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Analysis of Single-Phase SPWM Inverter

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Abstract: ***This project deals with studying the basic theory of a Sinusoidal Pulse Width Modulated Inverter (SPWM), its Simulink modeling, estimating various designing parameters and various instabilities. The project will be commenced by a basic understanding of the circuitry of the SPWM Inverter, the components used in its design and the reason for choosing such components in this circuitry. After this, it will be attempted to simulate a model circuit on any simulating software e.g. MATLAB and analyze the output waveforms for various values of the elements used in the circuit and hence study the system response and instabilities.***

Keywords: MATLAB/Simulink, SPWM, Inverter, Instabilities.

1. Introduction

An inverter is basically a device that converts electrical energy of DC form into that of AC. The purpose of DC-AC inverter is to take DC power from a battery source and converts it to AC. For example the household inverter receives DC supply from 12V or 24V battery and then inverter converts it to 240V AC with a desirable frequency of 50Hz or 60Hz. These DC-AC inverters have been widely used for industrial applications such as uninterruptible power supply (UPS), AC motor drives. Recently, the inverters are also playing an important role in various renewable energy applications as these are used for grid connection of Wind Energy System or Photovoltaic System. In addition to this, the control strategies used in the inverters are also similar to those in DC-DC converters. Both current-mode control and voltage-mode control are employed in practical applications. The DC-AC inverters usually operate on Pulse Width Modulation (PWM) technique. The PWM is a very advance and useful technique in which width of the Gate pulses are controlled by various mechanisms. PWM inverter is used to keep the output voltage of the inverter at the rated voltage(depending on the user's choice) irrespective of the output load. In a conventional inverter the output voltage changes according to the changes in the load. To nullify this effect of the changing loads, the PWM inverter correct the output voltage by changing the width of the pulses and the output AC depends on the switching frequency and pulse width which is adjusted according to the value of the load connected at the output so as to provide constant rated output. The inverters usually operate in a pulse width modulated (PWM) way and switch between different circuit topologies, which means that the inverter is a nonlinear, specifically piecewise smooth system. In addition to this, the control strategies used in the inverters are also similar to those in DC-DC converters. Both current-mode control and voltage-mode control are employed in practical applications. In the last decade, studies of complex behaviour in switching power converters have gained increasingly more attention from both the academic community and industry. Various kinds of nonlinear phenomena,3 such as bifurcation, chaos, border collision and coexisting attractors, have been revealed. Previous work has mainly focused on DC power supply systems including DC-DC converters and AC-DC power factor correction (PFC) converters.

2. Pulse Width Modulation (PWM)

The Pulse Width Modulation (PWM) is a technique which is characterized by the generation of constant amplitude pulse by modulating the pulse duration by modulating the duty cycle. Analog PWM control requires the generation of both reference and carrier signals that are feed into the comparator and based on some logical output, the final output is generated. The reference signal is the desired signal output maybe sinusoidal or square wave, while the carrier signal is either a sawtooth or triangular wave at a frequency significantly greater than the reference. There are various types of PWM techniques and so we get different output and the choice of the inverter depends on cost, noise and efficiency.

3. Basic PWM Techniques

There are three basic PWM techniques:
1. Single Pulse Width Modulation
2. Multiple Pulse Width Modulation
3. Sinusoidal Pulse Width Modulation

3.1 Single Pulse Width Modulation

In this modulation there is an only one output pulse per half cycle. The output is changed by varying the width of the pulses. The gating signals are generated by comparing a rectangular reference with a triangular reference. The frequency of the two signals is nearly equal.

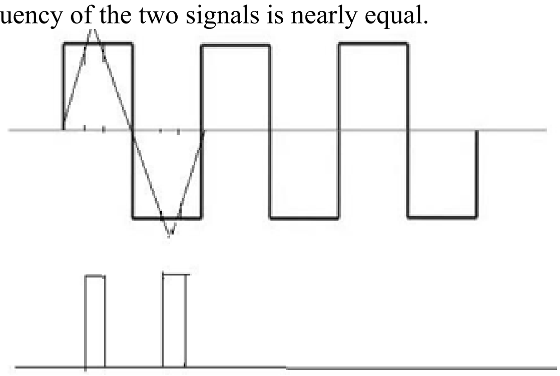

Figure 1: Single Pulse Width Modulation

The rms ac output voltage

$$Vo = Vs\sqrt{2t_{oN}/_{T}} = Vs\sqrt{2\delta}$$

Modulation Index (MI) $=\frac{Vr}{Vc}$

Where *Vr*= Reverence signal voltage
Vc= Carrier signal voltage

By varying the control signal amplitude *Vr* from 0 to *Vc* the pulse width ton can be modified from 0 secs to T/2 secs and the rms output voltage *Vo* from 0 to *Vs*.

Features for comparing various PWM Techniques

- Switching Losses
- Utilization of Dc power supply that is to deliver a higher output voltage with the same DC supply
- Linearity in voltage and current control
- Harmonics contents in the voltage and current

3.2 Inverter Types

There are generally three types of inverter for general purpose

- Square Wave Inverter
- Modified Square Wave Inverter
- True Sine Wave Inverter

3.2.1 Square Wave Inverter

This is the basic type of inverter. Its output is a alternating square wave. The harmonic content in this wave is very large. This inverter is not efficient and can give serious damage to some of the electronic equipment. But due to low cost, it has some limited number of applications in household appliances.

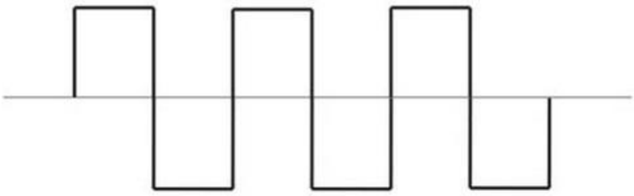

Figure 2: Square Wave Inverter Output

3.2.2Modified Square Wave Inverter

A modified sine wave inverter actually has a waveform more like a square wave, but with an extra step or so. Because the modified sine wave is noisier and rougher than a pure sine wave, clocks and timers may run faster or not work at all. A modified sine wave inverter will work fine with most equipment, although the efficiency or power will be reduced with some. But with most of the household appliances it works well.

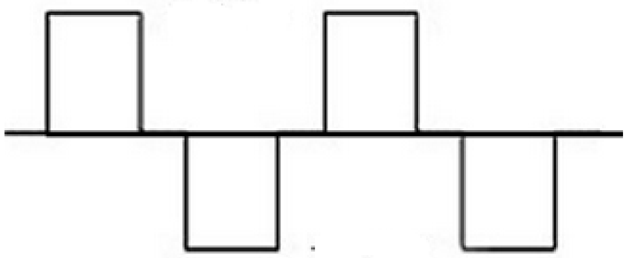

Figure 3: Modified Square Wave Inverter Output

3.2.3True Sine Wave Inverter

This type of inverter provides output voltage waveform which is very similar to the voltage waveform that is received from the Grid. The sine wave has very little harmonic distortion resulting in a very „clean" supply and makes it ideal for running electronic systems such as computers, digital fx racks and other sensitive equipment without causing problems or noise. Things like mains battery chargers also run better on pure sine wave converters.

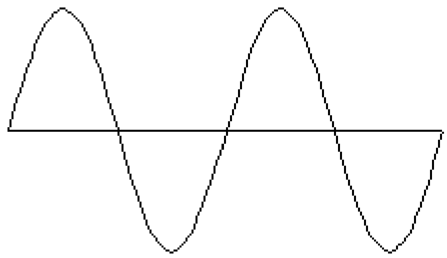

Figure 4: True Sine Wave Inverter

Benefits of using True Sine Wave Inverter:

- Most of the electrical and electronic equipments are designed for the sine wave.
- Some appliances such as variable motor, refrigerator, microwave will not be able to provide rated output without sine wave.
- Electronic clocks are designed for the sine wave.
- Harmonic content is less.

3.3Sine Wave Generation

The most common and popular technique for generating True sine Wave is Pulse Width Modulation (PWM). Sinusoidal Pulse Width Modulation is the best technique for this. This PWM technique involves generation of a digital waveform, for which the duty cycle can be modulated in such a way so that the average voltage waveform corresponds to a pure sine wave. The simplest way of producing the SPWM signal is through comparing a low power sine wave reference with a high frequency triangular wave. This SPWM signal can be used to control switches. Through an LC filter, the output of Full Wave Bridge Inverter with SPWM signal will generate a wave approximately 13 equal to a sine wave. This technique produces a much more similar AC waveform than that of others. The primary harmonic is still present and there is relatively high amount of higher level harmonics in the signal.

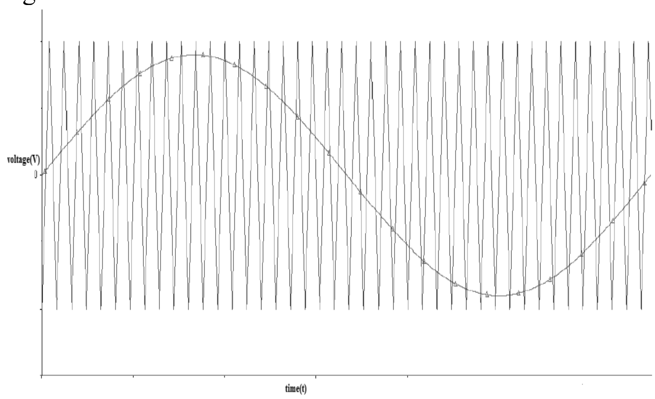

Figure 5: SPWM comparison Signals

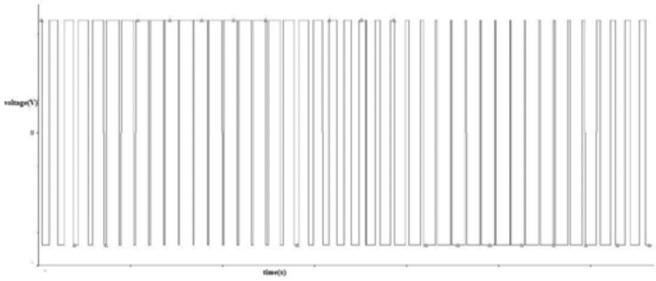

Figure 6: Unfiltered SPWM output

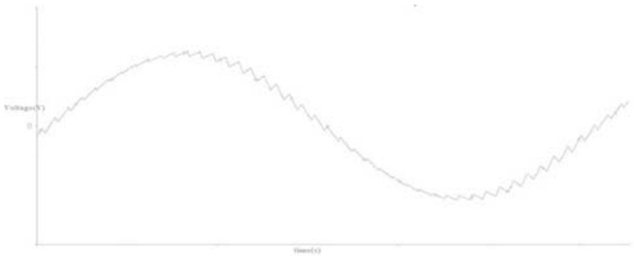

Figure 7: Filtered SPWM Output

4. SPWM Harmonic Elimination

The SPWM waveform has harmonics of several orders in the phase voltage waveform , the dominant ones are the fundamental and other of order of n and n±2 where n=fc/fm. With the method of Selective Harmonic Elimination, only selected harmonics are eliminated with the smallest number of switching. For a single phase-SPWM waveform with odd and half wave symmetry and n chops per cycle as shown in figure 2.

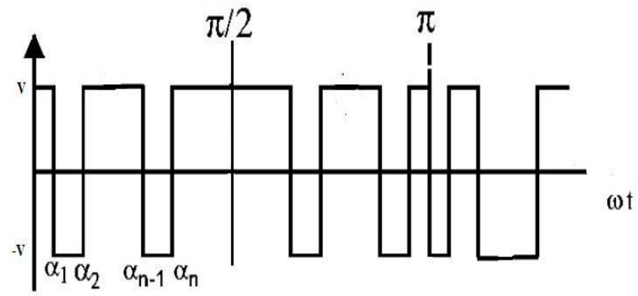

Figure 8: SPWM wave with odd and half wave symmetry

The Fourier coefficients of the waveform shown in the above figure can be given by

$$h1 = \left(4\frac{V}{\pi}\right)[1 - 2\cos\alpha 1 + 2\cos\alpha 2 - 2\cos\alpha 3 + \cdots 2\cos\alpha n]. h3$$

$$= \left(4\frac{V}{3\pi}\right)[1 - 2\cos 3\alpha 1 + 2\cos 3\alpha 2 - 2\cos 3\alpha 3 + \cdots 2\cos 3\alpha n]. \quad hn$$

$$= \left(4\frac{V}{n\pi}\right)[1 - 2n\cos\alpha 1 + 2n\cos\alpha 2 - 2n\cos\alpha 3 + \cdots 2n\cos\alpha n].$$

Where *hn* represents the magnitude of nth harmonic component and an is the primary switching Angle *n* is the no of chops.

Advantages of SPWM:
- Low power consumption
- High energy efficient upto90%
- High power handling capability
- No temperature variation-and ageing-caused drifting or degradation in linearity
- Easy to implement and control
- Compatible with today's digital microprocessors

Disadvantages of SPWM
- Attenuation of the wanted fundamental component of the waveform
- Drastically increased switching frequencies that leads to greater stresses on associated switching devices and therefore derating of those devices
- Generation of high-frequency harmonic components

5. Methodology

Designing a single phase inverter for household purpose or UPS (Uninterruptible Power Supply) of rating 220V or 230V, the basic things we have to design are: LC Filter ,PI controller and we have to choose an appropriate step-up Transformer.

5.1 PI Control

Proportional Integral (PI) control in VSI provides superior control over traditional Pulse Width Modulation or Sinusoidal Pulse Width Modulation (SPWM). In order to obtain a smooth desirable 26 waveform at the output side, the switching frequency must be constant and should be independent of output frequency and this can be achieved by PI Control.

Advantages of PI Control:
- Fixed inverter switching frequency resulting in known harmonics
- Instantaneous control and wave shaping

5.2 PI Control Structure

When a load is connected to the inverter output. The output voltage at the load side is sensed by means sensors and it is feedback to a comparator or subtractor which compares this load output with the reference signal (desired signal) and it produces the voltage error signal. This instantaneous error is fed to a proportional-integral (PI) controller. The integral term in the PI controller improves the tracking by reducing the instantaneous error between the reference and the actual voltage. .The error is forced to remain within the range defined by the amplitude of the triangular waveform. The resulting error signal is compared with a triangular carrier signal and intersections decide the switching frequency and pulse width.

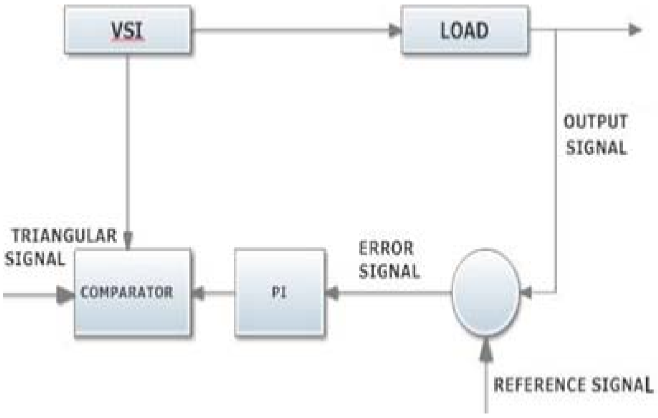

Figure 9: VSI PI Control

PI controller is a feedback controller which detects the error value which is the difference of the output signal and the desired or reference signal. PI controller works to minimise this error by controlling the system inputs. PI controller has two elements namely Proportional (P) and Integral (I). Proportional part reduces the error while Integral part reduces the offset. P depends on present error and I depends on past errors. So, step response of a system can be improved by using PI controller.

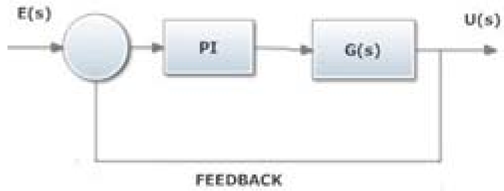

Figure 10: PI Control

Now PI element gains, Kp(proportional gain) and Ki(integral gain) should be tuned to obtain a better system response. The effect of each parameters value on increasing is given below

Table 1: PI Tuning

Response	Rise Time	Overshoot	Settling Time	Steady State Error
kp	Decrease	Increase	Minor change	Decrease
ki	Decrease	Increase	Increase	Eliminate

6. Results

6.1 Simulation Results

6.1.1 Simple Inverter (Simulink Model)

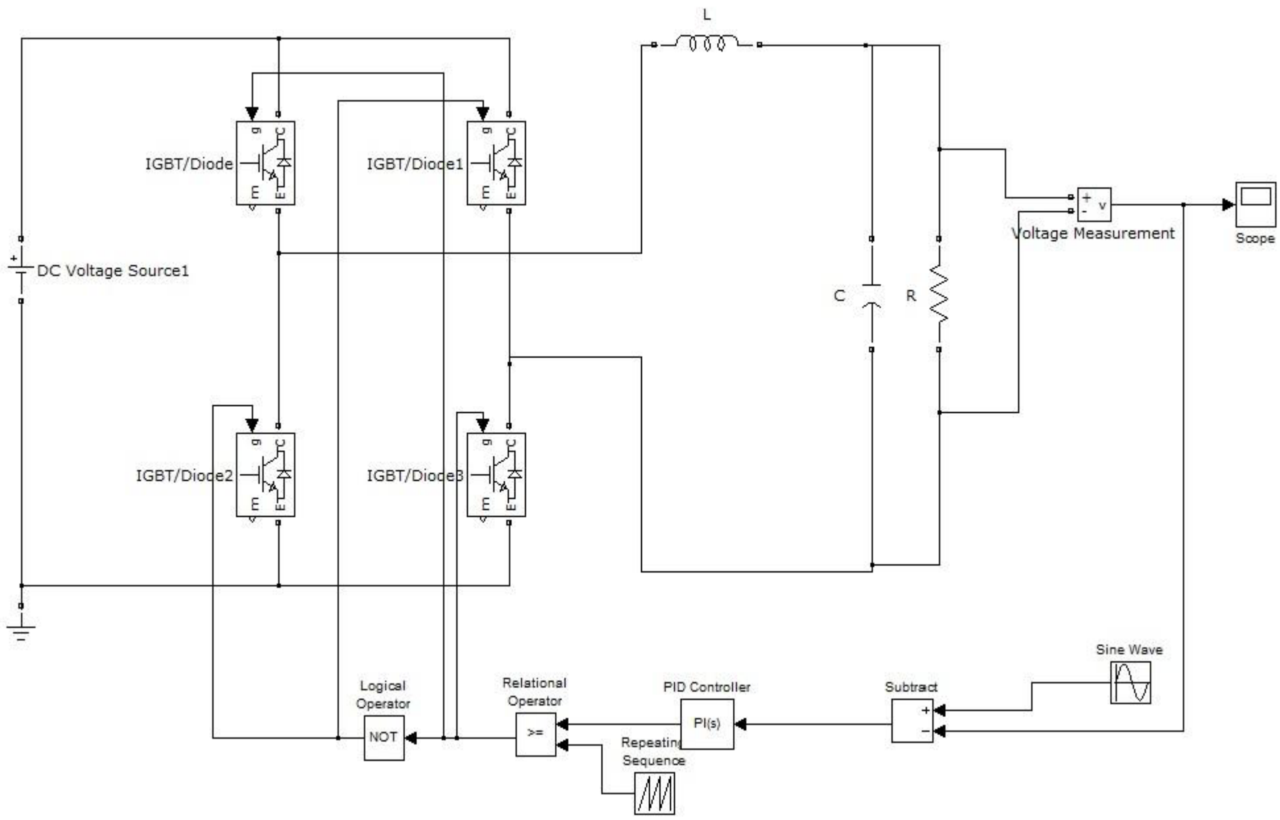

Figure 11: Simple inverter (simulink model)

(L= 100mH,C= 1000µF)

a) Voltage Waveform

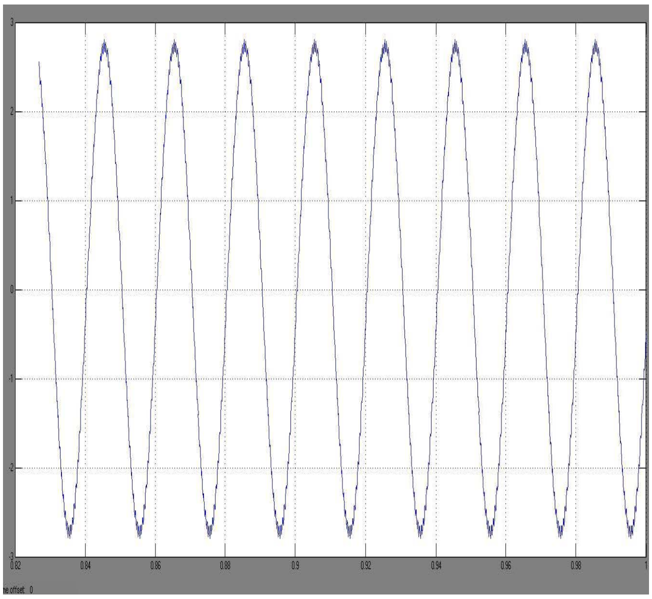

Figure 12: Voltage waveform

The voltage waveform obtained is nearly sinusoidal with little bit of distortions.

b) Current Waveform

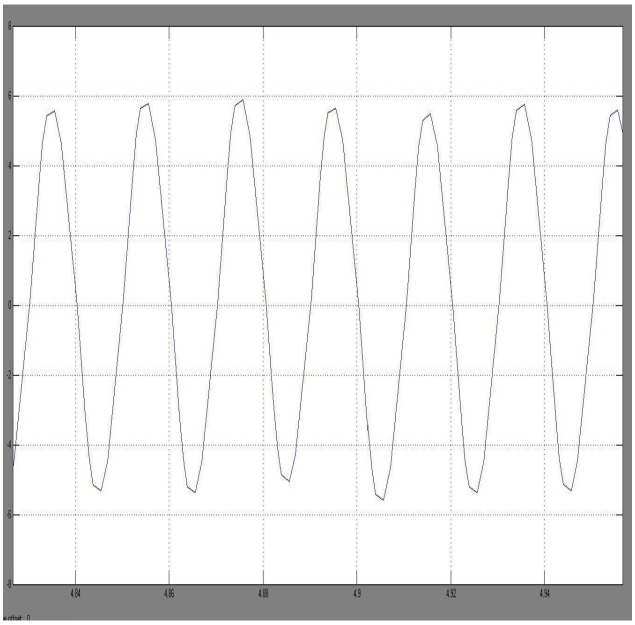

Figure 13: current Waveform

6.2 Practical Inverter (Simulink Model)

(vin=24V DC, Vout=220V AC)

(RL=1mΩ, L=152mH,Rc=10Ω,C=3200µF,R=1800Ω)

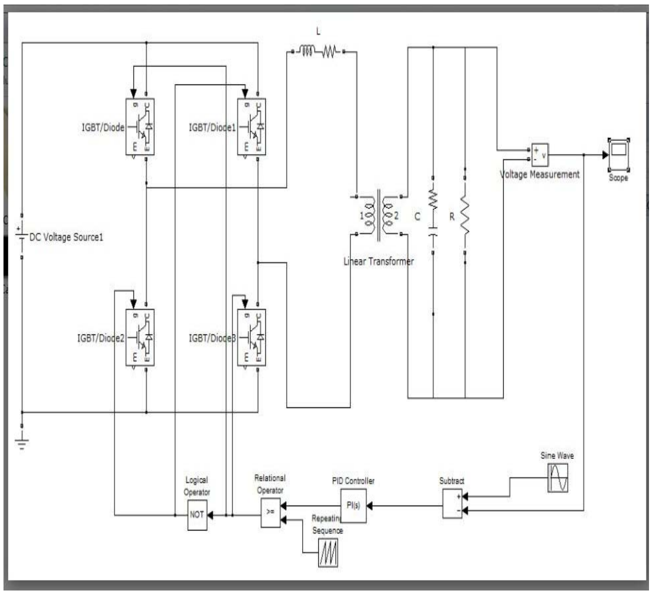

Figure 14: practical inverter (Simulink model)

a) Voltage Waveform

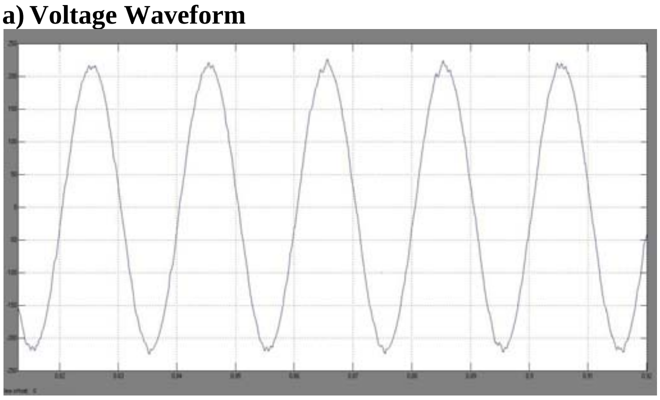

Figure 15: voltage Waveform

Inverter input is a 24V dc and the output is 220V AC. This inverter can be used for household appliances.

b) Current Waveform

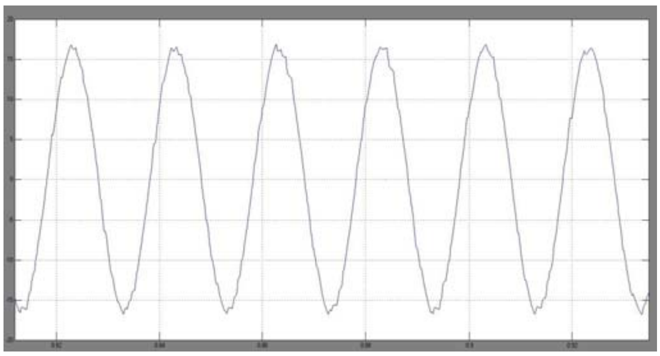

Figure 16: Current waveform

The current value depends on load and its waveform is also sinusoidal.

7. Conclusion

This paper deals with the analysis of Single Phase Sinusoidal Pulse Width Modulation (SPWM)-VSI. It includes both simple and practical SPWM-VSI. The Simulink model for both simple and practical inverter has been simulated in MATLAB. Its various parameters for PI controller and parasitic has been calculated for Simulink modeling and then simulated. These parameters are varied and the resulting voltage and current graphs has been studied.

8. Future Work

The future work includes improving the stability of the system and also to study various instability in SPWM-VSI with harmonic analysis and ways to eliminate it and to design an actual household SPWM-VSI with a better controller design.

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