Project Report

On

Modeling and Simulation of Multi-Level Power Converters for Wind Turbine Systems using Matlab-Simulink

BY

Group 7

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(March 2023)

ACKNOWLEDGMENTS

We would like to express our sincere gratitude to Dr. Sudha Radhika for giving us a chance to collaborate with her on this project and for taking the time to repeatedly give us the guidance we required. We also want to thank her for providing us with this excellent opportunity to apply what we learned in class to actual data and gain first-hand experience. We are indebted to her for all of her help and guidance, without which the development of this project up until this point would not have been conceivable.

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Abstract

In India, the renewable energy capacity has doubled in the past eight years. As of January 2023, it has the fourth-largest installed wind power capacity globally, clocking in at just under 42 Gigawatts (GW). This shows the potential and the need for renewable resources and the scope of execution. Diversifying the energy supply towards sources like wind, hydropower, solar energy, etc., is necessary to decrease dependence on fossil fuels. Wind farms are growing worldwide, and with the emergence of modern grid systems, wind energy systems are making a significant impact in penetrating the current energy market. Even though challenges persist, wind energy is a versatile source with a direct connection with power transmission with high scalability. In order to synchronize a wind turbine with the grid, a power electronic converter is used. This allows us to efficiently convert a variable frequency output of an induction generator, driven by a variable speed wind turbine, to one with a fixed frequency suitable for the grid. In this research, we will simulate various types of power converter models, including but not limited to a three-level neutral point clamped converter for wind turbines (3L-NPC/ANPC) and a modular multilevel converter. Various parameters, such as the turbine's frequency and output current, are analyzed to ensure that they are consistent with the frequency and phase of the grid voltage. The results obtained determine the efficiency and economic sustainability of the power electronics simulated, hence determining their future scope.

Keywords: *Power converter, Wind Turbine, Neutral Point Clamped (NPC) converter, Modular multilevel converter (MMC)*

Introduction

Wind energy is rapidly becoming one of the most promising and sustainable alternatives to conventional fossil fuels, due to its abundant availability and environmental friendliness. Multi-level power converters play a crucial role in the efficient and reliable integration of wind energy into the grid. These converters are able to handle the high voltage and power levels generated by wind turbines, and provide a smooth and stable output voltage to the grid. In recent years, multi-level power converters have gained attention due to their higher efficiency and reduced harmonic distortion compared to conventional two-level converters. Modeling and simulation play a vital role in designing, analyzing, and evaluating the performance of these converters for wind turbine systems. To this end, the use of MATLAB-Simulink for power electronics modeling and simulation has become increasingly popular due to its versatility, user-friendliness, and extensive library of models. [2] provides a comprehensive review of the modeling and simulation of multi-level power converters for wind turbine systems using MATLAB-Simulink, aiming to provide researchers and engineers with an in-depth understanding of the various aspects of this topic, and highlighting the challenges and opportunities for future research. The paper emphasizes the critical role that multilevel power converters play in wind turbine systems and their application, which is increasingly important in the renewable energy sector.

Blaabjerg and Ma [1] provide a thorough and informative overview of the application of power electronics in wind energy systems. Beginning with a discussion of the state-of-the-art technology and global market for wind energy systems, the paper continues with a look at the future of the industry. It provides an overview of several significant wind turbine concepts and power electronics solutions for individual turbines and wind farms as a whole. The authors also discuss some of the difficulties associated with integrating wind energy systems into power distribution networks, such as reliability performance issues for multimegawatt-scale wind turbines. This paper's thorough discussion of power electronics technologies utilized in wind energy systems is one of its strengths. The authors provide examples of how these technologies can be implemented to increase the efficiency and dependability of wind turbines, including control strategies for maximum power point monitoring, grid integration, and fault ride-through capabilities.

The paper also discusses potential future improvements to the efficacy and dependability of wind energy systems. The authors discuss, for instance, how sophisticated control strategies can be utilized to optimize the performance of individual turbines or entire wind farms. In addition, they discuss how new materials and manufacturing techniques can be utilized to reduce costs and enhance dependability.

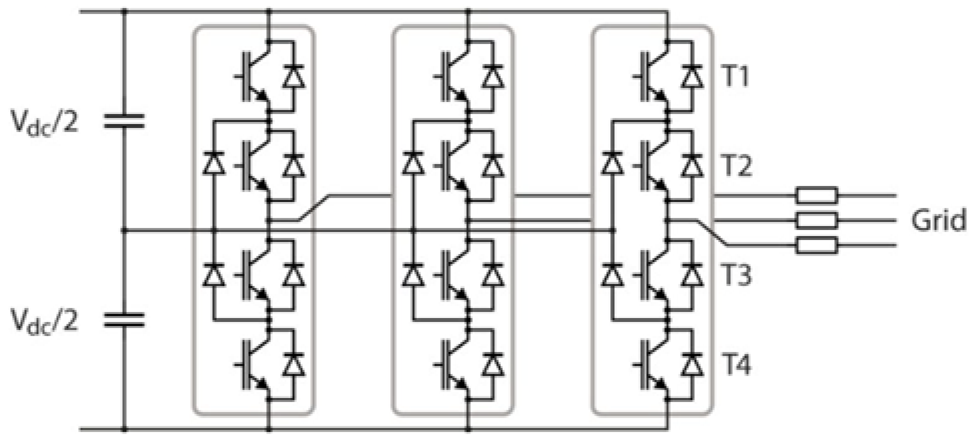

Fig. 1. Topology of a three-phase Neutral Point Clamped (NPC) Inverter

Definitions / Important terms

Neutral Point Clamped Converter (NPC)

An NPC (Neutral Point Clamped) converter is a kind of multilevel power converter utilized in high-power applications, including motor drives, renewable energy systems, and power grids. It is referred to as being "neutral point clamped" because it employs a clamping mechanism to keep the neutral point voltage constant, thereby lowering the common-mode voltage and electromagnetic interference.

An NPC converter generally functions by generating various voltage levels from a DC input by means of a series of switches and capacitors. The NPC converter can be expanded to include more levels if necessary, but it typically only has three levels of voltage output. The desired output voltage waveform is generated by controlling the switches with a pulse-width modulation (PWM) signal that determines how long each switch is on or off.

Active Neutral Point Clamped (ANPC)

An ANPC converter (Active Neutral Point Clamped) is a variant of an NPC converter that adds more active switches to the circuit. These active switches increase the converter's efficiency, which balances the voltage across the clamping capacitors. Additionally, the ANPC converter can generate higher voltage levels than the NPC converter, which is advantageous in some circumstances.

A difference between an ANPC converter and an NPC converter is the addition of active switches that regulate the voltage across the clamping capacitors. A number of methods, such as PWM, phase-shift modulation, and selective harmonic elimination, can be used to control the active switches. These methods decrease the circuit's switching losses, increasing converter efficiency.

In general, power converters used in high-power applications include both NPC and ANPC converters as significant types. They are beneficial in that they lower common-mode voltage, increase efficiency, and generate multiple voltage levels from a single DC input.

Modular Multilevel Converter (MMC)

The MMC topology consists of a series of sub-modules connected in series, with each sub-module comprising a full-bridge converter. The sub-modules are controlled to generate staircase voltage waveforms, combined to produce a high-quality output voltage waveform. The main advantages of the MMC topology are its modularity and scalability, which make it suitable for high-voltage applications. The number of sub-modules can be easily increased or decreased depending on the voltage level and power rating requirements.

The MMC operates based on the capacitor voltage balancing principle. The capacitor voltage levels are balanced by controlling the current flow through each sub-module. The current is controlled by switching the semiconductor devices in each sub-module, such as insulated-gate bipolar transistors (IGBTs) or thyristors. The operation of this converter is divided into two stages based on the capacitive action - the charging and the discharging phases.

The sub-module capacitors are charged to a pre-set voltage level based on a user requirement and system limitations; capacitive balancing is attempted to make sure that all the submodules are charged to the same level. The discharging phase is crucial as the formation of the output waveform is governed by the discharging of the capacitors. The semiconductors which are present in the submodules are responsible for the discharge action. The switching pattern is designed to generate a staircase voltage waveform, where the voltage levels of adjacent steps are different by a predetermined amount. The staircase voltage waveform is then combined using a filter to produce a high-quality output voltage waveform.

Working of a Neutral Point Clamped converter (NPC)

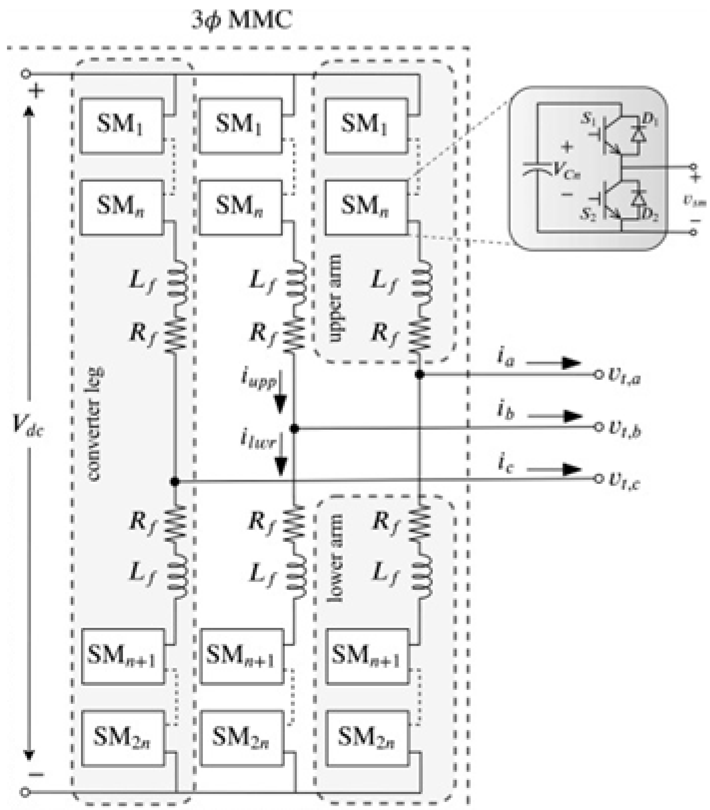

Fig. 2. Topology of an (n+1)-level 3-phase MMC

The working of an NPC/ANPC converter can be divided into three main stages:

- **Rectification**: The three-phase AC output from the generator is rectified using diodes to produce a DC voltage.
- **Inverter**: The DC voltage is then converted into a high-frequency AC voltage using a series of switches (IGBTs or MOSFETs). The switches are controlled by a pulse width modulation (PWM) signal to generate a sinusoidal waveform with the desired frequency and voltage.
- **Clamping**: In an NPC converter, the capacitors are clamped to the neutral point using a series of diodes, which reduces the voltage stress on the power devices. In an ANPC converter, the clamping is done using active techniques, such as resonant snubbers or auxiliary switches, to further reduce the voltage stress and improve the efficiency of the system.

Working of a Modular Multilevel Converter (MMC)

The general configuration of a 3-phase MMC comprises a DC terminal, AC terminal, and a control kernel, including legs with symmetric upper and lower arms. Fig 2. Shows the structure. It can be seen that the arms have identical submodular structures. The inductors seen are called chock inductors which help suppress high-frequency current components.

Proposed models

This section aims to briefly describe the simulated model of the improved system used. The input parameters chosen for the wind turbine system are:

TABLE I. Input Parameters for the wind turbine system

S. No.	Parameter	Value
1	Pitch angle	3 degrees
2	Base wind speed	12 m/s
3	Base generator speed	1.2 p.u.

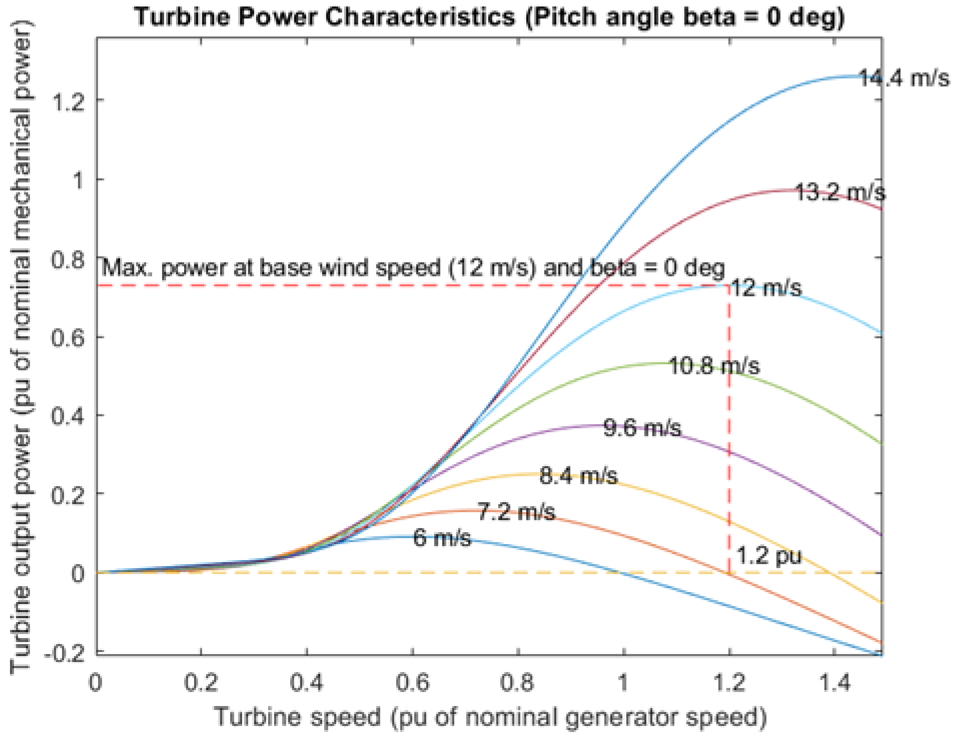

Fig. 3. Power characteristic of the wind turbine

As it can be clearly observed, the output power of the turbine reaches its maximum value at a base wind speed of 12 m/s. The output of the wind turbine system (mechanical torque) is fed to permanent magnet synchronous machine along with the three phase parameters (turbine voltage and current). The AC output is then fed to a thyristor rectifier that converts the AC voltage to a DC parameter.

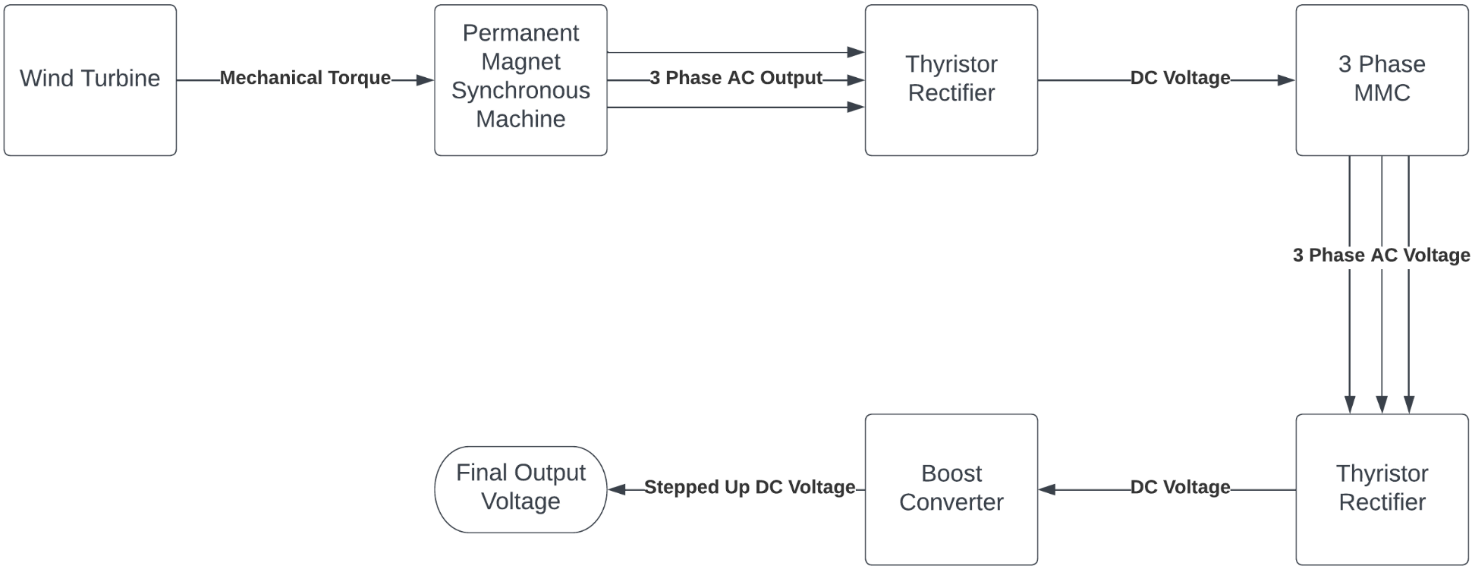

Fig. 4. Layout of the three-phase MMC circuit

A three-phase modular multilevel converter (MMC) works on the principle of a capacitive inverter. The DC output from the rectifier is fed to the MMC, giving an AC-natured output voltage. It is to be noted here that an MMC circuit was not utilized in the original model. Upon its use, the AC voltage obtained is higher in value which depicts improvement in an intermediary output. After the MMC inversion action we use a fully controlled thyristor to convert the AC-natured output to DC. Capacitors are connected in parallel to increase the electrical energy stored and reduce rippling (filtering action).

A boost converter is a step-up converter that helps to step up voltage while stepping down current. In a wind turbine system, the generator produces a variable DC voltage that depends on the wind speed. The output voltage from the generator is typically lower than the required grid voltage, which is usually around 400 V or 600 V. The boost converter is used to increase the voltage level of the generator output to the required grid voltage level. The duty cycle of the switch in the converter determines the output voltage level of the converter. The duty cycle is controlled by a PWM signal, which adjusts the on-time and off-time of the switch. By adjusting the duty cycle, the output voltage level of the converter can be increased or decreased.

Results

NPC

A 3 level-neutral point clamped inverter (3L-NPC) is often present in medium voltage transmission applications. The mean voltage received from the wind turbine can be increased by adjusting the voltage. Fig. [6] shows the three-phase output voltage received from the wind turbine. It can be observed that 3.773 V of output voltage from the wind turbine gets boosted via a boost converter by a factor of 9.5335 to a mean value of 35.97 V.

Fig. 5. shows the input voltage to the NPC in the circuit. The mean of this voltage comes out to be 14.75 V, and is rippled DC in nature. The ripple factor of this DC input is 0.2561.

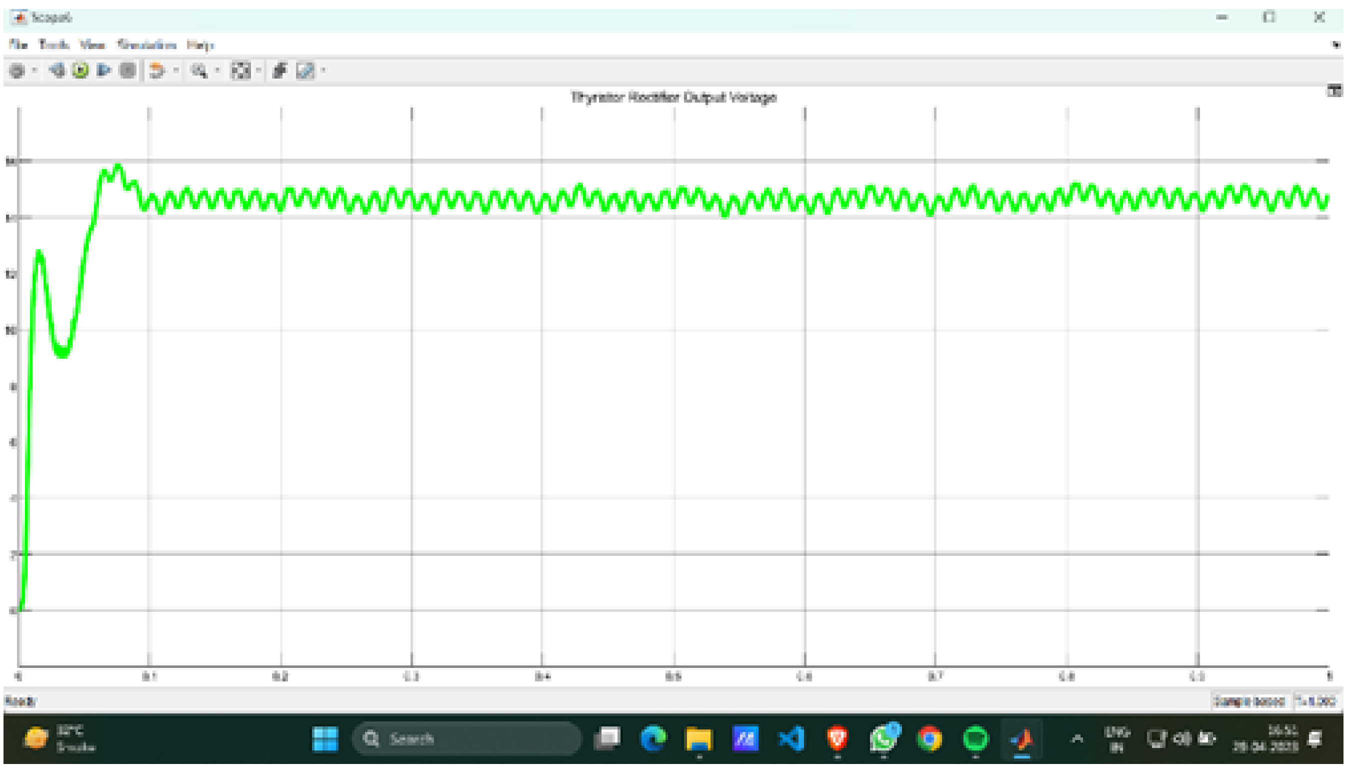

Fig. 5. Input voltage to the NPC (19.23 V)

The voltage and current obtained from the scope connected to the output load of the NPC can be found in Fig. [6]. Here, NPC is used to convert the DC voltage from the rectifier to a three-phase AC voltage output.

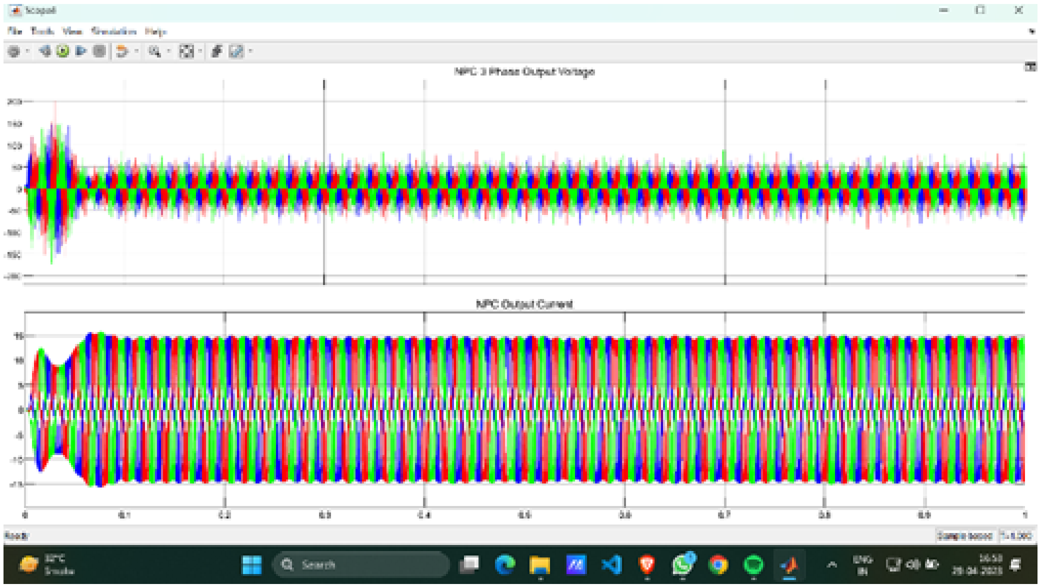

Fig. 6. NPC output parameters - voltage and current

The source and final output voltage, current of the NPC circuit is depicted in Fig. [7].

Fig. 7. Source, output voltages and currents

MMC

This section comprehensively explains the circuit through the medium of the graphs obtained from the scopes placed through the circuits.

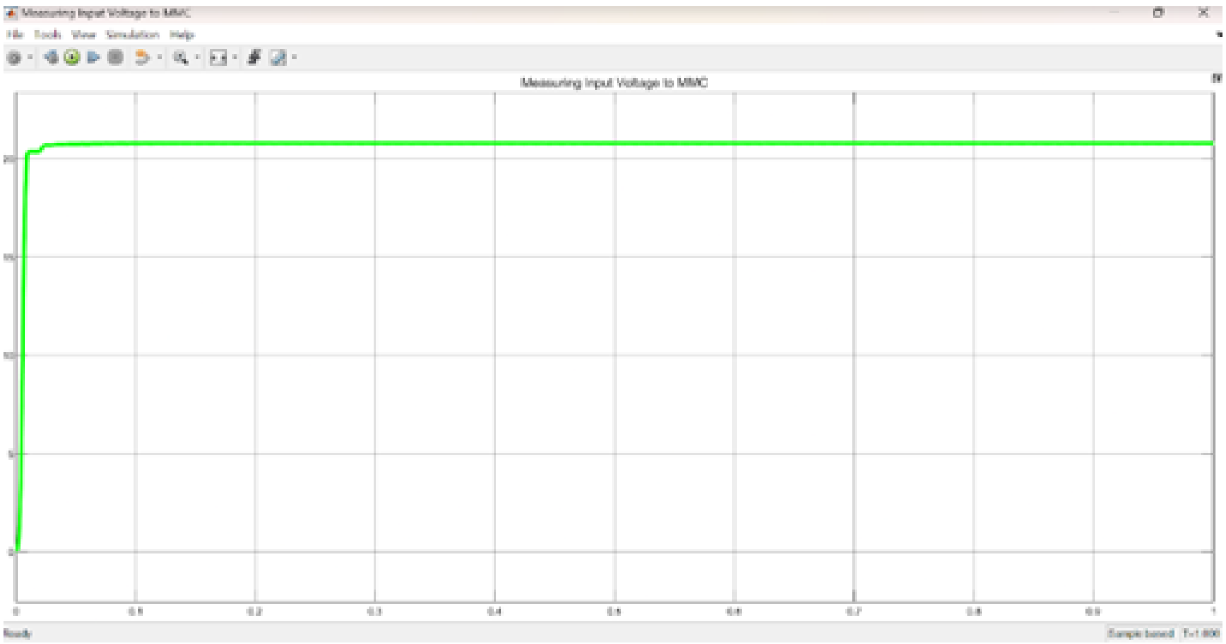

Fig. 8. Input voltage to the MMC (23.9 V)

This figure shows the input voltage to the MMC in the circuit. It is the output obtained from the fully controlled rectifier circuit. Thus, it is DC-natured with a value of 23.9 V

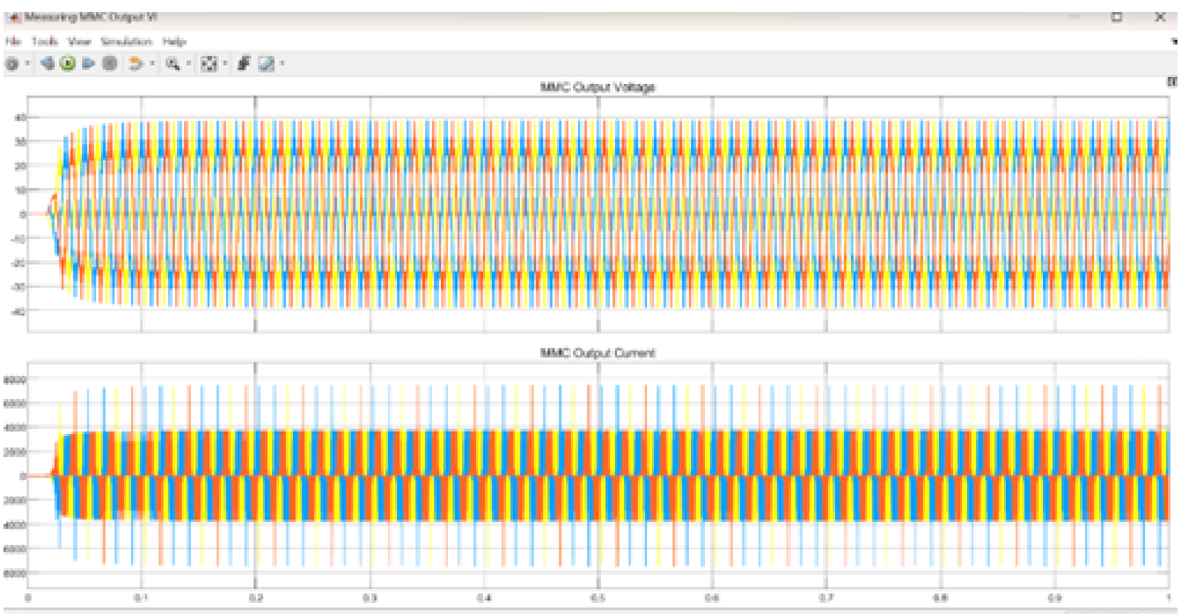

Fig. 9. MMC output parameters - voltage and current

As in the case of the NPC, the conversion of DC voltage from the rectifier to the AC voltage output takes place as shown in Fig. 9 (all three phases are seen in the figure - red, yellow, and blue).

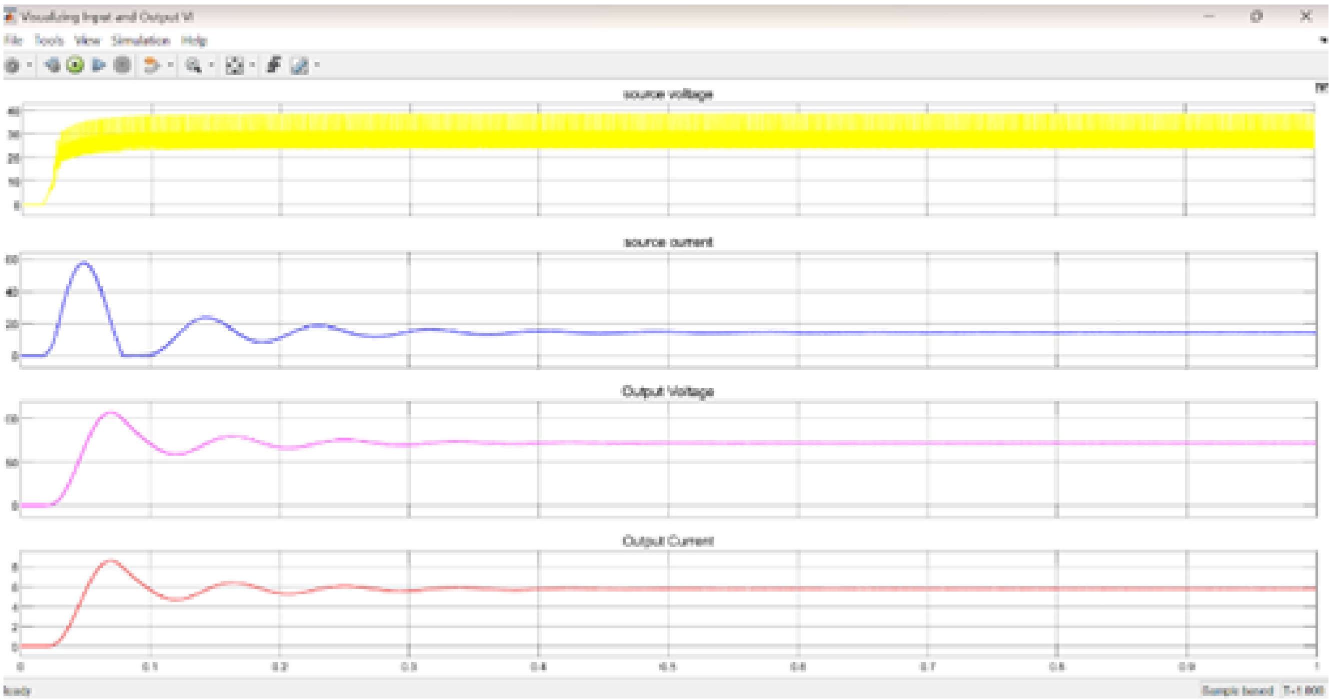

Fig. 10. Three-phase rectifier

Comparison

According to [citation], the voltage provided by the wind turbine to the boost-converter is 2.997 V. This voltage is boosted to 34.3 V. However, in an attempt to increase the input voltage to the boost converter, it is observed that the voltage gain decreases drastically. Therefore, it can be concluded that the boost converter may not always be the best option for high voltage boosting applications.

For a constant base wind speed of 12m/s,

TABLE II. Output parameters for wind speed 100 m/s

Simulink Model with wind speed 100 m/s	Source Voltage	Output Voltage	Voltage gain
Boost Converter	2.997	34.3	11.4447
NPC Converter	3.773	35.97	9.5335
MMC Converter	15.2	59.22	3.896

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