Complex networks-based control strategies for multi-terminal HVDC transmission lines

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Abstract

The work proposes and analizes complex network-based controllers for HVDC transmission lines. Two different control approaches are studied: Distributed PID strategies, which take into account just local information of the state of each single node, and Global PID algorithms, in which the control action for each node depends on the state of the whole network. Both control techniques are tested and numerically validated on a model of the North Sea Transnational Grid, which is a project of connecting already existing off-shore power plants in northern Europe countries with each other and with mainland distribution stations.

The thesis is structured in seven chapters: the first chapter is an introducion about HVDC transmission lines, the second contains the main theoretical aspects of complex networks, the third and fourth chapter are more technical and they are about the study case. The above indicated control strategies are compared and discussed along with the simulation results in chapters five and six. Finally conclusions and suggestions for further research works are drawn in chapter seven.

Trepida mi vegli,
spii il mio respiro,
è il tuo volto amato
che primo ritrovo al mattino.
Qualche bianco capello
io, lo so, te l'ho dato;
quella ruga sul viso
non solo il tempo l'ha disegnata;
or voglio donarti soltanto sorrisi
e da oggi risplenda sul caro tuo volto
l'immagine dolce della felicità.

Rosa Giliberti

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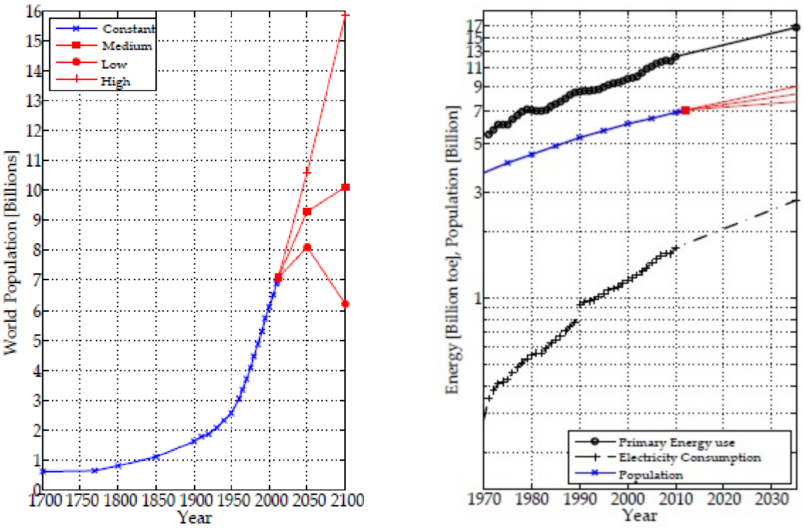
Introduction

1.1 Motivation

As the world population increases, urbanization intensifies and economies grow, it is expected that the global energy consumption will rise as well. According to the most recent United Nations estimates, the human population of the world is expected to reach 8 billion people in the spring of 2024. During the 20th century alone, it has grown from 1.65 billion to 6 billion. The actual growing rate is around 1.14% per year and reached its peack in the late 1960s, however it is currently declining and is projected to continue to decline in the coming years. Despite this decline, electricity consumption in the European Union will continue experiencing a strong annual growth , see Fig. 1.1. This to say that two problems are to be faced:



(a) *Population growth*

(b) *Energy consumption.*

Figure 1.1: Population and energy consumption growth [26]

- 1. Unlimited electricity consumption growth
- 2. The fact that the main energy source is made of fossil fuels.

The reason why using fossil fuels as the main energy source is something to avoid is twofold. First of all, they are not to be count on forever because they are a limited resource [12]; moreover, for the countries with little fossil-fuel provvisions there is no secure supply, and last but not least, the burning of fossil fuels releases cabon dioxide which increases the green house effect.

Therefore, besides energy efficiency and conscious energy consumption, a part of the solution should come from sustainable, renewable energy sources. Today the EU aims to get 20% of its energy from renewable sources by 2020. Renewables include wind, solar, hydro-electric and tidal power as well as geothermal energy and biomass. A good way to exploit wind energy, as will be discussed in next chapters, is to install off-shore wind farms connected to each other and to mainland by High Voltage Direct Current transmission systems.

Hence, the main motivation of this thesis is:
to propose and compare different complex network-based control approaches for HVDC transmission lines.

1.2 Power Grids and Microgrids

Electric power systems constitute one of the fundamental infrastructures of modern society[4]. Often continental in scale, electric power grids and distribution networks reach virtually every home, office, factory, and institution in developed countries and have made remarkable penetration in developing countries or emerging economies such as China and India. The electric power grid can be defined as the entire apparatus of wires and machines that connects the sources of electricity (i.e., the power plants) with customers and their myriad needs. Power plants convert a primary form of energy, such as the chemical energy stored in coal, the radiant energy in sunlight, the pressure of wind, or the energy stored at the core of uranium atoms, into electricity, which is no more than a temporary, flexible, and portable form of energy. At the end of the grid, at factories and homes, electricity is transformed back into useful forms of energy or activity, such as heat, light, information processing, or torque for motors.

Due to the growing energy consumption, as discussed in 1.1, the electricity grid faces, at least, three looming challenges: its organization, its technical ability to meet 25- and 50-year electricity needs, and its capacity to increase efficiency without diminishing reliability and security. The technical aspects of the challenges that will be posed by this rapid growth include both improving existing technology through engineering and inventing new technologies requiring new materials. Some materials advances will improve present technology (e.g., stronger, higher current overhead lines), some will enable emerging technology (e.g., superconducting cables,fault current limiters, and transformers), and some will anticipate technologies that are still conceptual (e.g., storage for extensive solar or wind energy generation).

1.2.1 The Grid

When most people talk about the "grid," they are usually referring to the electrical transmission system, which moves the electricity from power plants to substations located close to large groups of users [29]. However, the grid also encompasses the

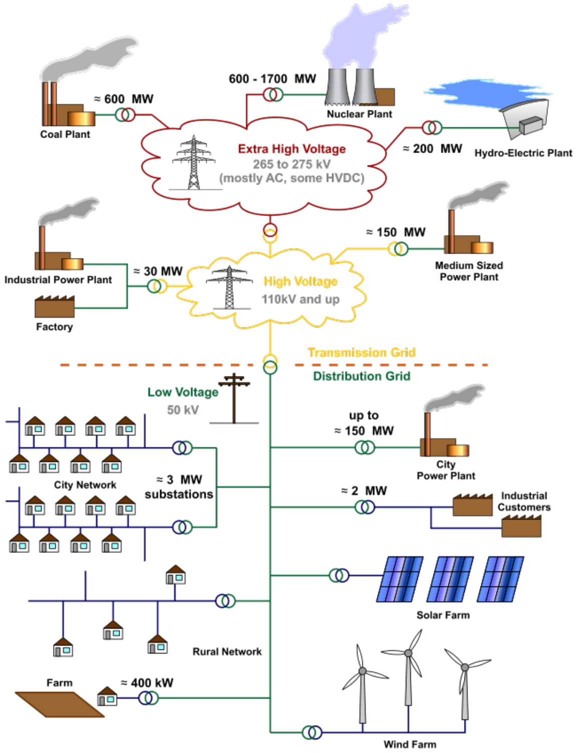


Figure 1.2: European Power Grid example

distribution facilities that move the electricity from the substations to the individual users.

Figure 1.3: Grid

It can be seen as a multilevel hybrid system consisting of vertically integrated hierarchical networks including the generation layer and the following three basic levels:

1. Transmission level, consisting of meshed networks combining extra high voltage (above 300 kV) and high voltage (100–300 kV), connected to large generation units and very large customers and, via tie lines, to neighboring transmission networks and to the subtransmission level;

2. Subtransmission level, consisting of a radial or weakly coupled network including some high voltage (100–300 kV) but typically medium voltage (5–15 kV), connected to large customers and medium-size generators;

3. Distribution level, typically consisting of a tree network including low voltage (110–115 V or 220–240 V) and medium voltage (1–100 kV), connected to small

generators, medium-size customers, and local low-voltage networks for small customers.

In its adaptation to disturbances, a power system can be characterized as having multiple states, or “modes,” during which specific operational and control actions and reactions are taking place. These modes can be described as normal, involving economic dispatch, load frequency control, maintenance, and forecasting, for example; disturbance, involving, for instance, faults, instability, and load shedding; and restorative, involving rescheduling, resynchronization, and load restoration, for example.

Why the need for a system of such daunting complexity? In principle, it might seem possible to satisfy a small user group— for example, a small city—with one or two generator plants. However, the electricity supply system has a general objective of very high reliability, and that is not possible with a small number of generators.

One of the important issues with the use of electricity is that the storage of electricity is very difficult, so the generation and use must be matched continuously: this means that generators must be dispatched as needed. Generally, generators are classified as baseload, which are run all the time to supply the minimum demand level; peaking, which are run only to meet power needs at maximum load; and intermediate, which handle the rest. Actually, the dispatch order is much more complicated than this, because of the variation in customer demand from day to night and from season to season.

1.2.2 The Micro Grid

A different approach from the one discussed in previous section is a distributed kind of grid: the Micro Grid.

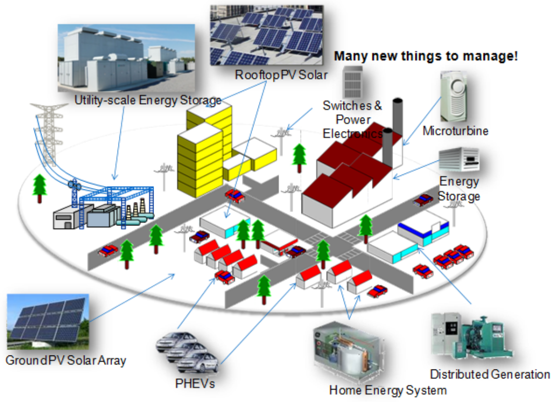


Figure 1.4: Micro Grid

A Micro Grid is a set of loads and sources of energy that operates a single controllable system with the aim of providing energy and heat to a local area. Micro Grids are effective when used in distribution systems where efficiency is a priority; this characteristic relates them to the concept of Smart Grids. The main advantages of their use use are economic efficiency and resources optimization. In fact, there is energy transport cost reduction (the consumption takes place where its producted), and control and administration of generators and load are improved.

Besides the economical benefit that this kind of grid introduces with the integration in average and big infrastructures, Micro Grids will have an important impact for the electrification of rural zones in developing countries, taking benefits from the growing penetration of renewable sources.

Micro Grids are usually employed in small urban or industrial areas, mainly because of:

- Power Quality improvement
- Greater reliability
- Smaller enviromental impact
- Money saving

In the concept of Micro Grid there is a strong focus on local energy supply. It works as an energy accumulator that stores electrical energy distributed in the network to which it is connected. Micro Grids tend to prefer local production to principal network production: when the micro-generation system is not able to provide the energy need the Micro Grid takes energy from the main supply source.

A Micro Grid should be able to manage operations on two operational states: connected network and isolated operation (without any connection to the principal network). Neverthless, most of future Micro Grids will work for most of the time within a connection to the network so that they can maximize the advantages offered from both operational states.

Micro Grid are interesting for this work because:

They represent a way to employ a technology like off-shore windfarms to provide energy supply for still isolated areas with low access to the principal transmission lines. Moreover they can help the integration of new renewable sources of energy in the already exisisting system.

1.3 Transmission Lines seen as Complex Networks

[1]The connection of distributed resources, primarily small generators, is growing rapidly. The extent of interconnectedness, like the number of sources, controls,and loads, has grown with time. In terms of the sheer number of nodes, as well as the variety of sources, controls, and loads, electric power grids are among the most complex networks made. Neverthless there are very few works that deal with grids using a complex network approach. Most of them are investigated in [22] whic is cited in this section.

Power Grid involve many scientific knowledge areas that contribute to the design, operations and analysis of power systems: Physics (electromagnetism, classical mechanics), Electrical engineering (AC circuits and phasors, 3-phase networks, electrical systems control theory) and Mathematics (linear algebra, differential equations). Traditional studies tend to have a “local” view of the Grid, e.g., defining how to design a transformer and predicting its functioning. Typically, studies tend to focus on the physical and electrical properties, or the characteristics of the Power Grid as a complex dynamical system, or again, the control theory aspects. The move from

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[1] This section is inspired by [22]

a "local" to a "global" view of the Power Grid as a complex system is possible by resorting to Complex Network Analysis and statistical graph theory.

The main aspects investigated in the literature are:

- *The small world property.* A small-world network is a type of mathematical graph in which most nodes are not neighbors of one another, but most nodes can be reached from every other by a small number of hops or steps. Specifically, a small-world network is defined to be a network where the typical distance$L$ between two randomly chosen nodes (the number of steps required) grows proportionally to the logarithm of the number of nodes N in the network, In the context of a social network, this results in the small world phenomenon of strangers being linked by a mutual acquaintance. Many empirical graphs are well-modeled by small-world networks. Social networks, the connectivity of the Internet, and gene networks all exhibit small-world network characteristics [33].

- *Node degree distribution.* The degree of a node is a property to understand how many other nodes it is connected to. However, this information is not particularly important for big graphs since keeping track of each node degree may not be manageable. Instead, it is better to have a general idea of the statistics of the node degree. In particular, its probability distribution gives us some insights of the general properties of the networks such as the likely or unlikely presence of nodes with very high degree (sometimes also referred as hubs). The investigation in [13] reports a node degree distribution for the Western U.S. and for the Nordic Grid that both seem to follow an exponential distribution.

- *Betweenness distribution.* Betweenness centrality is an indicator of a node's centrality in a network. It is equal to the number of shortest paths from all vertices to all others that pass through that node. A node with high betweenness centrality has a large influence on the transfer of items through the network, under the assumption that item transfer follows the shortest paths. Although the studies that perform this type of analysis are only few, one can see that there is a tendency for the High Voltage network to have a betweenness distribution close to a Power-law like:
    - $y(x) \sim (2500 + x)^{-0.7}$ [3]
    - $y(x) \sim 10000(785 + x)^{-1.44}$ [16]

- *Resilience analisys.* How a Power network reacts to faults or defection of nodes is really important expecially if it responsable of energy supply for a certain area. According to [22] there are different approaches to study resilience:
    - Connectivity loss [3]
    - Efficiency [16]
    - Loss of load probability
    - Influence on largest component size
    - Damages and improvements

- Nodes disconnection
- Reliability and disturbance
- Sensitivity
- Flow availability
- Line overload,cascade effects, network disruption

In this work are mainly studied efficiency, reliability and disturbance effects.

Therefore, a Power grid can be seen as complex network in the sense that it presents all the main characteristics discussed and it is possible to use complex network theory to model its operation states. Moreover complex network theory focuses on topology and interconnections which are of strong interest while projecting an integration for renewable energy networks.

1.4 Problem Definition

In the interest of exploiting as best as possible a renewable source of energy, is wise to install plants in remote places. This because of the available space, limited bother to the population, and, in case of wind energy, the chance of higher wind power accessibility. In fact, offshore wind power plants are exposed to a greater wind power, so they can produce more usable energy which, though, is more expensive[2].

In Europe the need for developing and integrating remotely located renewable resources is strong due both to the lack of fossil fuels and to the EU policies and regulatory schemes towards energy: by 2020 about 400 TWh in new electricity generation through different renewable technologies should be added [2].

According to the EU-27 National Renewable Energy Action Plans, wind energy has the potential to supply 41% of all renewable electricity; whereas offshore wind energy will account for 28% of the entire wind energy share. This estimate equals a total of 40 GW of installed offshore capacity throughout Europe by the end of this decade.

1.4.1 Multi-terminal HVDC transimission lines and the North Seas Transnational Grid

A way to exploit the off-shore power of the wind is employing Hig Voltage Direct Current transmission lines[3] . Multiterminal HVDC (M-HVDC) are meshed grids, as can be seen in Fig. 1.5. These kind of transmission lines became more interesting when Voltage Source Converters (VSC) started to be used; this is because of their smaller size and the possibility of flexible control techniques. Moreover they seem more efficient for long disance transimission than AC grids mainly because of the lower power losses of DC transmissions [6]. Although M-HVDCs present a more attractive alternative to point to point architecture[4], the development of Multi-Terminal HVDC networks still represents a challenge for many reasons [26]:

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[2] Further details are given in chapter 3

[3] More details about HVDC and HVAC will be given in chapter 3

[4] The reasons will be explained in chapter 3

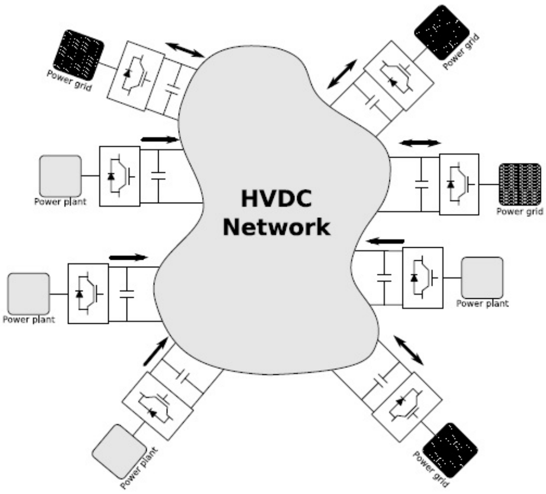


Figure 1.5: M-HVDC [6]

1. *System Integration.*
   The actual electrical network is the result of decades of development and growth and, similarly, M-HVDC should face a similar process but in a much shorter time and should also adapt to the preexisting system through a deep integration work.

2. *Power Flow Control.*
   A new transmission system must be reliable, safe and solid; it should also be a good investment, in the sense that it needs to provide an economic return. That's why the control aspect is crucial.

3. *Dynamic Behaviour.*
   Due to their switching behaviour, the dynamic equations describing the converters operation are discontinous and difficult to solve.

4. *Fault Behaviour.*

This work studies different complex network-based control approaches for M-HVDC transmission lines. *The North Sea Transnational Grid* will be used as a case example. The project of a North Seas transnational grid is really ambitious [26] with its objective of interconnecting about 40GW of offshore wind power between several countries in Northwest Europe up to 2030.

The first step will be to describe a possible architecture of the network, then to estabilish its operational modes and, finally, control the network with local and global approaches.

1.5 Outline and appoach

The main objective of this thesis is to formulate and test several Complex Network Control approaches to M-HVDC transmission system. The work is structured as follows:

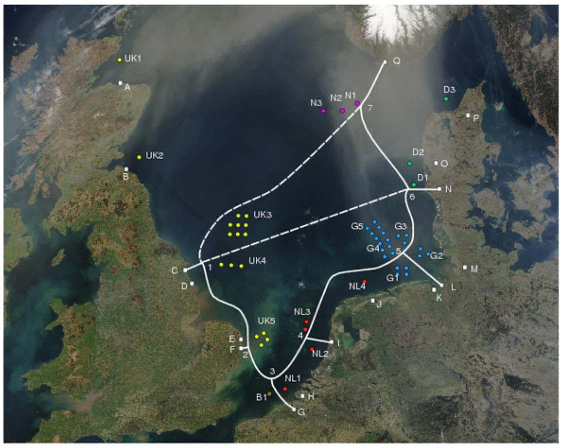


Figure 1.6: North Seas Transnational Grid Project

- *Chapter 1*: Which Problem is to face? Why is it worth to be faced?

- *Chapter 2*: Which are the fundamentals of Complex Network Theory? Definition of the main mathematical entities that will be used in the work.

- *Chapter 3*: How does a HVdc transmission system work? Description of the structure and brief history of the system and an accurate analysis of Voltage source Converters.

- *Chapter 4*: What is the North Sea Grid Project? Characteristics of the North Sea Transnational Grid in terms of voltage, power, distances...

- *Chapter 5-6*:Which control strategies can be applied to the System? Theory about Local and Global control and simulation results referred to NSTG.

- *Chapter 7*:Which is the best control strategy? Comparison between the control tecniques considered in the work so far.

Chapter 2

Complex Network Theory

2.1 Introduction

Traditional control focuses on the interaction between two main entities: the controller and the process to control, as depicted in Fig. 2.1.

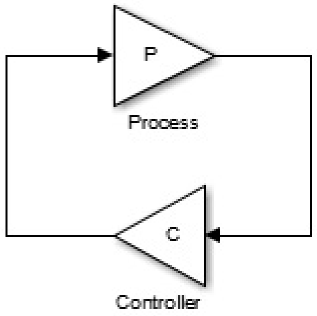


Figure 2.1: Control Paradigm

This paradigm does not fit for systems like:

- Internet
- Traffic
- Social Network Opinion Control
- Distribution Energy lines
- Neural Networks

These kind of systems are made of many entities that interact with each other by means of an interconnection network (tipically a retroaction), and show collective behaviours that cannot be neither explained from the single agents dynamics nor controlled with classical control theory. An example of emerging behaviour was found by Huygens, who observed that metronomes tended to synchronize if placed on a swinging base, see Fig. 2.3. The *emerging property* is the isochronism of oscillation which takes place at at a different frequency from the initial ones of any single metronome, and is reached without any external control. Other classical examples are the synchronization of a fireflies swarm brilliance, the audience applause, and swarm of fish that follow the same trajectory to escape a predator. The first progresses about complex systems networks theory were gained at the end of the 90s, mainly thanks to physicists.

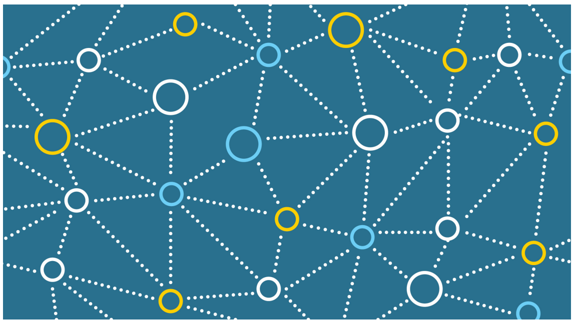
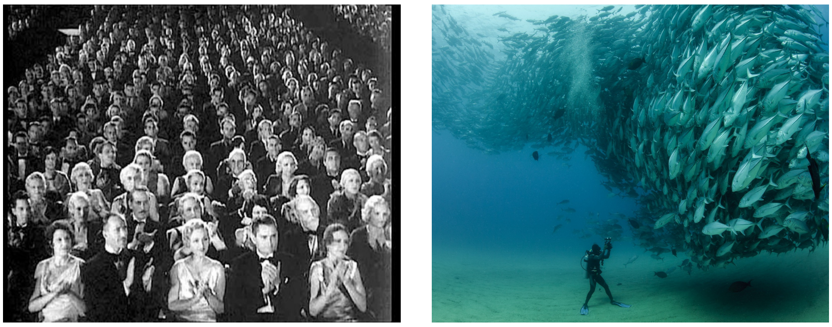


Figure 2.2: Network interconnections

(a) *Synchronized Metronomes* (b) *Fireflies swarm.*



(c) *Audience applause.* (d) *Fish swarm.*

Figure 2.3: Synchronization examples

The control objective in this context is to pass from a centralized control to a strongly distributed control strategy. The main issues are to understand, to be able to reproduce, and to control network emerging behaviours like:

- Synchronization;
- Flocking behaviour;
- Traffic control, internet...

2.1.1 The importance of feedback

Feedback is a very important mechanism that allows the rising of network dynamics in its overall. A simple example can be obtained considering a network of *agents*, defined as systems belonging to the network, connected by mono or bi-directional links (Fig. 2.4).

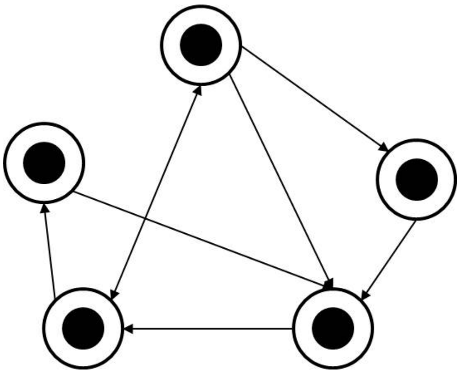
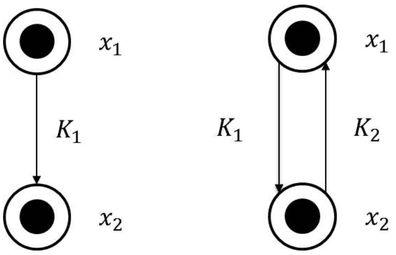


Figure 2.4: Oriented network

Let us consider just two linear agents connected without feedback, see Fig. 2.5*(a)* and described by the equations:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} A_1 & 0 \\ B_2 K_1 & A_2 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \tag{2.1}$$



(a) *No feedback linear agents* (b) *Feedback linear agents*

Figure 2.5: Agents connections.

It is possible to notice that the overall system dynamics is the combination of the single systems dynamics. However, if the connection becomes a feedback, as in Fig. 2.5*(b)* the system dynamic matrix will contain additional terms decided by the interconnection:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} A_1 & B_1 K_2 \\ B_2 K_1 & A_2 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \tag{2.2}$$

In a complex network there are many nested feedback connections which cause the showing of the peculiar emerging behaviour.

2.2 Model of a Complex Network

The three main entities useful to model a complex network are :

1. A model for the dynamics of the single agents
2. The *communication protocol* between the agents , also called *interaction model*
3. The interconnection structure between the agents

2.2.1 Agents Model

Each agent can be seen as a generic non-linear system in the form:

$$\dot{x}_i = f_i(x_i) + g_i(x_i)u_i \quad \text{with } i = 1, 2, \ldots, N. \quad \text{and } x_i \in \mathbb{R}^n, u_i \in \mathbb{R}^m \tag{2.3}$$

For example, the agents with the simplest dynamics are simple, see (2.4), or double integrators, see 2.5.

$$\dot{x}_i = u_i \tag{2.4}$$

$$\begin{cases} \dot{x}_i = y_i \\ \dot{y}_i = u_i \end{cases} \tag{2.5}$$

Definition 1 (Homogeneous Network)**.** A network where all the agents are equal, that is $f_i = f_j \; \forall i, j \in [1, \ldots, N]$, is said to be Homogeneous.

Definition 2 (Heterogeneous Network)**.** A Network where at leas one agent is different from the others, that is $\exists f_i \neq f_j$, is said to be Heterogeneous.

2.2.2 Interaction Model

The interaction between agents can be modeled choosing an appropriate coupling law. For instance, a *linear diffusive coupling* between nodes can be modeled as:

$$u_i = \sigma \sum_{j=1}^{N} a_{ij}(x_j - x_i) \tag{2.6}$$

The information exchanged here is the distance between the state of the *j-th* node and the *i-th* one multiplied by a gain σ that weights the coupling intensity, while a_{ij} is the generic element of the adjacency matrix, A:

$$A = (a_{ij}), \text{ with } \begin{cases} a_{ij} = 1, & \text{if node } i \text{ is connected to node } j \\ a_{ij} = 0 & \text{if node } i \text{ is not connected to node } j \end{cases} \tag{2.7}$$

More generally , (2.6) can be written as:

$$u_i = \sigma \sum_{j=1}^{N} a_{ij}[h(x_j) - h(x_i)] \tag{2.8}$$

Clearly, it is possible to consider other models including delays, different gains associated to each connection, adaptative gains . . . .

2.2.3 Structure of the Network

The agents inside the network communicate by the means of a certain topological structure that encodes the topology of their connections. Networks are tipically made of many *vertices* (or *nodes*) that are connected to each other with moderately few *branches* (or *links*). Therefore, the structure of the network is studied with the associated graph G. In particular it is possible to describe a network through the associated Laplacian matrix L.

Definition 3 (Laplacian)**.** The *Laplacian* matrix is defined by the difference between the matrix of the degrees D, which is a diagonal matrix formed by the number of connections of each node, and the Adjacency matrix A.

$$L = D - A \tag{2.9}$$

Definition 4 (Weighted Laplacian)**.** If each link of the network has an associated weight $w_{ij} \in \mathbb{R}^+$, the Laplacian is defined as:

$$\begin{cases} L_{ij} = \displaystyle\sum_{k=1, k\neq i}^{N} w_{ij} & \text{if } i = j \\ -w_{ij} & \text{otherwise} \end{cases} \tag{2.10}$$

The Laplacian,L, shows interesting properties:

- It is simmetric
- Its rows sum is zero
- Its spectrum is real
- If λ_i denotes its *i-th* eigenvalue, then : $\lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \cdots \leq \lambda_n$
- At least one of its eigenvalue equals to zero (λ_1) and the corresponding eigenvector is $[1, 1, \ldots, 1]$
- Its first eigenvalue different from zero (λ_2) is positive if there are no isolated nodes in the network

Beyond the Laplacian, there are several parameters that characterize a network:

Definition 5 (Node degree)**.** The *node degree K* the number of the *i-th* node interconnections.

Definition 6. The *average degree* of the network is the average value of its nodes degree:

$$< K >= \frac{1}{N} \sum_{i=1}^{N} k_i \tag{2.11}$$

.

Definition 7. The *degree distribution P(k)* is the probability that a node has degree K.

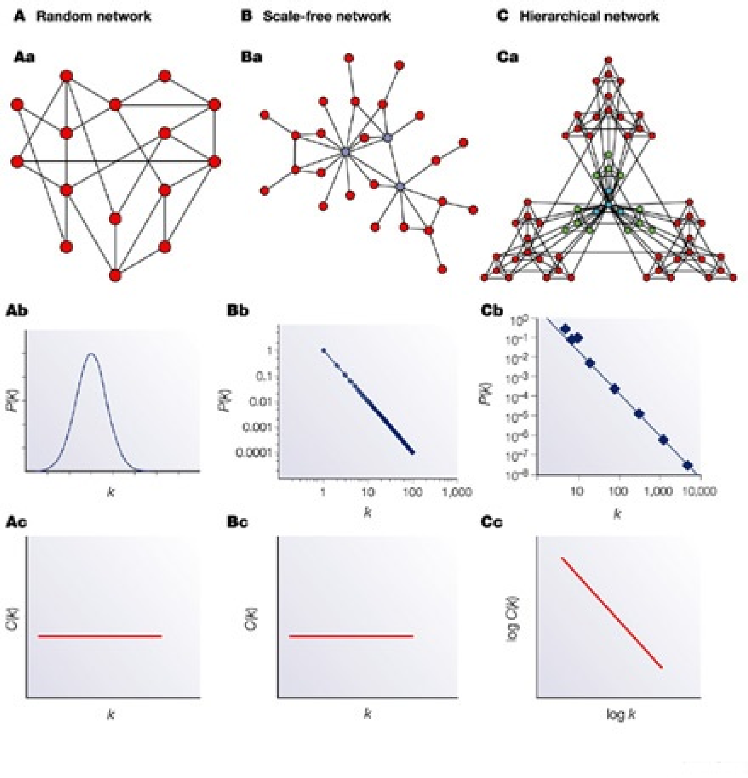


Figure 2.6: Network shape and Degree distribution

The degree distribution is relevant because if most of the nodes show a certain degree K, or the degree is distributed between the nodes with a certain trend, a specific qualitative change can be seen in the shape of the network as pictured in Fig. 2.6.

In *scale free* networks a small number of nodes, known as *hubs*, have many connections. Example of scale free networks are:

- Web pages
- Interaction between proteins
- Collaborations between mathematicians
- Networks for energy distribution[1]

Now that all the main elements have been introduced, it is possible to describe a complex network dynamics particularising (2.3):

$$\dot{x}_i = f(x_i) + \sigma \sum_{j=1}^{N} L_{ij} h(x_j), \tag{2.12}$$

where it was supposed for simplicity that all the nodes are described by the same dynamics and that u_i is substituted by $h(x_j)$, while L_{ij} stands for a generic Laplacian

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[1] This is the case of the North Sea Transnational Grid

element. In case of linear diffusive coupling the model becomes:

$$\dot{x}_i = f(x_i) + \sigma \sum_{j=1}^{N} L_{ij} x_j \tag{2.13}$$

2.3 Collective Behaviour

One of the most interesting properties of a network is its emerging behaviour. The simplest collective dynamics are:

1. Consensus
2. Synchronization

While consensus is usually referred to integrators (or, in a more general sense, to linear systems), synchronization is linked to non-linear systems. In this work, due to the nature of the HVDC transmission lines model, the Consensus problem will be investigated.

In a network made of agents, *consensus* means the reaching of a "deal" according to a certain quantity depending on the state of the all agents. A consensus algorithm is a law of interaction that rules the information exchange between an agent and its neighbours. Each agent uses the same algorithm shared by all the others and takes its decisions based on the locally available information and the one received by the other agents.

Let us consider a multi-agent network and let $G = (V, E)$ be a graph characterized by a set $V = (1, \dots, N)$ of nodes and by a set $E \subseteq V \times V$ of branches. Let N_i be the set of the neighbours of the *i-th* node, defined as $N_i = \{j \in V : a_{ij} \neq 0\}$ where a_{ij} is the generic element of the Adjacency matrix A. Let $x_i \in \mathbb{R}$ be the state of *i-th* node. The information contained in x_i is exactly the one needed to coordinate the agents. The nodes i and j agree in the network iff $x_i = x_j$:

Definition 8 (Consensus)**.** All the nodes reach consensus if:

$$x_1 = x_2 = \cdots = x_N \tag{2.14}$$

When the nodes of a network reach consensus, the common value is called *collective decision* $\alpha \in \mathbb{R}$.

Consensus for integrators

Let us suppose that each node of the network is a dynamic agent, and consider the simple case in which the network consists of integrators with dynamics $\dot{x}_i = u_i$. The algorithm that yelds the reaching of a collective convergence is:

$$\dot{x}_i = \sum_{j \in N_i} a_{ij}(x_j(t) - x_i(t)), \tag{2.15}$$

which is called *distributed consensus algorithm.* Assuming that the graph describing the network is udirected[2], the sum of the states of all the nodes is a constant quantity

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[2] An undirected network is one in which edges have no orientation.

or zero. Particularly:

$$\alpha = \frac{1}{N}\sum_{i}^{N} \dot{x}_i(0) \tag{2.16}$$

This means that if the network reaches consensus, then the collective decision α is necessarily equal to the average of all the initial states.

The dynamics of the system considered can be expressed using the Laplacian matrix as in (2.17):

$$\dot{x} = -Lx \tag{2.17}$$

The most important aspect is to notice that consensus is made possible by the structure of the Laplacian matrix. In fact, as said before, L has at least one eigenvalue equal to zero and the others are positive, so the ones of the system dynamic matrix (-L) are negative. This means that the system has a *center subspace* which is the subspace associated to the null eigenvalue and generated by the corresponding eigenvector $[1, 1, \dots, 1]$. That is why it is possible to conclude that the consensus dynamics converge to the equilibrium:

$$x^* = (\alpha, \alpha, \dots, \alpha)^T \tag{2.18}$$

Moreover, the trasversal dynamics to this variety is certainly stable because all of the other eigenvalues are negative: in the stady state the system evolves to the center variety so that it ends having all the states identical. If the network is connected, the system certainly reaches the equilibrium point x^* which is asymptotically stable A possible consensus scheme is shown in Fig. 2.7.

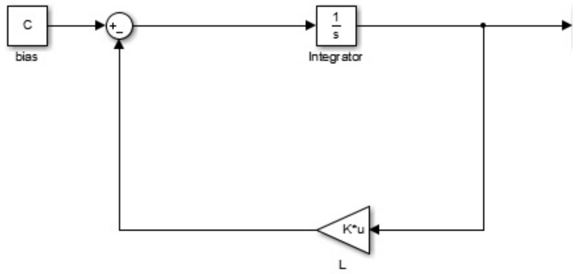


Figure 2.7: Consensus scheme

Another property of Consensus is that, for certain kinds of networks, its velocity can depend on the first Laplacian eigenvalue different from zero: the greater λ_i is, the faster the algorithm is.

2.4 Controllability

The problem of network controllability consists in finding a way to to make the network show the desired behaviour. Given an initial condition x_0, the objective is to reach a stable state x_f. To do so it is possible to operate on some nodes with an appropriate control action, modify the network structure (*rewiring network*) or a combination of both. An alternative control aproach is to act only on a subset of the nodes; this technique is called *pinning control.*

As said before, a network depends strictly on its topology, so it is natural that in order to find controllability conditions some *graph condition* must be investigated. For simplicity let us make two hypotesis:

1. Each node is a simple integrator $\dot{x}_i(t) = u_i(t)$
2. The communication protocol is linear and diffusive like in 2.6

For linear systems in the form:

$$\dot{x}(t) = Ax(t) + Bu(t), \tag{2.19}$$

controllability depends on the *Controllability Matrix* C:

$$C = [B\ AB\ \dots A^{n-1}B], \tag{2.20}$$

which must be full rank. Considering (2.17), calling $A = -L$ and using a state vector $\mathbf{x}(t)$, the network described by the model $\dot{x}_i = -\sum_{j=1}^{N} a_{ij}(x_i - x_j)$ can be written as:

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) \tag{2.21}$$

Adding a control action $\mathbf{v}(t)$ the system becomes:

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + B\mathbf{v}(t) \tag{2.22}$$

Now the question is which is the minimum nubmer of inputs that makes the system controllable. Two main algorithms are proposed in the literature:

- *Graph Partitions*
- *Maximum Matching*

Graph Partitions

The first method is based on partitions which can be defined as subsets of all the connections of a graph. Useful definitions and the main theorem are stated below.

Definition 9 (Externally Fair Partition)**.** A partition is said to be externally fair if each node of the partition has the same number of neighbours in every other possible partition.

Definition 10 (Banal Partition)**.** A partition is said to be *banal* if it is composed by only one node.

Theorem 1 (Controllability of simple integrators complex networks)**.** *A network made of N simple integrators that communicate with each other through a diffusive coupling, is controllable iff exists only one externally fair banal partition.*

Maximum Matching

This second approach is valid for oriented and weighted networks. As before, all the main definitions and results are given below.

Definition 11 (Edge matching)**.** The links which do not share the same starting or arrival node are said to be *matching edges.*

Definition 12 (Node matching)**.** The nodes pointed by a matching edge are said to be *matching nodes.*

The *maximum matching algorithm* consists in finding the configuration within the biggest number of matching edges and nodes.

Theorem 2 (Maximum Matching)**.** *The number of leader nodes*[3] *necessary to make the network controllable is:*

$$N_m = max\{\ N - M^*, 1\} \tag{2.23}$$

where M^* *is the number of matched nodes.*

---

[3] The leader nodes are the controlled ones.

Chapter 3

High Voltage Direct Current Networks

In this chapter a brief history of HVDC transmission lines and their main characteristics will be discussed, along with the technology used to build them from the very beginning to nowadays. The converters model and the whole nework general model will be given in the last two sections.

3.1 An Overview

The first commercial installation of HVDC transmissions was Gotland 1 in Sweden, in 1954, and since then many other plants have been installed in the world, as shown in Fig. 3.1.

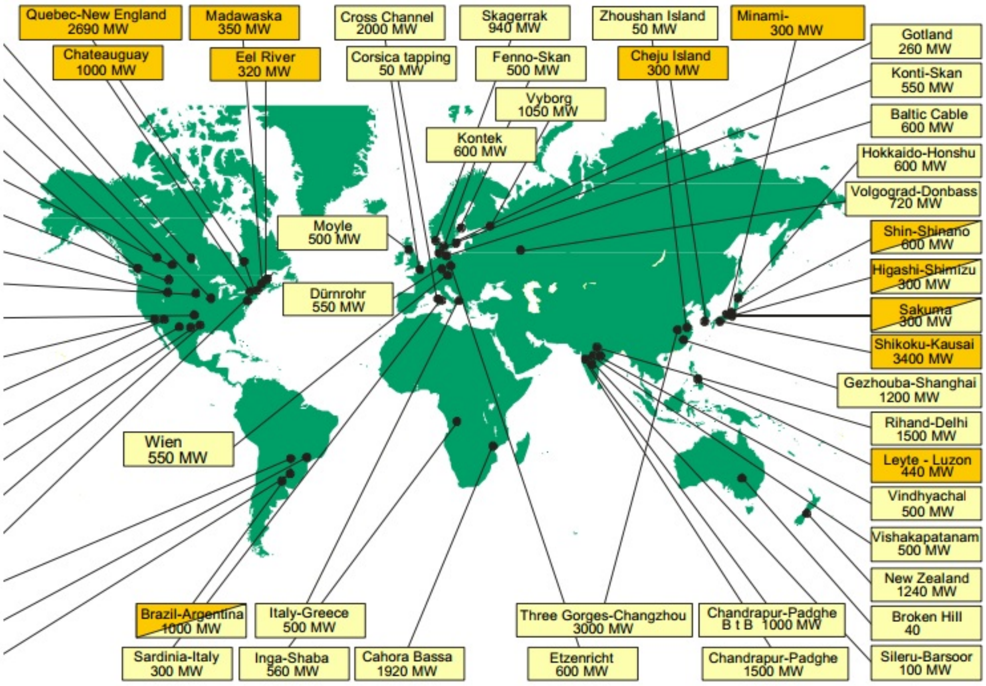


Figure 3.1: Distribution of HVDC transmissions.

HVDC technology is based on the conversion between DC and AC so its initial development was slowed down because of the lack of a suitable technology for the valves [24]. Thyristors were applied to DC transmissions in the late 1960's when solid state valves became a reality. In 1969, a contract for the Eel River DC link in Canada was awarded as the first application of solid state valves for HVDC transmission. Today, one of the highest functional DC voltages for DC transmission is +/- 600 kV for the 785 km transmission line of the Itaipu scheme in Brazil. DC transmission is now an integral part of the delivery of electricity in many countries throughout the world [34].

The first attempt to build an HVDC transmission system was done in Genoa, in 1889, using a thury system [21] [26]. It was not very efficient because it needed a motor-generator set to invert the current so that electricity had to be transformed into mechanical energy and then again into electrical. A revolutionary discovery was the one made by Peter Cooper Hewitt: the mercury-arc valve [19]. It worked as a diode and permitted rectification but not inversion until 1930, when the grid electrode was introduced [15]. The Gothland 1 project was based on the mercury-arc valve and it connected the Swedish mainland to Ygne in the Island of Gothland. It transmitted 20MW with a direct voltage of 100kV [34].

The evolution of HVDC projects, built with mercury-arc valve, is shown in Fig. 3.2 [14][26].

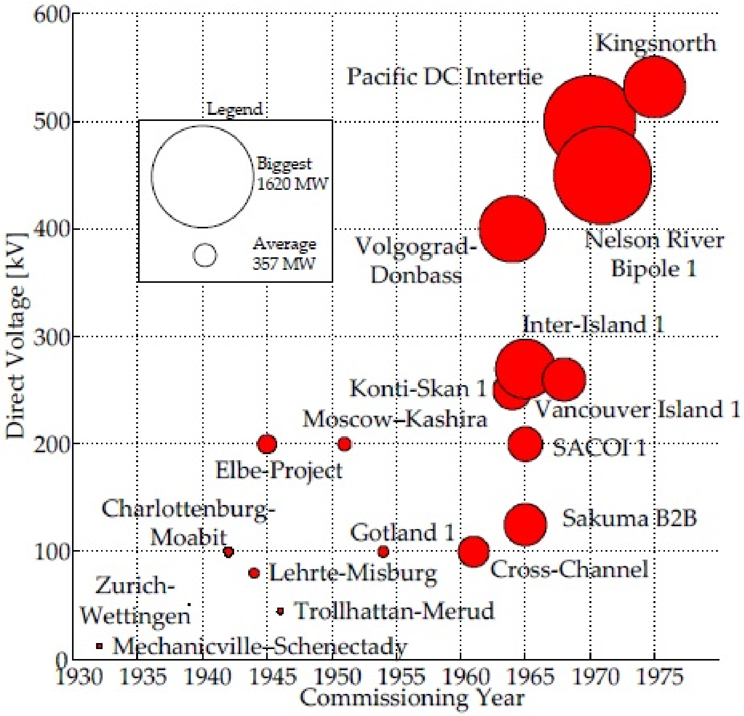


Figure 3.2: Evolution of mercury-arc valve based HVDC systems [26]

HVDC *Classic Technology* is commonly referred to the use of thyristors which made possible to reach transmission voltages that were not allowed with the mercury-arc valve. Fig. 3.3 shows the installed capacity of classic HVDC technology[14][17].

Most of HVDC classic systems have an extension between 180-1000 km, with voltages between 500 kV and 1000 kV, and power ratings in the range of 500 and

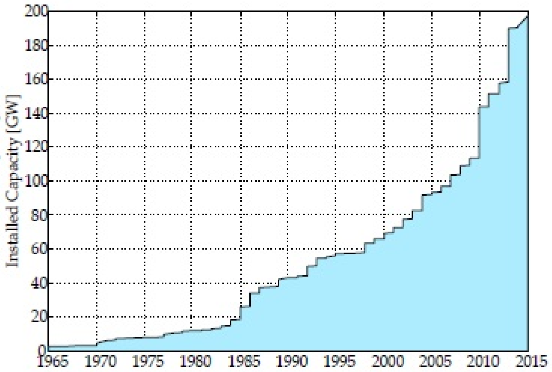


Figure 3.3: Evolution of HVDC systems thyristor based [26]

2500 MW.

In this work HVDC transmissions based on VSCs will be analized and further details about this specific technology will be given in section 3.4.

3.2 HVDC and HVAC for off-shore transmission systems

The first electricity ever obtained was DC, although when the first transmission lines were built AC was chosen over DC. But with time, challenges for AC systems emerged [24]:

- Difficulties in increasing the voltage for under-sea cables
- Transport over long distances, due to the developing of very large hydroelectric projects in remote areas

For economic and environmentally acceptable long distance dispatch of electricity in a Smart Grid context, High Voltage Direct Current is unequivocally superior to High Voltage Alternative Current (HVAC) [8]. Because of its economic, technical and environmental superiority, HVDC is presently the favored approach globally for long-distance electrical power dispatch[27]. HVDC technology is capable of:

- Laying the HVDC power lines under water bodies for offshore applications;
- Undergrounding the HVDC power lines in environmentally sensitive areas, valuable farm-land and urban high population areas;
- Using fewer conductors in the trasmission lines, and a smaller footprint than a comparable HVAC transmission infrastructure requires [8]
- Transferring larger amounts of power with lower line losses over long distances using 2 conductors for HVDC rather than three for HVAC lines;
- Damping power oscillations in an HVAC grid through fast modulation at the converter stations and thus improve the grid system stability;
- Complement existing HVAC networks without contribution to shortcircuit current power or additional reactive power requirements;

- Providing the system operators with direct control of the energy flows and managing the injection of intermittent wind power;
- Becoming cheaper for long distances (400/500km), because HVAC requires AC reactive power compensation stages.

Moreover the choice between AC and DC should be made according to the application. For instance, in [23] the following reasons are presented:

- In Itaipu, Brazil, HVDC was chosen to supply 50 Hz power into a 60 Hz system; and to economically transmit large amount of hydro power (6300 MW) over large distances (800 km).
- In Leyte-Luzon Project in Philippines, HVDC was chosen to enable supply of bulk geothermal power across an island interconnection, and to improve stability to the Manila AC network.
- In Rihand-Delhi Project in India, HVDC was chosen to transmit bulk (thermal) power (1500 MW) to Delhi, to ensure: minimum losses, least amount right-of-way, and better stability and control.
- In Garabi, an independent transmission project (ITP) transferring power from Argentina to Brazil, back-to-back HVDC was chosen to ensure supply of 50 Hz bulk (1000MW) power to a 60 Hz system under a 20-year power supply contract.
- In Gotland, Sweden, HVDC was chosen to connect a newly developed wind power site to the main city of Visby, taking into account the environmental sensitivity of the project area (an archaeological and tourist area) and power quality improvement.
- In Queensland, Australia, HVDC was chosen in an ITP to interconnect two independent grids (of New South Wales and Queensland) in order to: enable electricity trading between the two systems (including change of direction of power flow); ensure very low environmental impact, and reduce construction time.

About the cables, Fig. 3.4 shows a comparison between AC and DC cables capacity through long distances.

3.3 Configurations for HVDC tranmission systems

Leaving aside the chosen technology for converters or their topology, there are three main configurations for HVDC transimissions:

1. *Monopolar*
2. *Homopolar*
3. *Bipolar*

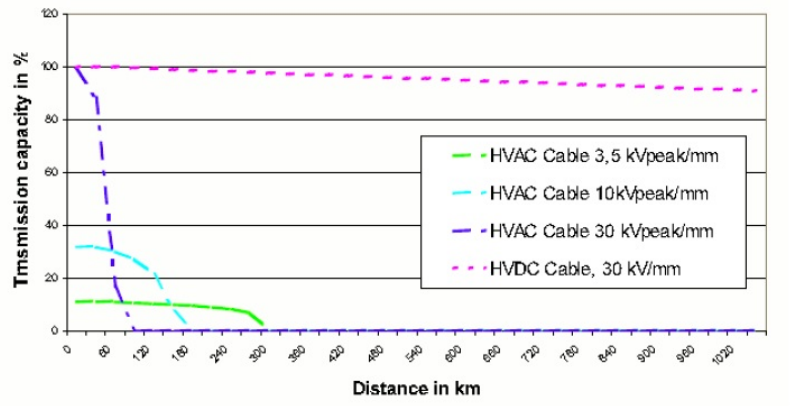
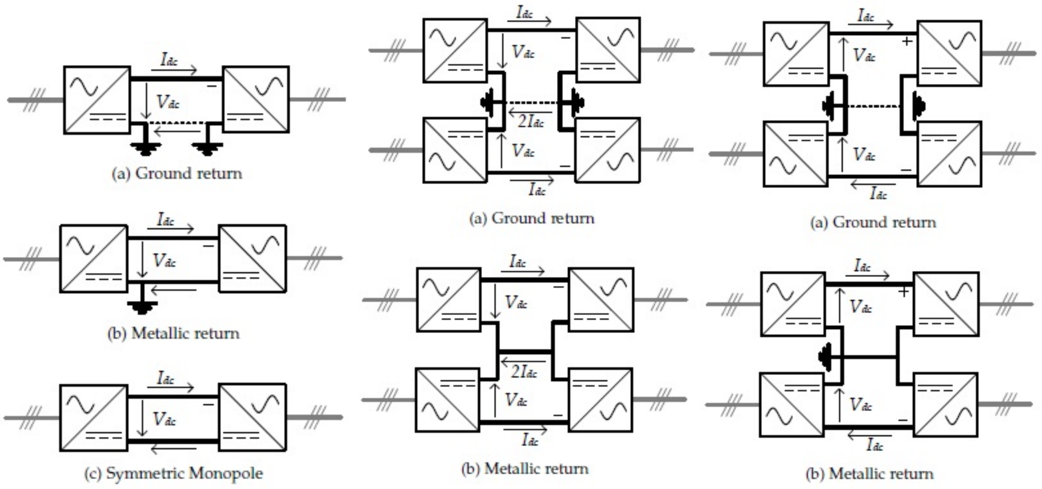


Figure 3.4: Comparison between AC and DC cables [20].

The *Monopolar* configuration consists in using just one cable of single polarity (often negative) as shown in Fig. 3.5*(a)*[1]. In the *Homopolar* one, two cables of the same polarity are used: this configuration reduces isolation costs because both conductors are identical, as can be seen in Fig. 3.5*(b)*. When the power to be transmitted is too high for a single cable capacity is wise to employ a *Bipolar* configuration: in this arrangement, differently from the homopolar, direct current can flow in opposite directions due to the fact that the cables have different polarity; this means that these last configuration is more expensive but sometimes it is necessary to transport a higher amount of power (Fig. 3.5*(c)*).



(a) *Monopolar Configuration.* (b) *Homopolar Configuration.* (c) *Bipolar Configuration.*

Figure 3.5: HVDC transmission configurations [26]

Another possible configuration is the *Back to Back* shown in Fig. 3.6, which is mainly used between asynchronous AC systems.

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[1] The source for all the figures of this section is [26]

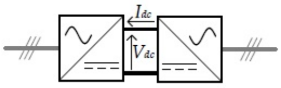


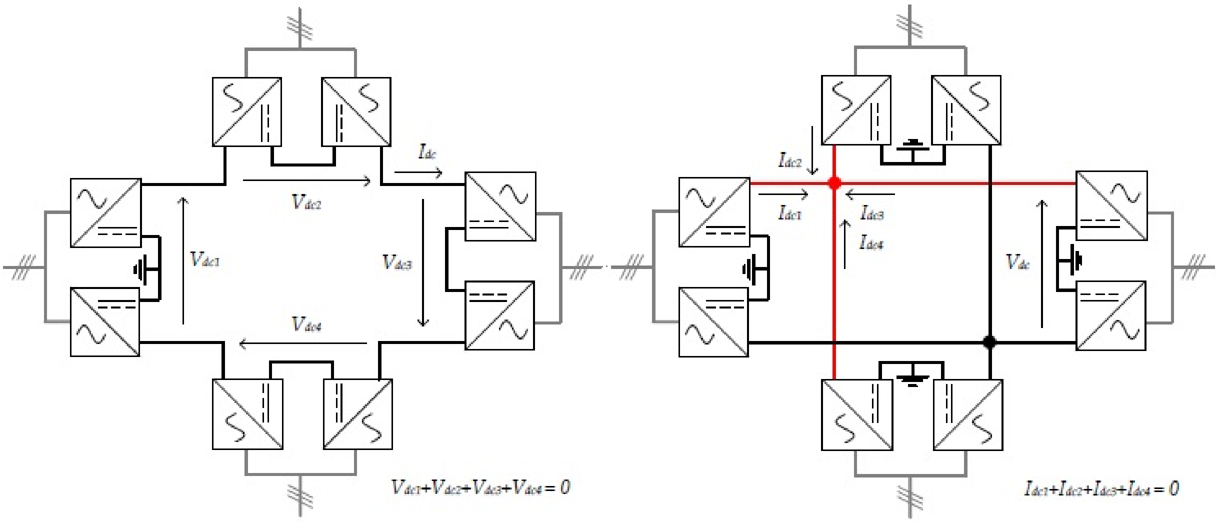
Figure 3.6: Back to Back configuration

3.3.1 Multi-terminal HVDC transmission systems Topology

With the development of converters technology, another arrangement for HVDC transmissions became interesting: multiterminal configurations. It consists in connecting more than two converter stations in order to form a multiterminal scheme like the one in Fig. 1.5. These stations can be connected in two main ways:

1. Series
2. Parallel

A series connected Multi-Terminal Direct Current (MTDC) network is shown in Fig. 3.7*(a)*.

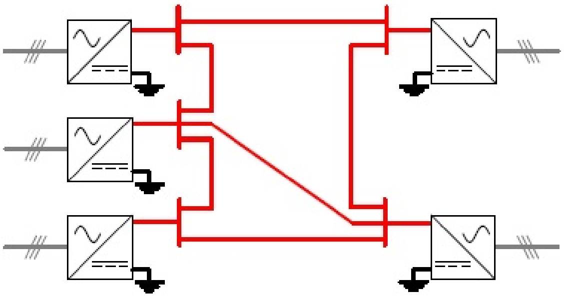


(a) *Series MTDC network* (b) *Parallel MTDC network*

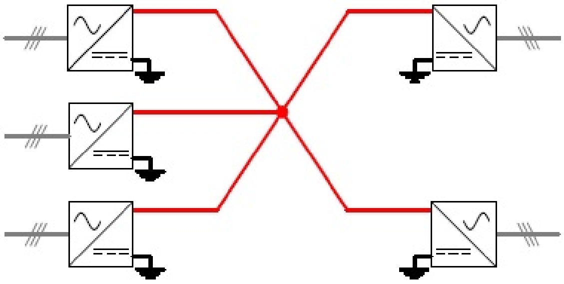
Figure 3.7: Network topologies

It is characterized by the fact that all the converters stations share the same direct current. Differently, in the parallel connected one, all the terminals share the same transmission direct voltage (Fig. 3.7)*(b)*. Referring to the parallel configuration, there can be two more forms: meshed and radial networks (see Fig. 3.8).

There are many differences between a series topology and a parallel topology. First of all, in the series case the power rating depends on the converter voltage rating, while in the parallel one it depends on the converter current rating; about the losses it is possible to say that parallel topology presents lower losses than series topology, while it is more difficult to isolate a series network than a parallel one; if a series connection gets affected by a fault, all the network becomes unavailable, while in the parallel case only the affected terminal becomes unavailable: this is why, until now, only parallel MTDC networks have been built.



(a) *Meshed MTDC network.*



(b) *Radial MTDC network.*

Figure 3.8: Meshed and Radial topologies.

3.4 Voltage Source Converters and Multi-terminal HVDC transmission systems

Since maintaining a constant DC voltage during all conditions is one expected and important feature of the MTDC, the thyristor based classical HVDC may not be a good candidate in developing MTDC. New converter topologies and lower priced fast-switching semiconductors have recently made it possible to build VSC-based HVDC transmission systems. The benefits of using VSC and fast switching are the ability to independently control the active and reactive power while reducing the size of the output filters needed to have a low harmonic distortion [32][11][7]. They present no commutation failure, black-start capability, and there is no need for voltage polarity reversal to reverse power. As additional advantages, the filters are more compact and the cables are lighter. On the other hand, the costs and the commutation losses are higher and they are able to handle only limited levels of voltage and power. Its characteristics make VSC an ideal component in constructing MTDC.

A schematic view of the converter is shown in Fig. 3.9. The series inductance on the AC side, also called AC reactor, smooths the sinusoidal current on the AC network and is also useful for providing the reference point for AC voltage, current and active and reactive power measurements. The shunt connected capacitors on the DC network side are used for DC voltage source and harmonic attenuation.

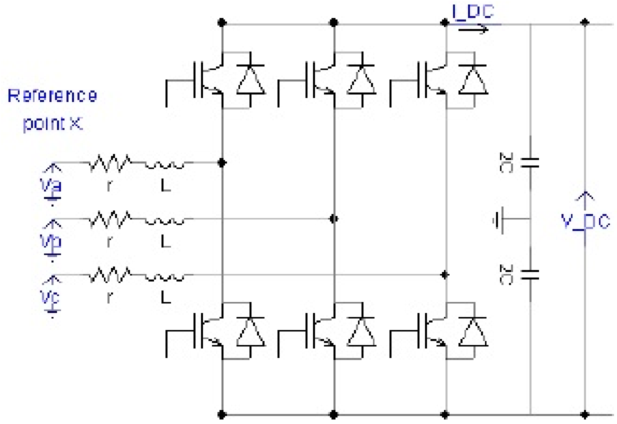


Figure 3.9: Voltage source converter scheme.

3.5 Model of a Multi-terminal VSC-HVDC Grid

A possible scheme of a Multi-terminal VSC-HVDC Grid terminal for offshore wind farms is the one shown in Fig. 3.10, while the whole nework can be depicted as in Fig. 1.5.

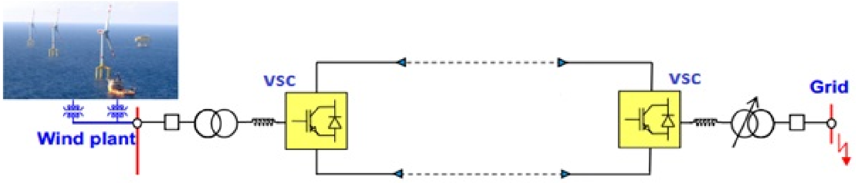


Figure 3.10: HVDC Terminal scheme.

In this work the VSC will be modeled as a current source in parallel with a capacitor [6] as in Fig. 3.11. In a complex network view, the VSCs are the nodes of the multi-terminal network. In this sense the subscript k in Fig. 3.11 is needed to specify that the *k-th* VSC node is being considered.

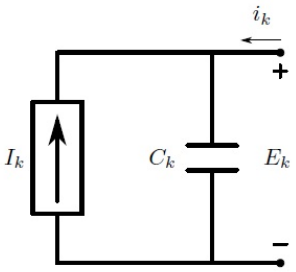


Figure 3.11: Equivalent circuit of a VSC [6].

The current in terminal k, I_k, takes positive values when power is being injected into the DC grid and negative values otherwise. A MTDC grid is a set of generating nodes and consuming nodes, which are both VSCs, therefore the current is considered positive for the first ones and negative for the second ones; changes of a node

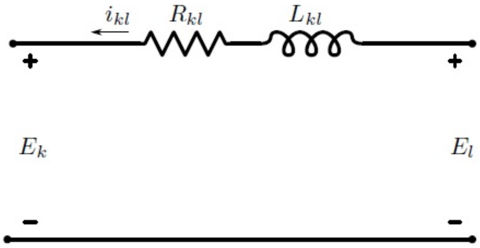


Figure 3.12: Equivalent circuit of a transmission line [6]

current sign are due to a change of role, which can be required for power balance [6]. The link between two nodes is assumed to consist of a resistor and an inductor, as depicted in Fig. 3.12. Applying Kirchhoff's laws at the circuit in Fig. 3.11 and assuming that the source current is a function of the node voltage like $I_k(E_k)$, the dynamics of each VSC is given by:

$$C_k \frac{dE}{dt} = I_k(E_k) + i_k, \tag{3.1}$$

where i_{kl} is the current flowing from node l to node k as in Fig. 3.12, and has the following expression:

$$i_k = \sum_{l=1}^{N} a_{kl} i_{kl}, \tag{3.2}$$

where a_{kl} is defined as in (2.7).

Now, applying the Kirchhoff's voltages law on the circuit in Fig. 3.12, it is possible to obtain the dynamics of a transmission line connecting nodes k and l:

$$E_l = E_k + R_{kl} i_{kl} + L_{kl} \frac{\mathrm{d} i_{kl}}{\mathrm{d}t}, \tag{3.3}$$

where R_{kl} and L_{kl} are respectively the resistance and inductance of each line, while $i_{kl} = -i_{lk}$ [6] [27]. In order to derive the model of the whole network is necessary to combine (3.1), (3.2) and (3.3), this yelding:

$$C_k \frac{dE}{dt} = I_k(E_k) + \sum_{l=1}^{N} a_{kl} \frac{1}{R_{kl}} \left(E_l - E_k - L_{kl} \frac{\mathrm{d} i_{kl}}{\mathrm{d}t} \right), \tag{3.4}$$

which is the *voltage form model.* Denoting E^* as the desired voltage, different for each node so as to allow power flow, and defining the error gap as:

$$e_k = E_k - E_k^*, \tag{3.5}$$

equation (3.4) becomes:

$$C_k \frac{\mathrm{d}e}{\mathrm{d}t} = I_k(E_k) + \sum_{l=1}^{N} \frac{e_l - e_k}{R_{kl}} + \sum_{l=1}^{N} \frac{E_l^* - E_k^*}{R_{kl}} - \sum_{l=1}^{N} \frac{L_{kl}}{R_{kl}} \frac{\mathrm{d} i_{kl}}{\mathrm{d}t}. \tag{3.6}$$

Equation (3.6) will be called *error form model.* In this work only resistive networks will be considered so the final model of the generic HVDC transmission line boils down to:

$$C_k \frac{\mathrm{d}e}{\mathrm{d}t} = I_k(E_k) - \sum_{l=1}^{N} \frac{e_k - e_l}{R_{kl}} - \sum_{l=1}^{N} \frac{E_k^* - E_l^*}{R_{kl}}. \tag{3.7}$$

To extend the model to the whole network, it is necessary to define:

- The current vector $\mathbf{I} = [I_1, \ldots, I_N]^T$.
- The error vector $\mathbf{e} = [e_1, \ldots, e_N]^T$.
- The reference vector $\mathbf{E}^* = [E_1^*, \ldots, E_N^*]^T$.
- The diagonal matrix for the capacities $C = diag[C_1, \ldots, C_N]$.

Moreover, to obtain the correct weighted Laplacian matrix, expression (2.10) must be particularized as :

$$\hat{G} := (\hat{g}_{kl}),\ \hat{g}kl := \begin{cases} -g_{kl} = \frac{1}{R_{kl}}\ ,\ k \neq l, \\ \sum_{\substack{l=1 \\ l\neq k}}^{N} |\hat{g}_{kl}|\ ,\ k = l. \end{cases} \tag{3.8}$$

that, as a laplacian, $\hat{G}$ is positive semidefinite. Therefore, the complete error model in matrix form becomes:

$$C\dot{\mathbf{e}} = \mathbf{I}(\mathbf{e}) - \hat{G}\mathbf{e} - \hat{G}\mathbf{E}^*. \tag{3.9}$$

3.6 Control Problem

The control of a power network should consist of three main stages:

- Low level control: keeping voltages in a certain zone or making them follow a certain reference;
- Medium level control: optimising energy flows by an appropriate setting of voltage and current references ;
- High level control: handling faults and network communication issues.

Inside a VSC-MTDC network, direct voltage control is certainly one of the most important tasks given to VSC-HVdc stations. A well-controlled direct voltage on a HVDC grid requires a balanced power flow between all the interconnected nodes [26]. If the DC system voltage starts to increase excessively, it may trigger protective equipment, such as dump resistors. On the other hand, a large direct voltage drop might generate nonlinear phenomena, creating difficulties for the control systems, limiting the capability of the reactive power and ac system voltage controllers. In point-to-point HVdc transmission systems the control is typically arranged so that one terminal controls the DC-link voltage while the other operates in current – or power – regulation mode. This control philosophy of having only one converter controlling the direct voltage can be extended to MTdc networks. However, disregarding losses, the net sum of the active power of all the converters operating in current regulation mode has to be, at all times, lower than the maximum ratings of the direct-voltage controlling station. As MTDC network grows it is increasingly difficult to assure power balance by having only one terminal responsible for the direct voltage regulation. Thus, for large MTDC networks, controlling the voltage at a single terminal is not desirable. Therefore, for its successful development and operation, MTDC networks will require a control strategy capable of sharing the direct voltage control among more than one network node.

This work is focused on the Low level control and two main strategies will be described in chapters 5 and 6:

1. *Local control strategy*, which is based on Droop control, with the objective of keeping voltages and currents in precise ranges, acting on each single node;
2. *Global control strategy*, which is based on a global PID strategy, with the aim of regulate the voltages by sending the errors to zero and applying consensus theory.

Further details will be given in the following chapters.

Chapter 4

Case example: the North Seas Transnational Grid

4.1 The project of a european Supergrid

The Supergrid is defined as “a pan-European transmission network facilitating the integration of large-scale renewable energy and the balancing and transportation of electricity with the aim of improving the European market”. The Supergrid is not just an extension of existing or planned point to point HVDC interconnectors between particular EU states.

Figure 4.1: Onshore plant

The Supergrid part in the North Sea will involve the creation of “Super Nodes” in order to collect, integrate and route energy sources to the best available markets while ensuring the same level of security as existing High Voltage networks as well as the maximum utilisation of those.

The Supergrid will:

- Help to meet EU and national plans to decarbonise Europe’s power sector: 20% by 2020 and 90% by 2050.
- Integrate all renewable energy into the continent’s energy mix. RES are not national resources but continental by their nature.
- Bring these renewable resources to load centres across Europe over long distances.

- Balance Europe's electricity network and enhance security of supply.
- Create a global opportunity for European companies to export sustainable energy technology and create new highly skilled jobs .
- Enhance the single European electricity market.

The concept of a european supergrid is fascinating and not to far from reality for what concerns technical aspects. In fact, the main issues facing the implementation of the grid are non-technical but legislative. The critical timeline for the introduction of new technology lies primarily in the solution of non-technical issues that will create a strong market growth and a technology push. An early solution of these hurdles will influence the future roadmap to a greater extent than may be foreseen, due to the extended time constraints in planning and construction of new transmission capacity. As it is easy to imagine, many new norms should be produced by governments to tutelate energy consumption and distribution and new organs should be created to overcome this heavy work. Since any Country would pursue its own objectives, supergrid is something uthopistic: when the lack of fossil fuels becomes a reality Europe will be forced to make something similar to the supergrid happen.

4.2 The North Sea Transnational Grid Project

Besides the Supergrid, there is a smaller but not less ambitious project regarding the North Sea area: The North Sea Transnational Grid Project (NSTGP).

The NSTGP, which will be taken as study case in this work, is a project involving five countries [18]. Its main objective is to determine the best solution (modular, flexible, most cost effective) for a high capacity transnational offshore grid, connecting all future wind farms in the northern part of the North Sea to the Netherlands, UK, Norway, Denmark and Germany. The NSTG project aims to identify and study technical and economic aspects with regard to the development of a transnational electricity network in the North Sea for the connection of offshore wind power and trade between countries. The project is jointly executed by the Energy Research Centre of the Netherlands and the Delft University of Technology and it started in October 2009. The project is particularly focused on:

- Determinating the optimal offshore grid configuration;
- Coordinating grid expansion plan;
- Evaluating the socio-economic consequences;

To achieve these objectives, the project is subdivided in the following specific subtasks:

- Inventory of available technologies;
- Technical and economic evaluation of different topology alternatives;
- Operation and control of a multi-terminal grid with different kinds of technologies;
- Real-time multi-terminal converter simulation and testing;

- Optimization of NSTG solutions
- Grid planning, congestion management, and stability evaluation;
- Costs, benefits, regulations, and market aspects of the NSTG and connection alternatives;

The NSTG research project is coordinated by the Energy Research Centre of the Netherlands.

4.3 Network Architecture

Before describing the network topology that will be taken as study case by this work, the reasons of the need of a specific kind of structure are explained in the subsection below.

4.3.1 System Design

It is very important to choose the most functional architeture from the beginning for large scale projects such as the NSTG one. A possible definition of system architecture is given by Ulrich [31]:

> System architecture is the scheme by which the function of a system is allocated to physical components.

Therefore, system architecture can be seen as the way how components inside a system interact and interface with each other [26]. There are two main types of system architecture:

1. Integrated
2. Modular

An integrated designed system generally accomplishes to maximise a certain performance mesure but, on the other side, modifications to one feature or component may affect the whole system design. Observing the objectives of the NSTGP within its complexity, it is easy to imagine that an integrated architecture would not be the best solution to provide development and changes to the stations already built in the northern area: redesign the whole would be the only chance to adopt an integrated architecture. Hence, a modular solution seems to be the most suitable choice [18]. Modularity can be seen as [5]:

> The practice of building complex systems or processes from smaller subsystems that can be designed independently yet function together as a whole.

The main feature of a modular system is certainly that each module can be designed independently, so this is the main reason why changes made in one module will not affect the whole system.

As a modular project, the NSTG needs to set global design rules an local design rules, as shown in Fig. 4.2[26].

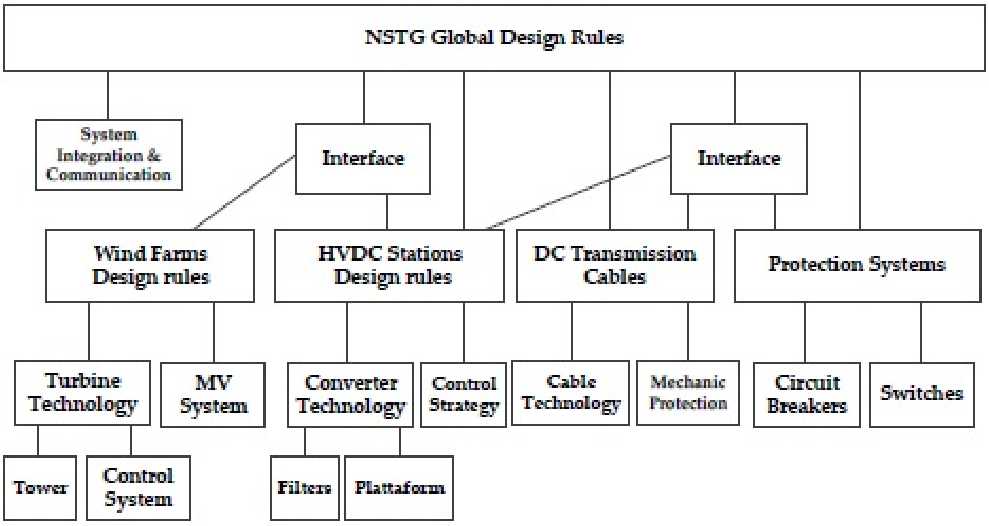


Figure 4.2: Design rules for the NSTG.

Before the development of such a complex system, system engineers should estabilish and take global designing rules into consideration. Proper development of the system global design rules can lead to dc grid code standards which could reduce costs by having a single common design, allowing systems to be built incrementally and by different suppliers, thus supporting incremental investment plans. In this way, a large pan-European offshore dc network would be developed "organically". First by the construction of a few small independent dc grids with four to six terminals that, in a later stage, would be combined to form together a larger offshore network with a more complex topology, such as a meshed multi-terminal dc network. Some stages of the possible evolution of the NTSG are shown in Fig. 4.3 [25].

4.3.2 Study Case

In order to study and test control strategies for Multi-terminal HVDC transmission lines, a 19-node meshed grid, corresponding to the third evolution stage of the NSTG, has been taken as an example. The network architecture is shown in Fig. 4.4 [30]

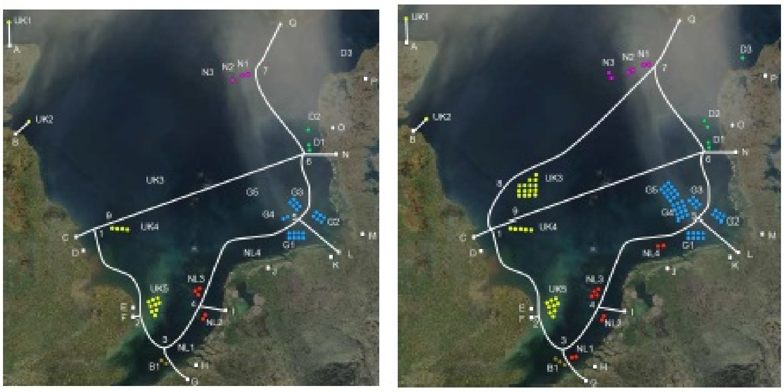
The network layout contains the five European countries with the highest expected installed offshore capacity: UK, Denmark (DN), Germany (DE), Netherlands (NL), and Belgium (BE). It is made of 19 DC nodes and 19 DC transmission lines whose parameters are displayed in Tab. 4.1.

Quantity	Value
Maximum Power P_{max}	150 MW
Maximum Voltage E_{max}	150 kV
Cable resistance R	0.02Ω/km

Table 4.1: Essential network parameters.

In the example network, nodes are constituted by two types VSCs, denoted as:

(a) *Phase 1.* (b) *Phase 2.*



(c) *Phase 3.* (d) *Phase 4.*

Figure 4.3: NSTG possible evolution.

- *Grid Side Converters (GSC)*: those placed on the mainland;
- *Wind Farm Converters (WFC)*: those placed off-shore.

Grid side and wind farm nodes are described in Table 4.2.

Wind Farm	Node	Grid Side	Node
Doggersbank	UK1	England	UK
Hornsea	UK2	Belgium	BE
Thortonbank	BE1	Netherlands	NL
Ijmuiden	NL1	Germany	DE
Eemshaven	NL2	Denmark	DK
Hochsee Sud	DE1		
Hochsee Nord	DE2		
Horns Rev	DK1		
Ringcobing	DK2		

Table 4.2: WFCs description.

In this study case all the nodes are supposed to consume/produce their maximum power. Moreover, since the network is heterogeneous, the agents are characterized by having differents values of capacities and desired voltages as shown Tab. 4.3.

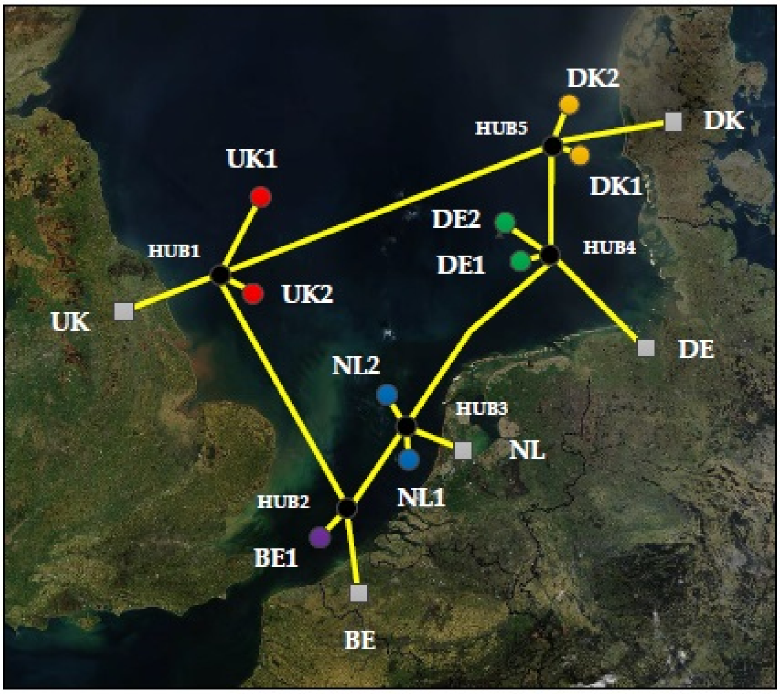


Figure 4.4: Study case.

Agent	Type	Capacity C_k	Power P_k^{max}	Reference E_k^*
UK1	WF	200 mF	140 MW	150 kV
UK2	WF	100 mF	150 MW	150 kV
UK	GS	100 mF	100 MW	145 kV
BE1	WF	140 mF	120 MW	150 kV
BE	GS	150 mF	100 MW	145 kV
NL1	WF	150 mF	130 MW	150 kV
NL2	WF	140 mF	140 MW	150 kV
NL	GS	200 mF	100 MW	145 kV
DE1	WF	100 mF	130 MW	150 kV
DE2	WF	200 mF	120 MW	150 kV
DE	GS	150 mF	100 MW	145 kV
DK1	WF	140 mF	140 MW	150 kV
DK2	WF	100 mF	140 MW	150 kV
DK	GS	150 mF	100 MW	145 kV

Table 4.3: Agents parameters.

Transmission lines lenght are given in Table 4.4.

Line Start	Line End	Lenght [km]	Resistance Ω
UK1	HUB1	100	2.0
UK2	HUB1	40	0.8
UK	HUB1	120	2.4
HUB1	HUB2	300	6.0
BE1	HUB2	50	1.0
BE	HUB2	100	2.0
HUB2	HUB3	120	2.4
NL1	HUB3	100	2.0
NL2	HUB3	40	0.8
NL	HUB3	70	1.4
HUB3	HUB4	250	5.0
DE1	HUB4	40	0.8
DE2	HUB4	70	1.4
DE	HUB4	150	3.0
HUB4	HUB5	120	2.4
DK1	HUB5	40	0.8
DK2	HUB5	50	1.0
DK	HUB5	150	3.0
HUB1	HUB5	380	7.6

Table 4.4: Network transmissions lenght.

In order to apply both Local and Global control strategies, there cannot be star nodes such as HUB1, HUB2, HUB3, HUB4 and HUB5 in the network. It is possible to obtain an equivalent network without hubs using Rosen's Theorem.

Ronsen's Theorem and Equivalent Network

Given a network with star nodes, Rosen's theorem allows to find a mesh equivalent network where all the nodes are connected to each other. Rosen's tranformation is graphically shown in Fig. 4.5 [28].

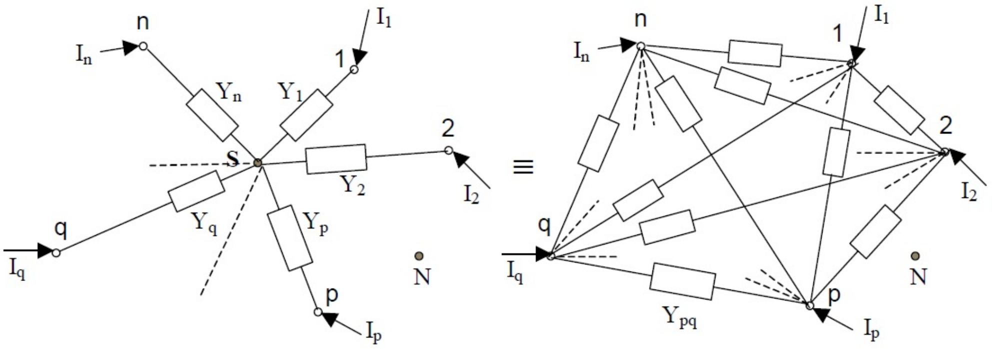


Figure 4.5: Application of Rosen's Theorem

Theorem 3 (Nodal-Mesh Transformation Theorem)**.** *For any network with N nodes connected to a single node in a star fashion, with* Y_1,Y_2,...,Y_N *being the conductances* *of each branch, it is possible to find a mesh equivalent circuit where all the nodes are connected to each other, and with conduntances given by:*

$$Y_{pq} = \frac{Y_p Y_q}{\sum_{k=1}^{N} Y_k} \tag{4.1}$$

Therefore, from now on the network to be considered is shown in Fig. 4.6 and :

1. It is meshed (not nodal);
2. It has all the nodes connected to each other;
3. The equivalent conductances of the transmission lines have been obtained using (4.1).

A program that automatically calculates Rosen's conductances has been written with MATLAB and it is presented in the appendix.

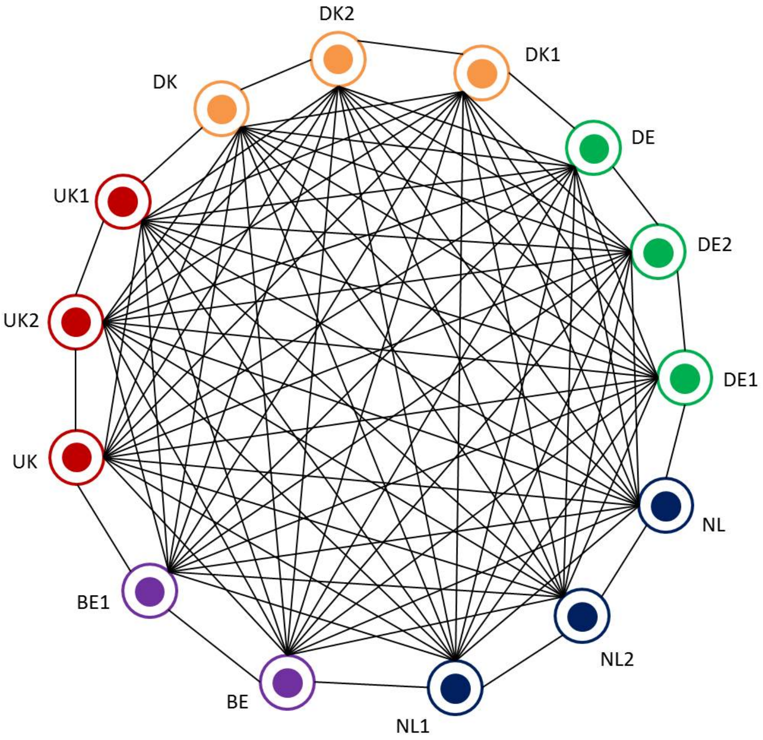


Figure 4.6: Study case network.

Chapter 5

Local Control

In this chapter the main results about local control strategy for the network described in 4.3.2 are presented. The first section will be focused on the Droop Control technique, which is a classical control approach to HVDC transmission lines, while the second will be about Droop control, in fact a proportional control, plus integral and derivative actions.

5.1 Droop Control

The idea of the Droop Control strategy is to achieve DC voltage regulation using a decentralized approach, designed to allow proper transmission of the generated power from the WFCs to the GSCs, while maintaining the voltage of the HVDC in a safe range of operation [1]. The droop controller is a proportional control law, that regulates the DC voltage and provides power sharing between the different power converters [10]. The conventional droop controller is a heuristic based on physical intuition gleaned from the study of high voltage Wide Area Electric Power System (WAEPS), and at its core relies on the decoupling of active and reactive power for small power angles and non-mixed line conditions [27].

Droop control consists in a nonlinear static relationship between the current provided by the VSC, I_k, and the voltage across each capacitor, E_k [6]. Its objective is to maintain the characteristic $\Phi_k^E := (E_k, I(E_k))$ inside an admissibility region which depends on the nature of the node, as can be seen in Fig. 5.1. The grey zone represents the admissibility region while the blue and red curves represent its limits and also the desired working mode to maximize power exploitation.

Droop control can be seen as an algorithm such as:

$$I_k = \begin{cases} I_k^{max} & \text{if } E_k \leq P_{kI}/I_k^{max} \\ \frac{P_{kI}}{E_k} & \text{if } P_{kI}/I_k^{max} < E_k < E_k^l \\ -m_k^d(E_k - E_k^*) & \text{if } E_k^l < E_k < E_k^h \\ \frac{P_{kC}}{E_k} & \text{if } E_k^l < E_k \end{cases} \tag{5.1}$$

Let us define the entites in (5.1):

- I_k^{max} is the maximum current that is able to flow trough the node k. It is the same for all the VSCs and it is equal to 1kA.
- $-m_k^d$ is the control proportional gain.

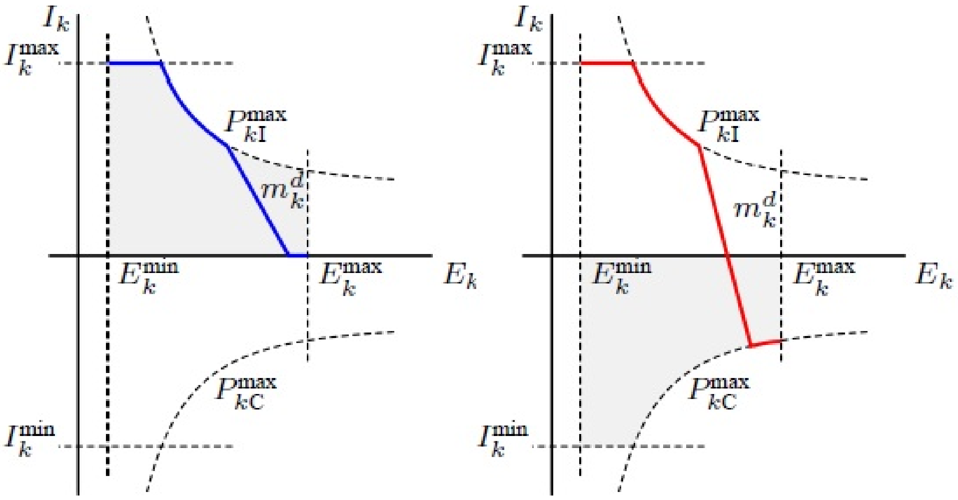


Figure 5.1: Droop Control Curves [6]

- P_{kI} is the power injected by the *k-th* WFC.
- P_{kC} is the power consumed by the *k-th* GSC.
- E_k^l is the lower limit of the droop zone for the node k.
- E_k^h is the higher limit of the droop zone for the node k.
- E_k is the voltage of the node k.

E_k^l and E_k^h define the droop operational mode dimension. In fact, a network can operate in:

1. *Normal* operation mode: when the characteristic $\Phi_k^E := (E_k, I(E_k))$ belongs to the semi-hyperbolic region, as can be seen in Fig. 5.1.
2. *Droop* operation mode: when the characteristic $\Phi_k^E := (E_k, I(E_k))$ follows the straight line with slope $-m_k^d$ and the droop control is active.

E_k^l and E_k^h can be obtained as [6]:

$$E_k^l = \frac{1}{2}\left(E_k^* + \sqrt{(E_k^*)^2 - 4\frac{P_{kI}}{m_k}}\right) \tag{5.2}$$

$$E_k^h = \frac{1}{2}\left(E_k^* + \sqrt{(E_k^*)^2 - 4\frac{P_{kC}}{m_k}}\right) \tag{5.3}$$

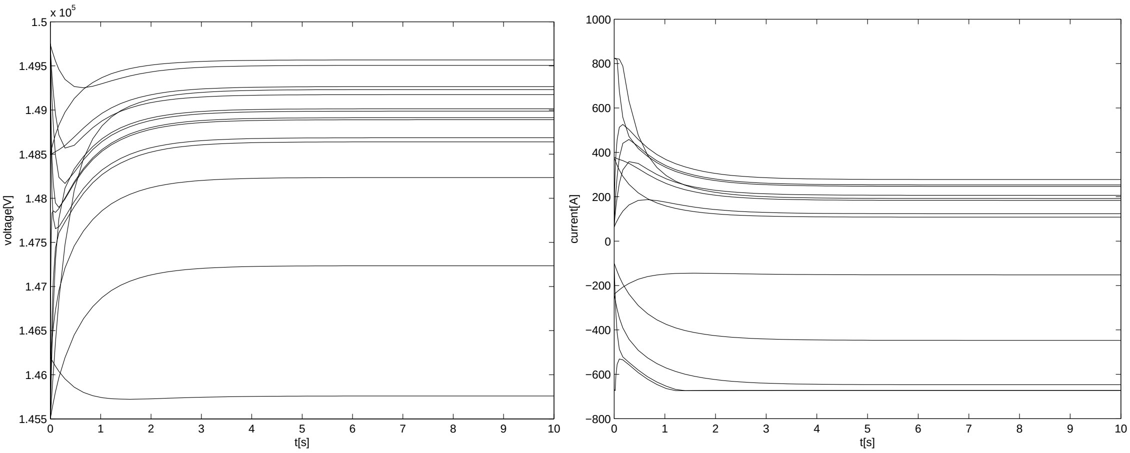
It is important to notice that the power is assumed to be:

- $P_{kC} = -P_k^{max}$ for the GSCs;
- $P_{kI} = P_k^{max}$ for the WFCs.

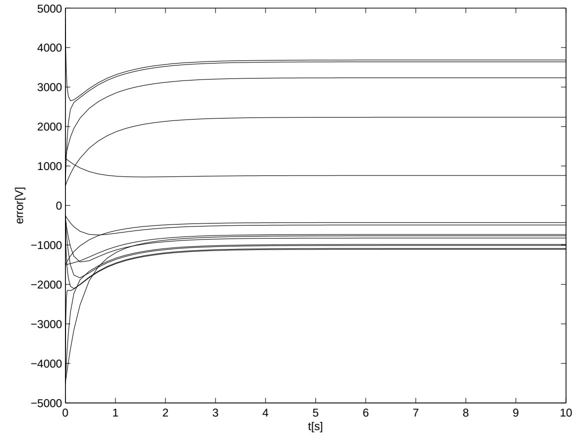
Moreover the consumed power is assumed to be 0 for the WFCs so their E_k^h coincides with E_k^*.

Simulations

The system described in section 4.3.2 has been simulated using MATLAB/Simulink. The first simulation refers to the system in regularl conditions, with constant power P^{max} as defined in last section. The results can be seen in Fig. 5.2.



(a) *Voltages.* (b) *Capacitors Currents.*



(c) *Error.*

Figure 5.2: Droop control: regular operation

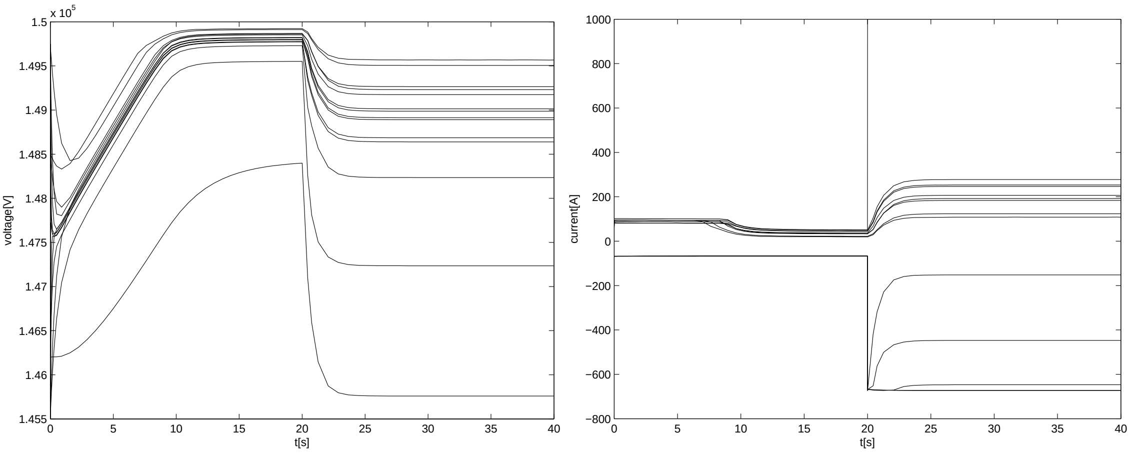
In the second simulation at $t = 20s$ the power P^{max} decreases by ten times. It is possible to see in Fig. 5.3 and 5.2, that in both cases stability is preserved and both voltages and currents remain in the admissibility region. This is shown in Fig. 5.4 for two WFCs, UK1 and DK1, and two GSCs, UK and DK: voltages, powers and curents is maintained into the admissibility region.

5.2 PID Droop Control

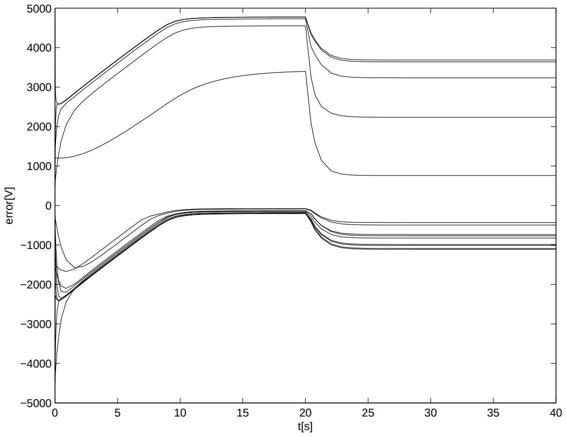
The PID droop control strategy replaces the conventional droop law (5.1) by:

$$I_k = -m_k^d(E_k(t) - E_k^*) - \beta \int (E_k(t) - E_k^*)dt - \gamma(\dot{E_k(t)} - E_k^*), \qquad (5.4)$$

with the necessary saturation in order to keep the system within the admissibility region. When integral and derivative actions are added, it is not possible to consider



(a) *Voltages.* (b) *Capacitors Currents.*



(c) *Error.*

Figure 5.3: Droop control: power decrease at $t = 20s$

the same saturation used in the previous section because E_k^l and E_k^h depend only on the proportional gain. Therefore, to be able to employ the integral action, a current saturation like the one in Fig. 5.5 has been used.

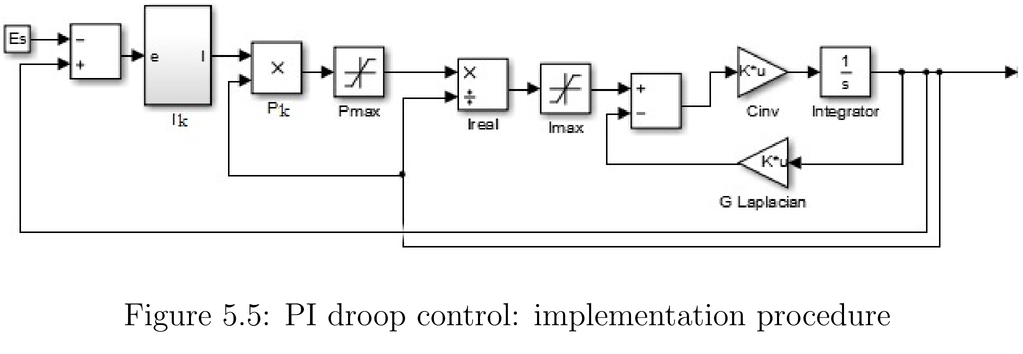
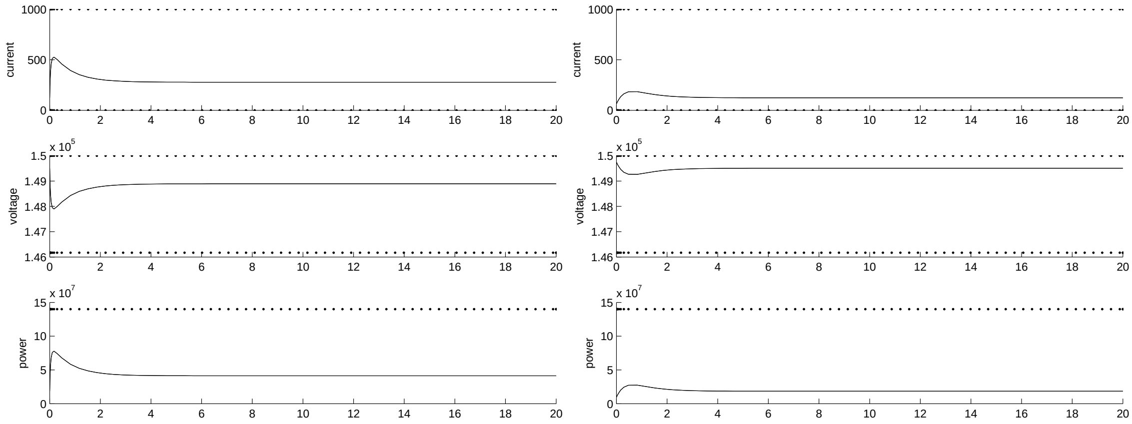
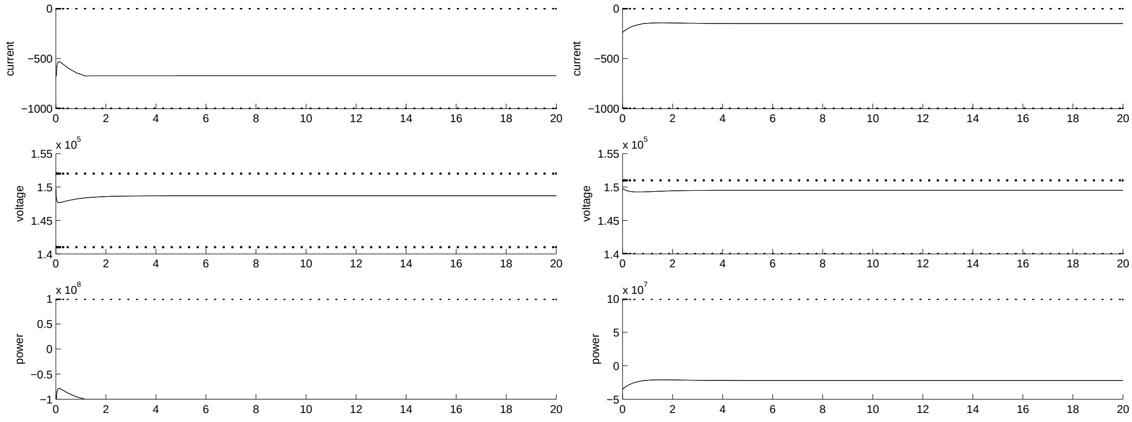


Figure 5.5: PI droop control: implementation procedure

As can be seen in Fig. 5.5, the control block produces the current I_k, which would be needed to make the error tend to zero. Multiplying it out by the actual network voltage E_k, one gets the required power, P_k. Since the control objective is to maintain currents and voltages in the admissibility region, and the network is not able to provide more than 200 MW, a power saturation is employed to avoid an



(a) *UK1.* (b) *DK1.*



(c) *UK.* (d) *DK.*

Figure 5.4: Droop control under regular operation: evolution of the curves within the admissibility region.

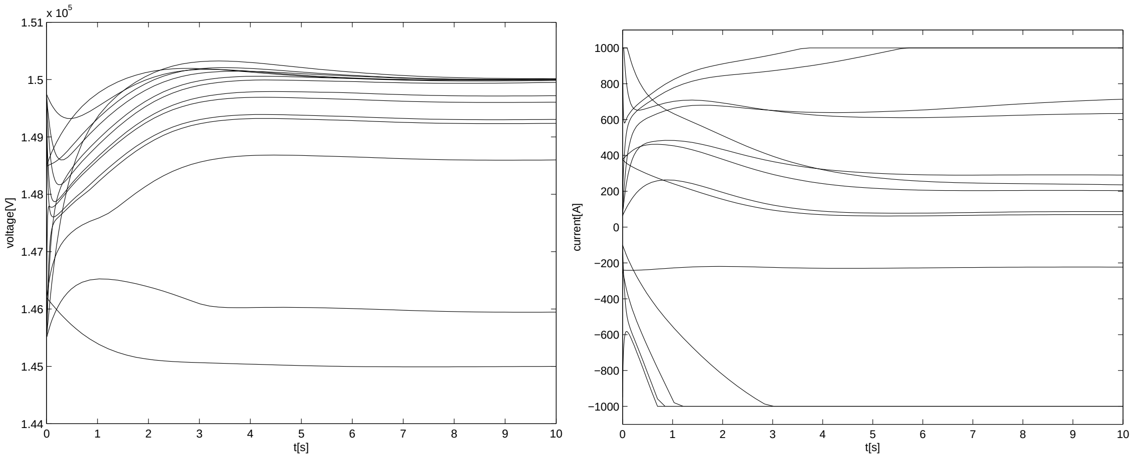
excessive power flow. After this step, dividing the *real power*, P_k^r, obtained by means of saturation, by the voltage E_k, one calculates the *real control current*, I_k^r, that can flow through the network without causing an excessive power flow. However, as I_k^r could be higher than I^{max} or lower than I^{min}, a current saturation is applied to obtain the current actually delivered to the system, I_k^f.

Simulations

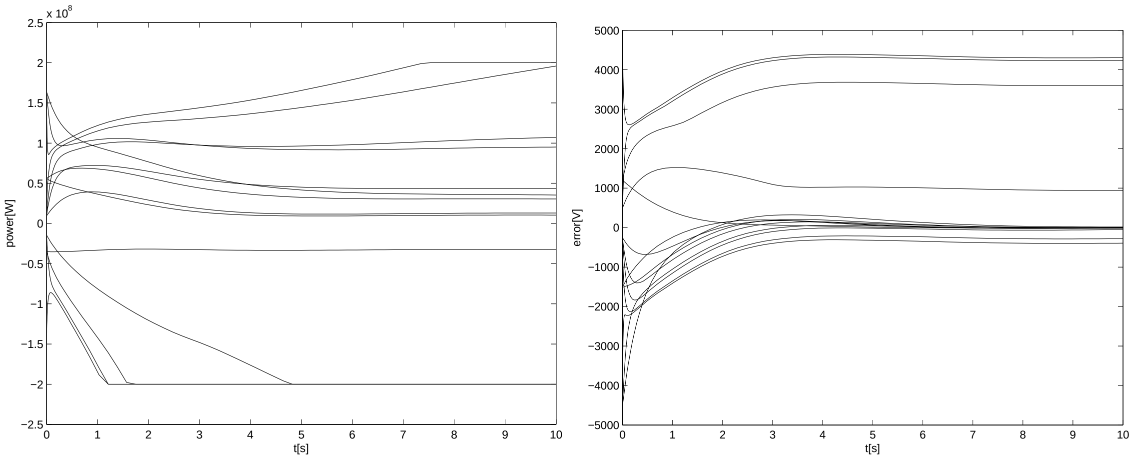
The first simulation, shown in Fig. 5.6, has been made using an integral gain $\beta = m^d$ which is 0.25 for the WFCs and 0.20 for the GSCs and $\gamma = 0$. In order to see how the system reacts when β tends to one, the second simulation has been made varying the integral gain as can be seen in Fig. 5.7. Considering Table 5.1, it is possible to notice that, as the gain grows the system dynamics is faster and the error decreases but there is a visible current overshoot which means an higher control effort.

Adding a derivative action with gain $\gamma = 0.1$ and setting $\beta = 0.6$, the system dynamics is shown in Fig. 5.8.

According to Fig. 5.9 it is possible to say that the derivative action does not bring any improvement to the system behaviour, in fact, the dynamics becomes a little slower and a small undershoot appears without any consistent error reduction. All



(a) *Voltages.* (b) *Capacitors Currents.*



(c) *Power.* (d) *Error.*

Figure 5.6: PI droop control under regular operation

the previous versions have proved to be stable and evolving within the admissibility region. Fig. 5.10 shows this feature to the nodes UK1, DK1, UK and DK evolve inside their admissibility region.

5.3 Conclusions and Comparisons

To conclude, a comparison between the two control techniques described in the previous sections is given. Since the derivative action does not provide any significant improvement, the comparison will be made considering the traditional Droop control law and the PI control law, obtained considering (5.4) with $\gamma = 0$.

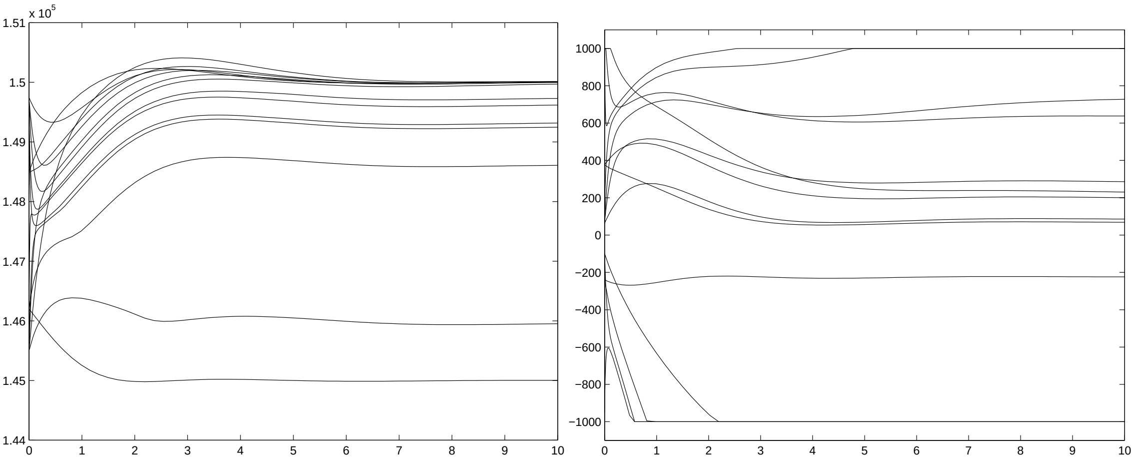
The first comparison shows the differences between the two strategies when the network is operating with constant power flow, the results can be seen in Fig. 5.11. The most relevant thing is that the Droop currents are in average lower than PI currents, so the required control effort is lower in the first case. Neverthless, as Fig. 5.11*(e),(f)* show, more nodes are able to reach exactly their reference with PI control and, the error is generally lower in this case.

The second comparison has been made considering a power reduction of ten times P^{max}, Fig. 5.12. It is clear that the network controlled by simple Droop reacts better

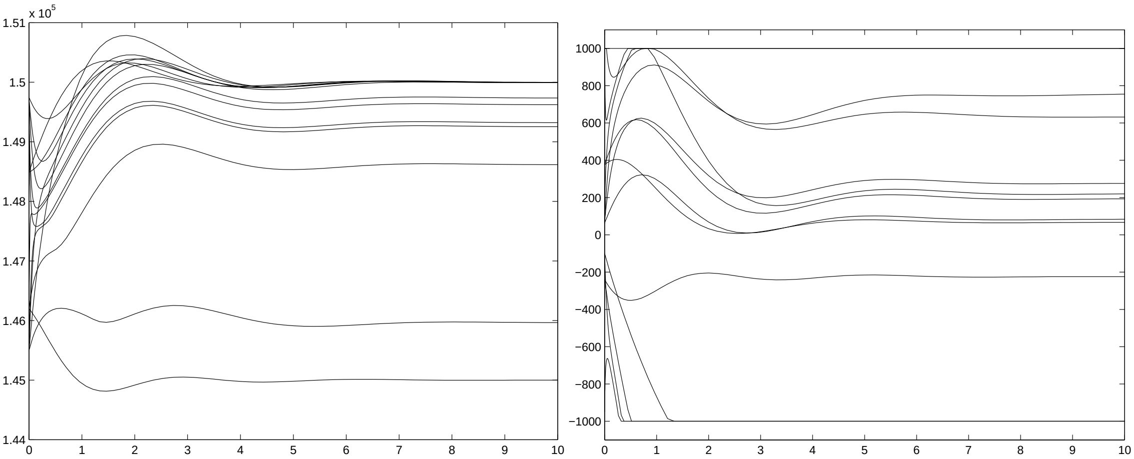
$\beta = 0.3$	$\beta = 0.6$	$\beta = 0.9$
$10^{-}4\times$		
-0.0531	-0.0518	-0.0507
-0.0753	-0.0739	-0.0728
0.8493	0.8476	0.8467
-0.0005	-0.0001	0.0005
0.8357	0.8341	0.8332
-0.0059	-0.0015	0.0001
0.0015	-0.0005	0.0003
0.7101	0.7092	0.7085
0.0016	-0.0004	0.0003
0.0027	-0.0006	0.0004
0.1874	0.1892	0.1892
0.0008	-0.0003	0.0002
0.0007	-0.0002	0.0001
0.0006	0.0000	-0.0000

Table 5.1: Squared 2-norm error.

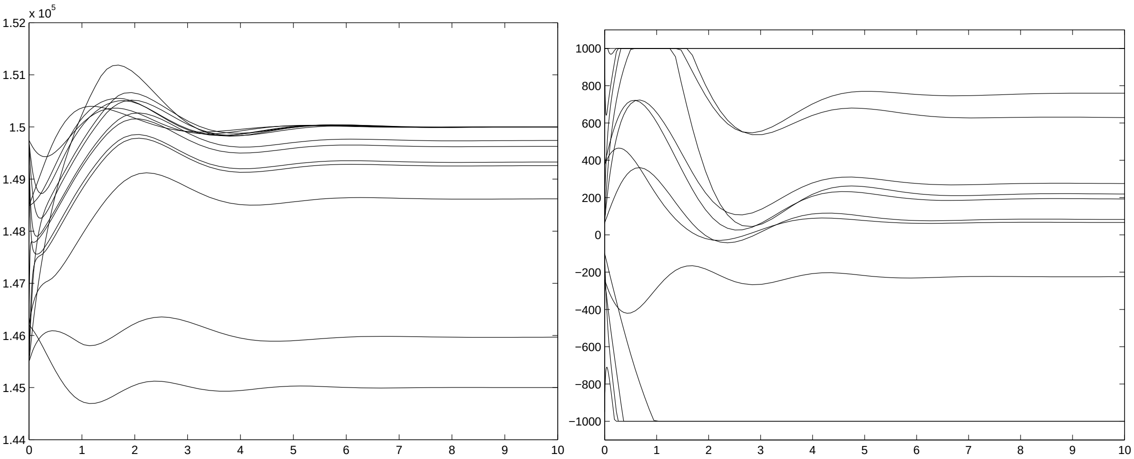
to this kind of disturbance. In fact, the reaction is almost instantaneous while, in PI control case, the system takes around ten seconds to reach the equilibrium again.



(a) *Voltages with* $\beta = 0.3$. (b) *Currents with* $\beta = 0.3$.

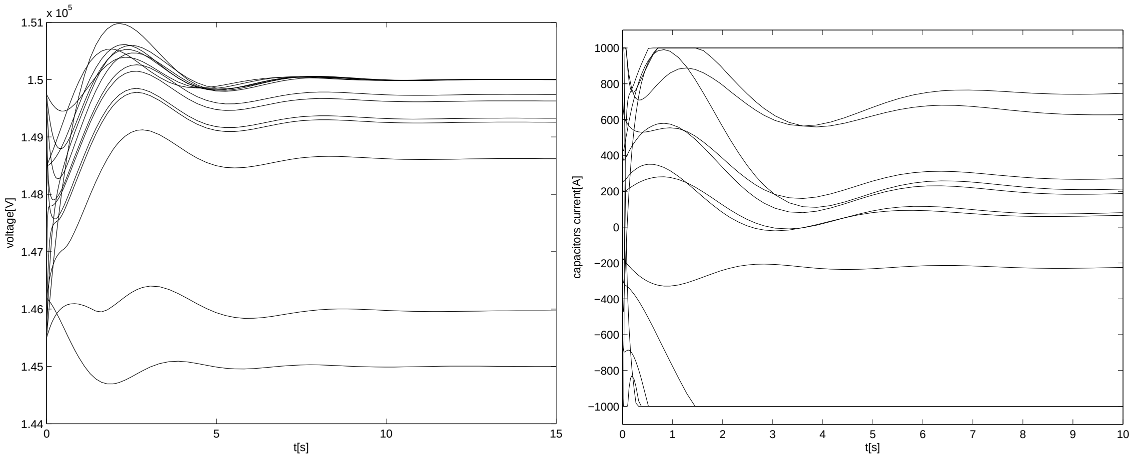


(c) *Voltages with* $\beta = 0.6$. (d) *Currents with* $\beta = 0.6$.

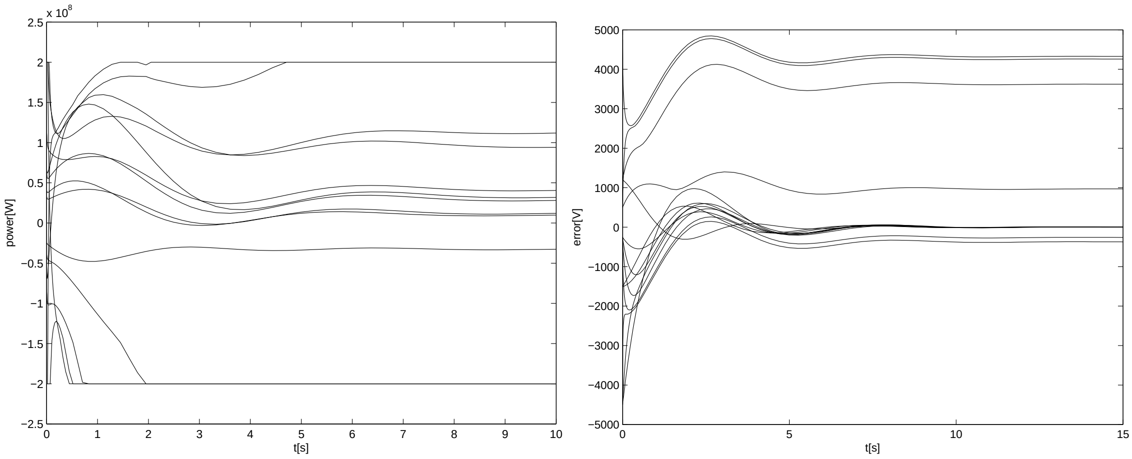


(e) *Voltages with* $\beta = 0.9$. (f) *Currents with* $\beta = 0.9$.

Figure 5.7: PI droop control regular operation: dynamics with different values of β

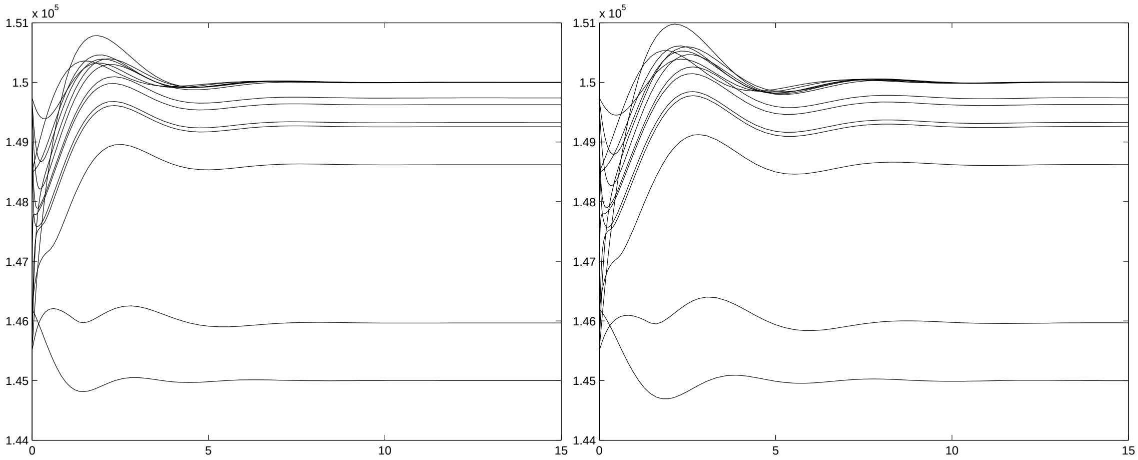


(a) *Voltages.* (b) *Capacitors Currents.*

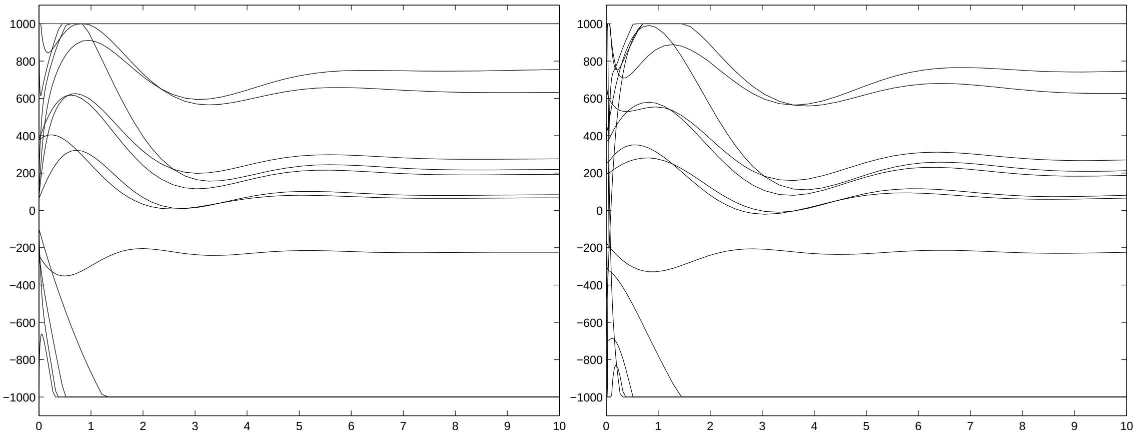


(c) *Power.* (d) *Error.*

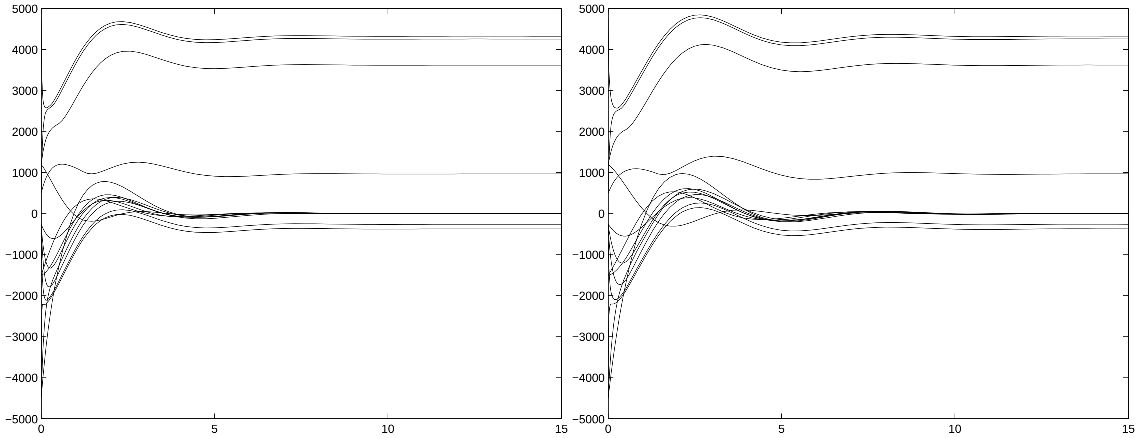
Figure 5.8: PID droop control regular operation



(a) *Voltages with PI* (b) *Voltages with PID*

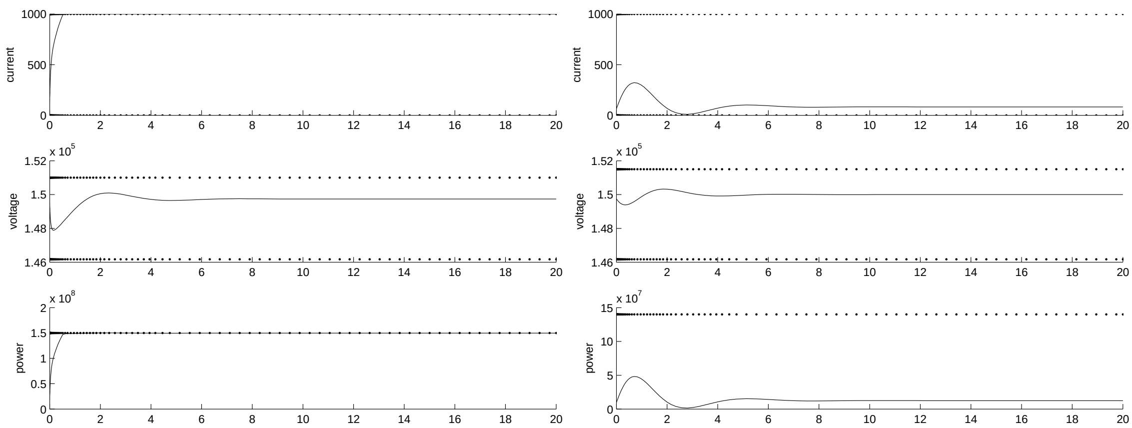


(c) *Currents with PI* (d) *Currents with PID.*

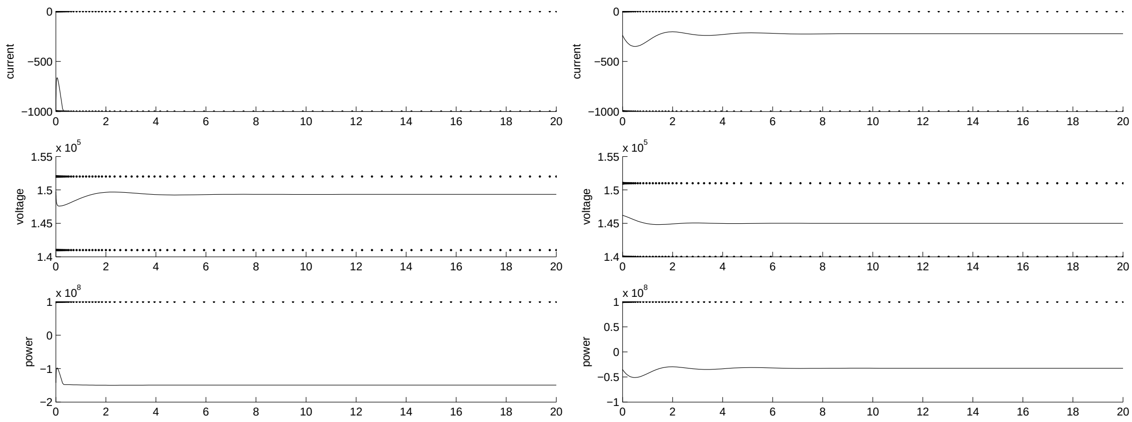


(e) *Errors with PI* (f) *Errors with PID*

Figure 5.9: PID droop control: comparison between PI and PID

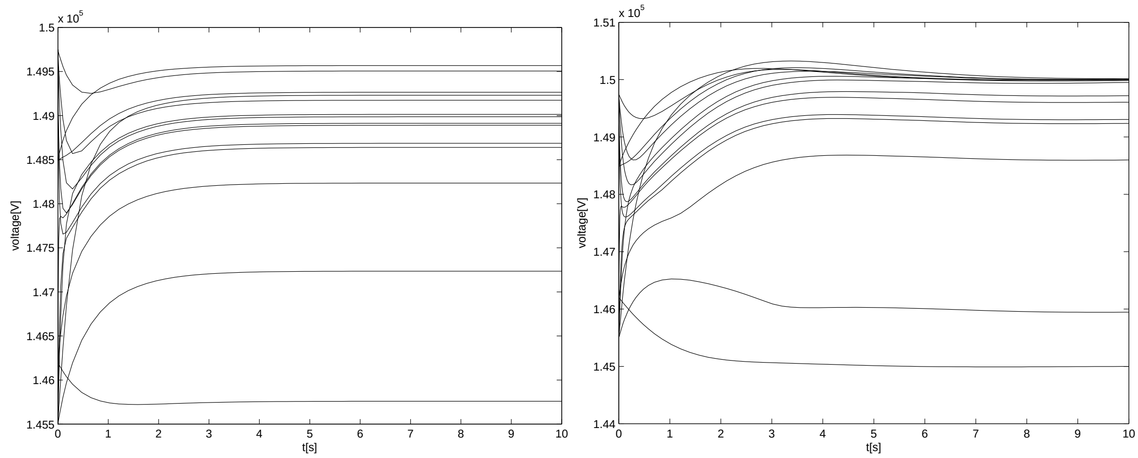


(a) *UK1.* (b) *DK1.*

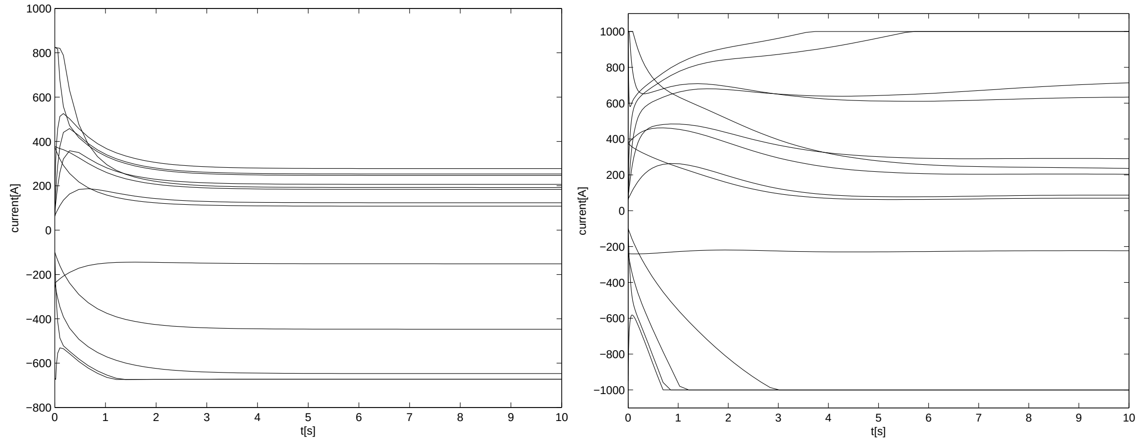


(c) *UK.* (d) *DK.*

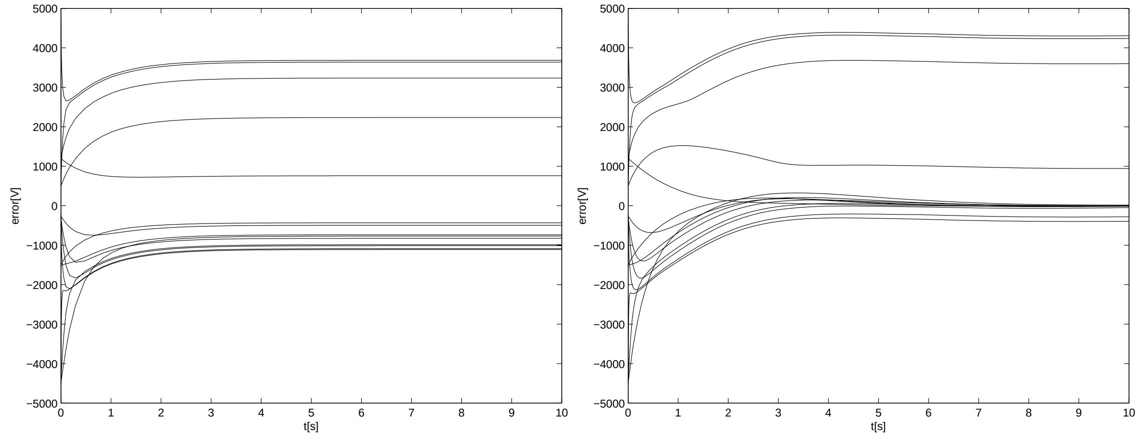
Figure 5.10: PID droop control: evolution of the curves within the admissibility region



(a) *Voltages with Droop* (b) *Voltages with PI Droop*

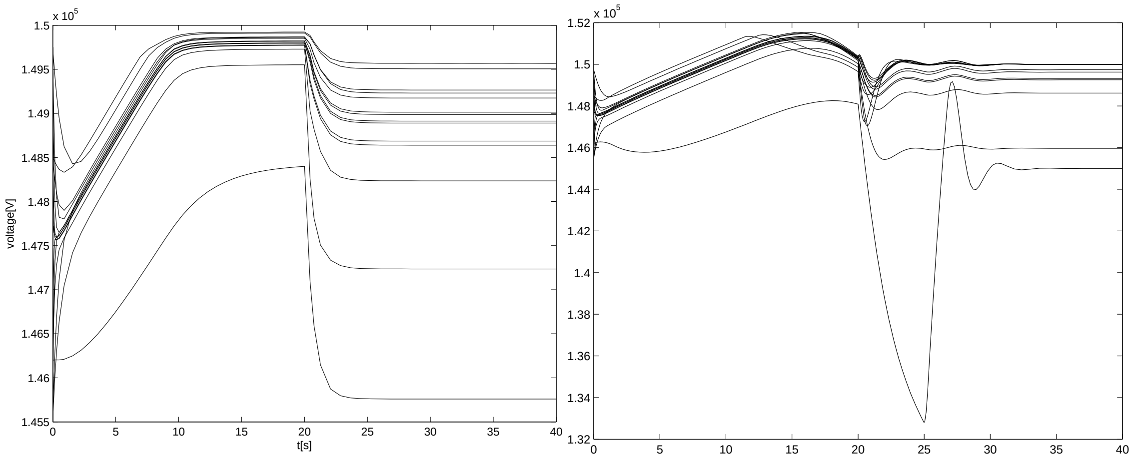


(c) *Currents with Droop* (d) *Currents with PI Droop.*

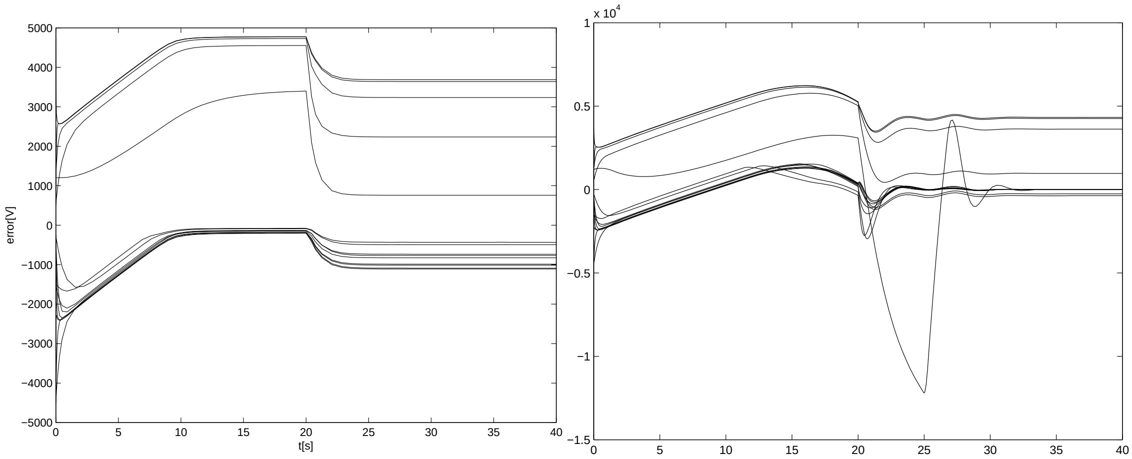


(e) *Errors with Droop* (f) *Errors with PI Droop*

Figure 5.11: PI droop and Droop control regular operation comparison



(a) *Droop Voltages* (b) *PI Droop voltages*



(c) *Droop Errors* (d) *PI Droop Errors*

Figure 5.12: PI droop and Droop control: power decrease comparison

Chapter 6

Global Control

This chapter is about a Global control technique. The term *global* is due to the fact that the implemented control law acts on the entire network to set the reference error to zero: a consensus strategy is employed to make voltages follow a constant reference. The idea is to consider the error model form (3.9) of the system given in Fig. 4.6 and make it reach consensus to zero. The control strategies used in this chapter are adapt those presented in [9] for generic networks.

6.1 Global PID Control

The main objective of this control strategy is to regulate the voltages to the set-point values E^*, given in Table 4.3. The control laws will be tested on the study case (heterogeneous) network, and also on an homogeneous version of it. The network parameters for the heterogeneous case are the ones in Table 4.3 while for the homogeneous case the only difference is that the capacities are assumed to be $C_1 = C_2 = \cdots = C_N = 200mF$, which means that all the VSCs are equal. As anticipated before, the regulation will be obtained by means of consensus technique. In particular, this section will refer to *admissible consensus.*

Definition 13 (Admissible Consensus)**.** A network is said to reach admissible consensus if, for any set of initial conditions:

$$\lim_{t\to\infty} x_i(t) \in \mathfrak{C}, \quad |u_i(t)| < +\infty \quad \forall t \geq 0,\ i \in \mathcal{N}, \tag{6.1}$$

where $\mathfrak{C}$ is the *Consensus Manifold.* Moreover, if:

$$\lim_{t\to\infty} \|x_j(t) - x_i(t)\| \leq \epsilon \quad \text{for } \epsilon > 0, \tag{6.2}$$

the network is said to achieve $\epsilon-$admissible consensus.

6.1.1 A different Model

In order to apply Global PID Control (GPIDC) , the system must be in the form:

$$\dot{x}_i(t) = \rho_i x_i(t) + \delta_i + u_i(t), i \in \mathbb{N}, \tag{6.3}$$

where:

- $x_i(t)$ is the state of the i-th agent
- $\rho_i \in \mathbb{R}$ is the agent pole determing its uncoupled dynamics
- $\delta_i \in \mathbb{R}$ is some constant disturbance
- $u_i(t) \in \mathbb{R}$ is the global control input

The desired control law is a PID in the form:

$$u_i(t) = -\sum_{j=1}^{N} G_{ij}\left(\alpha x_j(t) + \beta \int_0^t x_j(\tau)d\tau + \gamma \dot{x_j}(t)\right), \tag{6.4}$$

in which:

- G_{ij} are elements of the Laplacian matrix
- α, β, γ are respectively the Proportional, Integral and Derivative gains.

To apply the desired control law, the HVDC network model:

$$C_i\dot{E}_i = I_i(E_i) + \sum_{j=1}^{N} a_{ij}\frac{1}{R_{ij}}(E_j - E_i), \tag{6.5}$$

must be brought into the generic form (6.3), passing through the error formulation as in (3.7). Defining:

$$\delta = -\mathbf{G}\mathbf{E}^*, \tag{6.6}$$

rewriting the control law in matrix form:

$$\mathbf{u} = -\alpha\mathbf{G}\mathbf{e} - \beta\mathbf{G}\int \mathbf{e} - \gamma\mathbf{G}\dot{e}, \tag{6.7}$$

setting the current as:

$$\mathbf{I}(\mathbf{e}) = \mathbf{P}\mathbf{e} - \alpha\mathbf{G}\mathbf{e} - \beta\mathbf{G}\int \mathbf{e} - \gamma\mathbf{G}\dot{\mathbf{e}}, \tag{6.8}$$

where $\mathbf{P}$ is the diagonal matrix of the poles, and finally substituting in the original network model (3.9), the resulting model:

$$\mathbf{C}\dot{\mathbf{e}} = \mathbf{P}\mathbf{e} + \bar{\mathbf{u}} + \delta, \tag{6.9}$$

where:

$$\bar{\mathbf{u}} = -(1+\alpha)\mathbf{G}\mathbf{e} - \beta\mathbf{G}\int \mathbf{e} - \gamma\mathbf{G}\dot{\mathbf{e}}. \tag{6.10}$$

finally matches (6.3).

It is now possible to compare the Local PID control law (5.4), with (6.8). It can be seen that the first one, being local, takes into account single node dynamics: $I_k = I_k(e_k)$. The second is a global control law and, in fact, the current supplied to the *k-th* node depens not only on e_k but on $\mathbf{e}$ and on the topology, that is $I_k = I_k(\mathbf{e}, \mathbf{G})$.

Before moving forward to the control results, it is important to notice a property of δ.

Theorem 4 (Property of δ)**.** *The sum of all the components of the disturbance vector delta defined in (6.6) is zero, i.e.*

$$\sum_{k=1}^{N} \delta_k = 0 \tag{6.11}$$

Proof. Using (6.6) one has that:

$$\sum_{k=1}^{N} \delta_k = \left(\begin{pmatrix} 1 & 1 & 1 & 1 \end{pmatrix} \mathbf{G} \begin{pmatrix} E_1^* \\ E_2^* \\ E_3^* \\ E_4^* \end{pmatrix} \right)^T = \begin{pmatrix} E_1^* & E_2^* & E_3^* & E_4^* \end{pmatrix} \mathbf{G} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = 0, \tag{6.12}$$

The last equality follows from the fact that G is a laplacian and, therefore, $(1, \dots, 1)^T$ is an eigenvector of eigenvalue 0.

6.2 Homogeneous Network

In this section theoretical results and simulations regarding the network model built assuming identical converters will be given. The homogeneous network model is obtained by assuming capacities and poles to be the same for each VSC.

PID strategy

Theorem 5 (PID (homogeneous) strategy)**.** *The closed-loop network (6.9) with* $\rho_i = \rho_j = -\rho^*, \rho^* \in \mathbb{R}^+$ *for* $i, j \in 1, \dots, N$ *achieves admissible consensus for any positive value of* α, β *and* γ. *All node states converge to:*

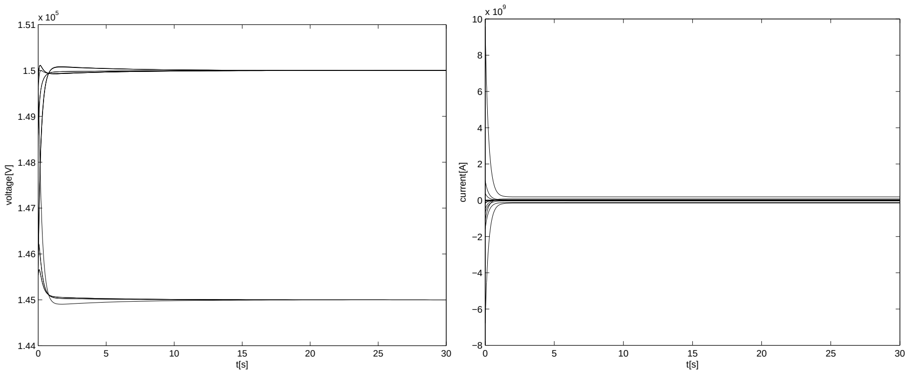
$$e_\infty = (1/N) \sum_{k=1}^{N} \delta_k / \rho^*, \tag{6.13}$$

and the integral action norm is limited by:

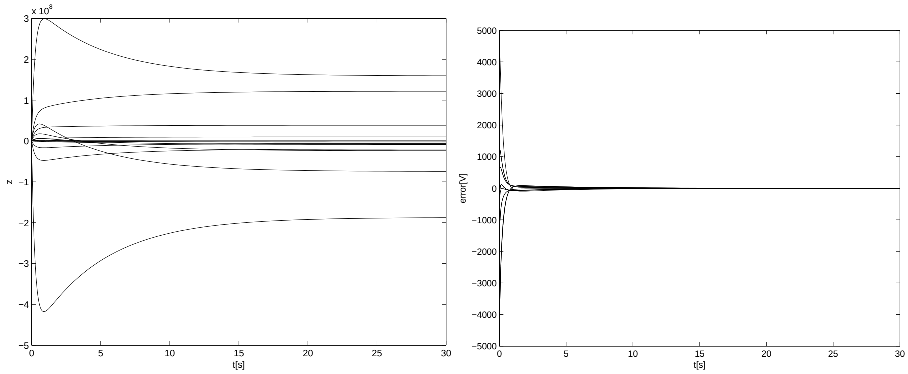
$$z_\infty \leq \frac{\sqrt{N^3(N-1)}}{\gamma \lambda_2 + 1} ||\delta||, \tag{6.14}$$

with $z = -\beta \boldsymbol{G} \int e$.

Since e_∞ is defined as (6.13), due to Theorem 4 it is always zero. This is why considering the system in the error state form and applying consensus theory, it is possible to achieve a perfect voltage regulation. The simulation results are shown in Fig. 6.1



(a) *Voltages* (b) *Currents*



(c) *Integral Actions* (d) *Errors*

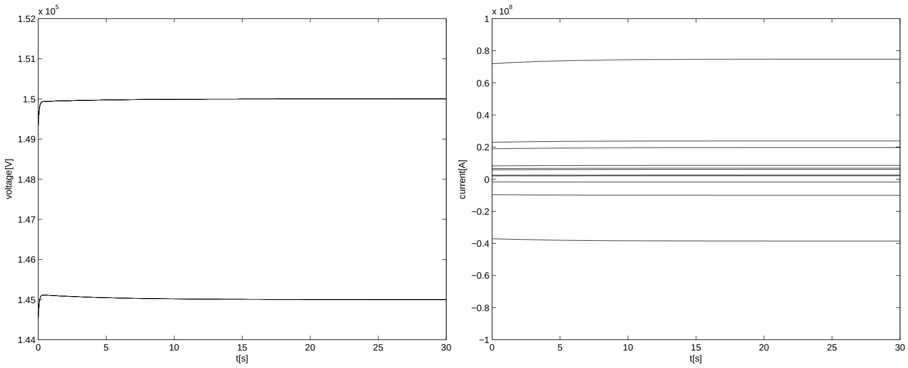
Figure 6.1: PID Homogeneous Control with $\alpha = 25$, $\beta = 5$, $\gamma = 6$

PI strategy

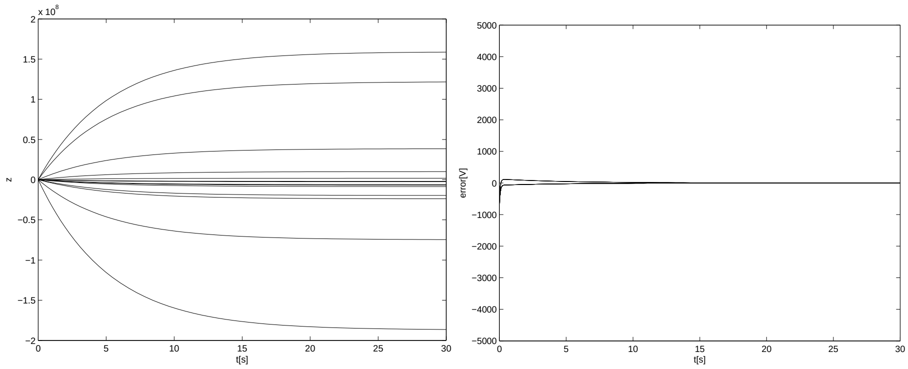
Theorem 6 (PI (homogeneous) strategy)**.** *Under the action of the global proportional-integral (PI) control obtained by setting $\gamma = 0$ in (6.10), an homogeneous network of N linear systems in the form (6.9), achieves admissible consensus for any positive value of α and β. All node states converge to (6.13) and the integral action norm is limited by:*

$$z_\infty \leq \sqrt{N(N-1)}||\delta|| \tag{6.15}$$

The simulation obtained with PI strategy are shown in Fig. 6.2.



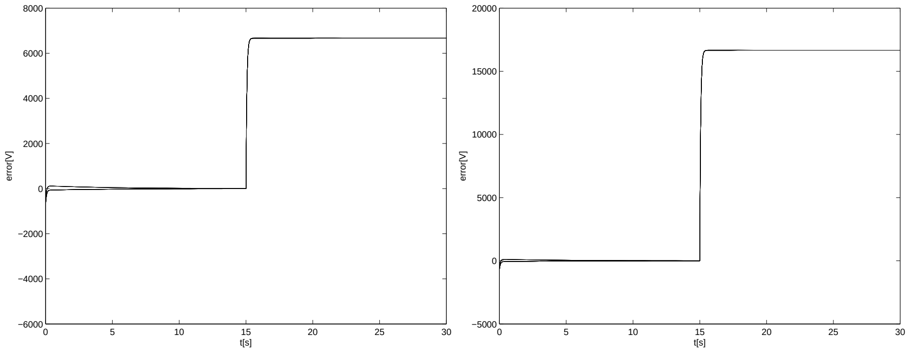
(a) *Voltages* (b) *Currents*



(c) *Integral Actions* (d) *Errors*

Figure 6.2: PI Homogeneous Control $\alpha = 25$, $\beta = 5$

It is possible to say, comparing Fig. 6.1 and Fig. 6.2, that without the derivative action the system is faster but much less smooth. An important characteristic of PI strategy is that it guarantees that all the nodes converge to the same asymptotic value despite the presence of disturbances. Although, consensus is reached at a value that depends on disturbance amplitude, as can be seen in Fig. 6.3, where a step disturbance has been added to δ at $t = 15s$.



(a) *Errors with disturbance amplitude=20000* (b) *Errors with disturbance amplitude=50000*

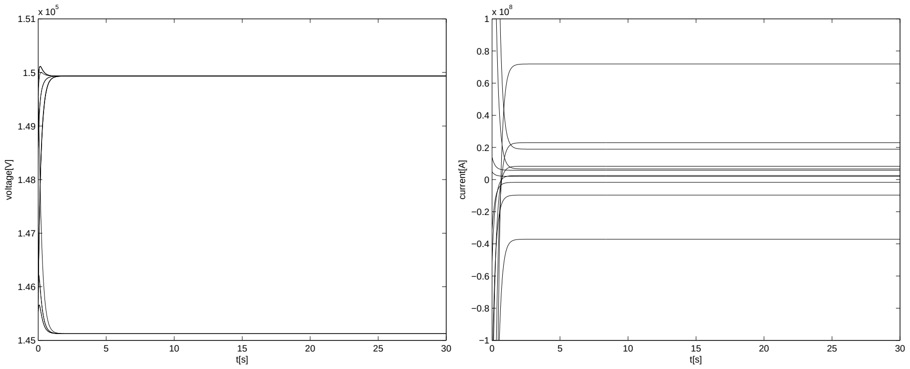
Figure 6.3: Network reaction to disturbances whith PI control

PD strategy

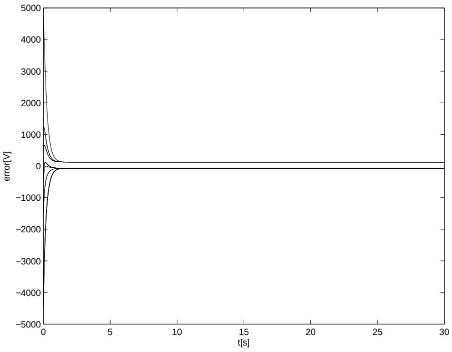
Theorem 7 (PD (homogeneous) strategy)**.** *The network with homogeneous node dynamics in the form (6.9), controlled by the distributed PD control obtained by selecting $\alpha > 0$, $\beta = 0$, $\gamma > 0$ in (6.10), achieves ϵ-admissible consensus with:*

$$\epsilon = \frac{\gamma\lambda_N + 1}{\gamma\lambda_2 + 1}\frac{N}{\alpha\lambda_N + \rho^*}||\delta|| \tag{6.16}$$

In fact, as shown in Fig. 6.4, whithout the integral action, the network is not able to reach perfect consensus and a little error still remains.



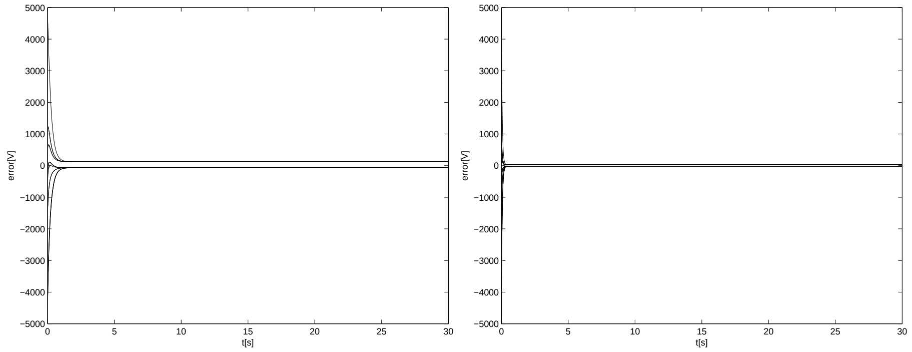
(a) *Voltages* (b) *Currents*



(c) *Errors*

Figure 6.4: PD Homogeneous Control $\alpha = 25$, $\beta = 0$,$\gamma = 6$

Moreover, since ϵ depends from α, increasing it will make the stady-state error decrease, as depicted in Fig. 6.5.



(a) *Errors with* $\alpha = 25$ (b) *Errors with* $\alpha = 100$

Figure 6.5: PD Homogeneous Control with different α, $\beta = 0$,$\gamma = 6$

6.3 Heterogeneous Network

In this section the network parameters to be considered are the ones in Table. 4.3. The nodes are characterized by having different capacities and different poles, therefore, this is the case of the North Sea Transnational Grid.

PID strategy

Theorem 8 (PID (heterogeneous) strategy)**.** *The heterogeneous group of agents controlled by the global PID strategy, achieves admissible consensus for any* $\beta > 0$ *and* $\gamma \geq 0$*, if the following conditions hold:*

1.

$$\psi = (1/N)\sum_{k=1}^{N}\rho_k < 0 \tag{6.17}$$

2.

$$\alpha > \frac{\gamma\lambda_2 + 1}{2\lambda_2}\left(\frac{|||\boldsymbol{H}_1|||^2}{2N\kappa}\frac{\bar{\rho}\bar{\rho}^T}{|\psi|} + |||\boldsymbol{H}_2|||\right) \tag{6.18}$$

where:

$$H_1 := \boldsymbol{I}_{N-1} + \hat{H}, \tag{6.19}$$

and

$$H_2 := \hat{H}(\bar{P} + \rho_1\boldsymbol{1}_{N-1}\boldsymbol{1}_{N-1}^T) + (\bar{P} + \rho_1\boldsymbol{1}_{N-1}\boldsymbol{1}_{N-1}^T)\hat{H}^T, \tag{6.20}$$

with I_{N-1} *identity matrix,* $\bar{P} = [\rho_2, \ldots, \rho_N]$*,* ρ_i *i-th pole,* $\boldsymbol{1}_{N-1} = (N-1) \times 1$ *vector of 1.*[1]

Moreover, all the nodes states converge to e_∞ *and the integral action is limted by:*

$$z_\infty \leq \sqrt{N(N-1)}||\hat{H}||\left(1 + \frac{||\bar{\rho}||}{N|\psi|}\right)||\delta||, \tag{6.21}$$

where:

$$\bar{\rho} = [\rho_2 - \rho_1, \ldots, \rho_N - \rho_1]. \tag{6.22}$$

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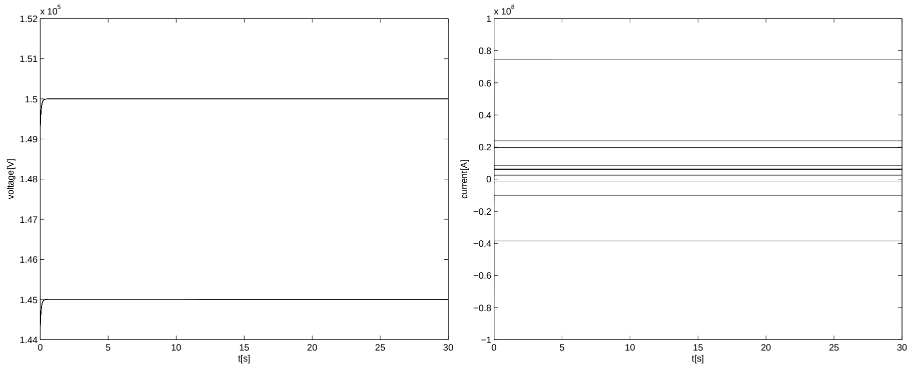
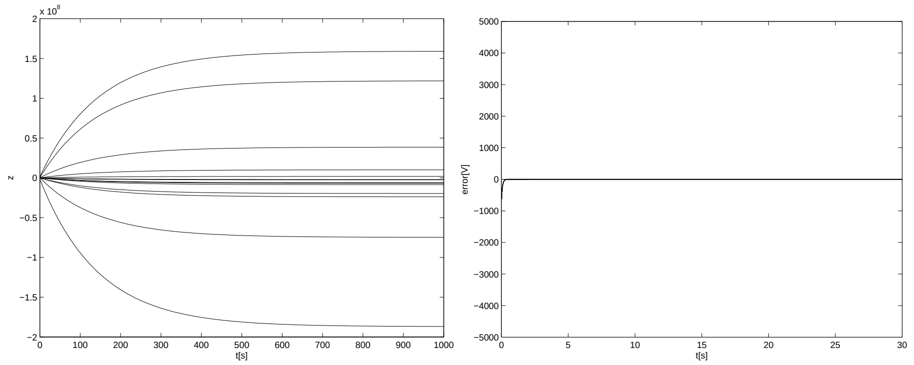
[1] The calculation of $\hat{H}$ is explicited in the appendix.

This case simulations are shown in Fig. 6.6.



(a) *Voltages* (b) *Currents*



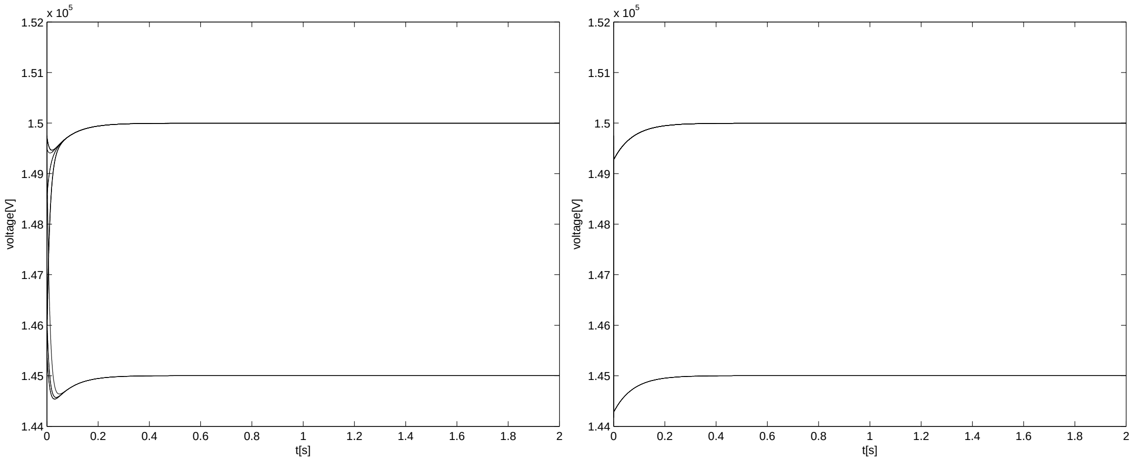
(c) *Integral Actions* (d) *Errors*

Figure 6.6: PID Heterogeneous Control $\alpha = \alpha_{min} = 720$, $\beta = 5$,$\gamma = 0.6$

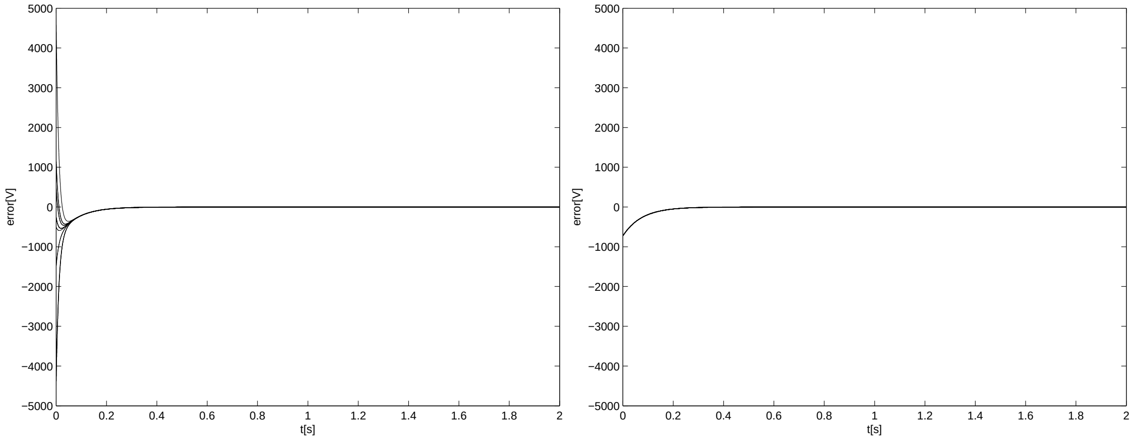
It is now interesting to carry out a comparison between PID and PI on the heterogeneous network. As can be seen in Fig. 6.7, the dynamics of the system with $\gamma = 0$ is faster than the other, but it is also true that, since the delay is really small, a lighter stress for the cables can be welcomed. Adding a 200V step disturbance in the action line, the reaction of the system is shown in Fig. 6.9. Making a zoom on the error it is possible to notice that the network PI controlled is able to reject the disturbance as good as the other one.

6.4 Conclusions and Comparisons

To make a comparison between homogeneous and heterogeneous dynamics, it is possible to say, as can be seen in Fig. 6.10, that in the first case the system is fast, in fact it reaches perfect consensus in a very short amount of time. Regarding the heterogeneous case, instead, low values of the error are obtained quickly but the integral action continues to grow until the value zero is reached. It is worth remarking that for the global control strategies the system was not required to evolve within an admissibility region, that is, no bounds were assumed for powers and curents. An attempt to use the current saturation procedure used for the local PID droop control described in Section 5.2 yielded unstable behaviors. The addressing of this issue is left for further research.

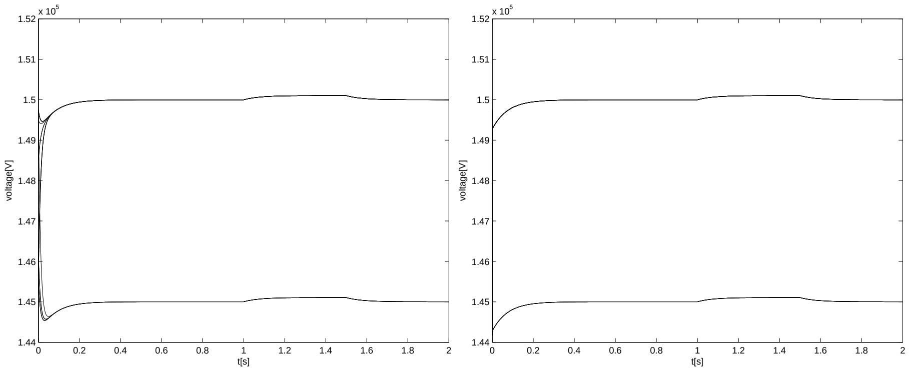


(a) *Voltages PID* (b) *Voltages PI*

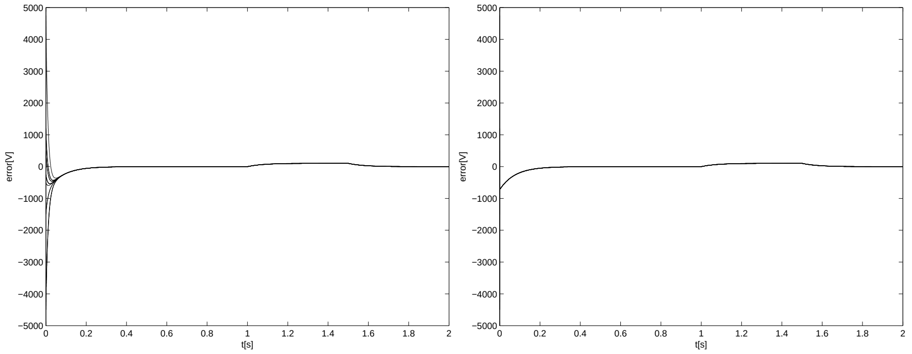


(c) *Errors PID* (d) *Errors PI*

Figure 6.7: PID and PI Heterogeneous Control comparison, $\alpha = 920$, $\beta = 5$,$\gamma = 10$ or $\gamma = 0$

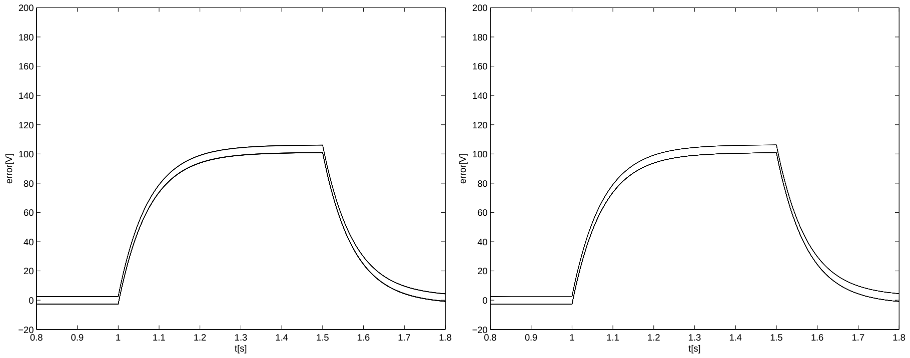


(a) *Voltages PID* (b) *Voltages PI*



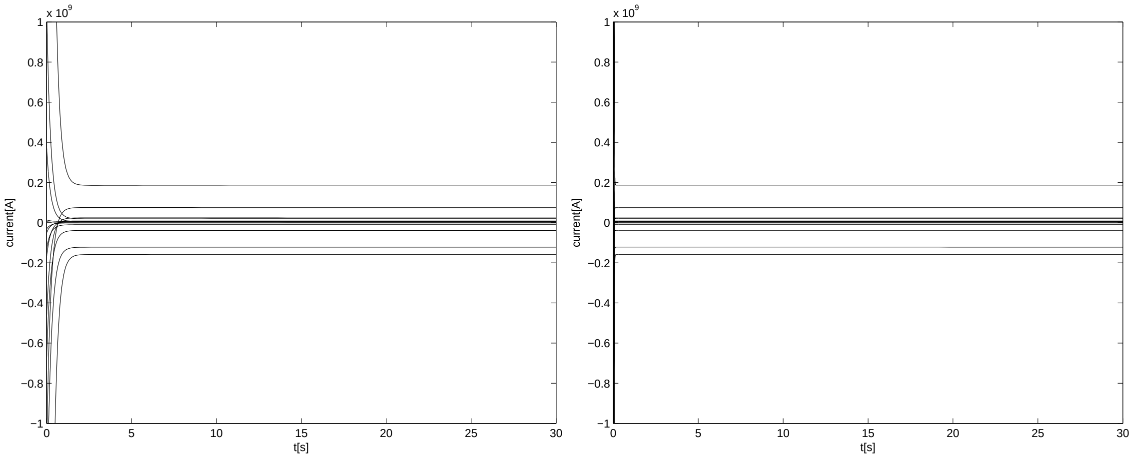
(c) *Errors PID* (d) *Errors PI*

Figure 6.8: PID and PI Heterogeneous Control comparison, disturbance reaction

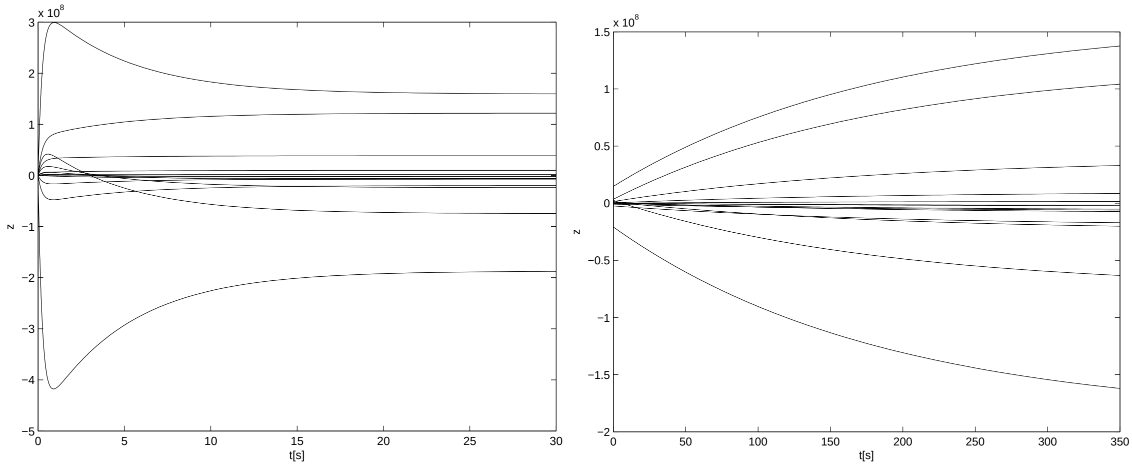


(a) *Errors PID* (b) *Errors PI*

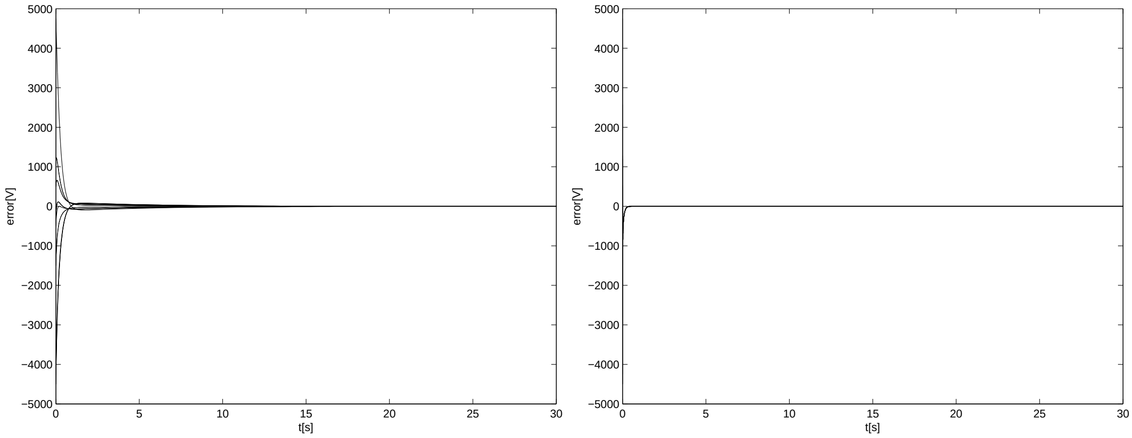
Figure 6.9: PID and PI Heterogeneous Control comparison, disturbance reaction



(a) *Currents PID Homo.* (b) *Currents PID Hetero.*



(c) *Integral Acion PID Homo.* (d) *Integral Action PID Hetero.*



(e) *Errors PID Homo.* (f) *Errors PID Hetero.*

Figure 6.10: PID Homogeneous and Heterogeneous Case Comparison.

Chapter 7

Conclusions

7.1 Comparison between Local and Global Control

Before comparing the control strategies described in chapters 5, 6, let us remember that thay have different objectives:

- The aim of the *Local Control* is to maintain voltages and currents into an admissibility region so that the network does not suffer an excessive amount of power flow;
- The goal of the *Global Control* is to make voltages perfectly follow a constant reference.

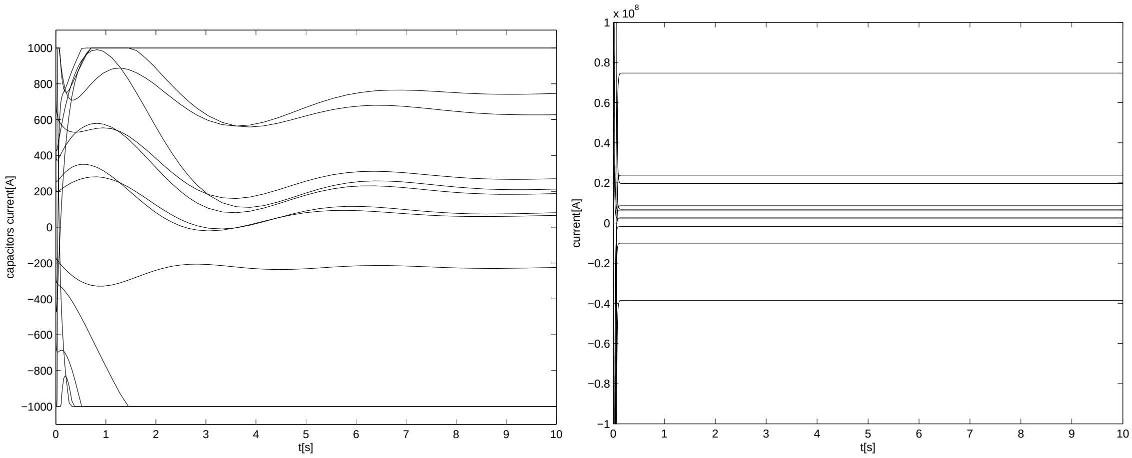
Hence, it is possible to say that control strategy should be chosen regarding the needs of the network and mostly on the middle and upper level controllers. For instance: if the middle level controller is structured to optimize voltages values, it can be wiser to chose global control so that there is no need to rebuild the whole control architecture; otherwise, if it is oriented to produce the optimal curve as in Fig. 5.1, it could be better to go for the local control technique.

Moreover, a relevant comparison can be made about the control effort. Since in both control strategies the current is used to control voltages, it is possible to see in Fig. 7.1 that the global control effort is much higher than the local one. Such a high current may not always be available or sustainable, so perfect consensus may come at a high price or even be unreacheable in a realistic system. On the other hand, local control cannot garantee that the error goes to zero for each node but, as discussed in chapter 5, this is accetable since the network is protected from too high values of voltage and power.

Therefore, to conclude it is possible to say that local control strategy represents a better compromise between results and control effort than the global one, but, if precise values of voltage are requested, the global control technique provides better performances.

7.2 Future Work

The complex network approach discussed in this thesis, is the first of many possible future works to improve the control of power networks. Possible fields of study can



(a) *Currents PID Droop* (b) *Currents PID Heterogeneous Global*

Figure 7.1: Control Effort Comparison.

be the following:

- Studying the stability conditions;
- Testing the obtained results on a physical system;
- Investigating a possible hybrid system, where a complex network approach on the producing nodes can coexist with a different control strategy on the consuming nodes;
- Formalizing and extending upper and middle level complex networks-based control techniques;
- Studying how much different topologies influence control performance;
- Adding a saturation in the Global PID control.

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