

# **End Semester Report**

## **Study and Analysis of Three Phase SPWM Inverter**

*Bachelor of Technology* in Electrical Engineering

By

Shiladitya Saha – 108EE065

Gaurav Agarwal – 108EE068

Kundan Kumar – 108EE081

Under supervision of

**Prof. Somnath Maity**



Department of Electrical Engineering

National Institute of Technology, Rourkela

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**National Institute Of Technology**

**Rourkela**

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**CERTIFICATE**

This is to certify that the work on the thesis entitled “**Analysis of Three phase SPWM Inverter**” has been jointly done by **Shiladitya Saha, Gaurav Agarwal and Kundan Kumar, Electrical Engineering** in partial fulfillment for the degree of **Bachelor Of Technology** embodies the bonafide work done by them in the final year of their degree under the supervision of the undersigned. The thesis or any part of it has not been submitted earlier to any other University or Institute for the award of any Degree or Diploma.

**Prof. Somnath Maity**

**Department of Electrical Engineering**

**National Institute of Technology**

**Rourkela 769008**

## ***Abstract***

This project deals with study of a Sinusoidal Pulse Width Modulated Inverter and all the parameters used to reduce the harmonics and give the good efficiency of the inverter. 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. Generally, only single phase SPWM inverters are used industrially, and certain instabilities have been found in their operation. With improper selection of system parameters, the inverter suffers different type of instabilities and many types of harmonics. Our attempt will be to observe the same for three phase SPWM inverter and analyze its parameters used to get a pure sinusoidal output waveform and fewer harmonic in its output current and voltage waveform. 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 observe the waveform distortion.

## *Acknowledgements*

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## ***CHAPTER I: Introduction***

What if we cannot use the stored power in a battery when we don't have power supply. Since the energy stored in a battery is in dc form so to use this stored power in battery we need to convert this dc form of energy to ac form. So here comes the concept of power inverters. The devices which can convert electrical energy of DC form into AC form is known as power inverters. They come in all sizes and shapes, from a high power rating to a very low power rating, from low power functions like powering a car radio to that of backing up a building in case of power outage. Inverters can come in many different varieties, differing in power, efficiency, price and purpose. The purpose of a DC/AC power inverter is typically to take DC power supplied by a battery, such as a 12 volt car battery, and transform it into a 120 volt AC power source operating at 60 Hz, emulating the power available at an ordinary household electrical outlet.

DC-AC inverters have been widely used in industrial applications such as uninterruptible power supplies, static frequency changes and AC motor drives. Recently, the inverters are also playing important roles in renewable energy applications as they are used to link a photovoltaic or wind system to a power grid. Like DC-DC converters, the DC-AC inverters usually operate in a pulse width modulated (PWM) way and switch between a few different circuit topologies, which means that the inverter is a nonlinear, specifically piecewise smooth system. In addition, the control strategies used in the inverters are also similar to those in DC-DC converters. For instance, current-mode control and voltage-mode control are usually employed in practical applications. In the last decade, studies of complex behavior in switching power converters have gained increasingly more attention from both the academic community and industry. Various kinds of nonlinear phenomena, 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.

## ***CHAPTER II: Background and Literature Review***

Devices that convert dc power to ac power are called inverters. The purpose of an inverter is to change a dc input voltage to ac output voltage which will be symmetric and will have desired magnitude and frequency. The output voltage can be varied by varying the input dc voltage and keeping constant inverter gain, however, if the input dc voltage is fixed and cannot be controlled, the gain of the inverter has to be varied to obtain variable output voltage. Varying the gain of the inverter is mainly done by a scheme which is known as Pulse Width Modulation (PWM). The inverter gain is basically the ratio of ac output voltage to the dc input voltage.

Based on the power supply, inverters can be broadly classified into two types: Voltage Source Inverter and Current Source Inverter. A VSI has small or negligible impedance at its input terminal that is, it has a stiff dc voltage source, whereas for a CSI, it is fed with adjustable current from a dc source with high impedance in this case. For the purpose of our project, all analysis throughout this paper has been done for Voltage Source Inverters (VSI). These can be classified into two types which are Single Phase Inverters and Three Phase Inverters. Either type can use controllable turn-on and turn-off devices e.g. BJTs, MOSFETs, IGBTs etc. Generally PWM control is used to obtain ac output voltage of desired frequency and magnitude.

### **2.1 Pulse Width Modulation control**

This is a method in which fixed dc input voltage is given to an inverter and the output is a controlled ac voltage. This is done by adjusting the on and off periods of the inverter components.

The advantages of PWM control are:



1. No additional components are required with this method.
2. Lower order harmonics are eliminated or minimised along with its output voltage control.

Hence, the filtering requirements are minimised since higher order harmonics can be filtered easily.

Different schemes of pulse-width modulation:

1. Single-pulse modulation
2. Multi-pulse modulation
3. Sinusoidal-pulse modulation

Since our project deals with Sinusoidal Pulse Width modulated Inverters, the basic concepts of Sinusoidal PWM are explained below.

In this method of modulation, several pulses per half cycle are used and the pulse width is a sinusoidal function of the angular position of the pulse in a cycle. A high frequency triangular carrier wave  $v_c$  is compared with a sinusoidal reference wave  $v_r$  of the desired frequency. The switching instants and commutation of the modulated pulse are determined by the intersection of  $v_c$  and  $v_r$  waves. The carrier and reference waves are mixed in a comparator. When the sinusoidal wave has higher magnitude, the comparator output is high, else it is low. The comparator output is processed in a trigger pulse generator in such a way that the output voltage wave has a pulse width in agreement with the comparator pulse width.

## **2.2 Unipolar and bipolar modulation**

If the half-cycle sine wave modulation, the triangular carrier only in a positive or negative polarity range of changes, the resulting SPWM wave only in a polarRange, called unipolar control mode. If the half-cycle sine wave modulation, triangular carrier in continuous change between positive and negative polarity, the SPWM wave is between

positive and negative changes, known as bipolar control. Unipolar and bipolar modulations are shown in Figure.

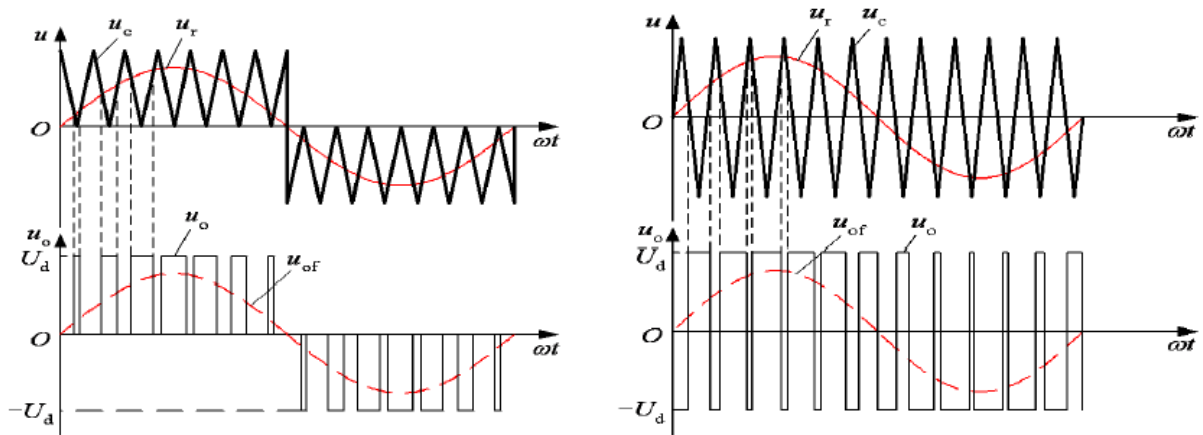


Fig 1: Unipolar and bipolar modulation

### 2.3 Three Phase Inverters:

Three phase inverters are generally used for high power applications. Three single phase half bridge inverters are to be connected in parallel to form a three phase inverter.

The inverter is fed by a fixed dc voltage and has three phase-legs each comprising two transistors and two diodes. With SPWM control, the controllable switches of the inverter are controlled by comparison of a sinusoidal control signal and a triangular switching signal. The sinusoidal control waveform determines the desired fundamental frequency of the inverter output, while the triangular waveform decides the switching frequency of the inverter. The ratio of the frequencies of the triangle wave to the sinusoid is referred to as the modulation frequency ratio. The switches of the phase legs are controlled based on the following comparison:

$V_{\text{control}}(\text{phase-a}) > V_{\text{triangle}}$ ,  $T_{a+}$  is on

$V_{\text{control}}(\text{phase-a}) < V_{\text{triangle}}$ ,  $T_{a-}$  is on

$V_{\text{control}}(\text{phase-b}) > V_{\text{triangle}}$ ,  $T_{b+}$  is on

$V_{\text{control}}(\text{phase-b}) < V_{\text{triangle}}$ ,  $T_{b-}$  is on

$V_{\text{control}}(\text{phase-c}) > V_{\text{triangle}}$ ,  $T_{c+}$  is on

$V_{\text{control}}(\text{phase-c}) < V_{\text{triangle}}$ ,  $T_{c-}$  is on

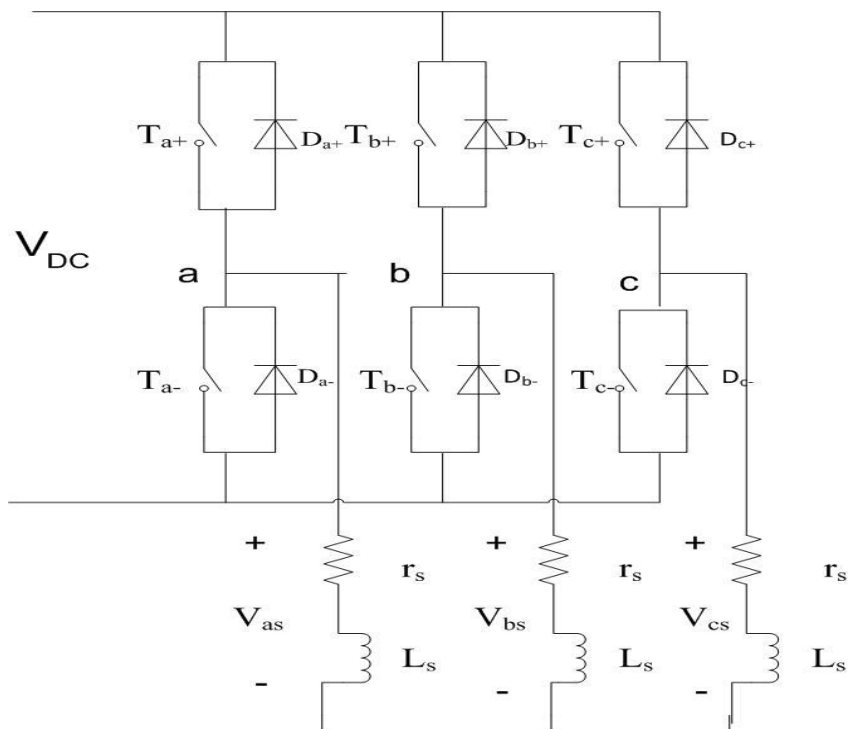


Fig 2: Basic Circuitry of a three phase inverter

The gating signals of single phase inverters should be advanced or delayed by  $120^\circ$  with respect to each other to get 3 phase balanced voltages. The transformer primary winding must be isolated from each other whereas secondary winding may be connected in either Y or  $\Delta$ .

The secondary winding of the transformer is usually connected in  $\Delta$  to get rid of triple harmonic appearing on the output voltages. Output voltages of single phase inverters are not balanced in magnitude or phase.

A three phase output may also be obtained by a configuration of six controllable switches and six diodes. Two types of control signals can be applied to these switches which are  $120^\circ$  and  $180^\circ$  modes of conduction.

#### 2.4 $180^\circ$ mode of operation:

Each transistor conducts for a period of  $180^\circ$ . Three of the transistors remain on at any instant of time. When  $T_{a+}$  is switched on, terminal a is connected to positive terminal of dc input voltage. When  $T_{a-}$  is switched on, terminal a is brought to negative terminal of dc input. There are six modes of operation in a cycle and duration of each mode is  $60^\circ$ .

The load can be connected in either Y or  $\Delta$ . Switches of any leg of the inverter cannot be switched on at the same time since this would result in a short circuit across the dc link voltage supply. Similarly to avoid undefined states and thus undefined ac output line voltage, the switches of any leg of the inverter may not be switched off simultaneously since this can result in voltages that depend on respective line current polarity.

State	State No.	$V_{ab}$	$V_{bc}$	$V_{ca}$
$T_{a+}$ , $T_{c-}$ and $T_{b-}$ are on	1	$V_{DC}$	0	$-V_{DC}$
$T_{c-}$ , $T_{b+}$ and $T_{a+}$ are on	2	0	$V_{DC}$	$-V_{DC}$
$T_{b+}$ , $T_{a-}$ and $T_{c-}$ are on	3	$-V_{DC}$	$V_{DC}$	0
$T_{a-}$ , $T_{c+}$ and $T_{b+}$ are on	4	$-V_{DC}$	0	$V_{DC}$
$T_{c+}$ , $T_{b-}$ and $T_{a-}$ are on	5	0	$-V_{DC}$	$V_{DC}$
$T_{b-}$ , $T_{a+}$ and $T_{c+}$ are on	6	$V_{DC}$	$-V_{DC}$	0
$T_{a+}$ , $T_{b+}$ and $T_{c+}$ are on	7	0	0	0
$T_{a-}$ , $T_{b-}$ and $T_{c-}$ are on	8	0	0	0

Table 1: Switch states for three phase voltage source inverter (VSI) for  $180^\circ$  conduction

For the purpose of our project we have proceeded with  $120^\circ$  mode of operation since it is easier for our simulation purposes, the details of which have been included in the next chapter. However, for practical applications,  $180^\circ$  mode of conduction is preferred since each transistor is better utilised in case of  $180^\circ$  mode of conduction as compared to  $120^\circ$  mode of operation for similar load conditions. Nevertheless, the analysis of the output waveforms of the inverter will not vary much for  $120^\circ$  since only the amplitude will vary for the two modes and not the vital characteristics. So, for our purpose, it will suffice to proceed with  $120^\circ$  mode of conduction.

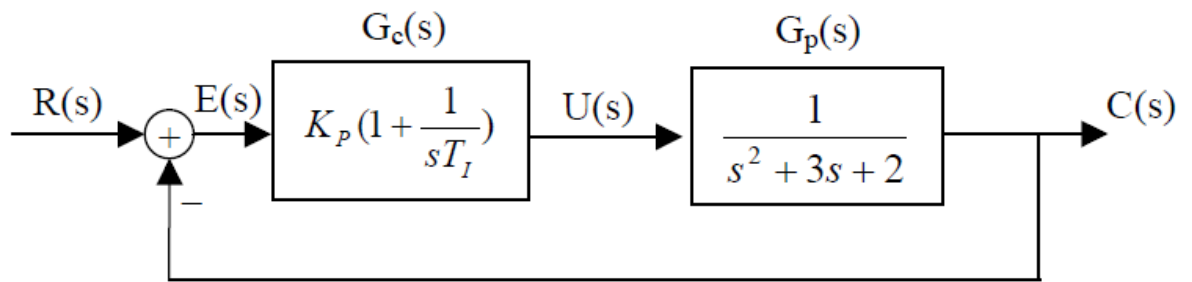
## 2.5 Proportional-Integral-Derivative (PID) Controllers

Proportional and Integral controllers were developed because of the desirable property that systems of type 0 or above when fed with a step input have zero steady state error. PID controllers use three basic modes of operation or behaviour types namely P-proportional which deals with the present errors, I- integral which is based on the accumulation of all past errors and D-derivative which takes into consideration all the possible future errors. While proportional and integral modes are often used as single control blocks in control systems, a derivative mode is rarely used individually in practical control systems. For our purpose, we have used the combination of PI as a controller to tune the feedback provided to the inverter and the value used for the derivative block is zero.

The general representation of the PI controller is:

$$\frac{U(s)}{E(s)} = K_p + \frac{K_I}{s}$$

Ex: We wish to apply PI controller to a type 0 plant:



Thus:

$$OLTF = K_p \left( s + \frac{1}{T_1} \right) \frac{G_p(s)}{s}$$

$$CLTF = \frac{C(s)}{R(s)} = \frac{K_p (s + 1/T_1)}{s(s^2 + 3s + 2) + sK_p + K_p/T_1}$$

## CHAPTER III: Methodology

### 3.1 Three phase inverters (120° Conduction)

In this type of control, each transistor conducts for 120°. Only two transistors conduct simultaneously. The gating signals are shown below.

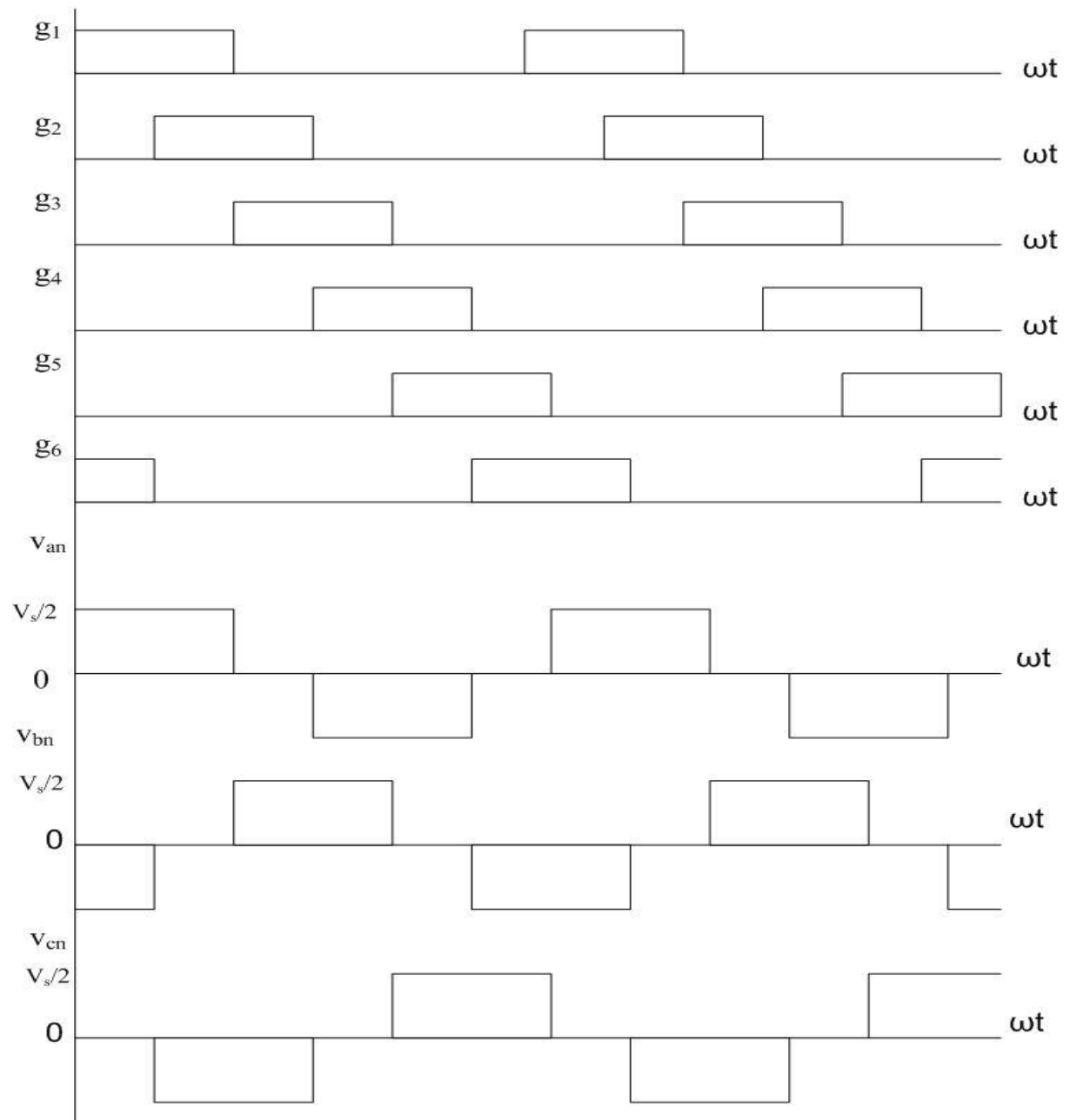


Fig 3 : Switching Sequence for 120° conduction mode.

The transistors conduct in a sequence 61,12,23,34,45,56,61. So there are three modes of operation in one half cycle and the equivalent circuits for a Y-connected load have been shown.

Mode 1:  $0 \leq \omega t \leq \pi/3$ , transistors 1 and 6 conduct.

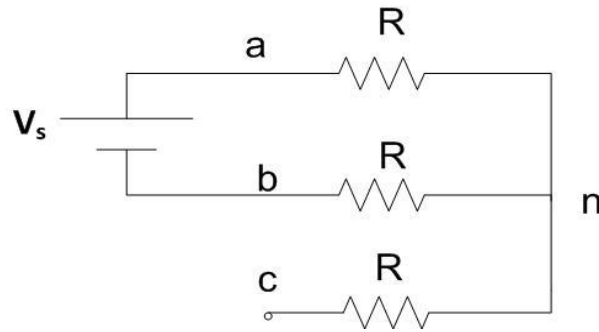


Fig 4: Mode 1

$$v_{an} = \frac{V_{DC}}{2}, \quad v_{bn} = -\frac{V_{DC}}{2}, \quad v_{cn} = 0$$

Mode 2:  $\pi/3 \leq \omega t \leq 2\pi/3$ , transistors 1 and 2 conduct.

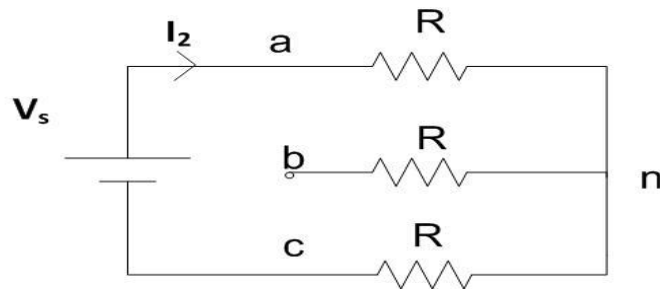


Fig 5: Mode 2.

$$v_{an} = \frac{V_{DC}}{2}, \quad v_{bn} = 0, \quad v_{cn} = -\frac{V_{DC}}{2}$$

Mode 3:  $2\pi/3 \leq \omega t \leq \pi$ , transistors 2 and 3 conduct.



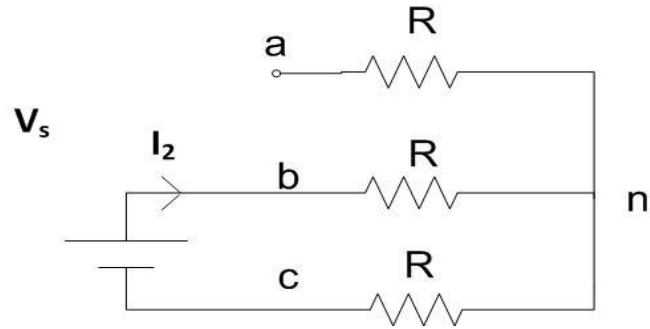


Fig 6: Mode 3.

$$v_{an} = 0, \quad v_{bn} = \frac{V_{DC}}{2}, \quad v_{cn} = -\frac{V_{DC}}{2}$$

### 3.2 Switches used (IGBTs):

An IGBT combines the advantages of both BJTs and MOSFETs. An IGBT has high input impedance and low on state conduction losses. There is no second breakdown problem as in BJTs. An IGBT is turned on by applying just a positive gate voltage to open the channel for n-carriers and turned off by removing the gate voltage. It has lower switching and conducting losses because of the above reasons. So an IGBT is inherently faster than a BJT. The current rating for single IGBT can be up to 1200V, 400A and the switching frequency can be up to 20KHz.

### 3.3 LC Filter

The LC-filter in Figure is a second order filter giving  $-40$  dB/decade attenuation. Since the L-filter achieves low attenuation of the inverter switching components, a shunt element is needed to further attenuate the switching frequency components. This shunt component must be selected to produce low reactance at the switching frequency. But within the control

frequency range, this element must present high magnitude impedance. A capacitor is used as the shunt element. The resonant frequency is calculated from the equation given below.

$$f_o = 1/2\pi\sqrt{LC}$$

This LC-filter is suited to configurations where the load impedance across C is relatively high at and above the switching frequency. The cost and the reactive power consumption of the LC-filter are more than to the L-filter because of the addition of the shunt element.

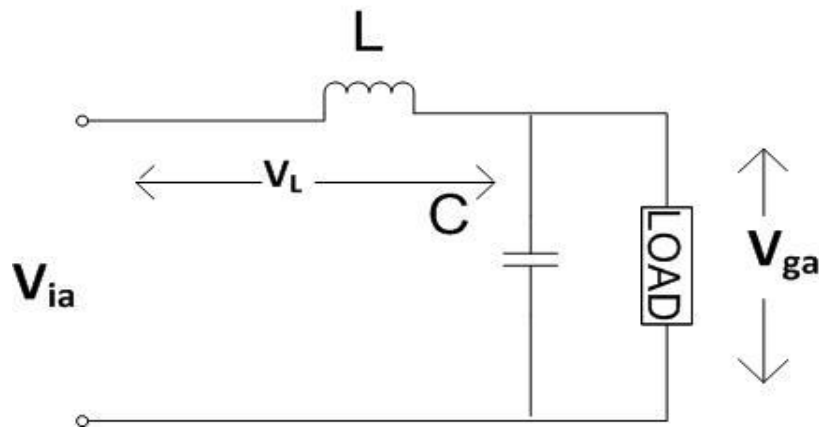


Fig 7: L-C filter topology.

The output current ripple is the same as the inductor current ripple with an L-filter, where the attenuation depends solely on the filter inductance. The LC low pass filter is able to attenuate most low order harmonics in the output voltage waveform. To minimize distortion, for linear or non linear loads, the inverter output impedance must be minimized. Therefore the capacitance should be maximized and the inductance minimized when specifying the cut-

off frequency. This decreases the overall cost, weight, volume and  $Q \left( \sqrt{L/C}/R \right)$ . But by

increasing the capacitance, the inverter power rating will be increased due to the reactive power increase due to the filter. The switching frequency in high power applications is

chosen with regard to inverter efficiency, since switching losses are a significant portion of the overall losses. It is desirable to minimize the size and cost of the filtering components by increasing the switching frequency, but efficiency sets a limit (a design trade off must be made). The associated module cannot be connected to the utility unless the high frequency components are attenuated from the output voltage.

The inductor determines the ripple in the inductor current and reduces the low frequency harmonic components. Consider the inverter phase 'a' voltage  $V_a$  in Figure 6, and assume that the output voltage  $V_{ga}$  varies slowly relatively to the switching frequency. Then the voltage across the inductor is:

$$V_L = V_{Ia} - V_{ga}$$

To determine the maximum inductor ripple current, the values of  $V_{Ia}$  and  $V_{ga}$  are as in equations given below. The phase voltage duty cycle at maximum output is 75%:

$$V_{Ia} = \frac{2}{3}V_{DC}, V_{ga} = \frac{1}{2}V_{DC}$$

$$V_L = \frac{2}{3}V_{DC} - \frac{1}{2}V_{DC} = \frac{1}{6}V_{DC}$$

According to the harmonic standard, the inequality mentioned is necessary to be considered,

$$|I_{0\ har}| < \frac{0.3\%P_{rated}}{3V_g}$$

And according to this harmonic standard, 15–20% of the rated current is allowable. The maximum ripple can now be calculated from equation given below. The ripple current depends on the DC link voltage, inductance, and the switching frequency. The DC link voltage and switching frequency are constant, thus the inductance can be calculated from equation mentioned below:

$$V_L = \frac{L\Delta I_L}{\delta T_s}, \Delta I_L = \frac{\delta T_s V_L}{L}$$

$$\Delta I_L = \frac{\delta V_L}{L f_s}, \Delta I_L = \frac{\delta V_{DC}}{6L f_s}$$

$$\delta = 1 - \frac{1}{4} = \frac{3}{4}$$

$$\Delta I_L = \frac{V_{DC}}{8L f_s}$$

$$L = \frac{V_{DC}}{8\Delta I_L f_s}$$

Where,

$V_L$  is inductor voltage,

$f_s$  is switching frequency,

$V_{DC}$  is DC link voltage,

$\delta$  is maximum duty cycle,

L is filter inductor

### 3.4 MATLAB Simulink Model:

The Simulink model in MATLAB provides a graphical user interface, users can call the standard library module from where the necessary blocks and components are selected and are properly connected to form the dynamic system model. There is a Dialog box for changing the properties of each individual component used in the module and also the system parameters as well as the configuration parameters for the type of simulation desired. For system modelling, address parameters and numerical algorithms are selected we can start the simulation program Simulation of the system. Scope are used to get the output waveform of voltages and current and workspace is also used for the same.

## Chapter IV: Simulink design in MATLAB

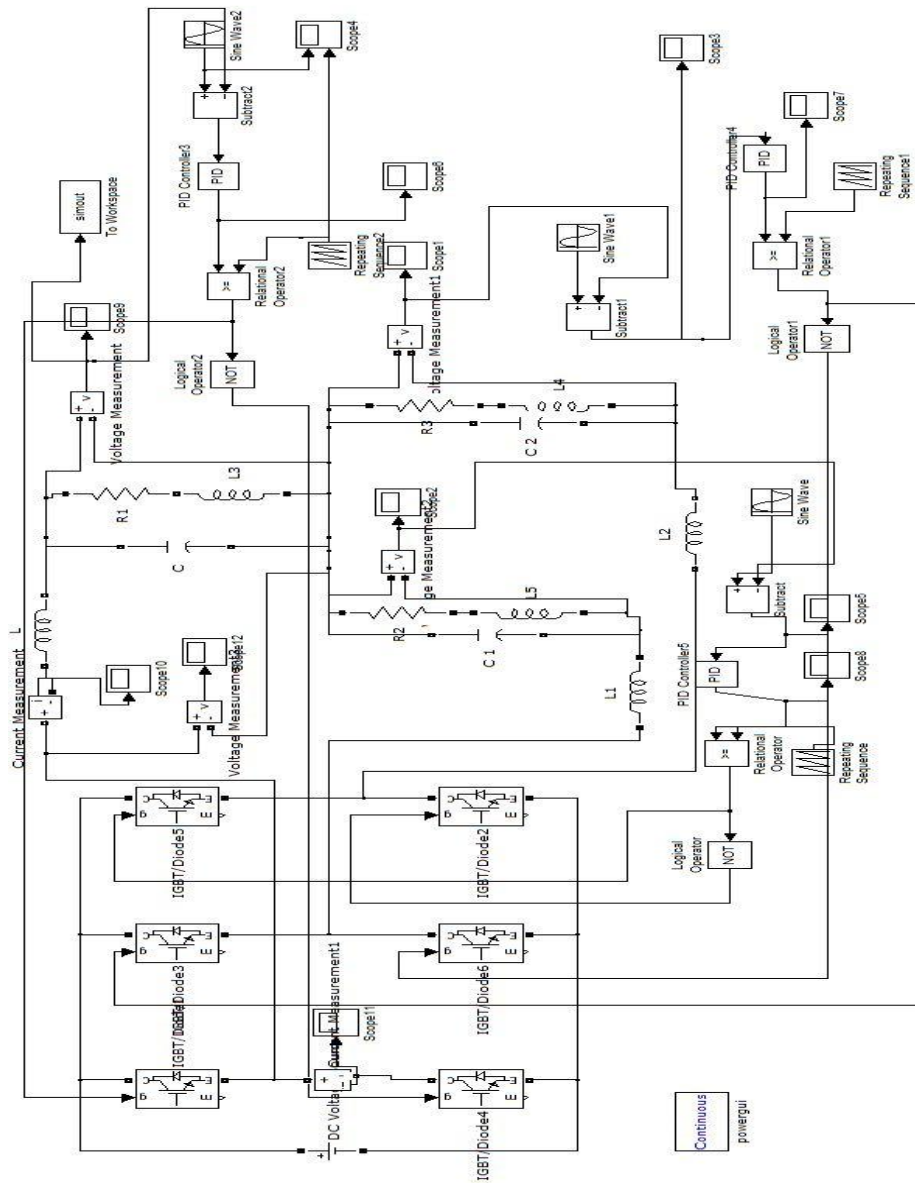


Fig 8: Simulink model

We are using IGBT switch since it has a number of advantages over MOSFET and BJT.

We used six IGBT/Diode switches and star connected RL load with a LC filter in between the inverter and star connected RL load. The use of filter is to reduce the distortion of output current and voltage of inverter. We used 120° mode of conduction as it is easier to simulate in MATLAB.

The power rating of the inverter has been taken to be 10 KVA that is,  $P_{\text{rated}}=10$  KVA. A constant DC voltage source of magnitude 400V has been used at the input terminal of the inverter that is,  $V_{\text{DC}} = 313.97\text{V}$ . Six IGBT/Diode switches as mentioned above, have been used, two in each leg of the inverter. The transistors in one leg of the inverter (switches 1 and 4) have  $180^\circ$  phase difference in their switching pulses and those in adjacent legs (switches 1 and 3) have a  $120^\circ$  phase difference. As mentioned above, an L-C filter of the topology shown earlier has been used in each phase to reduce the distortion of the current and voltage waveforms in the RL load. According to the design consideration of L-C filter in Chapter III, the range of L and C were found to be 1-10mH and 2.5-25 $\mu\text{F}$  respectively. We have given the inverter feedback by comparing the output voltage with a sinusoidal wave of amplitude 0.95V and frequency 47.619 Hz and has been, in turn, compared with another triangular reference voltage of amplitude 1V and a switching frequency of 1 KHz as per SPWM scheme.

Simulation 1: The above simulink model has been simulated using the values 10mH and 25 $\mu\text{F}$  for filter inductance 'L' and filter capacitance 'C' respectively.

Simulation 2: The above simulink model has been simulated using the values 1.0mH and 5.0 $\mu\text{F}$  for filter inductance 'L' and filter capacitance 'C' respectively.

*Results of Simulation 1:*

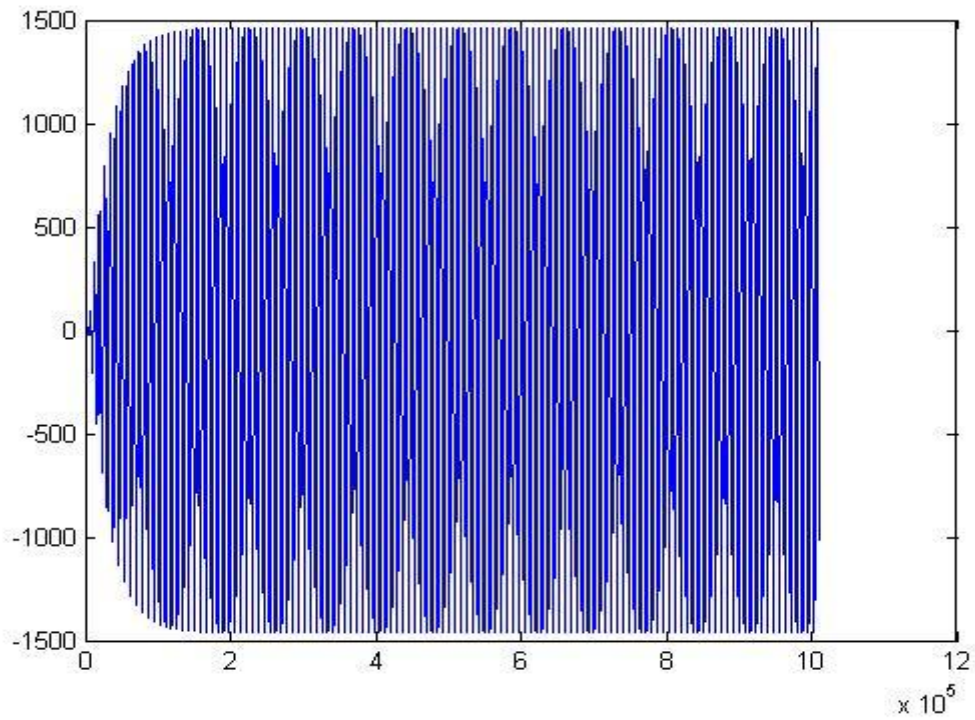


Fig 9: phase 'a' output voltage waveform

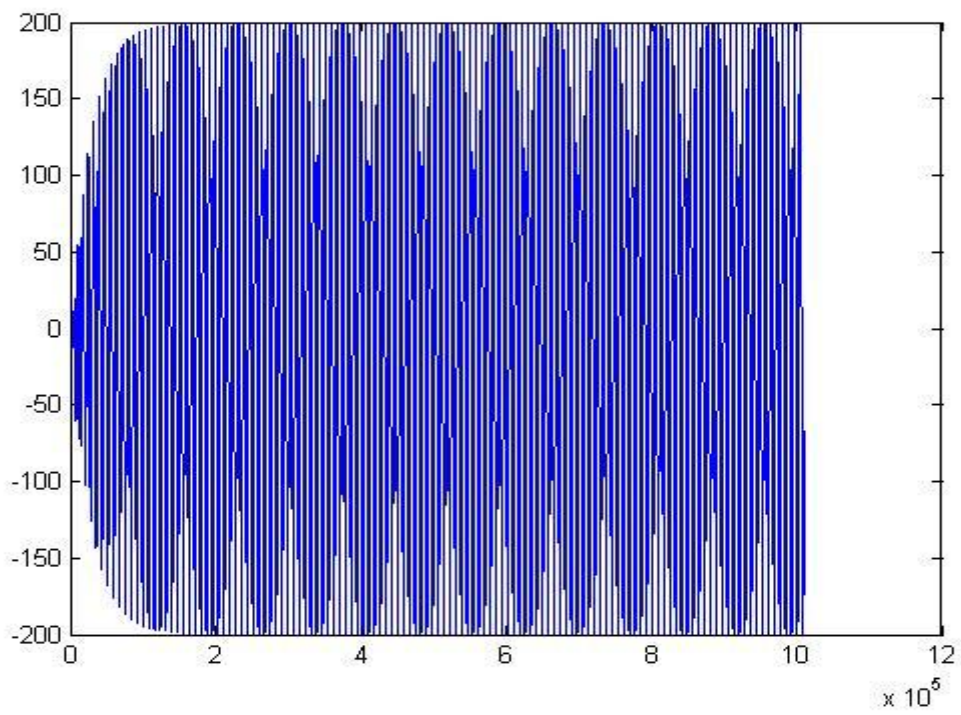


Fig 10: phase 'b' output voltage waveform.

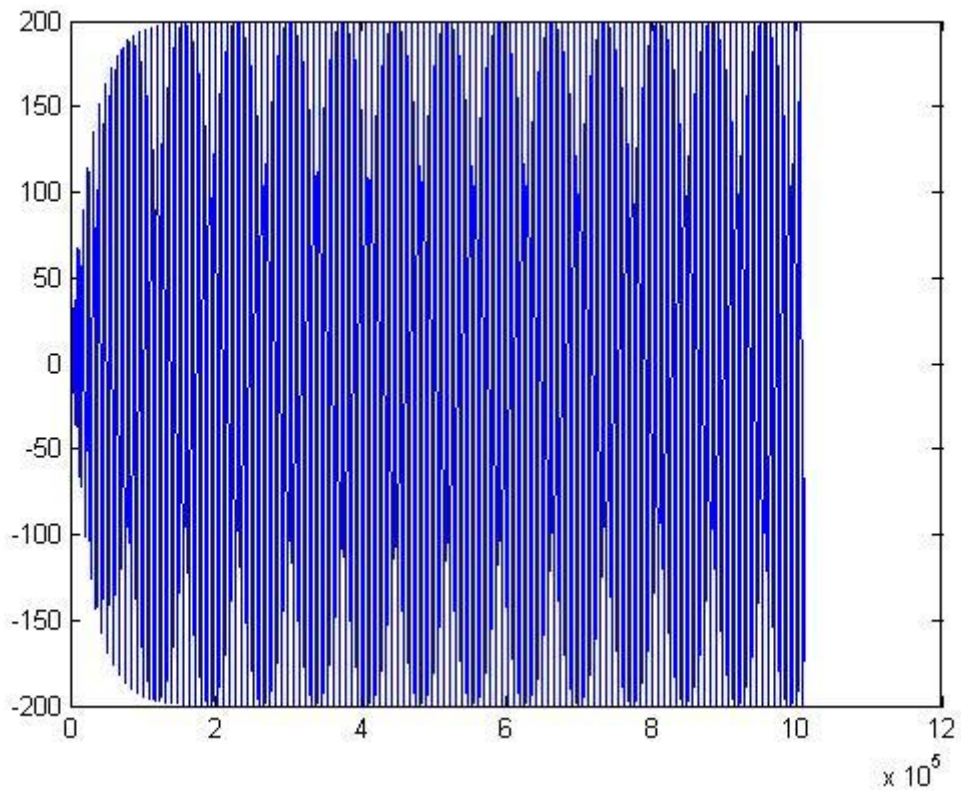


Fig 11: phase 'c' output voltage waveform

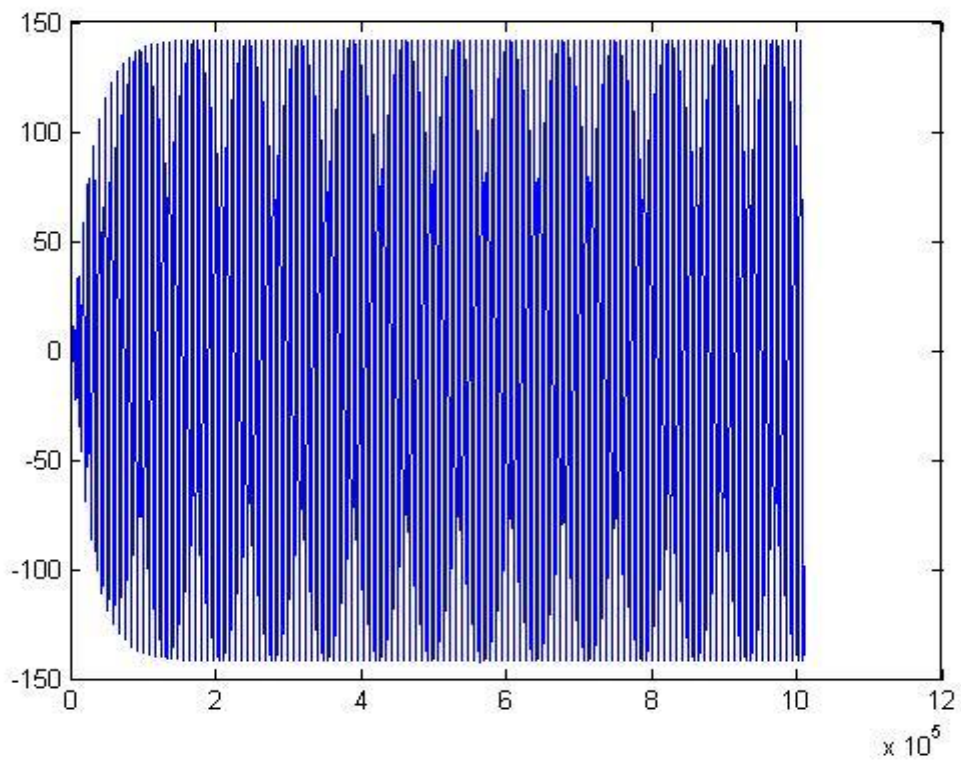


Fig 12: Output current waveform of phase 'a'.



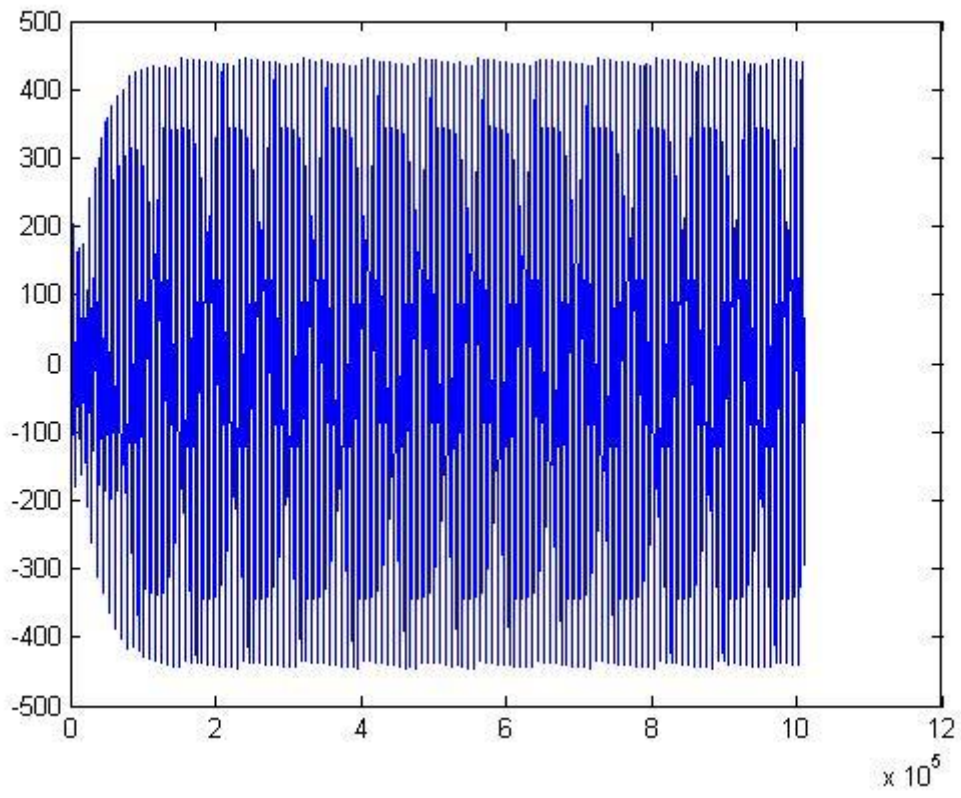


Fig 13: unfiltered voltage waveform of phase 'a'.

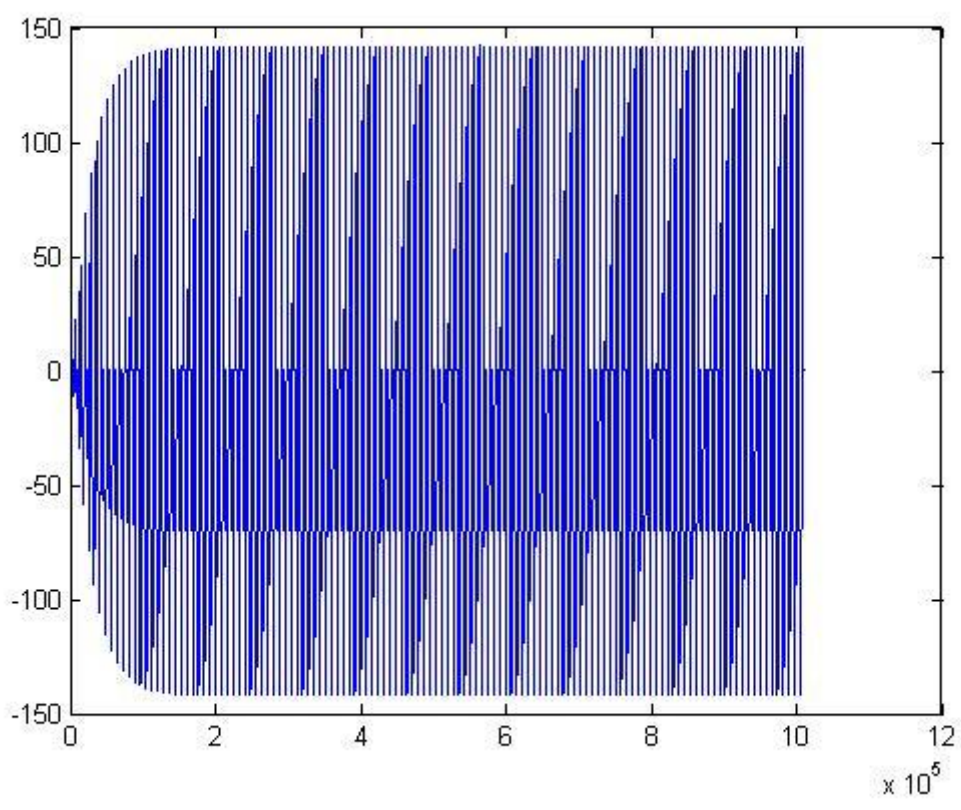


Fig 14: IGBT current waveform

*Results of Simulation 2:*

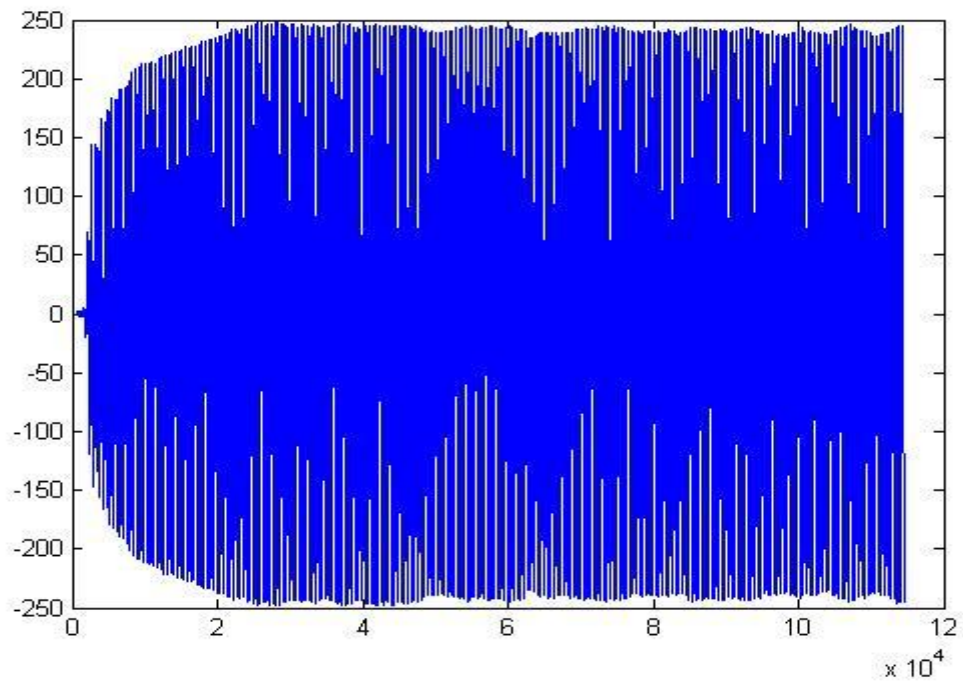


Fig 15: phase 'a' output voltage waveform

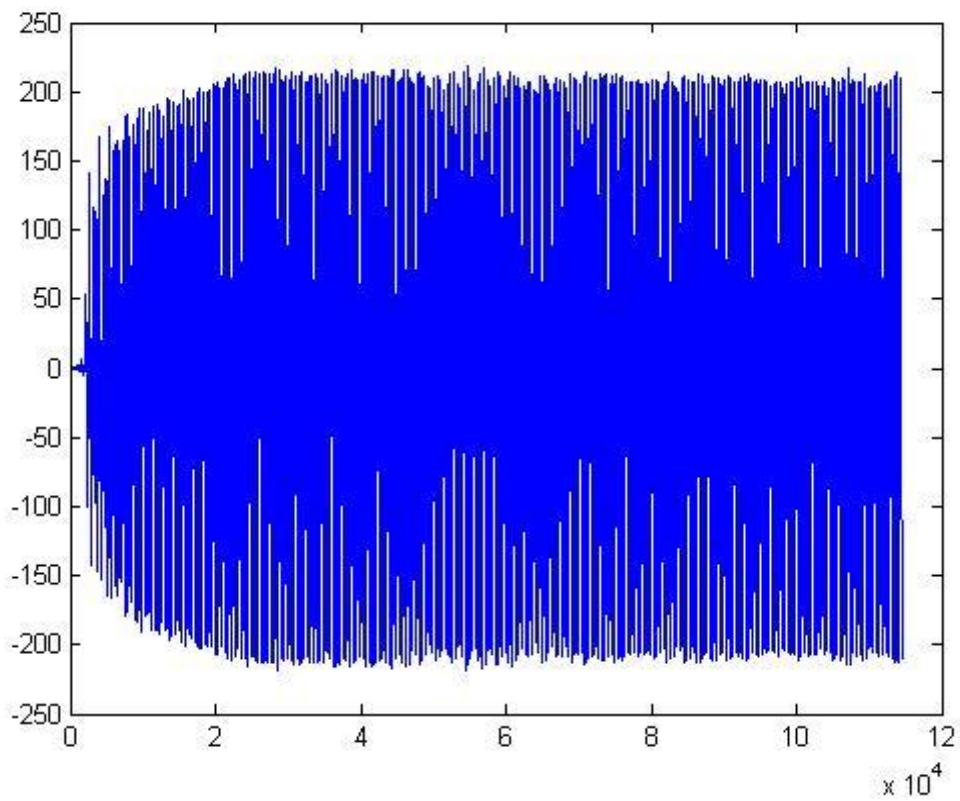


Fig 16: phase 'b' output voltage waveform

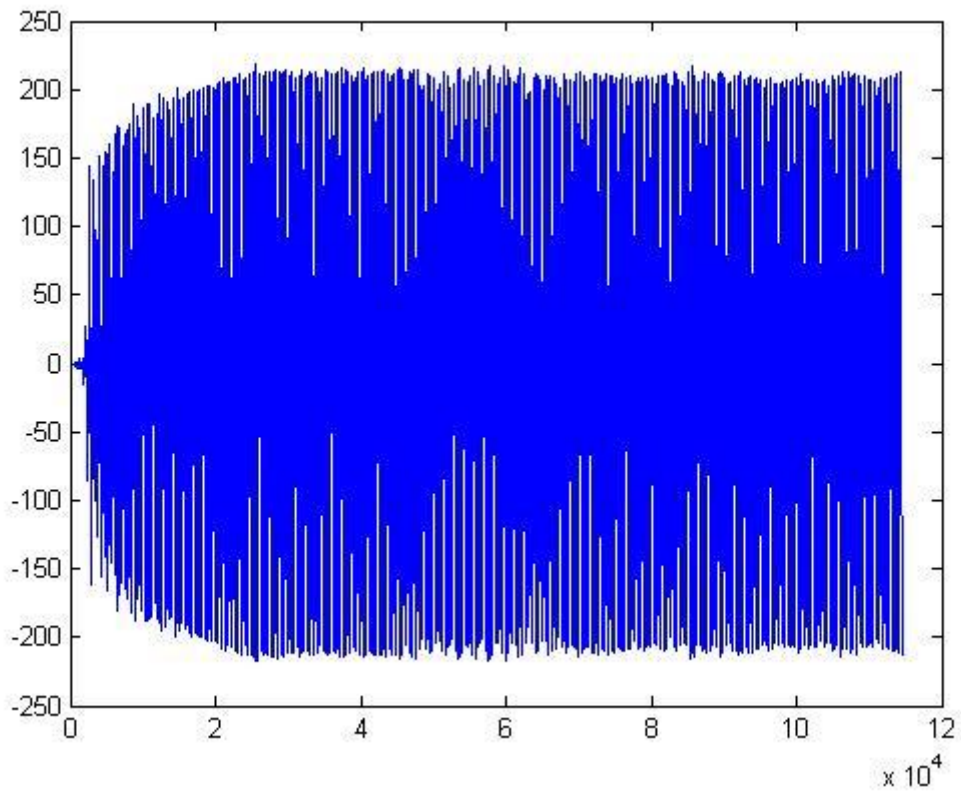


Fig 17: phase 'c' output voltage waveform

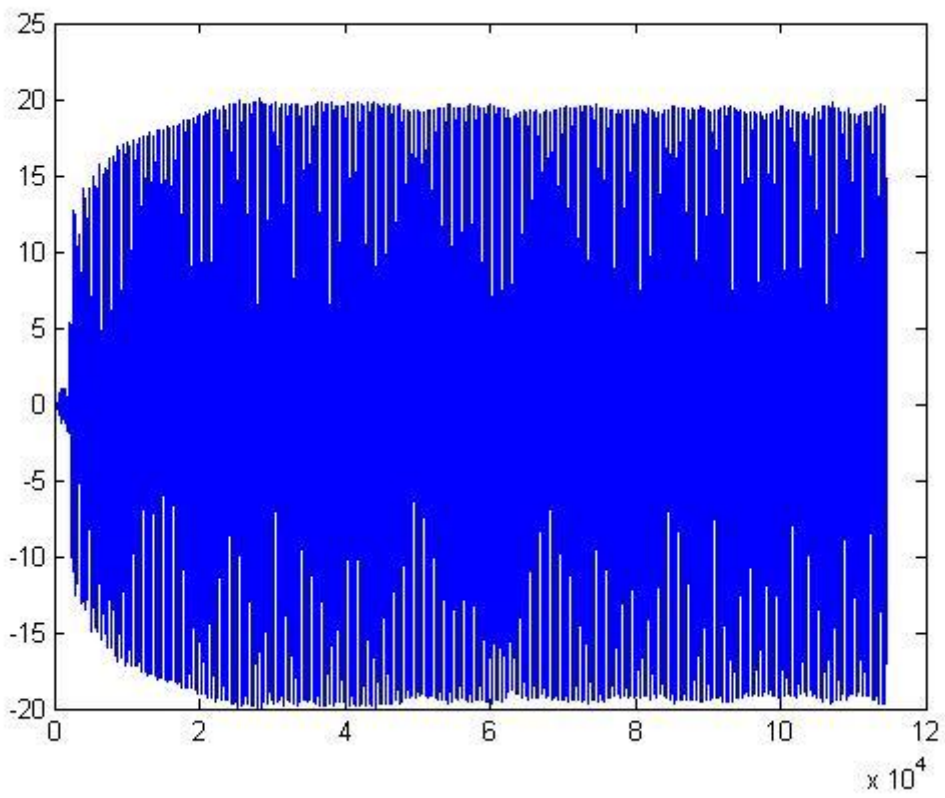


Fig 18: Output current waveform of phase 'a'

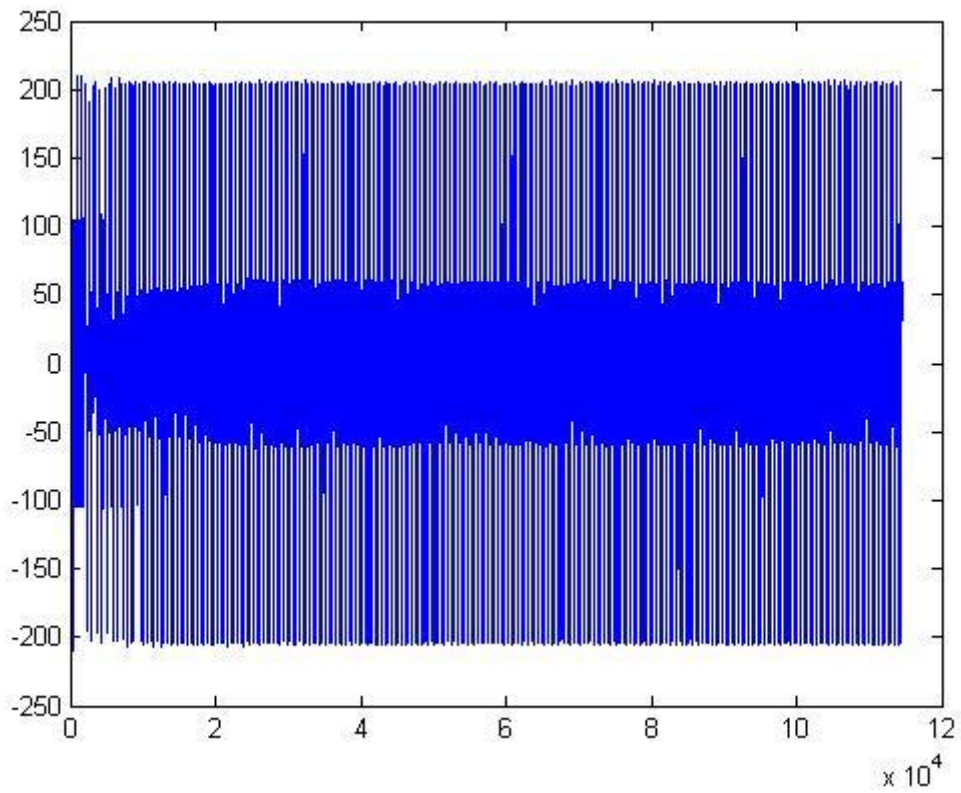


Fig 19: Unfiltered voltage waveform of phase 'a'.

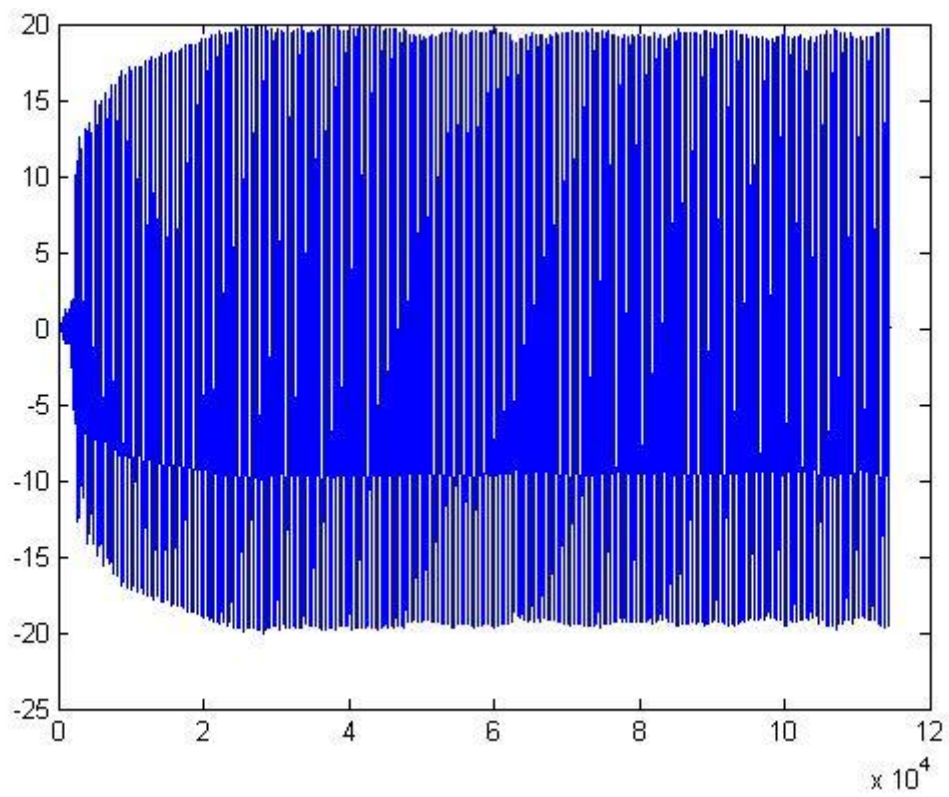


Fig 20: IGBT/Diode current waveform

## ***Conclusion:***

Two simulations namely simulation 1 and simulation 2 have been done based on the Simulink model presented above and the results of the waveforms for both the simulations have been shown.

It was found that for Simulation1, the output current and voltage waveforms of the inverter were of the desired sinusoidal nature with expected amplitude and frequency. For the same simulation, the unfiltered voltage and IGBT/Diode current waveforms were of similar nature.

On the other hand, for Simulation 2, even though the values of the filter inductance  $L$  and filter capacitance  $C$  were chosen from the stipulated range as calculated above according to the accepted methodology given in Chapter III, the waveforms of the output current and output voltage were not found to be of desired frequency and amplitude and there was significant distortion from the expected sinusoidal nature.

It was also observed that, as the value of filter inductance  $L$  is decreased, within the specified range, the amplitude of the distorted wave increases. Similarly, as the value of filter capacitance  $C$  is increased, the level of distortion decreases.

So, the further scope of this project is to find out the reasons leading to these instabilities within the particular range of filter parameters chosen according the accepted methodology.

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