(a) $V_{Left,RMS}$



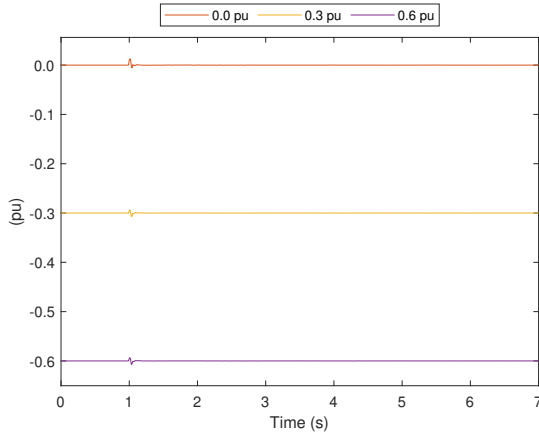
(b) $V_{Right,RMS}$



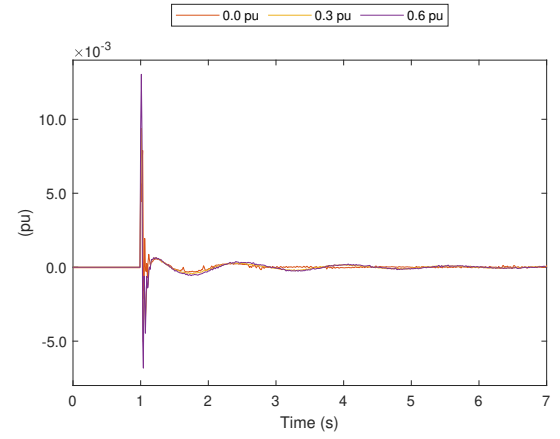
(c) $P_{HVAC,Right}$



(d) $Q_{HVAC,Right}$



(e) $P_{HVDC,Right}$



(f) $Q_{HVDC,Right}$

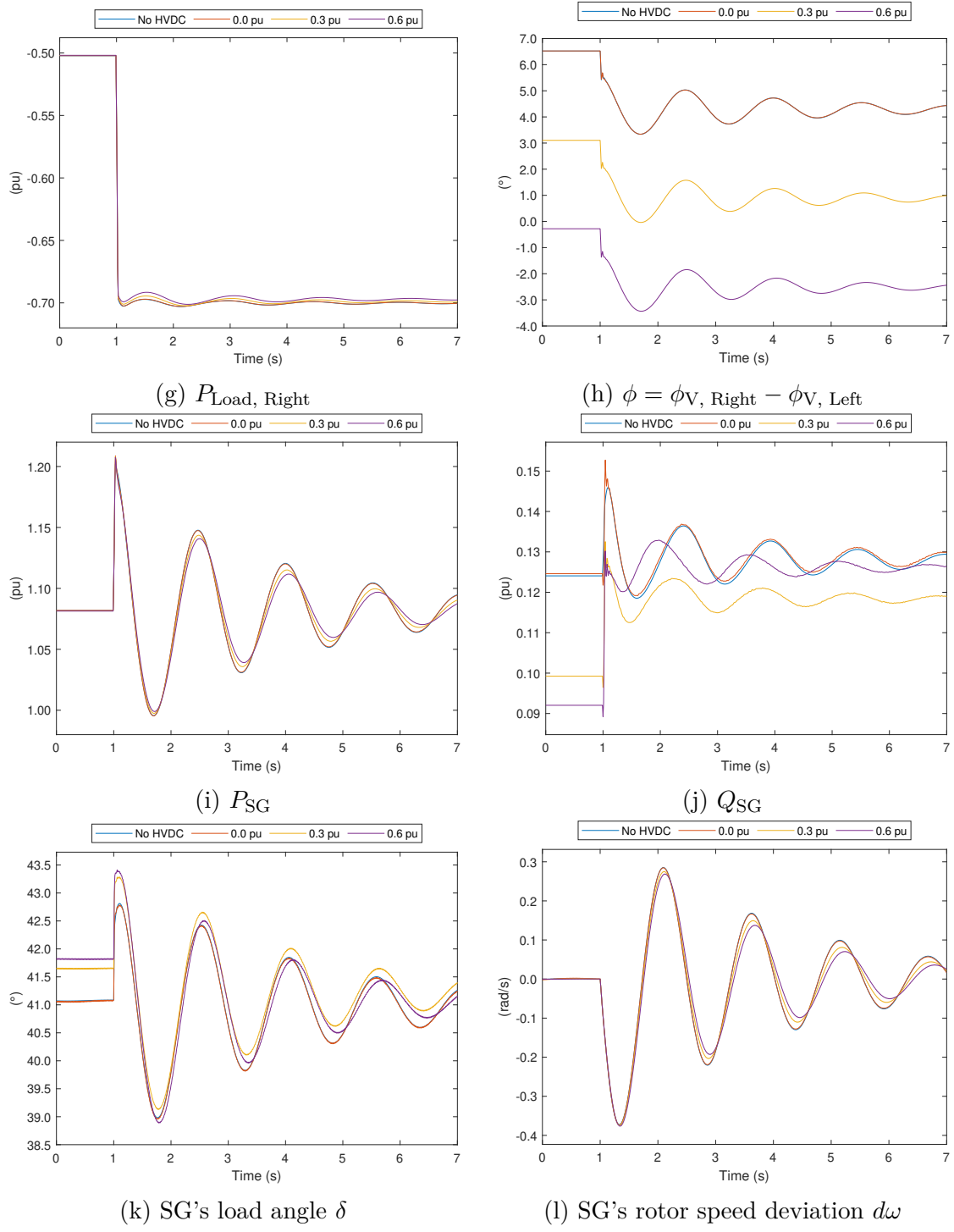


Figure 6.1: Results of the simulations on the effect of the active power control of the HVDC converters for the load variation scenario

The mechanism observed in this scenario is the same as the one explained in the topology variation scenario (Sec.5). The increase of consumption in active power must be compensated by the power flowing through the HVAC line. Therefore, $\sin \phi$ increases and $\cos \phi$ decreases causing more reactive power flowing into the HVAC line, which must be produced by the synchronous generator.

6.1.1 Impact of the HVDC line on the transient

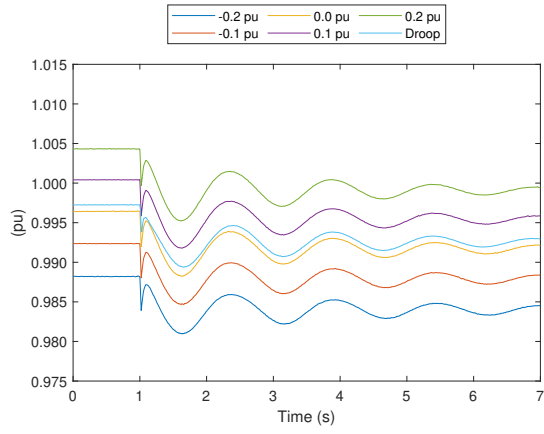
Q_{HVDC} (pu)	τ (s)	R^2 (%)	$ \Delta_{max}\delta $ (°)	$ \Delta_{max}d\omega $ (rad/s)
No HVDC	2.9	99.8	2.09	0.37
0.0	2.8	99.7	2.11	0.37
0.3	2.5	99.8	2.53	0.37
0.6	2.3	99.6	2.94	0.38

Table 6.1: Effect of the active power control of the HVDC converters for the load variation scenario on the damping time constants τ and their R^2 values of the rotor speed deviation and the maximal deviation of the load angle δ et rotor speed deviation $d\omega$

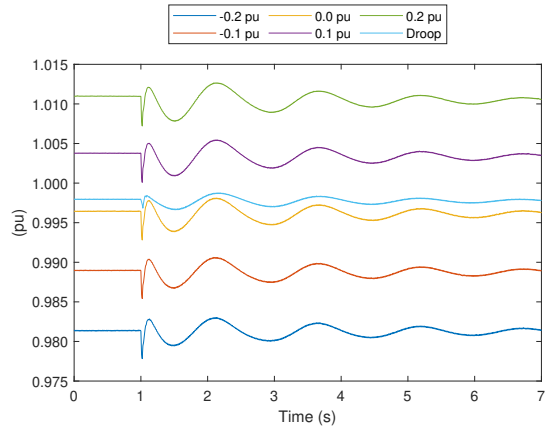
The reasons of this evolution are the same as in the Topology Variation scenario. The fact that all the damping time constants are under 3.0s whereas they were between 3.9s and 9.5s in the previous case is believed to be due to X_{HVAC} being twice as small and therefore, node Right profits from more the damping coming from the infinte grid.

6.2 Effect of the reactive power control of the HVDC converters

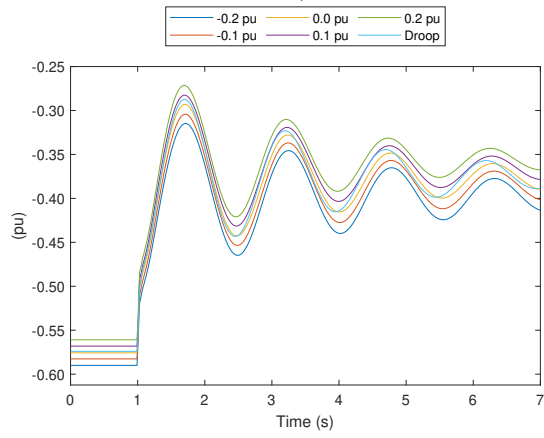
The results of the simulations are displayed in Fig.6.2.



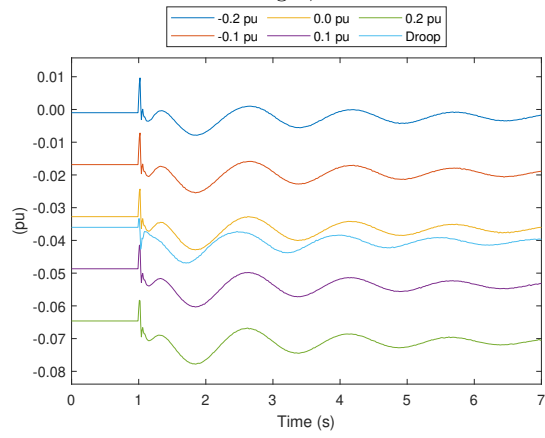
(a) $V_{Left,RMS}$



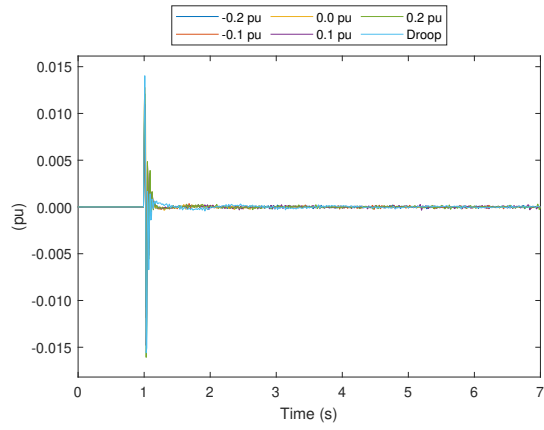
(b) $V_{Right,RMS}$



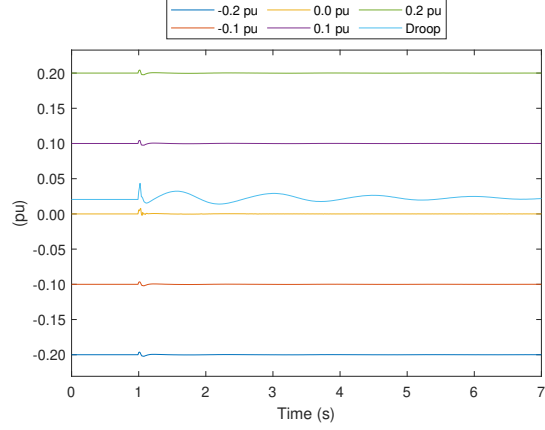
(c) $P_{HVAC,Right}$



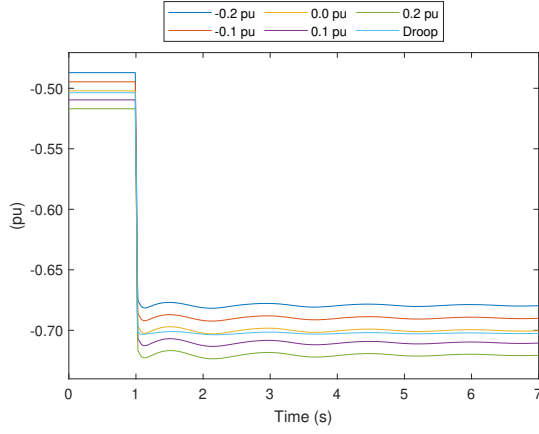
(d) $Q_{HVAC,Right}$



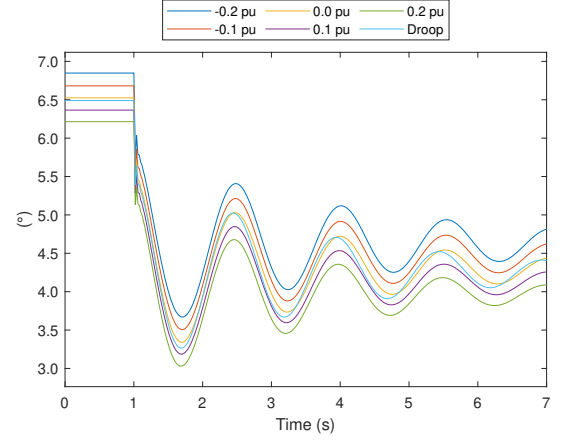
(e) $P_{HVDC,Right}$



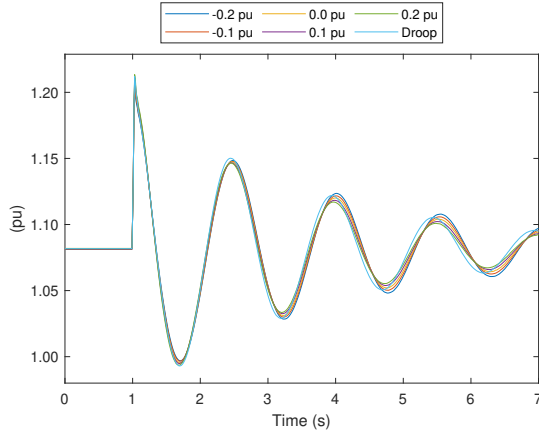
(f) $Q_{HVDC,Right}$



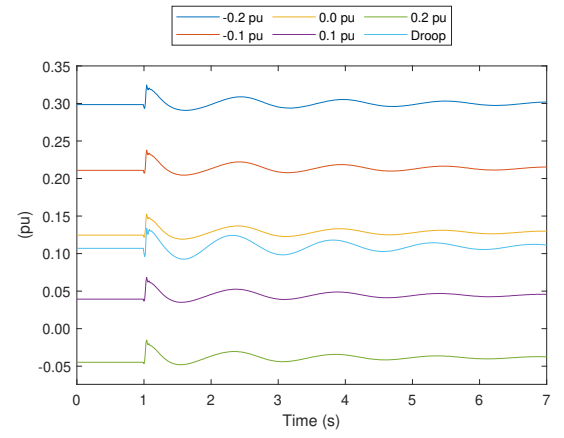
(g) $P_{\text{Load, Right}}$



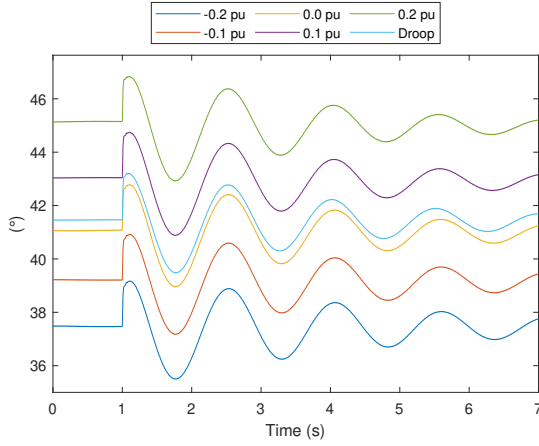
(h) $\phi = \phi_V, \text{ Right} - \phi_V, \text{ Left}$



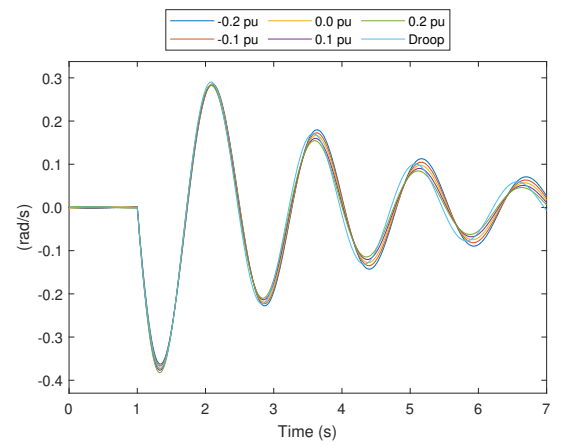
(i) P_{SG}



(j) Q_{SG}



(k) SG's load angle δ



(l) SG's rotor speed deviation $d\omega$

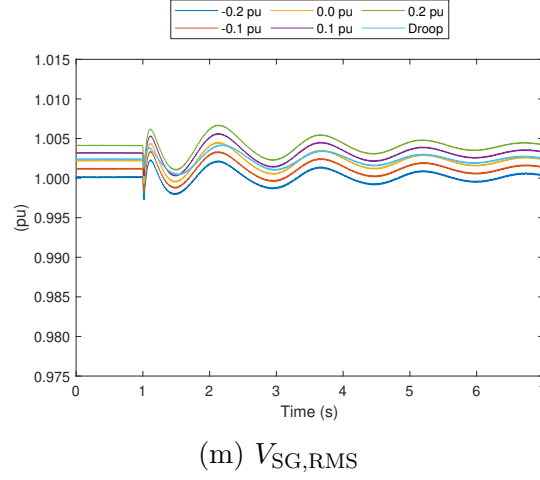


Figure 6.2: Results of the simulations on the effect of the reactive power control of the HVDC converters for the load variation scenario

6.2.1 Impact of the HVDC line

Q_{HVDC} (pu)	τ (s)	R^2 (%)	$ \Delta_{max}\delta $ ($^\circ$)	$ \Delta_{max}d\omega $ (rad/s)
-0.2	3.3	99.8	2.00	0.36
-0.1	3.0	99.8	2.06	0.37
0.0	2.8	99.7	2.11	0.37
0.1	2.6	99.8	2.17	0.38
0.2	2.5	99.7	2.22	0.38
Droop	2.8	99.8	1.99	0.37

Table 6.2: Effect of the active power control of the HVDC converters for the load variation scenario on the damping time constants τ and their R^2 values of the rotor speed deviation and the maximal deviation of the load angle δ et rotor speed deviation $d\omega$

For the reactive power control too, the reasons are the same as for the active power control. However, in this case, the Droop strategy does not improve the damping. This is because the voltage at node Right varies less and therefore, the converter injects/retrieves less reactive power, decreasing its damping capability.

Chapter 7

Fault

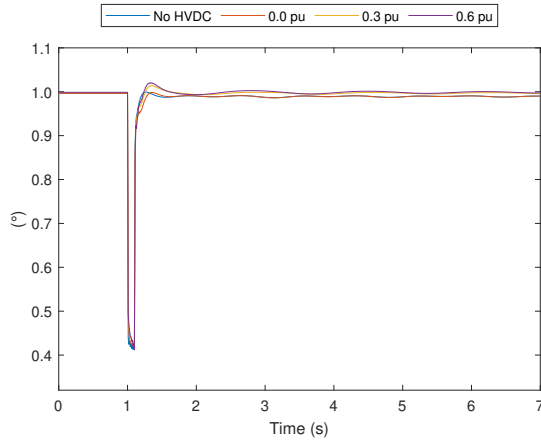
This chapter analyses the effect of varying the active and reactive power control strategies of HVDC converters on the rotor angle stability of the system in the P2P network presented in Chap.4 when a fault occurs at the middle of a branch of the line connecting the two nodes and is cleared once that branch is opened. It is shown that:

- When transferring active power through the HVDC line, the line stabilizes the SG connected to the node where the power is retrieved from the AC grid and dramatically increases the Fault Ride-Through (FRT) time. On the other hand, it is expected that the line would decrease the FRT time at the node where it injects power.
- Generating a constant amount of reactive power attenuates the transient and improves the damping. Using dynamic reactive power control gives significantly better results.

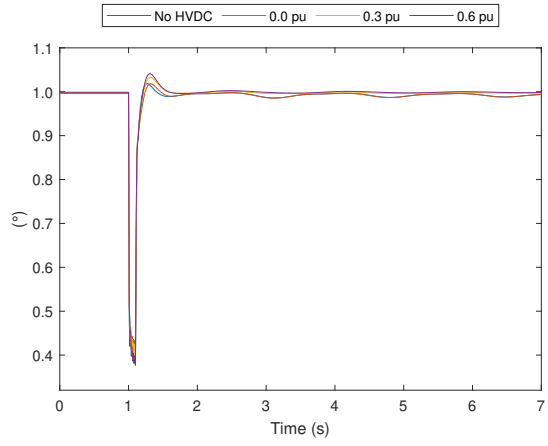
In this scenario, a default occurs on one of the two branches that make up the HVAC line at the time $t_{event} = 1$ s and is cleared 0.1 s later by opening the faulted branch. This will result in the line having an impedance twice as much as before the fault (0.196 pu to 0.392 pu). In practical cases, a default could also occur at a node but since the HVDC converters are GFL, the voltage at their point of common coupling dropping to 0 would make the PLL disconnect (and in simulations, creating an error), as they lose their voltage reference. For this reason, only a fault in the middle of the line will be analysed.

7.1 Effect of the active power control of the HVDC converters

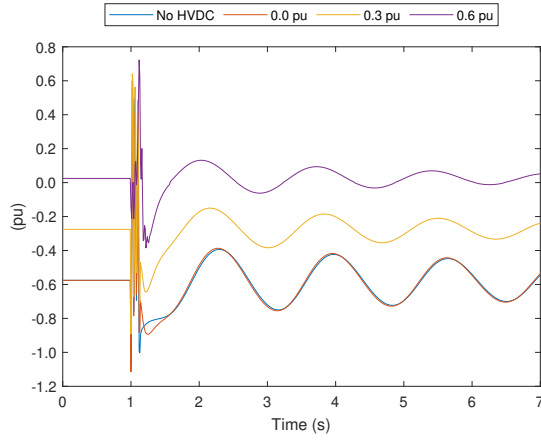
The results of the simulations are displayed in Fig.7.1.



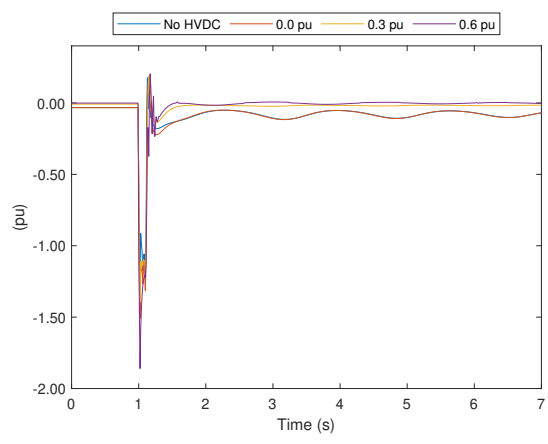
(a) $V_{\text{Left,RMS}}$



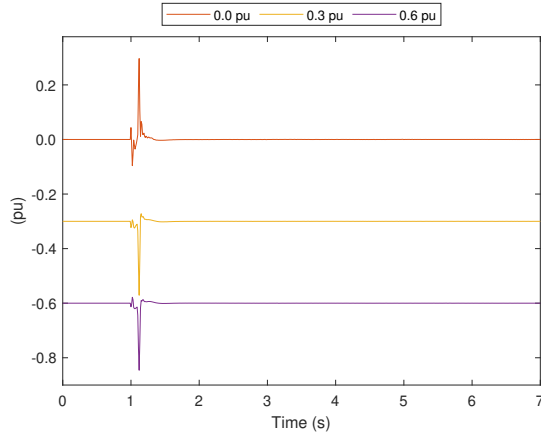
(b) $V_{\text{Right,RMS}}$



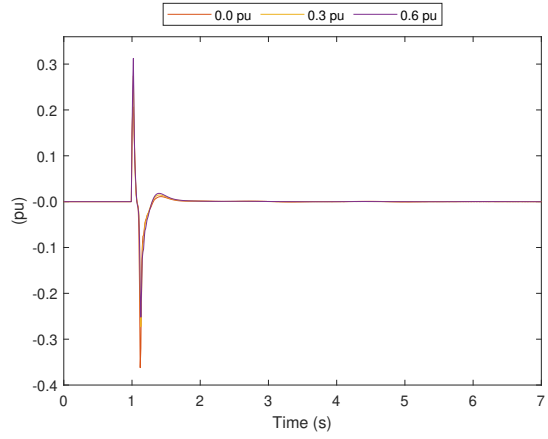
(c) $P_{\text{HVAC,Right}}$



(d) $Q_{\text{HVAC,Right}}$



(e) $P_{\text{HVDC,Right}}$



(f) $Q_{\text{HVDC,Right}}$

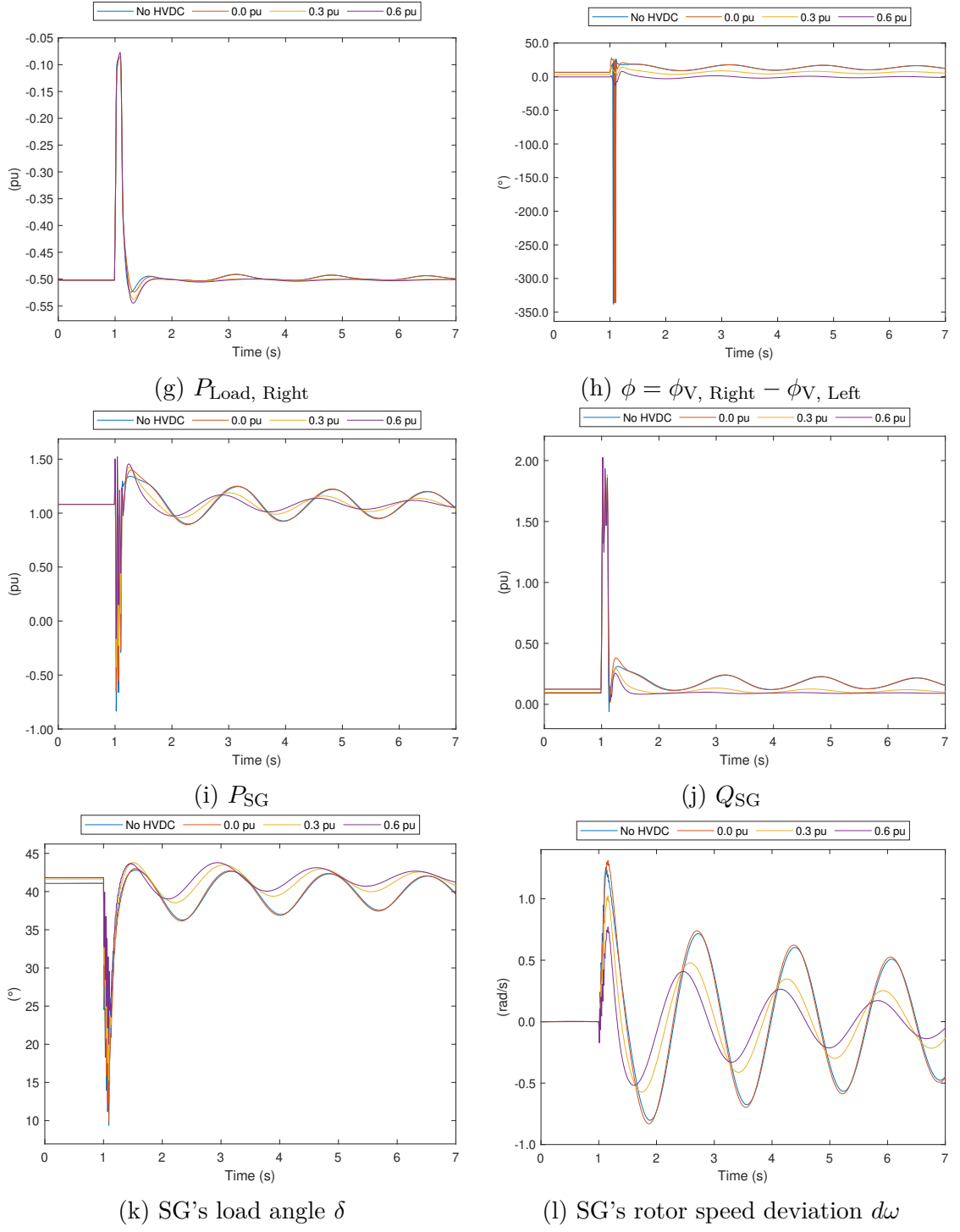


Figure 7.1: Results of the simulations on the effect of the active power control of the HVDC converters for the fault scenario

As expected, the voltages drop during the fault (Fig.7.1a and 7.1b) causing the power consumed by the load to decrease (Fig.7.1g), the rotor accelerates (Fig.7.1l) and the SG's load angle decreases (Fig.7.1k) as it produces less active power (Fig.7.1i) and more reactive power (Fig.7.1j). Since the electrical active and reactive powers are computed thanks to a PLL, during the fault, the computed values are inaccurate. Therefore, what is happening during the transient will not be studied.

7.1.1 Impact of the HVDC line on the transient

Because of its very fast control system, the power consumed during the fault by the HVDC converter is fairly constant. Therefore, the electrical power furnished by the generator is:

$$P_{SG} = P_{HVDC} + P_{Load, Right} = P_{HVDC} + P_{Load, Right, 1 pu} \left(\frac{V_{Right}}{1 pu} \right)^2 \quad (7.1)$$

The relationship $P_{Load, Right} = P_{Load, Right, 1 pu} (V_{Right}/1 pu)^2$ comes from the fact that the load is modelled as a resistor. Also, it is important to observe that the HVDC line has no impact on the voltage (Fig.7.1b).

Therefore, as explained in Sec.2.1.2, the rotor accelerates less since the difference between the mechanical and electrical powers is smaller. This can be seen in Tab.7.1 with $|\Delta_{max}d\omega|$ being smaller for larger P_{HVDC} .

P_{HVDC} (pu)	τ (s)	R^2 (%)	$ \Delta_{max}\delta $ (°)	$ \Delta_{max}d\omega $ (rad/s)	FRT time (s)
No HVDC	9.1	98.5	31.68	1.26	± 350
0.0	9.7	97.9	31.09	1.31	± 350
0.3	5.2	99.9	26.34	1.02	(500,550)
0.6	3.9	100.0	21.77	0.77	(750,800)

Table 7.1: Effect of the active power control of the HVDC converters for the fault scenario on the damping time constants τ and their R^2 values of the rotor speed deviation and the maximal deviation of the load angle δ et rotor speed deviation $d\omega$

For the damping, results are similar to the Topology Variation scenario (Chap.5) as once the fault is cleared, both scenarios are similar.

So the rotor accelerates less, but the critical angle is also expected to increase. Therefore, the FRT time is expected to dramatically increase.

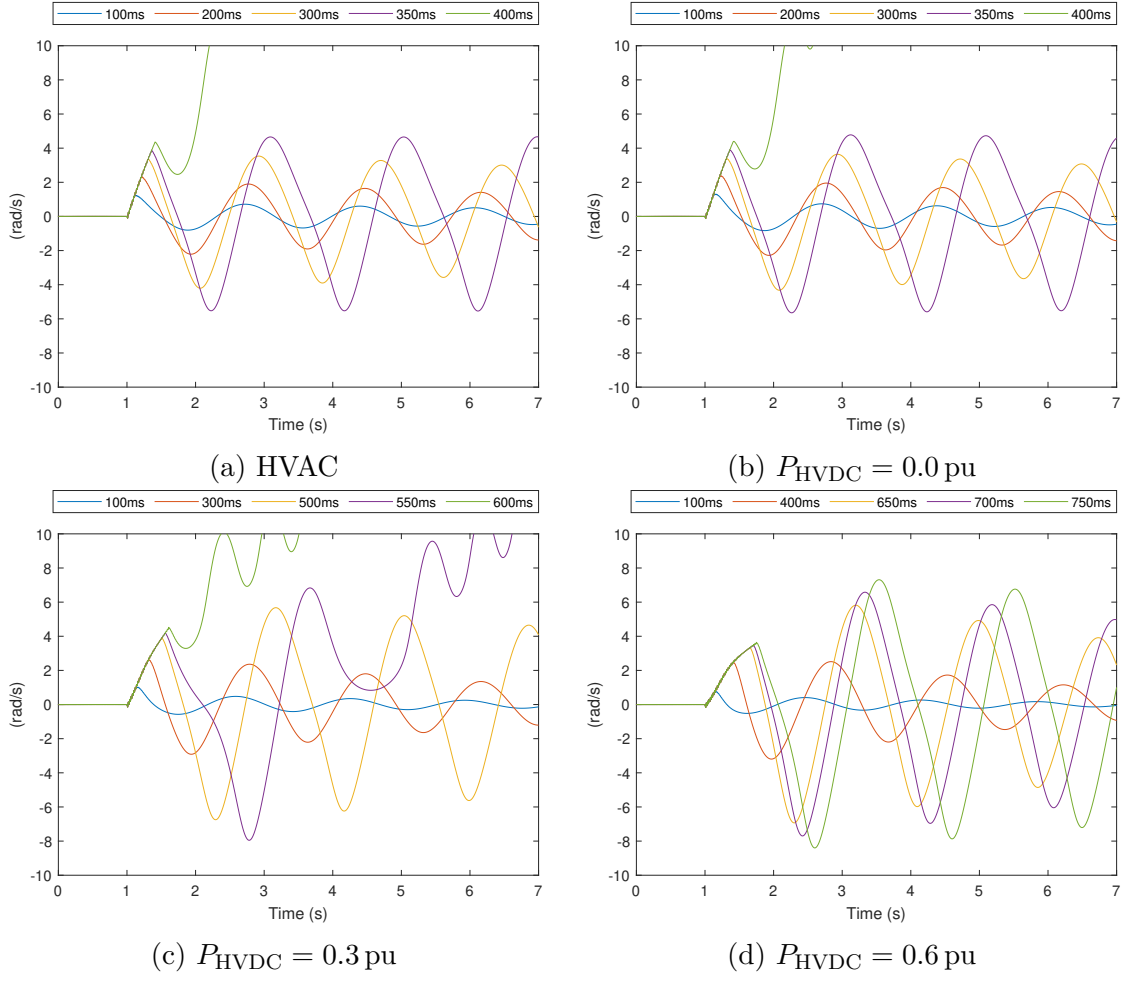


Figure 7.2: Rotor speed deviation $d\omega$ for different fault durations and different controls of the active power of the HVDC converters

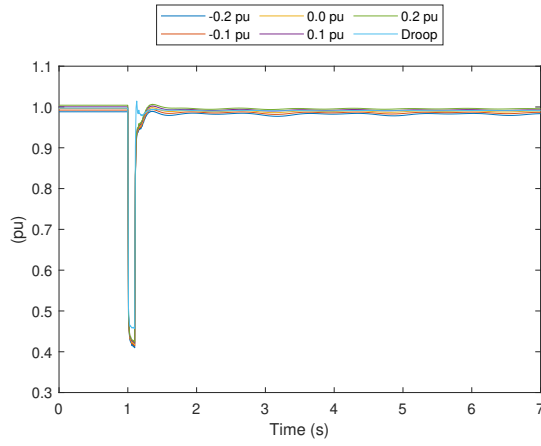
As a matter of fact, it increased up to 750 ms when $P_{\text{HVDC}} = 0.6 \text{ pu}$.¹

However, it is important to notice that if the HVDC converters were injecting power at node Right, the power the SG produces would decrease, and the SG could even consume power in extreme cases. Therefore, as a fault is rarely predicted, the HVDC line could save a blackout in one case, but creates one if the fault is a few kilometers further.

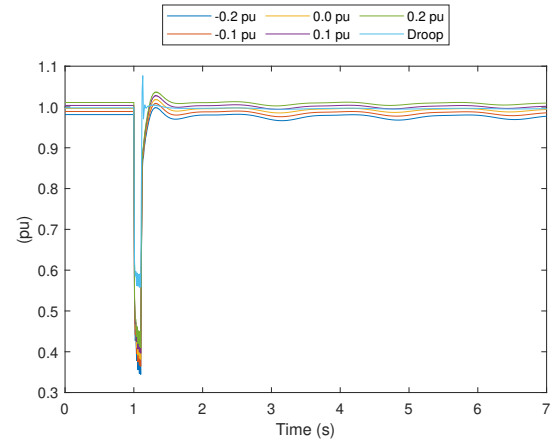
¹The case $t_{\text{fault}} = 800 \text{ ms}$ is not displayed because it created a simulation error.

7.2 Effect of the reactive power control of the HVDC converters

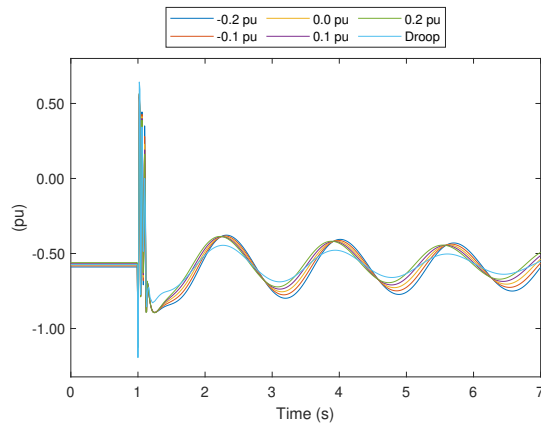
The results of the simulations are displayed in Fig.7.3.



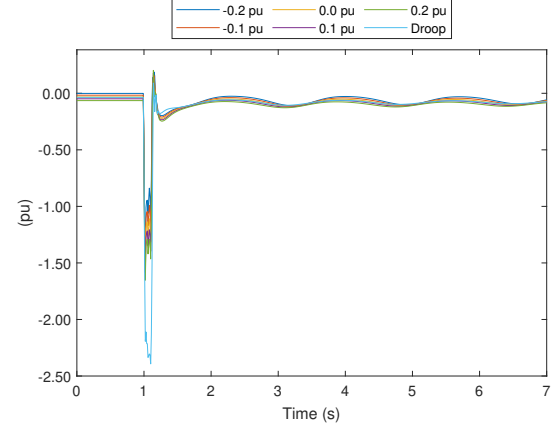
(a) $V_{\text{Left,RMS}}$



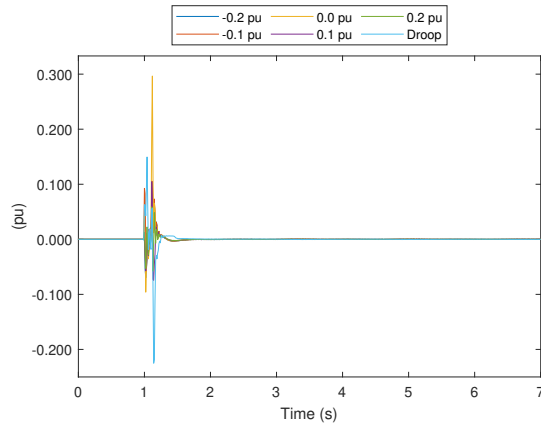
(b) $V_{\text{Right,RMS}}$



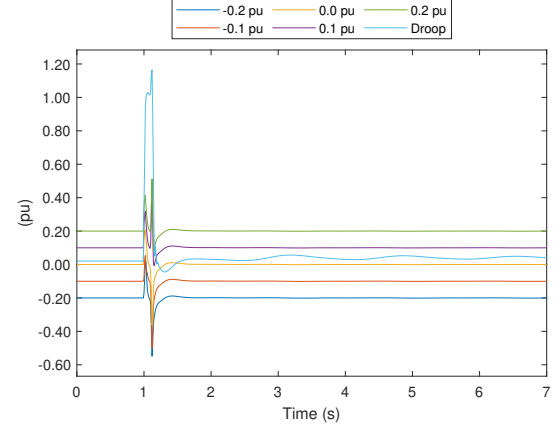
(c) $P_{\text{HVAC,Right}}$



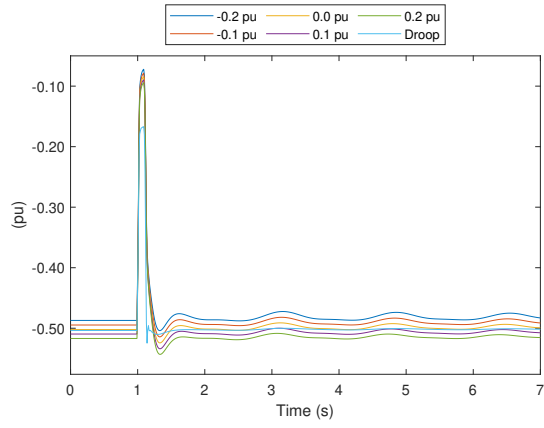
(d) $Q_{\text{HVAC,Right}}$



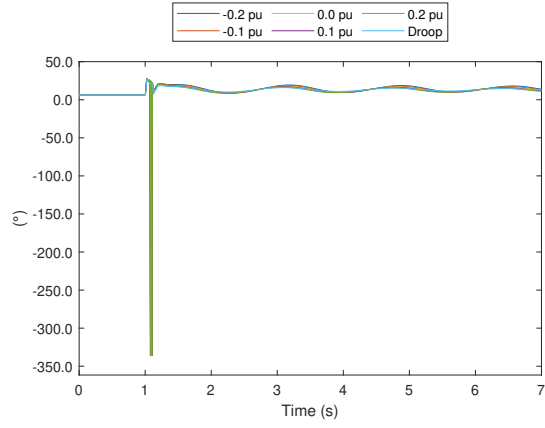
(e) $P_{\text{HVDC,Right}}$



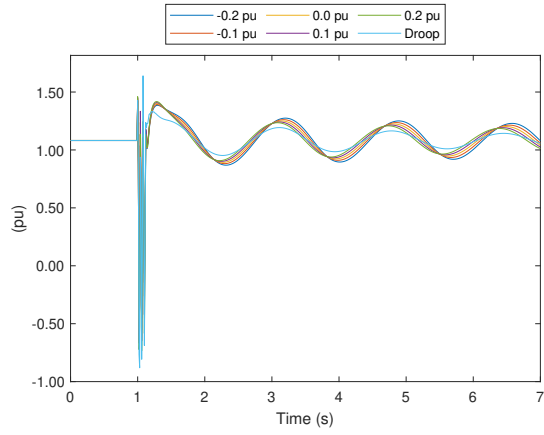
(f) $Q_{\text{HVDC,Right}}$



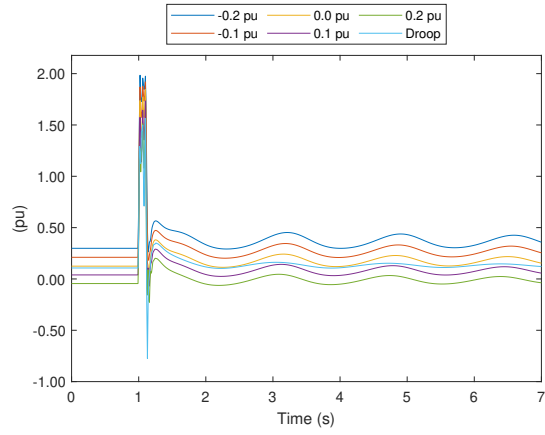
(g) $P_{\text{Load, Right}}$



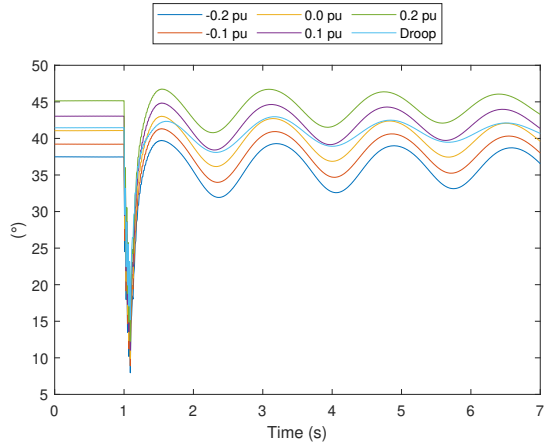
(h) $\phi = \phi_V, \text{Right} - \phi_V, \text{Left}$



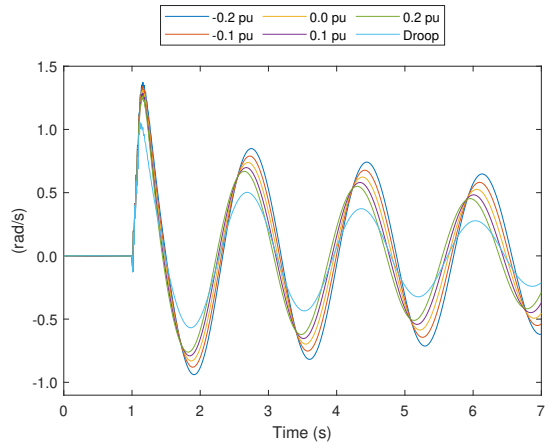
(i) P_{SG}



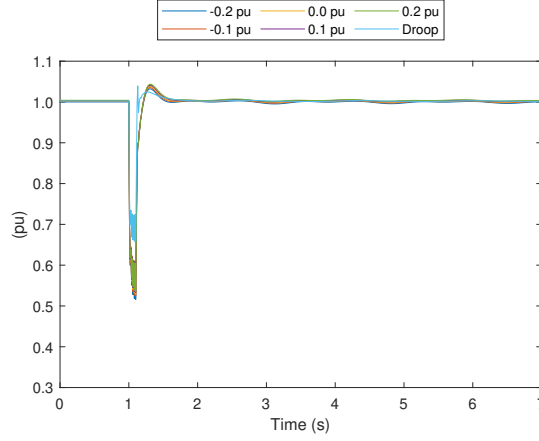
(j) Q_{SG}



(k) SG's load angle δ



(l) SG's rotor speed deviation $d\omega$



(m) $V_{SG,RMS}$

Figure 7.3: Results of the simulations on the effect of the reactive power control of the HVDC converters for the fault scenario

As for the effect of the active power control of the HVDC converters, the rotor accelerates (Fig.7.3l), the load angle of the SG decreases (Fig.7.3k) as it produces less active power (Fig.7.3i) and more reactive power (Fig.7.3j) and the voltages drop (Fig.7.3a and 7.3b).

7.2.1 Impact of the HVDC line on the transient

The difference with the active power cases is that V_{Right} varies with the injected reactive power. The more reactive power the HVDC converter injects, the less the voltage drops. According to Eq.7.1, the electrical power increases when V_{Right} increases too. For the same reasons as previously, the rotor accelerates less (Tab.7.2) and the critical angle is expected to increase, increasing the FRT time. This is observed in Fig.7.4 and Tab.7.2.

Q_{HVDC} (pu)	τ (s)	R^2 (%)	$ \Delta_{max}\delta $ ($^\circ$)	$ \Delta_{max}d\omega $ (rad/s)	FRT time (ms)
-0.2	10.9	94.3	29.47	1.37	(300,350)
-0.1	10.3	98.7	30.26	1.34	(300,350)
0.0	9.7	97.9	31.09	1.31	± 350
0.1	9.0	97.4	31.94	1.29	(350,400)
0.2	8.5	96.7	32.82	1.26	(350,400)
Droop	5.6	100.0	26.21	1.05	(550,600)

Table 7.2: Effect of the active power control of the HVDC converters for the fault scenario on the damping time constants τ and their R^2 values of the rotor speed deviation, the maximal deviation of the load angle δ and rotor speed deviation $d\omega$ and the FRT time

For the same reasons as when the active power varies, the results for the damping are similar to the Topology Variation scenario.

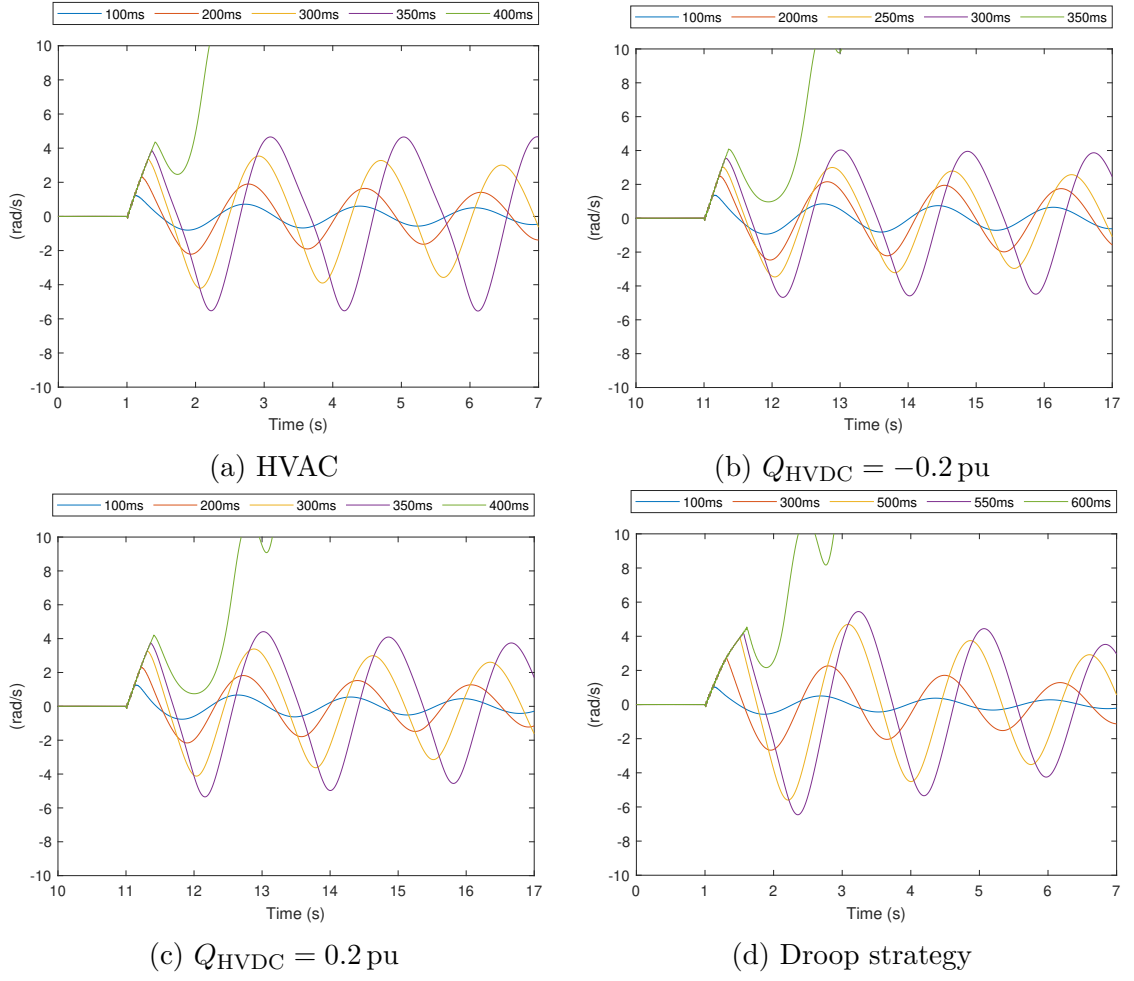


Figure 7.4: Rotor speed deviation $d\omega$ for different fault durations and different controls of the reactive power of the HVDC converters

As expected, the FRT time increases with the amount of reactive power injected during the fault. It can clearly be observed when the SG loses synchronism as the angular speed deviation never gets back to 0.

For the HVAC case, for a fault duration of 350ms, the angular speed deviation oscillates around 0 but as the ripples increases with time, it is considered unstable. However, the FRT time should be close to 350ms as it is a multiple-swing instability.

Part III

Simulations on the 3-node network

Chapter 8

3-node mesh network

This chapter analyses the effect of varying the active and reactive power control strategies of HVDC converters on the rotor angle stability of the system in the 3-node network presented in Chap.4 for different disturbances. It is shown that:

- As in the P2P case, transferring active power through the HVDC line instead of the HVAC line attenuates the transient when a line suddenly opens.
- An HVDC line whose nominal power is largely inferior to the one of the SGs present in the grid does not have significant impact on the stability of the network.

In this chapter, the same types of disturbances will be simulated. However, as they are two SGs with their own operating point, they will oscillate with different frequencies. Therefore, there is no obvious and easy method to measure the damping of the system through a well-defined metric.

8.1 Topology Variation

In this section, the topology variation where at the time $t_{event} = 1$ s, the Left-Right line will have its impedance doubled will be studied.

8.1.1 Effect of the active power control

As for the P2P case, the active power control makes the power flow to vary and therefore, the line to be opened is more or less loaded, as shown in Fig.8.1.

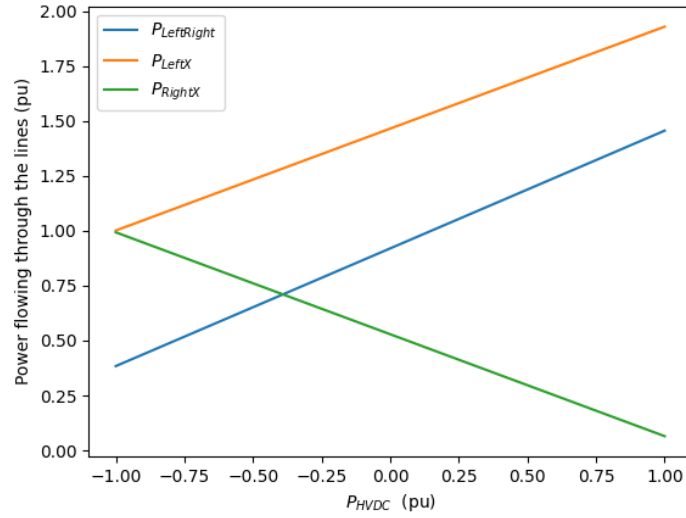


Figure 8.1: Active power flowing through the different lines of the system for different amount of active power flowing through the HVDC line. A positive P_{HVDC} means the power is flowing from node Right to node Left.

Also, we can observe that if power flows from node Right to node Left, some of that power will go round in circles which is inefficient, but this allows to unload other lines (in this case, the one connecting node Right and node X), which can be useful in some cases.

Since it is the same principles as in the P2P network, only a mere selection of the simulations results is presented in Fig.8.2.

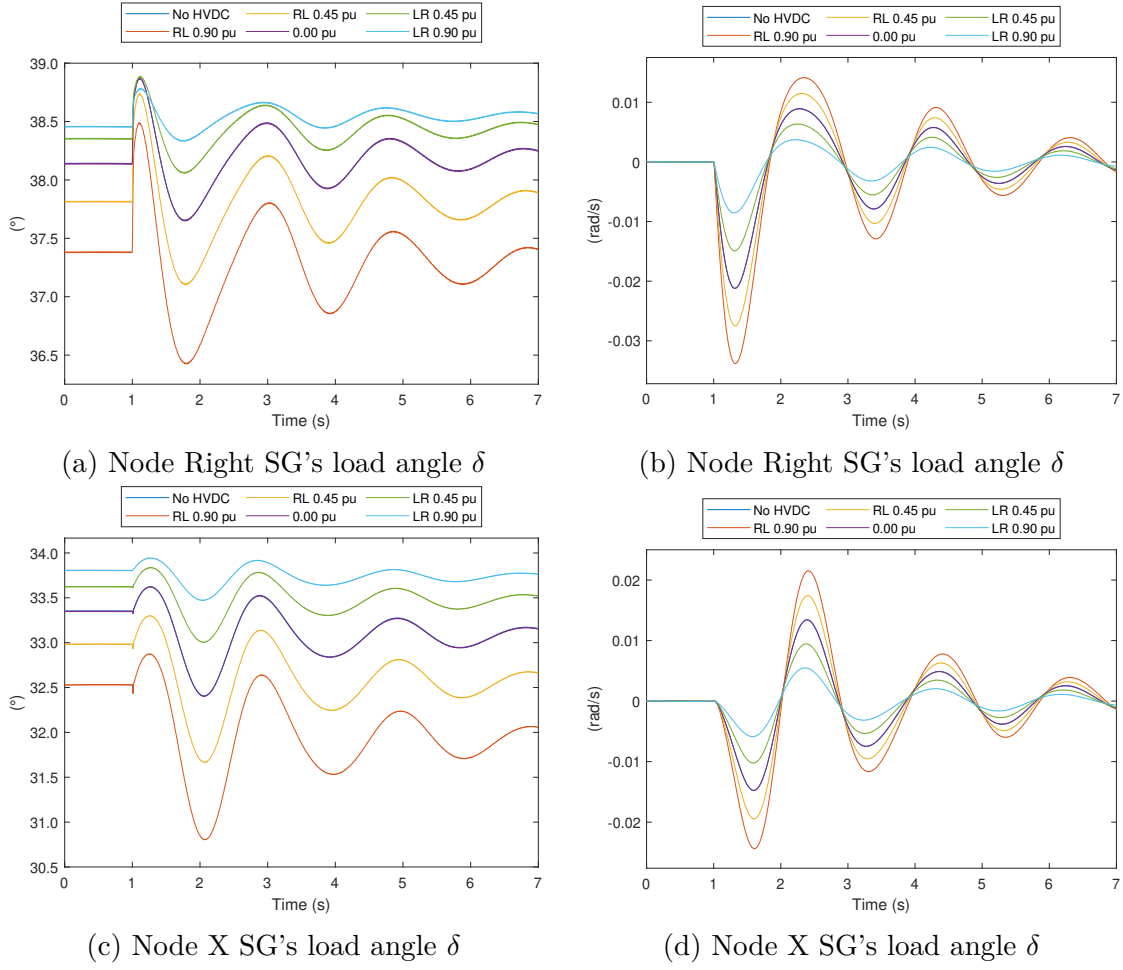


Figure 8.2: Results of the simulations on the effect of the active power control of the HVDC converters for the topology variation scenario

From Fig.8.2, the amount of power flowing through the Left-Right line is minimal when the HVDC line transmits power from node Left to node Right at full capacity. According to Chap.5, less transient in this case is expected. And indeed, this is what we observe.

8.1.2 Effect of the reactive power control

The rotor speed deviation and the load angle of both SGs are displayed in Fig.8.3.

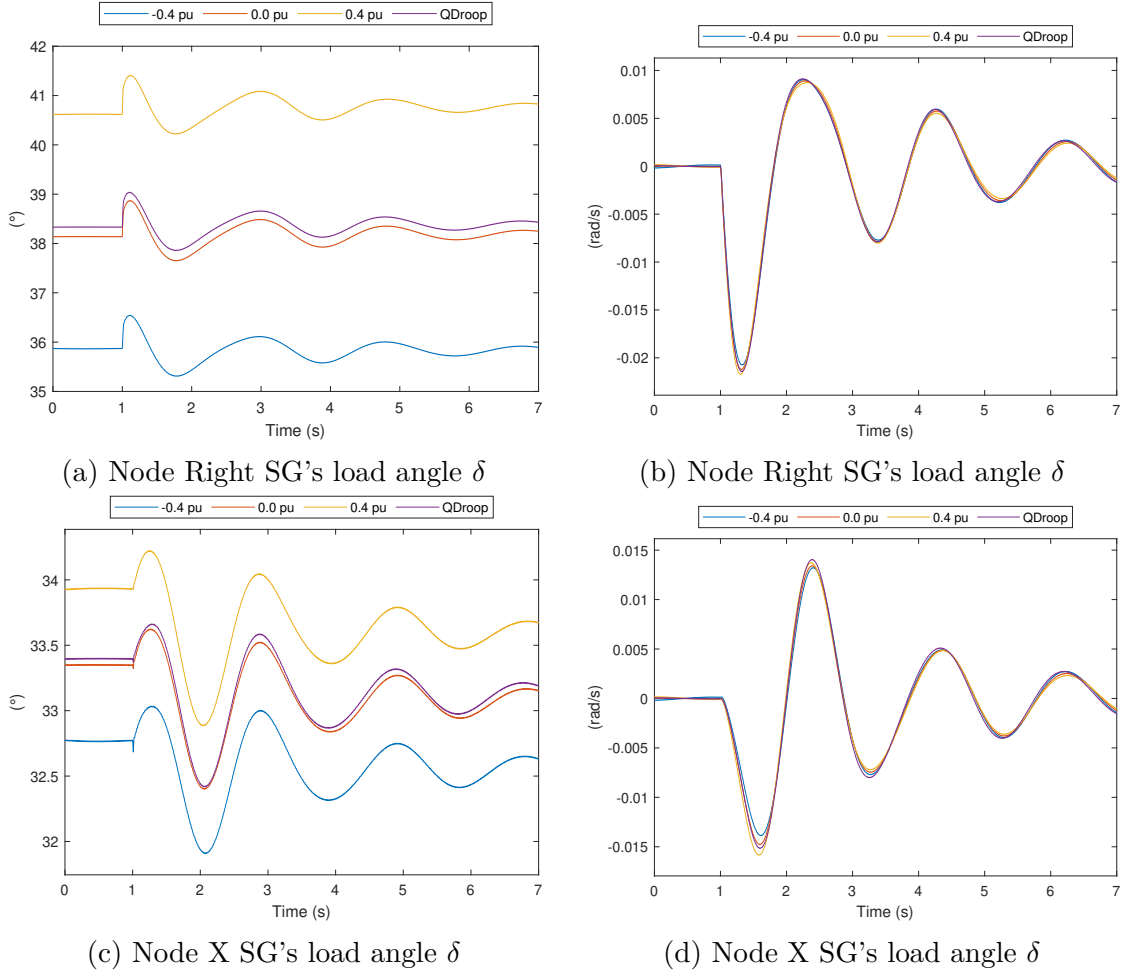


Figure 8.3: Results of the simulations on the effect of the active power control of the HVDC converters for the topology variation scenario

As for the P2P case (Chap.5), the load angle of the SG slightly varies as the SGs must compensate the injection/removal of the reactive power by the HVDC converters. Furthermore, we observe that the SG at node X is the least impacted of the two. In an ideal case, it would not be impacted at all but since V_{Right} varies with $Q_{\text{SG,Right}}$, the reactive power flowing through the lines vary as well and in reaction, impacts every SG in the network.

The damping seems to be similar in every case. This can be explained by the nominal power of the SGs being much greater than the one of the HVDC line and therefore, has a limited impact.

8.2 Load Variation

Electricity consumption is highly dependent on what is happening in the country. For instance, on 18 December 2022, France played Argentina in the final of the 2022 World Cup and RTE (the French TSO) experienced some huge deviations from normal consumption. During the match, French people sat behind their televisions. But when the final whistle blew, they started cooking, turning on lights in other rooms, etc. As a result, the demand suddenly increased by 2 GW [26].

In this hopeful scenario, Belgium will reach (and surely win) the 2026 World Cup final. In this section, the impact of a distributed 350 MW (0.350 pu) load increase (a variation of load per inhabitant similar to the 2022 French case) will be investigated. In more details, each load will increase by 6.3% at the time $t_{event} = 1$ s.

8.2.1 Effect of the active power control

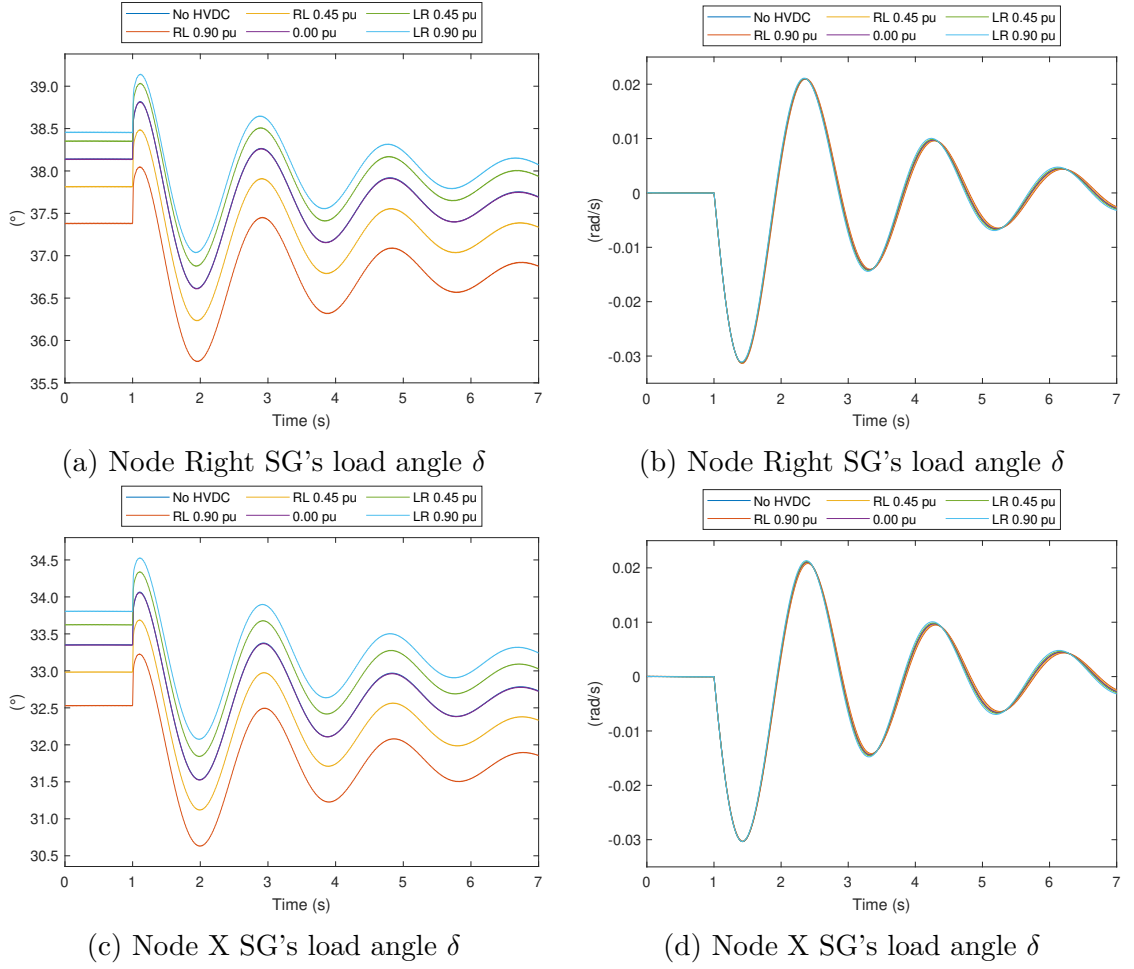


Figure 8.4: Results of the simulations on the effect of the active power control of the HVDC converters for the topology variation scenario

As for the P2P case, the HVDC line has no significant impact on the transient.

8.2.2 Effect of the reactive power control

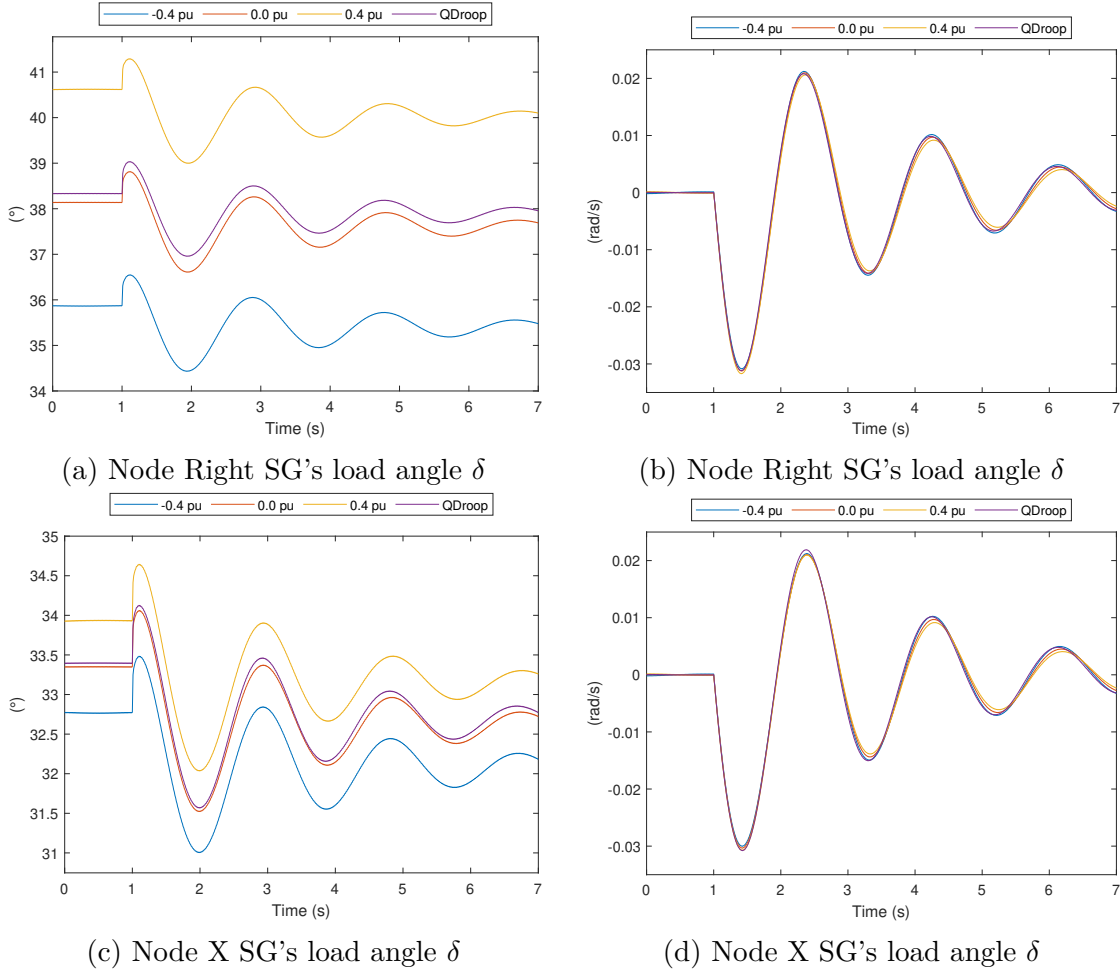


Figure 8.5: Results of the simulations on the effect of the active power control of the HVDC converters for the Load Variation scenario

For the reasons explained in the P2P Load Variation and 3-node Topology Variation, the HVDC line has no significative impact other than the load angle difference.

8.3 Fault

In this section, the case where a fault occurs at the time $t_{event} = 1$ s in the middle of either one of the two branches that make up the Left-Right line will be cleared in 0.1 s..

8.3.1 Effect of the active power control

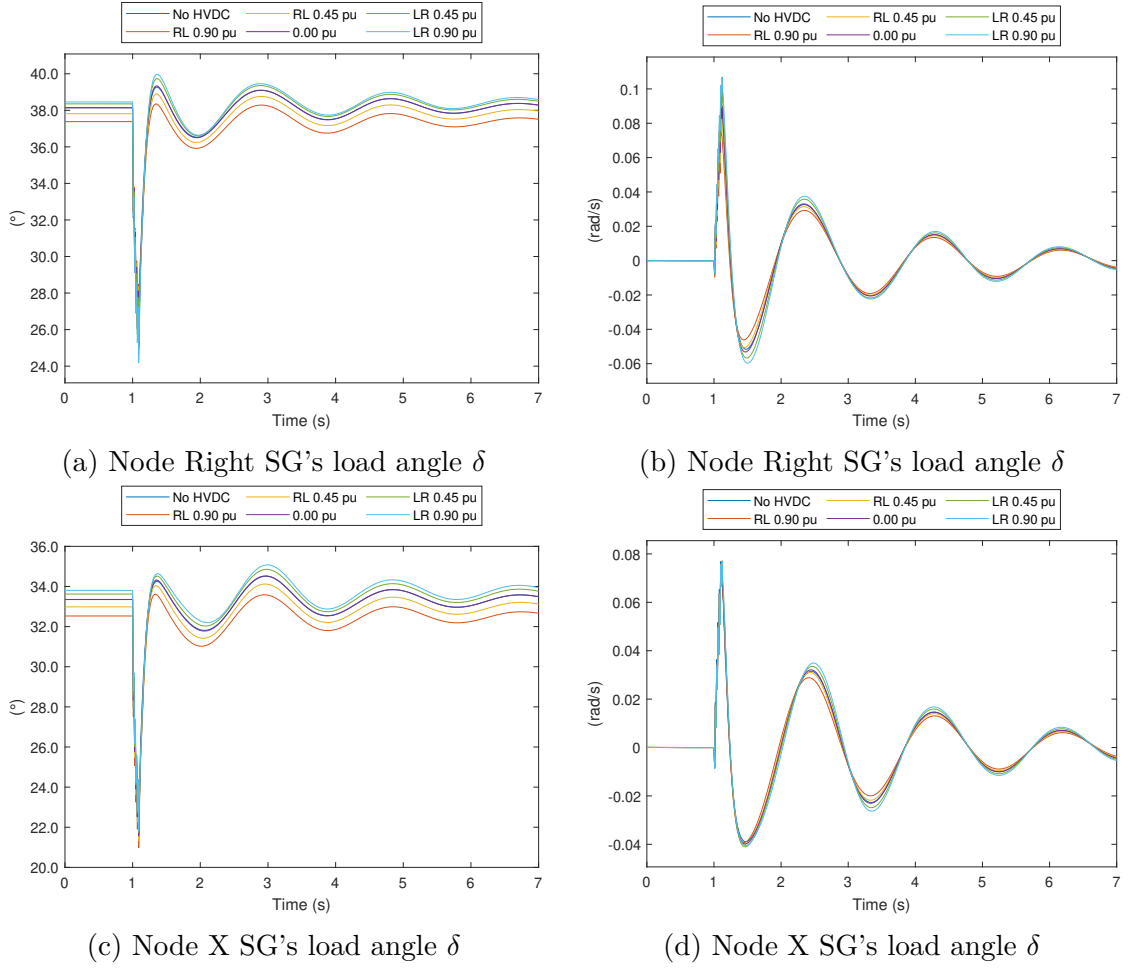


Figure 8.6: Results of the simulations on the effect of the active power control of the HVDC converters for a fault on the Left-Right line

As for the P2P fault, the SG at the node Right experiences less transient when the HVDC consumes power at this node. And so when the fault is cleared, it creates less disturbances in the grid and therefore, the SG connected to node X also recovers better from the transient.

8.3.2 Effect of the reactive power control

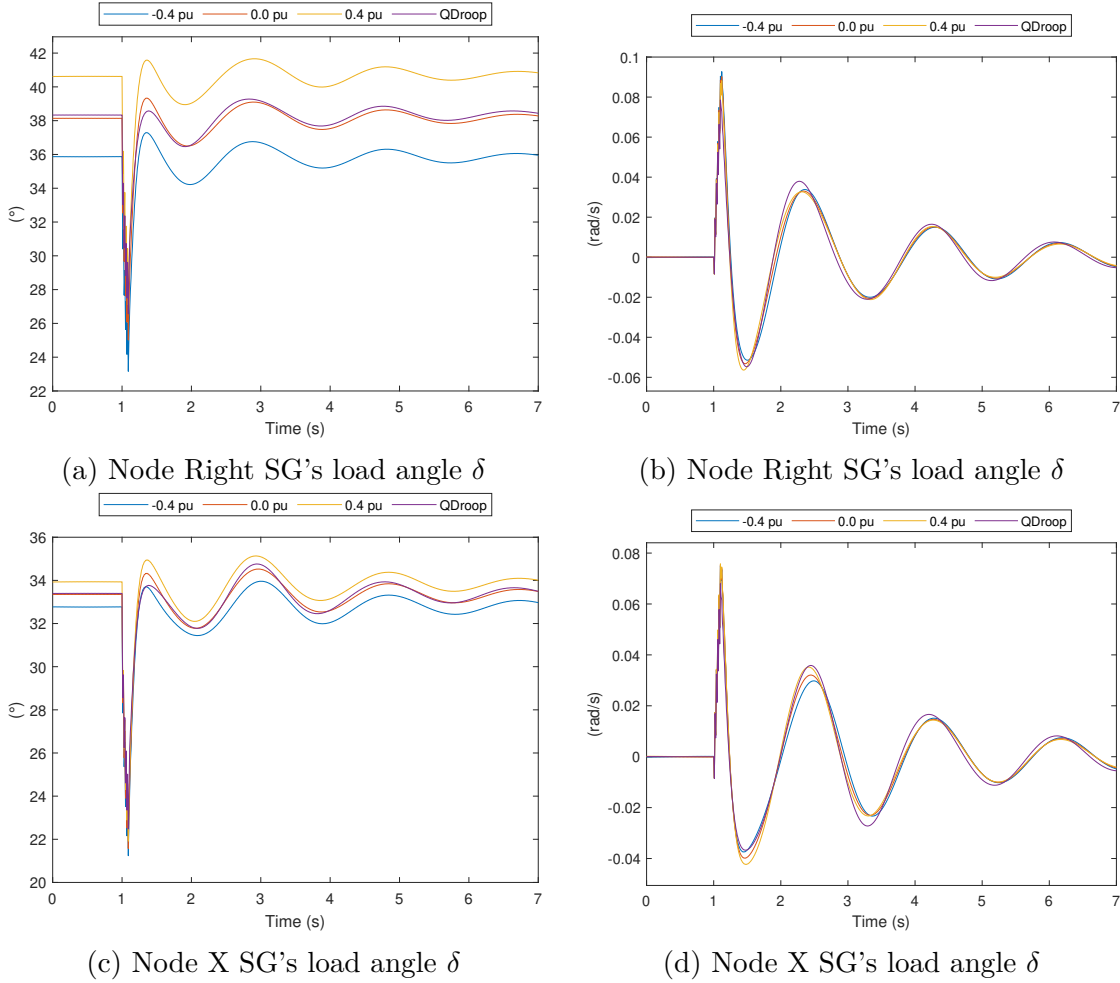


Figure 8.7: Results of the simulations on the effect of the reactive power control of the HVDC converters for a fault on the Left-Right line

The same conclusions as in the P2P for a constant production/consumption of reactive power by the HVDC converters cases applies. However, despite reducing the maximal deviation during the fault, the Droop control strategy seems to decrease the damping. This may be due to the fact that as it behaves as a proportional controller, it increases the ripple for the stability characteristics of this topology. In other words, the HVDC converter causes an instability in the system as it increases the rate of change of the voltage. But this theory should be validated by a stability analysis which has not been made in this study.

Part IV

Conclusion

Chapter 9

Conclusion

In this Master's thesis, it was shown that thanks to the fast control of the HVDC converters, these technologies can be completely transparent from the HVAC system point of view. Therefore, it is the TSO responsibility to carefully tune the system parameters in order not to deteriorate the stability of the system, or improve it if possible.

Some advantages of HVDC technologies over HVAC ones are:

- From the power flow point-of-view, building a new line with HVDC technologies allows a wider range of power flows in the system, without suffering from any limitations on the line capacity.
- In the case of a scheduled opening of a line, we can control the HVDC to minimize the power flowing through the line, and even cancel it in some cases. Therefore, the transient is minimized. This is not possible with HVAC technologies.
- The possibility to control the reactive power allows the network operator to use this capacity to damp the oscillations. But the control strategy must be carefully chosen as a poorly tuned model can deteriorate the stability of the system and might cause instabilities.

However, in the case of an unscheduled opening of a line or a fault, depending on where in the network the event occurs, the HVDC line can either avoid or create a blackout. Therefore, it must be very carefully controlled in order to minimise the likelihood of such catastrophic events.

9.1 Future perspectives

To go further, several options are on the table.

It should be possible to enhance the system stability with dynamical active power control strategies. For instance, as it has been shown, increasing the HVDC active power demand at a node reduces the transients in case of a fault. One can imagine a strategy that would increase its demand at the node closer to the fault.

Moreover, it was shown that the dynamical droop control strategy on the reactive power increased the damping and the FRT time. But this strategy did not result from any stability analysis of the system. Such analysis should allow to create a better control strategy.

It would also be interesting to investigate the case where the converters are not GFL but Grid-Forming (GFM), a technology that does not track the voltage at the PCC but creates its own voltage reference. Will it enhance or deteriorate the stability of the system?

Adding governors to the SG is a necessary step for the future in order to get rid of the infinite grid and modelling an independent network.

Obviously, it is also necessary to carry out these simulations on larger networks, composed of several SGs whose nominal power is more realistic.

Appendix A

ST1A

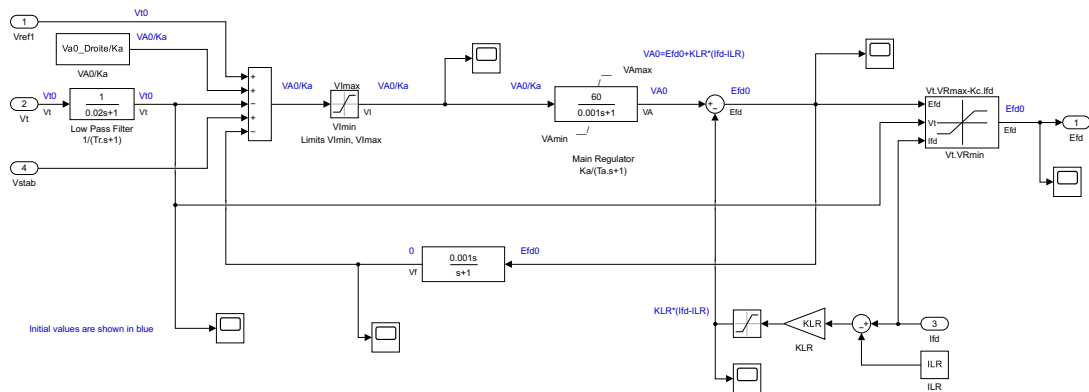


Figure A.1: The ST1A exciter block schematic

Appendix B

Load flow

To start the analysis on the effects of a HVDC line during transients, it is important to understand how the system behaves during steady state operations. Indeed, if the amount of power flowing through the HVDC line is poorly chosen, some instabilities could occur in the AC grid since the amount of power flowing through an AC line is determined by the phase difference between both buses.

To do so, a load flow analysis on two simple grids will be assessed. First, the Belgian grid will be simplified to a three-node grid, represented in Fig.B.1, where node X would be Mercator, Y would be Avelgem and Z would be Courcelles. Therefore, X and Y will be connected through a HVAC line, so are nodes X and Z and a HVDC line will connect nodes Y and Z. However, since the analysis focuses in all generality on meshed HVAC grid, the same 3-node grid with an extra HVAC connection between X and Y will be studied represented in Fig.B.2.

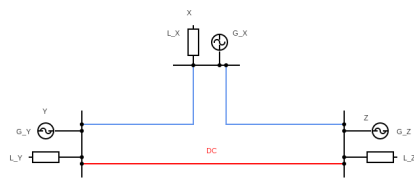


Figure B.1: 3-node radial grid with a HVDC line between nodes Y and Z

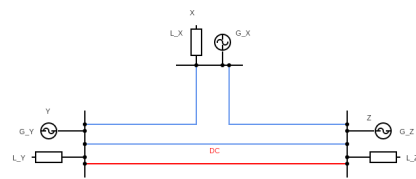


Figure B.2: 3-node meshed grid with a HVDC line between nodes Y and Z

One would notice that the radial grid is a particular case of the meshed grid. This is why the analysis will focus on the meshed grid.

To stay general in this very simple grid, each node is considered to be connected to a load and a generator. Thus, for each node, we have some active and reactive power generated (P_G and Q_G) and consumed (P_L and Q_L). Furthermore, the DC line between the nodes Y and Z implies, regarding the active power, an additional load to one node and an additional generator to the other one. In this simplified case, a perfectly efficient transmission is considered leading to the relationship: $P_{DC,Y} = -P_{DC,Z}$. And since the reactive power cannot be transmitted over DC lines, the reactive powers produced or consumed by the converters, $Q_{DC,Y}$ and $Q_{DC,Z}$, are independent. Mathematically, this gives:

$$\text{At node X: } P_X = P_{G,X} - P_{L,X} \quad (\text{B.1})$$

$$Q_X = Q_{G,X} - Q_{L,X} \quad (\text{B.2})$$

$$\text{At node Y: } P_Y = P_{G,Y} - P_{L,Y} + P_{DC,Y} \quad (\text{B.3})$$

$$Q_Y = Q_{G,Y} - Q_{L,Y} + Q_{DC,Y} \quad (\text{B.4})$$

$$\text{At node Z: } P_Z = P_{G,Z} - P_{L,Z} + P_{DC,Z} \quad (\text{B.5})$$

$$Q_Z = Q_{G,Z} - Q_{L,Z} + Q_{DC,Z} \quad (\text{B.6})$$

To represent the power lines, the pi model has been chosen, leading to the circuit displayed in Fig.B.3.

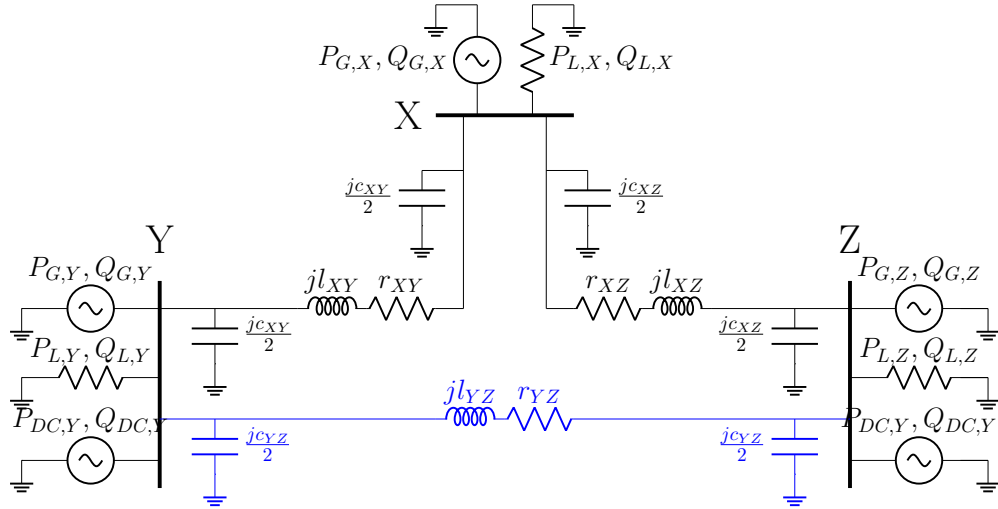


Figure B.3: Equivalent circuit of a meshed HVAC three-node grid with a HVDC line connecting node Y to node Z for a load flow analysis. Components in blue are to be considered or not according to the studied topology.

Thanks to this model, the admittance matrix can now be built as according to the

Load Flow theory, the following relationships stand

$$\overline{Y_{ii}} = \sum_k \overline{c_{ik}} + \sum_k \frac{1}{r_{ik} + jl_{ik}} \quad ; \quad \overline{Y_{ik}} = -\frac{1}{r_{ik} + jl_{ik}}$$

Then, since the Ohm's law is a linear relationship, the current injected at each node I_i is given by:

$$\overline{I_i} = \sum_k \overline{Y_{ik}} \overline{V_k}$$

Thus, the apparent power at each node S_i is given by

$$\overline{S_i} = \overline{V_i} \sum_k \overline{Y_{ik}}^* \overline{V_k}^* \leftrightarrow \overline{S_i}^* = \overline{V_i}^* \sum_k \overline{Y_{ik}} \overline{V_k}$$

So the real part is the active power at the node and the imaginary part the reactive power:

$$P_i = V_i \sum_k Y_{ik} V_k \cos(\theta_{ik} - \delta_i + \delta_k) \quad (\text{B.7})$$

$$Q_i = -V_i \sum_k Y_{ik} V_k \sin(\theta_{ik} - \delta_i + \delta_k) \quad (\text{B.8})$$

where θ_{ik} is the admittance argument and δ_m is the voltage phase angle at the bus m . One can notice that these relationships are highly non-linear and since the aim of this analysis is only to have a rough idea how will the grid behave, we can afford some approximations in the mathematical resolution.

First, one can assume that, because the grid is high voltage, the lines can be considered as lossless. Indeed, according to the data sheet, the conductance of the lines is negligible with regards to their capacitance and their resistance is also negligible with regards to their inductance. Thus, and according the order of magnitude of the lines' inductance and capacitance, the phase angle of each admittance Y_{ii} can be considered as equal to $-\pi/2$ and the one of each Y_{ik} with $i \neq k$ is equal to $\pi/2$.

Secondly, one can assume that the phase differences between two buses are small. This assumption is based on the fact that inductance is small (around 0.1 p.u.) and the line is considered lossless. This leads to $\sin(-\delta_i + \delta_k) \approx 0.1$ and, thus to a small difference of phase. However, this assumption has to be checked once the results are known.

With those two assumptions, Eq. B.7 and B.8 can be simplified to:

$$P_i = V_i \sum_{k, k \neq i} Y_{ik} V_k (\delta_i - \delta_k) \quad (\text{B.9})$$

$$Q_i = V_i \left(Y_{ii} V_i - \sum_{k, k \neq i} Y_{ik} V_k \right) \quad (\text{B.10})$$

Eq. B.9 and B.10 establish $2 \times n$ relationships (n being the number of nodes), but at each node, there are 4 parameters to determine: the active power P , the reactive power Q , the voltage magnitude V and the voltage phase angle δ . Therefore, $2 \times n$ extra relationships are needed. This is why 2 quantities must be specified to complete the model. Three main types of node types exist with different specified quantities:

1. **PV nodes** have their active power and their voltage magnitude specified. This is the case for nodes with power generation and voltage control capabilities such as nodes connected to power plants or to GFM converters.
2. **PQ nodes** have their active and reactive powers specified. These are nodes where mainly loads and/or generators without voltage control capabilities, such as GFL converters, are connected.
3. **1 slack node** has its voltage magnitude and phase angle specified. It is necessary to have one in the grid as it is a sort of reference for the rest of the grid. So, attention has to be paid while choosing it since this choice will affect the load flow. This node has to have large generation capabilities in order to keep its voltage insensible to small perturbations. This is why a node connected to a pumped hydro facility is usually chosen.

B.1 Application on the grid: first disposition

According to these criteria, X will be considered as a PV node as the nuclear power plants of Doel are located 20 kilometers away from Mercator, Z will be the slack node as the pumped hydro power plant of La Plate Taille is connected to the high voltage grid in Gouy, less than 2 kilometers away from Courcelles and Y would be a PQ node as the converters will be a GFL due to the high short circuit ratio in Avelgem. Taking these specificities into consideration, the following system is

obtained:

$$P_X = V_X [Y_{XY} \textcolor{red}{V}_Y (\delta_X - \delta_Y) + Y_{XZ} V_Z (\delta_X - \delta_Z)] \quad (\text{B.11})$$

$$\textcolor{red}{Q}_X = V_X [Y_{XX} V_X - Y_{XY} \textcolor{red}{V}_Y - Y_{XZ} V_Z] \quad (\text{B.12})$$

$$P_Y = \textcolor{red}{V}_Y [Y_{YX} V_X (\delta_Y - \delta_X) + Y_{YZ} V_Z (\delta_Y - \delta_Z)] \quad (\text{B.13})$$

$$Q_Y = \textcolor{red}{V}_Y [Y_{YY} \textcolor{red}{V}_Y - Y_{YX} V_X - Y_{YZ} V_Z] \quad (\text{B.14})$$

$$\textcolor{red}{P}_Z = V_Z [Y_{ZX} V_X (\delta_Z - \delta_X) + Y_{ZY} \textcolor{red}{V}_Y (\delta_Z - \delta_Y)] \quad (\text{B.15})$$

$$\textcolor{red}{Q}_Z = V_Z [Y_{ZZ} V_Z - Y_{ZX} V_X - Y_{ZY} \textcolor{red}{V}_Y] \quad (\text{B.16})$$

where quantities in red are the quantities to be determined by solving the system.

Eq. B.14 contains only one unknown, V_Y , and solving this equation leads to:

$$V_Y = \frac{Y_{YX} V_X + Y_{YZ} V_Z \pm \sqrt{(Y_{YX} V_X + Y_{YZ} V_Z)^2 + 4 Y_{YY} Q_Y}}{2 Y_{YY}} \quad (\text{B.17})$$

Where among both solutions, the one closest to 1.00 pu will be kept.

Now, V_Y can be replaced by its value found in Eq. B.17 in all the other equations leading to the values of Q_X and Q_Z and to the linear system formed by the Eq. B.11 and B.13 (where δ_Z has been set to 0):

$$\begin{bmatrix} P_X \\ P_Y \end{bmatrix} = \begin{bmatrix} V_X (Y_{XY} V_Y + Y_{XZ} V_Z) & -V_X Y_{XY} V_Y \\ -V_Y Y_{YX} V_X & V_Y (Y_{YX} V_X + Y_{YZ} V_Z) \end{bmatrix} \begin{bmatrix} \delta_X \\ \delta_Y \end{bmatrix} \quad (\text{B.18})$$

And finally, the value P_Z can be determined since all the other quantities are known.

B.1.1 Conditions to respect

While solving this system, some assumptions were made. The first one was that the second-order equation in V_Y accepted 2 real solutions. So, the first condition was the determinant must be positive:

$$-\frac{(Y_{YX} V_X + Y_{YZ} V_Z)^2}{4 Y_{YY}} < Q_Y \quad (\text{B.19})$$

In practice, Q_Y will be controlled such that $V_Y \approx 380$ kV.

Then, the system formed by Eq. B.11 and B.13 has been assumed to be solvable, therefore a nonzero determinant is required:

$$Y_{XZ} Y_{YX} V_X + Y_{XZ} Y_{YZ} V_Z + Y_{XY} Y_{YZ} V_Y \neq 0 \quad (\text{B.20})$$

which is always the case since all the quantities are magnitudes which are by definition non-negative and in practical situations positive.

The two following conditions must be verified in retrospect. The first one is small phase differences between neighboring nodes have been assumed by using the first-order Taylor sequence of the sines and cosines:

$$\delta_X, \delta_Y, |\delta_X - \delta_Y| \ll \quad (\text{B.21})$$

Finally, the last condition is that the lines must not be overloaded. Mathematically, the currents flowing through a line must not exceed its nominal current:

$$I_{ik} = \left| \left(\overline{V}_i - \overline{V}_k \right) \overline{Y}_{ik} \right| \leq I_{ik,nom} \quad (\text{B.22})$$

B.2 Application on the grid: second disposition

Previously, the roles of the different nodes were chosen based on the Belgian grid. In a general case, the slack node may not be at the point of connection of the HVDC connection. It is actually the case in a more detailed representation of the Belgian grid where it would be logical to choose the point of connection of the pumped hydro station of Coe-Trois-Ponts whose capacity is more than 8 times greater than the one in La Plate Taille (1164 MW compared to 143 MW). In this section, the slack node will be X and node Z will be PQ, that is to say that the converters are in grid following mode at both ends. This leads to the same system as in Sec. B.1 but the unknowns are here P_X , Q_X , V_Y , δ_Y , V_Z and δ_Z (in red):

$$P_X = V_X [Y_{XY} V_Y (\delta_X - \delta_Y) + Y_{XZ} V_Z (\delta_X - \delta_Z)] \quad (\text{B.23})$$

$$Q_X = V_X [Y_{XX} V_X - Y_{XY} V_Y - Y_{XZ} V_Z] \quad (\text{B.24})$$

$$P_Y = V_Y [Y_{YX} V_X (\delta_Y - \delta_X) + Y_{YZ} V_Z (\delta_Y - \delta_Z)] \quad (\text{B.25})$$

$$Q_Y = V_Y [Y_{YY} V_Y - Y_{YX} V_X - Y_{YZ} V_Z] \quad (\text{B.26})$$

$$P_Z = V_Z [Y_{ZX} V_X (\delta_Z - \delta_X) + Y_{ZY} V_Y (\delta_Z - \delta_Y)] \quad (\text{B.27})$$

$$Q_Z = V_Z [Y_{ZZ} V_Z - Y_{ZX} V_X - Y_{ZY} V_Y] \quad (\text{B.28})$$

Although we have the same number of equations as unknowns, the non-linearity in the 2×2 subsystem formed by Eq. B.26 and B.28 makes it hard to solve it analytically (a fourth-degree polynomial will appear). Thus, in order to get some results, the particular case where no HVAC line connects nodes Y and Z will be analysed. As previously said, the only difference is that $Y_{YZ} = Y_{ZY} = 0$ and values

of Y_{YY} and Y_{ZZ} are different in this grid. Thus, Eq. B.25, B.26, B.27 and B.28 become:

$$P_Y = V_Y [Y_{YX} V_X (\delta_Y - \delta_X)] \quad (\text{B.29})$$

$$Q_Y = V_Y [Y_{YY} V_Y - Y_{YX} V_X] \quad (\text{B.30})$$

$$P_Z = V_Z [Y_{ZX} V_X (\delta_Z - \delta_X)] \quad (\text{B.31})$$

$$Q_Z = V_Z [Y_{ZZ} V_Z - Y_{ZX} V_X] \quad (\text{B.32})$$

They are now 2 second-order equations with only one unknown which are easily solvable:

$$V_Y = \frac{Y_{YX} V_X \pm \sqrt{Y_{YX}^2 V_X^2 + 4 Y_{YY} Q_Y}}{2 Y_{YY}} \quad (\text{B.33})$$

$$V_Z = \frac{Y_{ZX} V_X \pm \sqrt{Y_{ZX}^2 V_X^2 + 4 Y_{ZZ} Q_Z}}{2 Y_{ZZ}} \quad (\text{B.34})$$

where again, the solution closest to 1.00 pu will be kept. And finally, Eq. B.29 and B.31 are two linear equations with one unknown, δ_Y and δ_Z , and finally, Eq. B.23 and B.24 are 2 linear equations with one unknown each.

B.2.1 Conditions to respect

While solving this system, the following conditions have been assumed:

- $-(Y_{YX} V_X)^2 / (4 Y_{YY}) < Q_Y$; $-(Y_{ZX} V_X)^2 / (4 Y_{ZZ}) < Q_Z$ in order to have a positive determinant.
- $\delta_Y, \delta_Z, |\delta_Y - \delta_Z| \ll 1$ in order to validate the sine and cosine approximation.
- $I_{ik} = \left| \left(\overline{V}_i - \overline{V}_k \right) \overline{Y}_{ik} \right| \leq I_{ik,nom}$ in order not to have any line overloaded.

Unfortunately, these criteria are only valid for the more simple grid without HVAC line between nodes Y and Z as $Y_{YZ} = Y_{ZY}$ were supposed to be equal to 0.

B.3 Application on the grid: third disposition

In this section, we will resolve the system where the slack node is at one end of the HVDC connection (Y), the other end (Z) is a grid forming converter, thus a PV node and node X is a PV node too. This gives the following system where the

unknowns (in red) are Q_X , δ_X , P_Y , Q_Y , Q_Z and δ_Z :

$$P_X = V_X [Y_{XY} V_Y (\delta_X - \delta_Y) + Y_{XZ} V_Z (\delta_X - \delta_Z)] \quad (\text{B.35})$$

$$Q_X = V_X [Y_{XX} V_X - Y_{XY} V_Y - Y_{XZ} V_Z] \quad (\text{B.36})$$

$$P_Y = V_Y [Y_{YX} V_X (\delta_Y - \delta_X) + Y_{YZ} V_Z (\delta_Y - \delta_Z)] \quad (\text{B.37})$$

$$Q_Y = V_Y [Y_{YY} V_Y - Y_{YX} V_X - Y_{YZ} V_Z] \quad (\text{B.38})$$

$$P_Z = V_Z [Y_{ZX} V_X (\delta_Z - \delta_X) + Y_{ZY} V_Y (\delta_Z - \delta_Y)] \quad (\text{B.39})$$

$$Q_Z = V_Z [Y_{ZZ} V_Z - Y_{ZX} V_X - Y_{ZY} V_Y] \quad (\text{B.40})$$

This system is quite straightforward to solve. There are 3 linear equations with only one unknown, Eq. B.36 for Q_X , B.38 for Q_Y and B.40 for Q_Z ; one system of 2 linear equations, Eq. B.35 and B.39, with two unknowns, δ_X and δ_Z ; and one more linear equation with only one unknown once δ_X and δ_Z are found, Eq. B.37 for P_Y .

B.3.1 Conditions to respect

As is Sec. B.1, the 2×2 system was supposed to be solvable, requiring a non-zero determinant leading to the following condition:

$$Y_{XY} Y_{ZX} V_X + Y_{XY} Y_{ZY} V_Y + Y_{XZ} Y_{ZY} V_Z \neq 0 \quad (\text{B.41})$$

Again as in Sec. B.1, the phase differences between neighboring nodes have been assumed to be small and the lines must not be overloaded:

$$\delta_X, \delta_Z, |\delta_X - \delta_Z| \ll \quad (\text{B.42})$$

$$I_{ik} = \left| (\bar{V}_i - \bar{V}_k) \bar{Y}_{ik} \right| \leq I_{ik, \text{nom}} \quad (\text{B.43})$$

B.4 Verification

In order to validate these results, a small example will be done. Tab. B.1 gathers the data from the lines:

Line	Length (km)	I_{nom} (A)	R (Ω)	X (Ω)	ωC (μS)
X-Y	88.1	2186	2.83	28.19	329.29
X-Z	78.7	2186	2.45	25.84	303.20
Y-Z	69.0	1999	2.14	22.63	266.44

Table B.1: Data used to model the lines

In this example, line X-Y's data comes from the lines Avelgem/Horta/Mercator, line X-Z from the lines Courcelles/Bruegel/Buggenhout-Mercator and line Y-Z from Courcelles/St-Amand/Gramme. Since there is no 380 kV line between Courcelles and Avelgem, another line was used to model line Y-Z.

The following admittance matrix can be calculated from those data:

$$\begin{aligned}\underline{Y} &= \begin{bmatrix} \overline{Y_{XX}} & \overline{Y_{XY}} & \overline{Y_{XZ}} \\ \overline{Y_{YX}} & \overline{Y_{YY}} & \overline{Y_{YZ}} \\ \overline{Y_{ZX}} & \overline{Y_{ZY}} & \overline{Y_{ZZ}} \end{bmatrix} = \begin{bmatrix} 7.2 - j 73.2 & -3.5 + j 35.1 & -3.6 + j 38.4 \\ -3.5 + j 35.1 & 7.7 - j 78.6 & -4.1 + j 43.8 \\ -3.6 + j 38.4 & -4.1 + j 43.8 & 7.8 - j 81.9 \end{bmatrix} \text{ mS} \\ &= \begin{bmatrix} 73.5 \angle -84.4^\circ & 35.3 \angle 95.7^\circ & 38.5 \angle 95.4^\circ \\ 35.3 \angle 95.7^\circ & 79.0 \angle -84.4^\circ & 44.0 \angle 95.4^\circ \\ 38.5 \angle 95.4^\circ & 44.0 \angle 95.4^\circ & 82.2 \angle -84.6^\circ \end{bmatrix} \text{ mS} \\ &= \begin{bmatrix} 10.61 \angle -84.4^\circ & 5.10 \angle 95.7^\circ & 5.56 \angle 95.4^\circ \\ 5.10 \angle 95.7^\circ & 11.41 \angle -84.4^\circ & 6.35 \angle 95.4^\circ \\ 5.56 \angle 95.4^\circ & 6.35 \angle 95.4^\circ & 11.87 \angle -84.6^\circ \end{bmatrix} \text{ pu}\end{aligned}$$

B.4.1 First disposition

In this section, the grid from Sec.B.1 will be used, thus node X is a PV node, Y a PQ one and Z is the slack node. Then, we have to choose the value of the quantities we must specify. For the voltages, since it is a 380 kV grid, both V_X and V_Z are set to this value. δ_Z is set to 0° (choosing 0 or any other value has no impact since only differences between the phases matter). Finally, P_X is arbitrarily chosen to 2.00 GW (this value is sensible since Doel's nuclear plants are connected to the grid in Mercator). Finally, $P_{G,Y} - P_{L,Y} = -1.5$ GW but since the "Boucle du Hainaut"'s capacity is 6.0 GW, P_Y can take any value between -7.5 GW and 4.5 GW. And Q_Y will be set to control V_Y .

So, first, Eq. B.14 must be solved since $V_Y \approx 380$ kV, Q_Y must be chosen wisely:

$$\begin{aligned}Q_Y &= V_Y (Y_{YY} V_Y - Y_{YX} V_X - Y_{YZ} V_Z) \\ &= 1.00 (11.41 \times 1.00 - 5.10 \times 1.00 - 6.35 \times 1.00) \\ &= -0.0429 \text{ pu} = -42.9 \text{ MVar}\end{aligned}$$

With $V_Y = 380$ kV = 1.00 pu, the values of Q_X and Q_Z are:

$$Q_X = -0.0455 \text{ pu} = -45.5 \text{ MVar} = \quad ; \quad Q_Z = -0.0409 \text{ pu} = -40.9 \text{ MVar}$$

Then, we can solve the system formed by Eq. B.11 and B.13:

$$\begin{aligned} \begin{bmatrix} \delta_X \\ \delta_Y \end{bmatrix} &= \frac{1}{\Delta} \begin{bmatrix} V_Y (Y_{YX} V_X + Y_{YZ} V_Z) & V_X Y_{XY} V_Y \\ V_Y Y_{YX} V_X & V_X (Y_{XY} V_Y + Y_{XZ} V_Z) \end{bmatrix} \begin{bmatrix} P_X \\ P_Y \end{bmatrix} \\ &= \frac{1}{96.07} \begin{bmatrix} 11.45 & 5.10 \\ 5.10 & 10.66 \end{bmatrix} \begin{bmatrix} 2.0 \\ P_Y \end{bmatrix} \\ &\Rightarrow \delta_X = 0.053 P_Y + 0.238 \quad ; \quad \delta_Y = 0.111 P_Y + 0.106 \end{aligned}$$

Where $\Delta = V_X V_Y V_Z (Y_{XZ} Y_{YX} V_X + Y_{XZ} Y_{YZ} V_Z + Y_{XY} Y_{YZ} V_Y)$. Therefore, in order to keep $\delta_X, \delta_Y, |\delta_X - \delta_Y| \ll P_Y$ must be around -1.00 GW leading to:

$$P_Y = -1.00 \text{ GW} \Rightarrow \delta_X = 10.6^\circ \quad ; \quad \delta_Y = -0.3^\circ$$

Finally, P_Z can be determined and is equal to:

$$P_Z = -1.00 \text{ GW}$$

However, it has been empirically observed that computing the reactive powers using the approximate relationship leads to non-negligible errors. Thus, it is required to recompute them with the exact relationships (Eq. B.8) and using the values of voltages' amplitudes and phases computed with the approximate relationships:

$$\begin{aligned} Q_X &= -V_X [Y_{XX} V_X \sin(\theta_{XX} - \delta_X + \delta_X) + Y_{XY} V_Y \sin(\theta_{XY} - \delta_X + \delta_Y) + Y_{XZ} V_Z \sin(\theta_{XZ} - \delta_X + \delta_Z)] \\ &= -0.0555 \text{ pu} = -55.5 \text{ MVar} \\ Q_Y &= -V_Y [Y_{YX} V_X \sin(\theta_{YX} - \delta_Y + \delta_X) + Y_{YY} V_Y \sin(\theta_{YY} - \delta_Y + \delta_Y) + Y_{YZ} V_Z \sin(\theta_{YZ} - \delta_Y + \delta_Z)] \\ &= 0.1582 \text{ pu} = 158.2 \text{ MVar} \\ Q_Z &= -V_Z [Y_{ZX} V_X \sin(\theta_{ZX} - \delta_Z + \delta_X) + Y_{ZY} V_Y \sin(\theta_{ZY} - \delta_Z + \delta_Y) + Y_{ZZ} V_Z \sin(\theta_{ZZ} - \delta_Z + \delta_Z)] \\ &= 0.1379 \text{ pu} = 137.9 \text{ MVar} \end{aligned}$$

Now that we have obtained the results of the manual computation of the load flow, it is time to compare them with the real values. To obtain those real values, the package *pandapower* in Python has been used. The results are gathered in Tab. B.2.

Node (type)	Active power		Reactive power		Voltage amplitude		Voltage phase	
	Error (%)		Error (%)		Error (%)		Error (%)	
	LF (GW)	pp (GW)	LF (MVar)	pp (MVar)	LF (kV)	pp (kV)	LF (deg)	pp (deg)
X (PV)	0.0	2.00	0.0	-55.5	0.0	380.0	0.0	10.6
Y (PQ)	0.0	-1.00	0.0	158.2	0.0	380.2	25.0	-0.4
Z (slack)	4.0	-0.96	2.3	137.9	0.0	380.0	0.0	0.0

Table B.2: Comparison of the hand-calculated values (LF) and the real ones obtained with *pandapower* (pp) for the load flow from Sec. B.4.1

Most of the errors are close to 0.0%. The only exception is δ_Y whose error is 25.0%. However, this big relative error is due to rounding error and to the small value of δ_Y . Indeed, the absolute error is only 0.1° .

B.4.2 Second disposition

In this section, the grid from Sec.B.2 will be used (without the HVAC line between nodes Y and Z), thus node X is the slack node and Y and Z are PQ ones. Because there is no HVAC line between nodes Y and Z, the admittance matrix becomes:

$$\underline{Y} = \begin{bmatrix} \overline{Y_{XX}} & \overline{Y_{XY}} & \overline{Y_{XZ}} \\ \overline{Y_{YX}} & \overline{Y_{YY}} & \overline{Y_{YZ}} \\ \overline{Y_{ZX}} & \overline{Y_{ZY}} & \overline{Y_{ZZ}} \end{bmatrix} = \begin{bmatrix} 10.61 \angle -84.4^\circ & 5.10 \angle 95.7^\circ & 5.56 \angle 95.4^\circ \\ 5.10 \angle 95.7^\circ & 5.07 \angle -84.2^\circ & 0.00 \\ 5.56 \angle 95.4^\circ & 0.00 & 5.54 \angle -84.6^\circ \end{bmatrix} \text{ pu}$$

Then, we have to choose the value of the quantities we must specify. For the voltages, since it is a 380 kV grid, both V_X and V_Z are set to this value. δ_X is set to 0° . Finally, $P_{G,Y} - P_{L,Y}$ and $P_{G,Z} - P_{L,Z}$ are respectively chosen to 0.50 GW and -2.00 GW, leading to ranges for P_Y and P_Z respectively from -5.50 GW to -6.50 GW and -8.00 GW and 4.00 GW. And Q_Y and Q_Z will be set to control respectively V_Y and V_Z .

First, we have to calculate the values of the reactive powers at nodes Y and Z Q_Y and Q_Z in order to set the voltage at those nodes at 1.00 pu:

$$\begin{aligned} Q_Y &= V_Y (Y_{YY} V_Y - Y_{YX} V_X) = -0.0237 \text{ pu} = -23.7 \text{ MVar} \\ Q_Z &= V_Z (Y_{ZZ} V_Z - Y_{ZX} V_X) = -0.0218 \text{ pu} = -21.8 \text{ MVar} \end{aligned}$$

Then, we have to set the amount of power flowing through the DC line. In this case, since it is a very simplified grid, there is no constraint. Thus, the criterion chosen to fix this quantity is to minimize the voltage phase shift between two neighbouring buses. Therefore, we have:

$$P_{DC,Y} = -P_{DC,Z} = -1.25 \text{ GW} \Rightarrow \delta_Y = \frac{0.50 + P_{DC,Y}}{V_X V_Y Y_{YX}} = -8.4^\circ \quad ; \quad \delta_Z = \frac{-2.00 + P_{DC,Z}}{V_X V_Z Y_{ZX}} = -7.7^\circ$$

Now that all voltage amplitudes and phases are known, we can compute or recompute every powers and compare them with the real values for that load flow. This comparison is made in Tab. B.3

Node (type)	Active power		Reactive power		Voltage amplitude		Voltage phase	
	Error (%)		Error (%)		Error (%)		Error (%)	
	LF (GW)	pp (GW)	LF (MVar)	pp (MVar)	LF (kV)	pp (kV)	LF (deg)	pp (deg)
X (slack)	1.3		6.1		0.0		0.0	
	1.50	1.52	-83.8	-79.0	380.0	380.0	0.0	0.0
Y (PQ)	0.0		0.0		0.2		2.3	
	-0.75	-0.75	98.7	98.7	380.0	379.2	-8.4	-8.6
Z (PQ)	0.0		0.0		0.0		1.3	
	-0.75	-0.75	105.6	105.6	380.0	380.0	-7.7	-7.8

Table B.3: Comparison of the hand-calculated values (LF) and the real ones obtained with *pandapower* (pp) for the load flow from Sec. B.4.2

Since all the relative and absolute errors are small, this simulation tends to validate the model.

B.4.3 Third disposition

In this section, the grid from Sec.B.3 will be used, thus nodes X and Z are PV nodes and node Y is the slack node. Then, we have to choose the value of the quantities we must specify. For the voltages, since it is a 380 kV grid, the three voltages are set to this value. δ_Y is set to 0° . Finally, P_X is arbitrarily chosen to -2.00 GW and $P_{G,Z} - P_{L,Z}$ to -0.5 GW , leading to P_Z being between -6.50 GW and 5.50 GW . While solving the system, it was determined that in order to keep δ_X , δ_Z and $\delta_X - \delta_Z$ small, P_Z must be set at 2 GW . Tab. B.4 gathers the results from the hand-calculated load flow and the ones from the load flow calculated by *pandapower*.

Node (type)	Active power		Reactive power		Voltage amplitude		Voltage phase	
	Error (%)		Error (%)		Error (%)		Error (%)	
	LF (GW)	pp (GW)	LF (MVA _r)	pp (MVA _r)	LF (kV)	pp (kV)	LF (deg)	pp (deg)
X (PV)	0.0		5.7		0.0		3.8	
	-2.00	-2.00	378.8	358.4	380.0	380.0	-7.6	-7.9
Y (slack)	100.0		3.8		0.0		0.0	
	0.00	0.05	32.6	31.4	380.0	380.0	0.0	0.0
Z (PV)	0.0		10.4		0.0		1.7	
	2.00	2.00	-37.3	-33.8	380.0	380.0	6.1	6.0

Table B.4: Comparison of the hand-calculated values (LF) and the real ones obtained with *pandapower* (pp) for the load flow from Sec. B.4.3

All the relative errors are small (except for P_Y but the error is small in absolute value and is due to the assumption of lossless transmissions). Therefore, this simulation tends to validate the model.

B.4.4 Conclusion

The model created seems to give results close to the real ones. However, attention should be paid regarding the calculations of the reactive powers. In order to obtain analytical results, the sines and cosines of both active and reactive powers have been approximated by the first-order approximation. For the active power, this approximation has been empirically validated but not for the reactive powers. Therefore, their must be recalculated in retrospect once the other quantities, especially the voltages phases, are known. This approximation is believed not be verified because $Y_{ii} - \sum_k Y_{ik} \approx 0$ and therefore, even though $|\sin(\theta_{ik} - \delta_i + \delta_k)|$ is approximately but not strictly equal to 1, it leads to massive errors once the admittances are weighted by the sines. A way to make this assumption valid would be to use a second-order approximation. However, it would lead to some terms with δ_k^2 in them and thus, the system would not be analytically solvable. This is why recalculating the reactive powers in retrospect is preferred.

Appendix C

Belgian grid

Substation 1	Substation 2	U	U/Nr.	Length	Inom	R	X	C
			(kV)	(Km)	(A)	(Ω)	(Ω)	(S)
ACHEN	GRAMM	380	380 / 10	36.9	1999	1.14	12.1	141.47
ACHEN	ACHES	380	380 / 200	0.1	2186	0.01	0.14	0
ANDUM	ZUTE+	380	380 / 12	6.3	2000	0.21	1.98	22.97
AUBAN	BRUME	380	380 / 13	104.4	2186	3.55	32.88	379.96
AVLGM	HORTA	380	380 / 101	39.7	1999	1.23	13.02	146.89
AVLGM	HORTA	380	380 / 102	39.7	2186	1.25	13	152.96
AVLGM	IZGEM	380	380 / 46	22.8	2186	0.71	7.48	87.65
AVLGM	IZGEM	380	380 / 47	22.8	2186	0.71	7.48	87.65
BRUEG	MEKI+	380	380 / 33	14	1999	0.45	4.63	54.18
BRUEG	COURC	380	380 / 34	47.3	2186	1.47	15.51	182.6
BRUEG	BUGG+	380	380 / 35	15.9	1999	0.61	5.11	59.8
BRUEG	BUGG+	380	380 / 36	15.9	2186	0.5	5.25	61.8
BRUME	GRAMM	380	380 / 1	44.3	1999	1.37	14.53	164
BRUME	GRAMM	380	380 / 2	44.3	2322	1.37	14.53	170.38
BRUME	COO	380	380 / 3	2	1999	0.06	0.66	7.72
BRUME	COO	380	380 / 4	2	1999	0.06	0.66	7.72
BUGG+	MERCA	380	380 / 35	15.5	1999	0.59	5	58.6
BUGG+	VERBR	380	380 / 35	21.7	2319	0.66	6.91	83.46
BUGG+	MERCA	380	380 / 36	15.5	2186	0.48	5.08	58.8
BUGG+	VERBR	380	380 / 36	21.7	2186	0.67	7.12	83.46
CHAMP	GRAMM	380	380 / 32	32.2	2186	1	10.56	124.25
CHAMP	COURC	380	380 / 56	44.1	2186	1.37	14.46	170.24
COURC	STAM+	380	380 / 31	12.6	1999	0.39	4.13	48.64
COURC	MEKI+	380	380 / 33	33.4	1999	1.03	10.95	128.2
COURC	GOUY	380	380 / 57	1.7	1999	0.05	0.56	6.6
COURC	GOUY	380	380 / 58	1.8	2186	0.06	0.59	7
DOEL	ZANDV	380	380 / 25	6.8	1999	0.24	2.4	24
DOEL	ZANDV	380	380 / 26	7.1	1999	0.07	2.57	22.92
DOEL	MERCA	380	380 / 51	22.8	1999	0.71	7.48	88
DOEL	MERCA	380	380 / 52	22.8	1999	0.71	7.48	88
DOEL	MERCA	380	380 / 53	22.2	2186	0.8	6.84	80
DOEL	MERCA	380	380 / 54	22.2	2186	0.8	6.84	80
DROGE	MEKI+	380	380 / 33	10.3	2186	0.32	3.38	39.61
EEKLN	HORTA	380	380 / 103	13	4560	0.4	4.26	50.27
EEKLN	MAERL	380	380 / 103	17.3	4689	0.28	4.07	79.6
GEZEL	MAERL	380	380 / 107	10.1	1635	0.09	2.24	725.81
GEZEL	MAERL	380	380 / 108	10.1	1635	0.09	2.23	725.81
GEZEL	MAERL	380	380 / 109	10.1	1635	0.11	2.21	725.81
GEZEL	MAERL	380	380 / 110	10.1	1635	0.11	2.21	725.81
GEZEL	STEVN	380	380 / 111	8	4644	0.13	1.9	18.42
GEZEL	STEVN	380	380 / 112	8	4644	0.13	1.9	18.42
GEZEL	NEMO	380	380 / 114	0.8	1635	0.01	0.07	56.19
GRAMM	LIXHE	380	380 / 11	53.4	2051	3.04	20.03	170.88
GRAMM	ZUTE+	380	380 / 12	55.6	2000	1.85	17.45	202.7
GRAMM	TIHA2	380	380 / 17	2.6	2186	0.08	0.85	10.04
GRAMM	TIHA3	380	380 / 18	3.3	2186	0.1	1.08	12.74
GRAMM	STAM+	380	380 / 31	56.4	1999	1.75	18.5	217.8
GRAMM	TIHA1	380	380 / 5	2.9	1999	0.09	0.95	11.19
GRAMM	TIHA1	380	380 / 6	2.9	1999	0.09	0.95	11.19
GRAMM	RMIE	380	380 / 7	14.6	1999	0.45	4.79	54
HORTA	MAERL	380	380 / 104	29	4689	0.43	7.94	115.83
HORTA	MERCA	380	380 / 73	48.4	3400	1.58	15.19	176.33
HORTA	RODE+	380	380 / 74	14.2	2186	0.44	4.64	54.71
LINT	MERCA	380	380 / 59	21.1	2186	0.65	6.92	73.8
LINT	MASSE	380	380 / 61	14.1	2188	0.46	4.56	50.17
LINT	MERCA	380	380 / 61	21.1	2186	0.65	6.92	73.8
LIXHE	VANYK	380	380 / 91	53	1999	2.07	16.53	192.96
MASSE	MEERH	380	380 / 21	32.5	2186	1.01	10.66	125.4
MASSE	MERCA	380	380 / 60	35	2186	1.09	11.54	123.2
MEERH	VANYK	380	380 / 23	57.5	2186	1.78	18.86	220.86
MERCA	RODE+	380	380 / 74	34.2	1999	1.07	11.21	132.2
RODE+	RODEN	380	380 / 74	0.2	2186	0.01	0.14	0
STAM+	TERGN	380	380 / 31	7.5	2186	0.23	2.46	27.76
TIBIS	TIHA2	380	380 / 15	1	2322	0.03	0.31	3.8
VANYK	ZUTE+	380	380 / 12	31.1	1999	0.72	9.55	114.35

Table C.1: Data of the Belgian grid. This table has been sent to me by TA Guy Walango who got it from enstoe.

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