Control of DC voltage in Multi-Terminal HVDC Transmission (MTDC) Systems

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Abstract

With recent advances in power electronic technology, High-Voltage Direct Current (HVDC) transmission system has become an alternative for transmitting power especially over long distances. Multi-Terminal HVDC (MTDC) systems are proposed as HVDC systems with more than two terminals. These systems can be geographically wide. While in AC grids, frequency is a global variable, in MTDC systems, DC voltage can be considered as its dual. However, unlike frequency, DC voltage can not be equal across the MTDC system. Control of DC voltage in MTDC systems is one of the important challenges in MTDC systems. Since the dynamic of MTDC system is very fast, DC voltage control methods cannot rely only on remote information. Therefore, they can work based on either local information or a combination of local and remote information.

In this thesis, first, the MTDC system is modeled. One of the models presented in this thesis considers only the DC grid, and effects of the AC grids are modeled with DC current sources, while in the other one, the connections of the DC grid to the AC grids are also considered.

Next, the proposed methods in the literature for controlling the DC voltage are described and in addition to these methods, some control methods are proposed to control the DC voltage in MTDC system. These control methods include two groups. The first group (such as Multi-Agent Control methods) uses remote and local information, while the second group (such as Sliding Mode Control and $H_{\infty}$ control) uses local information.

The proposed multi-agent control uses local information for immediate response, while uses remote information for a better fast response. Application of Multi-Agent Control systems leads to equal deviation of DC voltages from their reference values. Using remote information leads to better results comparing to the case only local information is used. Moreover, the proposed methods can also work in the absence of remote information.

When AC grid is considered in the modeling, the MTDC system has a non-linear dynamic. Sliding Mode Control, a non-linear control method with high disturbance rejection capability, which is non-sensitive to the parameter variations, is applied to the MTDC system. It controls the DC voltage very fast and with small or without overshoot.

Afterward, a static state feedback $H_{\infty}$ control is applied to the system which minimizes the voltage deviation after a disturbance and keeps the injected power of the terminals within the limits.

Finally, some case studies are presented and the effectiveness of the proposed methods are shown. All simulations have been done in MATLAB and SIMULINK.
Acknowledgment

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<td>HDVC</td>
<td>High-Voltage Direct-Current</td>
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<td>MTDC</td>
<td>Multi-Terminal HVDC</td>
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<tr>
<td>CSC</td>
<td>Current Source Converter</td>
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<td>VSC</td>
<td>Voltage Source Converter</td>
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<td>CPM</td>
<td>Constant Power Mode</td>
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<td>Voltage Control Mode</td>
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<td>Linear Matrix Inequality</td>
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<td>VMM</td>
<td>Voltage Margin Method</td>
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<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>$P_{inj,i}$</td>
<td>Injected active power into DC bus $i$</td>
</tr>
<tr>
<td>$P_{conv,i}$</td>
<td>Injected active power into converter $i$</td>
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<td>$P_{s,i}$</td>
<td>Injected active power at AC bus $i$</td>
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<tr>
<td>$V_{dc,i}$</td>
<td>Voltage of DC bus $i$</td>
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<td>$I_{dc,i}$</td>
<td>Injected DC current from DC bus $i$ to all buses adjacent to this bus</td>
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<tr>
<td>$N_i$</td>
<td>Set of all buses adjacent (directly connected) to DC bus $i$</td>
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<td>Voltage of terminal $i$ projected on $d$-axis</td>
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<td>Voltage of AC bus $i$ projected on $d$-axis</td>
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<td>$U_{q,i}$</td>
<td>Voltage of AC bus $i$ projected on $q$-axis</td>
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<tr>
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<td>Injected current by the ideal DC current source $i$</td>
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Chapter 1

Introduction

1.1 Background

Thomas Alva Edison invented the first Direct-Current (DC) generator. But, not so long after that, Nikola Tesla and George Westinghouse came up with Alternating Current (AC) idea. AC had an undeniable advantage: its voltage could be changed using AC transformers. Therefore, the power loss was decreased and it was possible to transmit power over long distances.

After world war II, the need for electric power increased. In some countries like Sweden, the hydro power is located far from the population centers. Therefore, the Swedish engineers in Swedish State Power Board (now Vattenfall) and ASEA (now ABB) tried to use DC to transmit power over long distance, but the power electronic technology could not offer this capability. As a result they utilized 380(kV) series-compensated AC lines instead. By advances in power electronic technology, the High-Voltage Direct-Current (HVDC) system became more close to be commercial. The first order for an HVDC system was given to ASEA in 1950 to connect the system of the Swedish island of Gotland to the mainland system. This project was commissioned in 1954.

To choose between AC and HVDC power transmission, a number of factors, both economical and technical must be considered. From economic point of view, HVDC transmission is more expensive than AC transmission. Yet, above a specific transmission distance, HVDC transmission is cheaper than AC [1, 2]. From technical point of view, HVDC transmission does not need any reactive power on the DC side.

With the advances in power electronic and invention of Insulated Gate Bipolar
Transistor (IGBT), Voltage-Source Converters (VSC) was introduced and used in the HVDC systems. The first commercial HVDC based on IGBT was in island of Gotland in Sweden, which was commissioned in 1997. It was a 50(MW) underground link from southern part of the island to its northern part [3]. A more complete list of VSC-HVDC projects can be found in [4, 5].

HVDC systems can be based on Current Source Converter (CSC) or Voltage Source Converter (VSC) or a combination of them. The HVDC systems using these converters are called CSC-HVDC and VSC-HVDC, respectively. CSC-HVDC systems are normally used to transmit bulk power over long distances.

VSC-HVDC offers many advantages compared to CSC-HVDC, namely:

- VSC-HVDC does not need an active commutation voltage. The commutation failures resulting from disturbances in AC network will be omitted when VSC is used.

- VSC offers independent control of active and reactive power, which improves the system stability [6]. Also, it makes it possible for VSC-HVDC to provide the connected AC grids and wind farms with ancillary services like reactive power and AC voltage support [2].

- In contrast to CSC-HVDC, it is possible to connect VSC-HVDC to a weak network, because VSCs do not need any reactive power. VSC-HVDC can also be connected to a “black” network and helps it to black start, provided that one of the AC grids connected to the VSC-HVDC system operates in the normal condition [7].

- VSCs have higher PWM frequency which results in very fast dynamic and smaller filter size [8]. However, this high frequency can increase the switching losses and can also cause Electromagnetic Compatibility (EMC) and Electromagnetic Interference (EMI) issues. On the other hand, multi-level VSCs are introduced, which have lower switching frequency and a waveform which is more sinusoidal. As a result, the AC filters will be smaller or there is no need to AC filters anymore.

Figure 1.1(a) shows connection of terminal \( i \) of a VSC-HVDC system to the AC grid \( i \) through a phase reactor and a transformer [9]. The filter on the AC side reduces the harmonic entering from the DC side into the AC side. The DC capacitor is used to keep the DC voltage smooth.
1.2. MULTI-TERMINAL HVDC

Multi-Terminal HVDC (MTDC) systems are HVDC systems consist of more than two terminals. The first MTDC system, was built based on CSC technology by adding a 50(MW) converter station at Corsica island to connect Sardinia to the mainland Italy HVDC link. This system was commissioned in 1986 [3]. However, in CSC-MTDC systems, in order to change the flow of power, DC voltage polarity

In this thesis, the AC grid is modeled by its Thevenin equivalent which is a voltage source ($\bar{U}_{Th,i}$) behind an impedance ($\bar{Z}_{Th,i}$) as shown in Figure 1.1 (b). Next as seen from the terminal $i$, the AC part is modeled as a voltage source ($\bar{U}_i$) with constant magnitude and phase angle, behind behind an impedance ($\bar{Z}_i$) as shown in Figure 1.1 (c).

Figure 1.1: (a) The positive sequence diagram of terminal $i$ connected to AC grid $i$ (b) AC grid is represented by its Thevenin equivalent (c) the model used in this thesis.

Multi-Terminal HVDC
must be changed. Since a terminal may be connected to more than one terminal, it produces undesirable changes in flow of power in other lines. In contrast, in VSC-HVDC system it is possible to change the flow of power without changing the polarity. Therefore, it is easier to extend the number of terminals in VSC-MTDC system, which makes the VSC technology a more attractive solution for MTDC systems [10, 11].

As an example, we consider offshore wind farms. Offshore wind farms may be one of the main sources of renewable energy in the future. Major offshore wind sources can be far away from the coast. The energy extracted from the wind farms must be transmitted to the shore by means of submarine cables. As stated earlier, VSC-HVDC system can be an attractive solution. Moreover, wind has an intermittent nature, and by interconnecting wind farms to other grids, the effect of intermittency decreases [12]. VSC-MTDC systems make it possible to connect many of these wind farms together and to the multiple AC grids and form a DC system. On the other hand, there are a lot of oil and gas platforms in the sea. These platforms usually use gas turbines. It would be more efficient if these platforms are supplied from the offshore grid or wind farms [8]. VSC-MTDC systems make it possible to build a grid under the sea, which can supply offshore platforms.

VSC-MTDC system in presence of offshore wind farms is studied in different papers for example in [13–15]. Figure 1.2 shows an MTDC system connected to 3 AC grids and two offshore wind farms and an offshore platform. The system configuration is very similar to the system presented by Airticity where AC System 1 can be considered as UTCE, AC System 2 as the Nordic AC system and AC System 3 as the British AC system.

The challenges of operating MTDC systems, like controlling the DC voltage, power flow in DC lines, interaction between converters, have been discussed in [16]. One of the most important issues is that the DC voltage across the MTDC system must be kept in an acceptable range. DC over-voltage could damage the converters, whereas DC under-voltage may result in reducing the converter controllability [17]. If the power balance in the MTDC system is not maintained, the DC voltage will change. VSC operating in rectifying mode injects active power to the MTDC system, while the VSC operating in inverting mode extract active power from it. If more active power is injected into the DC grid, the DC voltage will increase. An analogy for the DC voltage control in a 5-terminal MTDC system is presented in Figure 1.3. Each converter is replaced by an avatar and the height of the balls from the earth resembles the voltage of terminals. These avatars try to keep the height of the grid in the acceptable area, which is identified by max and min.
1.3 DC VOLTAGE CONTROL STRATEGIES

To control the DC voltage of the converters, remote information may be useful as input data. However, since the dynamic of the VSC-MTDC system is very fast, we may not only rely on remote information, especially during disturbances or just after a disturbance. Therefore, any proposed control algorithm should rely on either local data or on a combination of local and remote data. In the power system literature, different DC voltage control methods have been proposed. Among them, Voltage Margin Method (VMM) and Voltage Droop Method (VDM) are the most well-known methods. These two methods rely on local information as input data to control the DC voltage of the converters. Ref. [18] reviews VMM and different
types of VDM strategies. Some authors [19, 20] proposed control strategies, which are a combination of VDM and VMM.

In VDM, all or some converters participate in the DC voltage control by changing their injected active powers (or DC currents) based on a predefined droop. Application of this method results in a steady-state DC voltage deviation from the pre-disturbance values. In contrast, in VMM one converter (slack converter) is responsible to maintain its DC voltage in the desired level, while other terminals operate at constant power mode [21]. Due to some technical constraints, when the DC voltage controller converter is not any longer able to supply or extract the active power necessary for controlling its DC voltage, another converter will operate as the slack converter [22]. A margin must be considered between the reference DC voltages of terminals. The transition between these two reference voltages puts a lot of stress on the converter [23]. Moreover, the voltage margin must be considered large enough in order to avoid interactions between controllers [22]. VMM may be single stage or multi-stage. Different types of VMM in presence of off-shore windfarms and also a discussion on prioritizing converters in controlling DC voltage is presented in [24].

Ref. [25] implements the droop control for a VSC-MTDC system. In this reference, VDM is used, and the droops are determined using Linear Matrix Inequality (LMI) to minimize the voltage deviation, and only the DC dynamics are considered. Authors of [8], modeled the VSC-MTDC system as a Multi-Input Multi-Output (MIMO) system. Then, the different values of droops of the controllers have been analysed in this paper using Singular Value Decomposition (SVD).

Ref. [26] uses an adaptive method for calculating this droop. After each contingency, converters work at new operating points. The aim is that, converters with more headroom available for the power, should participate more in the DC voltage control.

Ref. [27] implements a variable droop method. In the proposed method in this study, the droop is changed according to the injected power of the converter to minimize the loss in the DC grid. On the other hand, this change in the injected active power of the converters may be considered as a disturbance from the AC grid point of view. This can have an impact on the AC grid stability. This issue is studied in paper [28].

VSC-MTDC system can control the frequency in the connected AC grids. If frequency drops in an AC grid, the VSC-MTDC system injects more active power to (or extract less active power from) the AC grid. This reflects on the DC voltage, and since in VDM different terminals participate in DC voltage control, other AC grids will be affected by this change. This issue is discussed in [29].
1.3. DC VOLTAGE CONTROL STRATEGIES

Ref. [30, 31] studied the power flow when VDM is applied to the VSC-MTDC system. The different power sharing in converters using VDM is discussed in [32]. The stability of VSC-MTDC system in general and also in the presence of offshore wind farms is discussed in [6, 33, 34].

Multi-agent system

Multi-Agent System (MAS) is an application of distributed intelligence, which brings intelligence on a component level [35]. An agent is a software entity, which is situated within an environment and can act autonomously in response to the environment changes [36, 37]. A multi-agent system is a system comprising two or more agents. It should be noted that there is no global goal in the multi-agent system. Each agent has its own goal and changes its behavior dynamically to achieve its own goal. Agents may or may not communicate with each other.

MAS is used for different aims in the literature. Ref. [36, 38] reviewed some applications of MAS to power systems. Some authors [35, 39–41] studied the power system restoration using MAS. Secondary control of power system in presence of FACTS devices is another application of MAS, which is studied in [42, 43].

In this thesis, the proposed MAS control methods use both local and remote information to control the DC voltage and make the DC voltage deviation of the DC buses equal. MAS can use different strategies like incremental strategy, consensus strategy and diffusion strategy. The consensus strategy is used in this thesis.

Sliding mode control

Sliding Mode Control (SMC) is a variable structure control, which is originally used for systems whose dynamics can be modelled with ordinary differential equations. SMC has some features like insensitivity to parameter variations, external disturbance rejection and fast dynamic response [44, 45]. In this method, the idea is to define a surface along which the tracking error is zero. The controller forces the system to slide along this surface. One of the common problems of SMC is chattering around this sliding surface.

SMC is used for power oscillation damping in [46]. In [47] SMC is applied to a 2-terminal HVDC system. However, SMC has not been applied to the MTDC system. In this thesis, a control method based on SMC for MTDC system is presented. Based on this method, one converter controls the DC voltage, while other converters operate in constant power mode.


\section*{CHAPTER 1. INTRODUCTION}

\textbf{H}_\infty control

In the \textbf{H}_\infty control design method, a feedback controller is sought to stabilize the closed-loop system and satisfy a prescribed level of performance. In this method, the control problem is expressed as a mathematical optimization problem. The desired performance requirements will be expressed as constraints of this optimization problem. In this method, the controller tries to minimize the maximum of the transfer function of the desired signal over the time. This leads to solving a Linear Matrix Inequality (LMI).

Ref. [48] applies the \textbf{H}_\infty to control the DC voltage in HVDC system which is installed in parallel with an AC line. Also in [49] an \textbf{H}_\infty control is designed to enhance the stability of the VSC-HVDC system. In this thesis, a static-feedback \textbf{H}_\infty is applied to MTDC system with injection model. The purpose of this controller is to minimize the deviation of the DC voltage of the MTDC system, after a disturbance. Meanwhile, it limits the powers injected from the AC grids and also prevents the congestion in some of the DC lines. Moreover, the converters participate in voltage control, based on their available capacity. In this method, like VDM, some or all converters participate in voltage control.

\subsection*{1.4 Scope and aim of the project}

As mentioned before, one of the important challenges in MTDC systems is to control the DC voltage and to keep secure operation of the VSC-MTDC system in normal conditions and after each contingency in the system. Another challenge is to find the optimal injected active powers of converters before and after the contingency, which is beyond the scope of this thesis. Also, the stability and oscillations of the AC grids are not studied in this thesis. This issues will be studied in the next phase of this project.

The aim of this thesis is to develop new control methods for controlling the DC voltage in VSC-MTDC system. To achieve this aim, first the MTDC system is modeled using two approaches. In the first approach, only the dynamic of the DC grid is considered and AC grids are modeled with DC current sources. In the second approach, both AC grid and DC grid are modeled. The AC grid is modeled by its Thevenin equivalent. The \textbf{H}_\infty control is applied on the first model, while the sliding mode control is applied on the second model. Other control methods are applied using both models. In this thesis the fast dynamics due to the inductances of the DC lines have not been considered. Also, it is supposed that the AC grids are not connected to each other.
1.5. CONTRIBUTION

Next, the control methods proposed in the literature for controlling the DC voltage are presented and their advantages and disadvantages are described. Since in controlling the DC voltage both local information and a combination of local and remote information can be used, the methods presented in this paper can be divided into two groups. The first group, including Multi-Agent Control methods, use remote and local information, while the second group (Sliding Mode Control and $H_{\infty}$ control), use local information.

This work will be later developed to consider the more detailed model of AC grids, the economic aspects of using MTDC systems and optimal injected powers.

1.5 Contribution

This thesis addresses different aspects of control of VSC-MTDC system. In this regard, the following contributions are listed:

- The future MTDC systems may be geographically wide with long distances between the converters. Therefore, a distributed and intelligent control methodology may be needed to operate such systems. This thesis aims to propose DC voltage control algorithms based on MAS. These methods may rely on either local information or a combination of local and remote data. First proposed control method has a smaller steady-state error comparing to VDM.

- Another MAS-based control method is proposed. In this method, the system tries to minimize the voltage deviation after a disturbance and at the same time, terminals participate exactly proportional to their droop.

- A sliding-mode control for VSC-MTDC system is proposed in this thesis. This method is robust, fast, insensitive to parameter variations and disturbances. It works based on local information.

- An $H_{\infty}$ controller is proposed for control of DC voltage in MTDC systems. Using this controller, the deviation of DC voltage will be minimized and the injected active power of converters will be kept within the limits.

List of publications

- C1 Mohammad Nazari and Mehrdad Ghandhari, "Application of multi-agent control to multi-terminal HVDC systems", IEEE EPEC Conference (Canada),
2013. Mohammad Nazari carried out the work and wrote the paper under supervision of Mehrdad Ghandhari.

- **C2** Martin Andreasson, Mohammad Nazari, Dimos Dimarogonas, Henrik Sandberg, Karl H. Johansson and Mehrdad Ghandhari, "Distributed Voltage and current control of VSC multi-terminal high voltage direct current transmission systems", Accepted in IFAC 2014 conference. This paper was result of collaboration between Electric Power System and Automatic Control departments. Mohammad Nazari and Martin Andreasson carried out the work and wrote the paper under supervision of other authors.

- **C3** Mohammad Nazari, Mehrdad Ghandhari, "$\mathcal{H}_\infty$ control of Multi-Terminal HVDC systems", CIGRE AORC conference, 2014. Mohammad Nazari carried out the work and wrote the paper under supervision of Mehrdad Ghandhari.

- **J1** Mohammad Nazari, Mehrdad Ghandhari, Amin Ramezanifar, "Sliding-mode control of Multi-Terminal HVDC transmission system", Submitted to IEEE Transactions on Power Delivery. Mohammad Nazari carried out the work and wrote the paper under supervision of Mehrdad Ghandhari. He used the comments of Amin Ramezanifar.

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<th>SMC</th>
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### 1.6 Thesis outline

The outline of this thesis is as follows

- Chapter 2 gives the technical background related to modeling of VSC-MTDC system. Two main modeling approaches are considered in this chapter, namely:
1.6. THESIS OUTLINE

- **Injection model**: In this model, only the dynamic of DC grid is considered and the AC grids are modeled with DC current sources. The DC cables are modeled with resistances.

- **AC/DC model**: In this model, the AC grid is modelled as a voltage source connected to the converter. The instantaneous values of the currents and voltages, in $dq$ coordinate, are considered. In this model, the controller consists of inner controller and outer controller. The DC grid is modelled like the previous model.

- Chapter 3 describes the control methods.

  - First, the main methods of DC voltage control proposed in the literature is reviewed. Voltage Margin Method (VMM) and Voltage Droop Method (VDM) are described and advantages and disadvantages of these methods are discussed. Then, DC voltage control strategies are addressed. These strategies usually are applied to VDM and define how different terminals should participate in DC voltage control. These strategies may define the power ratio of different terminals. Also, one terminal could have precedence over other terminals in receiving or giving power; Then, the DC voltage controller for the models mentioned in Chapter 2 are described.

  - In the next section of this chapter, multi-agent concept is introduced. Three controllers based on this concept are proposed and capabilities of each controller are discussed. All of these controllers work based on Multi-Agent System (MAS) theory. These controllers work using local and remote information, but they do not rely only on remote information. The delay of communication is also considered in the analyses.

  - Next, Sliding Mode Control (SMC) will be presented briefly and a SMC-based controller will be presented for controlling the DC voltage in the VSC-MTDC system. Finally, an $H_\infty$ controller will be proposed to control the DC voltages in MTDC systems.

- In Chapter 4, the control methods presented in Chapter 3 are simulated for different scenarios and the results are discussed and compared.

- Chapter 5 concludes and the future research areas are described.
Chapter 2

MTDC system modeling

2.1 System modeling

Consider again Figure 1.1 (a). As mentioned in chapter 1, a VSC-MTDC system consists of DC Cables, converters, filters and DC capacitors. Different approaches for modeling MTDC system have been proposed in the literature [10, 50].

Depending on the purpose of the study, DC cables can be modeled with distributed model [33] or with π-circuit model [23]. The distributed model is suitable for transient analysis, while the π-circuit model is utilized for slower dynamics. For applying the proposed control methodologies in this thesis, the π-circuit model is chosen and the fast dynamic due to the inductances of the DC cables and the switchings of the converters are not considered in this study. The shunt DC capacitor installed in each DC bus is also included in the capacitor of the π-circuit model.

Converters are responsible for injecting active power to MTDC system or extracting power from it. Different modeling approaches are presented in the literature. Two models have been used for the purpose of this thesis. In the first model, only the dynamic of the DC grid is considered and the power exchange between AC and DC are represented by DC current sources. In the second model, the AC grids are modeled as voltage sources connected to the converters. In this model, the instantaneous values of currents and voltages, in $dq$ reference frame, are considered [10].
**Model 1: Injection model**

Figure 2.1 illustrates an asymmetric monopole MTDC system with ground return, and with $n$ DC buses. These buses (1 to $n$) are connected to the AC terminals through converters. The AC terminals are connected to AC grids 1 to $n$. Since the interactions between the AC grids and the MTDC system are represented by current sources, the AC terminals are not shown in this figure.

Other DC buses ($n+1$ to $m$), called DC hubs, are the junctions between the DC cables. However, in this thesis, we suppose that there is no DC hub in the MTDC system, and as a result $m = n$.

![Figure 2.1: An n-terminal MTDC grid. Converters are modeled as DC current sources.](image)

In this figure, $C_i$ is the aggregated capacitance of the DC cables connected to the converter $i$ and the DC capacitor of the converter $i$, $V_{dc,i}$ is the DC voltage of the DC bus of the converter $i$. The active power exchange between the AC grid $i$ and the MTDC system is represented by DC current source indicated by $I_{inj,i}$. The injected active power is defined as follows

$$P_{inj,i} = V_{dc,i} \times I_{inj,i} \quad (2.1)$$
2.1. SYSTEM MODELING

In this thesis, a positive $P_{in,j,i}$ means active power is injected from the AC grid $i$ into the MTDC system, while a negative $P_{in,j,i}$ means active power is extracted from the MTDC system. Thus, the dynamic of the converter $i$, which is connected to the AC grid $i$, is described by (for $i = 1 \ldots n$)

$$V_{dc,i} = \frac{1}{C_i} (I_{in,j,i} - I_{dc,i}) \tag{2.2}$$

where $I_{dc,i}$ is the DC current from bus $i$ to the adjacent buses, and it is expressed by

$$I_{dc,i} = \sum_{j \in N_i} g_{ij} (V_{dc,i} - V_{dc,j}) \tag{2.3}$$

In equation (2.3), $N_i$ is the set of adjacent buses to bus $i$, $g_{ij} = \frac{1}{R_{ij}}$, and $R_{ij}$ represents the resistance of the cable between the terminals $i$ and $j$.

Thus, the dynamic of the $n$-terminal MTDC system can be described by a set of differential equations of the form

$$\dot{x}_{DC} = A_{DC} x_{DC} + B_{DC} u_{DC} \tag{2.4}$$

where,

$$x_{DC} = \begin{bmatrix} V_{dc,1} \\ \vdots \\ V_{dc,n} \end{bmatrix}, \quad u_{DC} = \begin{bmatrix} I_{in,j,1} \\ \vdots \\ I_{in,j,n} \end{bmatrix} \tag{2.5}$$

and

$$A = \begin{bmatrix} -\frac{1}{C_1} \sum_{j \in N_i} g_{1j} & \cdots & \frac{g_{i1}}{C_1} \\ \vdots & \ddots & \vdots \\ \frac{g_{nj}}{C_n} & \cdots & -\frac{1}{C_n} \sum_{j \in N_n} g_{nj} \end{bmatrix} \tag{2.6}$$

$$B = \begin{bmatrix} \frac{1}{C_1} & 0 & \cdots & 0 \\ 0 & \frac{1}{C_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & \frac{1}{C_n} \end{bmatrix} \tag{2.7}$$
CHAPTER 2. MTDC SYSTEM MODELING

Model 2: AC/DC model

Consider again Figure 1.1 (c). If we draw the diagram for an \( n \)-terminal MTDC system, the result will be as shown in Figure 2.2.

![Figure 2.2: An n-terminal MTDC grid.](image)

In the AC/DC model the three phase configuration as shown in Figure 2.3 is of concern. To control the active and reactive power of the converter, two transformations have commonly been used, namely the \( \alpha\beta \) transformation and the \( dq \) transformation. Using the \( \alpha\beta \) transformation, the active and reactive powers can be controlled instantaneously and in a decoupled manner, but the control variables are sinusoidal functions of time. In contrast, using the \( dq \) transformation, we may be able to control active and reactive power instantaneously and in a decoupled manner. Furthermore, the control variables will be DC quantities in the steady-state [33, 51]. Therefore, the \( dq \) transformation is used for controlling the converters in this model.

From Figure 2.3, we have
2.1. SYSTEM MODELING

Averaged ideal three-phased VSC, a \( i \) and \( v \) connected to the converter \( i \).

\[
\begin{align*}
u_{a,i} - v_{a,i} &= l_i \frac{d i_{a,i}}{d t} + r_i i_{a,i} \\
u_{b,i} - v_{b,i} &= l_i \frac{d i_{b,i}}{d t} + r_i i_{b,i} \\
u_{c,i} - v_{c,i} &= l_i \frac{d i_{c,i}}{d t} + r_i i_{c,i}
\end{align*}
\]

(2.8)

These equations are transformed to the \( dq \) reference frame [10], and the following are obtained

\[
\begin{bmatrix}
U_{d,i} \\
U_{q,i}
\end{bmatrix} - 
\begin{bmatrix}
V_{d,i} \\
V_{q,i}
\end{bmatrix} = 
\begin{bmatrix}
-\omega l_i & r_i \\
\omega l_i & -r_i
\end{bmatrix}
\begin{bmatrix}
I_{d,i} \\
I_{q,i}
\end{bmatrix} + 
\begin{bmatrix}
l_i & 0 \\
0 & l_i
\end{bmatrix}
\frac{d}{d t}
\begin{bmatrix}
I_{d,i} \\
I_{q,i}
\end{bmatrix}
\]

(2.9)

where \( I_{d,i} \) and \( I_{q,i} \) are the \( d \) and \( q \) components of the current flowing from AC grid to the converter, \( U_{d,i} \) and \( U_{q,i} \) are the \( d \) and \( q \) components of the voltage source of the AC grid \( i \) which are assumed constant, and finally \( V_{d,i} \) and \( V_{q,i} \) are the \( d \) and \( q \) components of the AC terminal \( i \).

Thus, the dynamic of the terminal \( i \) is described by a set of differential equations of the form (for \( i = 1 \ldots n \))

\[
\begin{align*}
I_{d,i} &= \frac{-r_i I_{d,i}}{l_i} + \omega I_{q,i} + \frac{U_{d,i}}{l_i} - \frac{V_{d,i}}{l_i} \\
I_{q,i} &= \frac{-r_i I_{q,i}}{l_i} - \omega I_{d,i} + \frac{U_{q,i}}{l_i} - \frac{V_{q,i}}{l_i}
\end{align*}
\]

(2.10) (2.11)

Figure 2.3: The three phase model of AC grid \( i \) connected to the converter \( i \).
CHAPTER 2. MTDC SYSTEM MODELING

The equations of the terminal \(i\) can be written in a general form as

\[
x_{AC,i} = f_{AC,i}(x_{AC,i}) + B_{AC,i}u_i
\]  

(2.12)

where

\[
x_{AC,i} = \begin{bmatrix} I_{d,i} \\ I_{q,i} \end{bmatrix}, \quad u_i = \begin{bmatrix} V_{d,i} \\ V_{q,i} \end{bmatrix}
\]  

(2.13)

\[
f_{AC,i}(x_{AC,i}) = \begin{bmatrix} f_{1,i} \\ f_{2,i} \end{bmatrix} = \begin{bmatrix} -r_{d,i}I_{d,i} + \omega_i I_{q,i} + \frac{V_{d,i}}{l_{di}} \\ -r_{q,i}I_{q,i} - \omega_i I_{d,i} + \frac{V_{q,i}}{l_{qi}} \end{bmatrix}
\]  

(2.14)

\[
B_{AC,i} = \begin{bmatrix} -\frac{1}{l_{di}} & 0 \\ 0 & -\frac{1}{l_{qi}} \end{bmatrix}
\]  

(2.15)

To complete the dynamical model, the DC part of the system must also be considered. From Figure 2.2, the link between the AC and DC parts of terminal \(i\) can be expressed by

\[
\dot{V}_{dc,i} = P_{inj,i}V_{dc,i}C_i - I_{dc,i}C_i
\]  

(2.16)

where \(I_{dc,i}\) is given in (2.3).

Therefore the dynamic of terminal \(i\) can be expressed as

\[
x_i = f_i(x_i) + b_iu_i
\]  

(2.17)

where

\[
x_i = \begin{bmatrix} x_{AC,i} \\ x_{DC,i} \end{bmatrix} = \begin{bmatrix} I_{d,i} \\ I_{q,i} \\ V_{dc,i} \end{bmatrix}
\]  

(2.18)

\[
f_i(x_i) = \begin{bmatrix} f_{1,i} \\ f_{2,i} \\ f_{3,i} \end{bmatrix} = \begin{bmatrix} -r_{d,i}I_{d,i} + \omega_i I_{q,i} + \frac{V_{d,i}}{l_{di}} \\ -r_{q,i}I_{q,i} - \omega_i I_{d,i} + \frac{V_{q,i}}{l_{qi}} \\ \frac{P_{inj,i}}{V_{dc,i}} - \frac{1}{C_i} \sum_{j \in N_i} g_{ij}(V_{dc,i} - V_{dc,j}) \end{bmatrix}
\]  

(2.19)
2.1. SYSTEM MODELING

In Figure 2.2, the active power exchange with AC grid $i$ is expressed by

$$P_{s,i} = U_{d,i}I_{d,i} + U_{q,i}I_{q,i}$$  \hspace{1cm} (2.20)

and the power received by the converter $i$ is

$$P_{\text{conv},i} = U_{d,i}I_{d,i} + U_{q,i}I_{q,i} - r_i(I_{d,i}^2 + I_{q,i}^2)$$  \hspace{1cm} (2.21)

Since the converter is considered to be lossless, we have

$$P_{\text{in},i,j} = P_{\text{conv},i}$$  \hspace{1cm} (2.22)

Next, based on Figure 2.2, the reactive power exchange with AC grid $i$ can be expressed as

$$Q_{s,i} = U_{q,i}I_{d,i} - U_{d,i}I_{q,i}$$  \hspace{1cm} (2.23)

Using Phase-Locked Loop (PLL), the $d$ axis of the $dq$ reference frame will be aligned with the $a$-phase of the $abc$ reference frame. Supposing that the PLL tracking is perfect, it results in $U_{q,i} = 0$, and equations (2.20) and (2.23) can be written as, [51].

$$P_{s,i} = U_{d,i}I_{d,i}$$  \hspace{1cm} (2.24)

$$Q_{s,i} = -U_{d,i}I_{q,i}$$  \hspace{1cm} (2.25)

Thus, $P_{s,i}$ is controlled by $I_{d,i}$ and $Q_{s,i}$ is controlled by $I_{q,i}$. 
Chapter 3

Control strategies

3.1 Introduction

Different control strategies have been proposed in the literature. Voltage Margin Method (VMM) and Voltage Droop Method (VDM) are the two most well-known methods. These methods do not need any communication between terminals. However, as mentioned in Section 1.3, each of these methods has some disadvantages. In this section, we first explain voltage margin method and voltage droop method. Then, some new methods based on Multi-Agent Systems (MAS) and Sliding Mode Control (SMC) are proposed to enhance the VMM and VDM. The MAS methods require communication between terminals to achieve their goals, however, they can still work without communication. SMC controller proposed in this thesis is a modification of VMM and does not need any communication between terminals.

3.2 Voltage margin method

In VMM one converter is responsible to maintain the DC voltage of the MTDC system on a desired level, while other converters operate at Constant Power Mode (CPM) [21]. If the converter on DC Voltage Control Mode (VCM) is no longer able to supply or extract the required power to control the DC voltage, the DC voltage changes, and when the voltage reaches reference value of another converter, then the corresponding converter will operate as slack converter [22].

Figure 3.1 shows the characteristics of VMM for a two-terminal HVDC system. A margin must be considered between two control voltage levels [21]. If
the voltage margin is not large enough, it is possible that, in transients, more than one converter participate in the DC voltage control and this causes the interaction between converters [22]. In this figure, the operating point is marked with a red point. As can be seen, converter 2 is operating in VCM and keep the DC voltage at its reference value \( V_{dc,2}^{ref} \) and terminal 1 is operating in CPM. Recalling that, in this thesis, a positive injected power represents the power injected to the MTDC system, it can be concluded that converter 1 is operating as inverter and converter 2 is operating as rectifier. Therefore, the flow of the power is from DC bus 2 to DC bus 1.

![VMM control strategy characteristics](image)

Two methods are proposed in the literature to change the direction of power flow. In the first method, the reference power of converter 1 is changed (Figure 3.2(a)), and in the second method, the reference voltage of converter 2 is changed, which is shown in Figure 3.2(b). In the latter, both characteristics cross the vertical axis. As a result, if one converter stops working, the other one can work at \( P_{inj} = 0 \). In other words it can supply the reactive power, i.e. working as a STATic synchronous COMpensator (STATCOM) [22].

As it can be seen in Figure 3.1, if converter 1 reaches its limits or stops operating, converter 2 is responsible for control of DC voltage. However, if converter 1 reaches its limit and converter 2 cannot control the DC voltage, the DC voltage will be out of control [52]. Considering the delays in communication [53], some authors proposed a VMM controller with two stages [21, 52], whose \( V_{dc} - P_{inj} \) characteristic is shown in Figure 3.3.
In this strategy, there are two constant voltage levels. Each of these levels has a maximum and minimum allowable injected power. If the injected power of the converter reaches these values, it switches to CPM. If the voltage changes again and reaches to one of these constant voltage levels, it switches again to the VCM. The two-stage characteristic has two other advantages. First, the active power in all terminals can be set by changing $P_{\text{ref}}$. Second, it would be possible to assign a certain amount of importance to each terminal; for example, if one converter is connected to a very strong AC grid which can produce as much active power
as needed, then $P_{\text{min}}$ and $P_{\text{max}}$ can be chosen far from each other. Therefore, this converter can operate as the slack in the system [22].

Since VSCs can operate both as rectifier and inverter, [52] suggests that another stage, can also be added to the converter control characteristics. In this thesis, ordinary (single-level) VMM is considered. Figure 3.4 shows the block diagram of VMM controller for converter $i$ when the injection model is used. As shown in

Figure 3.4: VMM controller for converter $i$ when the injection model is used.

the figure, a Proportional-Integral (PI) controller is used. If the injected power hits one of the limits ($P_{\text{max}}^{\text{inj}}$ or $P_{\text{min}}^{\text{inj}}$), terminal $i$ switches to CPM. If AC/DC model is used, the controller is implemented as shown in Figure 3.5. The controller gives the reference values of the $d$-axis and $q$-axis currents to the inner controller.

Figure 3.5: VMM controller for terminal $i$ when the AC/DC model is used.
3.3. Voltage droop method

Another proposed method in the literature is Voltage Droop Method (VDM) [22, 54, 55]. If more than one converter are supposed to participate in the DC voltage control, VDM is a reliable method, which does not need any communication between converters [11, 56, 57]. In this method some or all converters change their injected active powers according to pre-defined $V_{dc} - P_{inj}$ droops [22]. Figure 3.6 shows this characteristic.

![Figure 3.6: VDM control strategy characteristics for a two-terminal HVDC system.](image)

As can be seen, converters 1 and 2 are operating at $OP1$ and $OP2$, respectively. It must be noted that in this figure, for convenience, it is supposed that the voltages of DC buses are equal. However, this is not the case in reality.

It must be stated that, some authors [23, 31, 58] use $V_{dc} - P_{inj}$ characteristic for voltage droop control, whereas others [17, 25, 57] studied $V_{dc} - I_{inj}$ characteristic.

DC voltage droop control has some disadvantages. Considering the type of the system, application of VDM leads to steady-state voltage deviation. The controller adjusts power according to this voltage deviation. Considering that the voltage deviation is not equal in all DC buses (especially when buses are located very far from each other and as a result the DC resistance is large), the power is not shared proportional to the droops of converters. Moreover, if the network topology changes, the droop characteristic is not valid anymore [52].

Employing high droop gain leads to large DC voltage deviation. On the other hand, AC grid $i$ considers the changes in the $P_{inj,i}$ as a disturbance and low droop gain results in large disturbance from the corresponding AC grid point of view.

Figures 3.7 and 3.8 represent the block diagram of the VDM controller when injection model and AC/DC model is used, respectively.
Comparing Figures 3.5 and 3.8, it is evident that only DC voltage controllers are different in these two methods. While VMM uses a PI controller, VDM utilizes a proportional controller.

The VDM used in this thesis is ordinary (proportional) VDM. However, some authors propose another schemes for VDM [18]. As an example, we mention the priority power sharing VDM. In the systems with priority power sharing, some terminals have precedence over others in receiving or giving power. For instance, as shown in Figure 3.9, converter 2 does not participate in DC voltage control. If the voltage increases and reaches $V_{dc,2}^{min}$, converter 2 starts to extract active power from the MTDC system and controls the DC voltage.
3.4. MULTI-AGENT CONTROL

Mathematical background

Since Multi-Agent Systems (MAS) utilize graph theory, in this section a very short introduction to graph theory is given.

Consider a graph \( G = \{V, \varepsilon\} \) consisting of a set of vertices (nodes) \( V = \{1, \ldots, N\} \) and edges \( \varepsilon \), as shown in Figure 3.10, where

\[
a_{ij} = \begin{cases} 
1 & \text{if nodes } i \text{ and } j \text{ are adjacent} \\
0 & \text{otherwise} 
\end{cases} \quad (3.1)
\]

If there is a link or edge between two nodes \( i \) and \( j \), they are called adjacent nodes i.e., \( \varepsilon = \{(i, j) \in V \times V : i, j \text{ adjacent}\} \). A graph is called 'connected' if there is a path connecting each two nodes together. The distance between two nodes is the shortest path with minimum number of edges that connects those nodes and is shown by \( d(i, j) \). The degree matrix \( D \) with the elements of \( d_i \) is a diagonal matrix whose elements are the cardinality of agent \( i \) neighbor set \( N_i = \{j \in V : (i, j) \in \varepsilon\} \).

Figure 3.10 shows an information graph. As can be seen, \( N_1 \) consists of nodes 2, 3 and 6. A tree is defined as a undirected graph in which any two nodes are
Figure 3.10: Information graph $G$.

connected by only one simple path. A spanning three is a tree which consists of all nodes of a graph. One of the most important matrices in graph theory, which reflects significant characteristics of the graph is Laplacian matrix. The $ij$–th element of the Laplacian matrix $L$ is determined as

$$l_{ij} = \begin{cases} 
\sum_{k=1, k \neq i}^{n} a_{ik} & j = i \\
-a_{ij} & j \neq i 
\end{cases}$$

(3.2)

Considering undirected graph as shown in Figure 3.10, the Laplacian matrix is symmetric and positive semi-definite in which the sum of the elements in each row is zero. Therefore, $L$ has a zero eigenvalue, i.e. $\lambda_1 = 0$. The second smallest eigenvalue ($\lambda_2$) is called connectivity of the graph. In a connected undirected graph we have [59]:

$$0 = \lambda_1 < \lambda_2 \leq \ldots \leq \lambda_n$$

(3.3)

Consider a graph, in which each node $i$ has the following control law:

$$u_i = \sum_{j \in \mathcal{N}_i} -a_{ij}(x_i - x_j)$$

(3.4)

where $u_i$ is the control input and $x_i$ is state variable. We say nodes of the network reach a consensus if and only if $x_i = x_j = \ldots = x_n = x^*$. Then, the dynamic of the
3.4. **MULTI-AGENT CONTROL**

The system can be written as

\[
\dot{x}(t) = -\mathcal{L}x(t)
\]  

(3.5)

Since eigenvalues of \(\mathcal{L}\) are positive, eigenvalues of \(-\mathcal{L}\) are in Left-Hand Plane (LHP). Therefore the system is stable. One can show that the nodes of the undirectional graph reaches consensus if and only if there is a spanning tree in the graph [60].

**Application to MTDC system**

Consider an MTDC system consisting of several converters. Each terminal is considered as a node in the graph. Some terminals like the ones connected to wind farms or offshore oil and gas platforms operate in CPM. Other nodes contribute in DC voltage control. If a disturbance occurs in the system, these nodes share the power balancing task to control the DC voltage. An agent is assigned to each node that participates in DC voltage control. Figure 3.11 shows the overlaid communication graph assigned to the MTDC system.

![Multi-Agent Information Graph](image)

**Figure 3.11:** Agent configuration in MAS system applied to a 7-terminal MTDC.

Different communication technologies are available. Among them, satellite and optic fiber may be the most promising technologies for our purpose. However, considering that the MTDC system has a very fast dynamic, optic fiber, which
is faster than satellite - seems to be a more attractive choice. Each agent receives information from its local measurement \( (x_i(t)) \) and from other agents \( (x_j(t)) \). According to communication delays, this cannot be in real time. Therefore, it is supposed that each agent receives this information with \( t_d \) seconds delay. Figure 3.12 shows the structure of agent \( i \), which is assigned to node \( i \).

![Agent configuration in MAS system](image)

**Figure 3.12:** Agent configuration in MAS system.

The proposed MAS methods behave similar to VDM, with exception that the reference value of the voltage will be controlled. Since the dynamic of the MTDC system is very fast, the proposed control strategies in this thesis cannot rely only on remote information. The controllers consist of two parts: fast-response part and medium-response part. The fast response part is a VDM controller. The medium-response part deals with updating the reference voltages of converters in real-time. The MAS control strategies update the reference voltage of each converter with time, which means that the characteristic of the converter shifts upwards or downwards. Figure 3.13 demonstrates how the operating point of converter \( i \) varies during the DC voltage control process. As shown in this figure, when disturbance occurs, the operating point shifts from point 0 to point 1. When the reference voltage is updated, the DC voltage does not change immediately. The operating point is transferred to a new characteristic (point 2) and more active power will be injected. Then the DC voltage is increased (point 3). Since this DC voltage is still less than the initial DC voltage, the control system changes the reference voltage again and this process continues until operating point reaches point \( n \).

The algorithm presented in Figure 3.14 demonstrates how the agent \( i \) controls the DC voltage at terminal \( i \).

As can be seen, first, it calculates the amount of injected power to the MTDC grid. This power cannot be more (less) than maximum (minimum) allowable power of the terminal. Then the equation of MAS is solved and the voltage reference is
updated. If the system has reached the desired value, it stops updating reference values, otherwise the reference values will be updated again.

Figures 3.15 and 3.16 show the block diagram of the MAS controller for injection model and AC/DC model, respectively.
Multi-agent system strategies

Different Multi-Agent System (MAS) strategies are proposed in this thesis. Each of these strategies has its own goals and limitations.

Strategy 1

In this strategy the dynamic of the controller can be expressed by

\[
\begin{align*}
    u_i &= K_{pi}(V_{dcref} - V_{dc,i}) \\
    V_{dcref} &= \alpha_i \times (V_{dcref,0} - V_{dc,i}) + \sum_{j \in N_i} \beta_j \times (V_{dcref,0} - V_{dc,j})
\end{align*}
\]  

(3.6)

where, \(N_i\) denotes the set of converters, which participating in the DC voltage control and can communicate with converter \(i\), \(V_{dcref,0}\) is the initial reference voltage of converter \(i\), and \(\alpha_i\) and \(\beta_j\) are constants, which determine the participation of the
local information of agent $i$ and the information from the other agents in the behavior of agent $i$, respectively. If there is no communication between agents, then $\beta = 0$ and only the local information of each agent affects its behavior.

According to the multi-agent theory, if a disturbance happens, this controller tries to make the DC voltages of terminals equal to their initial voltage. But, since the power flow in the system has been changed, this is not possible to reach the previous equilibrium point. Therefore, each controller stops updating the reference values when the DC voltage is close enough to the initial value.

**Strategy 2**

As mentioned in Section 3.3, when a disturbance happens in the MTDC system, the deviation of the DC voltages from their initial voltages are not exactly equal. Therefore, the power imbalance will not be divided proportional to the droop gains. In [61], we have shown this fact using another argument.

In this strategy, the goal of this controller is to make voltage deviations $(x_i(t) = V_{dc,i}^{ref,0}(t) - V_{dc,i}(t))$ equal.

The proposed distributed controller takes the following form:

$$
u_i = K_{p,i} (V_{dc,i}^{ref} - V_{dc,i})$$

$$
\dot{V}_{dc,i}^{ref} = -\gamma \sum_{j \in N_i} \phi_{ij} \left( (V_{dc,j}^{ref} - V_{dc,j}) - (V_{dc,i}^{ref} - V_{dc,i}) \right)
$$

(3.7)

where $\phi_{ij} = \phi_{ji} > 0$ and $\gamma > 0$ are constants. These converters can be considered as an agent. In this set-up, the state of these converters is the difference between its DC voltage setting and the measured DC voltage. These agents with single integrator dynamic and DC voltage states can come to a global agreement on their states if they share their states.

**Strategy 3**

This strategy is a combination of VMM, VDM and MAS strategies. This method is based on leader-follower MAS theory [62, 63]. In this theory some agents are considered as leaders, while other agents are considered as followers. Each set of followers, follows one of the leaders and each agent has its own goal.

The aim of controller is to recover the DC voltage as close as possible to the initial voltage, while at the same time makes the power distribution proportional to the droop gains ($K_{p,i}$). To achieve this goal, one agent is selected as the
leader (slack converter), while other agents follow this converter. The consensus is reached for voltage deviation of all buses, therefore the expected power sharing will be achieved. On the other hand, reference voltages of all converters follow the reference voltage of the slack converters. Therefore, the voltage will be close to the initial voltage.

Suppose that converter \( m \), without loss of generality, is regulating DC voltage to its value before the disturbance. The proposed distributed controller takes the form

\[
\dot{V}_{dc,m}^\text{ref} = K_V(V_{dc,m}^\text{ref,0} - V_{dc,m}) - \gamma \sum_{j \in N_m} \phi_{mj} \left( (V_{dc,m}^\text{ref} - V_{dc,m}) - (V_{dc,j}^\text{ref} - V_{dc,j}) \right)
\]  (3.8)

where \( K_V = 1 \). For converter \( i (i \neq m) \), the control law is like (3.7).

The first row of (3.8) (fast response) ensures that the controlled injected currents are quickly adjusted after a change in the voltage. The second row ensures that the voltage is restored at converter \( m \) by integral action, and that the controlled injected currents are proportional to the proportional gains \( K_{p,i} \) at stationarity. In vector-form, (3.8) can be written as

\[
\begin{align*}
\mathbf{u} &= K_P (V_{dc}^\text{ref} - V_{dc}) \\
\dot{V}_{dc}^\text{ref} &= K_V (V_{dc,m}^\text{ref,0} - V_{dc,m}) - \gamma \mathbf{\phi} (V_{dc}^\text{ref} - V_{dc})
\end{align*}
\]  (3.9)

where \( \gamma = \text{diag}(\gamma_1, \ldots, \gamma_n) \), \( K_P \) is defined as before, \( K_V \) is a \( n \times n \) matrix whose elements are zero except its \( m \)-th diagonal element, which is equal to 1, and \( \mathbf{\phi} \) is the weighted Laplacian matrix of the graph representing the communication topology, whose edge-weights are given by \( \phi_{ij} \), and which is assumed to be connected.

In [61], we have shown that this controller results in a stable closed loop system (for Injection model) if

\[
\begin{align*}
\lambda_{\min} \left( \frac{1}{2} \mathbf{C} \mathbf{L}_R + \frac{1}{2} \mathbf{L}_R \mathbf{C} \right) + \min_i C_i K_{P,i} &> 0 \\
\lambda_{\min} \left( \frac{1}{2} \mathbf{L}_\phi \mathbf{C} \mathbf{L}_R + \frac{1}{2} \mathbf{L}_R \mathbf{C} \mathbf{L}_\phi \right) &> 0
\end{align*}
\]  (3.10)  (3.11)

where \( \mathbf{C} = \text{diag}(C_1^{-1}, \ldots, C_n^{-1}) \) and \( C_i \) is the aggregated capacitance of converter \( i \) (see Figure 2.1), \( \mathbf{L}_R \) is the weighted Laplacian matrix of the graph representing the transmission lines whose edges are equal to \( g_{ij} \) (see (2.3)) and \( \lambda_i \) is
the $i$-th eigenvalue of $L_R$. We have shown that for a sufficiently large $K_{P_i}$ and a sufficiently small $\gamma_i$ such that the first condition will be fulfilled. Also, if the topology of the communication network is identical to the topology of the power transmission cables up to a positive scaling factor, the second condition will also be fulfilled.

### 3.5 Sliding mode control

As mentioned in chapter 1, Sliding Mode Control (SMC) is a variable structure control, which is originally used for systems whose dynamics can be modelled with ordinary differential equations [44].

SMC has some features like insensitivity to parameter variations, external disturbance rejection and fast dynamic response. Considering that the values of the parameters of the system may change and also considering the fast dynamic of the MTDC grid, SMC can be a good option for controlling the MTDC grid. Moreover, if the value of each of the parameters in the system changes (due to uncertainty or any other reason), SMC still has a good performance. On the other hand, since in SMC best approximation of the plant is used, it can control the voltage of a bus without knowing the exact voltage of adjacent buses. In this thesis, SMC is applied to the AC/DC model.

### Mathematical background

Two approaches for SMC design are discussed in this thesis: basic control and integral control:

**Basic control**

Suppose that $\tilde{x} = x - x_{ref}$ is the traction error of variable $x$. Consider a time-varying surface $S(x,t)$:

$$S(x,t) = \left( \frac{d}{dt} + \lambda \right)^{n-1} \tilde{x}$$

where, $\lambda$ is a strictly positive constant and $n$ is the relative degree of the variable $x$. Sometimes output variable $V_{dc,i}$ is not expressed explicitly based on control inputs. If we differentiate an output variable $n$ times, control inputs appear in the expression. Then, the output variable is told to have relative degree of $n$. Remaining on
the manifold $S = 0$ is equal to having zero tracking error. SMC converts the tracking control problem into a first-order differential equation. In such a system, if the error is negative, it is simply enough to push hard in positive direction [64].

Generally, if the system trajectory satisfies a generalized Lyapunov stability requirement to the surface $S = 0$, there exists a sliding mode on manifold $S = 0$. Based on lyapunov stability requirement, the sliding mode exists if $u$ is chosen such that

$$\frac{1}{2} \frac{d}{dt} S^2 \leq -\eta |S|$$  \hspace{1cm} (3.13)$$

where $\eta$ is a strictly positive constant. Therefore, the state trajectory reaches the sliding surface in less than $s(t = 0)/\eta (s)$ and slides along the surface toward $x_{ref}$ exponentially with a time constant equal to $\frac{1}{\lambda}$ [64].

If the dynamics of the system is known, an equivalent control term ($u_{eq}$) is chosen so that the system remains on the sliding surface ($\dot{S} = 0$). If the dynamics is not exactly known, the best estimation of the dynamics is used and the equivalent term ($\hat{u}_{eq}$) is calculated.

$$u = \hat{u}_{eq}$$  \hspace{1cm} (3.14)$$

On the other hand $u$ must satisfy the equation (3.15):

$$u = \begin{cases} u^+ & \text{if } S(x) > 0 \\ u^- & \text{if } S(x) < 0 \end{cases}$$  \hspace{1cm} (3.15)$$

where $u^+ < u_{eq}$ and $u^- > u_{eq}$. Therefore a switching function $u_{sw} = k \text{sgn}(S)$ must be added to the $u$, where $k$ is a positive scalar and $\text{sgn}(\cdot)$ is the sign function. Therefore:

$$u = \hat{u}_{eq} - u_{sw}$$  \hspace{1cm} (3.16)$$

Suppose that we have an equation of the general form

$$\dot{x} = F + u$$  \hspace{1cm} (3.17)$$

Consider (3.12) for the case of $n = 1$. Then,

$$\dot{S} = F + u - x^{ref}$$  \hspace{1cm} (3.18)$$
3.5. SLIDING MODE CONTROL

In order to fulfill the requirement of stability ($\dot{S} = 0$), we must have

$$u_{eq} = -F + \dot{x}^{ref} \tag{3.19}$$

For the equations of the general form

$$\ddot{x} = F + u, \tag{3.20}$$

equation (3.12) with $n = 2$ then gives:

$$\dot{S} = F + u - \dot{x}^{ref} + \lambda \dot{x} \tag{3.21}$$

Therefore the equivalent control input must be

$$u_{eq} = -F - \lambda \dot{x} + \ddot{x}^{ref} \tag{3.22}$$

**Integral control**

Based on (3.12), if we consider $\int_0^t \ddot{x}(t')dt'$ as the error we want to be eliminated, then the sliding surface can be expressed as

$$S(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \left( \int_0^t \ddot{x}(t')dt' \right) = \dot{x} + 2\lambda \dot{x} + \lambda^2 \int_0^t \ddot{x}(t')dt' \tag{3.23}$$

Next, we choose the equivalent control so that $\dot{S} = 0$:

if $n = 1$:

$$\dot{S} = F + u - \dot{x}^{ref} + \lambda \dot{x} \tag{3.24}$$

$$u_{eq} = -F + \dot{x}^{ref} - \lambda \dot{x} \tag{3.25}$$

if $n = 2$

$$\dot{S} = F + u - \dot{x}^{ref} + 2\lambda \dot{x} + \lambda^2 \dot{x} \tag{3.26}$$

$$u_{eq} = -F - 2\lambda \dot{x} - \lambda^2 \dot{x} + \ddot{x}^{ref} \tag{3.27}$$


**3.6 Application to MTDC system**

In this section the SMC controllers are applied AC/DC model of MTDC presented in 2.1. The output variable can be DC voltage (or active power) and reactive power (or AC voltage). Considering (2.24) and (2.25), if the aim is to control the active power, we choose the output vector \( \mathbf{h}_{1,i} \). If the DC voltage is of interest, \( \mathbf{h}_{2,i} \) is chosen as output vector.

\[
\mathbf{h}_{1,i} = \begin{bmatrix} V_{dc,i} \\ I_{q,i} \end{bmatrix}, \quad \mathbf{h}_{2,i} = \begin{bmatrix} I_{d,i} \\ I_{q,i} \end{bmatrix}
\]  

(3.28)

In this study, \( V_{dc,i} \) has relative degree of 2, because the control inputs appear in \( \dot{V}_{dc,i} \). However, \( I_{d,i} \) and \( I_{q,i} \) have relative degree of 1.

If \( \mathbf{h}_{1,i} \) is considered as output vector, the new output variables can be written as

\[
\begin{bmatrix}
\dot{h}_{1,i}(1,1) \\
\dot{h}_{1,i}(2,1)
\end{bmatrix} = \begin{bmatrix} \dot{V}_{dc,i} \\ \dot{I}_{q,i} \end{bmatrix} = \mathbf{F}_i(\mathbf{x}_i) + \mathbf{B}_i(\mathbf{x}_i)u_i
\]

(3.29)

where,

\[
\mathbf{F}_i(\mathbf{x}_i) = \begin{bmatrix} F_{1,i} \\ F_{2,i} \end{bmatrix}
\]

(3.30)

\[
\mathbf{B}_i(\mathbf{x}_i) = \begin{bmatrix} \frac{(U_{d,i} - 2r_iq_i)}{\epsilon c_i V_{dc,i}}(\frac{-1}{n}) \\ \frac{(U_{q,i} - 2r_iq_i)}{\epsilon c_i V_{dc,i}}(\frac{-1}{n}) \end{bmatrix}
\]

(3.31)

with

\[
F_{1,i} = \frac{(U_{d,i} - 2r_iq_i)}{c_i V_{dc,i}}f_{1,i} + \frac{(U_{q,i} - 2r_iq_i)}{c_i V_{dc,i}}f_{2,i} + \left( \frac{-1}{c_i V_{dc,i}^2} \left( U_{d,i}I_{d,i} + U_{q,i}I_{q,i} - r_i(I_{d,i}^2 + I_{q,i}^2) \right) - \sum_{i=j}^{N} \frac{R_{ij}}{c_i} \right) f_{3,i}
\]

(3.32)

\[
F_{2} = f_{2,i}
\]

\( f_{1,i} \), \( f_{2,i} \) and \( f_{3,i} \) in the above equations are given in (2.19).
3.6. APPLICATION TO MTDC SYSTEM

Consider now the second output vector \( \mathbf{h}_{2,i} \). The dynamics of terminal \( i \), based on new variables, can be written as

\[
\begin{bmatrix}
    h_{2,i}(1,1) \\
    h_{2,i}(2,1)
\end{bmatrix} =
\begin{bmatrix}
    \dot{I}_{d,i} \\
    \dot{I}_{q,i}
\end{bmatrix} = \mathbf{E}_i(x_i) + \mathbf{D}_i \mathbf{u}_i
\]  
(3.33)

where

\[
\mathbf{E}_i(x_i) = \begin{bmatrix} f_{2,i} \\
    f_{1,i}
\end{bmatrix}, \text{ see (2.19)} 
\]  
(3.34)

\[
\mathbf{D}_i = \begin{bmatrix}
    \frac{1}{r} & 0 \\
    0 & -\frac{1}{r}
\end{bmatrix}
\]  
(3.35)

The controller structure is shown in Figure 3.17. As long as \( V_{dc,i} \) is not equal to its reference voltage, converter \( i \) will remain in CPM. In this case the output vector is \( \mathbf{h}_{2,i} \). After \( V_{dc,i} \) reaches \( V_{dc,i}^{ref} \), the converter \( i \) switches to the VCM. In this case SMC regulates \( V_{dc,i} \) at \( V_{dc,i}^{ref} \) and the output vector is \( \mathbf{h}_{1,i} \).

![Figure 3.17: SMC controller for converter i when the AC/DC model is used.](image)

In the figure, \( \tilde{V}_{dc,i}, \tilde{I}_{d,i} \) and \( \tilde{I}_{q,i} \) represent the tracking errors of \( V_{dc,i}, I_{d,i} \) and \( I_{q,i} \), respectively, which are expressed by

\[
\begin{align*}
    \tilde{V}_{dc,i} &= V_{dc,i} - V_{dc,i}^{ref} \\
    \tilde{I}_{d,i} &= I_{d,i} - I_{d,i}^{ref} \\
    \tilde{I}_{q,i} &= I_{q,i} - I_{q,i}^{ref}
\end{align*}
\]  
(3.36)
Suppose that converter $i$ controls the DC voltage and reactive power. The equivalent control terms for basic and integral controls are chosen as follows:

**Basic control**

As mentioned in Section 4.2, $V_{dc,i}$ has relative degree 2, while $I_{d,i}$ and $I_{q,i}$ have relative degree 1. For slack terminal, according to (3.19) and (3.22), the equivalent control can be written as

$$u_{eq,i}^{h_1} = -F_i + \begin{bmatrix} \dot{V}_{dc,i}^{ref} - \lambda_i \dot{V}_{dc,i}^{ref} \\ \dot{I}_{q,i}^{ref} \end{bmatrix} \quad (3.37)$$

For other terminals, where the output vector is $h_2$, we obtain the following control input:

$$u_{eq,i}^{h_2} = -E_i + \begin{bmatrix} \dot{I}_{d,i}^{ref} \\ \dot{I}_{q,i}^{ref} \end{bmatrix} \quad (3.38)$$

Assuming there is no communication available between terminals and each terminal does not have access to DC voltages of other terminals, then $F_i(x_i)$ and $E_i(x_i)$ are not exactly known, but it has a bounded imprecision. As a result we use the best estimation of these vector fields (indicated by $\hat{F}_i(x_i)$ and $\hat{E}_i(x_i)$) to calculate equivalent term. In addition, we write the equivalent control terms given in (3.38) and (3.37) as $\hat{u}_{eq,i}$. Therefore, the controller needs a switching (discontinuous) term as mentioned in (3.16) and (3.15). For $h_{1,i}$, this term can be written as

$$u_{sw,i}^{h_1} = \begin{bmatrix} -k_{1,i} \text{sgn}(S_{1,i}) \\ -k_{3,i} \text{sgn}(S_{3,i}) \end{bmatrix} \quad (3.39)$$

and for $h_{2,i}$

$$u_{sw,i}^{h_2} = \begin{bmatrix} -k_{2,i} \text{sgn}(S_{2,i}) \\ -k_{3,i} \text{sgn}(S_{3,i}) \end{bmatrix} \quad (3.40)$$

where

$$S_{1,i} = \ddot{V}_{dc,i} + \lambda_i \dot{V}_{dc,i} \quad (3.41)$$

$$S_{2,i} = \dot{I}_{d,i} \quad (3.42)$$

$$S_{3,i} = \dot{I}_{q,i} \quad (3.43)$$
3.6. APPLICATION TO MTDC SYSTEM

and \( k_{1,i}, k_{2,i} \) and \( k_{3,i} \) are positive constants.

In order to have a more smooth control law, the \( \tanh \) function can be used instead of sign function. Therefore, the equations can be restated as

\[
\begin{align*}
\mathbf{u}_{sw,1}^h &= \begin{bmatrix} -k_{1,i} \tanh(S_{1,i}) \\ -k_{3,i} \tanh(S_{3,i}) \end{bmatrix} \\
\mathbf{u}_{sw,2}^h &= \begin{bmatrix} -k_{2,i} \text{sgn}(S_{2,i}) \\ -k_{3,i} \text{sgn}(S_{3,i}) \end{bmatrix}
\end{align*}
\tag{3.44}
\tag{3.45}
\]

Finally, according to (3.29), (3.33) and (3.16), the complete control input is

\[
\mathbf{u}_i^h = \mathbf{B}_i^{-1} \left( \mathbf{u}_{eq,i}^h - \mathbf{u}_{sw,i}^h \right)
\tag{3.46}
\]

Similarly, for \( h_{2,i} \) we obtain

\[
\mathbf{u}_i^h = \mathbf{D}_i^{-1} \left( \mathbf{u}_{eq,i}^h - \mathbf{u}_{sw,i}^h \right)
\tag{3.47}
\]

**Integral control**

If \( h_{1,i} \) is chosen as the output vector, the equivalent control input is

\[
\mathbf{u}_{eq,i}^h = -\hat{\mathbf{F}}_i + \begin{bmatrix} V_{ref}^{dc,i} - 2\lambda_i \hat{V}_{dc,i} - \lambda_i^2 \hat{V}_{dc,i} \\ I_{ref}^{q,i} - \zeta_i \hat{I}_{q,i} \end{bmatrix}
\tag{3.48}
\]

Similarly, for \( h_{2,i} \) we have the following control input:

\[
\mathbf{u}_{eq,i}^h = -\hat{\mathbf{E}}_i + \begin{bmatrix} \dot{I}_{d,i}^{ref} - \bar{\xi}_i \hat{I}_{d,i} \\ \dot{I}_{q,i}^{ref} - \bar{\xi}_i \hat{I}_{q,i} \end{bmatrix}
\tag{3.49}
\]

Switching terms are calculated using (3.39) and (3.40), but the sliding surfaces are defined as follows:

\[
\begin{align*}
S_{1,i} &= \hat{V}_{dc,i} + 2\lambda_i \hat{V}_{dc,i} + \lambda_i^2 \int_0^t \hat{V}_{dc,i} dt \\
S_{2,i} &= \hat{I}_{d,i} + \bar{\xi}_i \int_0^t \hat{I}_{d,i} dt \\
S_{3,i} &= \hat{I}_{q,i} + \bar{\zeta}_i \int_0^t \hat{I}_{q,i} dt
\end{align*}
\tag{3.50}
\tag{3.51}
\tag{3.52}
\]

where \( \bar{\xi}_i \) and \( \bar{\zeta}_i \) are positive constants.
3.7 $\mathcal{H}_\infty$ control design

In the $\mathcal{H}_\infty$ control design method, a feedback controller is sought to stabilize the closed-loop system and satisfy a prescribed level of performance to achieve reference tracking and disturbance attenuation. In this thesis, since all the states of the system are measurable, the $\mathcal{H}_\infty$ state-feedback is chosen as the control strategy.

Let us consider the following state-space representation for an LTI system

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + B_1 d(t) + B_2 u(t) \\
y(t) &= x(t) \\
z(t) &= C_1 x(t) + D_{11} d(t) + D_{12} u(t)
\end{align*}
\]

(3.53)

where $x(t) \in \mathbb{R}^n$ is the state vector, $y(t) \in \mathbb{R}^n$ is the measurement vector, $z(t) \in \mathbb{R}^n$ is the vector of controlled outputs (representing a predefined performance like error or control effort), $d(t) \in \mathbb{R}^n$ is exogenous disturbance vector and process noise signals with finite energy, and $u(t) \in \mathbb{R}^n$ is the control input vector.

The first step is to select a pair of inputs and outputs to reflect the system performance requirements and then design a controller by minimizing the maximum energy-to-energy gain of the corresponding transfer matrix. The $\mathcal{H}_\infty$ state-feedback controller seeks for

\[
u(t) = Kx(t)
\]

(3.54)

to minimize the energy-to-energy gain of the system from disturbance $d(t)$ to output $z(t)$. Alternatively, the $\gamma$-suboptimal $\mathcal{H}_\infty$ control problem seeks for a controller that yields the energy-to-energy gain less than a positive scalar $\gamma$ [65]. Note that the $\gamma$-suboptimal design guarantees that the output vector energy will be bounded by $\gamma\|d\|_{L_2}$ for all possible bounded energy disturbance inputs $d(t)$. For the sake of simplicity, we first consider the problem of regulation, i.e., designing the state-feedback controller (3.54) such that the states of the system asymptotically converge to zero, regardless of the initial values of the states or the presence of disturbances while the control effort is of affordable magnitude. Indeed, the control design objective is not only to regulate the states and reject the exogenous output disturbances, but also to keep the control action below a threshold due to the maximum power limitation of converters. Afterwards, by a mapping, we can easily handle the problem of reference tracking in which the states of the system track a desired values not necessarily zero. We can also use weighting functions to weight minimization of the elements of the vector $z$.

Figure 3.18 shows the augmentation of the weighting function with the open-loop system ($G(s)$) and the state-feedback controller [66].
3.7. $\mathcal{H}_\infty$ CONTROL DESIGN

In this section, we provide the $\mathcal{H}_\infty$ state-feedback control design formulation in terms of a Linear Matrix Inequality (LMI) problem.

**Theorem 1:** Assuming that the augmented system in Figure 3.18 is described by the state-space representation (3.53), there exists a state-feedback control law (3.54), which stabilizes the system and guarantees an upper bound $\gamma$ on the energy-to-energy gain of the closed-loop system from disturbance $d(t)$ to the vector $z(t)$, if there exist a positive-definite $X \in \mathbb{R}^{n \times n}$ and $W \in \mathbb{R}^{nu \times n}$ such that

$$
\begin{bmatrix}
\dot{X} + AX + XA^T + B_1W + W^TB_2^T & B_1 & \begin{bmatrix} 0 & I \end{bmatrix} \\
B_1^T & -\gamma I & D_{11} \\
C_1X + D_{12}W & D_{11} & -I
\end{bmatrix}
< 0 \quad (3.55)
$$

$$
K = WX^{-1}. \quad (3.56)
$$

**Proof:** See [67].

Note that since it is supposed that the controllers in this method only use the local information, we want to design a block diagonal controller so that the comprising subsystems of (3.53) become decoupled. In this way, each subsystem is controlled independently by feeding the state variables of itself, without needing the information of other subsystems. In order to derive a block diagonal controller matrix $K$, it is required to constrain the structure of LMI variables $X$ and $W$ in Theorem 1 to be block diagonal. To solve this inequality we use MATLAB LMI toolbox to solve the Theorem 1 which support different structures of the LMI variables.
CHAPTER 3. CONTROL STRATEGIES

including block diagonal. So far, we have designed a controller for the regulation problem. Now, we must consider the tracking problem of nonzero reference inputs by performing a mapping on the controller matrix $K$ derived in Theorem 1.

Reference tracking

Consider the open loop system (3.53) without external disturbance $d$, and let $y_d$ denote the desired constant value for output $y$. Since in general $y_d \neq 0$, the state variable $x$ and control input $u$ converge to nonzero steady state value $x^*$ and $u^*$, respectively. Therefore, after asymptotic convergence of these variables, we have

$$
\begin{bmatrix}
A & B_2 \\
C & 0
\end{bmatrix}
\begin{bmatrix}
x^* \\
u^*
\end{bmatrix} =
\begin{bmatrix}
0 \\
y_d
\end{bmatrix}.
$$

(3.57)

By tacking matrix inversion, we can deduce $x^* = My_d$ and $u^* = Ny_d$. Defining new variables $\Delta x = x - x^*$ and $\Delta u = u - u^*$, the tracking problem becomes a regulation problem for which we solved the controller $K$ in Theorem 1. Therefore, for the tracking problem we have $u = u^* + \Delta u = u^* - K\Delta x = u^* - K(x - x^*)$. Replacing for steady state values $x^*$ and $u^*$, we obtain $u = Ny_d + K(My_d - x)$.

The configuration of the closed-loop system for the tracking problem is shown in Figure 3.19.

![Figure 3.19: Reconfiguration of the closed-loop system for set point tracking.](image)

Application to MTDC system

As stated before, using $\mathcal{H}_\infty$ controller, we can reach a specific level of performance. The controller can control the DC voltage and meanwhile can control the injected...
power of converters and current of some DC lines. It can also make the participation of converters proportional to their available headroom. None of the other mentioned methods, has these capabilities.

In this thesis, we apply $H_\infty$ method only on Injection model. According to (2.5), in (3.53) we have:

$$x(t) = x_{DC} \quad \text{and} \quad u(t) = u_{DC}$$

We design an $H_\infty$ control for the MTDC system so that for each terminal the tracking error of the DC voltage (deviation of DC voltage from its reference value) is minimized, the control input is of low amplitude and also the currents of one or some of the DC lines is within a reasonable range. By stacking these quantities, we construct the vector as shown in Figure 3.18. The weighting functions signify how each of these values contribute in the minimization process.

For instance, here, we explain the procedure of selection of weights for the control inputs. Each converter has a maximum allowable injected power. The difference between this power and the power which is being injected by the converter, is called headroom. We define the headroom index of converter $i$ ($\Xi_i$) as

$$\Xi_i = \frac{\Upsilon_i}{\sum_{j=1}^{n} \Upsilon_i}$$

where $\Upsilon_i$ is the available headroom of converter $i$ and $n$ is the number of converters. We determine the gain of each controller proportional to the headroom index of each converter. To achieve this goal we choose gains such that $w_u = (\Xi_i)^{-1}$. Now the question is which maximum limit of the converter must be consider to calculate $\Upsilon_i$. For each converter, we calculate two $\Upsilon_i$, i.e. one when increasing $P_{inj,i}$, and the other one when decreasing $P_{inj,i}$. As a result, $H_\infty$ controller uses two different droops depending on the disturbance.
Chapter 4

Case studies

4.1 Introduction

Consider the 4-terminal MTDC system shown in Figure 4.1. The initial values of the voltages at the DC buses, injected powers to the DC buses as well as reference voltages of converters are given in Table 4.1. Also, the maximum allowable injected powers of converters are shown in this table. The parameters of the DC cables are shown in Table 4.2.

Terminal 4 connects a wind farm to the MTDC system and harvests maximum power from the wind farm, therefore it does not contribute to the DC voltage control. This converter also needs to control the AC voltage at wind farms side.

Table 4.1: Initial values of the simulation and reference voltages of terminals for both SMC and VMM.

<table>
<thead>
<tr>
<th></th>
<th>Converter 1</th>
<th>Converter 2</th>
<th>Converter 3</th>
<th>Converter 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC voltage (p.u.)</td>
<td>1.0</td>
<td>0.9957</td>
<td>1.0009</td>
<td>0.9964</td>
</tr>
<tr>
<td>$P_{inj}$ (p.u.)</td>
<td>-0.2824</td>
<td>-0.7143</td>
<td>0.8571</td>
<td>0.1429</td>
</tr>
<tr>
<td>$V_{ref}^{dc,i}$ (pu)</td>
<td>1</td>
<td>1.02</td>
<td>0.98</td>
<td>-</td>
</tr>
<tr>
<td>$P_{max}$ inj,i</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>$P_{min}$ inj,i</td>
<td>-1</td>
<td>-2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

To compare the results of the control methods, two disturbances have been considered in this chapter. These disturbances are included in two cases. The performance of each control method has been studied for one or both cases.
CHAPTER 4. CASE STUDIES

Figure 4.1: An MTDC system with four terminals.

Table 4.2: Parameters of the DC cables.

<table>
<thead>
<tr>
<th></th>
<th>$L_{12}$</th>
<th>$L_{13}$</th>
<th>$L_{24}$</th>
<th>$L_{34}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (km)</td>
<td>500.0</td>
<td>50.0</td>
<td>50.0</td>
<td>500.0</td>
</tr>
<tr>
<td>Resistance (p.u.)</td>
<td>0.0154</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0154</td>
</tr>
</tbody>
</table>

Case 1 (Change in wind turbine injected power) As can be seen in Table 4.1, initially, the wind farm (converter 4) injects 0.1429 (pu) to the MTDC system. At $t = 1(s)$ wind increases and since the converter 4 harvests the maximum power from the wind, its injected active power is increased, with a step, to 0.5 (pu).

Case 2 (Disconnection of converter)

We study the disconnection of the slack converter in this case. Suppose that at $t = 1(s)$ terminal 1 is disconnected. Initially, this converter was operating as inverter; therefore, its disconnection leads to active power surplus in the MTDC system and as a result, the DC voltage increases.
4.2 Study 1

In this study, Case 1 is applied to all control methods. For VMM, it is supposed that converter 1 is the slack terminal and controls $V_{dc,1}$. The converters 2 and 3 are working in CPM, therefore they are controlling $P_{inj,2}$ and $P_{inj,3}$. As mentioned in section 3.3, in VDM more than one terminal participate in controlling the DC voltage. The voltage droop constants are given in Table 4.3. As can be seen, converter 4 does not participate in the DC voltage control.

Table 4.3: Voltage droop constants of converters.

<table>
<thead>
<tr>
<th>Converter 1</th>
<th>Converter 2</th>
<th>Converter 3</th>
<th>Converter 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{p,i}$</td>
<td>9</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.4 shows which control methods are applied for each model in this thesis.

Table 4.4: Table of the methods used in papers

<table>
<thead>
<tr>
<th>Injection Model</th>
<th>VDM</th>
<th>VMM</th>
<th>MAS</th>
<th>SMC</th>
<th>$H_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC/DC model</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Figure 4.2 shows the variation of the $V_{dc,2}$ from its initial value in response to the disturbance mentioned in Case 1. In order to compare the results more conveniently, in this study we have chosen only one DC voltage. Other DC voltages show similar behaviors.

As stated above, the injected active power of converter 4 is increased which leads to an active power surplus in the MTDC system, which increases the voltages at the DC buses. In VMM, converter 1, which is the slack converter, must control the DC voltage. To this aim, it extract more active power from the MTDC system. Then, the DC voltage at bus 1 return to its initial value, but since the MTDC system operates at a new operating point, the voltages at other DC buses will not be the same as their voltages before disturbance.

In VDM, converters 1-3 try to control the DC voltage. As can be seen, application of this method leads to a steady state voltage deviation.

In this study only one of the MAS strategies is selected. The comparison between MAS strategies is presented in Study 3. In MAS strategy 3, both power sharing and returning to a level close to initial voltage are important. It is not shown in this figure, but the voltage reaches to steady state at around $t = 12(s)$ (see
CHAPTER 4. CASE STUDIES

Figure 4.2: Study 1: Variation of the voltage at DC bus 2 ($\Delta V_{dc,2}$) when Injection model is used and different control methods are applied. VMM (in red), VDM (in black), MAS strategy 3 (in blue), $H_\infty$ (in green).

Note that in MAS strategies the communication graph is considered to be the same as the topology graph of the MTDC system. According to MAS theory, if an agent is fixed and does not update its position, all other agents converge to its position and therefore the solution will not be optimal solution. Considering this fact, since the converter 4 does not participate in voltage control, its data is not used as a remote data by other converters. The droop coefficients are the same as VDM.

It can be seen that application of $H_\infty$ leads to a voltage deviation very smaller than the VDM. This is reasonable because the $H_\infty$ uses a static feedback here and therefore its response should be like VDM, which uses a proportional controller. On the other hand, since $H_\infty$ uses an optimization and minimizes the voltage deviation, the steady state voltage deviation must be smaller than VDM. It must be noted that for applying the $H_\infty$ method in this thesis, the limitations of the AC grids are not considered.

Figure 4.3 shows the variation of voltages at the DC buses when AC/DC model is used. As shown in the figure, the behavior of the system is very much like the case where Injection model is used, however, since in AC/DC model the dynamic of the AC part is also considered, the injected active power cannot change as fast as in the previous case and therefore, the voltage variations are larger.
4.2. STUDY 1

Figure 4.3: Study1: Variation of the voltage at DC bus 2 ($\Delta V_{dc,2}$) when AC/DC model is used and different control methods are applied. VMM (in red), VDM (in black), MAS strategy 3 (in blue), basic SMC (in green), integral SMC (in dashed green).

Moreover, in this model, the two SMC control methods are also implemented. As can be seen, application of both SMC methods leads to a behavior like when VMM is applied, but with smaller overshoot and faster response. The voltage when integral SMC is applied has less overshoot comparing to when basic SMC is applied, but it has a small oscillation. Since $V_{dc,2}$ is shown in this figure and considering that the operating point has been changed, the final values of $V_{dc,2}$ is different from its initial values. However, the final values of $V_{dc,1}$ is the same as its initial values if VMM and SMC methods are applied and if the slack converter can successfully control the DC voltage.

To study how the converters share the active power change, it is desired to compare the final values of the injected powers of different terminals. Table 4.5 shows changes in the injected active powers of converters when different control strategies are used. Since in the next section, SMC and VMM will be studied, in order to cover the power distribution from all control methods, the injection model is used to achieve the results of this table in this section. However, to cover the results of SMC, in the next study, the results from the AC/DC model is used for completing the table. Only one of the MAS methods has been chosen for this comparison.
Table 4.5: Changes in the injected active powers of converters.

<table>
<thead>
<tr>
<th></th>
<th>VMM</th>
<th>VDM</th>
<th>MAS 3</th>
<th>H∞</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔP_{inj,1}</td>
<td>0.3587</td>
<td>0.2096</td>
<td>0.215</td>
<td>0.0215</td>
</tr>
<tr>
<td>ΔP_{inj,2}</td>
<td>0</td>
<td>0.125</td>
<td>0.1194</td>
<td>0.2822</td>
</tr>
<tr>
<td>ΔP_{inj,3}</td>
<td>0</td>
<td>0.0234</td>
<td>0.0239</td>
<td>0.0536</td>
</tr>
<tr>
<td>ΔP_{inj,4}</td>
<td>0.3571</td>
<td>0.3571</td>
<td>0.3571</td>
<td>0.3571</td>
</tr>
<tr>
<td>Sum</td>
<td>-0.0016</td>
<td>-0.0009</td>
<td>-0.0012</td>
<td>-0.0002</td>
</tr>
</tbody>
</table>

As can be seen, when VMM is used, converter 1, which is the slack converter, changes its injected active power and other converters remain in CPM. If VDM is used, converters 1, 2 and 3 change their injected active powers to control the DC voltage. As can be seen, the change in the injected active power is not exactly proportional to their droops. The application of MAS strategy 3 causes the converters share the power imbalance proportional to their droops. As can be seen, in $H_{\infty}$ the main focus is on distribution of the power between converters considering their available headrooms, according to their maximum allowable injected power which is given in Table 4.1. Therefore, the converter with more available headroom has more important role in the DC voltage control. The sum of the injected active powers, which shows the change in the loss, is also shown in this table. Note that in MAS strategies, we can use the remote data and change the reference voltage somehow that minimize this loss, which is not studied in this thesis.

4.3 Study 2

In this study, we consider Case 2. Since in this case, it is supposed that the slack converter is disconnected and slack converter is only defined in VMM and SMC methods, in this study we only consider these two methods. The AC/DC model is used in this study. It must be noted that in other methods which do not have a slack converter the disconnection of converter 1 is only a load change like Case 1. Since this disturbance has been investigated in Study 1, we do not consider those methods in this study.

Converter 1, which is the slack converter, is operating as inverter. If Case 2 happens, the active power which was extracted by this converter, remains in the MTDC system and increases the DC voltage. When the voltage at DC bus 2 reaches the reference voltage at converter 2 ($1.02(\text{pu})$), this converter switches to VCM and decreases its injected active power to the MTDC system and as a result,
controls the DC voltage.

Figure 4.4 shows the variation of voltage at DC bus 2. As can be seen both SMC controllers are faster and have less overshoot than VMM. It can be seen that the performance of the integral SMC control is faster and without overshoot. This is an advantage of this method which makes it suitable to apply on the MTDC systems with higher numbers of terminals without being worried about the interaction between controllers.

![Figure 4.4: Study2: Variation of the voltage at DC bus 2 when AC/DC model is used and different control methods are applied. VMM (in red), basic SMC (in blue), integral SMC (in black).](image)

Table 4.6 shows the changes of the injected active power of converters.

Table 4.6: Changes in the injected active powers of converters.

<table>
<thead>
<tr>
<th></th>
<th>VMM</th>
<th>basic SMC</th>
<th>integral SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta P_{in,1}$</td>
<td>0.2824</td>
<td>0.2824</td>
<td>0.2824</td>
</tr>
<tr>
<td>$\Delta P_{in,2}$</td>
<td>-0.2798</td>
<td>-0.28</td>
<td>-0.28</td>
</tr>
<tr>
<td>$\Delta P_{in,3}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta P_{in,4}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>0.0026</td>
<td>0.0024</td>
<td>0.0024</td>
</tr>
</tbody>
</table>

The AC/DC model is used for this comparison. It is evident that since converter 1 is lost, its extracted power will remain in the MTDC system. On the other hand,
since converter 2 is the next slack converter, it should extract this power surplus from the MTDC system. However, since the operating point has been changed and as a result the loss in the MTDC system has been changed, these two quantities are not equal.

### 4.4 Study 3

In this study, we focus on MAS control strategies and consider Case 1. Only AC/DC model, which is more accurate, is chosen for this study.

Figure 4.5 shows the variation of the DC voltage at bus 2.

![Figure 4.5: Study3: Variation of the voltages at DC bus 2 for different MAS strategies when the AC/DC model is used. MAS strategy 1 (in green), MAS strategy 2 (in black), MAS strategy 3 (in blue).](image)

In MAS strategy 1, the voltage is going to return to a level close to its initial value. In MAS strategy 2, the behavior of the voltage is not supposed to be so much different with VDM. The focus in this strategy is on the power sharing between converters proportional to their droops. As mentioned in study 1, in MAS strategy 3 the voltage return to a level closed to its initial value and the power sharing will be proportional to the droops.
Since MAS controllers use remote information, the communication delay may affect the response of these strategies. Therefore, in this study the effect of delay is also considered. There are different values given for delay in the literature [68]. The sources of delay are measurement delay and communication delay. The former depends on the technology of measurement devices, while the latter depends on the technology being used for transferring data. If fiber optic technology is used, the delay can be considered around 100\( (ms) \), while the satellite technology has a delay around 700\( (ms) \).

If a constant delay equal to \( t_d = 100\text{(ms)} \) is considered, the variation of the voltage at DC bus 2 is shown in Figure 4.6.

As can be seen, MAS strategy 1 is the most sensitive strategy to the delay and becomes unstable. The delay cause MAS strategy 2 to have larger voltage deviation, but MAS strategy 3 controls the DC voltage and returns to a level its initial value. Of course, by changing the values of the MAS controllers, their sensitivity to delay will change. Longer delays make the convergence of the MAS strategy slow and can even lead to instability (see [61]). In order to increase the convergence speed, we can increase \( \gamma \). Note that, in this study we suppose that \( \gamma_1 = \gamma_2 = \gamma_3 = \gamma \). However, in the presence of delay, the larger \( \gamma \) can even worsen the results. The effect of the parameters on the behavior of the system in the presence of delay has not been investigated analytically in this thesis.
Next, we study the difference between voltage at each converter and its reference voltage, \( \Delta u_{ref_i} = u_{ref_i}^{dc,i} - V_{dc,i} \). To show the behavior of \( \Delta u_{ref_i} \), only MAS strategy 3 has been selected.

Figure 4.7 shows the change in \( \Delta u_{ref_i} \) for participating converters in MAS strategy 3. As shown in the figure, they converge to a common value at around \( t = 12(s) \). Since the \( \Delta u_{ref_i} \) for all converters will be the same, the changes of their injected active powers only depend on their droops. It must be noted that the convergence of the MAS strategy 2 is much faster than MAS strategy 3.

Next, we study the contribution of \( \alpha \) and \( \beta \) in MAS strategy 1.

As mentioned in Chapter 3, \( \alpha \) is the weight we give to the local information, while \( \beta \) is the weight of remote information. Considering that the wide-area communication can not be without delay, if we consider \( \beta \) to be large, it can cause stability problems. Figure 4.8 shows the response of the system for \( t_d = 50(ms) \) and \( \beta = 1 \) and \( \beta = 1.5 \). The variation of the voltage at DC bus 2 is stable for \( \beta = 1 \) and the oscillations will be damped after 3(s) but for \( \beta = 1.5 \) it is unstable.

4.5 Comments

The VDM method used in this thesis, uses local information, i.e. each converter uses its own DC voltage. No Proportional Integral (PI) or Integral (I) controller is used to implement this controller and it is supposed that if a disturbance happens,
converters inject exactly the active power according to their droop curves and there is no mismatch.

Figure 4.8: Study 3: Variation of the voltage at DC bus 2 with MAS 1 control and $t_d = 50 \text{(ms)}$ and $\beta = 1$ (in blue) and $\beta = 1.5$ (in black).

Figure 4.9: Two other proposed schematics for implementing VDM: (a) scheme I, (b) scheme I (reduced), (c) scheme II

Figure 4.9 shows two other schemes for VDM. In the first scheme (scheme
I), which is shown in Figure 4.9 (a), in addition to the proportional gain ($K_i$) an I controller (with coefficient $\alpha_i$) is also utilized. This scheme is reduced as shown in Figure 4.9 (b), where $T_G = \frac{1}{K_i \alpha_i}$ [69]. In the second scheme (scheme II), a PI controller is used (Figure 4.9 (c)) and $P_{inj}$ is the expected injected active power according to the voltage droop curve. Both PI and I controllers make sure that the actual injected power will be equal to the desired injected power (based on the droop).

Although one can call it a slope voltage controller, since the VDM controllers in this thesis use local information and considering that the DC voltage is not a global variable like frequency in AC system, the proposed system in this thesis has the same steady state results as two other methods. To show this, Study 1 is simulated again and the results are compared together. Figure 4.10 shows behavior of $V_{dc,1}$ with changes in the injected active power ($P_{inj,1}$) for all VDM control schemes. The system is operating at the point $(P_{inj,1}, V_{dc,1})$, which is marked with a circle. After disturbance, the voltage in all methods reach to the same final value, which is marked with a cross. The only difference between these methods is their dynamic behavior. The other terminals show similar behaviors. As can be seen, the final value which both controllers reach to, are the same.

![Graph](image-url)

Figure 4.10: The voltage against the injected active power at DC bus 1: VDM presented in this thesis (in black), VDM scheme I (in blue), VDM scheme II (in green) and the steady-state characteristic (in dashed red).
Chapter 5

Conclusion and future work

5.1 Conclusion

This thesis has covered the issues regarding the control of the DC voltage in Multi-Terminal high-voltage Direct-Current (MTDC) systems. After a literature review, the MTDC system has been modeled. Two modeling approaches have been presented for the purpose of this thesis: Injection model and AC/DC model. In the Injection model, only the DC grid has been considered, while in the AC/DC model, the dynamic of the converter, the AC filter and the phase reactor connecting the terminal to the AC grid has also been considered. The AC systems have been modeled with their Thevenin equivalents and it has been supposed that the Thevenin voltage has constant magnitude and phase. The modeling has been done in MATLAB/Simulink and a 4-terminal MTDC system has been chosen for the case studies. This grid is connected to three AC grids and one wind farm. Comparing the results in Figures 4.2 and 4.3, it is evident that the only difference of these models is in their transient response, where the AC/DC model shows larger variations, but their steady-state response is the same. Depending on the scope of the study, we can choose one of these models. If including detailed model of AC grid is of interest, the AC/DC model has this capability to add it. On the other, if only the DC grid behavior is of interest, the Injection model can be used.

Two main methods Voltage Droop Method (VDM) and Voltage Margin Method (VMM), which are presented in the literature, have been discussed. Then, two series of control methods presented. The first series of control methods are Multi-Agent System (MAS) control methods. These control methods can be considered as modified VDM. In this method the reference voltage of each controller is up-
dated continuously after disturbance happens. These methods use both remote and local information, but do not rely only on remote information. When remote information is not available, these methods simply operate like VDM. Each of these control methods has their own aim in control.

When MAS strategy 1 has been applied to the MTDC system, the DC voltage has returned to a level close to their initial values. Then we have developed the MAS controller further and presented MAS strategies 2 and 3. Application of MAS strategies 2 and 3 has resulted in equal deviation of DC voltages from their reference values. As a result, the power has been distributed equal to the droop constants (similar to the frequency control in AC grids).

We have shown how the power mismatch after a distribution is distributed between different converters. We have also shown the changes in the loss of the MTDC system due to application of different control strategies in Tables 4.5 and 4.6. In MAS strategies we can optimize the amount of this loss using remote information, but it has not been addressed in this thesis.

Since MAS strategies use remote information and remote information may come with delay, a sample delay of 100\((ms)\) has been chosen and the MAS strategies have been implemented for this delay. We have shown in figure 4.6 that the MAS strategy 3 has the best performance in the presence of delay.

We have simulated all above control methods using both Injection and AC/DC models. The results have shown the effectiveness of the control methods. It has been shown in figures 4.2 and 4.3 that the behavior of the system for these two models are similar but the voltage deviation is different.

The second group of control methods have been presented in this thesis includes two Sliding Mode Control (SMC) methods and \(\mathcal{H}_\infty\). This group use only local information. We have implemented the SMC controllers, basic and integral, on AC/DC model and \(\mathcal{H}_\infty\) on Injection model.

We have developed the aforementioned SMC control method using a philosophy similar to VMM, i.e., at each time only one of the converters controls the DC voltage (as slack converter) and other converters control their injected active powers. Because of this similarity, these methods have been compared together. The simulation results have shown that both SMC controllers can control the DC voltage in MTDC system very fast and with less overshoot compared to VMM. Then we have compared the performances of the two SMC control methods with each other and have shown that in the case of changing the slack converter, basic SMC controls the voltage with small overshoot while integral SMC controls the voltage almost without overshoot. Consequently we have concluded that it is possible to choose an even smaller voltage margin, which, unlike VMM, makes this method...
suitable for MTDC systems with high number of terminals.

Finally, we have applied $\mathcal{H}_\infty$ control on the MTDC system. We have shown that it results in a very small voltage deviation after disturbance. This control method makes it possible to not only control the voltage, but also limit the injected active powers and weight the contribution of different converters proportional to their available headroom.

5.2 Future work

As seen in the simulation results, the delay has an negative effect on the performance of MAS control methods. It would be interesting to study the effect of delay on the stability of different MAS methods. Considering that the performance of the controller for a given delay was different in Injection model and AC/DC model, it is important to analyse these effect separately for each model. Moreover, study of effect of time varying delays on the proposed MAS controllers can be interesting.

The models presented in this thesis can be further developed to be able to identify and analyze relevant electromechanical dynamics such as rotor angle stability, voltage stability and frequency stability.

Also supplementary controls (such as Power Oscillation Damping (POD)) can be developed for the converters to improve dynamical performance of the AC/DC system. The impact of the proposed DC voltage control strategies in this thesis and the aforementioned supplementary controls on the hybrid AC/DC system can be studied. The aim is to fulfill N-1 criterion for both MTDC and AC systems.

Different market and operation issues can be considered in this MTDC system. In the hourly operation of the system, balance between production and consumption has to be kept continuously in an economical and reliable way, considering production and transmission limits. The continuous balance is kept with Frequency Containment Reserves (FCR) (frequency controlled power plants that keep enough margins for this) which is distributed between power plants in different regions. Used FCR are restored using Frequency Restoration Reserves (FRR) which in the market means accepted bids to the regulating market. In many systems there is also an Automatic Generation Control (AGC) system which automatically redistribute the production in order to fulfil requirements concerning security limits and economic generation. The question is how can FCR between the asynchronous AC systems connected by MTDC system be coordinated?

An important issue is the set-up of the AGC systems and the needed control. The instant reaction after a contingency in, e.g., the MTDC system causes direct
changes in the AC systems. This may not be efficient from internal bottleneck point of view and/or from economic point of view. This then means a) the instant reaction has to be distributed in such a way that AC system stability is maintained, b) each AGC system must be set up in order to consider the price signals so an economic operation is obtained, c) there must be a coordination between the different AC systems so one do not get a suboptimum in each system, i.e., re-distribute the power between the different AC systems in an efficient way, d) there must be a system set-up so the correct price signals can be considered in the controllers, e.g. through a real time pricing system. Therefore, the distributed coordination of different operational zones can be studied.
Bibliography


