B. Tech. Project Mid-Sem Report

On

Power Electronic Converter Modelling for High-Frequency Applications using Black-Box Approach

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Chapter 1

Introduction

With the increasing integration of renewable energy sources, power electronics have become an essential component of modern power systems. Power electronic devices offer highly efficient and compact solutions for power conversion, with switches capable of operating at frequencies as high as 2 MHz. Their applications are vast and continue to expand in the current energy landscape. However, with these advancements come certain challenges. One of the main concerns is the complexity of stability analysis over a wide frequency range. The intricate dynamics of these systems make stability assessment a complicated task. Fortunately, modern stability analysis methods, along with the computational power of advanced tools and software, allow us to conduct these assessments more efficiently. However, these converters are implemented from different original equipment manufacturer (OEMs) with limited information about internal dynamics makes the stability analysis more challenging and complex.

One of the goals of this project is to develop an analysis tool to simplify these time-consuming methods. The first step is to model the electronic converter to evaluate its stability across a broad frequency spectrum. For this, PSCAD is being used, a software renowned for its capabilities in simulating EMTP model of power systems. Once the converter is modeled, the next step is to implement closed-loop control. By integrating multiple control loops, the converter station is implemented and generates real-time simulation results. Then, the MATLAB and Python software's would be used for accessing the scanned data and stability analysis.

1.1 Literature Survey

At the initial stages of this project, I went through various research papers, books and sources to gain knowledge regarding Power Electronics, PSCAD, Converters, Black-Box Modelling, White-Box Modelling and their Stability Assessment. Going through them I got to know why this specific topic of Renewable Sources of Energy integration is so popular in modern times. Its importance and popularity were also mentioned to us by our professor in our Power Electronics course. I have gone through various sources about the above topics and now I am able to answer certain questions that came up in my mind and were also mentioned in the research papers during reading about these topics. Most of them included future prospects specifically on topic of Stability Assessment of these systems. Although the topic of this project is limited to Black-Box modelling, thanks to my supervisor I shall be taking it a step further and try to contribute to the topic of Stability Analysis of these systems by trying to devise a new method or add on to the currently used high time-consuming methods. At the end of this paper, I have attached a list of references which have helped me to learn a lot during the course of this project.

1.2 Motivation for BTP

During the course of Power Electronics in the institute, I found great interest in the topic. At that particular time, I didn't think that I would be doing mine BTech Project in the same. But when the time for project selection came, I just knew I wanted something related to Power and Control System. As I approached my supervisor for the same, he presented me with various projects in the area of Power Systems, Control Systems. This project consisted application of Control Systems in Power Electronics. After researching on and finding such widespread applications and so much future prospects for research in the Power Electronics, it became the main motivation behind choosing this specific topic for my BTech Project. I once dreamed of becoming a scientist, to invent something which is useful to everyone. And this project certainly has touched the inner scientist in me to create something wonderful, or at the very least try to. I hope to achieve the goals that I have made for this project.

1.3 Problem Statement and Objective

One of the problems that comes up during analysis of any power electronic converter being currently used in electric grids is that generally, the Manufacturer of the converter doesn't disclose the inner components of the product which hinders its stability analysis by a lot. There are also converters available for which we know the Differential Equations, which are known as White-Box models for which stability analysis even though complicated is possible. But majority of converters do not have any information regarding their components. So, we can't just assume that it would be stable in every scenario. We have to somehow conduct its stability assessment through a model designed to replicate its working. Or try to just ignore the inner components and develop a new method to assess its stability without even knowing what's inside the converter. That's exactly how Black-Box Models work. We create a system transfer function by using principles of Control Systems wherein we analyze various input-output plots, which can replicate the system's behavior for any disturbances. The ultimate goal for this project is to create a small real-world power system simulation containing both Black-Box models and White-Box Models and try to assess the stability of the whole system.

Chapter 2

Converter Modelling and its Closed-Loop Control

2.1 Converter Modelling

There are 4 types of Converters in Power Electronics based on Power conversion, namely – Cyclo-converters (AC-AC), Rectifiers (AC-DC), Choppers (DC-DC), Inverters (DC-AC). We shall be more focused towards modelling of 3-phase Inverter based on their wide usage in Renewable Energy Sources. As discussed before, we shall be using PSCAD software to effectively model the Inverter.

For initial modelling we used ideal sources and ideal wires for simplicity. But as we progressed, we added Impedances for each to replicate a real-world system. The first component is the incoming voltage for this converter, i.e. a DC source. For simplicity, we can model the DC source with a battery or a constant current source.

Then, we connected 6 switches (IGBT + anti-parallel Diode) as given in the Fig 1. Each phase leg of inverter has two switches that complement it each other in binary logic. The gate pulses for each switch comes from the PWM controller designed separately.

Then the output for each phase leg represents the 3 phases of the desired AC output. Which is in-turn connected to the Power Grid using Transformer. We also added LC filters in order to reduce High-Frequency Harmonics due to switching action of IGBTs.

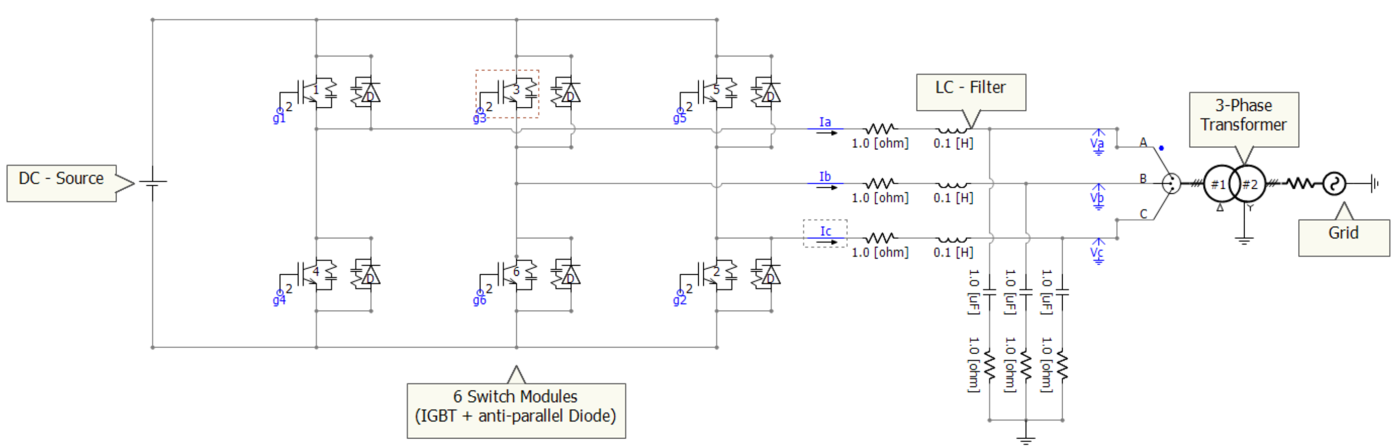


Fig. 1 – 3-phase Grid connected Inverter (actual values for electrical components may differ)

2.2 Controllers

In order to design a Closed-Loop control system for the above designed 3-phase Inverter, we require 4 major control loops working together.

<u>Inner Current Control Loop</u>: This loop is responsible for regulating the current flowing through the inverter's output. It ensures fast and accurate tracking of reference current, i.e. ensuring that actual current is close to reference current. It has a really quick response for rapidly changing load or input conditions with its higher Bandwidth.

<u>Outer Control Loop</u>: This loop is responsible for regulating voltage or power. It has a slower response as the variables that it regulates change gradually. It compares Output Voltage (or Power) with reference voltage (or Power) to generate an error signal which is processed through PI controller to produce the Reference current for inner loop.

<u>Phase-Locked Loop</u>: As the name suggests, it is responsible for synchronizing the amplitude and phase of inverter's output voltage and grid voltage. It consists of 3 major blocks - **Phase Detector**, which detects and outputs an error signal equal to phase difference in inverter output and grid voltage. **Loop Filter**, which filters out 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. PSCAD contains a pre-made block for PLL.

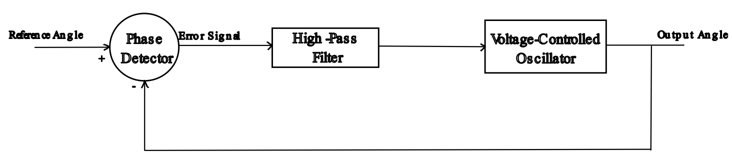


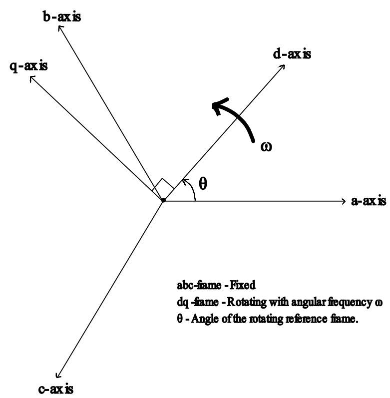
Fig. 2 – Closed Loop representation of Phase-Locked-Loop

<u>PWM Controller (sine-triangular PWM)</u>: It is responsible for the generation of Gate pulses for the 6 switches in order to generate the desired output of 3 phases. It takes the carrier signal as high-frequency triangular wave. This carrier wave's frequency decides **Switching Frequency** of the switches. It compares final output signal from control loop in abc-frame with the carrier signal to generate triggering pulse for a switch in a leg (each leg represented a phase, remember!) and the other switch in the same leg gets the complemented signal.

2.3 Direct-Quadrature-Zero Reference Frame (dq0-frame)

Now that we have studied the 3-phase inverter and its closed loop control, we shall reveal that the all controllers actually work in dq0-frame rather than typical abc-frame (general 3-phase) and therefore need necessary conversion. It is much harder to analyze and control quantities in abc-frame, therefore we transform it in a rotating frame where current and voltages become time-invariant quantities whose analysis and control is much simpler. PSCAD contains a pre-made block for abc-dq0 conversion.

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 below in the Fig. 3.



$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Fig. 3 – abc-dq0 frame representation and mathematical transformation

Chapter 3

Stability Assessment

3.1 Introduction

Power systems need to operate reliably to supply uninterrupted electricity. Stability analysis must be done by Grid operators to identify potential instability which can lead to equipment failures, electrical fires and large-scale blackouts. We shall be discussing two methods - Eigenvalue and Impedance-Based Stability Analysis. Both of the stability analysis methods can effectively determine the stability of the system.

3.2 Eigenvalue Analysis

It is a crucial aspect of power system stability that focuses on system's ability to maintain synchronism when subjected to small disturbances and is essential as it helps prevents oscillations. The linearized system is represented in state-space form as: $\dot{x} = Ax + Bu$ where x is state vector, A is state matrix, B is input matrix and u is input vector.

Now, the *Eigenvalues* of the State Matrix A are calculated. Each eigenvalue corresponds to a *Mode* of the system. Negative real part of each eigenvalue indicates that the corresponding mode is stable and positive real part implies that corresponding mode is unstable. Imaginary part of each eigenvalue indicates its frequency of oscillation.

Participation Factors are also very crucial in this analysis as it indicates 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. Participation Factor of j^{th} state variable in i^{th} mode is defined as: $p_{ij} = \varphi_{ij}.\psi_{ij}$ where φ_{ij} represents *Left Eigenvector* and ψ_{ij} represents *Right Eigenvector*.

High Participation Factors for a particular component suggest localized instability issues. Modes with widespread high participation factors indicate global oscillatory issues, requiring system wide solutions. One of the limitations of this analysis is that it requires a detailed state-space model of the system and therefore cannot be used in real-time stability analysis. Eigenvalue Analysis cannot predict sustained harmonic oscillations caused by an ac–dc power converter.

3.3 Impedance-Based Stability Analysis

It is also known as *Frequency-domain Stability Analysis*. Currently, majority of stability analysis is done using time-domain methods which have long computational times and are very complex to model. These also often require initial system conditions to produce reliable results, which are not available in real-world scenario. Alternatively, Frequency-domain methods are much simpler and are much more reliable for Renewable Energy Sources involving Power Electronic Converters. These methods rely on Impedance representation of the power system components which are then interconnected following KCL and KVL, thus forming a closed-loop feedback representation, which is used to determine system stability.

In this method, the system is divided into 2 subsystems - *Source subsystem* and *Load subsystem* as shown in Fig. 4 and the stability of the system is assessed based on the source-load impedance ratio.

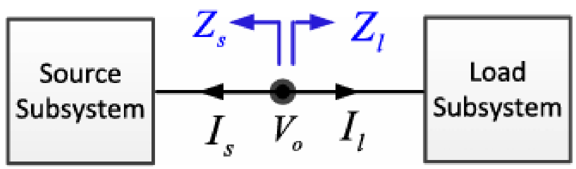


Fig. 4 – Source-Load System

Source Impedance and Load Admittance are then calculated by the relation:

$Z_S(s) = \frac{\Delta V_O(s)}{\Delta I_S(s)}$ and $Y_L(s) = Z^{-1}_L(s) = \frac{\Delta I_L(s)}{\Delta V_O(s)}$

Generalized Nyquist Criteria (GNC) is applied on L(s) to assess its stability at a particular operating point, by evaluating *Nyquist Plot* of $L(s) = Z_S(s) * Z^{-1}_L(s)$. GNC states that the system is stable for a given operating point if and only if *Eigenloci* of L(s) never encircles the (-1, 0j) point in the plane.

Stability Margins, i.e. *Gain Margin* and *Phase Margin* are also evaluated from Bode plot analysis of L(s). Higher the stability margins, the higher is the *Robustness* of the system.

One of the advantages of this method is that even when the given system is a *Black-Box*, this method can be applied as we can obtain impedance if the subsystem using *Perturbation Method*. A weakness of the impedance-based method is that it cannot predict the stability of the entire system from a particular interfacing point thereby making it necessary to investigate the stability at different interfacing points.

Chapter 4

Simulation Results

We have modelled an HVDC system containing two Voltage Source Converters (VSCs) in PSCAD as given below in Fig. 5. Both the converters are modelled with switched-model and they are connected with a π-model transmission line. Here, the Master converter (VSC1) is used for Active-Power Control and the Slave converter (VSC2) is used for Reactive-Power Control and Voltage Control. The aim of this simulation is to observe how the actual output follows the inputted reference values.

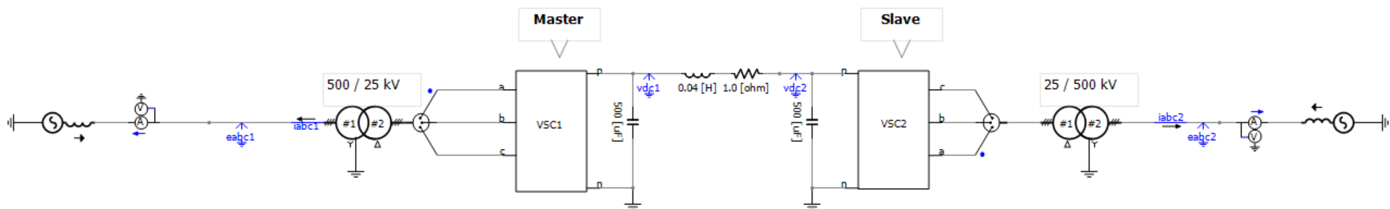


Fig. 5 – HVDC system

4.1 Active and Reactive Power Control

For Active and Reactive Power Control, we used reference switching between 0.5 and 1, and then we compared the actual values with the reference values.

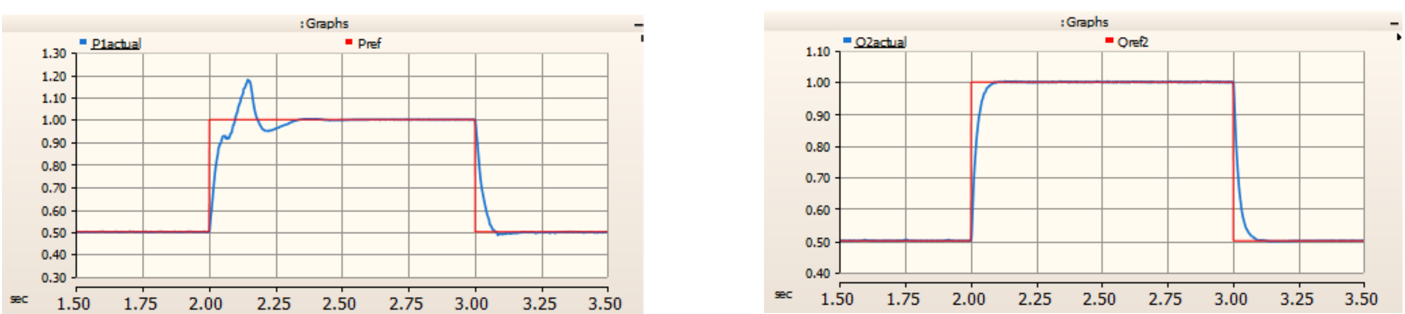
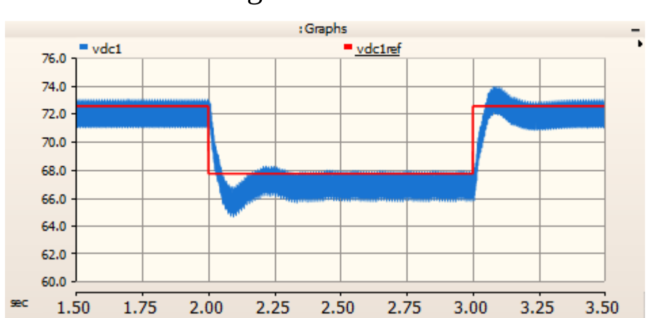


Fig. 6 – Active and Reactive Power Control

4.2 Voltage Control

For Voltage Control, we used reference switching with 5% of actual value of Voltage.



Chapter 5

Conclusions and Planned Workflow

5.1 Conclusions

We now have completed our first phase of the project where we learnt how to model a 3-phase grid connected inverter in PSCAD and implement its closed-loop control. We also saw how is the stability of the system is assessed using two methods – Eigenvalue Analysis and Impedance-Based Stability Analysis. Both have their own advantages and disadvantages and should be used where they are valid. Now that we have gained sufficient knowledge about the topic and its area of application, we are ready to begin the final phase of the project with the planned workflow given below.

5.2 Planned Workflow

The following shall be implemented till the end of course of BTech Project:

- Modelling for various HVDC systems
- Use of Frequency-Scanning Tool(Z-tool) to better assess stability of system
- Modelling of Modular Multilevel Converter (MMC)
- Black-Box Modelling
- Modelling of systems containing both Black-Box and White-Box model converters

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