Power Electronics Converter Modeling for High Frequency using Black-Box Approach

B.Tech. Project

Submitted in partial fulfillment of the requirements of the degree of

Bachelor of Technology

in

Electrical Engineering

By

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Under the guidance of

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Dec. 2024

Declaration

I hereby declare that the project entitled **“Power Electronics Converter Modeling for High Frequency using Black-Box Approach”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in ‘Electrical Engineering’ completed under the supervision of Dr. Lokesh Kumar Dewangan, Assistant Professor, Department of Electrical Engineering, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

I declare that this written submission represents my ideas in my own words and where other’s ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misinterpreted or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

Jash

Jash Nilesh Faladu

Date: 04/12/2024

Place: Indian Institute of Technology, Indore

Preface

This report on **"Power Electronics Converter Modeling for High Frequency using Black-Box Approach"** is prepared under the guidance of Dr. Lokesh Kumar Dewangan.

This report delves into the application of black-box modeling techniques for power electronics converters, with a focus on high-frequency applications. As the demand for efficient and reliable high-performance systems continues to rise, understanding the behavior of power converters under such conditions has become increasingly vital.

The work presented here is motivated by the challenges posed by traditional modeling approaches, particularly their complexity and computational intensity. By leveraging black-box methods, this study aims to provide a practical and scalable solution for capturing the dynamic behavior of power converters across a wide frequency spectrum.

The report combines theoretical insights with practical case studies to illustrate the potential of black-box modeling in advancing power electronics research. It is intended for researchers, engineers, and practitioners seeking efficient tools for analyzing and designing high-frequency power electronic systems.

We hope this work will contribute to the growing body of knowledge in power electronics modeling and inspire further exploration of innovative approaches in this dynamic field.

Jash Nilesh Faladu

B. Tech. IV year

Department of Electrical Engineering

B. Tech. Project Approval Certificate

This is to certify that the dissertation titled **"Power Electronics Converter Modeling for High Frequency using Black-Box Approach"** submitted by **Jash Nilesh Faladu**, (Roll No. 210002040) is approved for the award of degree of **Bachelor of Technology** in **Electrical Engineering.**

Lokesh

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Acknowledgements

I would like to express my sincere gratitude to my project guide, Prof. Lokesh Kumar Dewangan for providing me immeasurable amount of support and encouragement throughout the study. He was extremely helpful in every way possible and has inspired me a lot. He has extensive knowledge in this topic and it was a wonderful opportunity to do my project under his generous guidance.

I would like to thank my friends who have constantly refreshed and lifted me up with their support and encouragement.

A special gratitude and love goes to my family for their unfailing support.

Abstract

High-frequency modeling of power electronic converters is critical for analyzing their dynamic behavior in advanced applications, such as EMI/EMC studies, stability assessments, and control system design. A black-box approach offers a practical solution by characterizing the converter's input-output behavior without requiring detailed knowledge of its internal circuitry. This methodology relies on frequency-domain techniques, where small-signal perturbations are applied to measure and model the system's response, such as input impedance, output impedance, or transfer functions.

By employing system identification techniques, such as fitting rational transfer functions or state-space models to the measured data, black-box modeling captures key dynamics with high accuracy. This approach is particularly advantageous for proprietary or complex systems where internal details are inaccessible. It also enables efficient analysis of interconnected systems, such as HVDC grids or modular converters, where high-frequency interactions and control loops play a significant role.

The resulting black-box models facilitate rapid simulations, robust controller design, and effective filter optimization for mitigating high-frequency noise. This paper discusses the theoretical foundation, implementation steps, and applications of black-box modeling for high-frequency converter analysis.

Keywords – *High-frequency modeling, Power electronic converters, Dynamic behavior, EMI/EMC studies, Stability assessments, Control system design, Black-box approach, Input-output behavior, Frequency-domain techniques, Small-signal perturbations, Transfer functions, State-space models, HVDC grids, Modular converters, High-frequency interactions, Rapid simulations, Robust controller design, Filter optimization*

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List of Abbreviations

Abbreviations

AC	Alternating Current
DC	Direct Current
HVDC	High-Voltage Direct Current
PSCAD	Power System Computer Aided Design (software)
PLL	Phase Locked Loop
dq0	Direct-Quadrature-Zero
VSC	Voltage Sourced Converter
IGBT	Insulated Gate Bipolar Transistor
BJT	Bipolar Junction Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PCC	Point of Common Coupling
PWM	Pulse-Width Modulation
PI	Proportional-Integral
MMC	Multi-Modular Converter
EMI/EMC	Electromagnetic Interference/ Electromagnetic Compatibility

Chapter 1

Introduction

1.1 Introduction

Power electronics converters are integral components in modern energy systems, providing efficient solutions for energy conversion and control. Their applications span a wide range of industries, including renewable energy integration, electric vehicles, high-speed trains, and industrial automation. As the demand for more compact, efficient, and high-performance systems continues to grow, understanding the behavior of these converters under high-frequency operating conditions has become a critical area of research and development.

One of the key challenges in analyzing power electronic systems for high-frequency applications lies in accurately capturing their dynamic behavior without excessive computational overhead. Traditional white-box modeling approaches, which rely on detailed circuit-level representations, often become impractical due to the complexity of these systems and the high computational cost involved. This has led to a growing interest in black-box modeling techniques as an alternative.

The black-box approach focuses on developing models based solely on input-output data, without requiring detailed knowledge of the internal system structure. This method offers several advantages, including reduced complexity, ease of implementation, and scalability. It is particularly suited for high-frequency applications where the interaction between power electronic converters and their surrounding environment needs to be studied across a broad frequency spectrum.

This report explores the application of black-box modeling techniques for power electronics converters, with a specific focus on high-frequency behavior. The methodology emphasizes the development of accurate and efficient models capable of capturing key dynamic characteristics. The models are intended for use in system-level simulations, enabling engineers to perform frequency-domain analysis and assess the impact of converter dynamics on system performance.

1.2 Motivation for BTP and Problem statement

Power electronics converters are crucial components in modern electrical systems, particularly in high-frequency applications such as telecommunications, high-speed data transmission, and electric vehicles (EVs). The increasing demand for efficient and compact systems has prompted the development of converters that operate at higher frequencies. However, modeling such systems at high frequencies presents significant challenges due to their complex dynamic behavior, non-linearities, and interactions between various components.

Traditional modeling techniques, specifically white-box modeling, involve detailed analysis of the physical parameters of each component within the converter (e.g., switches, inductors, capacitors, etc.). While this approach is highly accurate, it is computationally expensive and requires deep knowledge of the internal characteristics of the system. This becomes problematic, especially when scaling up to high-frequency applications where the system's complexity can increase exponentially, leading to issues such as long simulation times and limited practicality.

In contrast, the black-box approach to modeling focuses on using input-output data to infer the system's behavior without delving into the internal workings of the components. This approach is ideal for high-frequency power electronics systems where the behavior can be captured effectively through data-driven techniques, simplifying the modeling process. By applying the black-box method, the goal is to create efficient models that can predict system performance while requiring less computational effort, making them particularly suitable for real-time applications.

High-frequency power electronics converters exhibit complex behaviors that are challenging to model accurately using traditional techniques. White-box modeling requires detailed knowledge of the system's internal components and interactions, which can lead to impractical computation times and inefficiency, especially in high-frequency applications. There is a need to develop an alternative modeling paradigm that can simplify the process of simulating and predicting the behavior of these systems while maintaining accuracy and computational efficiency.

Power system operators are responsible for ensuring the stability, efficiency, and reliability of electrical grids. As more high-frequency power electronics converters are integrated into the grid (such as inverters for renewable energy generation, electric vehicles, and other industrial applications), the complexity of managing these systems increases. Operators face several challenges like real-time stability analysis, and time-to-time maintenance of power systems. Adopting a black-box modeling approach could alleviate some of the challenges faced by power system operators, offering faster simulations, better adaptability, and more efficient management of high-frequency power electronics converters within modern power grids.

1.3 Organization of the Report

Chapter 2 of this report describes the working of a two-terminal grid-connected HVDC converter, and the components required to build it. It also contains detailed description of power switches and switching bridge construction. The whole modeling was done in PSCAD software.

Chapter 3 of this report describes the working of a closed-loop control of a two-terminal HVDC converter in dq0-frame. It also contains information on frame transformations and the benefits of using dq0-frame for closed-loop control. It contains comparison of current-controlled and voltage-controlled power controller, and why one is preferred over the other. The working and importance of PLL is also mentioned. The entire closed-loop control was performed in PSCAD. This concluded the work done in Mid-Sem Report.

Chapter 4 of this report describes the full construction of a white-box model using basic principles of network theory to illustrate working of every component in its equations. finally, a state-space model is created by using these equations and the system's stability is analyzed using a nyquist plot. The whole system was modeled using MATLAB software.

Chapter 5 of this report is the main objective of this report containing details on modeling a two-terminal HVDC converter using Black-Box approach. Frequency Scanning Techniques are introduced and Python is used to automate PSCAD and the program for frequency scanning is created. AC and DC scanning blocks are introduced to perform frequency scanning.

Chapter 6 of this report contains the outputs of the tasks performed in the previous chapters, i.e. Active/Reactive Power Control, Stability Analysis using created State-space model, and Bode Plots for AC and DC scanning blocks.

Chapter 7 of this report concludes the project and sheds light on future prospects regarding the topic. Stability Analysis using Generalized Nyquist Criterion and Participation Factors analysis using Eigenvalue Decomposition of the created Black-Box model are discussed.

Chapter 2

Modelling of Two-terminal HVDC Converter

2.1 Introduction

An HVDC converter is a specialized Power Electronic device that converts AC to DC or vice-versa. It enables efficient and reliable transmission of electrical power over long distances. HVDC transmission has reduced energy losses than AC transmission. It is very flexible and can operate with different AC system frequencies and voltage levels.

In case of two-terminal HVDC converter, it is used for connecting two 3-phase AC systems situated far from each other, using HVDC transmission line. Essentially, it contains two VSCs, i.e. a Rectifier and Inverter connected through a HVDC transmission line. It provides very stable interconnection between two systems, even if they are asynchronous (running at different frequencies). It also helps in expanding the existing power system to new regions.

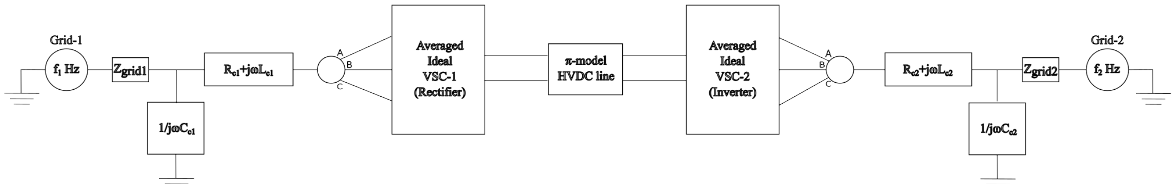

Figure 2.1: Two-Terminal HVDC Converter.

In recent times, with the increase in usage of renewable energy sources, two-terminal HVDC converters have become increasingly important as they are used to connect Wind Turbines and Solar Panels directly to the grid. These converters incorporate well-designed automatic closed-loop control to monitor and correct any deviation in frequency, voltage or power exchange between the connected grids. Figure 2.1 contains the general figure of a typical grid connected two-terminal HVDC converter, which also contains the AC and DC scanning blocks whose working shall be analyzed in later part of this report. It also assumed that the grids are stiff i.e. they provide stable voltage and frequency, which limits its interaction with the converter's dynamics.

2.2 Modelling of Power Switches

The power switches used in the VSCs for the system in consideration for this report are IGBTs and anti-parallel diodes with snubber circuits in parallel. IGBT has high input impedance and fast switching (like MOSFET), with high current and voltage handling capabilities (like BJT). The IGBTs handle primary switching of the current. When IGBT is off, the anti-parallel diode provides the path for the current to prevent high-voltage spikes due to back-EMF. The snubber circuit acts a buffer, providing a path for transient currents produced during high-frequency switching of the power switch into a resistor to protect the switching device. There are two models of switches which are used – *Switched Model* and *Averaged Model*.

Switched Model directly simulates the switching of ON/OFF state of the switch, including the precise timing of the switching events. It captures detailed behavior of switching components and is mainly used for time-domain simulations which includes transient and harmonic analysis. It provides high accuracy and can capture switching losses and Electromagnetic Interference (EMI). The main limitation of this model is that it leads to very long simulation times as it requires smaller time steps in simulation. Since, we have High-Frequency switching of our switches we do not use this model.

Averaged Model on the other hand demonstrates the behavior of switches in a time-averaged manner. It replaces the instantaneous switching waveforms with their averaged equivalents over a switching period, which generally is a sinusoidal waveform. It significantly reduces simulation time and captures essential dynamic behavior, used for control design and stability analysis. It is a much preferable model for our switches, although being less accurate than *Switched Model*.

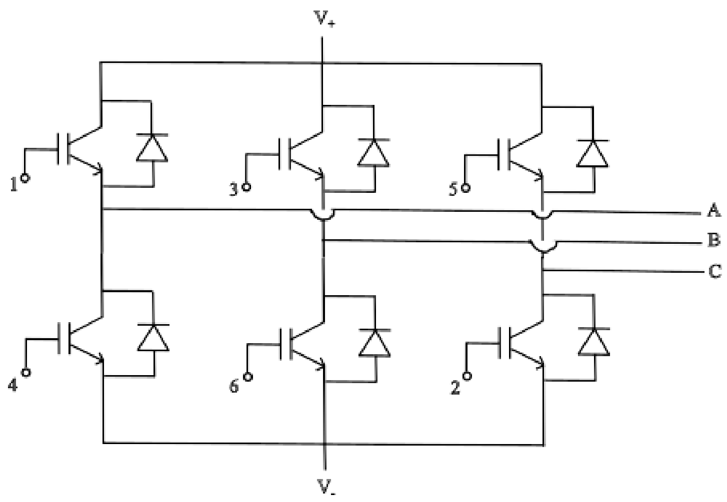

Figure 2.2: Switching Bridge with switching sequence.

2.3 Modeling of Switching Bridge

The switching bridge present in a VSC contains six power switches (IGBTs + anti-parallel diodes) in such a configuration that there are three legs of the bridge and each leg contains two switches. The top of each leg represents the positive voltage of the DC line and the bottom represents the negative voltage. The point of each leg in between both the switches is connected to a phase of 3-phase of AC line. The bridge configuration and switching order of all the switches is given above in Figure 2.2. The bridge configuration is common for both VSCs.

2.4 Summary

In this chapter, the basics of a HVDC converter were discussed and how a two-terminal HVDC converter connecting two grids using two VSCs connected by a DC transmission line was modeled. For simplicity the frequency of both the grids was kept at 50Hz, but it need not be the same. Then two different model of switches were discussed and how the connections for AC/DC or DC/AC conversion were made. The subsequent chapter sheds light on the closed-loop control of two-terminal HVDC converter and its active/reactive power control.

Chapter 3

Closed-Loop Control of Two-Terminal HVDC Converter

3.1 Introduction

In the previous section, the modeling of our system in consideration was described. This section presents how the converter is controlled in closed-loop mode. It also consists discussion of Active/Reactive Power Control mechanisms through current-mode control and voltage-mode control. The concept of control in *dq0-frame* is also discussed with its advantages over standard *abc-frame* and *$\alpha\beta$-frame*.

3.2 Direct-Quadrature-Zero Reference Frame

For closed-loop control of the converter, a different reference frame is used rather than the standard *abc-frame* used for three phase quantities. This frame is known as *dq0-frame*. It is a rotating reference frame where current and voltage become time-invariant quantities which makes the analysis of the system much easier. Clark and Park Transformations are used to convert *abc-frame* to *dq0-frame*. Direct-axis component(d-axis) represents component aligned with rotating reference frame and Quadrature axis component(q-axis) represents component orthogonal to d-axis as shown in Figure 3.1.

$\alpha\beta$-frame is an intermediate step in the *abc-dq0* transformation. It is a stationary two-phase reference frame which when converted from *abc-frame* results in two orthogonal components. It simplifies the system analysis by reducing the number of variables but it still maintaining sinusoidal nature of the signals. It is generally used for Harmonic Analysis. We use Clark Transformation given below to get quantities in *$\alpha\beta$-frame* from

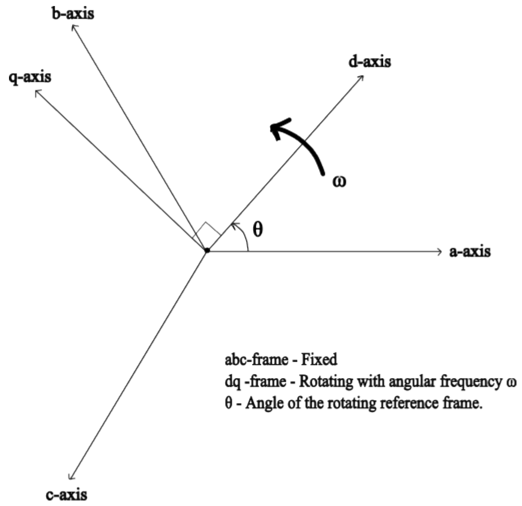

Figure 3.1: *abc-dq0 frame* representation.

abc-frame.

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix}$$

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix}$$

To obtain *dq0-frame* from *$\alpha\beta$-frame*, we further use Park Transformation given above. The *dq0-frame* essentially contains only 2 components, as the third component is just zero which can also be verified from the transformations. It can also be simply written as *dq-frame.*

The *dq-frame* of reference makes the system analysis much more easier by reducing the number of variables and making the sinusoidal quantities time-invariant. It is generally used for Harmonic Analysis.

3.3 Current-mode control vs Voltage-mode control

There are 2 ways in which the closed-loop controller can be modeled for active/reactive power control - current-mode control and voltage-mode control.

In voltage-mode control, real/reactive power are controlled, respectively by phase and amplitude of VSC AC-side voltage relative to PCC voltage. If voltages of grid and VSC AC-side terminal are almost similar in phase and amplitude, then active and reactive powers are almost decoupled and two independent compensators can be used for their control. One shortcoming of this method is that there is no control loop closed on the VSC line current. So, VSC is not protected against overcurrents.

In current-mode control, real/reactive power is controlled by phase and amplitude of VSC line-current w.r.t. the PCC voltage. There is a tight regulation of VSC line current using a dedicated current-control scheme, through VSC AC-side terminal voltage. This mode of control is better than voltage-mode control in terms of robustness, dynamic performance and higher control precision.

3.4 Active/Reactive Power Control

The closed-loop active/reactive power control includes taking reference values of active/reactive power as input, which when passed through two loops - inner and outer loop outputs PWM signals for the switches.

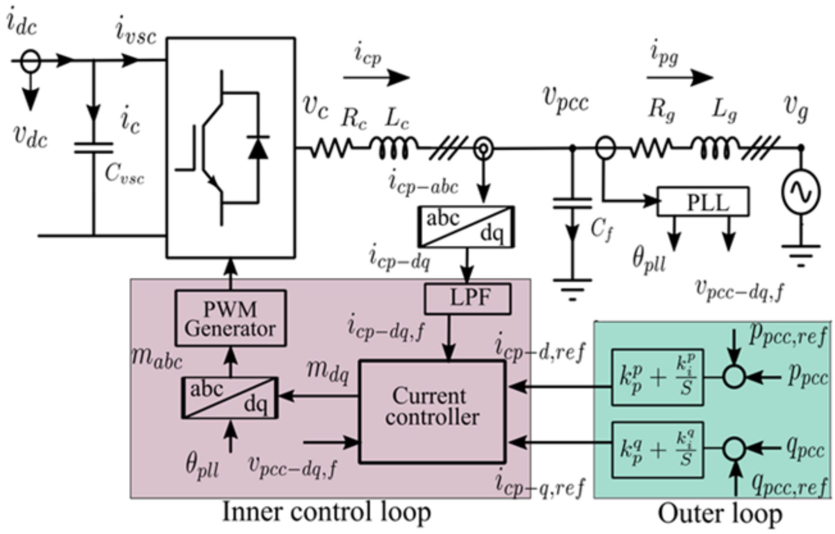

Figure 3.2: Schematic diagram of current-controlled Active/Reactive Power controller in *dq-frame*.

The outer loop compares output power with reference power to generate an error signal which is processed through PI controller to produce the reference current for the inner loop. The PI controller's gain is adjusted using pole-placement method. The outer loop has a slower response as the variable it controls ,i.e. power changes gradually.

The inner loop is responsible for regulating the current flowing through the inverter's output. The inner loop also contains PI controllers whose gain are also adjusted using pole-placement method. It ensures fast and accurate tracking of reference current. It has very quick response and a higher bandwidth for rapidly changing load or input conditions.

The end output of the inner control is converted back to abc-frame from dq0-frame and when passed through PWM generator generates gate pulses for the switches.

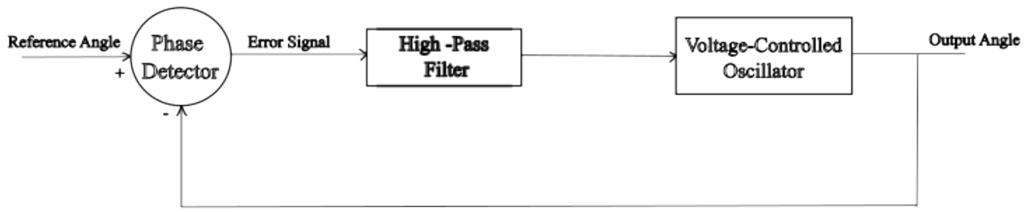

Figure 3.3: Block Diagram of a Phase-Locked Loop.

The Phase-Locked Loop is responsible for synchronizing the amplitude and phase of inverter's output voltage and grid voltage. It is made up of 3 blocks – *Phase Detector*, which detects error signal equal to phase difference in inverter output and grid voltage. *Loop Filter*, which filters high frequency components (noise) from error signal. *Voltage-Controlled Oscillator*, which generates sinusoidal waveform (reference signal) for inverter's control system to ensure inverter's output phase is locked to grid.

3.5 Summary

This chapter covers the principles and techniques for regulating the operation of a two-terminal HVDC converter in a closed-loop control system. It focuses on maintaining stable power transmission between two points by adjusting the converter's output voltage and current.

Chapter 4

White-Box Modeling

4.1 Introduction

Accurate modeling of HVDC systems is essential for analyzing their dynamic behavior and optimizing their performance under closed-loop control. This chapter presents a white-box model for a two-terminal HVDC converter. The white-box approach leverages a detailed understanding of system equations, electrical circuit principles, and control strategies to derive a mathematical representation of the HVDC system. The model captures the dynamics of converter stations, DC transmission lines, and their interactions with the control system.

The following sections outline the equations governing the HVDC system and culminate in the creation of a state-space model for analysis and simulation.

4.2 AC System Modeling

The average model of the VSC on AC side is given by the

$$L_c \frac{d}{dt}\mathbf{i}_{l,\mathrm{dq}} = -R_c \mathbf{i}_{l,\mathrm{dq}} + \mathbf{V}_{c,\mathrm{dq}} - \mathbf{V}_{o,\mathrm{dq}} \pm \omega L_c \mathbf{i}_{l,\mathrm{qd}} \tag{4.1}$$

$$L_g \frac{d}{dt}\mathbf{i}_{o,\mathrm{dq}} = -R_g \mathbf{i}_{o,\mathrm{dq}} + \mathbf{V}_{o,\mathrm{dq}} - \mathbf{V}_{g,\mathrm{dq}} \pm \omega L_g \mathbf{i}_{o,\mathrm{qd}} \tag{4.2}$$

$$C_f \frac{d}{dt}\mathbf{V}_{o,\mathrm{dq}} = \mathbf{i}_{l,\mathrm{dq}} - \mathbf{i}_{o,\mathrm{dq}} \pm \omega C_f \mathbf{V}_{o,\mathrm{qd}} \tag{4.3}$$

Where:

- $\mathbf{i}_{l,\mathrm{dq}}$: Inductor current in the dq reference frame
- $\mathbf{i}_{o,\mathrm{dq}}$: Output current in the dq reference frame
- $\mathbf{V}_{c,\mathrm{dq}}$: Control voltage in the dq reference frame
- $\mathbf{V}_{o,\mathrm{dq}}$: Output voltage in the dq reference frame
- $\mathbf{V}_{g,\mathrm{dq}}$: Grid voltage in the dq reference frame
- L_c, L_g: Inductances of the filter and grid respectively
- R_c, R_g: Resistances of the filter and grid respectively
- C_f: Filter capacitance
- ω: Angular frequency

The equations given above in (4.1), (4.2) and (4.3) constitute 6 equations in themselves taking into account both Inverter and Rectifier, where actual values for each side may differ.

4.3 Converter and Controller Modeling

The equations for converter and controller dynamics are given as:

$$V_{c,d} = V_{dc}\frac{1}{V_{dc,f}}\Big(K_{i,P}\big(i_{l,d,\mathrm{ref}} - i_{l,d}\big) + K_{i,I}\gamma_{l,d} + V_{o,d} - \omega_{pll}L_c i_{l,q}\Big) \tag{4.4}$$

$$V_{c,q} = V_{dc}\frac{1}{V_{dc,f}}\Big(K_{i,P}\big(i_{l,q,\mathrm{ref}} - i_{l,q}\big) + K_{i,I}\gamma_{l,q} + V_{o,q} + \omega_{pll}L_c i_{l,d}\Big) \tag{4.5}$$

Where:

- $V_{c,d}$, $V_{c,q}$: Control voltages in the dq reference frame
- V_{dc}: DC voltage
- $V_{dc,f}$: Filtered DC voltage
- $K_{i,P}$, $K_{i,I}$: Proportional and integral gains of the controller
- $i_{l,d,\mathrm{ref}}$, $i_{l,q,\mathrm{ref}}$: Reference inductor currents in dq reference frame

- $i_{l,d}$, $i_{l,q}$: Inductor currents in dq reference frame
- $\gamma_{l,d}$, $\gamma_{l,q}$: Integral error terms for dq currents
- $V_{o,d}$, $V_{o,q}$: Output voltages in dq reference frame
- ω_{pll}: Angular frequency from phase-locked loop
- L_c: Inductance of the filter

Similar to AC System Modeling, the equations given above in (4.4) and (4.5) constitute 4 equations in themselves taking into account both Inverter and Rectifier.

4.4 DC System Modeling

The equation for the DC voltage dynamics is given as:

$$C_{\text{eqn}} \frac{dV_{\text{dc},1}}{dt} = \frac{P_{\text{dc},1}}{V_{\text{dc},1}} \pm \sum_{\substack{m=1 \\ m \neq n}}^{M} i_{\text{dc}(n,m)} \tag{4.6}$$

where:

- C_{eqn}: Equivalent capacitance,
- $V_{\text{dc},n}$: DC voltage of the n-th terminal,
- $P_{\text{dc},n}$: DC power at the n-th terminal,
- $i_{\text{dc}(n,m)}$: DC current between terminal n and terminal m,
- M: Total number of terminals.

The above given equation (4.6) is written for a MMC with multiple terminals. For a two-terminal HVDC converter, this reduces to only 2 equations, one for Inverter(n=2, m=1) and other for Rectifier(n=1, m=2).

4.5 Summary

The equations obtained in this chapter with their actual values defines white-box modeling of the two-terminal HVDC converter. These are then used to create a state-space model also including the information of the already available state-space model of the grids.

The system dynamics are described by the following equations:

$$\Delta \dot{X}_n = A_n \Delta X_n + B_{1,n} \Delta X_{s,n} + B_{2,n} \Delta X_{c,n} + E_n \Delta U_n, \tag{4.7}$$

$$\Delta Y_n = C_n \Delta X_n + D_n \Delta U_n, \tag{4.8}$$

where the state vector X_n is then defined as:

$$X_n = \begin{bmatrix} V_{o,d,f} & V_{o,q,f} & i_{l,d,f} & i_{l,q,f} & \gamma_P & \gamma_Q & \gamma_{l,d} & \gamma_{l,q} & \theta_{pll} & \omega \\ i_{l,d} & i_{l,q} & V_{o,d} & V_{o,q} & i_{o,d} & i_{o,q} & V_{dc} & V_{dc,f} & & \end{bmatrix}.$$

Where:

- $V_{o,d,f}, V_{o,q,f}$: Filtered output voltages in dq reference frame
- $i_{l,d,f}, i_{l,q,f}$: Filtered inductor currents in dq reference frame
- γ_P, γ_Q: Integral errors for active and reactive power
- $\gamma_{l,d}, \gamma_{l,q}$: Integral errors for inductor currents in dq reference frame
- θ_{pll}: Phase angle from the phase-locked loop (PLL)
- ω: Angular frequency
- $i_{l,d}, i_{l,q}$: Inductor currents in dq reference frame
- $V_{o,d}, V_{o,q}$: Output voltages in dq reference frame
- $i_{o,d}, i_{o,q}$: Output currents in dq reference frame
- V_{dc}: DC voltage
- $V_{dc,f}$: Filtered DC voltage

The input vector u is defined as:

$$u = \begin{bmatrix} P_{\text{ref}} \\ V_{\text{dc,ref}} \end{bmatrix},$$

where:

- P_{ref}: Reference active power,
- $V_{\text{dc,ref}}$: Reference DC voltage.

The above equations shows that each converter station has 16 states (6 states are controller states, 6 states are ac system dynamics,4 states are filter dynamics) which highlights, why there is a need to change the modeling paradigm and adopt more efficient and real-world suitable methods.

Chapter 5

Black-Box Modeling

5.1 Introduction

This method involves creating a simplified mathematical representation of the converter's behavior without delving into its internal structure. This technique focuses on the input-output relationship of the system, allowing for efficient modeling even when the detailed internal circuit of the converter is unknown or complex. This approach is useful when the converter operates at high frequencies, where parasitic elements, switching dynamics, and control mechanisms might be difficult to model using traditional white-box (detailed physical modeling) techniques.

5.2 Frequency Scanning Techniques

Frequency scanning techniques are methods used to analyze the frequency response of electrical systems, particularly power systems, converters, or electrical networks. These techniques involve applying a range of frequencies to a system and observing its response in terms of impedance, admittance, or transfer functions. They are crucial for understanding stability, resonance, and performance characteristics of systems in various frequency domains.

Since, there are controllers included with the system, it is known as Closed-Loop Frequency Scanning. It takes into account the impact of these controllers on the frequency response. It is useful in studying harmonic interactions and to analyze small-signal stability and control interactions.

For performing Frequency Scanning, two scanning blocks were constructed in PSCAD – AC scanning block and DC scanning block, and were placed on AC and DC side of a converter, respectively.

To perform efficient frequency scanning, Python was used to create a program which automates PSCAD. The program uses AC and DC Scanning blocks to inject sinusoidal voltage perturbations into the system and measure current changes in steady-state. All perturbations are run sequentially. It then records the admittance values corresponding to each frequency and which are used to plot the frequency response on a bode plot.

5.3 Creating Transfer Functions

Sinusoidal voltage perturbations are injected into the closed-loop system and corresponding to that the change in steady-state currents are measured. For each frequency, an admittance value is obtained using Fast Fourier Transform. This admittance value is nothing but the transfer function at that particular frequency.

Then a range of frequencies is defined for which frequency scanning is performed. All the sinusoidal voltage perturbations occur sequentially. The scanning blocks created to perform the frequency scan have two sides defined as – ground and converter side.

For the voltage perturbations in AC scanning block, in total eight admittances are obtained for a single frequency, four corresponding to each side calculated as given in (5.1), (5.2), (5.3) and (5.4). These admittances are in *dq-frame* and so we get four different transfer functions for combinations possible for voltage and currents in *dq-frame*.

$$Y_{dd}(j\omega) = \frac{\Delta I_{ac}^{d}(j\omega)}{\Delta V_{ac}^{d}(j\omega)} \tag{5.1}$$

$$Y_{dq}(j\omega) = \frac{\Delta I_{ac}^{d}(j\omega)}{\Delta V_{ac}^{q}(j\omega)} \tag{5.2}$$

$$Y_{qd}(j\omega) = \frac{\Delta I_{ac}^{q}(j\omega)}{\Delta V_{ac}^{d}(j\omega)} \tag{5.3}$$

$$Y_{qq}(j\omega) = \frac{\Delta I_{ac}^{q}(j\omega)}{\Delta V_{ac}^{q}(j\omega)} \tag{5.4}$$

For the voltage perturbations in DC scanning block, only two admittances are obtained for a single frequency, one corresponding to each side calculated as given in (5.5). Finally, transfer function corresponding to all the frequencies in the defined range were plotted on a bode plot.

$$Y_{dc}(j\omega) = \frac{\Delta I_{dc}(j\omega)}{\Delta V_{dc}(j\omega)} \tag{5.5}$$

5.4 Summary

The Black-Box approach described above eliminates the need for detailed knowledge of internal system dynamics, relying solely on input-output behavior. Frequency Scanning when performed using AC and DC scanning blocks creates the transfer function from admittance values obtained for each frequency. The transfer function is then plotted on a bode plot which is helpful in identifying system resonances, harmonic analysis and other dynamics for the system. This approach serves as a superb alternative for the typical white-box modeling when the information on internal components of a power electronic converter is not known.

Chapter 6

Simulation Results

6.1 Active/Reactive Power Control

As it can be observed, the controller is able to track active/reactive power quite well. The deviations are due to transients present initially and should be ignored if they occur for a short period of time. The actual power also follows the response of a first order system, confirming the presence of PI controller.

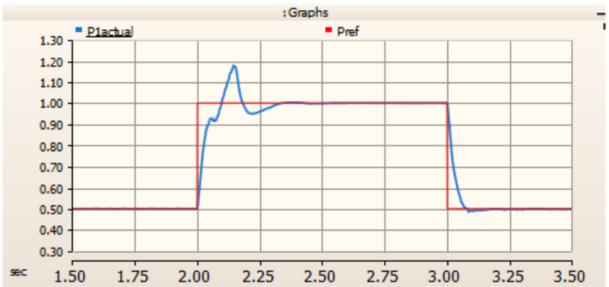

Figure 6.1: Active Power Response.

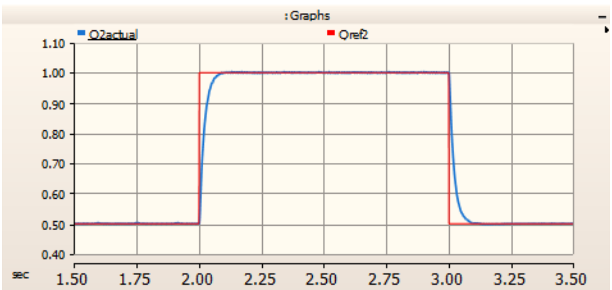

Figure 6.2: Reactive Power Response.

6.2 Nyquist Plot and Oscillation Mode Identification for White-Box Model

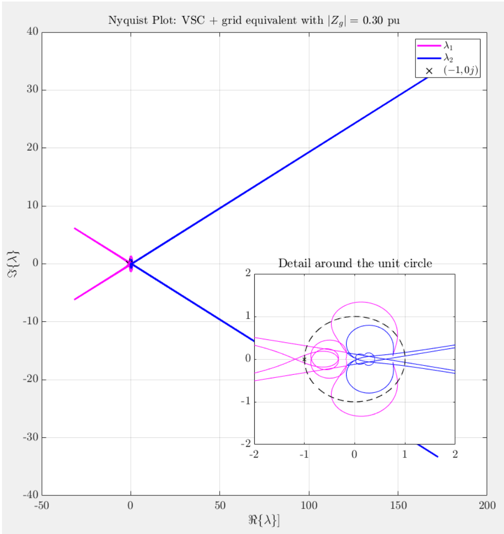

Figure 6.3: Nyquist Plot for a two-terminal HVDC converter with grid equivalent.

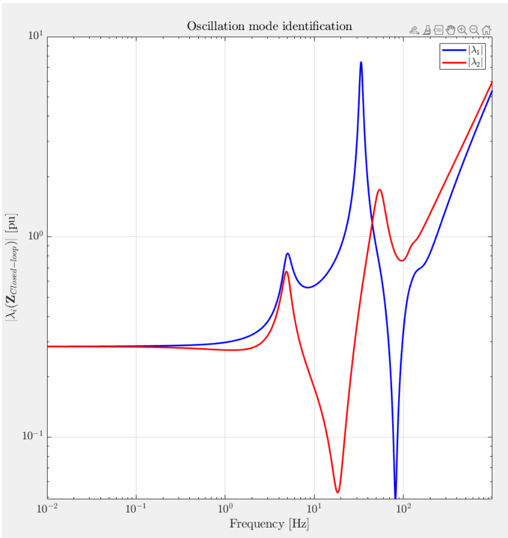

Figure 6.4: Oscillation Mode Identification.

6.3 Bode Plots for Black-Box Model

As it is observed, the bode plot for converter-side admittances deviates a little and is not as perfect as the bode plot for ground-side admittances. This is due to not having perfect intervals for taking snapshots. When those snapshots are taken, the system might not have reached its steady-state for that particular perturbation, leading to deviation from perfect plot.

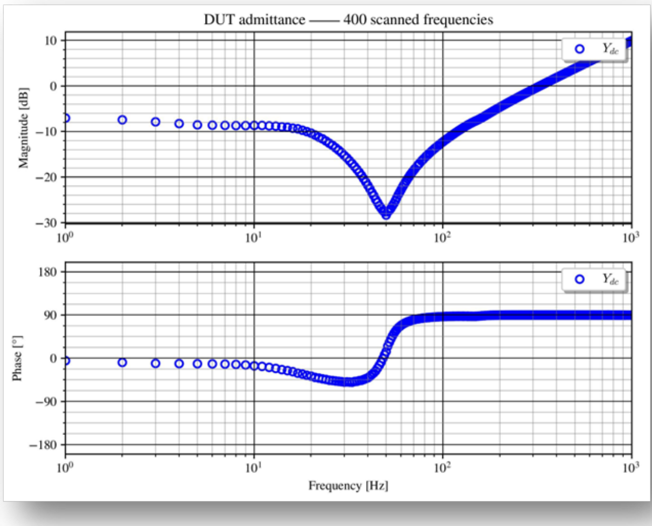

Figure 6.5: Ground-side Admittance values for DC scanning block for 400 scanned frequencies in 1-1000Hz.

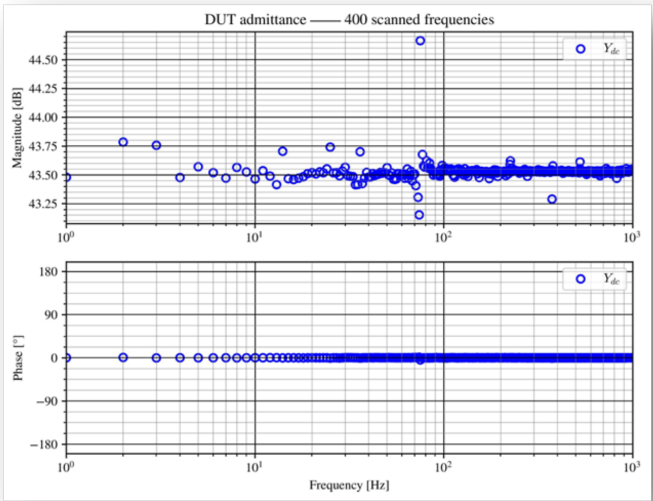

Figure 6.6: Converter-side Admittance values for DC scanning block for 400 scanned frequencies in 1-1000Hz.

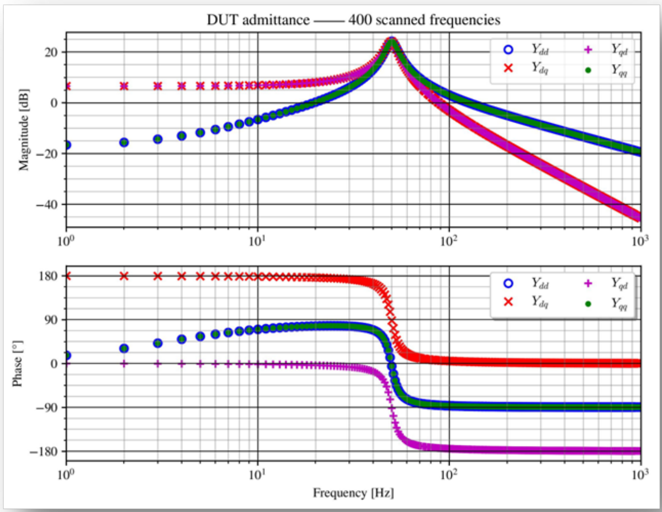

Figure 6.7: Ground-side Admittance values for AC scanning block for 400 scanned frequencies in 1-1000Hz.

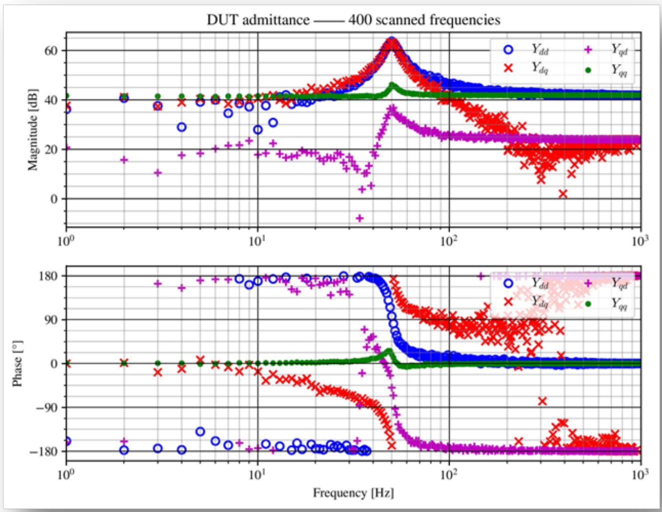

Figure 6.8: Converter-side Admittance values for DC scanning block for 400 scanned frequencies in 1-1000Hz.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This section summarizes the outcomes of this B.Tech. Project. Initially, PSCAD software was used to model various electric circuits which helped a lot in learning the software. Then, a controller was designed to control power for a three phase inverter. The Mid-Sem report concluded the work on modeling a two-terminal HVDC converter and application of the closed-loop controller to control active/reactive power.

The second phase consisted working towards the main aim of this B.Tech. Project. It started with creating a Python script to automate PSCAD. Then, AC and DC Scanning blocks were constructed to inject sinusoidal voltage perturbations. The Python script included automated recording of steady-state current, creation of transfer functions and bode plots with the frequency range for the scanning and snapshot time (regular interval after which system's data is recorded) pre-defined by the user.

The final phase consisted of creation of a White-Box model for two-terminal HVDC converter. MATLAB software was used to create a detailed state-space model using the information on the system in terms of differential equations, and implementing basic circuit theorems. Finally, Generalized Nyquist Criterion was used to assess the system's stability. Creating a white-box model was crucial to understand why Black-Box modeling is better when the converter's information is unknown.

7.2 Future scope of work

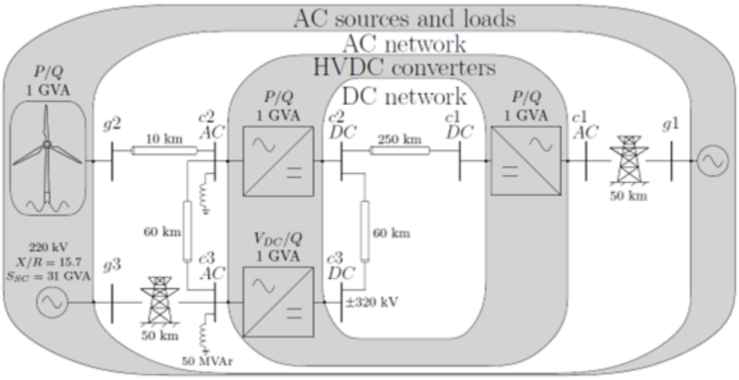

Figure 7.1: A modern power system.

As mentioned in the previous section, the next step is the automatic assessment of stability of the system. For this we divide a given power system in Figure 7.1 into 2 subsystems namely - *Edge* and *Node Subsystems. Edge subsystem* (white) contains AC/DC transmission lines and transformers whose information is generally known. Meanwhile, *Node subsystem* (grey) contain grids, renewable energy sources, and power electronic converters for which we construct black-box model. For each subsystem, we create an Admittance matrix using frequency scanning technique explained in the report. From the so obtained matrices - Y_{node} and Y_{edge}, we create two different transfer functions L and M.

$$L = Y_{edge}^{-1} Y_{node} \tag{7.1}$$

$$M = (Y_{node} + Y_{edge})^{-1} \tag{7.2}$$

$$p_{ij} = \frac{\partial \lambda_n}{\partial Z_{ij}(j\omega)} \tag{7.3}$$

$$p_{ij} = \phi_{ij} \psi_{ij} \tag{7.4}$$

Using the transfer function L calculated in (7.1), we create a Nyquist plot. Applying Generalized Nyquist Criterion on it, we can comment on system's stability.

Secondly, using the transfer function calculated in (7.2), we can analyze participation factors from the *Eigenvalue Decomposition* of the function M. Each eigenvalue corresponds to a Mode of the system. The eigenvalues λ_n thus obtained are further operated as shown in (7.3) to obtain participation factors.

Participation factor of j^{th} state variable in i^{th} mode is defined in (7.4), where ϕ and ψ are left and right eigenvectors, respectively. These are very crucial as they indicate the contribution of each state variable to each mode of the system, i.e. they help in identifying which system components are most involved in each oscillation mode.

High participaton factors for a particular component suggest localized instability issues. Modes with widespread high participation factors indicate global oscillatory issues, requiring system wide solutions.

Generally, for this analysis, a detailed state-space model of the system is necessary and this approach provides a better way to assess the system's stability and analyze participation factors.

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