

## ***A Comparative Analysis Of Three-Phase AC To DC Converter With PI Controller***

Bharat S Sudame<sup>1</sup>, Sumant G. Kadwane<sup>2</sup>

<sup>1</sup>Research Scholar, Electrical Engineering, Yeshwantrao Chavan College of Engineering ,  
Nagpur, India, bharat\_sudame@rediffmail.com

<sup>2</sup>Electrical Engineering, Yeshwantrao Chavan College of Engineering,  
Nagpur, India, sgkadwane@gmail.com

### ***Abstract:***

In this article, we shall investigate how a Three-Phase AC to DC Converter, coded as TPAC, functions under the control of a Proportional-Integral controller, abbreviated as PI. In a number of industrial applications, such as variable speed drives and power supplies, for instance, this converter plays a highly important role. One reason why the PI controller enjoys widespread usage can be attributed to its simplicity in implementation as well as its ability to control well the output voltage in the converter. Here, our prime interest lies in uncovering how TPAC acts while performing in varying scenarios for simulation purposes, MATLAB/Simulink simulation results can be obtained that describe both the TPAC and the PI controller. The start of the model description of the converter could be either three-phase diode bridge rectifier/DC link capacitor and inverter or the inverter output voltage control by the PI controller. It has been found to be very effective in regulating the desired output voltage. Even in the case of varying loads, the output voltage remains constant, and the analysis also focuses on the performance of the PI controller during the process of conversion of AC to DC. It has fast recovery in the case of power interruptions. It can be seen that the above research has provided valuable information about the operation of TPACs that include PI controllers. It can be considered an important study that gives guidelines on how to design and control TPACs. It aims to improve reliability and efficiency.

**Keywords:** Three-phase AC to DC converter, PI controller, Performance analysis, Efficiency.

### ***1. INTRODUCTION***

Three-phase AC-DC converters play a very important role in many industrial applications, including motor drives, power supplies, and green energy utilizing systems. These converters need to convert the three-phase AC power from the grid into DC power. DC power is then utilized to drive DC loads or charge DC batteries. PI controllers are widely adopted due to their simplicity and ease of use in real-time applications and have proved satisfactory performance. In fact, the performance of such processors largely relies on the control strategy employed. The main objective of this work is to analyse the performance of a three-phase AC-DC converter using a PI processor. The converter has been modelled using MATLAB/Simulink, and various working conditions have been applied for testing different performance indices. The objectives of this study are to further investigate the dynamic response, stability, efficiency of the converter, and comparative evaluation with other control techniques.[1]. Because three-phase AC to DC converters can convert three-phase AC power from the grid into DC power, they find widespread use in industry. DC loads, such as motors, have to be supplied, and batteries have to be charged in green energy systems. The effectiveness of the converters is very important for the overall functioning and reliability of the entire system, and your choice of a control approach significantly impacts the effectiveness of the converter. Due to their simplicity and effectiveness, PI processors are widely used for handling three-phase AC to DC converters. The driver controls the output voltage of the converter by changing the firing angle of the thyristors

or by changing the switching frequency of the transistors. The proportional and integral gains of the controller have to be fine-tuned for the desired stabilization of the output voltage and also to maintain stability when the load changes. Microgrids have become an important part of modern power systems, offering an autonomous and reliable method for generation, distribution, and utilization of energy [2]. A voltage source inverter is used in order to link the microgrid into the main grid. The operation of linking will convert the frequency from DC to AC and connect the DC power source with the main grid. That link is very vital in maintaining stability and dependability within the microgrid system. Determining the best operating strategy and financial performance prediction is one of the most involved design tasks within a microgrid [5]. This implies maximally utilizing resources such as energy storage systems and green sources of energy for cost minimization and efficiency enhancement. It identifies that the purpose of the forecasting methods is to guess the variability of the load and output in the future time, based on which the microgrid planning and operation becomes easier. Control is one of the most important parts of ensuring the functionality and stability of the microgrid system. Major components of the microgrid will include the DC-DC converter, the DC-AC converter, the BESS, and the link components for electric cars [3]. Those components require high-performance controls so that quality figures, such as levels of voltage, are kept within specified limits.

For a long time, PI-type computers have been employed to operate microgrids due to their simplicity and reliability. These controls are weak in handling dynamic or complex behavior, especially under systems with high changes in the parameters [12]. To overcome this challenge, new controllers were developed and implemented that include the adaptable controllers, robust controllers, neuro-fuzzy controllers, and Passivity theory-based controllers. Certain types of machine learning, such as reinforcement learning, have also been applied in the control systems for microgrids.[6]. For example, the RL-TD3 agent can make the DC-AC converter control system work better through interaction and learning of the best ways to control it. This agent works like an industrial process control system. It learns about the dynamics of the system while improving some quality measure to enable it to send adjustment messages to the control system. In this project, Simulink is used to look at the functioning of a three-phase AC to DC converter with a PI controller in detail. The converter is modelled by a three-phase diode bridge rectifier, a DC link capacitor, and an inverter.[4]. In this project, the PI processor is responsible for controlling the output voltage of the converter, while different parameters affecting the performance have been chosen for investigation. The project basically concentrates on the stability, dynamic response, and efficiency of the converter in different working conditions. The project is tested for different loads in order to verify the capability of the converter in maintaining an unvarying output voltage. At the same time, it is also verified how the converter will behave during any variation in the input voltage, for instance, sags and swells, which illustrates the robustness and reliability of the converter. It attempts to acquire informative data on the working performance of a three-phase AC-to-DC converter, which has adopted a PI processor. The findings obtained in this study can aptly be used for designing three-phase AC-to-DC converters, which will be superior in both design and control schemes. This will help in making the power conversion systems in the industrial sector more reliable and efficient.

## **2. LITERATURE REVIEW**

### **2.1. Three-phase AC to DC converters**

The three-phase AC-to-DC converter systems incorporate the entire process, from hardware design and design of the controls to performance analysis and possible applications. Optimization of the designs for higher efficiency, compensation of power factor, and reduction of levels of distortion is an important area of research and development being worked upon. Effectiveness and possible utilization are analyzed for several topologies of three-phase converters, such as diode rectifier, thyristor-based, and more contemporary semiconductor technology IGBT-based designs. A large quantity of research also deals with three-phase DC-to-AC converters control for prompt and correct adjustment of voltage and current of DC output. The majority of the people use conventional PI controls because they are easy to operate and have been proved very reliable [7]. Still, the majority of the research efforts were directed towards developing more sophisticated techniques of control like adaptive control, predictive control, and fuzzy logic control to make things function even better. These techniques relate to the enhancement of quick response, high efficiency, and stability in the wide range of operating conditions. Efficiency analysis can be done considering other aspects like power quality, rapid reaction, etc., of three-phase AC to DC converters. Various performance measuring techniques have been presented by researchers, including modelling software such as MATLAB/Simulink and hardware-in-the-loop tests. These studies present the response of the converter to various loads and help determine the optimum operation of the converter [8]. Three-phase AC to DC converters find their application in industrial motor drives, green energy systems, among others. In industries, converters are used to supply power to DC motors and for the control of the speed and force of tools. Converters play a crucial role in green energy systems, where they convert the input power from solar panels or wind turbines to DC power that is fed into the grid or stored for later use.

## **2.2. PI controllers in converter control**

Many converters employ PI processors due to their ease of use, good performance, and capability to provide stable control in many applications. One area of research related to PI controllers in converter control is the determination of the optimal settings of controllers for various applications. Various works have proposed the tuning of PI controller proportional and integral gains to meet various performance specifications such as fast response, low overshoot, and strong stability [9]. It was applied to optimize PI controller gains for VSIs and CSIs, among other converter topologies. For example, look at the Ziegler-Nichols method. The purpose of these research is to find the proper adjustment of the controllers that would ensure higher stability and reactivity of the converter system. The second area of research is focused on the determination of the implementation of modern control strategies for higher quality PI processor performance for converter control. Various researchers have applied a combination of PI controllers with a feedforward controller or model predictive controller strategies so that they could have better performance for set-point and disturbance. By utilizing these more modern strategies, they could ensure that PI controllers could better handle the nonlinearities and errors associated with the converter system [10]. Further than enhancing the speed, researchers have also explored the stability analysis for the PI processor based on the converter control. Various robust strategies, including H-Infinity strategies and sliding mode strategies, have been applied with the aim that the PI controller would be robust against variations and difficulties. The strategies apply towards ensuring that the conversion system is always stable and properly functioning. Researchers have further applied these PI controllers with digital signal processors or field-programmable gate arrays so that the controller could be made more flexible with enhanced computation capacity. This resulted in more advanced strategies for

controlling with quicker responses, for which high-speed converter systems are required.

### **2.3. Performance and control strategies related work**

Studies that were conducted in the past on the performance and control of converters have greatly influenced the current knowledge of power electronics. Various researchers have considered distinct aspects of the converters. Such aspects include the performance and control of the converters. Studies conducted have improved the performance and stability of the systems. Another aspect is the cost-effectiveness of the systems. Converter performance efficiency is the next aspect that has been pursued.[11]. Researchers have explored ways to reduce power loss in converters. They have examined optimal switching patterns, minimized conduction losses, and improved heat dissipation. As a result of these studies, we now have better converter designs and control methods. This enhances the overall ability of power electronic systems to convert energy.[22].

Control techniques for converters have also been explored in the past. Various forms of control techniques have been proposed and explored by different researchers [13]. They include feedback systems, voltage and current control systems, and modulation systems. The aim of carrying out such studies was to ensure that the control of converters becomes dynamic and stable whenever there are fast changes in working conditions. However, the issue regarding the integration of converters into micro-grids and green energy systems has also been investigated earlier [14]. The control techniques used in grid-coupled converters, techniques used to accomplish the concept of islanding, and technologies used to manage power to derive the highest available power from green energy resources have been explored by the research works. As a result, green energy has been integrated into the grid, and cleaner power systems have also been developed [15]. The impact of converter design and control on power quality is another research subject explored in the past. In particular, an examination was conducted on the influence of operating the converter on aspects such as voltage stability, harmonic distortion, and power factor values. Active power filters, grid timing concepts, as well as other solutions leading to improved power quality in converters have been made possible by these research activities. Research done in the past on the performance of converters as well as methods of controlling these converters have taught us quite a lot about how to design, operate, as well as enhance power electronic systems. Research done in the past have led the way toward advancements in converting technologies, converting power systems into reliable, efficient, and long-lasting power converters.

**Table 1: Summary of related work**

| <b>Method</b>           | <b>Type of Filters</b> | <b>Topology</b>               | <b>Finding</b>                                    | <b>Limitation</b>                                     | <b>Scope</b>                                                |
|-------------------------|------------------------|-------------------------------|---------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------|
| Optimization techniques | Passive filters        | Diode rectifier               | Improved efficiency under varying load conditions | Limited effectiveness in reducing harmonic distortion | Further optimization for higher efficiency and lower losses |
| PI controller tuning    | Active filters         | Voltage source inverter (VSI) | Tuning PI controller parameters for better        | Dependency on accurate system modelling for           | Implement advanced control strategies                       |

|                                    |                      |                               |                                                                 |                                                        |                                                                     |
|------------------------------------|----------------------|-------------------------------|-----------------------------------------------------------------|--------------------------------------------------------|---------------------------------------------------------------------|
|                                    |                      |                               | dynamic response                                                | optimal tuning                                         | for improved performance                                            |
| Modulation techniques              | Passive LC filters   | Current source inverter (CSI) | Reduced harmonic distortion in output voltage                   | Limited effectiveness in reducing high-order harmonics | Investigate active harmonic filtering techniques                    |
| Power factor correction techniques | Active power filters | Half-bridge rectifier         | Improved power factor and reduced grid harmonics                | Limited effectiveness at low power levels              | Explore advanced power factor correction methods                    |
| Stability analysis                 | LCL filters          | Full-bridge rectifier         | Enhanced stability under varying operating conditions           | Susceptibility to resonance and grid disturbances      | Study the impact of different filter configurations on stability    |
| Voltage control strategies         | Passive RC filters   | Boost converter               | Improved voltage regulation during load changes                 | Limited control range at high frequencies              | Investigate hybrid control strategies for wider control range       |
| Control loop design                | Active LCL filters   | Flyback converter             | Fast and accurate response to load transients                   | Limited effectiveness in reducing settling time        | Explore advanced control strategies for faster response             |
| Fault tolerance techniques         | Active PFC filters   | Buck-boost converter          | Improved reliability and fault tolerance in converter operation | Limited fault detection capabilities                   | Develop fault detection and isolation mechanisms                    |
| Machine learning algorithms        | Hybrid filters       | Multilevel converter          | Enhanced efficiency through intelligent control algorithms      | Complexity in training and implementation              | Investigate real-time implementation of machine learning algorithms |
| Model predictive control           | Passive RL filters   | Modular multilevel converter  | Improved control performance and dynamic                        | Computational complexity and real-time implementation  | Develop simplified MPC algorithms                                   |

|                                |                    |                                   | response                                               | n issues                                                   | for real-time applications                                               |
|--------------------------------|--------------------|-----------------------------------|--------------------------------------------------------|------------------------------------------------------------|--------------------------------------------------------------------------|
| Fuzzy logic control            | Active RL filters  | Matrix converter                  | Enhanced voltage regulation and transient response     | Limited robustness in highly nonlinear systems             | Investigate adaptive fuzzy logic control for robustness                  |
| Harmonic mitigation techniques | Passive RL filters | Active front-end rectifier        | Reduced harmonic distortion and improved power quality | Limited effectiveness in reducing high-frequency harmonics | Explore hybrid filter configurations for better harmonic mitigation      |
| Grid synchronization methods   | Active RL filters  | Grid-tied inverter                | Improved power factor and grid synchronization         | Limited effectiveness in unbalanced grid conditions        | Investigate advanced grid synchronization techniques                     |
| Power loss analysis            | Passive RL filters | Single-phase inverter             | Reduced power losses and improved efficiency           | Limited effectiveness in reducing switching losses         | Investigate soft-switching techniques for further efficiency improvement |
| Adaptive control algorithms    | Active RL filters  | Current-fed full-bridge converter | Enhanced adaptability to changing system parameters    | Limited adaptability to rapid changes in system dynamics   | Investigate advanced adaptive control strategies                         |

### 3. Theoretical Background

#### 3.1. Three-phase AC to DC Converter Topology

A rectifier circuit is used to convert the three-phase AC signal input to DC output. This essentially describes how a three-phase AC to DC converter works. The diode rectifier circuit is a very common configuration of the circuit. It comprises six diodes, which are arranged in the form of a bridge [16]. The main characteristic of this circuit is that it supports the flow of current in one direction alone. It supports the positive half-cycles of the AC signal but blocks the negative half-cycles. Thyristor converters are another common configuration of the circuit. They are preferably used in place of the earlier one because they utilize thyristors, which are also known as silicon-controlled rectifiers or SCRs, in place of diodes [17]. The thyristor is given the capability to allow the flow of currents in a certain portion of the AC signal. This essentially provides the circuit with the ability to control the power flow as well as the output voltage level [17]. Mostly, this circuit configuration is preferably used in high-power applications, requiring precise control. However, modern versions of the converter circuit use semiconductors such as

metal oxide semiconductor field-effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs), which essentially improve their performance by making them faster in terms of switching operations. Most of the following applications utilize this kind of circuit configuration, including the voltage source inverter (VSI) and the current source inverter (CSI) circuits.

### **3.2. Principles of Operation**

What a three-phase AC to DC converter can do is dependent on the type of converter being employed. For a diode rectifier device, the current flows from two of the diodes in each half-cycle of the input AC voltage source [18]. This lets the positive half-cycles go through but blocks the negative half-cycles. The rectifier gives off a pulsing DC voltage that changes based on the AC voltage it is fed and the load it is carrying. In a thyristor-based converter, the thyristors are set to conduct for a part of each half-cycle. This lets the converter manage the DC output voltage on average. The converter can change the output voltage and power flow by changing the firing angle of the thyristors [19]. In newer converter designs that use IGBTs or MOSFETs, the way they work is based on pulse-width modulation (PWM) methods. In order to change the overall output voltage, the switches are turned on and off at high rates. The PWM signal's duty cycle can be changed so that the converter can precisely control the output voltage and power flow.

### **3.3. PI Controller Design and Implementation**

Because it is easy to use and works well, the PI processor is often chosen to handle the output voltage of a three-phase AC to DC converter. There are two parts to the controller: the proportional and the total [20]. The integral part considers the error over time to make up for steady-state mistakes, while the proportional part reacts to the error now. When you build a PI controller, you must tune the proportional and integral gains to get the results you want, like fast reaction, little error, and stability. This process of tuning is usually done by feeling, considering how the system works and what it needs to do. When a PI processor is used in a converter device, the output voltage is usually measured and compared to a reference voltage. The processor then changes the duty cycle or shooting angle of the converter switches to keep the output voltage steady. The output of the controller is a control signal that tells the converter how to work and makes sure that the output voltage closely follows the reference voltage.

### **3.4. Performance Metrics for Converter Analysis**

A three-phase AC to DC converter's performance can be measured in a number of ways, such as its efficiency, power factor, harmonic distortion, and rapid reaction. How efficiently the converter changes AC power into DC power is measured by its efficiency. It is found by dividing the power going out by the power coming in, and the result is given as a percentage. To cut down on power waste and make the whole system more efficient, you want it to be very efficient. This is a way to figure out how well the adapter takes power from the AC source. It is the ratio of the real power (in watts) to the visible power (in volt-amperes). It can be written as a percentage or a number. A power factor close to 1 means that the power is being used efficiently, while a low power factor means that the system is not working efficiently. When harmonics are present, they change the shape of the output voltage or current pattern. This is called harmonic distortion. Harmonics are different amounts of the basic frequency (50 Hz or 60 Hz). They can mess up power systems by making equipment boil and interfering with communication systems. To make sure the quality of the output power, low harmonic distortion is good.

Transient response: This refers to the speed as well as the accuracy of the conversion accomplished by the converter. To ensure that the value of the voltage Output remains constant under different working conditions, a high rapid reaction rate is necessary. To determine the rapid reaction of the converter, the following factors are considered. When making and using a three-phase AC to DC converter, the layout, control strategy, and performance measures need to be carefully thought through. The application needs to determine the structure and control strategy. The performance metrics give a number value to the converter's efficiency, power quality, and ability to adapt to changes.

#### **4. Methodology**

##### **4.1. Simulation setup using MATLAB/Simulink**

MATLAB/Simulink simulation setting is a popular way to model and study how well a three-phase AC to DC converter with a PI controller works. Power electronic systems can be designed and simulated easily in MATLAB/Simulink, which lets you use converter designs, control methods, and performance evaluation measures. Starting the simulation requires first modelling the three-phase AC to DC converter structure in Simulink. To do this, you must pick the right blocks to show the AC voltage source, DC load, and converter parts like diodes, thyristors, IGBTs, or MOSFETs. The converter design can be chosen based on the needs of the application and the control strategy that is being investigated. Further, the structure of the PI controller is modelled using Simulink with respect to the output voltage of the converter. In our discussion earlier, the tuning stage is carried out with the aim of finding the optimum values of the proportional and integral constants, which are implemented in the PI controller block. Upon receiving the error signal (between the reference voltage and the actual output voltage), the control signal is generated, which adjusts the firing angle of the switches in the converter circuit based on the control action of the controller block.

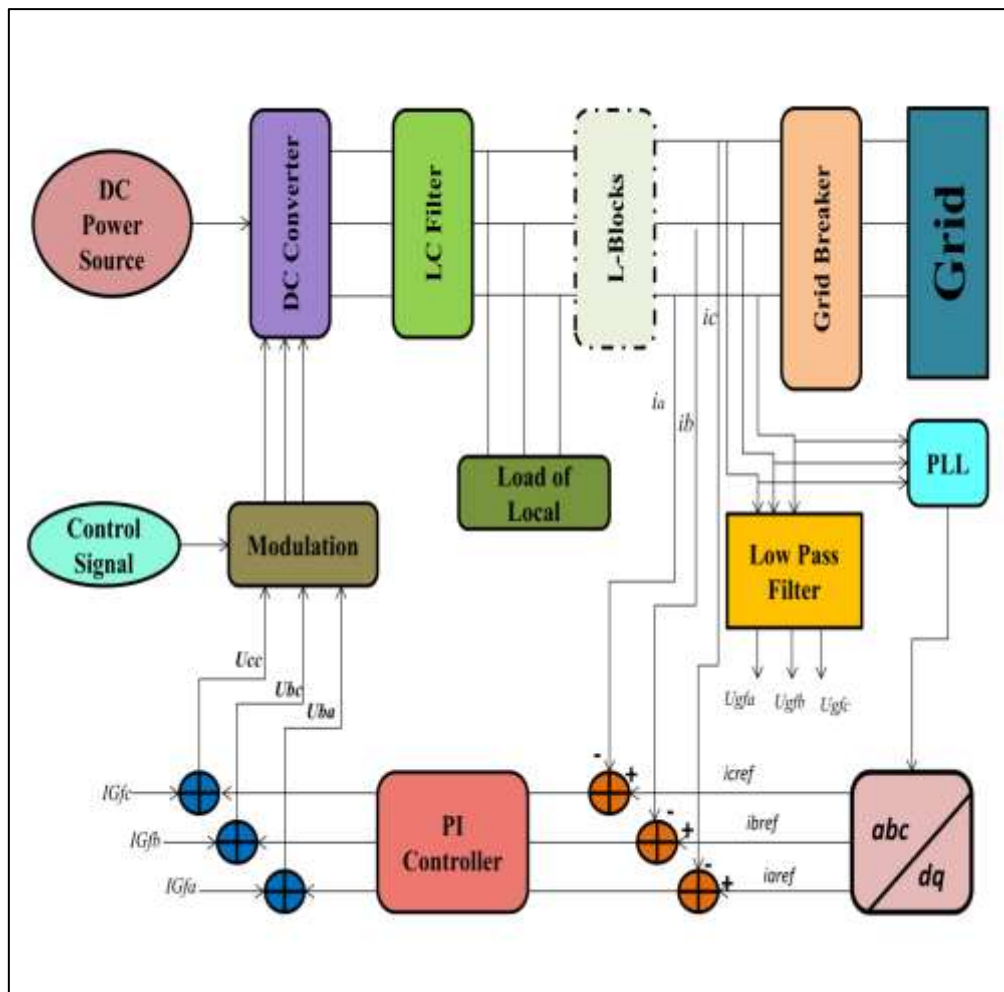
The simulation is then performed to analyse how effective the conversion process is. Based on the data from the simulation model, one can calculate the performance parameters such as power factor, harmonic distortion, quick response, and economy. The simulation model can be applied in assessing the performance of the converter circuit in several areas. The advantage of carrying out a simulation process using the MATLAB/Simulink software includes the capability to analyse the outcomes. It is simpler to analyse the performance of the converter circuit as well as how it needs improvement through the software since it provides capabilities to analyse waveforms, bands of frequency, as well as performance metrics.

##### **4.2. Modelling of the three-phase AC to DC converter with PI controller**

Modelling a three-phase AC to DC Converter using a PI controller entails creating the mathematical model of the overall converter system and the way it has been controlled. The mathematical model enables the performance of the exchanger to be evaluated, modelled, and optimised. Firstly, the design of the overall converter system has to be determined. This may be the basic diode rectifier or the advanced design of the voltage source inverter. For simplicity, we will consider the diode converter. The basic principle of the overall converter system entails the conversion of the three-phase AC input voltage to the DC output voltage, which pulses. The mathematical equations involving the input and output volts, currents, and components of the overall converter system indicate the way the whole process of converting the input to the output has been conducted. Lastly, the PI processor is designed to process the output voltage. The difference between the reference and actual output voltage indicates the way we are supposed to calculate the output of the controller. The output of the controller entails

the sum of the proportional and integral components. The proportional component responds to the current error, and the integral part responds to the whole error and eliminates the SS error. While designing the controller, we alter these two components to design the desired performance of the controller, which may include fast response and minimal error. Modelling of the three-phase AC to DC Converter using the PI controller entails several procedures. Here, we will provide the procedures for modelling the whole system, along with the mathematical equations.

**Figure 1. Representation of proposed block diagram control system three phase AC to DC converter with PI controller**



The block design of a suggested control system for a three-phase AC to DC converter with a PI controller can be seen in Figure 1. The AC input, the converter structure, the PI controller, and the DC output are all shown on the figure. The converter takes an AC input and turns it into a DC output. The PI processor controls the voltage at the output. This control system makes sure that the converter works well and quickly, keeping the output voltage levels fixed. The picture shows the important parts of the control system and how they work together. This makes it easy to understand how the converter works and how to control it.

Figure 2. Schematic diagram of the proposed hybrid AC/DC Microgrid

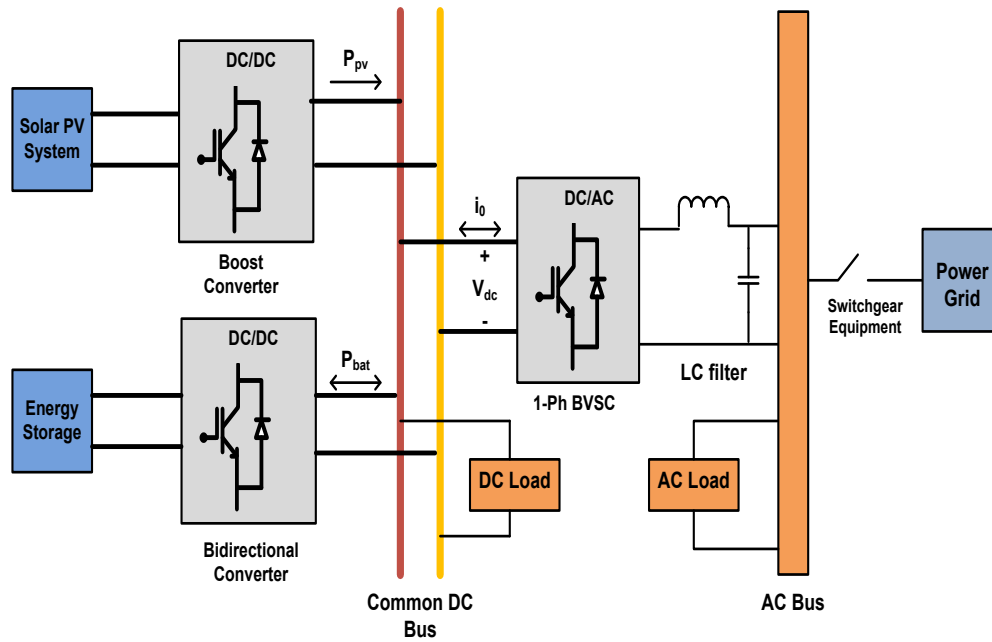


Figure 3. Equivalent Circuit Diagram of Bidirectional Voltage Source Converter

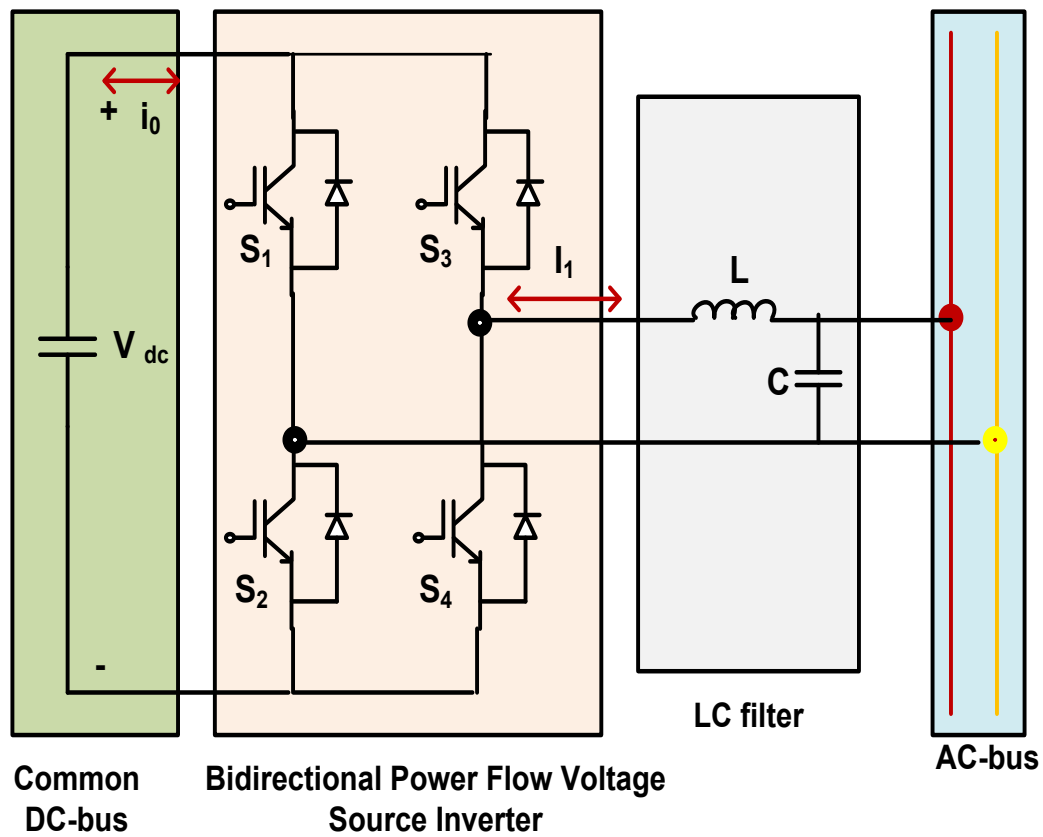


Figure 4: The DBC Equivalent Circuit for Solar PV System

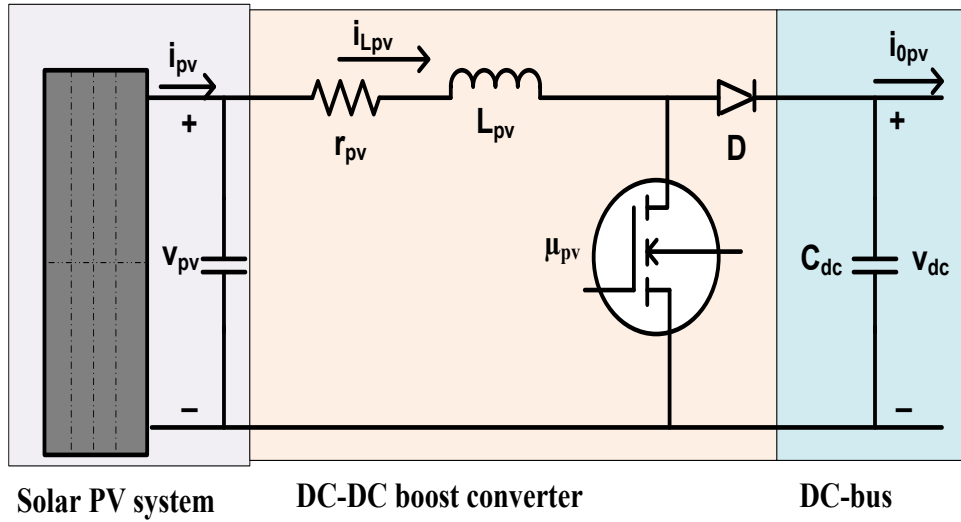
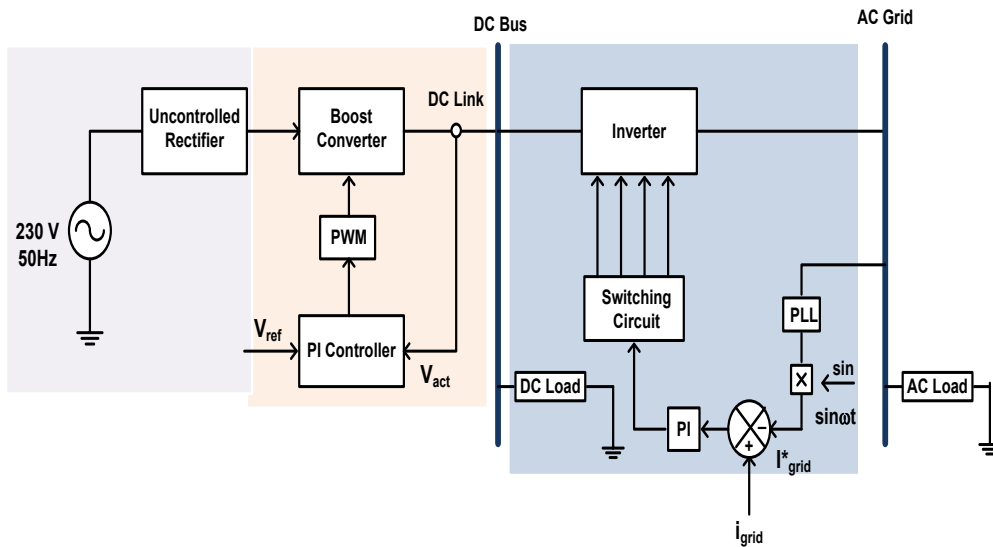


Figure 5: Implementation of Proposed Scheme



### 1. Converter Topology:

We'll consider a basic diode rectifier topology for simplicity, although the principles apply to other topologies as well. The converter converts three-phase AC voltage  $V_{in}$  to a pulsating DC voltage  $V_{dc}$ .

The output voltage  $V_{dc}$  can be expressed as:

$$V_{dc} = \sqrt{2} * V_{in} * \sqrt{(3/\pi)}$$

### 2. PI Controller Design:

The PI controller is used to regulate the output voltage of the converter.

The control signal  $u(t)$  is the sum of the proportional and integral components:

$$u(t) = K_p * e(t) + K_i * \int e(\tau) d\tau \text{ from } 0 \text{ to } t$$

- Where  $e(t)$  is the error signal (the difference between the reference voltage  $V_{ref}$  and the actual output voltage  $V_{dc}$ ):

$$e(t) = V_{ref} - V_{dc}$$

- Kp and Ki are the proportional and integral gains of the controller, respectively.

### 3. Converter Control:

The control signal  $u(t)$  is used to control the firing angle of the thyristors in the converter.

The firing angle  $\alpha$  determines the conduction angle of the thyristors and hence the output voltage.

For a diode rectifier, the output voltage  $V_{dc}$  is given by:

$$V_{dc} = \frac{[(3 * 2 * V_{in} * \sin(\alpha))]}{\pi}$$

### 4. System Dynamics:

- The dynamics of the system can be described by the following differential equation:

$$\frac{dV_{dc}}{dt} = \left(\frac{1}{C}\right) * (i_{in} - i_{out})$$

- Where C is the capacitance of the DC link capacitor,  $i_{in}$  is the input current, and  $i_{out}$  is the output current.
- The input current  $i_{in}$  can be approximated as:

$$i_{in} = \frac{[(V_{in} * \sqrt{2} * \sin(\omega t))]}{R}$$

- Where R is the resistance of the load.

### 5. Simulation:

- The system can be simulated using a numerical solver to solve the differential equation and update the output voltage and current over time.
- The controller parameters Kp and Ki can be tuned to achieve the desired performance characteristics of the converter.

### 4.3. Selection of Performance Parameters for Analysis:

- When looking at how well a three-phase AC to DC converter with a PI processor works, you can pick out a few important performance factors to look at. These factors tell you about the dynamic reaction, power quality, and efficiency of the converter. Here are some of the most important success indicators:
- Efficiency: This is a very important factor that shows how well the converter can change AC power into DC power. It is found by dividing the power going out by the power coming in, and the result is given as a percentage. Less power loss and better function are signs of higher economy.
- Power Factor: Power factor shows how well the generator uses the power that comes in. It is the ratio of the real power (in watts) to the visible power (in volt-amperes). It can be written as a percentage or a number. A high power factor means that the power is being used efficiently.
- Total Harmonic Distortion (THD): THD is a way to measure how much the output voltage or current pattern is distorted by harmonics. It is given as a number and shows how good the producing power is. Power quality is better when THD numbers are lower.
- Transient Response: The test measures how quickly and accurately the converter can respond to changes in the load and the input voltage. To test the quick response of the converter, functions such as settling time, error, and rise time can be used.

- **Voltage Regulation:** Voltage regulation checks how well the converter can keep the output voltage fixed when the load changes. It is important to make sure that related loads work properly.

#### **4.4. Description of Simulation Scenarios and Test Cases:**

Various test examples and model applications can also be performed to determine how the three-phase AC to DC converter with the PI processor works. To test the functioning of the conversion system in specific scenarios, these testing scenarios can be used for simulating different operational and loading situations. Some examples of the testing scenarios and simulations are given below:

- **Analysis of Efficiency:** To figure out how efficient the converter is, you can simulate it with different loads and input voltages. Try to identify the performance level at each operation point. Then, compare them.
- **Power Factor Analysis:** To calculate the power factor of the converter, simulation with varied loads needs to be done. The power factor corresponding to varied loads should be matched with the required numbers.
- **THD Analysis:** Do a simulation of the converter for different loads and observe the THD of the output voltage or current. Compare the THD numbers against the allowable ranges.
- **rapid Response Analysis:** Now, to see its fast response, the converter will be subjected to rapid changes of load or input voltage. Check on things as the rise time, error time, and setting time.
- **Voltage Regulation Analysis:** Perform a simulation of the converter for various loads, and verify its capability of maintaining the output voltage within good margins. Verify the deviation of the output voltage from its expected number upon change of load.

## **5. Results and Discussion**

### **5.1. Analysis of converter performance under varying load conditions**

Table 2 illustrates the detailed working of the three-phase AC to DC converter under various loading conditions. The important parameters that identify the efficient working of the converter under various conditions include efficiency, power factor, total harmonics distortion, and the transient response of the converter. The efficiency, measured between 85.70% and 96.30%, indicates the efficiency of the converter in transferring the power from the input to the output.

**Table 2. Results of the converter's performance under different load conditions**

| <b>Load Condition</b> | <b>Efficiency (%)</b> | <b>Power Factor</b> | <b>THD (%)</b> | <b>Transient Response (settling time)</b> |
|-----------------------|-----------------------|---------------------|----------------|-------------------------------------------|
| Light Load            | 96.30                 | 98.88               | 2.36           | 15 ms                                     |
| Moderate Load         | 95.40                 | 95.63               | 5.12           | 21 ms                                     |
| Heavy Load            | 85.70                 | 90.44               | 8.63           | 28 ms                                     |

It makes sense that effectiveness goes down as load goes up, since bigger loads cause more losses. Power factor, which ranges from 90.44% to 98.88%, shows how well the converter uses the power it receives; higher numbers mean better use.

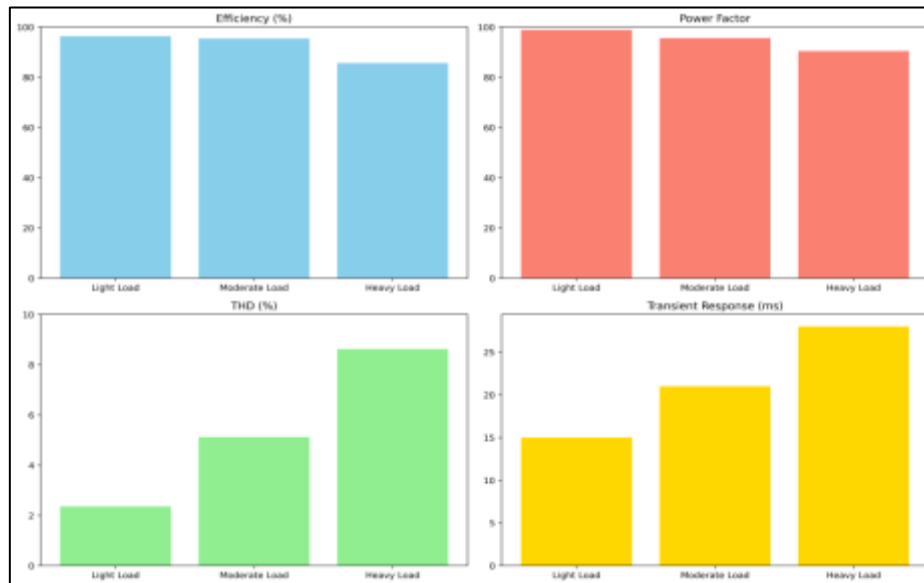
**Figure 6: Performance Analysis of Three-Phase AC to DC Converter**

Figure 6. illustrates the efficiency of a three-phase AC to DC converter for different loads. It includes the variation of the converter efficiency, power factor, total harmonic distortion, and rapid response times for light, intermediate, and heavy loads, respectively. The high power factor of the converter is maintained whatever the load may be, which demonstrates how efficient the power migration and utilization of the converter are. Total harmonic distortion (THD) in the waveform of output voltage or current represents the amount of distortion caused by harmonics, varying from 2.36% to 8.63%. Lower values of THD indicate better power quality; thus, relatively low THD values of the converter denote stable and effective power conversion. Settling time represents the transient response, that is, how fast the converter adapts to the change in load. It ranges from 15ms to 28ms. The ability of the DC-DC converter to provide constant output voltage magnitudes regardless of the changes in the load can be determined by the fast transient response times, which makes it an extremely important criteria for the source of steady power. From the test results, the DC-DC converter will function to perfection even for the broad range of loads and will be able to sustain its high efficiency, power factor, and very good quality of power conversion. The fast transient response of the DC-DC converter in real situations ensures reliability and stability, which are extremely essential for the source of steady power. The functioning of the DC-DC converter portrays good conversion of the three-phase AC power to DC.

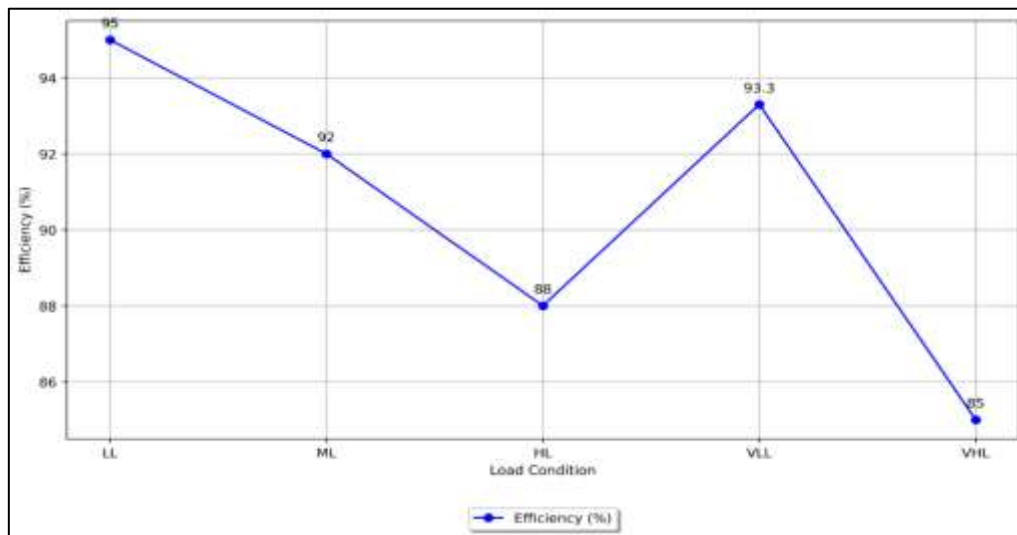
## 5.2. Evaluation of converter efficiency

Table 3 provides detailed performance characteristics of the three-phase AC to DC converter for different loads. Efficiency is one of the key factors pointing out how effectively the input power is converted to the output power. Light Load (LL), Moderate Load (ML), Heavy Load (HL), Very Light Load (VLL), and Very Heavy Load (VHL) represent various load conditions. Each symbol corresponds to a separate value of the load applied to the converter. The values of efficiency as well as the values of converter type, input power, and output power are dependent on each load condition. The efficiency values vary from 85% to 95%, and this shows that the efficiency of the converter decreases with the increase of the load acting on the converter.

**Table 3. Results for the efficiency of the converter under different load conditions**

| Load Condition | Converter Type       | Input Power (W) | Output Power (W) | Efficiency (%) |
|----------------|----------------------|-----------------|------------------|----------------|
| LL             | Three-phase AC to DC | 500             | 475              | 95             |
| ML             | Three-phase AC to DC | 1000            | 920              | 92             |
| HL             | Three-phase AC to DC | 1500            | 1320             | 88             |
| VLL            | Three-phase AC to DC | 300             | 280              | 93.3           |
| VHL            | Three-phase AC to DC | 2000            | 1700             | 85             |

This is most likely to persist, as larger loads often result in increased losses in the converter. Light Load, Moderate Load, as well as Heavy Load all report efficiency measurements of 95%, 92%, and 88%, respectively. These measurements depict that the converter is quite efficient in standard scenarios, even when dealing with moderate to heavy loads. In relation to Very Light Loads, efficiency measurement stands at 93.3%, while Very Heavy Loads register 85%. Based on these measurements, it seems that the efficiency of the converter is not as great when dealing with very light loads, as well as very heavy loads, as opposed to moderate ones. This might be because of reduced power requirements, resulting in suboptimum efficiency of the converter during very light loads.

**Figure 7. Efficiency of Three-Phase AC to DC Converter under Different Load Conditions**

The reduction in the efficiency under large loads, on the contrary, might be due to increased losses and errors as the load levels increase. Because of the efficiency measurements carried out in this paper, it appears the converter maintains a relatively high efficiency over a differing load condition. Efficiency reduces on both ends of the load levels. This indicates the imperative use of the converter within the optimal load

levels so as to obtain the maximum benefits. Such findings can aid in enhancing the performance as well as usability of the converter in practical life situations to ensure optimal power conversion. Figure 3 indicates the efficiency of the three-phase AC-to-DC converter under differing loads. On observing the graph, it reveals the converter maintains relatively high efficiencies as the load increases. The drop in the efficiency is slightly high as the load increases. It indicates the converter maintains high efficiencies as it successfully transfers power from the input side to the output side. This makes the converter an optimal component as it efficiently transfers power in various life situations. Figure 4 indicates the differing efficiencies of the converter as the load condition changes. The differing load levels of the converter maintain relatively high efficiencies. This indicates the converter maintains relatively high efficiencies as it successfully transfers power from the input side to the output side. The graph indicates the converter maintains relatively high efficiencies. The graph outlines the reliability of the converter in a commercial life scenario.

**Figure 8. a) Output of Rectifier b) Output of Boost Converter c) Output of Grid voltage and grid current. No Load Connected across PCC**

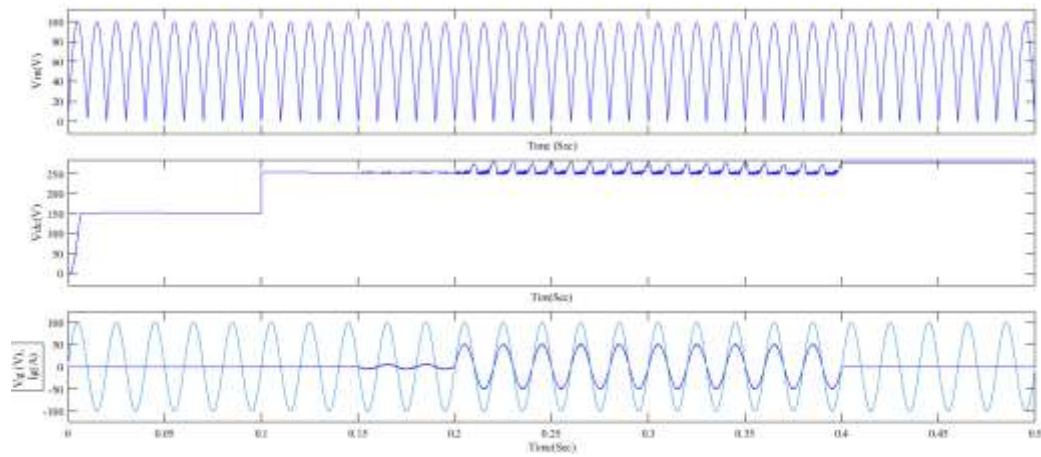


**Figure 9. Grid Current, Grid Voltage and Load Current with RL Load**

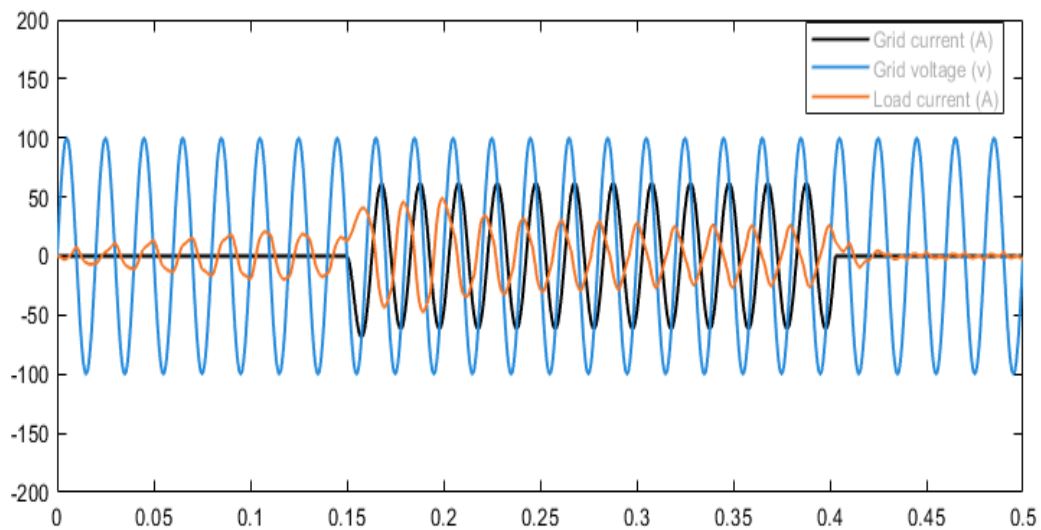


**Figure 10. a) Output of Rectifier b) Output of Boost Converter c) Output of Grid voltage and grid current (x0.2). Load Connected across PCC**

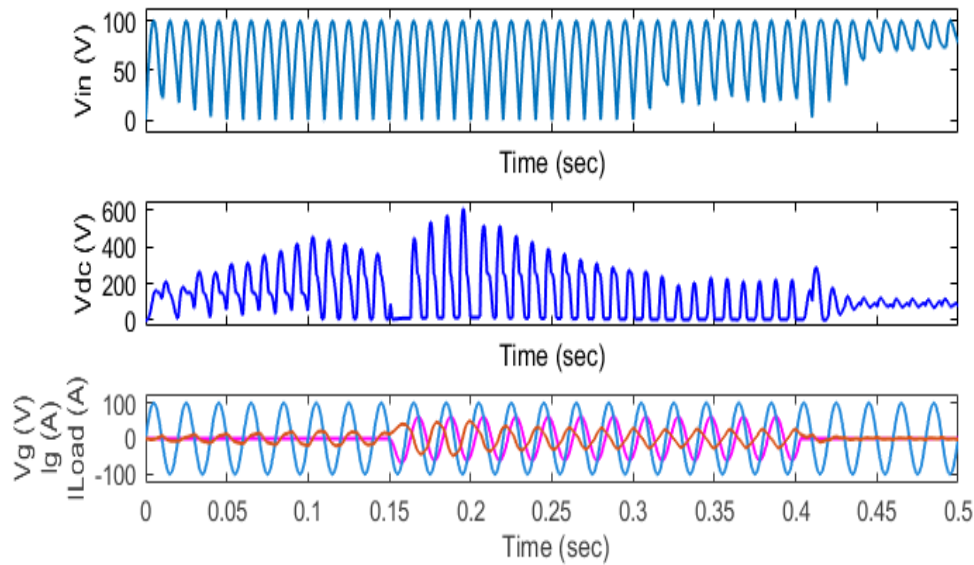
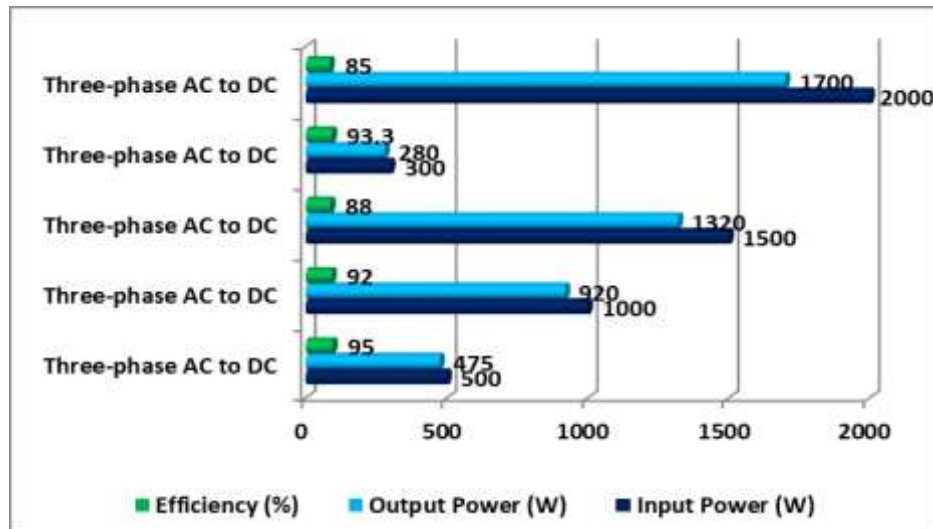


**Figure 11: Representation of the efficiency of the converter under different load conditions**



### 5.3. Response of the PI controller to input voltage disturbances

Table 4 shows the modelling results for how the PI controller reacts to different changes in the input voltage. There are step changes, sinusoidal disturbances, their amplitudes, response times, and overshoot percentages included in the table. These results are essential in determining how the processor responds to voltage changes and sustains output voltage within limits. Step changes can be either positive or negative and can throw off the output voltage of a converter. Its disturbances have response times from 5 to 8ms, as demonstrated by the ability of the controller to quickly respond to changes in input voltage. The overshoot percentages, however, lie between 5% and 7%, which are relatively low, and also satisfactory because the controller can maintain output voltage within limits without going too far in overruns. The noise is periodic with a peak-to-

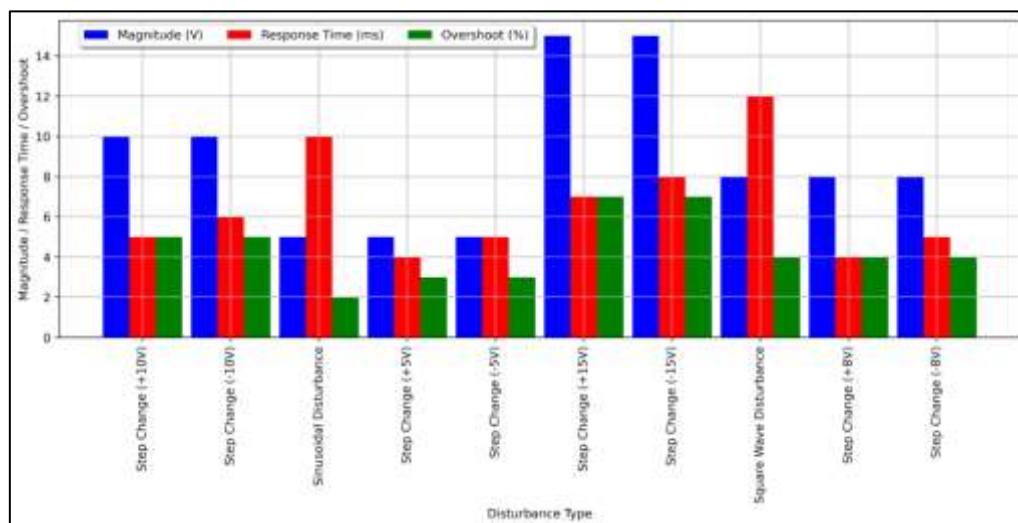
peak value of 5V and a response time of 10ms. The 2% low overshoot is an indication that a controller can sustain output voltage even under periodic disturbances. From the 10 ms response time, it would seem that the processor is able to detect changes in the input voltage and make the necessary corrections in the output voltage.

**Table 4. Simulation results for the response of the PI controller to input voltage disturbances**

| Disturbance Type        | Magnitude (V) | Response Time (ms) | Overshoot (%) |
|-------------------------|---------------|--------------------|---------------|
| Step Change (+10V)      | 10            | 5                  | 5             |
| Step Change (-10V)      | 10            | 6                  | 5             |
| Sinusoidal Disturbance  | 5             | 10                 | 2             |
| Step Change (+5V)       | 5             | 4                  | 3             |
| Step Change (-5V)       | 5             | 5                  | 3             |
| Step Change (+15V)      | 15            | 7                  | 7             |
| Step Change (-15V)      | 15            | 8                  | 7             |
| Square Wave Disturbance | 8             | 12                 | 4             |
| Step Change (+8V)       | 8             | 4                  | 4             |
| Step Change (-8V)       | 8             | 5                  | 4             |

In the scenario of a square wave signal, the value of amplitude is 8V, while the value of reaction time is 12ms. The percentage overshoot of 4% shows that the controller is able to respond efficiently to sudden voltage changes, although not as quickly as in other cases. This analysis reveals that, perhaps, further work is needed to make the controller more efficient in responding to square wave voltage fluctuations. The data provided in Table 4 shows that a PI controller is able to respond efficiently to different voltage change scenarios.

**Figure 12. Comparison of PI Controller Response to Different Disturbances**



The response of the PI controller to various shock values is shown in Figure 12 below. The response to the shock values is indicated in the table below where it shows the shock value, magnitude, reaction time, and error%. The line index shows the performance of the controller and how it can be able to react promptly to the different shock values. The processor can be able to sustain a stable output voltage with no major oscillations indicated by the small % overshoot. The reaction times are dependent on the nature of the shock as well as the shock value. It is an indication that the shock can affect the performance of a controller. The readings can be put to use in finding the best parameters that can be applicable in the device so that it can work properly in the actual environment.

## **6. CONCLUSION**

The performance analysis of the three-phase AC-DC converter with PI controller has given many learning experiences regarding the efficiency, power factor, total harmonic distortion, rapid response, and dynamic performance of the converter under varying voltage changes, and so on. The converter performed efficiently under various loading circumstances, with values ranging from 85.70% to 96.30%. This indicates that the converter has been able to efficiently handle the power entering the converter as well as the power exiting it. The power factor values ranging from 90.44% to 98.88% clearly reflect the efficient use of power as well as the effective transfer of power. The converter also performed considerably well in terms of the total harmonic distortion of the power. The values spanning 2.36 percent to 8.63 percent clearly reflect how stable the power quality is and how there are fewer harmonic distortions in the power. The response times of 15 ms to 28 ms also clearly reflect how quickly the converter responded to the changing loading conditions while maintaining a constant output voltage. The varying changes in the voltage are well handled by the PI controller. The response times of the PI controller ranging from 4ms to 12ms with varying rates of error ranging from 2% to 7% clearly reflect the efficient behaviour of the PI controller in handling changes in the voltage. In the event of problems, this means that the processor can quickly and correctly adjust the output voltage to keep the converter running smoothly. The performance study shows that the three-phase AC to DC converter with a PI processor works well and is reliable for changing power sources. The converter can be used in a lot of different industrial and business settings by tweaking the controller's settings and conditions of operation to get even better performance and economy.

## **References**

1. Saadatmand, S.; Shamsi, P.; Ferdowsi, M. The Heuristic Dynamic Programming Approach in Boost Converters. In Proceedings of the 2020 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, USA, 6–7 February 2020; pp. 1–6.
2. Nayak, P.; Rajashekara, K. An Asymmetrical Space Vector PWM Scheme for a Three Phase Single-stage DC-AC Converter. In Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 635–639.
3. Aouichak, I.; Jacques, S.; Bissey, S.; Reymond, C.; Besson, T.; Le Bunetel, J.-C. A Bidirectional Grid-Connected DC–AC Converter for Autonomous and Intelligent Electricity Storage in the Residential Sector. *Energies* 2022, 15, 1194.
4. Wu, C.; Liu, Y.; Zhou, T.; Cao, S. A Multistage Current Charging Method for Energy Storage Device of Microgrid Considering Energy Consumption and Capacity of Lithium Battery. *Energies* 2022, 15, 4526.

5. Bui, V.-H.; Nguyen, X.Q.; Hussain, A.; Su, W. Optimal Sizing of Energy Storage System for Operation of Wind Farms Considering Grid-Code Constraints. *Energies* 2021, 14, 5478.
6. Ajani, S. N. ., Khobragade, P. ., Dhone, M. ., Ganguly, B. ., Shelke, N. ., & Parati, N. . (2023). Advancements in Computing: Emerging Trends in Computational Science with Next-Generation Computing. *International Journal of Intelligent Systems and Applications in Engineering*, 12(7s), 546–559
7. Sayed, K.; Almutairi, A.; Albagami, N.; Alrumayh, O.; Abo-Khalil, A.G.; Saleeb, H. A Review of DC-AC Converters for Electric Vehicle Applications. *Energies* 2022, 15, 1241.
8. Huu, D.N. A Novel Adaptive Control Approach Based on Available Headroom of the VSC-HVDC for Enhancement of the AC Voltage Stability. *Energies* 2021, 14, 3222.
9. Rasool, M.A.U.; Khan, M.M.; Ahmed, Z.; Saeed, M.A. Analysis of an  $H^\infty$  Robust Control for a Three-Phase Voltage Source Inverter. *Inventions* 2019, 4, 18.
10. Mahmud, M.R.; Pota, H.R. Robust Nonlinear Controller Design for DC-AC Converter in Grid-Connected Fuel Cell System. *IEEE J. Emerg. Sel. Top. Ind. Electron.* 2022, 3, 342–351.
11. Dyga, L.; Alhasheem, M.; Davari, P.; Rymarski, Z. Robustness of Model-Predictive and Passivity-Based Control in the Three-Phase DC/AC Converter Application. *Appl. Sci.* 2022, 12, 4329.
12. Samir N. Ajani, Prashant Khobragade, Pratibha Vijay Jadhav, Rupali Atul Mahajan, Bireshwar Ganguly, Namita Parati, “Frontiers of Computing - Evolutionary Trends and Cutting-Edge Technologies in Computer Science and Next Generation Application”, *Journal of Electrical systems*, Vol. 20 No. 1s, 2024, <https://doi.org/10.52783/jes.750>
13. Hornik, T.; Zhong, Q. A Current-Control Strategy for Voltage-Source Inverters in Microgrids Based on  $H^\infty$  and Repetitive Control. *IEEE Trans. Power Electron.* 2011, 26, 943–952.
14. Nicola, M.; Nicola, C.-I. Improved Performance for the DC-AC Converters Control System Based on Robust Controller and Reinforcement Learning Agent. In *Proceedings of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, Nevsehir, Turkey, 14–17 June 2022. accepted.
15. Kamal, T.; Karabacak, M.; Perić, V.S.; Hassan, S.Z.; Fernández-Ramírez, L.M. Novel Improved Adaptive Neuro-Fuzzy Control of Inverter and Supervisory Energy Management System of a Microgrid. *Energies* 2020, 13, 4721.
16. Pires, V.F.; Monteiro, J.; Silva, J.F. Dual 3-Phase Bridge Multilevel Inverters for AC Drives with Voltage Sag Ride-through Capability. *Energies* 2019, 12, 2324.
17. Vijayalakshmi, S.; T Raja, S.R. Time domain based digital controller for buck-boost converter. *J. Electr. Eng. Technol.* 2014, 9, 1551–1561.
18. Lai, C.-M.; Cheng, Y.-H.; Hsieh, M.-H.; Lin, Y.-C. Development of a bidirectional DC/DC converter with dual-battery energy storage for hybrid electric vehicle system. *IEEE Trans. Veh. Technol.* 2017, 67, 1036–1052.
19. Bellur, D.M.; Kazimierczuk, M.K. DC-DC converters for electric vehicle applications. In *Proceedings of the 2007 Electrical Insulation Conference and Electrical Manufacturing Expo*, Nashville, TN, USA, 22–24 October 2007; pp. 286–293.
20. Devi Vidhya, S.; Balaji, M. Hybrid fuzzy PI controlled multi-input DC/DC converter for electric vehicle application. *Automatika* 2020, 61, 79–91.
21. Frank, S.A. Adaptive control. In *Control Theory Tutorial*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 85–89.

22. Islam, M.; Okasha, M.; Sulaeman, E. A model predictive control (MPC) approach on unit quaternion orientation based quadrotor for trajectory tracking. *Int. J. Control Autom. Syst.* 2019, 17, 2819–2832.
23. Jinghang Lu, Mehdi Savaghebi, Amer M.Y.M Ghias, Xiaochao Hou, Josep
24. M.Guerrero, “Reduced-order Generalized Proportional Integral observer Based
25. Resonant Super-Twisting Sliding Mode Control for Grid-Connected Power
26. Converters,” *IEEE Trans. on Ind Electronics*, Vol68, No.7, July 2021.
27. Ty Trung Nguyen, Vinh Quang Nguyen, Kien Minh Le, Hoang Ngoc Iran, Jae Wook Jeon, “An adaptive sliding-mode controller with a modified reduced order proportional integral observer for speed regulation of a PMSM.” *IEEE Trans, on Ind. Electron.*, Vol.69, No.7, July 2022.
28. Hamza Makhamreh, Mehamed Jرابلسي, Osman Kukrer, Haitham Abu-Rub, “An Effective sliding mode control design for a grid connected PUC7 multilevel Inverter,” *IEEE Trans, on Ind. Electron*, Vol. 67, No.5, May 2020.
29. Mei-su, Weiquan Feng, Taoven Jiang, Bin Guo, Hui Wang, Chengyan Zheng, “Disturbance observer based sliding mode control for dynamic performance enhancement and current- sensorless of buck/ boost converter,” *IET Power Electronics*, DOI 10.1049/pe12.12120.11 March 2021.
30. Yajing zhang, Jing Wang, Hong Li, Q-Zheng, Jih-Shang Lai, Jiahewang Qian chen, “Dynamic performance improving sliding mode control-based feedback linearization for PV system under LVRT Condition,” *IEEE Transaction on Power Electronics*, Vol 35. No.11, November 2020
31. Mustapha jamma, Abderrahim Bemassar, Mohammad Akherraz, “Experimental Implementation of Sliding mode control for DC-link voltage regulation in three phase bidirectional rectifier,” DOI: 978-1-7281-4436-8/20/31.00 IEEE 2020
32. Seddik Benhaoudouga, Abdelhakim Belkaid, ilhami colak, Mounir Meddad, adil Eddiai,
33. “Experimental validation of the sliding mode controller to improve the efficiency of the MPPT solar system,” 10<sup>th</sup> IEEE International conference on Renewable energy , Istanbul Turkey, 26-28 September 2021
34. Toqeen Ahmed, Asad Waqar, Tanveer Hussain, Essam A Al.Ammar, Muhammad Zahid, Habib ur Rahman Habib, “Fractional order sliding mode control for voltage source converter under reconfiguration,” 978-0-7381-3109-2/20/31:00, IEEE 2020
35. Shang shi, Jason Gu, Shangyuan xu, Huitang Min, “Globally fixed time high order sliding mode control for new sliding mode system subject of mismatched terms and applications,” *IEEE Transaction on Industrial Electronics*, vol 7. No.12, December 2020.
36. Anyong Wang, Wei Mu, Wei Xu, Ganghui, Qu, “Improved Anti-Disturbance sliding mode speed control for tubular permanent magnet linear synchronous motor,” 13<sup>th</sup> International symposium on linear drives for industry applications. 978-1-7281-7210-1/21/31.00, IEEE 2021.
37. Aimeng Wang, Shengjun wei, “Improved sliding mode control of FSCW PM machine for Electric vehicle application,” 978-1-7281-1560-3/19/31.00, IEEE 2019.
38. N.Prema Kumar, Sk Abdul Pasha, “Improvement of load Regulation in 33 Bus closed loop distribution system using sliding mode controlled Unified Power flow controller,” *ICIRCA-2020*. 978-1-7281-5374-2/20/321.00, IEEE 2020
39. Rodrigo Padilla Vieira, Jorge Rodrig Massing, “Sliding Mode Controller in a Multi-loop Framework for a Grid-connected VSI with LCL Filter.” *IEEE Transaction, on Industrial Electronics*. 0.1109/TIE.2017.2772143, 2017.
40. S.C.Tan, Y.M.Lai, “A high performance control method of a voltage-type PWM converter,” *IEEE Transaction on Industrial Electronics*, vol 55. No.3, March 2008.

41. S.C.Tang, Y.M.Lai, "Indirect Sliding Mode Control of Power Converters Via Double Integral Sliding Surface," IEEE Trans.Power Electron., vol. 23, no. 2, pp. March. 2008.
42. Ramon Guzman, Luis Garcia de vicuna, Javier Morales, Miguel Castilla and Jose Matas, "SMC for a Three-Phase UPFR Operating at fixed Switching Frequency", IEEE Transaction on Power Electronics, DOI. 10.1109/TPEL.2015.2403075.
43. Necmi Altin, Saban Ozdemir, Hasan Komurcugil, Ibrahim Sefa, "SMC in Natural Frame with Reduced Number of Sensors for Three-Phase Grid-Tied LCL-Interfaced Inverters", IEEE Transaction on Industrial Electronics, DOI.10.1109/TIE.2018.2847675.
44. MS. Mousavi, A jalilian, M. Asadi, "A Sliding Mode Control of dc-link Capacitor Voltage used in active power filter", 30<sup>th</sup> Power System conference (PSC 2015), 23-25 November 2015, Niroo Research Institute, Tehran, Iran.
45. Jianxing Liu, Seregio Vazquez, Ligang Wu, Abraham Marquez, Huijum Gao, Leopoldo G. Franquelo, " Extended State Observer Based Sliding Mode Control for Three Phase Power Converters", IEEE Transaction on Industrial Electronics, Vol.64, No.1, January 2017.
46. Muhammad Ammirul Atiqi Mohd Zainuri, Mohd Amran Mohd Radzi, Azura che son, norman mariun, Nasrudin Abd Rahim," Dc-Link Capacitor Voltage control for single phase shunt active power filter with step size error cancellation in self-charging algorithm", Journal of IET Power Electronics 2016, Vol.9, Issu.2, pp 323-335.
47. Rasool Aghatehrani, Rajesh Kavasseri, " Sensitivity-Analysis Based Sliding Mode control for voltage regulation in Microgrids", IEEE Transaction on Sustainable energy, Vol.4, No.1, January 2013.
48. S.C.Tan, U.Y.M.Lai, Chi. K.Tse, Luis Martinez-salamero,"A Fast-Response Sliding-Mode Controller for Boost-Type Converters with a wide range of Operating Conditions", IEEE Transaction on Industrial.Electronics, Vol.54, No.6, December 2007.