Performance Improvement of Single-Phase Inverter using Different Control Methods

by

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Declaration of Authorship

This is the attestation of the work done in the thesis paper by the students Md Toufiquzzaman, Md Tahmid Wara Ucchas and Mehrab Mustafiz Nuhas under the supervision of Dr. Md. Fokhrul Islam, Professor of Department of Electrical and Electronic Engineering (EEE), Islamic University of Technology (IUT).

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Table of Contents

List of Tables

List of Figures

List of Acronyms

P	Proportional
PI	Proportional-Integral
PD	Proportional-Derivative
PID	Proportional-Integral-Derivative
THD	Total Harmonic Distortion
PWM	Pulse Width Modulation

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Abstract

This research examines the performance of a single-phase PWM inverter equipped with a P, PD, PI and PID controllers. The research aims to decrease Total Harmonic Distortion (THD) in case of fixed and variable output voltages. To reduce THD, different controllers are used, which are tuned using PID tuner and Trial and Error methods , and the THD is measured using the Simulink powergui's FFT analysis tool. MATLAB Simulink is used for inverter modelling and simulation. For PI controller-based Inverter, the THD is 0.45% for fixed 400V output voltage and it is increased to 50.85% for rapidly changed output voltage. Furthermore, for PID controller-based Inverter, the THD is 0.01% for fixed 400V output voltage and it is increased to 52.41% for rapidly changed output voltage. So, PI controller-based inverter works better for rapidly changing output voltage, but the PID controller-based inverter performs better for fixed output voltage, according to the comparison analysis.

This research also examines the performance analysis of Unipolar and Bipolar PWM techniques and finds which PWM technique gives least value of THD for PI and PID controller based inverters for both fixed and variable voltages. For PI controller-based inverter with unipolar PWM technique , the THD is 0.44% for fixed 400V output voltage and it is increased to 15.57% for rapidly changed output voltage. And for PI controller-based inverter with bipolar PWM technique , the THD is 3.58% for fixed 400V output voltage and it is increased to 16.41% for rapidly changed output voltage. Furthermore, for PID controller-based inverter with unipolar PWM technique , the THD is 0.01% for fixed 400V output voltage and it is increased to 15.98% for rapidly changed output voltage. And for PID controller-based inverter with bipolar PWM technique , the THD is 0.02% for fixed 400V output voltage and it is increased to 16.01% for rapidly changed output voltage. So, unipolar PWM technique performs better than bipolar PWM technique for both fixed and variable voltages.

CHAPTER I
INTRODUCTION

1.1 Introduction

Power electronics have contributed to the development of modern technology in the last few years. Power electronics mainly deal with controlling and converting electric power, and one of the main components that help in doing it and has several applications is the power inverter [1]-[3].

In power inverter, it converts DC power to AC power, which is used to activate a wide range of devices. It is mainly used in UPS, induction motor, automatic voltage regulator systems, active power filtering, and many more [4]-[5]. The power inverters in these systems must produce clean, pure, and accurate sinusoidal output voltage waveform regardless of the type of load connected to it. This can be obtained by having a feedback controller [6]-[9]. The inverter can be categorized by its control of voltage and frequency.

Also, the use of inverters in non-linear load conditions has become a big concern as the non-linear behavior leads to harmonics being created in the voltage and current output, which reduces the efficiency of the system. Moreover, for changing the output voltage rapidly, THD becomes more. But for different applications (For speed control of Induction motor etc.), the output voltage needs to be changed rapidly [10]. Many types of controllers are being used nowadays like the P, I, PI, PID, PR controllers to overcome this problem, [11]-[12]. Each has some advantages and disadvantages over the others and is used according to a particular system requirement [13]-[17].

1.2 Problem Statement

(a) While converting from DC to AC, we face some distortion in AC output due to harmonics. Harmonics are the integer multiples of the fundamental frequency that are present in an AC sinusoidal wave, causing distortions in the waveform. This occurs due to nonlinear loads present in the circuit such as electronic switches: MOSFETs, IGBTs, diodes and so on.

(b) Effects of harmonics:

(i) Heating Effect: Due to the harmonics, the circuit elements get heated which might reduce the overall performance of the whole circuit.

(ii) Overvoltage is the phenomenon in which the voltage of an element or a system reaches a voltage higher than its rated value. Because of this, the system might become unstable leading to overheating and damage it.

(c) Another major problem we face is ripple current. Ripple current is the periodic non-sinusoidal waveform with high amplitude and narrow bandwidth pulses. This current causes power dissipation in capacitors if its equivalent series resistance (ESR) is high. As a consequence, there will be high loss of electrical energy as heat.

(d) If the ripple current is more than 5% of the DC power supply, the power supply may begin to show overcurrent phenomena. Overcurrent is the phenomenon in which a current greater than the rated current passes through an element. This might cause the circuit to excessive heating and a possible damage of equipment.

(e) Also, high ripple current puts too much load on the output capacitors, leading to early failure

1.3 Objectives

(i) Finding optimum gain value of controllers to reduce THD.

(ii) Finding the response of different control methods in single phase PWM Inverter.

(iii) Finding the response of different PWM techniques.

(iv) Finding better output signal with lowest THD for both Fixed and Variable output voltages.

1.4 Research Methodology

(i) Pulse Width Modulations required for the inverters, is achieved by using different control topologies - PI, PID.

(ii) The output of the inverters is then compared to find which controller topology gives the best performance

(iii) After finding the closed loop transfer function, PID tuner is used to find the optimum gain values.

(iv) Trial and Error method is used to get more optimum gain values.

(v) Unipolar and bipolar PWM techniques have also been used.

5 Organization of the Thesis

In our research, we have worked with different control topologies to observe their performance and tried to obtain which one of these topologies resulted in the lowest total harmonic distortion (THD) values. The first controller we used was P controller where we simulated the circuit in MATLAB Simulink and observed the response for both fixed and variable voltage. From the FFT analysis tool in MATLAB, we then obtained the THD values for each case. Similarly, we then used PD controller- based inverter and compared the results with P controller- based inverter. The same process was followed using PI and PID based inverter and their respective THD valued were obtained and compared for both fixed and variable reference voltage.

We used two different types of tuning methods to obtain the gain values of each controller. One is the PID tuner that is available in the MATLAB Apps. Using it the gain values can be obtained for each controller. Another method we used was the trial-and-error method. We took a range of values then simulated it and tried to find out which gain values gave the lowest THD. By following a logical approach, we then narrowed down the range to find and optimized gain value for the controller that would give the lowest THD.

We also used different types of PWM techniques like unipolar and bipolar, to find out which technique gives the lowest THD and works better and more efficiently for fixed and variable voltage for both PI and PID controllers. From observing their performance, we tried to discover which method or technique would give the least value of THD and thus we reached the goal of our research as reducing the THD for different cases and to find out which method works better in each case and how the system can be made more efficient was our motive.

Chapter II
Literature Review

2.1 Background

Many researches have been done on this topic and some of the well-known recognized work and their authors are listed below.

Authors	Topics
Salam Waley Shneen et al	**Single-phase PWM inverter through software simulation [1]**
S. M. Cherati et al.	**Tuned a PI controller-based single-phase PWM inverter using "sisotool" [2]**
Trung-Kien Vu et al.	**Compared PI and PR controller-based single-phase inverter [3]**
Tracy Chai Anak Ajot et al.	**Single-phase PI controller-based inverter and tuned it using a trial-and-error method to compensate for harmonic distortions [4]**
R. Ramesh et al.	**Proposed a PID controller-based inverter to eliminate dc components and steady-state error for high load applications [5]**
M. Parvez et al.	**Observed the performance of a single-phase inverter based on a PR controller [6]**
KC. Chen et al.	**Observed the harmonic reduction performance of a single-phase inverter based on a PR current controller for non-linear loads [7]**

2.2 Single Phase PWM Inverter

A single-phase inverter is a circuit that converts a dc input voltage to a symmetrical single phase ac output voltage of a desired magnitude and frequency. The circuit consists of a dc voltage source with four transistors (i.e., MOSFET or IGBT) which act as electronic switches by giving gate pulses, generated using one of the PWM techniques. When two transistors G1 and G4 are turned on, the input voltage Vdc appears across the load. When transistors G2 and G3 are turned on, the input voltage -Vdc appears across the load. The output voltage obtained is a rectangular wave. The rectangular wave is then passed through an LC filter to make it a sinusoidal wave of a constant magnitude and frequency.

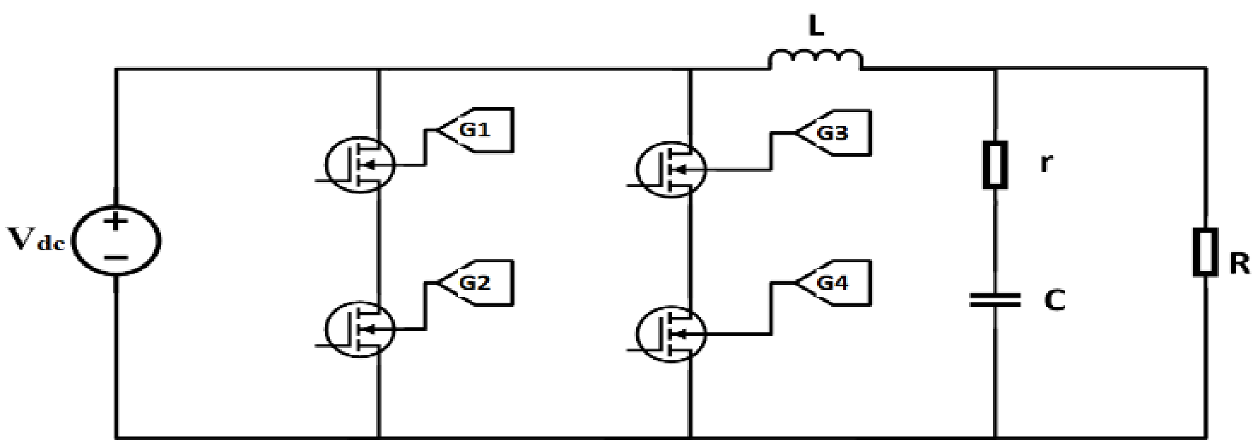

Fig 2.1. Single Phase PWM Inverter Circuit

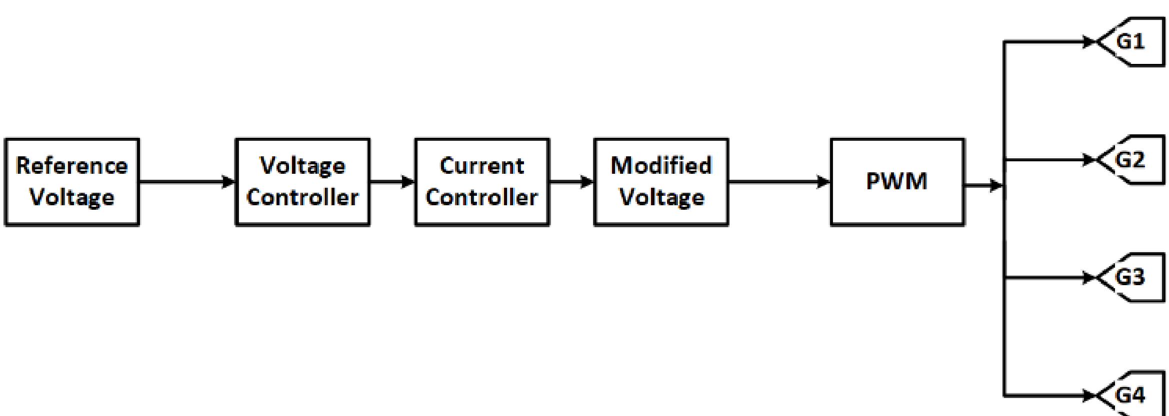

Fig 2.2. Block Diagram of Control Circuit of Single Phase PWM Inverter

The Transfer Function of our full-bridge inverter circuit is stated below.

$$\frac{-7.64 \times 10^{-6}s^2 - 1.32 \times 10^{-11}s + 1.44 \times 10^{-17}}{s^3 + 1.224 \times 10^{-5}s^2 + 3.252 \times 10^{-10}s + 3.972 \times 10^{-15}}$$

This closed loop transfer function is generated using MATLAB system identification tool. 3 poles and 2 zeros are taken for generating the transfer function. The number of free co-efficient is 6. Circuit Parameters for PWM single phase inverter is shown in Table I [4].

TABLE 2.1. Circuit Component Values

Component	**Value**
Filter Capacitor (C)	13.2 uF
Filter Inductor (L)	1.2 mH
Resister with Capacitor (r)	0.05 ohm
Load Resister (R)	10 ohm
Input DC voltage (V_{dc})	800 V

2.3 PWM Techniques
2.3.1 Unipolar

The unipolar PWM technique have two reference signals that have the same magnitude and frequency but are 180 degrees out of phase. In unipolar, a triangular wave is considered as the carrier wave and the two reference signals are compared with this triangular carrier wave. The output of a unipolar PWM inverter varies from 0 to +Vdc in one cycle and 0 to -Vdc in another cycle. So, in once cycle we get only positive output and, in another cycle, we get only negative output. This is why it is called unipolar PWM technique.
There are two comparators used in unipolar PWM technique. In the first comparator, if positive reference voltage is higher than carrier voltage, then switch S1 in turned on. If positive reference voltage is lower than carrier voltage, then switch S4 is turned on. Similarly, the second comparator also compares between the negative reference voltage and carrier voltage. If the negative reference voltage is greater than carrier voltage then switch S3 is turned on. And if negative reference voltage is lower than carrier voltage then switch S2 is turned on. In this way the switching method is carried out in unipolar PWM technique.

The switching method in unipolar PWM technique is a bit complex. However, this gives it some advantages. There is less fluctuations in line-to-line voltage compared to bipolar PWM technique. Switching frequency is higher than bipolar as well. There is reduced switching losses, and generates less electromagnetic interference. Thus, all these makes unipolar PWM based inverter more efficient. [3]

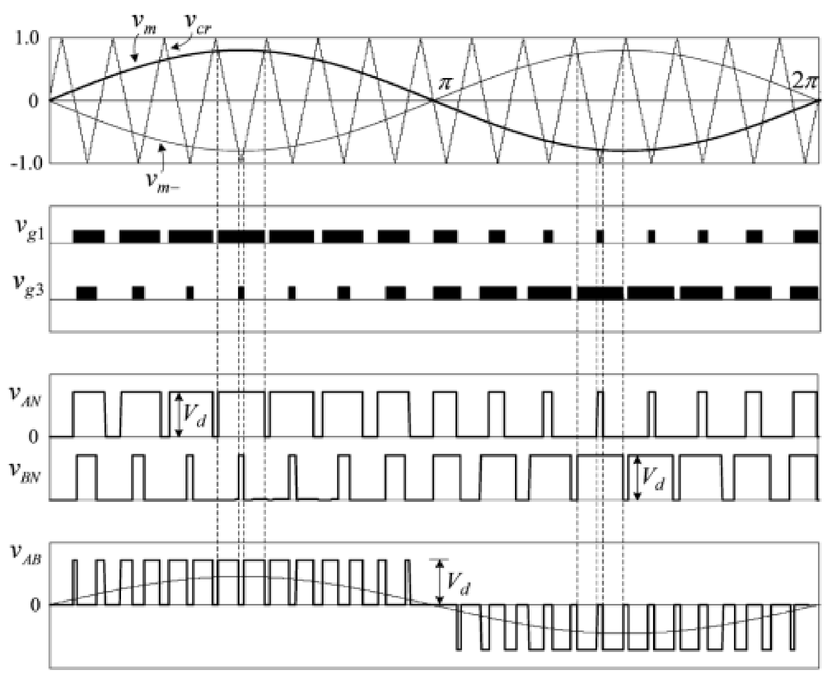

Fig 2.3. Waveform of unipolar modulation scheme

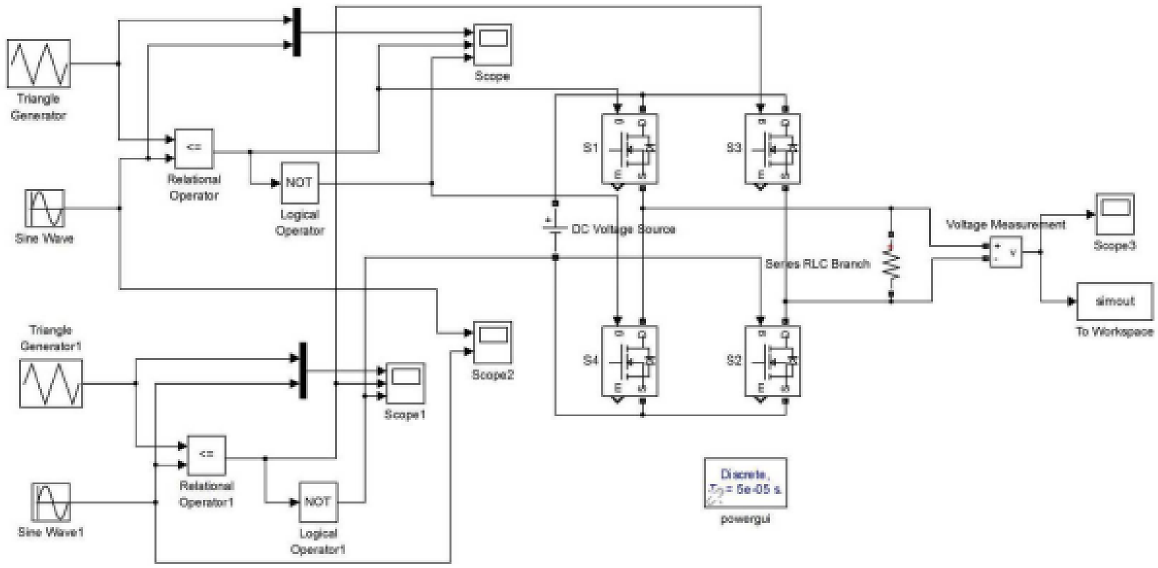

Fig 2.4. Simulink Model of Unipolar PWM Inverter

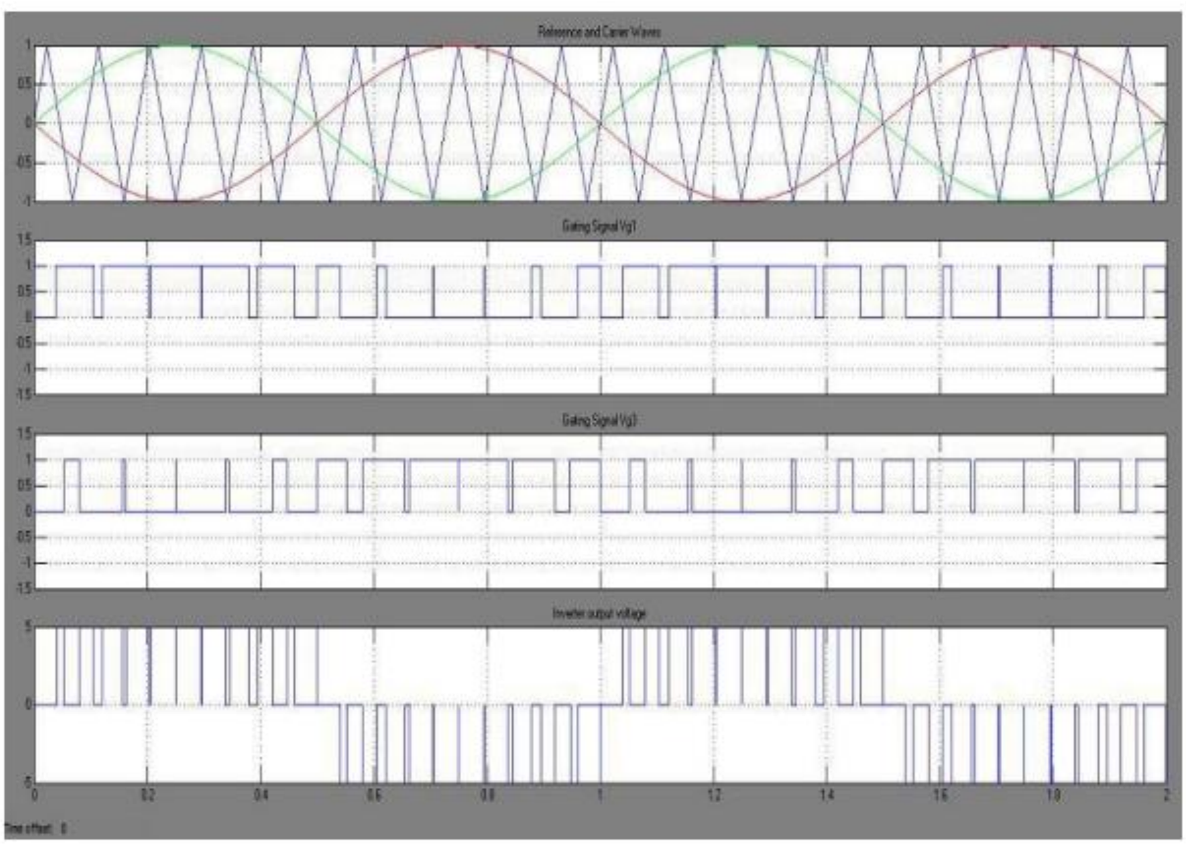

Fig 2.5. Unipolar PWM Waveform, Gating Signal and Output Voltage

2.3.2 Bipolar

The bipolar PWM technique have one sinusoidal reference signal and a triangular wave is considered as the carrier wave. The reference signal is compared with this triangular carrier wave. The output of a bipolar PWM inverter varies from -Vdc to +Vdc. So, in once cycle we get both positive and negative output waveforms. This is why it is called bipolar PWM technique. [1]

There is only one comparator that compares the reference signal to the carrier signal. When the reference voltage is greater than the carrier voltage, switches S1 and S2 are fired. And when it is the opposite, switches S3 and S4 are fired. [2]

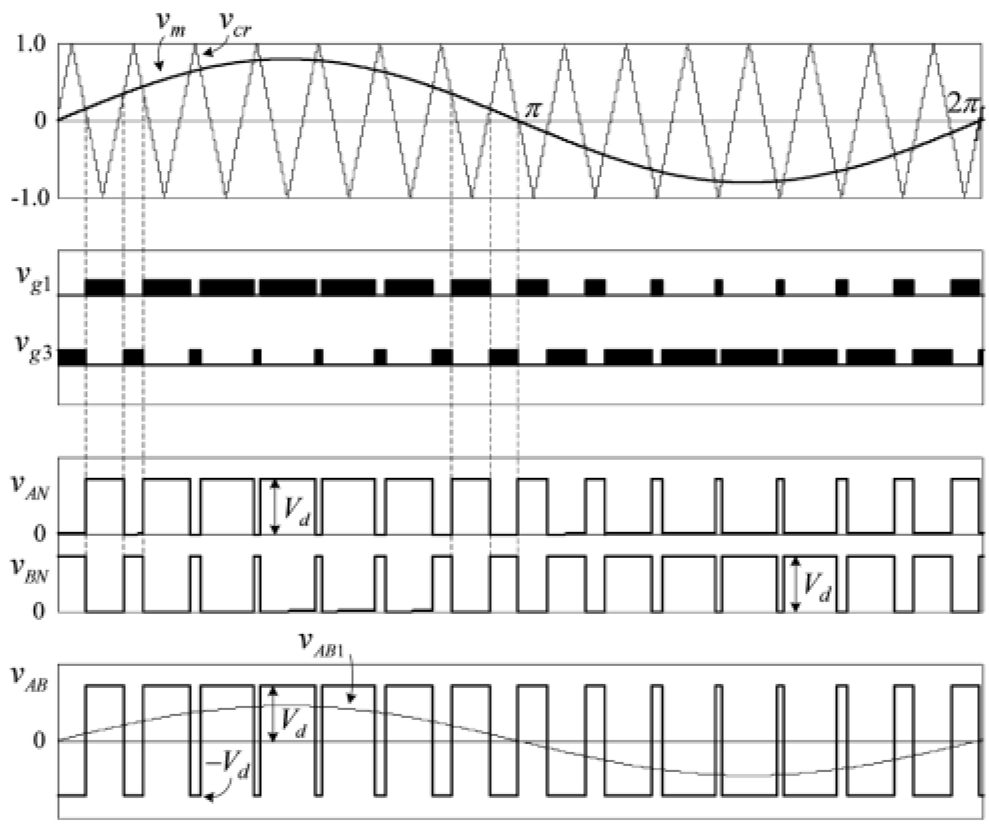

Fig 2.6. Waveforms of Bipolar Modulation Scheme

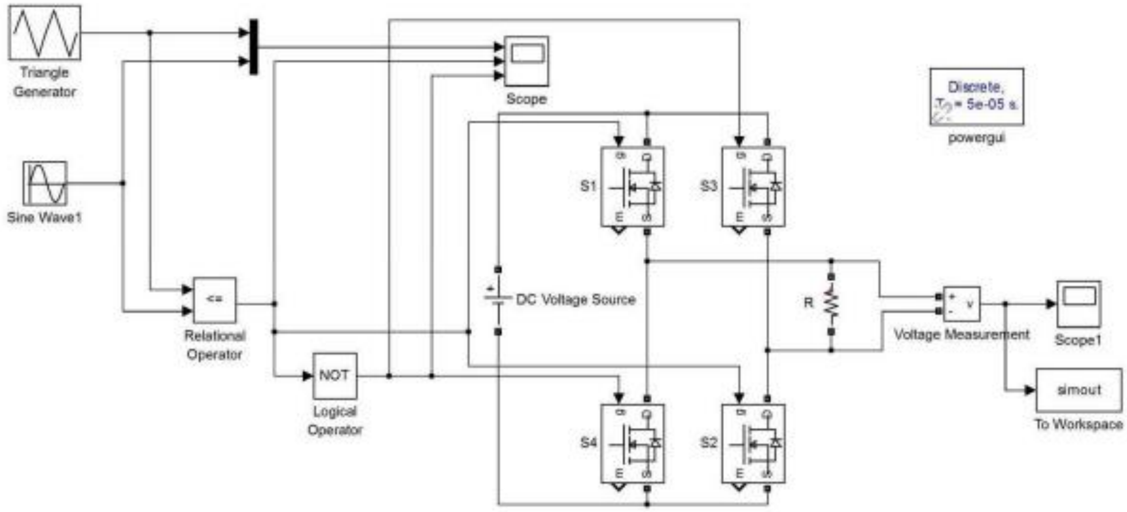

Fig 2.7. Simulink Model of Bipolar Inverter

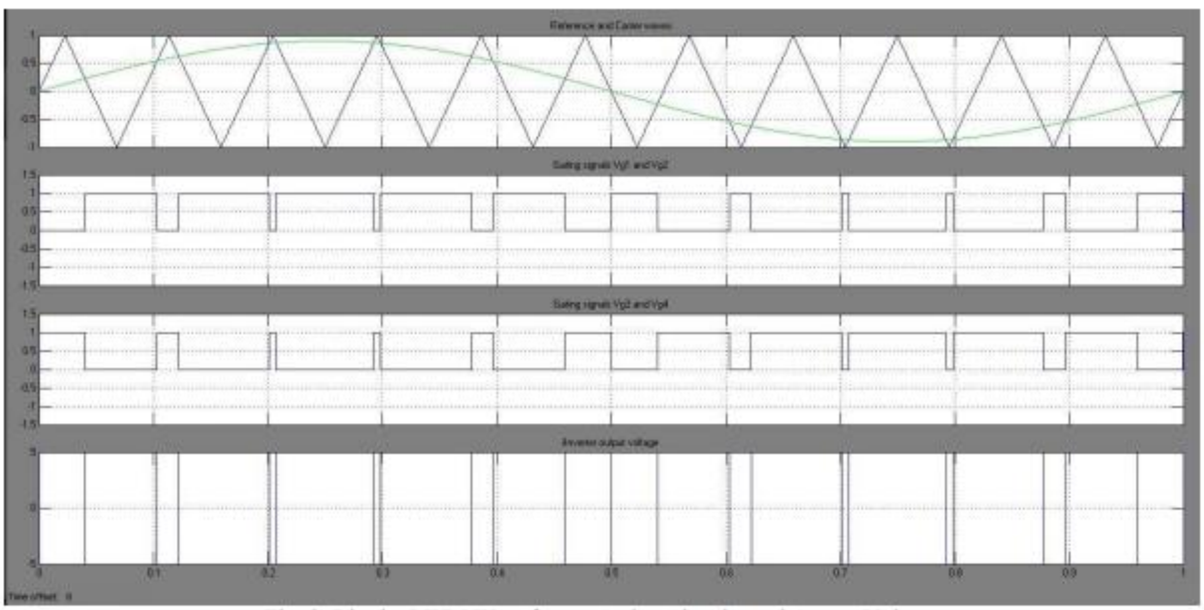

Fig 2.8. Bipolar PWM Waveforms, Gating Signals and Output Voltage

2.4 Control Topologies

2.4.1 P Controller

P controller is a proportional controller and as the name suggests, here the output signal (also called the actuating signal) is proportional to the error signal. It is used to change the transient response of the system as per requirement. Mathematically, it can be written as:

$$A(t) \propto e(t)$$

Removing the proportionality sign, we get:

$$A(t) = K_p \times e(t)$$

Where Kp is called the proportional constant. This Kp value is usually kept greater than 1 as a Kp value greater than 1 would amplify the error signal and this makes it easier to detect the error signal. [4]

For a proportional controller, there are some conditions that the system must have. They are:

(i) There should not be large deviation between the output and the input signal
(ii) The deviation should not be sudden.

P controller can give various advantages. Some of them are:

(i) It helps to reduce the steady state error, making the system more stable
(ii) Response can be made faster of overdamped system

However, it does bring some disadvantages with it as well.

(i) It increases the maximum overshoot of the system
(ii) Some offsets are obtained in the system.

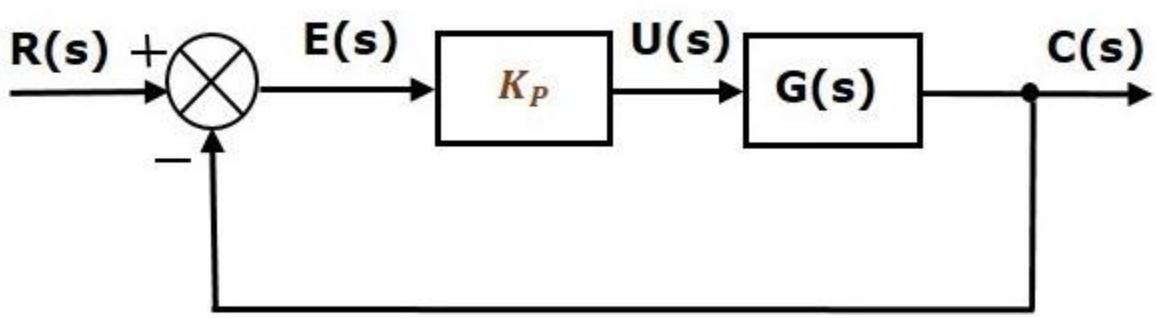

Fig 2.9. Block Diagram of P Controller

2.4.2 PD Controller

It is a combination of Proportional and Derivative controller. The output or actuating signal obtained is the summation of proportional and derivative of the error signal. Mathematically, it can be written as:

$$A(t) \propto \frac{de(t)}{dt} + A(t) \propto e(t)$$

Removing the proportionality sign, we get:

$$A(t) = K_d \frac{de(t)}{dt} + K_p e(t)$$

Where Kd and Kp are the derivative and proportional constants respectively. [4]
Using PD controller, transient responses can be improved. Also, it improves the stability of the control system without affecting the steady state error.

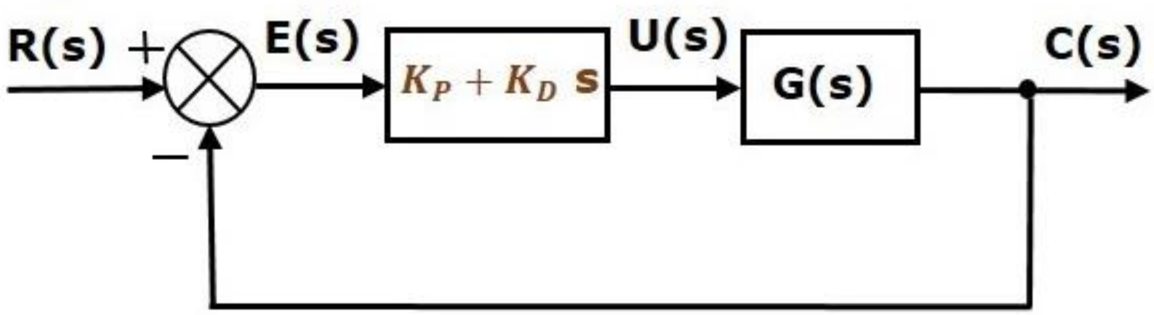

Fig 2.10. Block Diagram of PD Controller

2.4.3 PI Controller

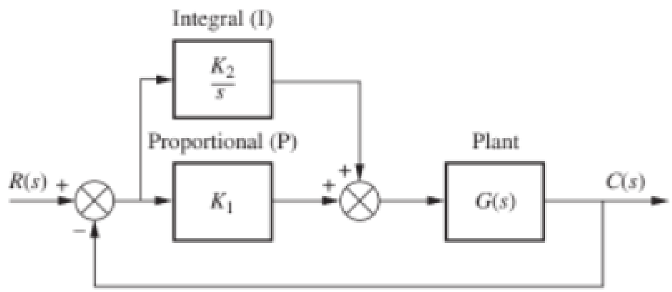

Fig 2.11. Block Diagram of PI Controller

The full form of PI controller is proportional and integral controller. PI controller is a controller having two gain blocks summed together: A proportional(P) gain block and an integral(I) gain block. This controller is used to improve the steady state error of the control system. However because of an addition of a pole to the system from the integral block, the overall system becomes less stable. The transfer function for this controller in the frequency domain is: $G_c(s) = K_p + K_i/s$. Here, K_p is the proportional gain and K_i is the integral gain,

2.4.4 PID Controller

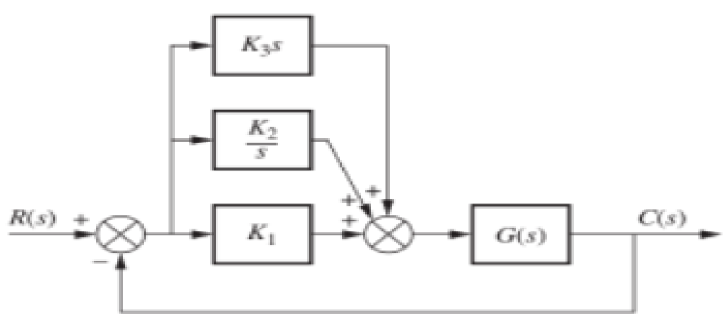

Fig 2.12. Block Diagram of PID Controller

The full form of the PID controller is proportional, integral and derivative block. This controller has three gain blocks summed together: A proportional(P) gain block, an integral(I) gain block and a derivative(D) gain block. This integral block reduces the steady state error of the system and the derivative block improves the transient response of the system by making the system response faster. The transfer function for this controller in the frequency domain is: $G_c(s) = K_p + K_i/s + K_d s$. Here, K_p is the proportional gain, K_i is the integral gain and K_d is the derivative gain.

CHAPTER III
Tuning Methods

3.1 Trial and Error Method

Firstly, a wide range of proportional (Kp) and integral (Ki) gain values is used for the PI controller. With each Kp and Ki value, output shape in MATLAB SIMULINK is found. The output waveforms are observed and which gain values give the best output shape, with low ripples and less overshoot is found out. The input voltage is then changed to see the change in output waveform when the transition in voltage is made. Each gain value gave different total harmonic distortion (THD) values. Using the different Kp and Ki values sets, the one that gave the least THD is identified. The reference voltage is initially given as 400V. Then it is changed to 200V and 600 V to observe the change in output voltage due to the change in reference voltage. Moreover, the time for the observed output was taken 0.1 seconds. Table 3.1 represents the Gain Values for PI Controller.

TABLE 3.1. Gain Values for PI Controller

Serial	**Voltage Controller**		**Current Controller**		**Total Harmonic Distortion (THD)**
	K_P	K_I	K_P	K_I	
1	0	0	0	0	N. A
2	0.5	1	0.5	1	2.26%
3	1	5	1	5	0.53%
4	5	5	1	2.5	0.45%
5	10	10	5	10	1.21%
6	0.25	15	10	20	0.46%
7	0.05	20	20	6	1.95%
8	0.02	25	25	8	5.11%
9	0.03	30	30	7	3.34%
10	0.04	40	40	6.5	2.34%
11	0.035	21	26	6.6	2.95%
12	0.031	20.5	27	6.70	3.34%
13	0.032	20.75	27.2	6.80	3.22%
14	0.0305	20.5	27.1	6.75	3.40%
15	0.0304	20.5	27.05	6.70	3.41%

Table 3.1 shows that data set numbers 4 and 6 gives the minor THD percentages. However, from observing the output waveshapes, it is found out that the graph from data set number 6 gives less ripple than the other one. Also, when the voltages have changed, the transition in the graph using data set 6 was smoother and traced accurately, giving less overshoot than the other one. Thus, the Kp and Ki values from data set 6 is taken and used values close to those to find more output shapes and THD.

TABLE 3.2. New Gain Values for PI Controller

Serial	**Voltage Controller**		**Current Controller**		**Total Harmonic Distortion (THD)**
	K_P	K_I	K_P	K_I	
1	0.25	15	10	20	0.46%
2	0.2	15	9	20	0.50%,
3	0.3	15	11	20	0.44%
4	0.2	14	9	19	0.50%
5	0.2	16	9	21	0.50%
6	0.3	14	11	19	0.44%
7	0.3	16	11	21	0.44%
8	0.1	13	12	18	0.80%
9	0.4	13	8	22	0.44%
10	0.35	12.5	9.5	20.5	0.44%

Again, from the Table 3.2, several data set and their THD percentages is seen. This time mostly all THD were low, but amongst them, the lowest we obtained was 0.44% which is found from several data set. Data set 6 had the lowest values of Kp and Ki from them. So, data set 6 is considered to give the best output. This time also, the voltages were changed from 400 V to 200 V to 600 V. Time observed was given as 0.1 seconds.

Then it is approached in the same way using a PID controller. A wide range of differential (Kd) gain values for the PID controller is taken as shown in Table 3.3. The Kp and Ki values were kept constant, and the ones that gave the best output in the PI controller was used. The output voltage for different Kd was then observed to find out their THD and which graph gave the least ripple and overshoot in the output waveshape.

First, input voltage was kept constant at 400 V. The THD for fixed voltage was then observed. Then the THD for variable voltage was found. The input voltage was changed at regular intervals from 400 V to 200 V to 700 V to 100V to 600 V and finally to 200 V again. More changes were made to observe the changes in output waveshape properly. Time was given as 0.1 seconds to observe.

TABLE 3.3. Gain Values for PID Controller

Serial	**Voltage Controller**			**Current Controller**			**THD With fixed voltage**	**THD With variable voltage**
	K_P	K_I	K_D	K_P	K_I	K_D		
1	0.3	14	1	11	19	1	0.44%	13.82%
2	0.3	14	1	11	19	10	0.44%	20.51%
3	0.3	14	10	11	19	1	0.86%	14.19%
4	0.3	14	5	11	19	20	0.56%	21.23%
5	0.3	14	20	11	19	10	0.25%	21.04%
6	0.3	14	30	11	19	25	0.09%	21.80%
7	0.3	14	40	11	19	15	0.09%	21.62%
8	0.3	14	50	11	19	50	0.03%	18.71%
9	0.3	14	15	11	19	50	0.10%	18.92%
10	0.3	14	60	11	19	40	0.03%	21.08%
11	0.3	14	20	11	19	60	0.07%	38.05%
12	0.3	14	100	11	19	90	0.01%	41.70%
13	0.3	14	70	11	19	100	0.01%	15.63%
14	0.3	14	0.5	11	19	0.5	0.44%	19.21%
15	0.3	14	0.2	11	19	0.7	0.44%	20.14%

The Table 3.3 shows that the lowest THD obtained was 0.01% for fixed voltage and 15.63% for variable voltage from data set 13. These gain values gave us the best output waveshape for ripple, harmonics, and overshoot in the PID controller.

3.2 PID Tuner

PID tuner is also used to find the gain values. Table 3.4. and Table 3.5. Shows the comparison between two methods. For PI controllers, we get lower THD using trial and error method for variable voltage. For PID controller, tuned method performs better, however the gain values are very high. So, trial and error method provide almost similar result with low gain values. That's why, gain values from trial-and-error methods are used instead of tuned values to compare the performance between PI and PID controller-based inverter.

TABLE 3.4. Comparison between tuned and trial and error for PI Controller

Method	**Voltage Controller**		**Current Controller**		**THD With fixed voltage**	**THD With variable voltage**
	K_P	K_I	K_P	K_I		
Tuned	-437.605	-0.168	-437.605	-0.168	0.07%	20.24%
Trial and Error	0.3	14	11	19	0.44%	19.74%

TABLE 3.5. Comparison between tuned and trial and error for PID Controller

Method	**Voltage Controller**			**Current Controller**			**THD With fixed voltage**	**THD With variable voltage**
	K_P	K_I	K_D	K_P	K_I	K_D		
Tuned	-274.4519	-0.13754	-9981.2772	-274.4519	-0.13754	-9981.2772	Almost 0%	18.74%
Trial and Error	0.3	14	70	11	19	100	0.01%	21.86%

CHAPTER IV
Performance observation of P and PD controller-based Inverters

4.1 Performance observation of P controller for Fixed Voltage

PID tuner is used to get optimum gain values. Again, trial and error gains from data set 13 are also used to compare between THD for these different gains. The Table represents the gain values and THD for different methods for fixed 400V output voltage and simulated for 0.1 second.

TABLE 4.1. Comparison between tuned and trial and error for P Controller for fixed voltage

Method	**Voltage Controller**	**Current Controller**	**THD** **With fixed voltage**
	K_P	K_P	
PID Tuner	-383.6076	-383.6076	0.01%
Trial and Error	0.3	11	0.45%

For PID tuner gains:

The output waveshape of the inverter (based on P controller) is illustrated below.

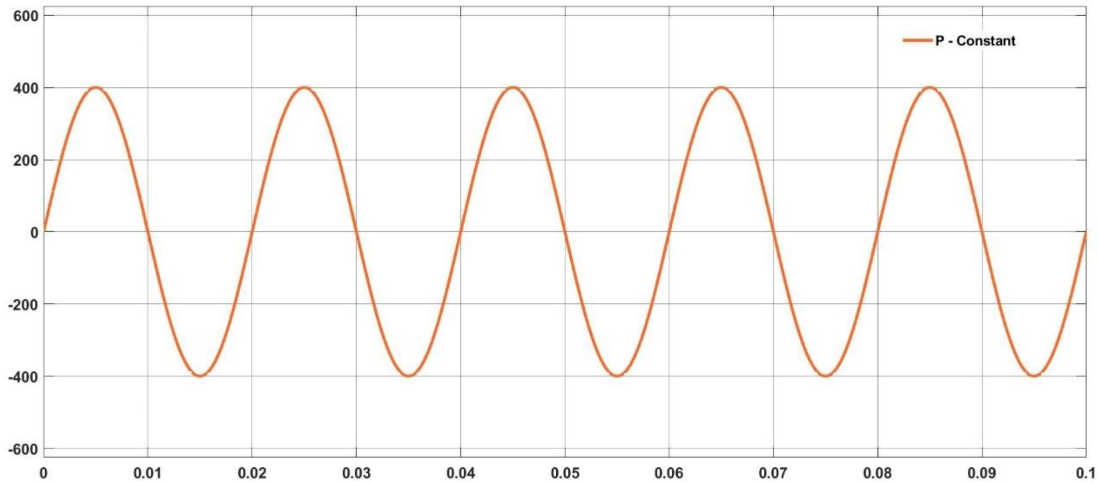

Fig 4.1. Output Waveshape of P Controller-based Inverter for Fixed Voltage using PID Tuner

From the FFT analysis in MATLAB, the THD is 0.01%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds.

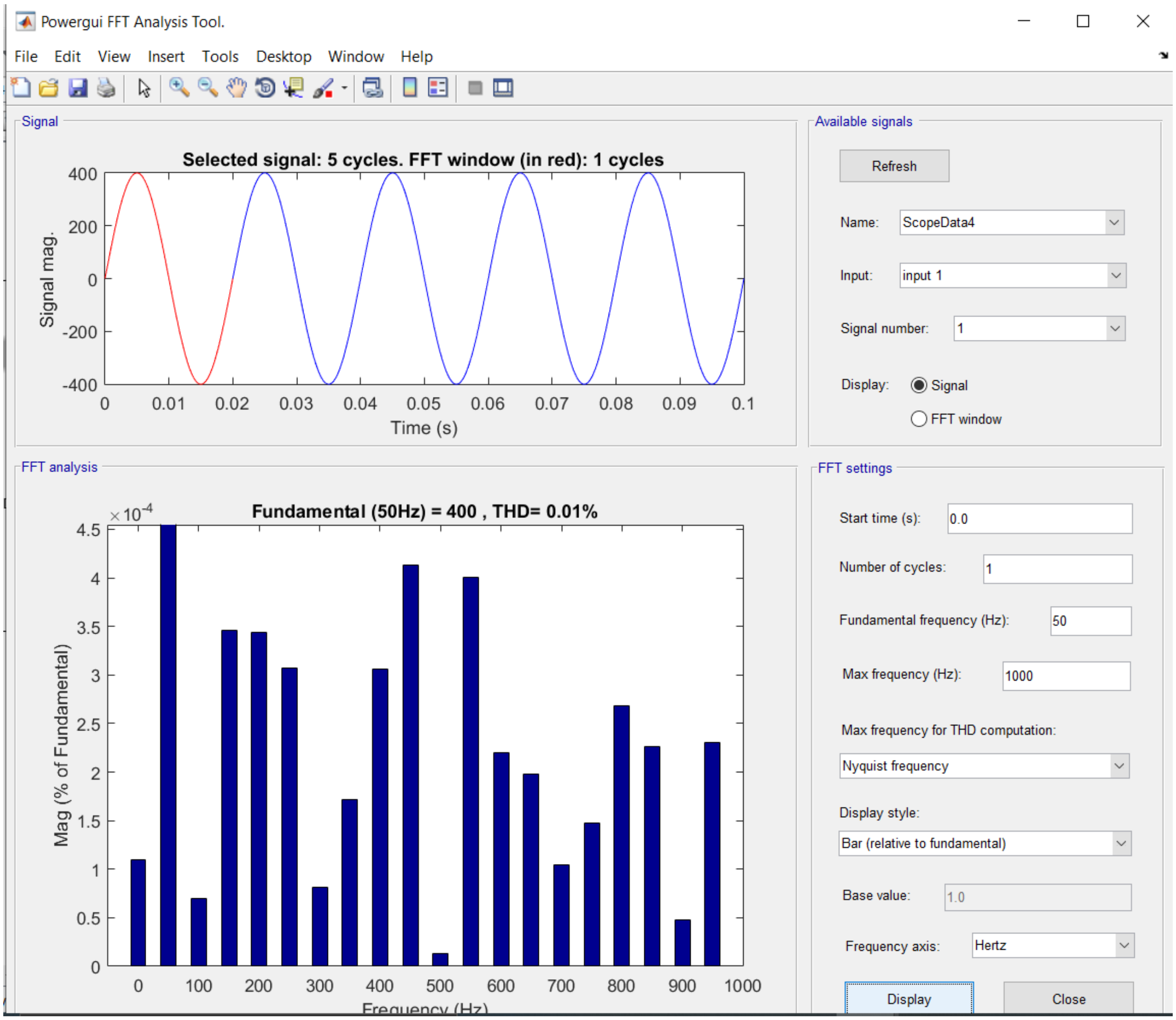

Fig 4.2. FFT Analysis of P Controller-based Inverter for Fixed Voltage using PID Tuner

For Trial and Error gains:

The output waveshape of the inverter (based on P controller) is illustrated below.

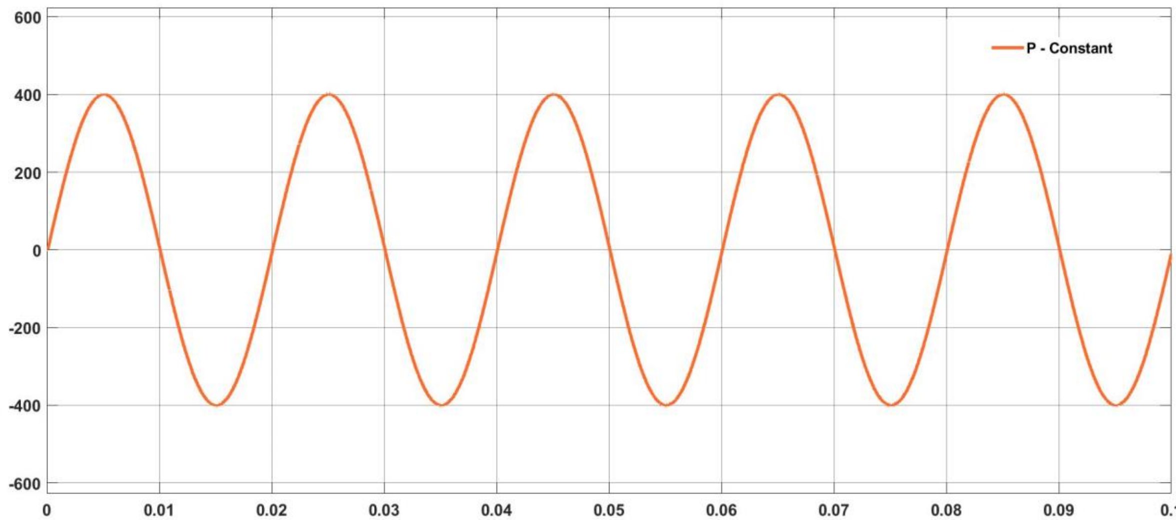

Fig 4.3. Output Waveshape of P Controller-based Inverter for Fixed Voltage using Trial and Error

From the FFT analysis in MATLAB, the THD is 0.45%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds.

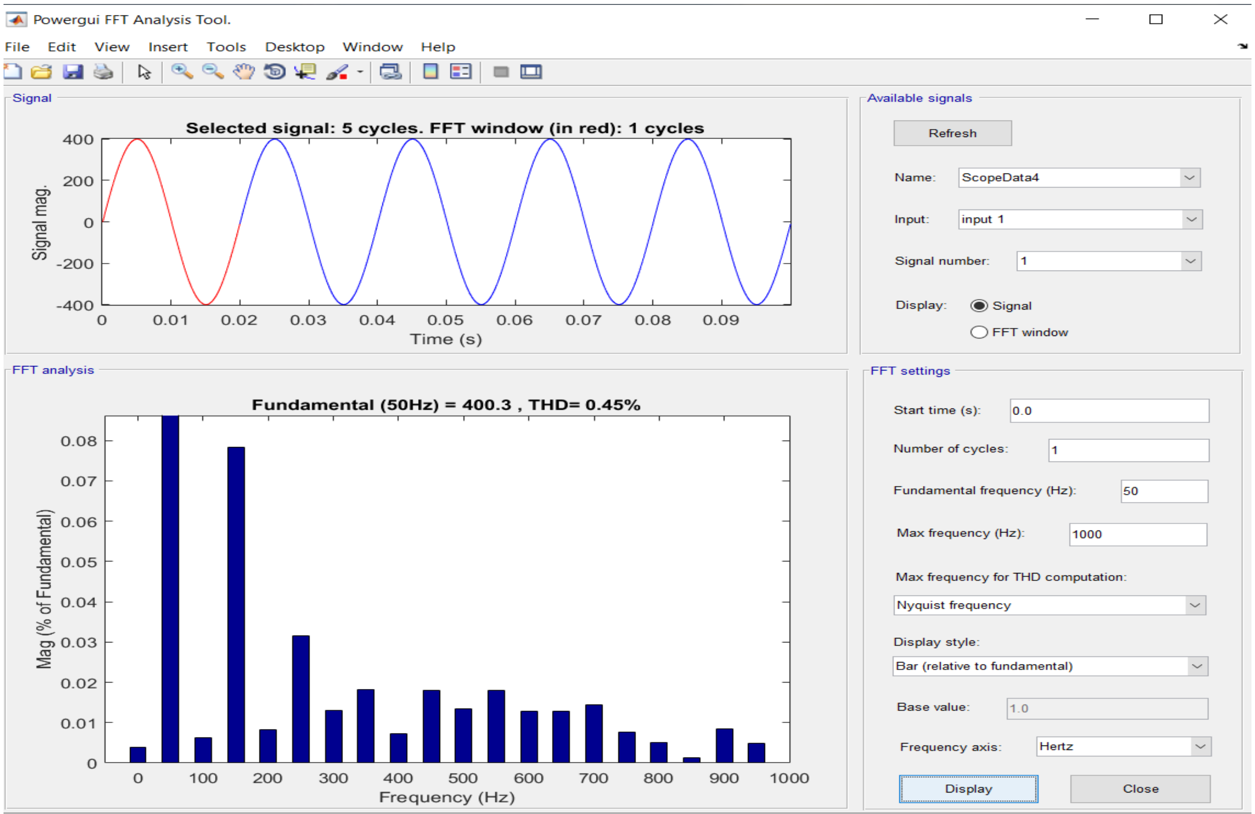

Fig. 4.4. FFT Analysis of P Controller-based Inverter for Fixed Voltage using Trial and Error

4.2 Performance observation of P controller for Variable Voltage

PID tuner is used to get optimum gain values. Again, trial and error gains from data set 13 are also used to compare between THD for these different gains. The Table represents the gain values and THD for different methods for variable output voltage and simulated for 0.1 second.

TABLE 4.2. Comparison between tuned and trial and error for P Controller for Variable Voltage

Method	**Voltage Controller**	**Current Controller**	**THD With variable voltage**
	K_P	***K_P***	
PID Tuner	-383.6076	-383.6076	17.32%
Trial and Error	0.3	11	18.42%

For PID tuner gains:

The output waveshape of the inverter (based on P controller) is illustrated below .

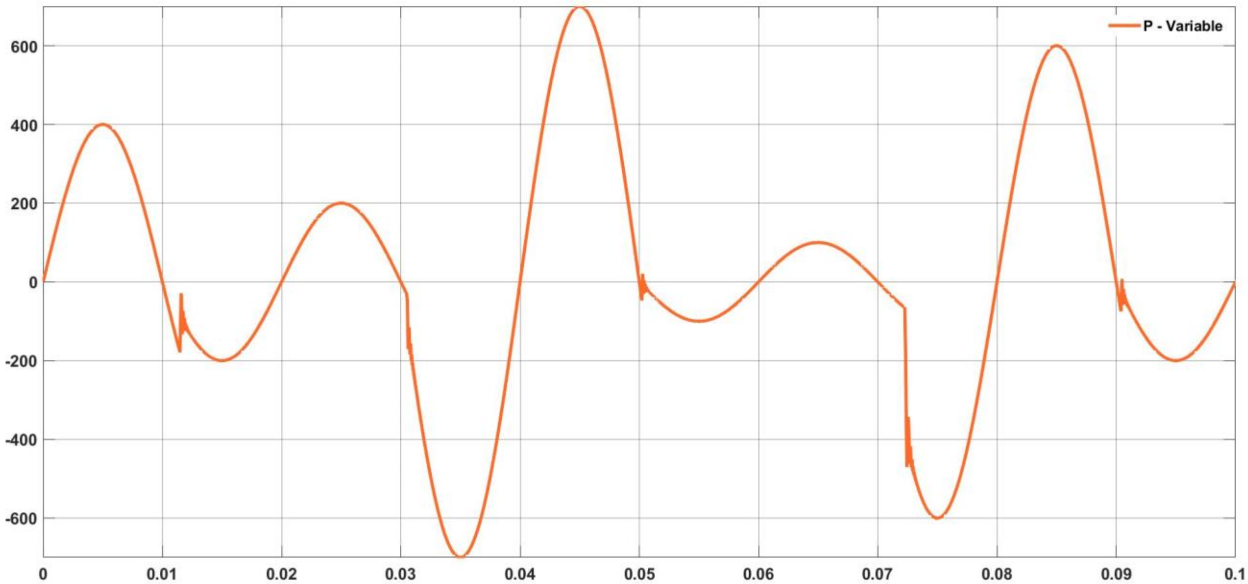

Fig.4.5. Output Waveshape of P Controller-based Inverter for Variable Voltage using PID Tuner

From the FFT analysis in MATLAB, the THD is 17.32%. The reference voltage was changed several times and simulated for 0.1 seconds.

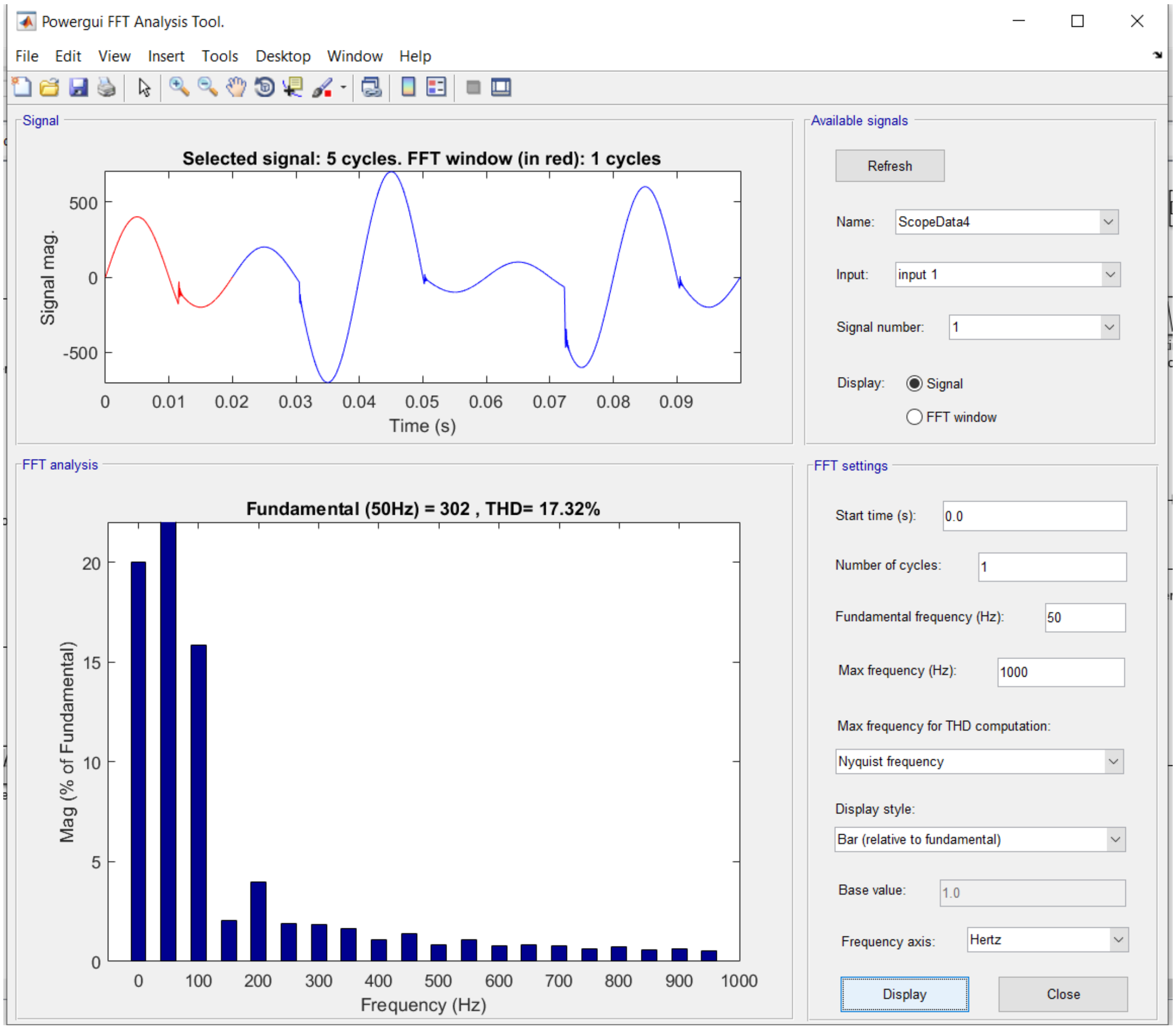

Fig 4.6. FFT Analysis of P Controller-based Inverter for Variable Voltage using PID Tuner

For Trial and Error gains:

The output waveshape of the inverter (based on P controller) is illustrated below.

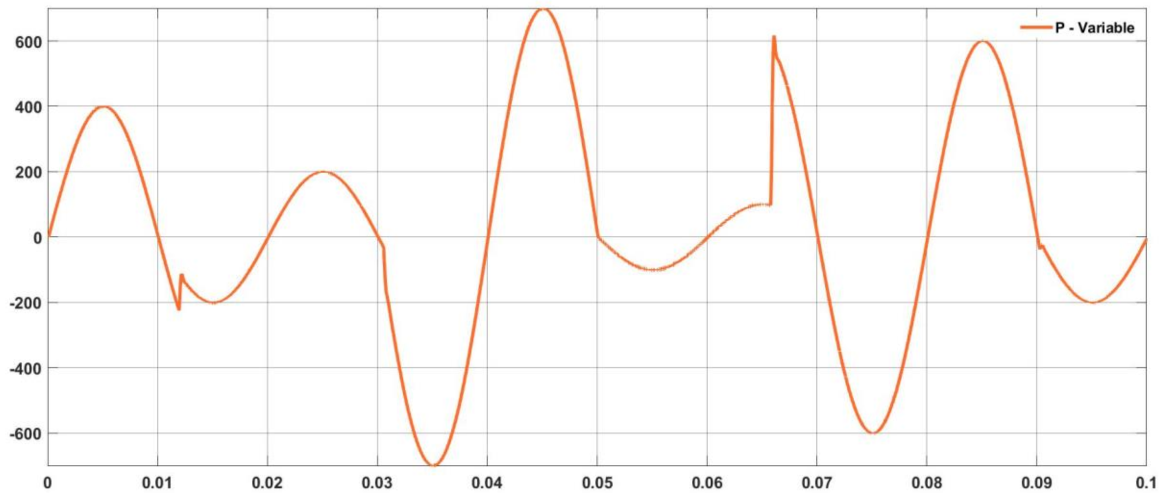

Fig 4.7. Output Waveshape of P Controller-based Inverter for Variable Voltage using Trial and Error

From the FFT analysis in MATLAB, the THD is 18.42%. The reference voltage was changed several times and simulated for 0.1 seconds.

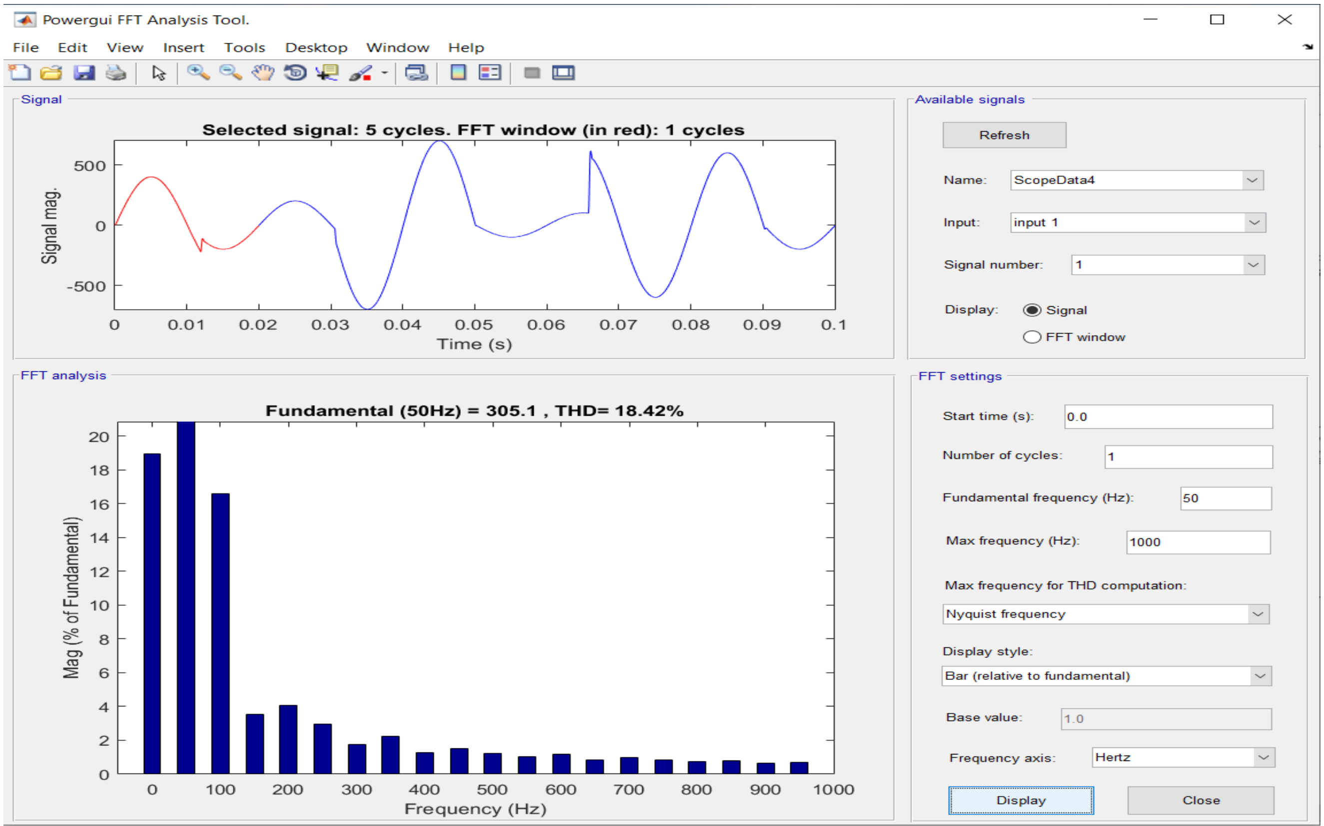

Fig 4.8. FFT Analysis of P Controller-based Inverter for Variable Voltage using Trial and Error

4.3 Performance observation of PD controller for Fixed Voltage

PID tuner is used to get optimum gain values. Again, trial and error gains from data set 13 are also used to compare between THD for these different gains. The Table represents the gain values and THD for different methods for fixed 400V output voltage and simulated for 0.1 second.

TABLE 4.3. Comparison between tuned and trial and error for PD Controller for Fixed Voltage

Method	**Voltage Controller**		**Current Controller**		**THD With fixed voltage**
	K_P	K_D	K_P	K_D	
PID Tuner	-415.8683	0	-415.8683	0	0.07%
Trial and Error	0.3	14	11	19	0.01%

For PID tuner gains:

The output waveshape of the inverter (based on PD controller) is illustrated below.

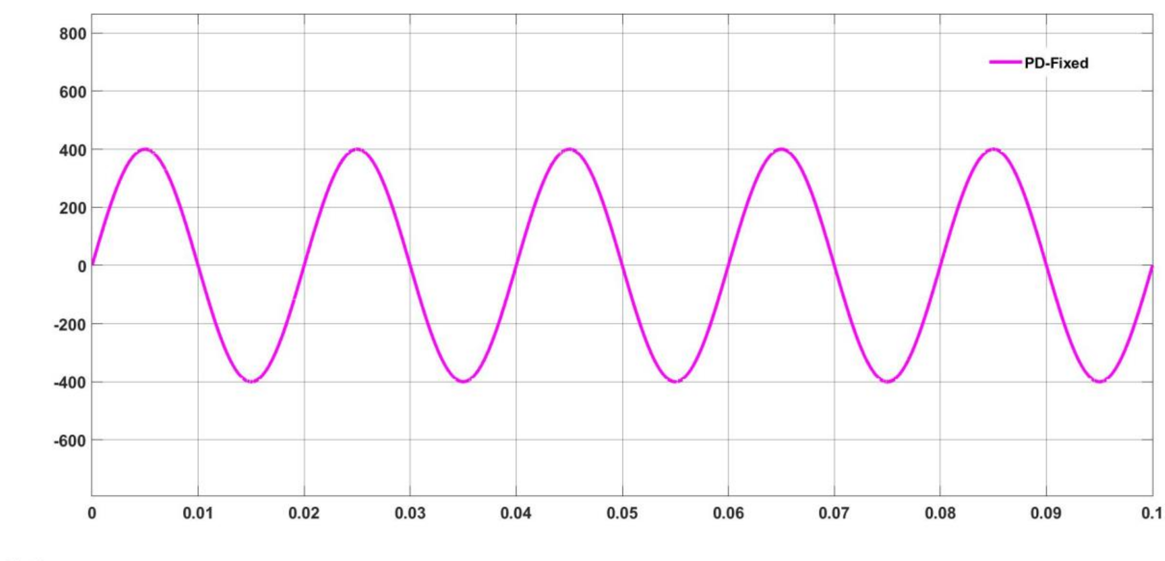

Fig 4.9. Output Waveshape of PD Controller-based Inverter for Fixed Voltage using PID Tuner

From the FFT analysis in MATLAB, the THD is 0.07%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds.

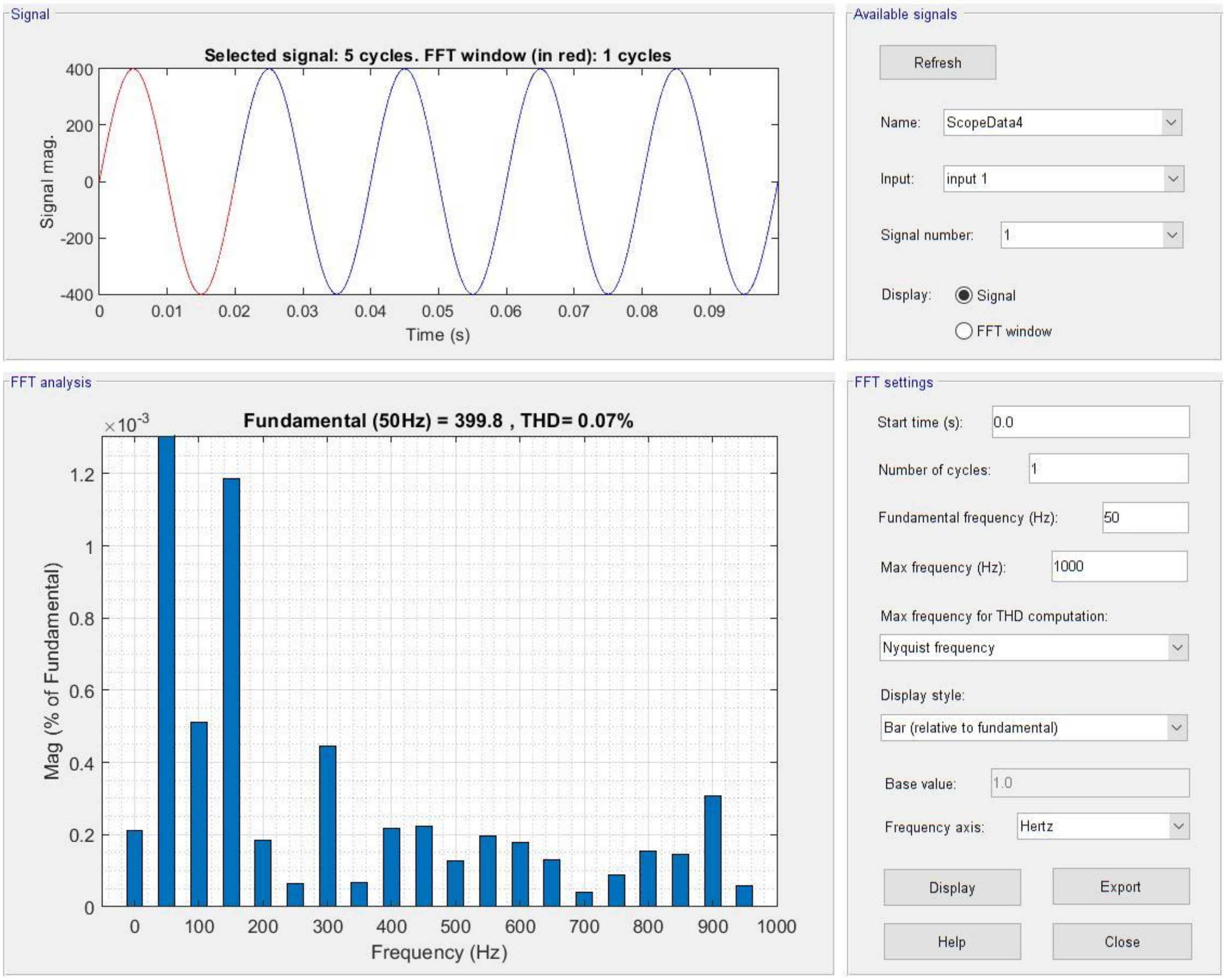

Fig 4.10. FFT Analysis of PD Controller-based Inverter for Fixed Voltage using PID Tuner

For Trial and Error gains:

The output waveshape of the inverter (based on PD controller) is illustrated below

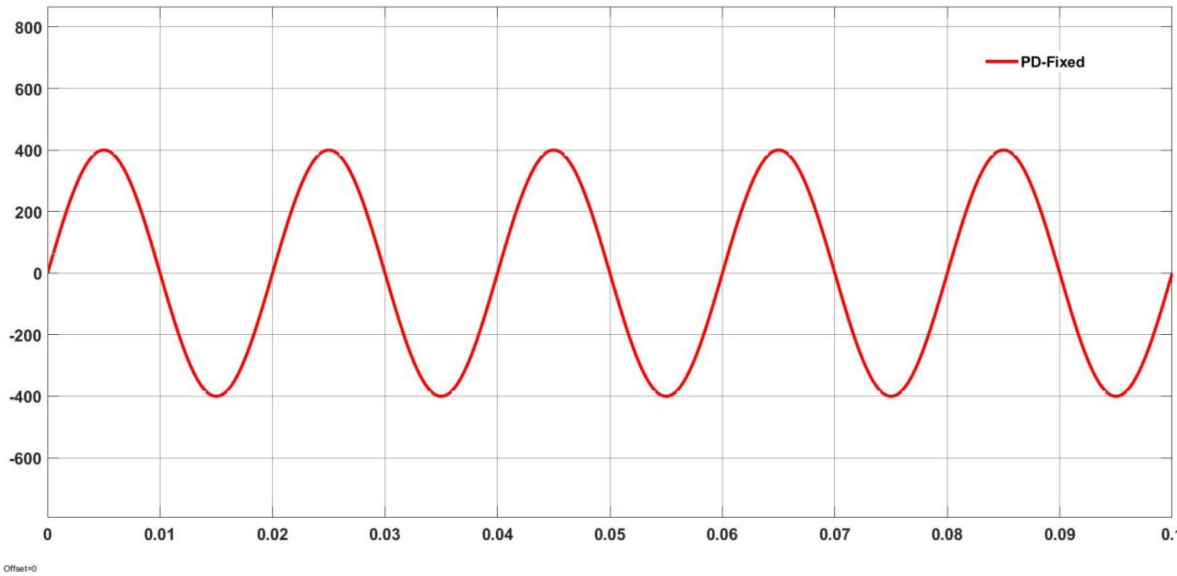

Fig 4.11. Output Waveshape of PD Controller-based Inverter for Fixed Voltage using Trial and Error

From the FFT analysis in MATLAB, the THD is 0.01%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds.

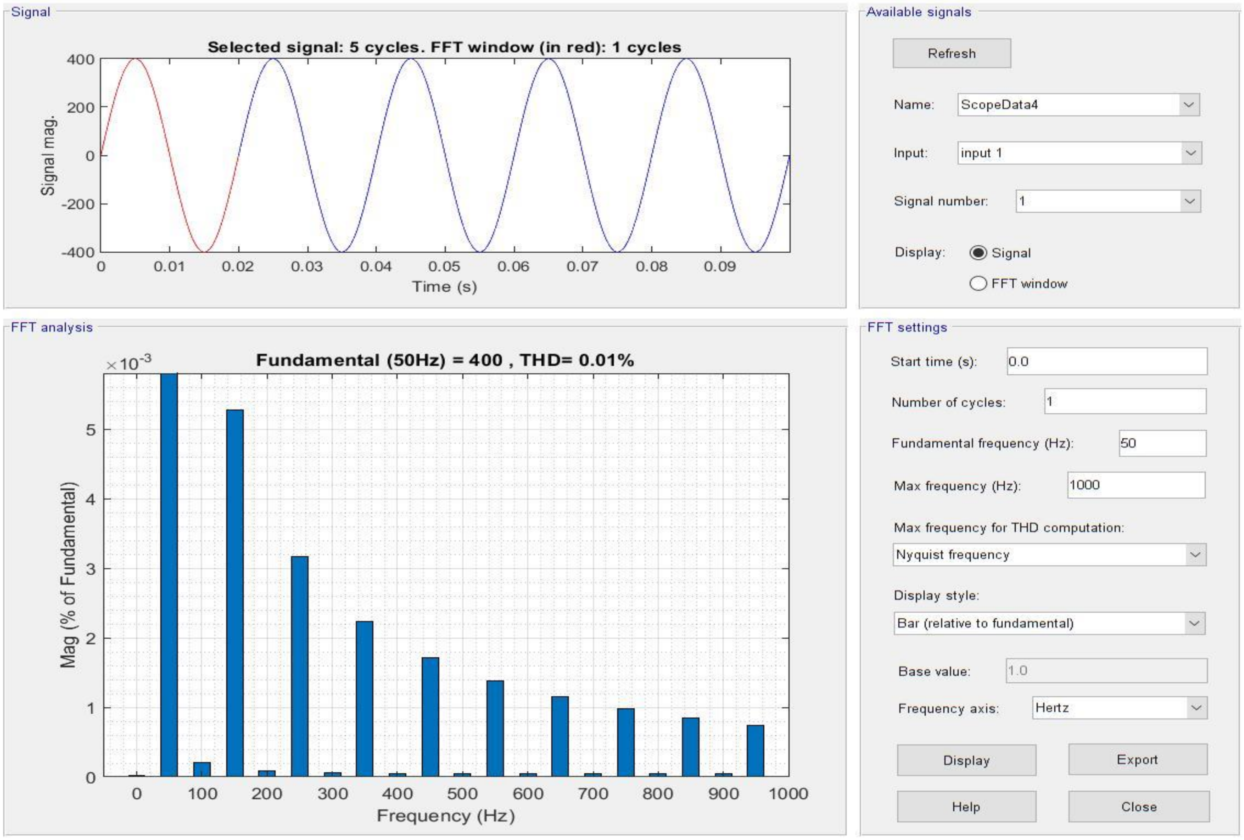

Fig 4.12. FFT Analysis of PD Controller-based Inverter for Fixed Voltage using Trial and Error

4.4 Performance observation of PD controller for Variable Voltage

PID tuner is used to get optimum gain values. Again, trial and error gains from data set 13 are also used to compare between THD for these different gains. The Table represents the gain values and THD for different methods for variable output voltage and simulated for 0.1 second.

TABLE 4.4. Comparison between tuned and trial and error for PD Controller for Variable Voltage

Method	**Voltage Controller**		**Current Controller**		**THD With Variable voltage**
	K_P	K_D	K_P	K_D	
PID Tuner	-415.8683	0	-415.8683	0	30.79%
Trial and Error	0.3	14	11	19	34.60%

For PID tuner gains:

The output waveshape of the inverter (based on PD controller) is illustrated below

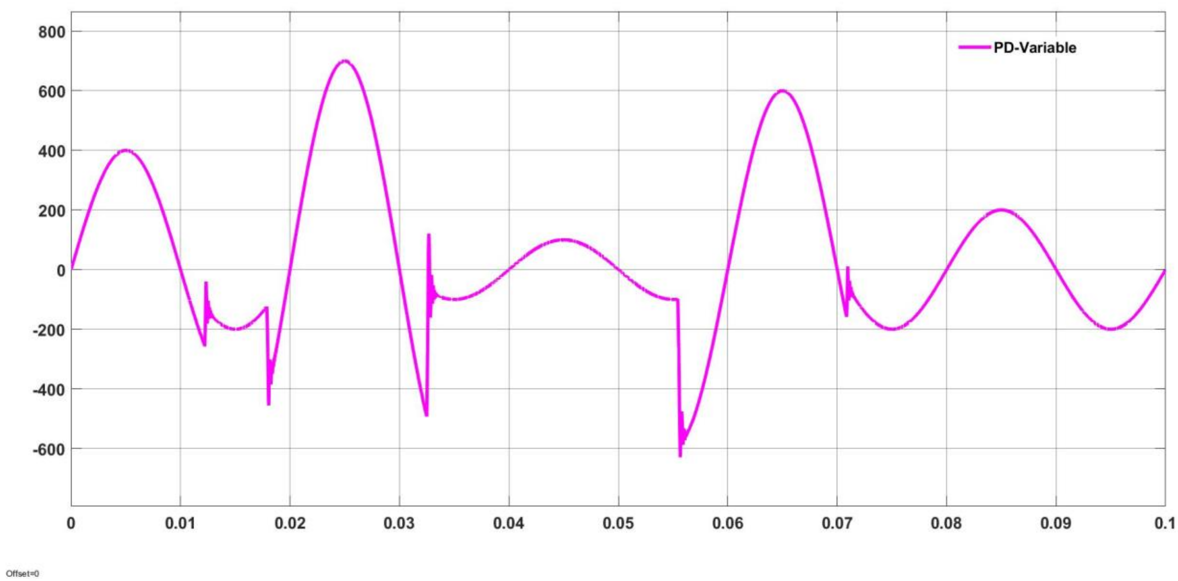

Fig 4.13. Output Waveshape of PD Controller-based Inverter for Variable Voltage using PID Tuner

From the FFT analysis in MATLAB, the THD is 30.79%. The reference voltage was changed several times and simulated for 0.1 seconds.

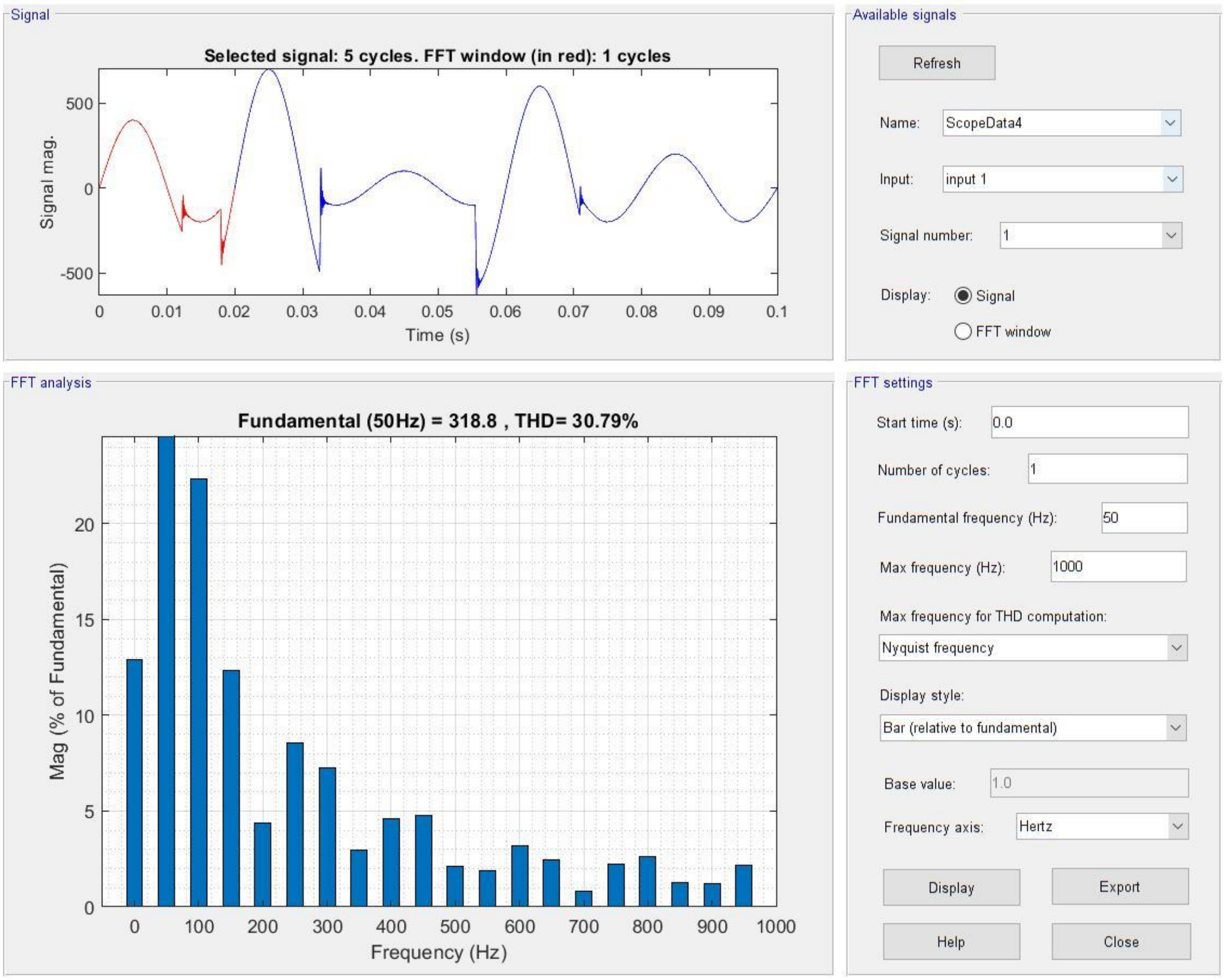

Fig 4.14. FFT Analysis of PD Controller-based Inverter for Variable Voltage using PID Tuner

For Trial and Error gains:

The output waveshape of the inverter (based on PD controller) is illustrated below

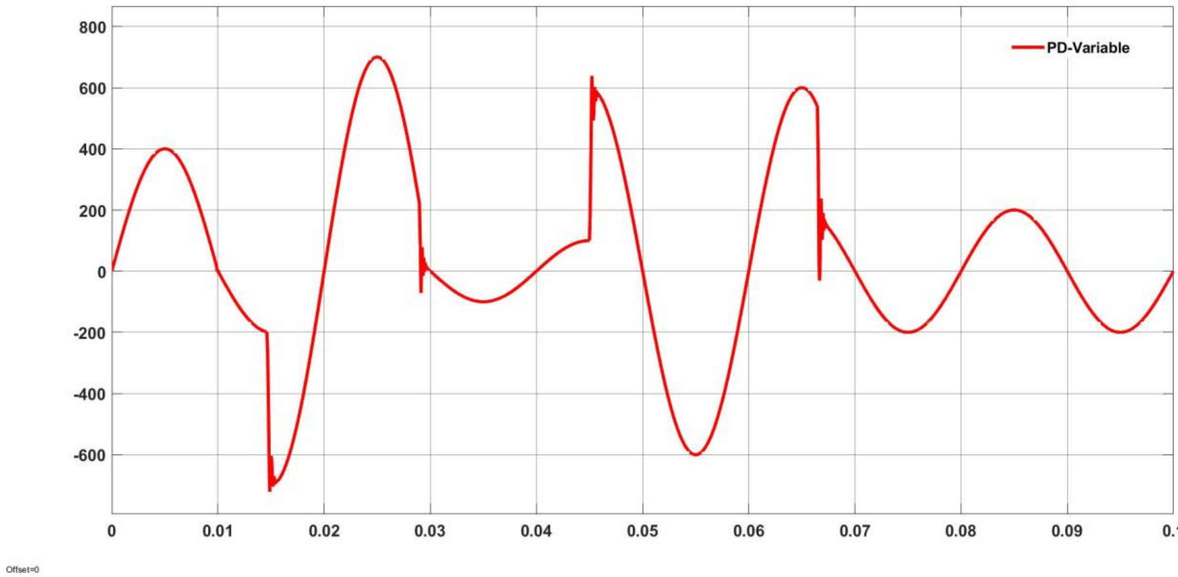

Fig 4.15. Output Waveshape of PD Controller-based Inverter for Variable Voltage using Trial and Error

From the FFT analysis in MATLAB, the THD is 34.60%. The reference voltage was changed several times and simulated for 0.1 seconds.

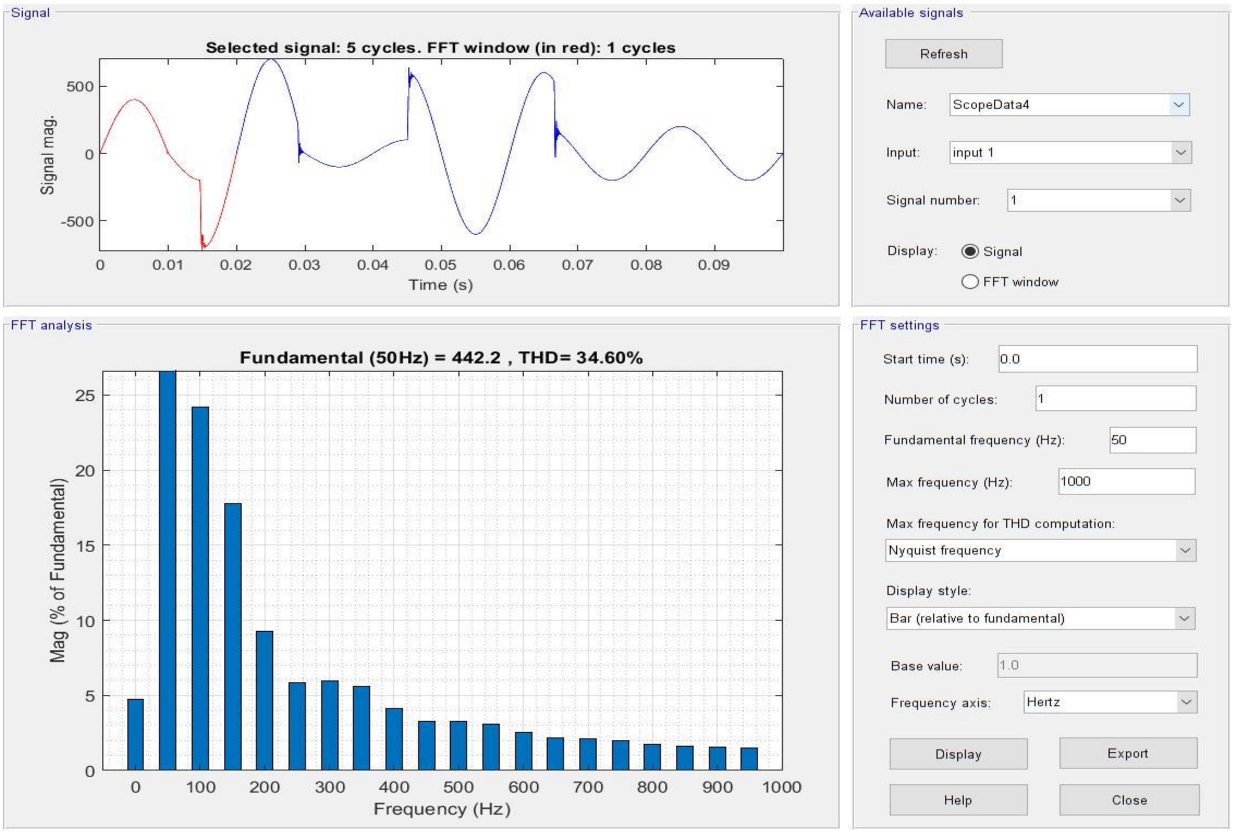

Fig 4.16. FFT Analysis of PD Controller-based Inverter for Variable Voltage using Trial and Error

CHAPTER V

Comparison between PI and PID contrller based Inverters

5.1 Performance observation of PI controller for Fixed Voltage

The output waveshape of the inverter (based on PI controller) is illustrated in fig. 5.1. From the FFT analysis in MATLAB, the THD is 0.45%. The reference voltage was kept constant at 400V and simulated for 0.2 seconds.

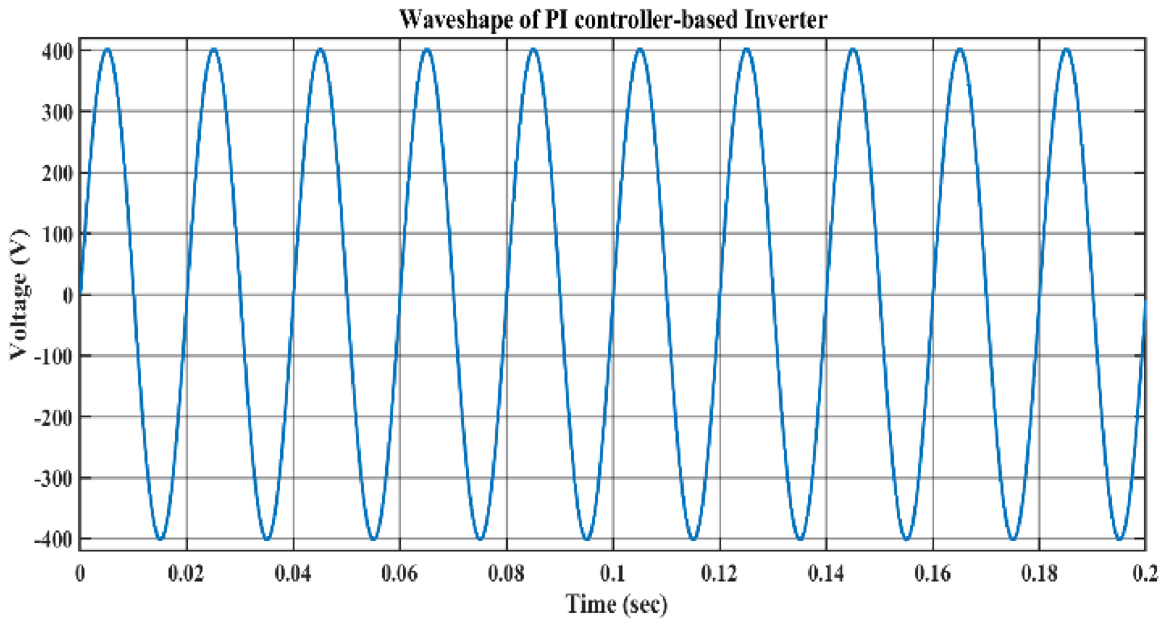

Fig 5.1. Waveshape of PI controller-based Inverter for Fixed Voltage

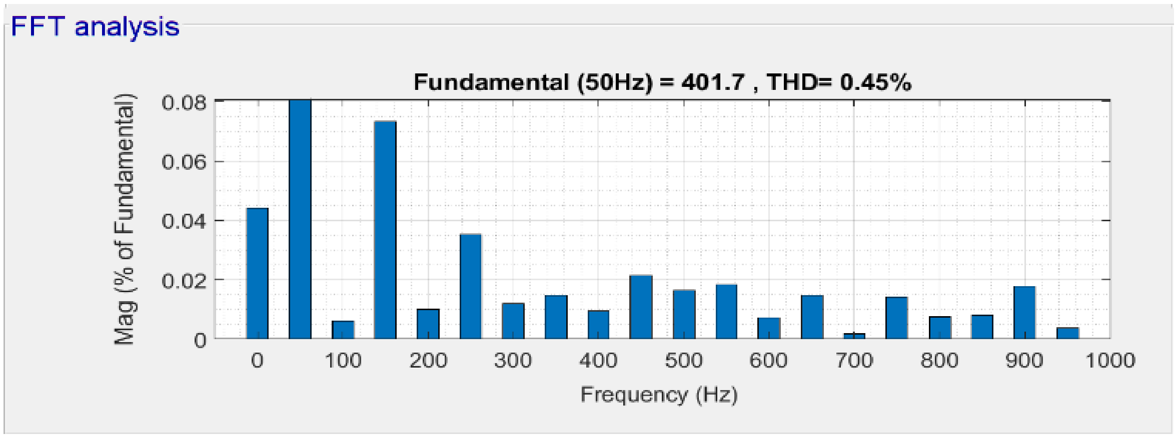

Fig 5.2. FFT Analysis of PI controller-based Inverter for Fixed Voltage

5.2 Performance observation of PI controller for Variable Voltage

In fig. 5.3 the output waveshape of the inverter (based on PI controller) is given. This time the reference voltage is changed several times to observe how the PI controller-based inverter performs when the reference voltage rapidly changes. It is simulated for 0.2 seconds. From the FFT analysis in MATLAB, the THD is found 50.85%. For the same inverter and same time duration, but for fixed 400V reference voltage, previously we found the THD 0.45%.

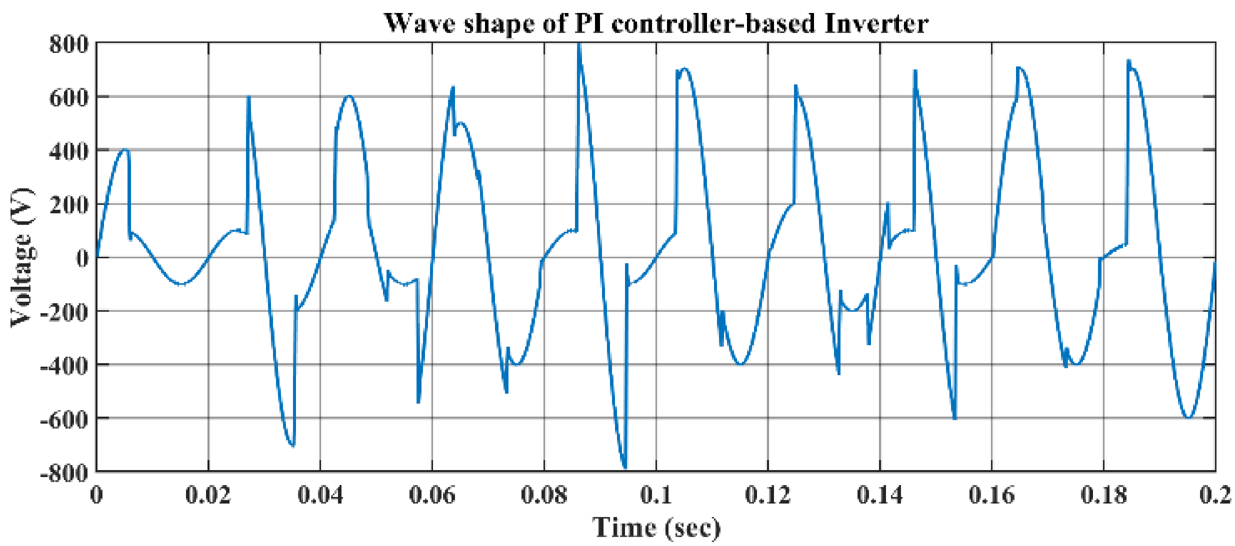

Fig 5.3. Waveshape of PI controller-based Inverter for Variable Voltage

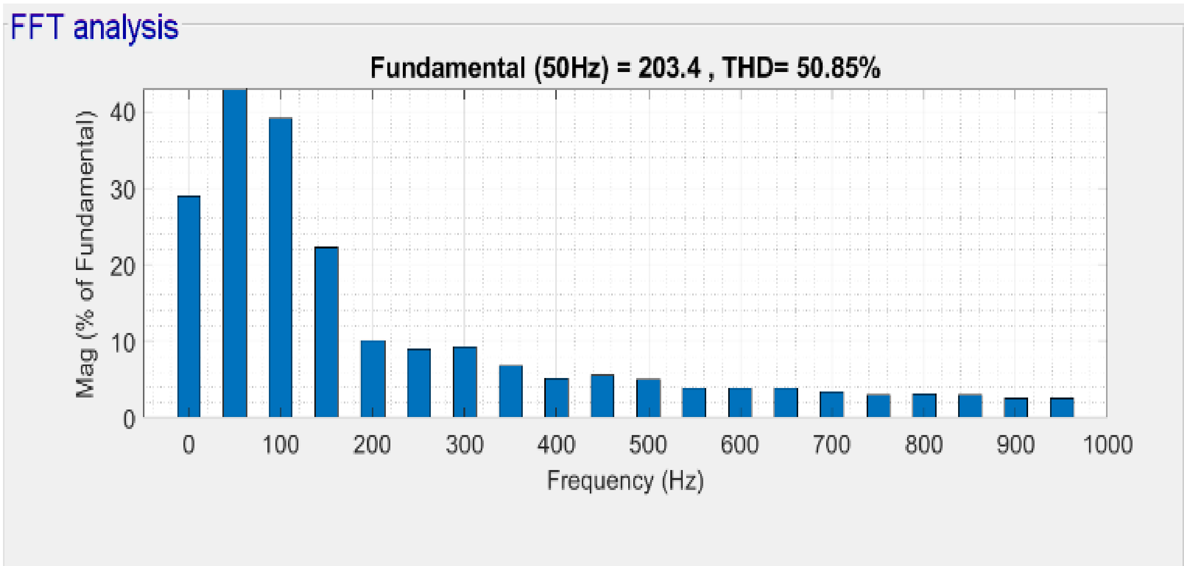

Fig 5.4. FFT Analysis of PI controller-based Inverter for Variable Voltage

5.3 Performance observation of PID controller for Fixed Voltage

The output waveshape of the PID controller-based inverter is illustrated in fig. 5.5. Like the previous test, the reference voltage was kept constant at 400V and simulated for 0.2 seconds. From the FFT analysis in MATLAB, the THD is found to be 0.01%.

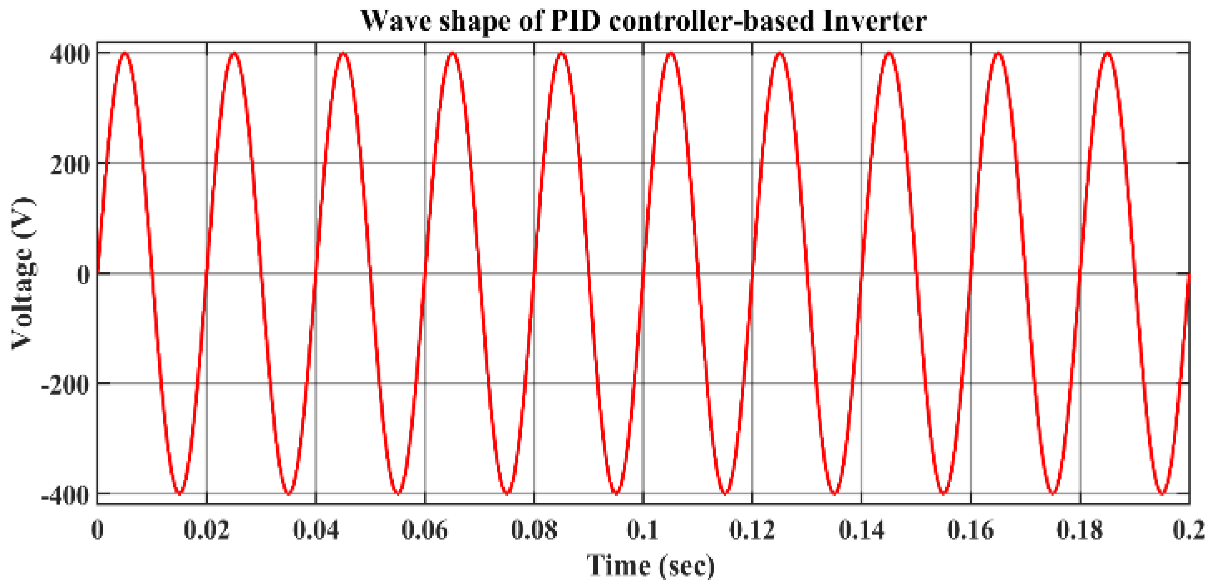

Fig 5.5. Waveshape of PID controller-based Inverter for Fixed Voltage

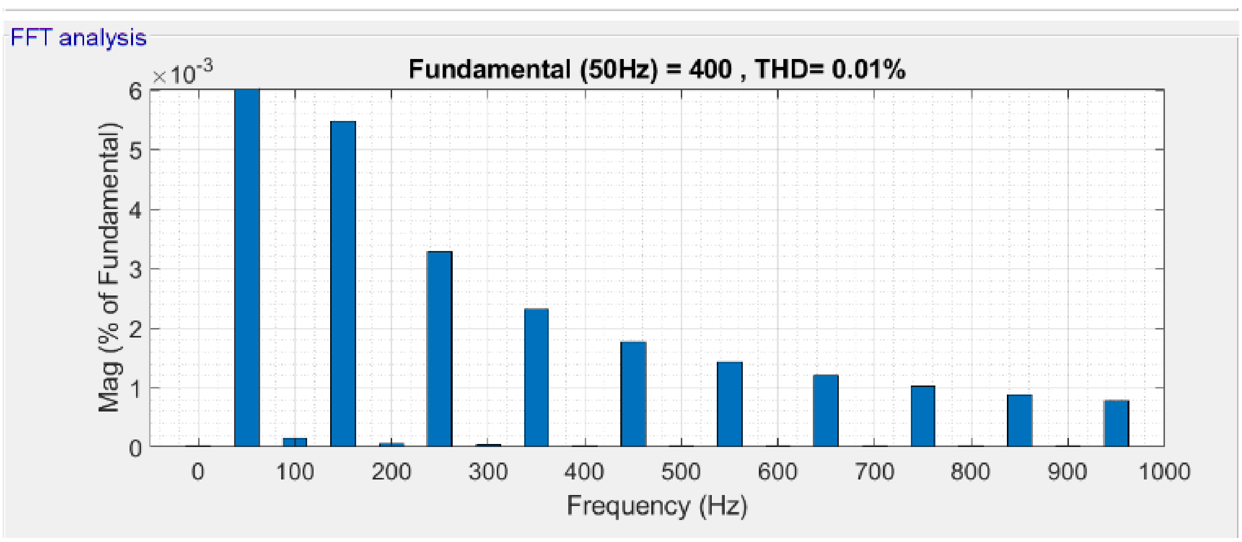

Fig 5.6. FFT Analysis of PID controller-based Inverter for Fixed Voltage

5.4 Performance observation of PID controller for Variable Voltage

The output waveshape of the inverter (based on PID controller) is illustrated in fig. 5.7. This time also, the reference voltage is changed several times to observe how the PID controller-based inverter performs when the reference voltage changes rapidly. It is simulated for 0.2 seconds. From the FFT analysis in MATLAB, THD is found 52.41%. For the same inverter and same time duration, but for fixed 400V reference voltage, previously we found the THD 0.01%.

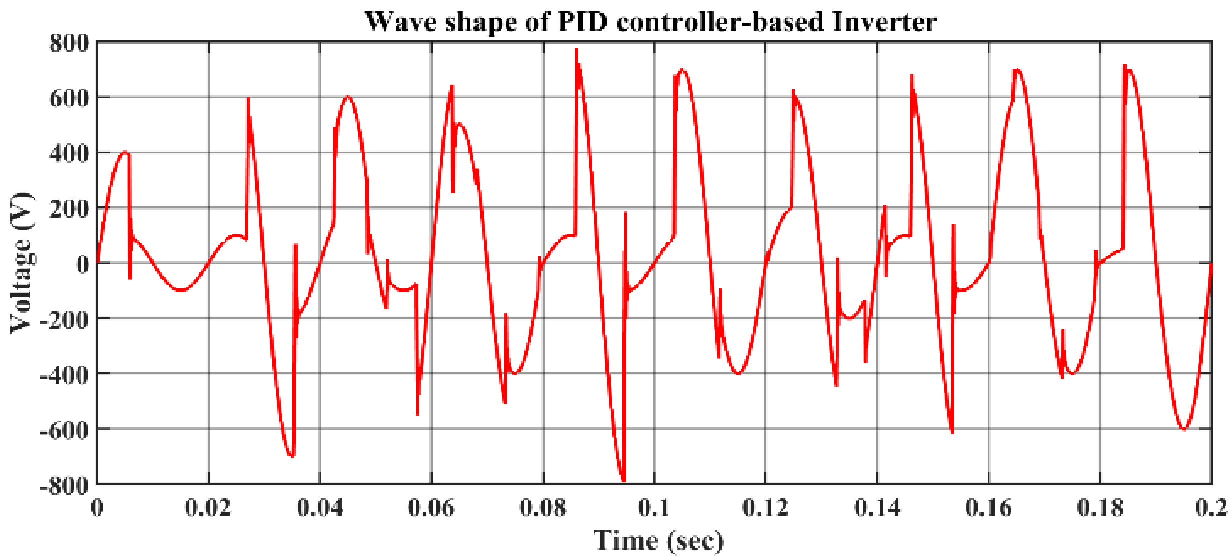

Fig 5.7. Waveshape of PID controller-based Inverter for Variable Voltage

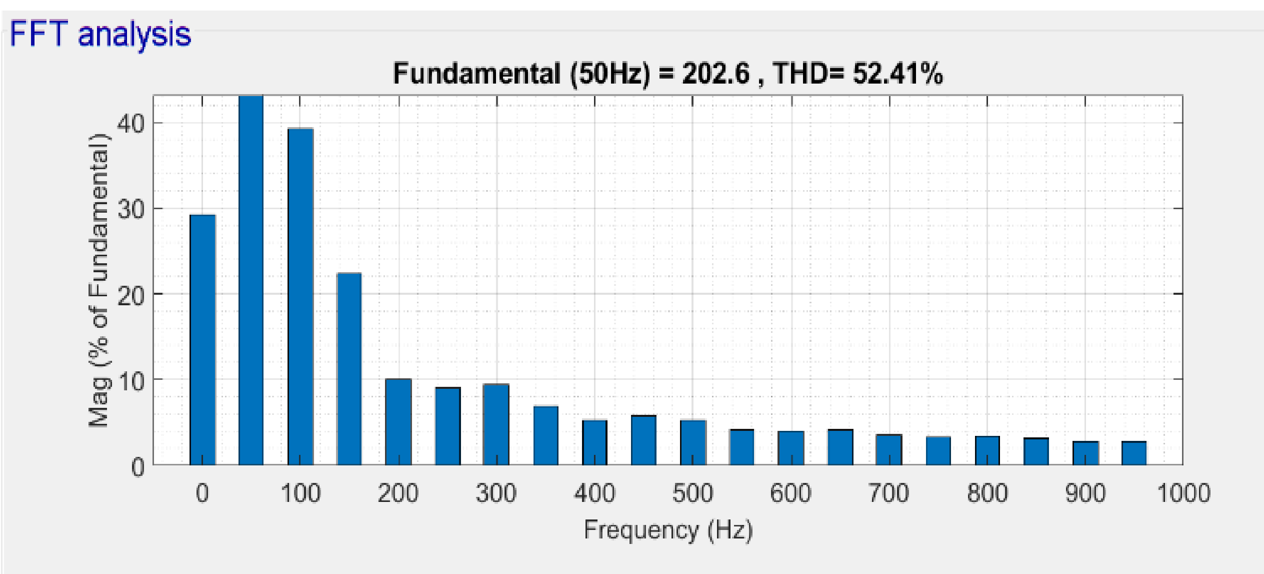

Fig 5.8. FFT Analysis of PID controller-based Inverter for Variable Voltage

5.5 Ripple and Overshoot in PI and PID controller-based Inverters

In fig. 5.9 a zoomed shot from the output waveshape of both the Inverters is taken. The Blue one is for PI controller-based Inverter and the RED one is for PID controller-based Inverter. For this test, the reference voltage was kept constant at 400V. It can easily be observed that the blue signal has an overshoot of almost 4 volts, whereas the RED one has almost zero overshoot. Again, the ripple and THD is also observed very high for the blue signal compared to the red signal. So, it is observed that, for fixed reference voltage, PID controller-based Inverter performs better than PI controller-based Inverter.

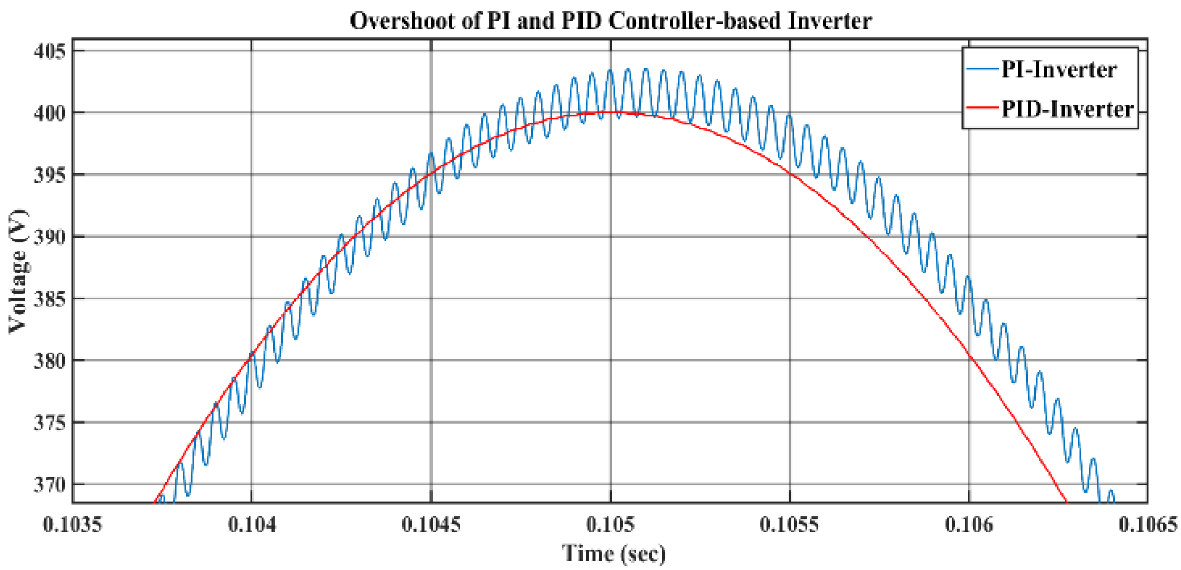

Fig 5.9. Comparison of Overshoot of PI and PID controller-based Inverter

5.6 Distortion in Voltage Transition in PI and PID controller-based Inverters

In this fig. 5.10, the behaviour of both the inverter when the Reference voltage is changed is shown. Here it gives the output signal for changing the reference voltage twice. The Blue signal is for PI controller-based Inverter and the Red signal is for PID controller-based Inverter. It is observed that when a reference voltage is changed, Red signal is more distorted and more ripple is observed to follow the new Reference voltage, compared to the Blue signal. So, the THD is very high in the transition time for PID controller-based Inverter compared to PI controller-based inverter.

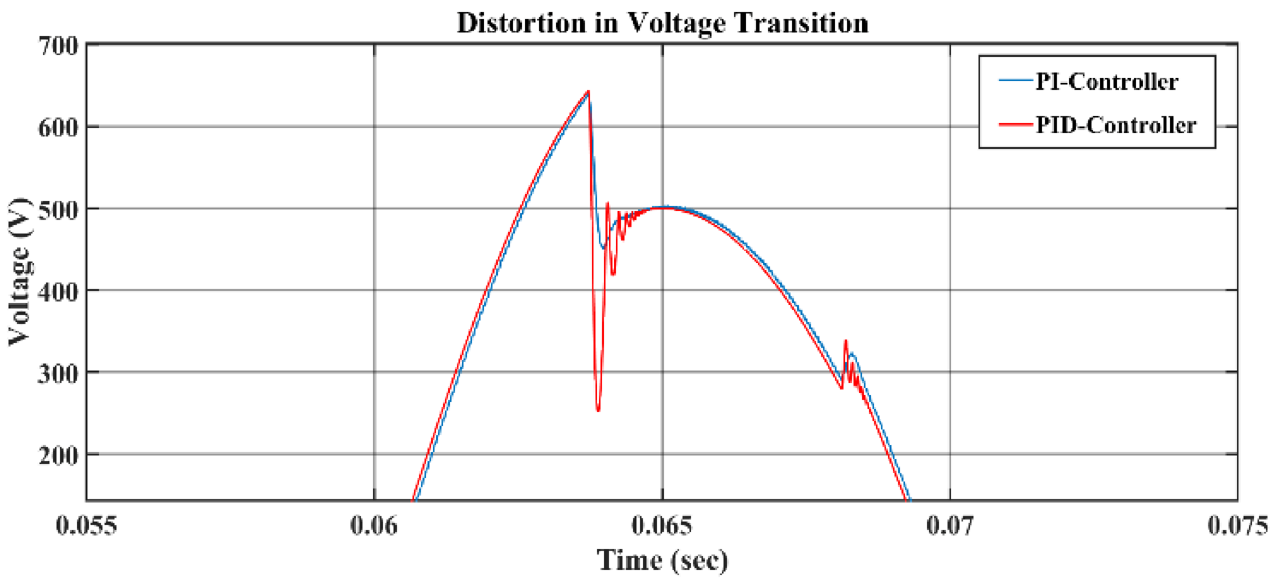

Fig 5.10. Comparison of Distortion in Voltage Transition in PI and PID controller-based Inverter

5.7 Summary

THD Comparison

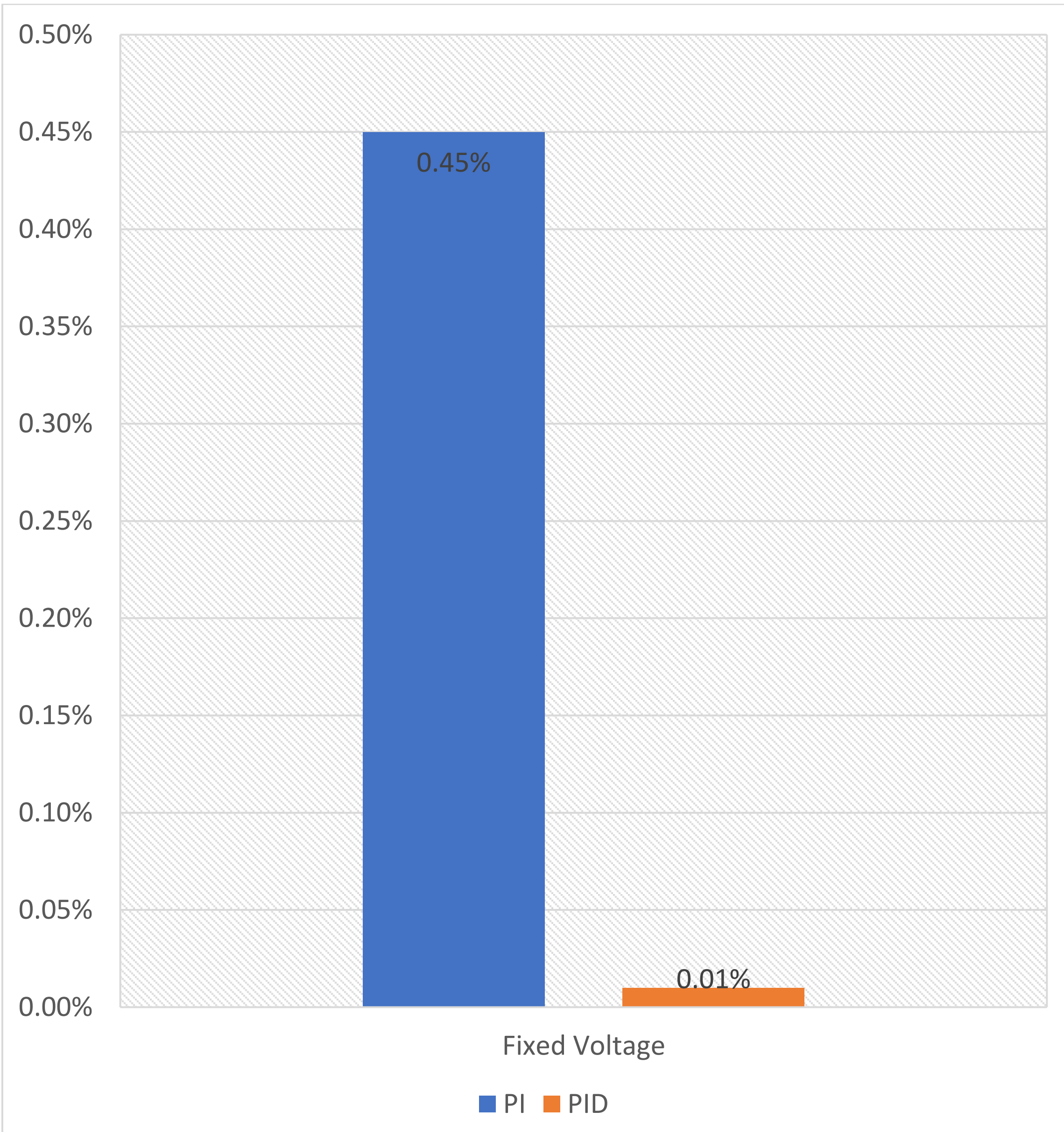

Fig 5.11. Bar Chart showing the Comparsion of THD between PI and PID controller based Inverter for Fixed Voltage

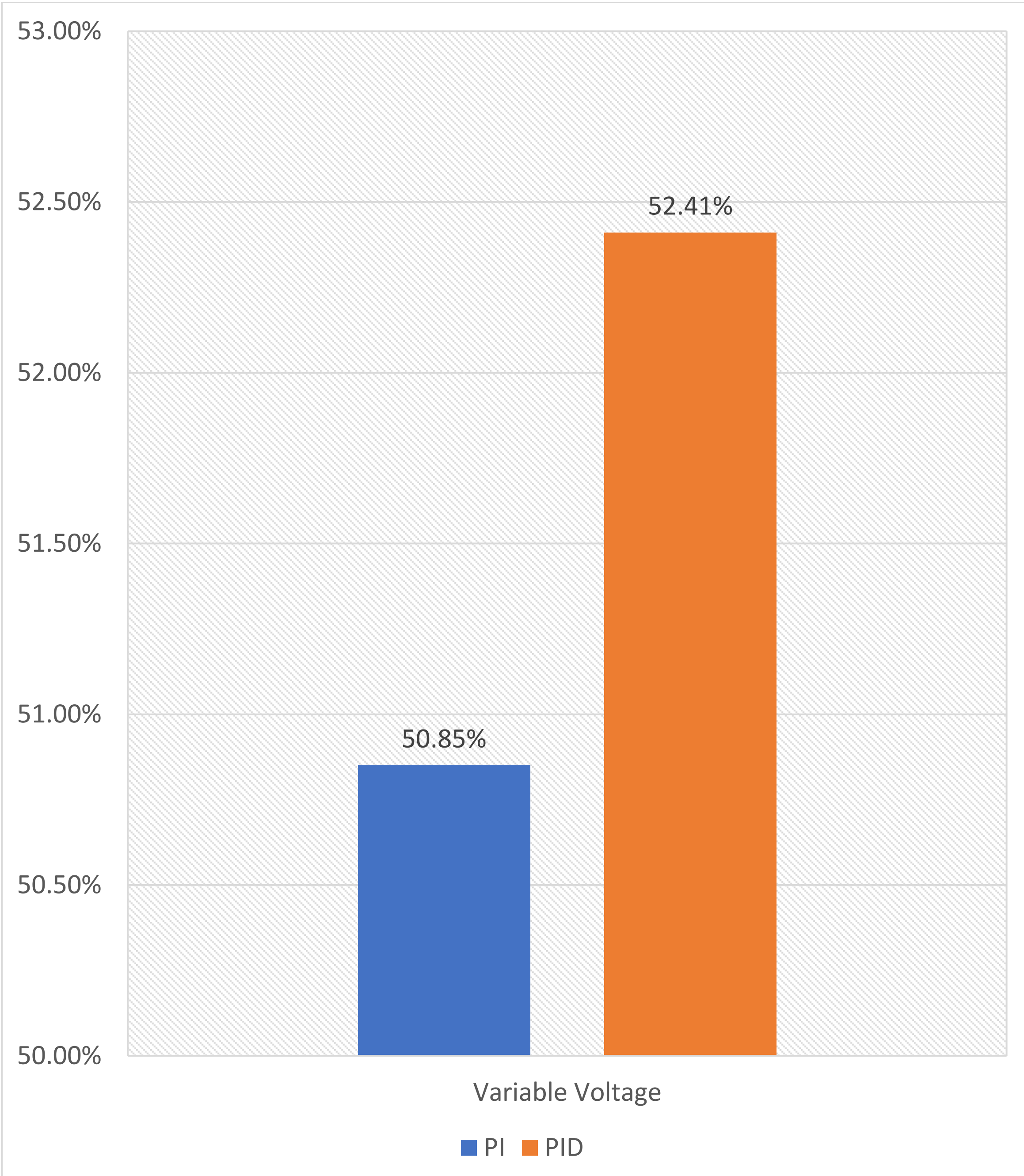

Fig 5.12. Bar Chart showing the Comparsion of THD between PI and PID controller based Inverter for Variable Voltage

CHAPTER VI

Comparison between Unipolar and Bipolar PWM Techniques

6.1 Performance observation of PI controller for Unipolar PWM for Fixed Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for unipolar PWM technique for fixed 400V output voltage and simulated for 0.1 second using PI controller.

TABLE 6.1. THD value using Trial and Error method for Unipolar PWM for Fixed Voltage

Method	**Voltage Controller**		**Current Controller**		**THD With fixed voltage**
	K_P	K_I	K_P	K_I	
Trial and Error	0.3	14	11	19	0.44%

The output waveshape of the inverter (based on PI controller) using unipolar PWM technique is illustrated below.

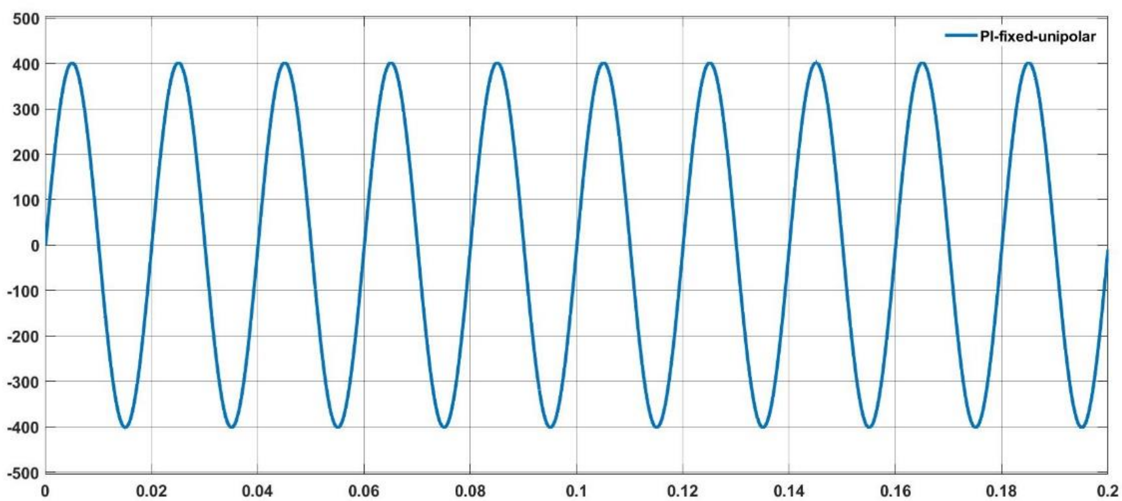

Fig 6.1. Output Waveshape of PI Controller-based Inverter for Unipolar PWM for Fixed Voltage

From the FFT analysis in MATLAB, the THD is 0.44%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds

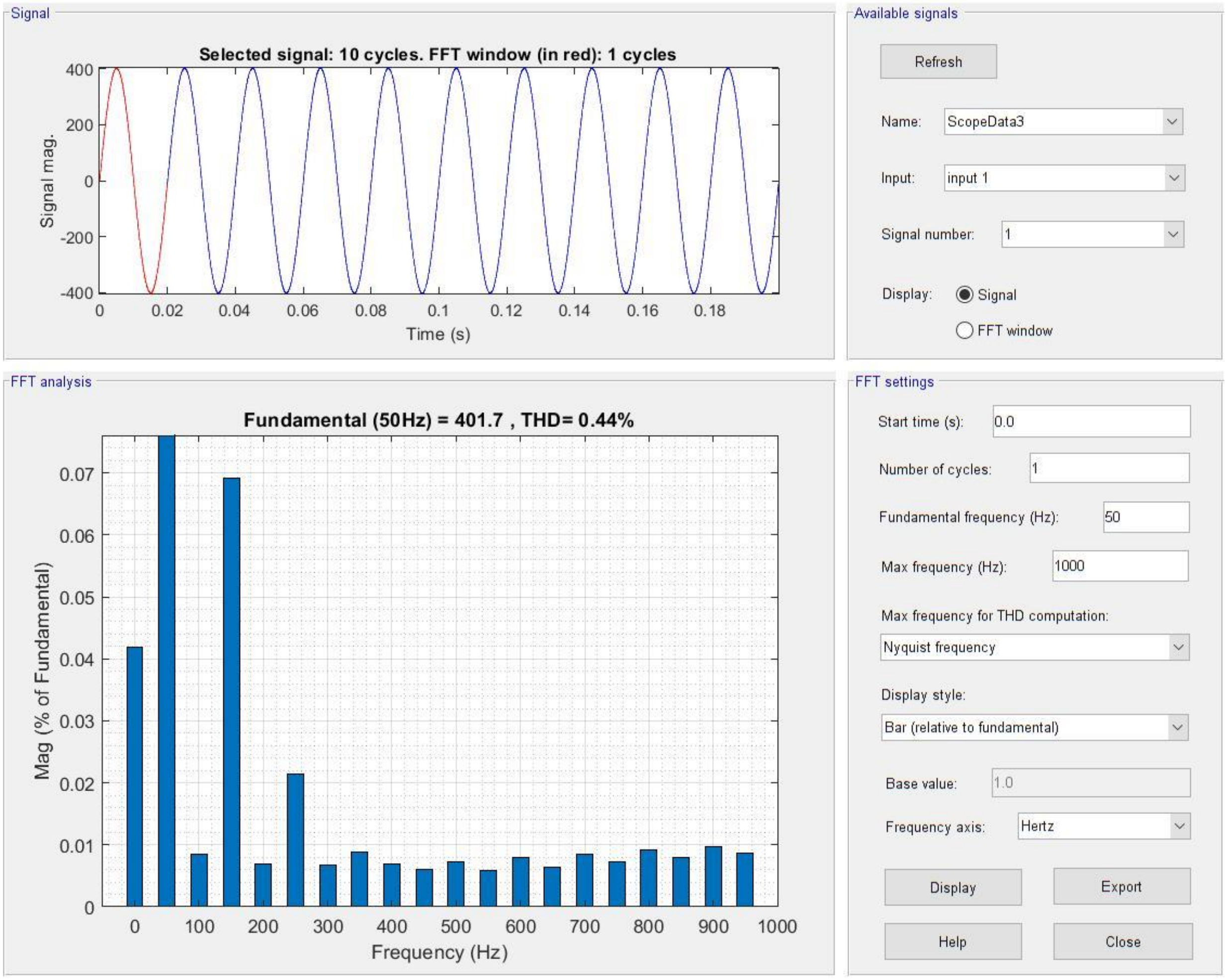

Fig 6.2. FFT Analysis of PI controller-based Inverter for Unipolar PWM for Fixed Voltage

6.2 Performance observation of PI controller for Unipolar PWM for Variable Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for unipolar PWM technique for variable output voltage and simulated for 0.1 second using PI controller.

TABLE 6.2. THD value of PI controller-based Inverter using Trial and Error method for Unipolar PWM for Variable Voltage

Method	**Voltage Controller**		**Current Controller**		**THD With variable voltage**
	K_P	***K_I***	***K_P***	***K_I***	
Trial and Error	0.3	14	11	19	15.57%

The output waveshape of the inverter (based on PI controller) using unipolar PWM technique is illustrated below:

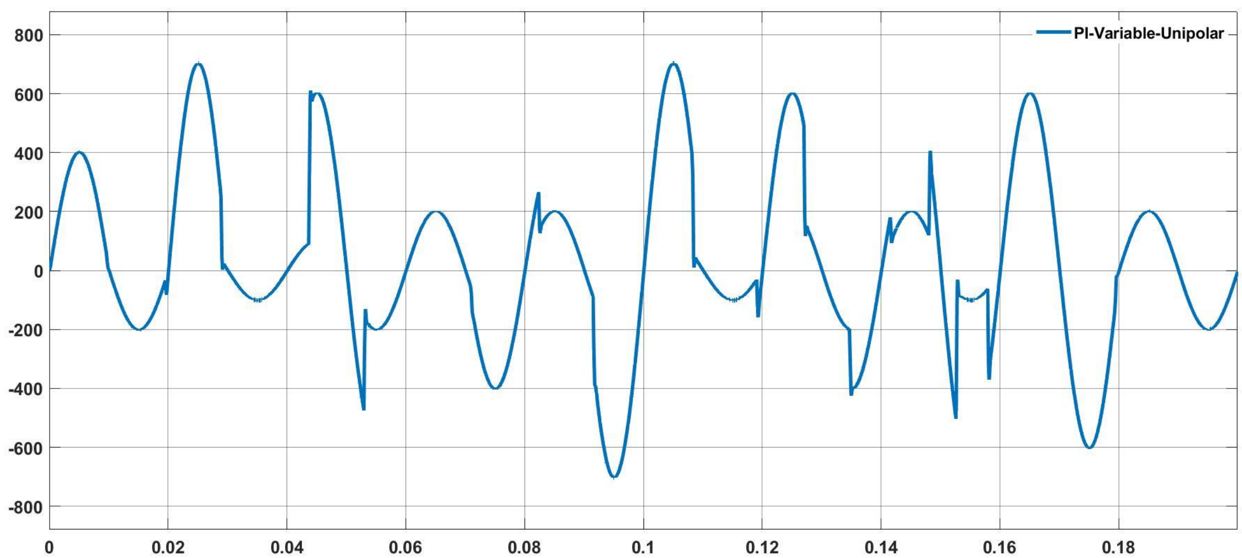

Fig 6.3. Output Waveshape of PI Controller-based Inverter for Unipolar PWM for Variable Voltage

From the FFT analysis in MATLAB, the THD is 15.57%. The reference voltage was changed several times and simulated for 0.1 seconds.

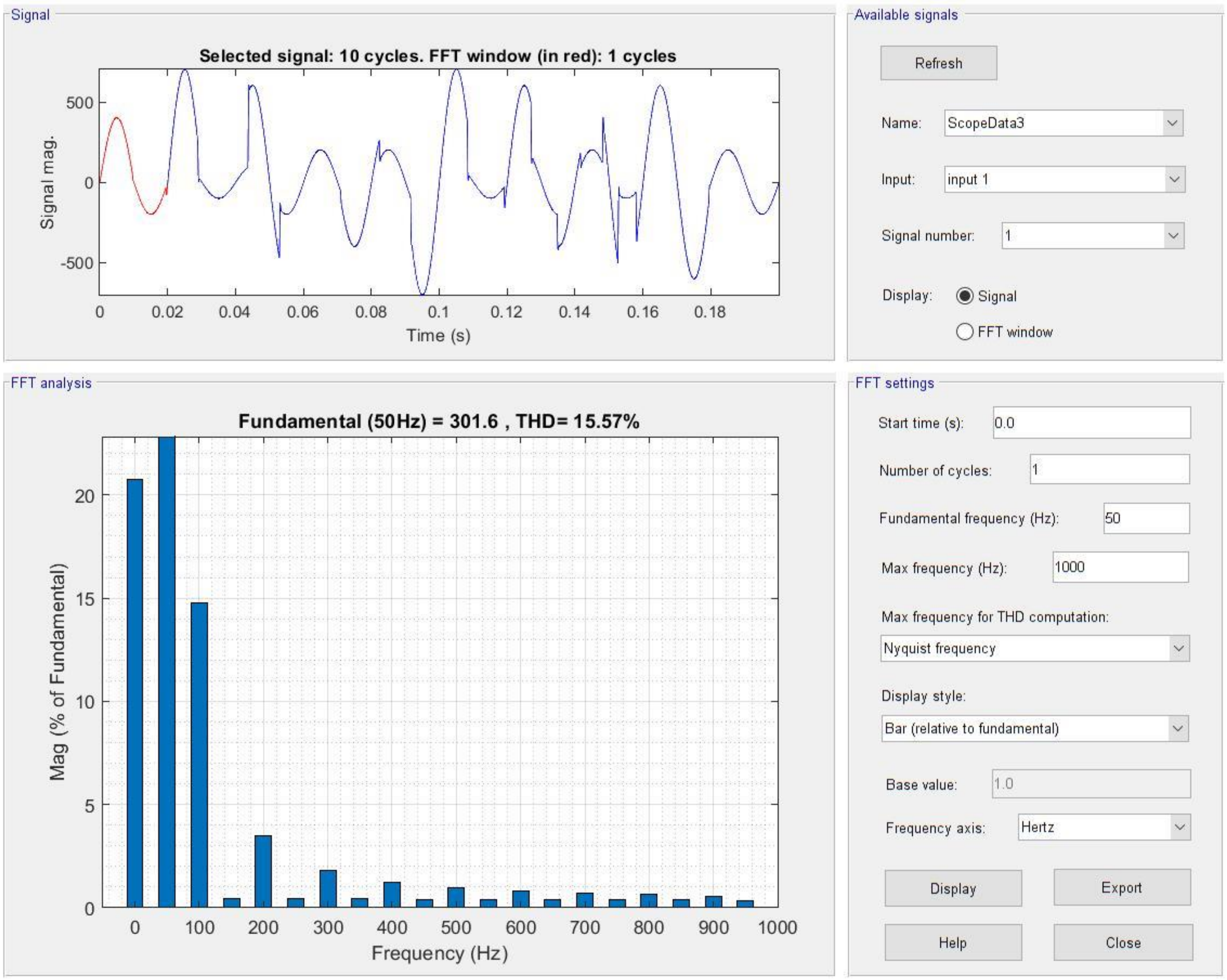

Fig 6.4. FFT Analysis of PI Controller-based Inverter for Unipolar PWM for Variable Voltage

6.3 Performance observation of PID controller for Unipolar PWM for Fixed Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for unipolar PWM technique for fixed 400V output voltage and simulated for 0.1 second using PID controller.

TABLE 6.3. THD value of PID controller-based Inverter using Trial and Error method for Unipolar PWM for Fixed Voltage

Method	**Voltage Controller**			**Current Controller**			**THD With fixed voltage**
	K_P	K_I	K_D	K_P	K_I	K_D	
Trial and Error	0.3	14	70	11	19	100	0.01%

The output waveshape of the inverter (based on PID controller) using unipolar PWM technique is illustrated below

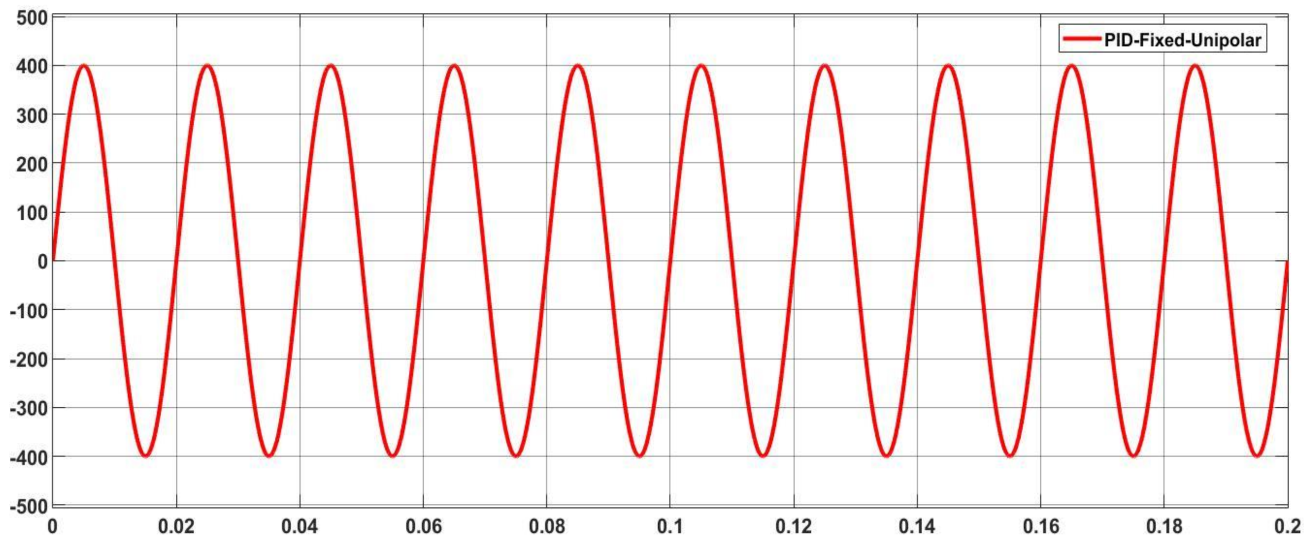

Fig 6.5. Output Waveshape of PID Controller-based Inverter for Unipolar PWM for Fixed Voltage

From the FFT analysis in MATLAB, the THD is 0.01%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds

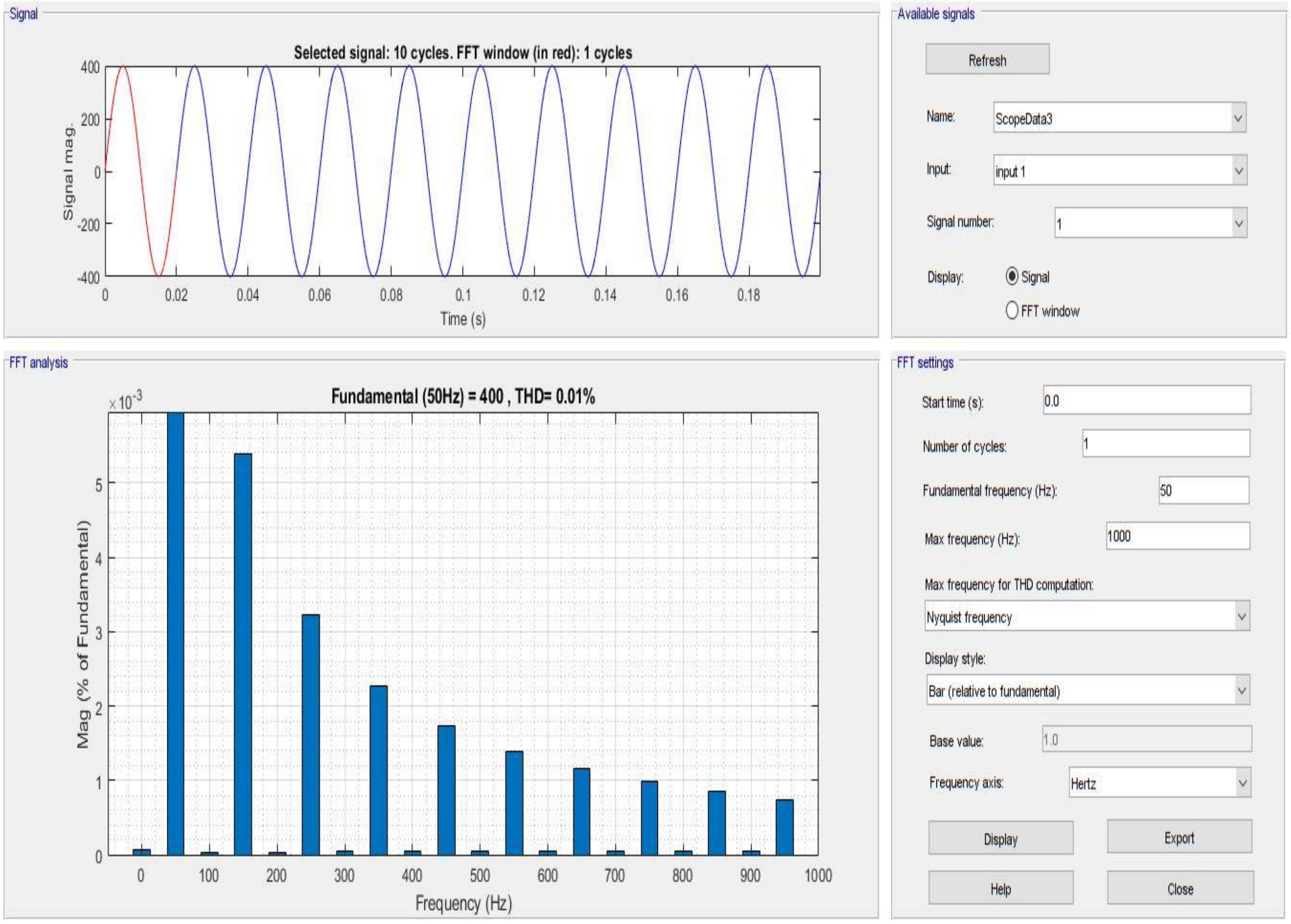

Fig 6.6. FFT Analysis of PID Controller-based Inverter for Unipolar PWM for Fixed Voltage

6.4 Performance observation of PID controller for Unipolar PWM for Variable Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for unipolar PWM technique for variable output voltage and simulated for 0.1 second using PID controller.

TABLE 6.4. THD value of PID controller-based Inverter using Trial and Error method for Unipolar PWM for Variable Voltage

Method	**Voltage Controller**			**Current Controller**			**THD With Variable voltage**
	K_P	K_I	K_D	K_P	K_I	K_D	
Trial and Error	0.3	14	70	11	19	100	15.98%

The output waveshape of the inverter (based on PID controller) using unipolar PWM technique is illustrated below

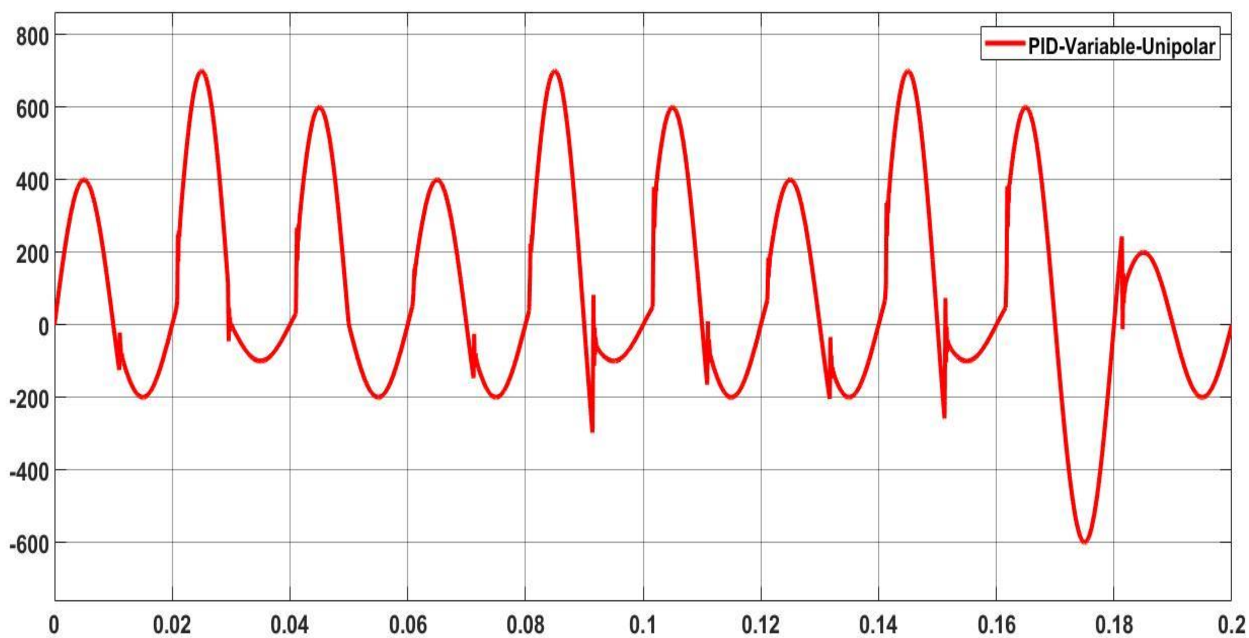

Fig 6.7. Output Waveshape of PID Controller-based Inverter for Unipolar PWM for Variable Voltage

From the FFT analysis in MATLAB, the THD is 15.98%. The reference voltage was changed several times and simulated for 0.1 seconds.

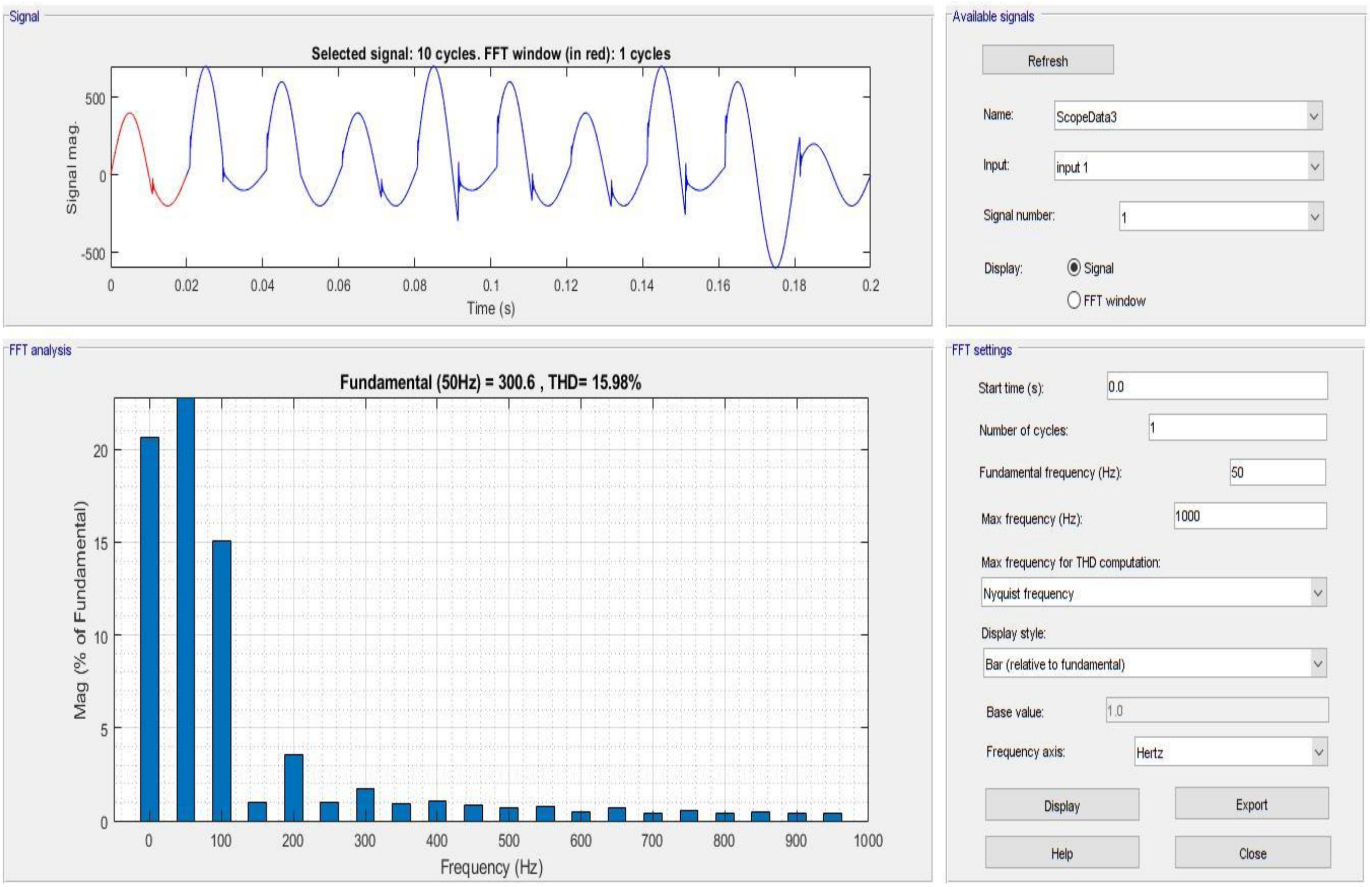

Fig 6.8. FFT Analysis of PID Controller-based Inverter for Unipolar PWM for Variable Voltage

6.5 Performance observation of PI controller for Bipolar PWM for Fixed Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for bipolar PWM technique for fixed 400V output voltage and simulated for 0.1 second using PI controller.

TABLE 6.5. THD value of PI controller-based Inverter using Trial and Error method for Bipolar PWM for Fixed Voltage

Method	**Voltage Controller**		**Current Controller**		**THD With fixed voltage**
	K_P	K_I	K_P	K_I	
Trial and Error	0.3	14	11	19	3.58%

The output waveshape of the inverter (based on PI controller) using bipolar PWM technique is illustrated below.

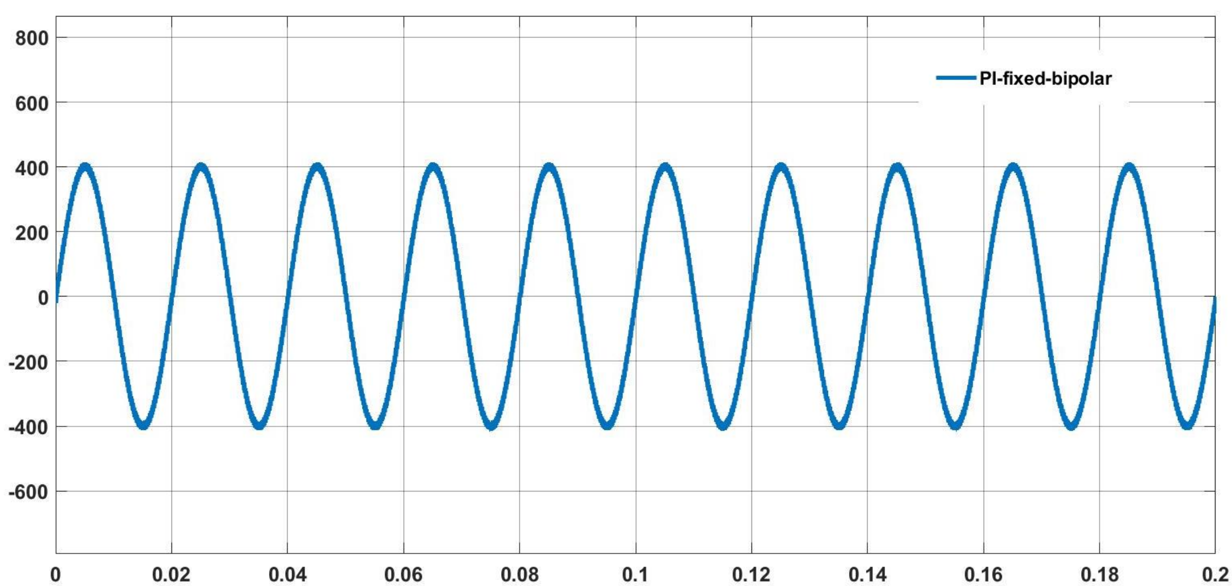

Fig 6.9. Output Waveshape of PI Controller-based Inverter for Bipolar PWM for Fixed Voltage

From the FFT analysis in MATLAB, the THD is 3.58%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds

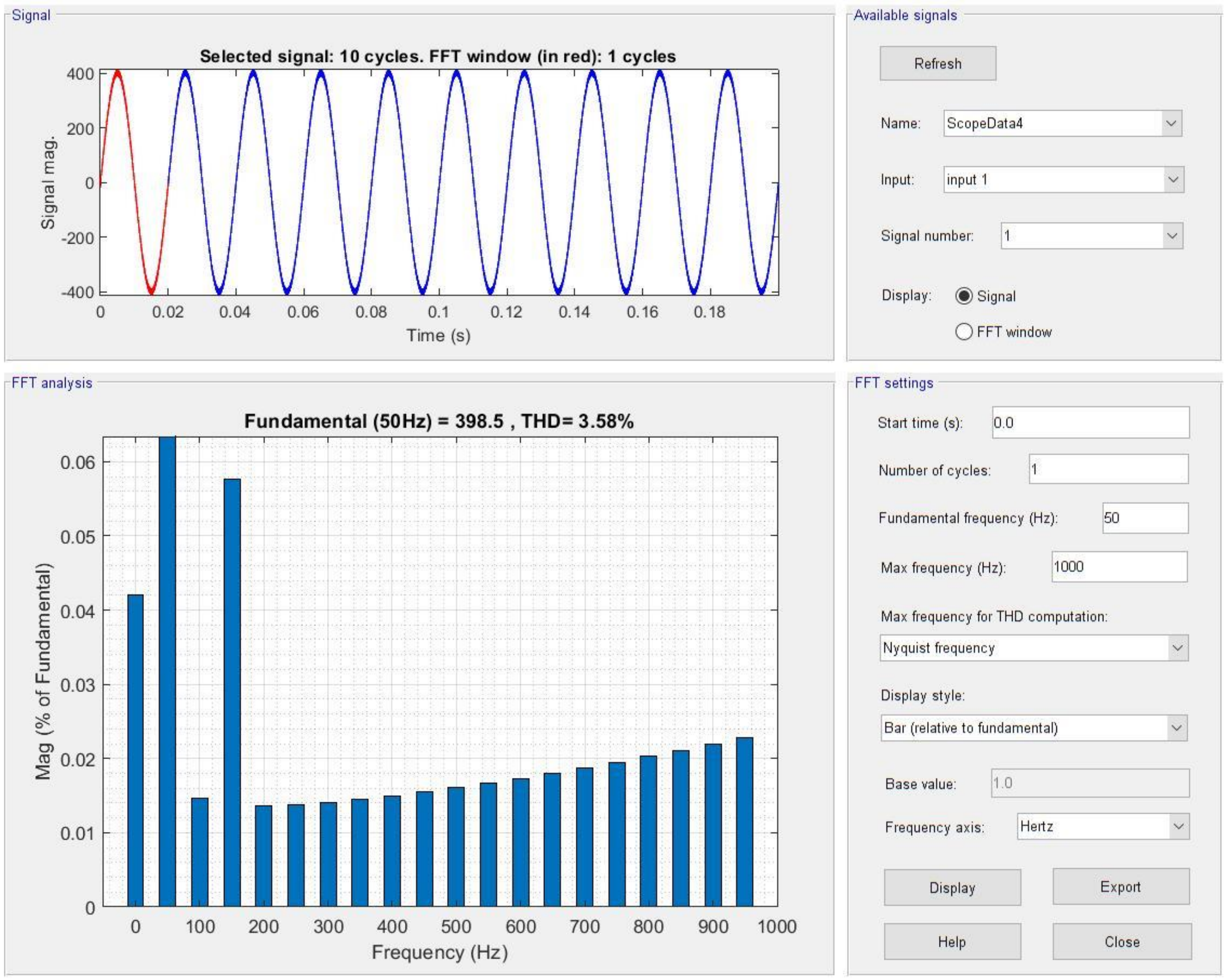

Fig 6.10. FFT Analysis of PI Controller-based Inverter for Bipolar PWM for Fixed Voltage

6.6 Performance observation of PI controller for Bipolar PWM for Variable Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for bipolar PWM technique for variable output voltage and simulated for 0.1 second using PI controller.

TABLE 6.6. THD value of PI controller-based Inverter using Trial and Error method for Bipolar PWM for Variable Voltage

Method	**Voltage Controller**		**Current Controller**		**THD With variable voltage**
	K_P	K_I	K_P	K_I	
Trial and Error	0.3	14	11	19	16.41%

The output waveshape of the inverter (based on PI controller) using bipolar PWM technique is illustrated below:

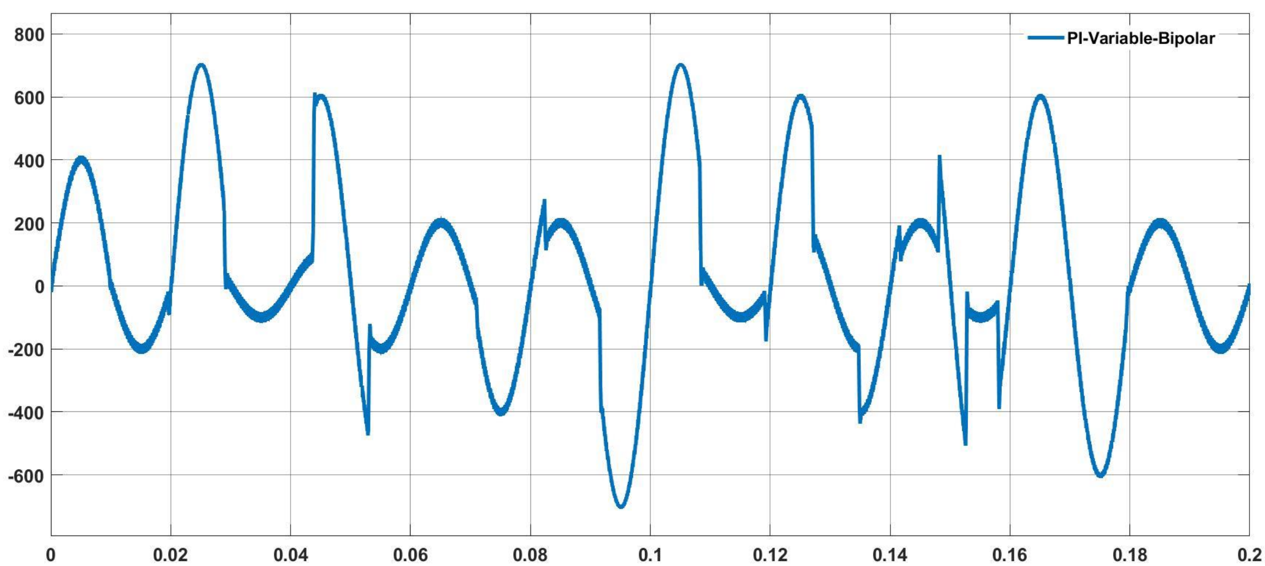

Fig 6.11. Output Waveshape of PI Controller-based Inverter for Bipolar PWM for Variable Voltage

From the FFT analysis in MATLAB, the THD is 16.41%. The reference voltage was changed several times and simulated for 0.1 seconds.

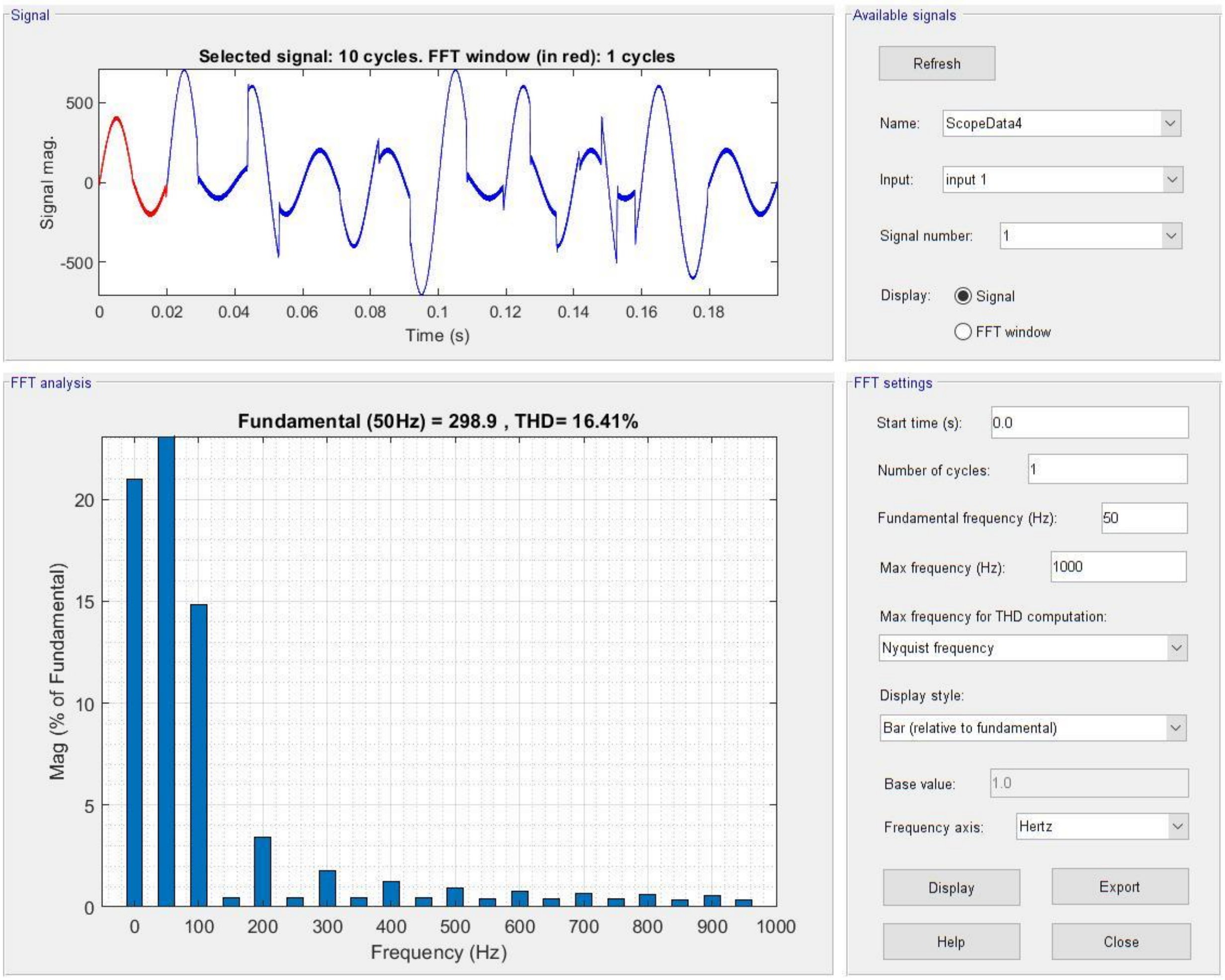

Fig 6.12. FFT Analysis of PI Controller-based Inverter for Bipolar PWM for Variable Voltage

6.7 Performance observation of PID controller for Bipolar PWM for Fixed Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for bipolar PWM technique for fixed 400V output voltage and simulated for 0.1 second using PID controller.

TABLE 6.7. THD value of PID controller-based Inverter using Trial and Error method for Bipolar PWM for Fixed Voltage

Method		**Voltage Controller**			**Current Controller**			**THD With fixed voltage**
		K_P	K_I	K_D	K_P	K_I	K_D	
Trial and Error		0.3	14	70	11	19	100	0.02%

The output waveshape of the inverter (based on PID controller) using bipolar PWM technique is illustrated below

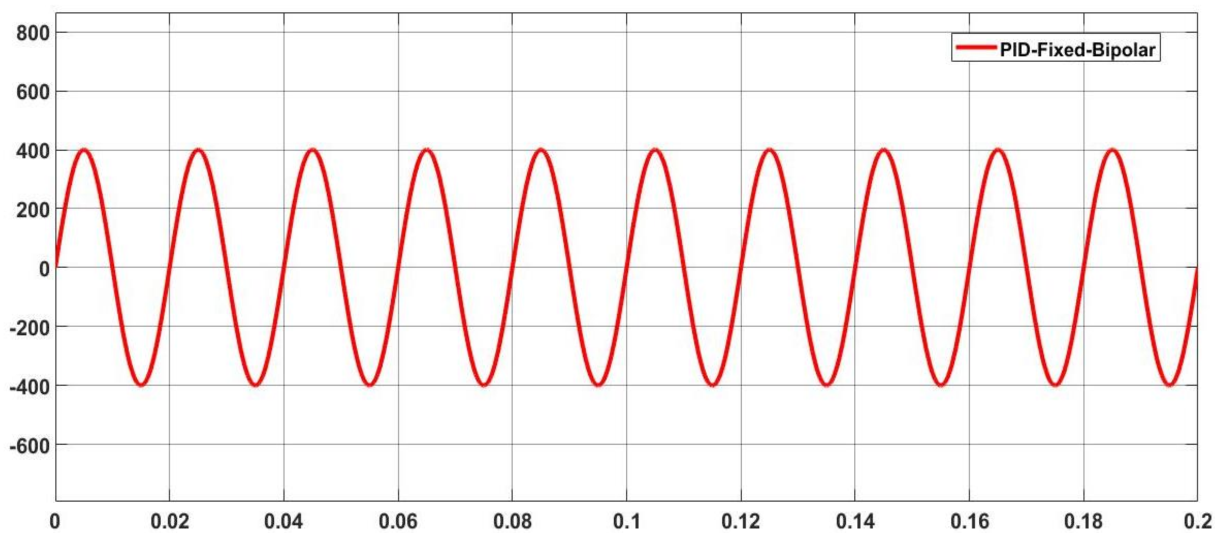

Fig 6.13. Output Waveshape of PID Controller-based Inverter for Bipolar PWM for Fixed Voltage

From the FFT analysis in MATLAB, the THD is 0.02%. The reference voltage was kept constant at 400V and simulated for 0.1 seconds

Fig 6.14. FFT Analysis of PID Controller-based Inverter for Bipolar PWM for Fixed Voltage

6.8 Performance observation of PID controller for Bipolar PWM for Variable Voltage

Trial and error gains from data set 13 are used to compare between THD for these different gains. The Table represents the gain values and THD for bipolar PWM technique for variable output voltage and simulated for 0.1 second using PID controller.

TABLE 6.8. THD value of PID controller-based Inverter using Trial and Error method for Bipolar PWM for Variable Voltage

Method	**Voltage Controller**			**Current Controller**			**THD With Variable voltage**
	K_P	K_I	K_D	K_P	K_I	K_D	
Trial and Error	0.3	14	70	11	19	100	16.01%

The output waveshape of the inverter (based on PID controller) using bipolar PWM technique is illustrated below

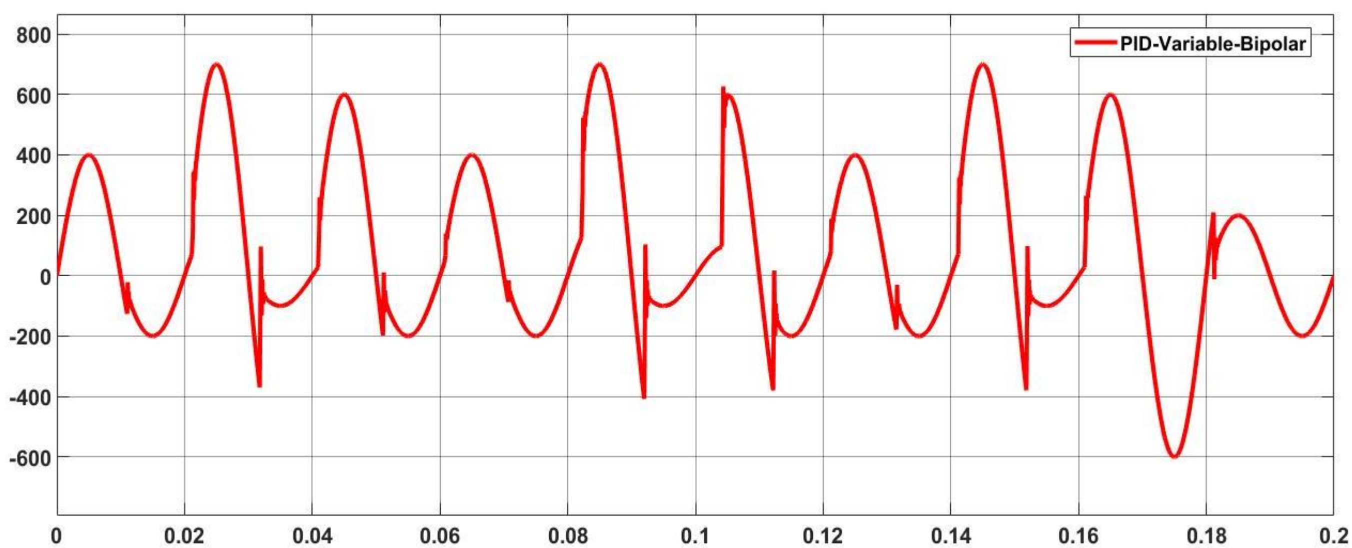

Fig 6.15. Output Waveshape of PID Controller-based Inverter for Bipolar PWM for Variable Voltage

From the FFT analysis in MATLAB, the THD is 16.01%. The reference voltage was changed several times and simulated for 0.1 seconds.

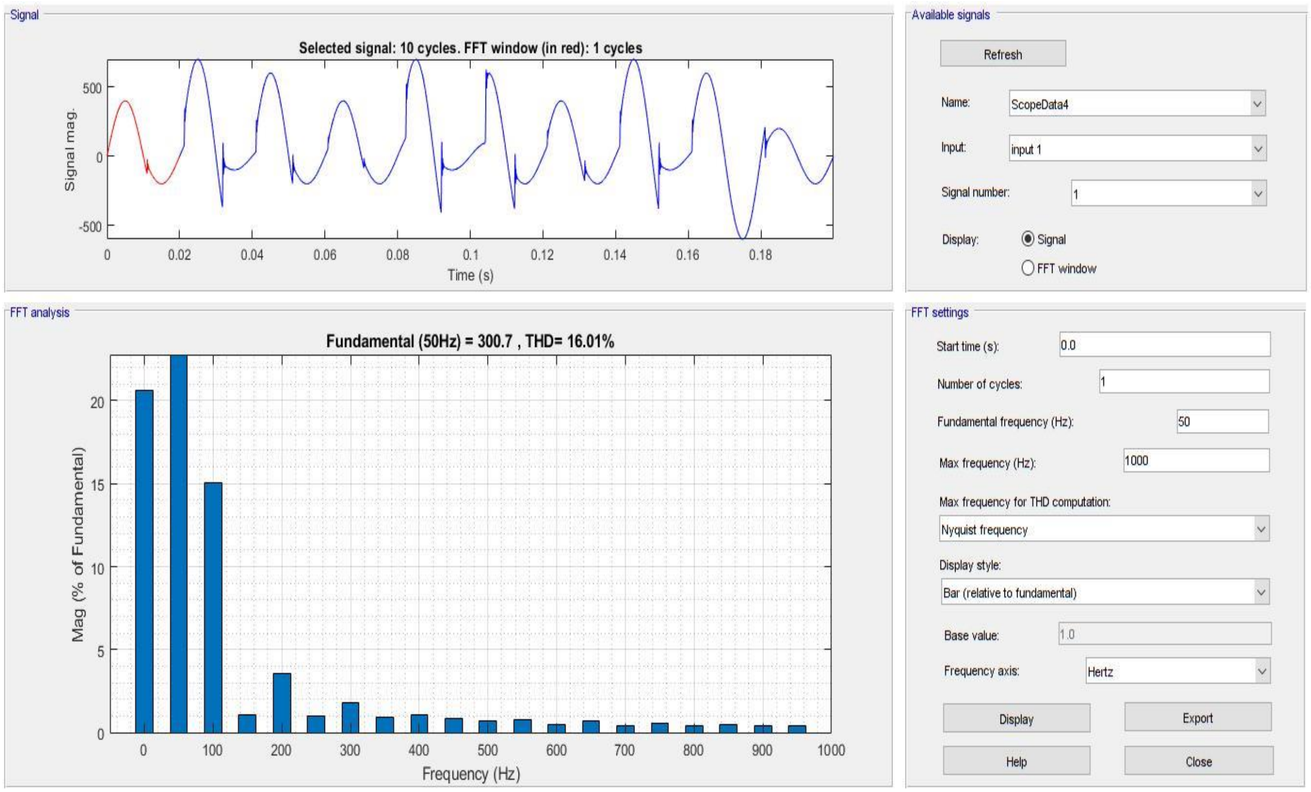

Fig 6.16. FFT Analysis of PID Controller-based Inverter for Bipolar PWM for Variable Voltage

6.9 Summary

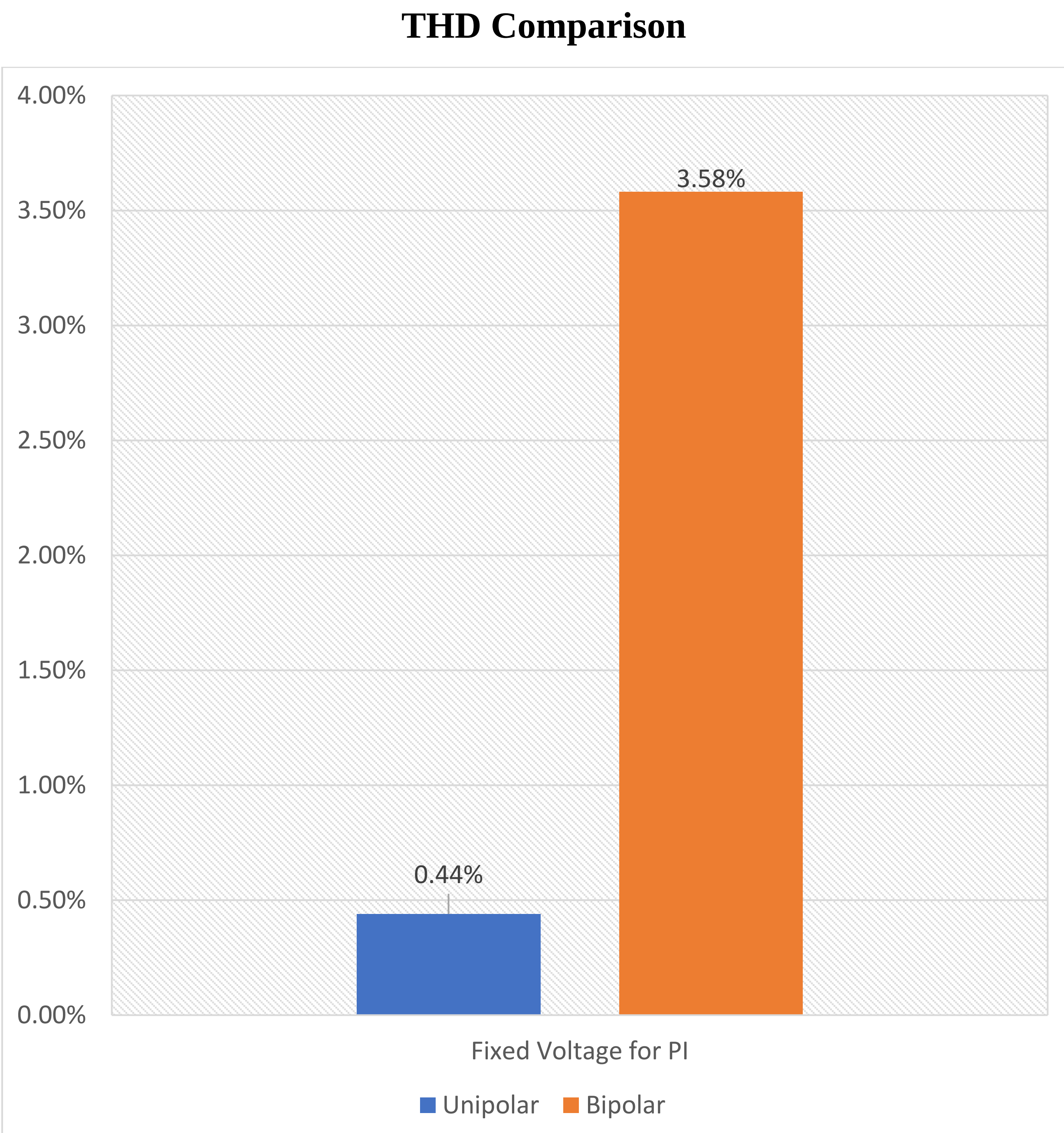

Fig 6.17. Bar Chart showing the Comparsion of THD between Unipolar and Bipolar PWM Technique for PI controller-based Inverter for Fixed Voltage

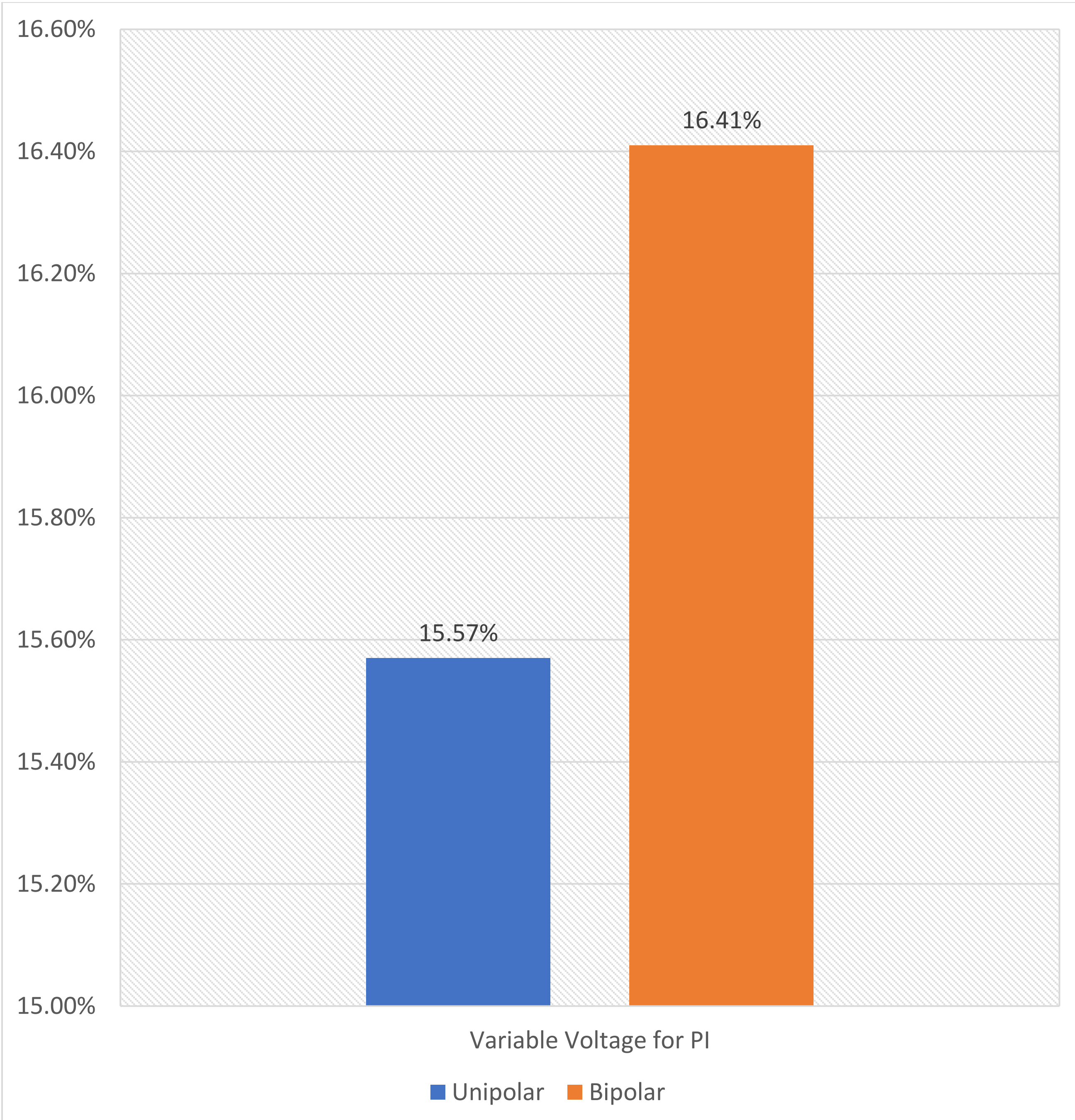

Fig 6.18. Bar Chart showing the Comparsion of THD between Unipolar and Bipolar PWM Technique for PI controller-based Inverter for Variable Voltage

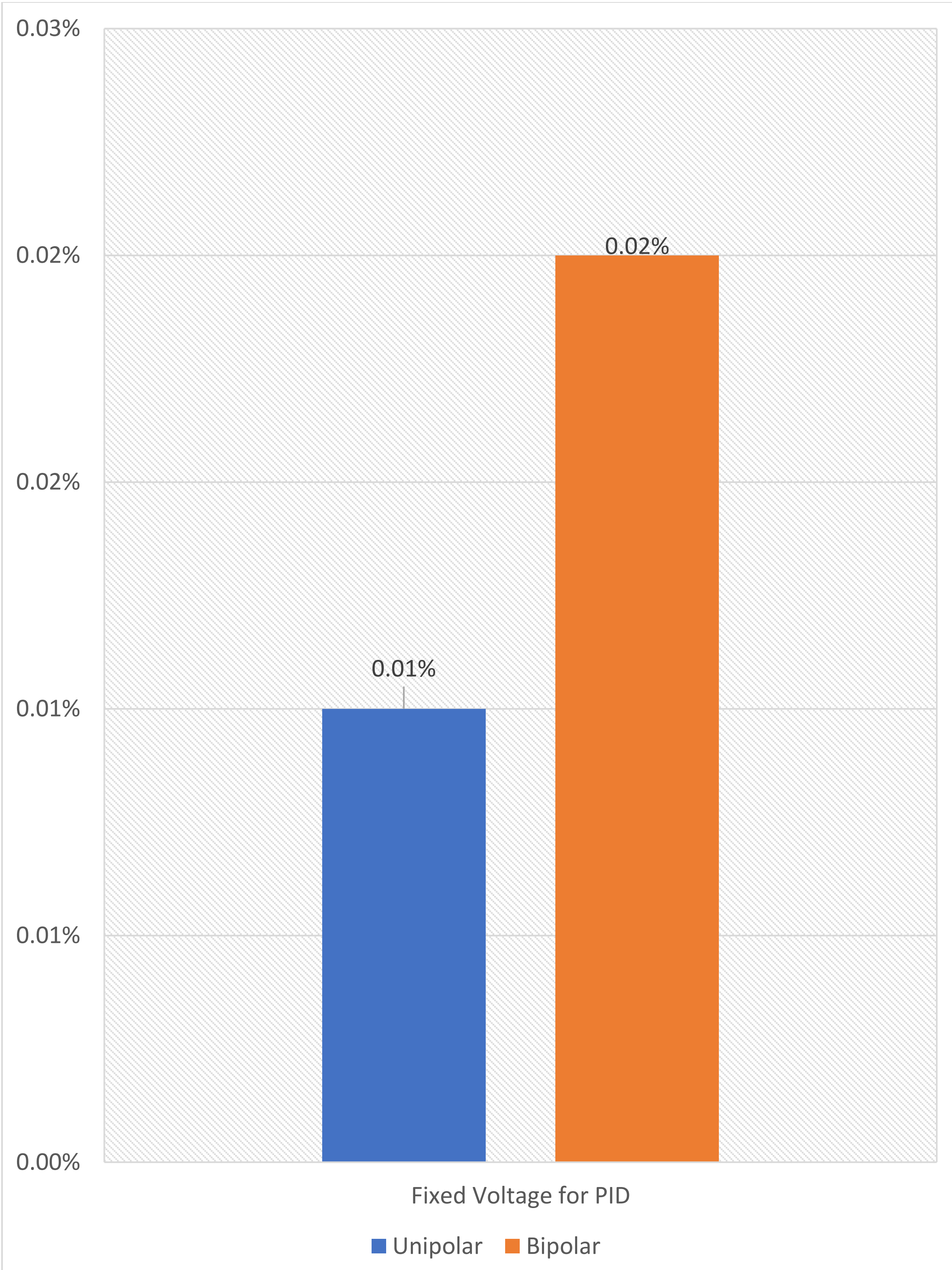

Fig 6.19. Bar Chart showing the Comparsion of THD between Unipolar and Bipolar PWM Technique for PID controller-based Inverter for Fixed Voltage

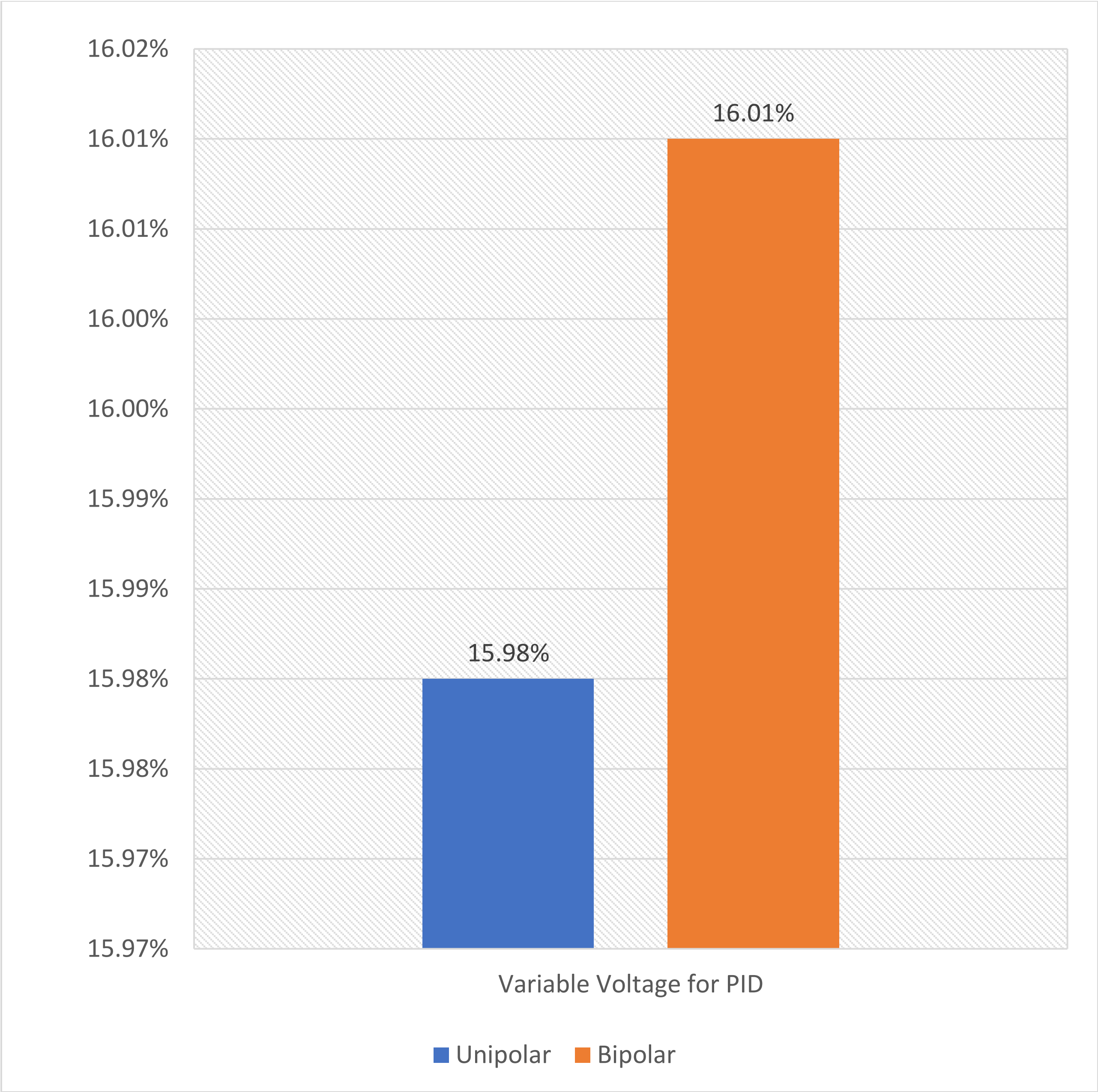

Fig 6.20. Bar Chart showing the Comparsion of THD between Unipolar and Bipolar PWM Technique for PID controller-based Inverter for Variable Voltage

CHAPTER VII

CONCLUSIONS AND FURTHER WORK

7.1 Conclusions

Our research work is based on power electronics which have a big role to play in our everyday lives. So, this make this research work very important and significant as we are working with inverters and its different control methods which has a wide application all around us. Thus, from our research work we have observed which control method gives better performance for single phase PWM inverter. Using this we can find out which method makes the system more efficient and reduces the overall total harmonic distortion. From our observation we can conclude that in case of system where the voltage remains fixed, PID controller works better than PI controller as PID reduces the total harmonic distortion significantly. As observed, we found out PI gave 0.45% of THD whereas PID gave only 0.01% of THD. However, in case of applications where the voltage keeps changing, PI controller performs better than PID as the total harmonic distortion was obtained lesser in PI (i.e., 50.85%) than PID (i.e., 52.41%) in case of variable voltage.

We also used different pulse width modulation techniques to observe the performance of inverter for each technique. Both unipolar and bipolar PWM technique was applied and it was found out that unipolar PWM resulted in better output waveshapes with less total harmonic distortion for both fixed and variable voltage, making the system more efficient and reliable. Unipolar PWM gave only 0.44% of THD for fixed voltage compared to bipolar PWM that gave a much higher THD of 3.58%. In case of variable voltage, unipolar gave 15.57% of THD as compared to bipolar that gave a higher THD of 16.41%.

7.2 Further Work

This topic has a lot of prospects to be considered as our future work. Optimisation algorithm can be used to obtain more accurate gain values that would give even better performance of the single phase inverter and reduce the THD values even more. As here we only found out the gain values using PID tuner or the trial and error method, using different optimisation algorithms can lead to even better gain values. Also, different filters can be designed that would suit a particuar system to reduce the total harmonic distortion. Finally, here we used only unipolar and bipolar PWM techniques, but other PWM techniques can also be applied like the sinusoidal PWM, multiple PWM, Space Vector PWM etc. All these may contribute in different ways to improve the system and make it more efficient.

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