Design and Simulation of a Sine Wave Inverter with PID Control for Nonlinear Load Applications

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ABSTRACT: DC to AC Converters generate discrete output wave forms. Mostly, neither the voltage nor the current have the desired wave forms and also produce harmonic, power losses and high frequency noise. The non-sinusoidal wave form will make the electronic equipment to burn early. The loss of power will make the system uneconomical. All this include the poor performance of the existing DC to AC converters. In this paper, pure sine wave with voltage control for nonlinear load applications is presented for single phase full bridge inverter. PWM (Pulse Width Modulation) technique is used to control voltage while pure sine wave obtained by using two techniques one is through band pass filter (as high value inductor are rarely available and also difficult to build thus combination of high pass and low pass filter used) at output and other is by DAC (Digital to Analog Conversion). Moreover, the proposed controller used for output voltage control is PID. It works as voltage controller for inverter control to eliminate the steady state error under heavy load applications. The better sine wave output and reduce steady state error will make this inverter both efficient and economical in terms of energy savings. The experimental results verify the simulation results obtained using Matlab® Simulink and Proteus®.

KEYWORDS: Converters, harmonics, frequency, noise, band pass filter, DAC.

1 INTRODUCTION

Energy crises are of great consideration now-a-days. An inverter with reasonable rating and uniform output can be used to smoothly operate electrical and electronic machines. Majority of inverters available in market have square wave output. Lights and fans can only be operated with them while other electronic devices cannot, as they can damage them [14]. Commercially available sine wave inverters are very expensive and by analyzing the output wave, it is observed that it is not up to the mark as output waveform and voltage not remains constant under nonlinear load conditions. Quality of an inverter is known by the harmonic contents present in output waveform. An ideal inverter must have a fundamental harmonic component at the desired frequency. Square wave inverter contains odd harmonics from which fundamental harmonic component can be obtained by applying higher order filter. Higher order filters in terms of inductors are practically unrealizable, as its mathematical analysis becomes complex and gain of the system decreases drastically [6]. They are widely used for commercial and industrial use like home appliances. The basic design of an inverter [10, 11] involves rectification and inversion modes using bridge technique, PWM technique, converter or a transformer, output filter and a feedback loop for voltage regulation. Analysis of PWM full bridge inverter is explained in [12]. As our main focus was to regulate voltage for nonlinear load conditions, among different topologies like SPWN,SVPWM and many other for implementing sinewave inverter as discussed in [1], due to simple methodology and easy implementation we used two topologies for desired waveform, one is through band pass filter which allows a specific band of frequency and attenuates other frequencies [13], but due to nonlinear output under nonlinear load conditions, DAC (Digital to Analog Conversion) can be used as discussed in

[5]. In band pass filter we used combination of high and low pass filter due to constrains of inductor availability as discussed in [6]. After achieving pure sine wave, PID (Proportional Integral Derivative) is used for regulation of voltage under nonlinear load conditions by controlling PWM [3]. The prior research was on design and simulation of soft start inverter. Soft start inverter was based on variable frequency, to vary output of water pump so that stall current can be decreased. It was only used to power water pump so harmonics in output wave form were considered negligible as discussed in [2]. The process flow of prior methodology is shown in Figure 1. In next section prior methodology is briefly discussed and then in comparison the proposed revised methodology is presented in section 3. In following sections PWM implementation for voltage control and Sine wave generation with PID control of output voltage is explained.
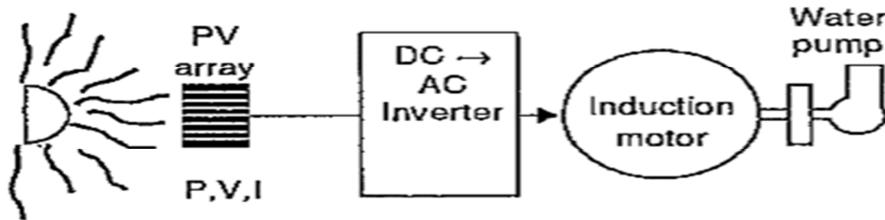

Figure 1: Process flow of the System [2]

2 PRIOR METHODOLOGY

The prior research was based on renewable energy resources in which PV module were used as backup module. The Arduino controller was used to switch H-bridge module operated without feedback. Due to open loop the final output voltage varies between 200-240 AC Volts as backup module voltage varies. Moreover, the output of inverter was step with harmonics, power losses and high frequency noise. The hardware output is shown in Figure 2. This prior designed model was dealing with solar powered submersible pump. Among many available schemes, it consists of a PV panel, a storing backup, a variable-frequency inverter, a charge controller and induction motor coupled with a water pump. The inverter drives the induction motor, which drives the water pump. To obtain maximum output power of the Solar panel, the inverter operated at variable frequency or soft start to minimize stall current of induction motor [2]. As the main aim of project was to control frequency so that output wave form was not given so much importance. Although the output was roughly equal to square wave in Simulink® simulation as shown in Figure 3 [3]. The same concept was applied on hardware to drive simple 1hp pump as in case of inductive loads we can ignore harmonics. The output of hardware is shown in Figure 4 which is also square wave.
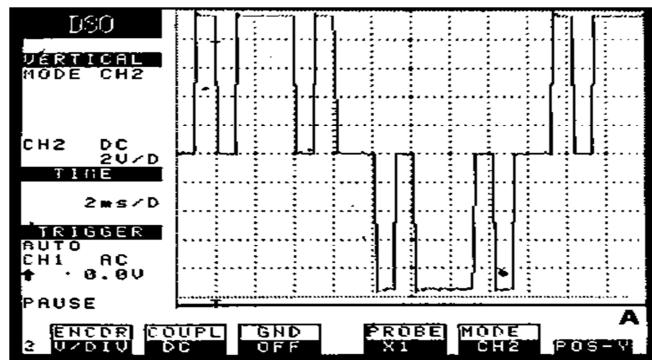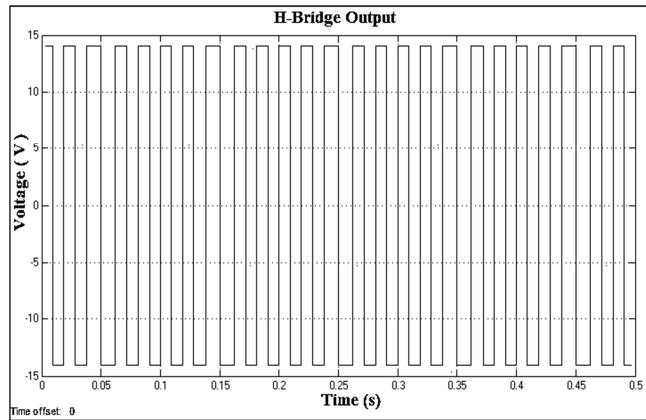

Figure 2: Output response of VFD kit at 20 Hz [4]

Figure 3: Simulink DC-AC Inverter Bridge output at 60 Hz
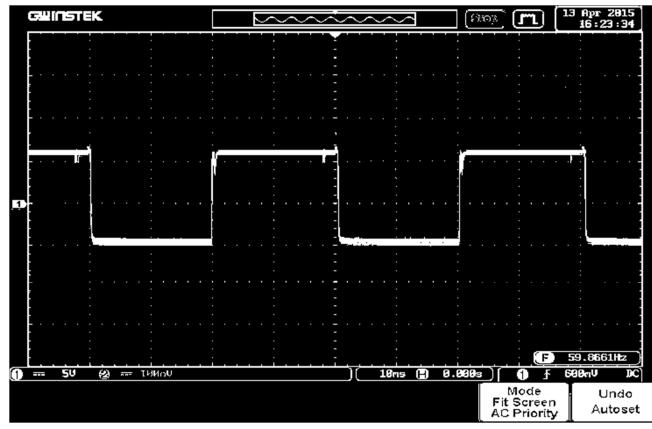

Figure 4: Hardware DC-AC Inverter Bridge output at 60 Hz

For simulation of DC-AC bridge Inverter in Simulink® 12V dc battery and four IGBT's (Insulated Gate Bipolar Transistor) were used for full H-bridge circuit. Gate pulse was generated by PWM generator. A linear transformer was used for inductive load. Simulink® model of simple inverter is shown in Figure 5.
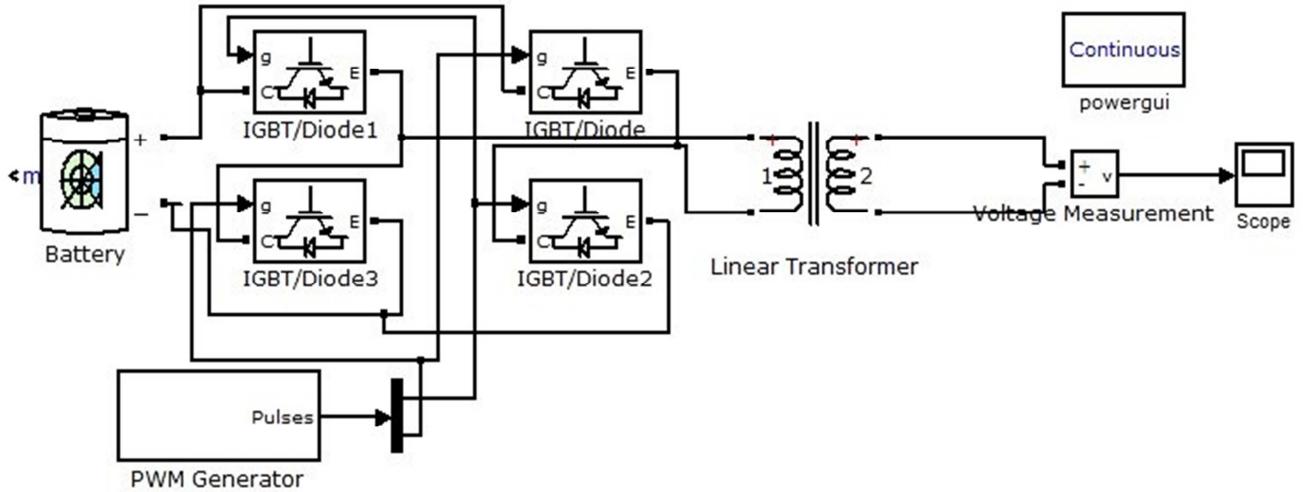

Figure 5: Simulink Model for DC-AC Bridge Inverter

Figure 6 shows process flow of DC-AC bridge inverter .12 Volt DC from battery is given to SG3525 oscillator circuit which converts it into 220V AC to power Variable frequency drive (VFD) module. VFD module through Arduino UNO R3 controller is used to control PWM of full H-bridge with variable frequency from 5Hz to 50Hz.75N75 MOSFET is used because of fast

switching speed, high current rating and also economical. The output is then fed into 1200 watt FET module in which six pairs of 75N75 MOSFETs are connected in parallel to increase wattage, each pair gives 250 watts. In last before output a step-up transformer step up the voltage from 12V to 220V AC [4].
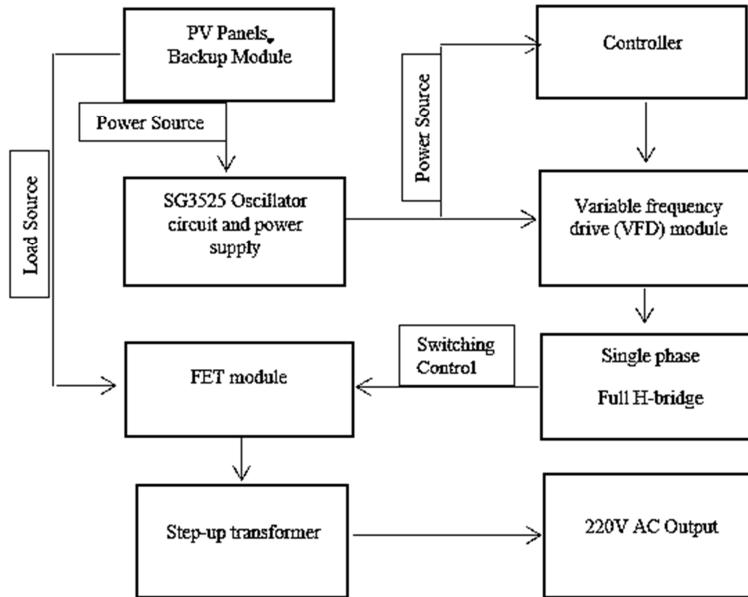

Figure 6: Process flow of DC-AC Bridge Inverter [4]

3   REVISED METHODOLOGY

In revised model the square wave was modified to pure sine wave [16] by using two topologies, band pass filter [6] and DAC [5]. To keep output voltage constant PID controller is used as voltage controller. In designed model backup module is used to give voltage to FET module, Full H-bridge and Controller. PID is used to control voltage of H-bridge by PWM. If voltage vary due to nonlinear load condition or backup module but output voltage must remain constant to specified set point by varying PWM controlled by PID [6]. Figure 7 shows process flow of inverter .12 Volt DC from battery is given to VFD (Variable Frequency Drive) [4] and full H-bridge module. Arduino UNO R3 controller is used to control full H-bridge. IGBT are used because of fast switching speed and high current rating. The output is then fed to band pass filter using high and low pass filter which connects to 1200 watt FET module in which six pairs of 75N75 MOSFETS are connected in parallel to increase wattage, each pair gives 250 watts. In last before output a step-up transformer step up the voltage from 12v to 220v AC. Full H-bridge output is also fed back to controller through ADC (Analog to Digital Conversion) and calibrating for PID control. PID varies PWM to control voltage amplitude [6].
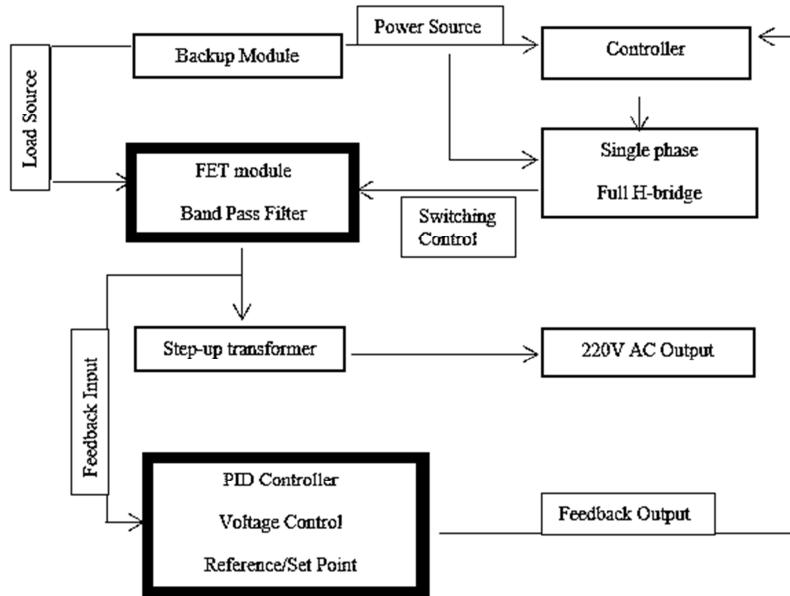
Figure 7: Revised Process flow of Inverter with PID Control

4 PWM FREQUENCY

Frequency of PWM is function of Clock frequency and Prescaler where 256 are the number of samples of ADC such that from 0 to 255.It is shown in equation (1)

$$f_{PWM} = \frac{f_{Clock}}{N \times 256} \qquad (1)$$

The frequency of the resulting wave is function of PWM frequency and number of Samples (N_S) as given by equation (2)

$$f_{WAVE} = \frac{f_{PWM}}{N_S} \qquad (2)$$

To change the frequency of the sine wave we can:

1. Change PWM frequency (set prescaler or system clock)
2. Change the number of samples

5 MODIFIED SINE WAVE

As shown in Figure 2&3 the output of DC to AC inverter with full H-bridge driver becomes square wave. It contains harmonics which need to be reduced for which we have proposed two methods DAC and Band Pass Filter. These methods [5, 13] are discussed below.

5.1 RESISTOR LADDER

Resistor ladder circuit is one of the way to perform digital to analog conversion (DAC). The most famous networks are the binary weighted ladder and the R/2R ladder. Both topologies will convert digital data in the form of voltage to analog, but the R/2R ladder is more reliable due to accuracy, inexpensive and ease of manufacture. Figure 8 is a diagram of the basic R/2R ladder network with N bits. The "ladder" portrayal comes from the ladder-like topology of the network [15].
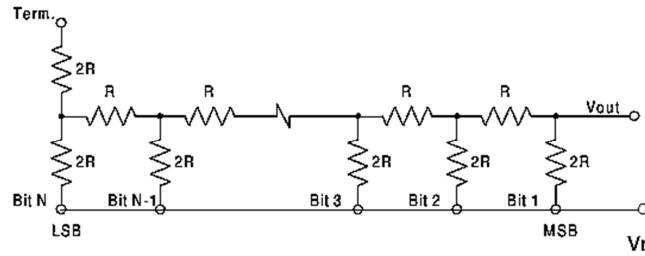
Figure 8: R/2R ladder network for DAC [15, 17]

If all bits connected to V_r, the full-scale output of the network approaches V_r as shown in equation (3) [15, 17].

$$V_r = \lim_{N \to \infty}(V_r) \sum_{i}^{N} \frac{1}{2^i} \qquad (3)$$

For a digital value VAL, of a R-2R DAC of N bits, the output voltage V_{out} [5] is:

$$V_{out} = V_{ref} \times VAL/2^N \qquad (4)$$

Where VAL is the step count between 0 to (2^N-1).

N is the number of input bits.

Practically the output of R/2R ladders is less than V_r, so maximum output of network was calculated using formula shown in equation (5). This equation is used to calculate the full-scale output of an R/2R ladder of N bits [15, 17].

$$Full\ Scale\ Output\ Voltage = V_r \sum_{i-1}^{N} \frac{1}{2^i} \qquad (5)$$

PWM was generated through DAC and hence sine wave was obtained by passing through low pass filters. Figure 9 shows output of DC to AC inverter through DAC [5] in software.
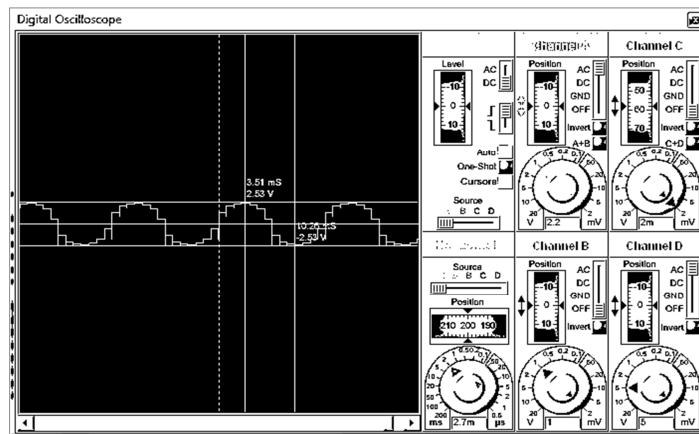

Figure 9: DC-AC Inverter output using DAC in Proteus

5.2   FILTERS

As discussed earlier Square wave or wave generated using DAC contains odd harmonics and it can be reduced by using band pass filters which allows a specific band of frequencies [9]. Higher order filters in terms of inductors are physically unrealizable as its mathematical analysis becomes complex and gain of the system decreases drastically [6]. To overcome this problem, we used combination of high and low pass filter in a way that high pass filter block lower frequencies while low pass filter block high frequencies [13]. In Figure 10 [13] dotted line shows low pass filter while continuous line as high pass filter.
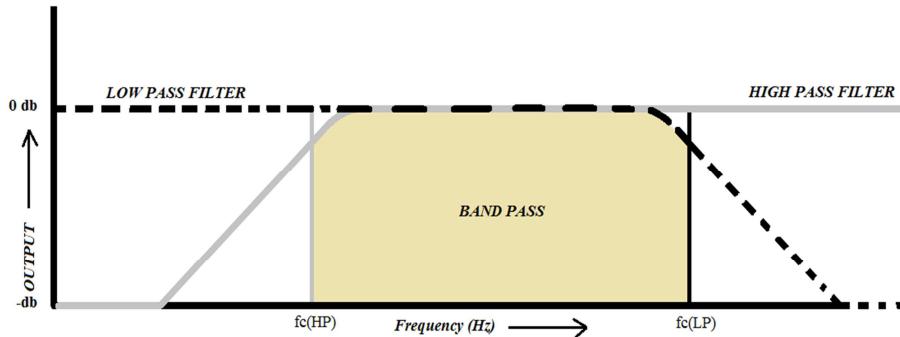
Figure 10: High and Low Pass Filter as Band Pass Filter

5.2.1 BAND PASS FILTER RESONANT FREQUENCY

The "Resonant" or "Centre Frequency" (**fr**) point of the band pass filter were the output gain at its maximum or peak value. It is in fact the "geometric" or mean value as shown in equation (6) [13].

$$f_r = \sqrt{f_L + f_H} \qquad (6)$$

Where, f_r is the resonant or centre frequency

f_L is the lower -3dB cut-off frequency point

f_H is the upper -3db cut-off frequency point

While doing the mathematical modeling of pure sine wave we have to come across certain parameters that includes:

A capacitors reactance (complex impedance) changes with frequency. A capacitors reactance decreases with increasing frequency, XC = 1/ (j2πfC). The filter passes or block frequency depending upon the calculated components. Good filter should generate smooth waves in desired frequency of sine wave. The equation (7) used for calculating component values.

$$f_{cuttoff} = \frac{1}{2\pi RC} \qquad (7)$$

The gain or frequency response of the low or high pass filter is given in equation (8)

$$V_{out}/V_{in} = \frac{1}{\sqrt{1 + (\omega RC)^2}} \qquad (8)$$

The phase of the output filter (output voltage with respect to the input voltage) is given in equation (9)

$$\varphi = -\tan^{-1} \omega RC \qquad (9)$$

Figure 11 shows Simulink model [8] of DC to AC inverter with band pass filter.
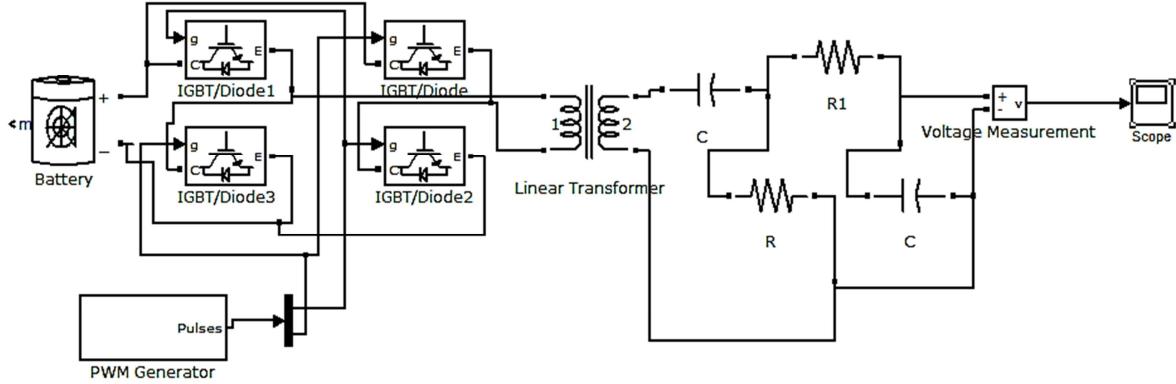
Figure 11: DC-AC Inverter with Band Pass Filter

As discussed in section 3 two methods to obtain sinewave, second is through bandpass filter discussed above.Figure 12 &13 [8] shows the output of DC to AC Inverter with band pass filter simulated on Simulink and verified on proteus before implementation.
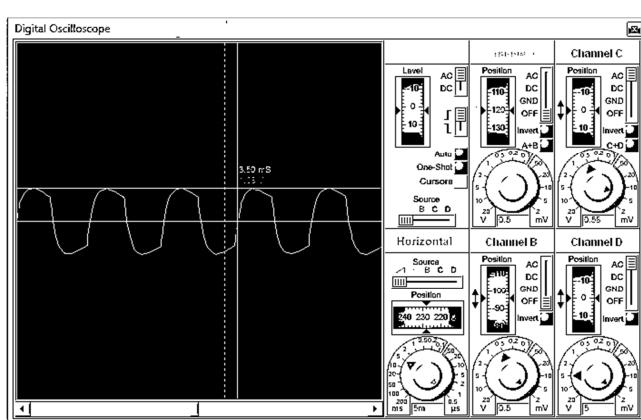

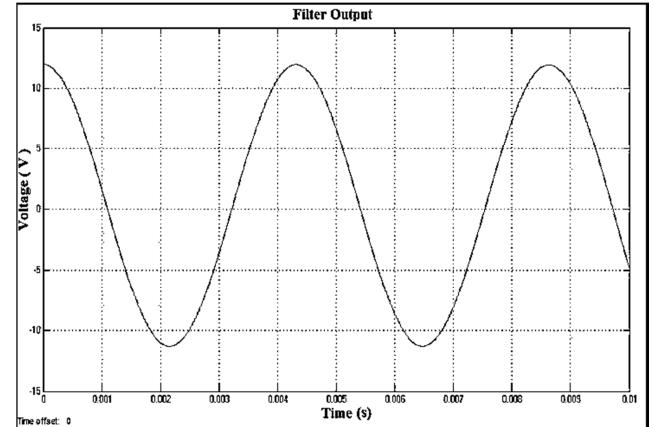*Figure 12: Output with Band Pass Filter on Proteus*

Figure 13: Output with Band Pass Filter

6 PID CONTROLLER

PID Controller (Proportional, Integral, and Differential) is a control method that tries to adjust for characteristics in system. There are three essential components to consider in a PID control algorithm. Each component is prefixed with a gain constant, and when added together, give us the instantaneous control value. Typically, control system is used to control voltage so every component can be considered as contributing a specific voltage to final output. We have voltage component to control that is called a ``Process Variable'' or *PV*. The *PV* is the value used by PID control to tell current state of the system. *SP* is a set point voltage, the value we want *PV* to attain. Actually, we want PID loop to control system so that *SP* and *PV* becomes equal. *u* is a control voltage, which relates to the instantaneous voltage using towards its *SP* voltage.

The closed loop PID control shown in Figure 14 and PID algorithm in Equation (8).

$$U(t) = K_p e(t) + K_i \int_0^t e(\tau) d(\tau) + K_d \frac{d}{dt} e(t) \qquad (8)$$
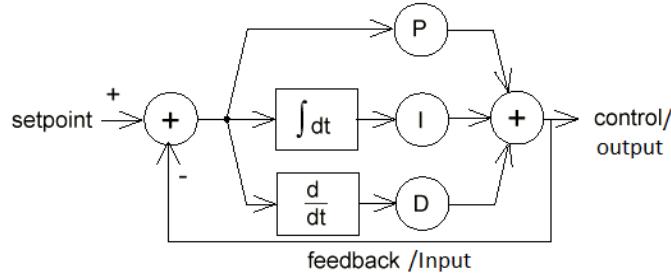
Figure 14: PID Controller (Proportional, Integral, Differential)

There is a proportional, integral and differential part in Equation (8). The constants Kp, Ki, and Kd (2,5,1) are used to set the sign and contribution gain of each part of this equation. e (t) is our proportional "error" compared to *SP*. t variable is the current time in system. Proportional portion corresponds to how far away our *PV* is from our *SP*. The differential part corresponds to abrupt change that is measure of over shoot and if used can reduce the proportional portion, or speed us up if we are experiencing resistance despite our proportional contribution. The integral part corresponds to how long we have been off of the set point. Figure 15 [3] shows the output of DC to AC inverter varying voltage without PID control.
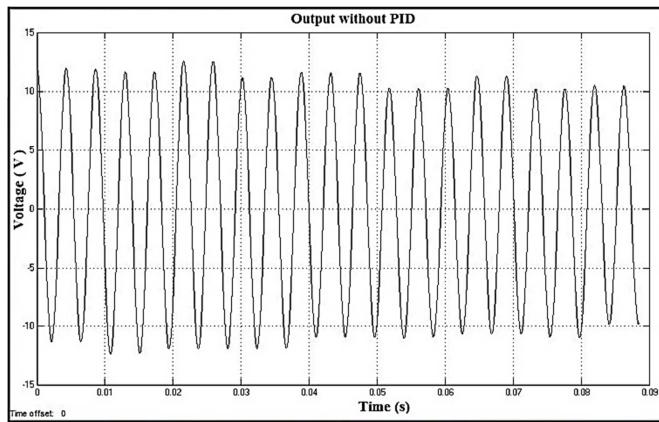

Figure 15: DC to AC Inverter output without PID Control

6.1   CONTROLLING WITH PID

Composing one's own PID control algorithm isn't that difficult, but there are a lot of elements to consider. A good way to begin is with an existing library, set of tools written by manufacturer can be utilized. So we have used an Arduino library of PID control. PID Arduino library and PID Auto tune library were used to control PWM. The desired set point or reference point was given while gain parameters were calculated by PID Auto tune. Figure 16 shows PWM control using PID in Arduino with Channel C as input and Channel D as Output. Figure 17 shows Input, Output and Gain Parameters of PID on virtual terminal of Proteus[®].
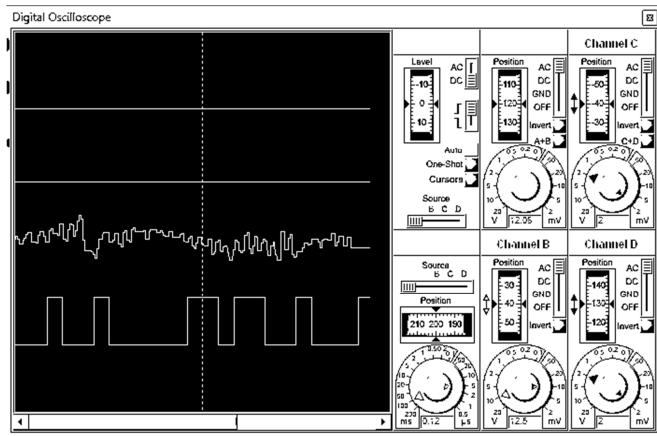
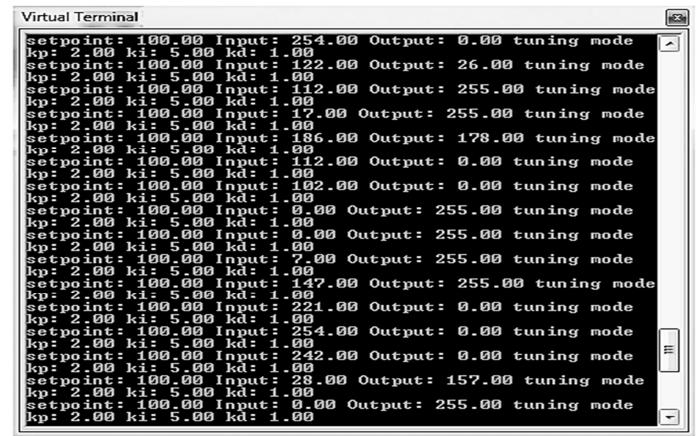*Figure 16: PID as Voltage Control using PWM in Arduino*

Figure 17: PID parameters with Input and Output on virtual terminal of Proteus

Figure 18 [7] shows a simulation model of DC to AC inverter with PID as voltage control. Output voltage is used as feedback input in ADC and compared with reference voltage, difference is then compared with set point. In response PID is used to control PWM.
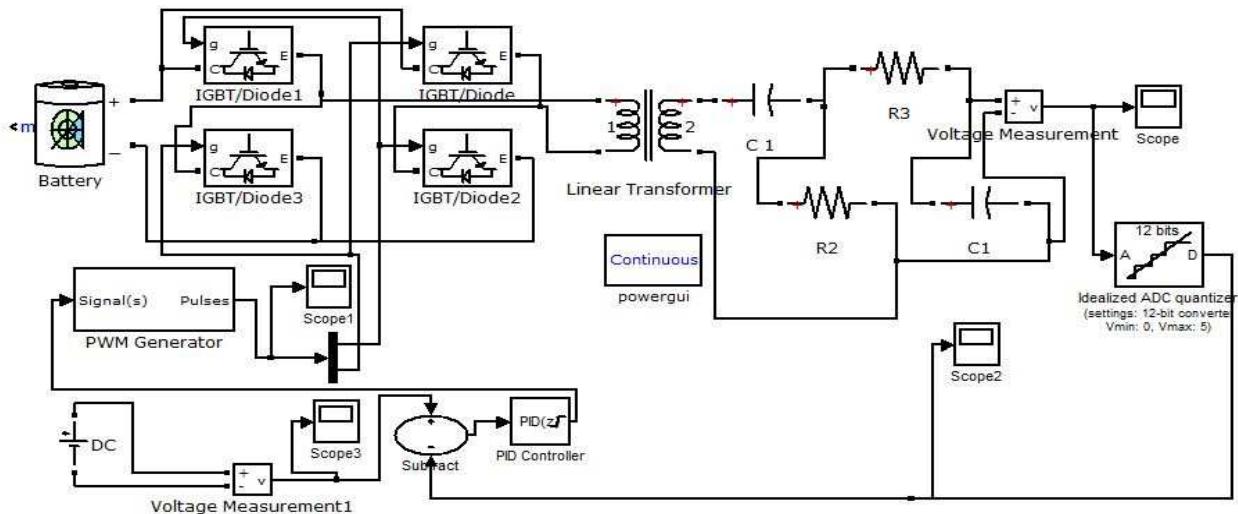

Figure 18: DC to AC Inverter with PID Voltage Control

With PID control amplitude of voltage becomes constant. Figure 19 [3] Shows DC to AC Inverter with PID voltage control output.
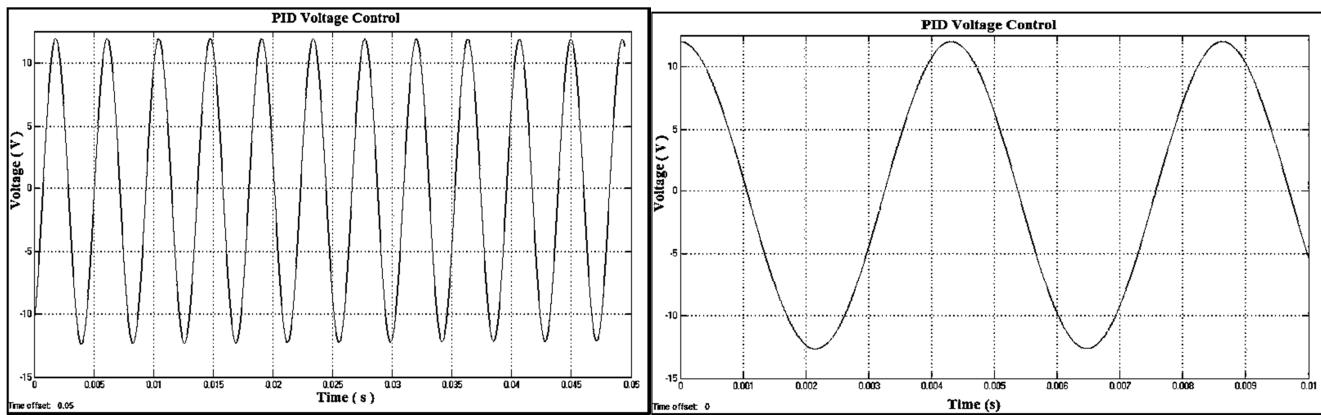
Figure 19: DC to AC Inverter with PID Voltage Control Simulink® Output

Mostly the desired model is restrained to simulation so an additional work was done with hardware implementation using arduino controller built in PID library.Figure 20 [3] shows DC to AC Inverter output with PID voltage control using arduino controller before step-up of 12V AC to 220V AC .
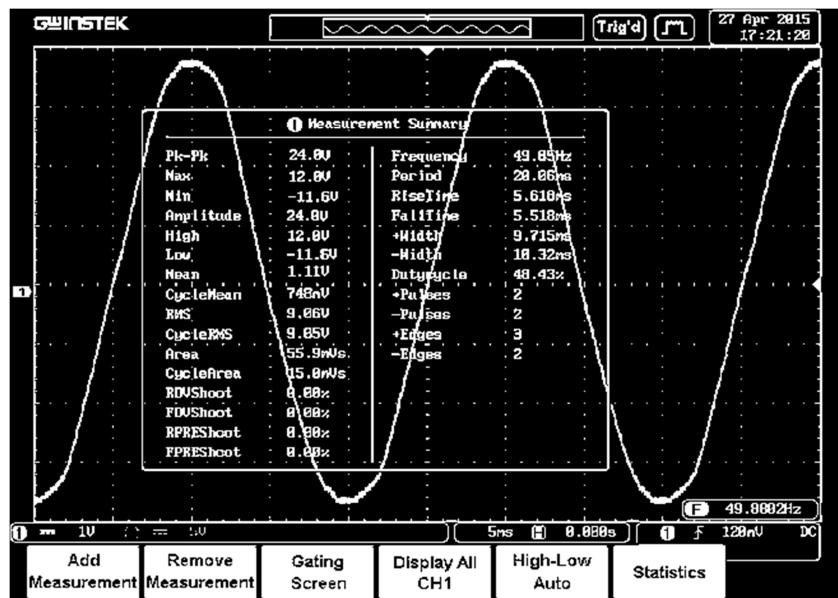

Figure 20: Hardware implementation of DC-AC Inverter with PID Voltage Control using Arduino

7   CONCLUSION

Output voltage of inverter was made constant for nonlinear load conditions using PID controller. Moreover, to obtain sine wave two methods DAC and band pass filter were used, as its results were satisfactory. Before hardware implementation desired model was simulated on Simulink® and verified on Proteus®, hence final results were satisfactory.

8   RECOMMENDATION

MOSFETS were used for DC to AC conversion due to cost constraint and can be replaced with IGBT (Insulated Gate Bipolar Transistor) to increase efficiency. Moreover, other types of controller like PIC can be used for switching purpose and fuzzy logic for voltage control.

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