SIMULATION AND ANALYSIS OF POWER CONVERTER FOR SPECIAL APPLICATION

A REPORT

on

Project & Thesis Part-I (EE761)

BY

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DECLARATION BY THE CANDIDATE

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I, do hereby, forward the report on Project & Thesis Part-I entitled **SIMULATION AND ANALYSIS OF POWER CONVERTER FOR SPECIAL APPLICATION** prepared by **Purusattam Ghosh, Yogesh Kumar Chauhan, Nishant Bansal, & Shivendra Kumar** under my guidance, as partial fulfillment of requirements for the completion of degree of B. Tech. (Electrical) at IIEST, Shibpur.

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CONTENTS

OBJECTIVE

As the title of this Thesis report "SIMULATION AND ANALYSIS OF POWER CONVERTER FOR SPECIAL APPLICATION" suggests that the project is about simulating different types of power converters and analyzing them for some special applications. So, the main application we are working on is the "INDUCTION HEATING" which is the most clean, efficient, cost-effective, precise, and repeatable method of material heating available to the industry, today.

In this project we are simulating two power electronic converters:

1. AC-DC Rectifier
2. DC-AC Single Phase Inverter

to control the extent of heat given to workpiece through induction. Actually the extent of heat depends on resistivity of the material, shape of induction coil and permeability of the material. The depth of heat penetration into the workpiece depends on the frequency: the lower the frequency, the deeper the penetration. So, the frequency and nature of current waveform in the induction coil can be controlled by using the above stated converters even with the standard input supply. Rectifier is controlled using α controlling scheme, i.e., triggering the thyristor at a specific time can give desired DC output (with the use of filters to reduce the ac content). Inverter is also controlled in a similar manner: here IGBT switches are controlled by corresponding signals to get the desired ac output with desired frequency and amplitude. With this controlled frequency output of inverter the depth of heating of the workpiece can be controlled and the objective of melting/moulding or reshaping or any other requirement of workpiece can be completed.

INTRODUCTION

In industries, furnaces and ovens are primarily used for various heat treatment and metallurgical processes. A furnace is a device in which heat is generated and transferred to materials with the object of bringing about physical and chemical changes. Furnace designs vary as to its function, heating duty, type of fuel and method of heat transfer. On the basis of source of heat, the furnaces can be primarily classified into following two types: Fuel-fired furnaces & Electrically heated furnaces.

Fuel fired furnaces can be further classified on the basis of fuel used:

- Solid fuel, e.g., coal, wood, etc.
- Liquid fuel, e.g., Gasoline, kerosene, etc.
- Gaseous fuel, e.g., Natural gas, coke-oven gas, water gas, etc.

Electrical furnaces are more popular and are extensively used nowadays. It can be attributed to so many advantages of electrical furnaces over conventional furnaces.

Depending on the method of heating, electrical furnaces can be classified as below:

- Resistance furnace
- Arc furnace
- Induction furnace
- Plasma arc furnace
- Electron beam furnace

Apart from these, recently solar furnace is also a hot topic of research and finds many applications in various industries. A solar furnace is a structure that uses concentrated solar power to produce high temperatures, usually for industry. Parabolic mirrors or heliostats concentrate solar radiation onto a focal point. It provides eco-friendly heating solutions over conventional methods.

Here forth, we will be primarily focusing on the electrical aspects of induction heating/furnace. Also, we will be discussing in this report brief description of industrial heating methods, block schematic of the induction heating, open loop control of the Induction heater, controlling strategy, closed loop schematic, MATLAB simulation and circuit topologies for the converter.

INDUCTION HEATING

Induction heating is a non-contact heating process and also nowadays the heating technology of the choice in many industrial, domestic, and medical applications. It uses high frequency electricity to heat materials that are electrically conductive. Since it is non-contact, the heating process does not contaminate the material being heated. It is also very efficient since the heat is actually generated inside the workpiece. This can be contrasted with other heating methods where heat is generated in a flame or heating element, which is then applied to the workpiece. For these reasons Induction Heating lends itself to some unique applications in industry. Advances in key technologies, i.e., power electronics and control techniques, have allowed the development of compact heating systems superior to their primitives' processes such as flame heating, resistance heating, etc., in terms of reliability, cost, efficacy, speed, accuracy, safety, and efficiency.

This project focusses on one such heating application involving development of rectifier and inverter schematics for high frequency heating systems primarily used in the many metal industries.

PRINCIPLE OF INDUCTION HEATING

Induction heating is based on the principles of an electric transformer. The job or work-piece is the secondary while a surrounding copper coil is the primary. The two are linked or coupled by air. Thus, this is an air core transformer with a single turn secondary. High frequency (HF) current (1,000–100,000 Hz) is passed through the primary (coil) by connecting it to a suitable HF generator.

A similar HF current is induced in the job, i.e., secondary. This current circulates and produces heat. These are induced eddy currents and circulate circumferentially as shown. Eddy currents, and therefore the heating, is concentrated in a thin outer layer or skin of the work.

The primary coil gets heated due to the I^2R losses in it. Some heat is also absorbed from job radiation. The coil is therefore made of copper tubing through which cooling water is circulated.

The job thus gets heated by the induced current and there is no contact between the primary and secondary.

Iron and other soft magnetic materials are used in ordinary transformers to act as susceptors, i.e., to concentrate the magnetic linking flux. They cannot be used in high frequency fields as they heat up excessively. Hence, air is used as the coupling medium. A few large scale induction heating processes (melting, heavy billet heating) that operate at mains or low frequencies (50–150 Hz), do use iron or alloy cores.

The concentration of induced currents in the surface layer is called the “skin effect.” It is discussed in detail in subsequent sections. Skin effect plays an important role in the design and operation of the induction heating process.

Factors on which heating effect depends

The depth δ at which the current is 0.368 (= 1/e) of surface current is defined as the "depth of penetration." It is given by-

$$\delta = 5000\sqrt{\frac{\rho}{\mu_\gamma f}}\ \text{cm}$$

where

δ = Depth of penetration (cm)

ρ = Resistivity of object (ohm.cm)

μ_γ = Relative permeability of object

μ_γ = 1 for paramagnetic materials

μ_γ = 25–10,000 for ferromagnetic materials

f = Frequency cps or Hz

The above equation shows that the depth of penetration decreases with increasing frequency (if ρ and μ are constant). Qualitatively, this indicates that for deep or through heating, a low frequency is preferred while a high frequency should be used for surface or shallow heating. The statement is to be qualified by γ/δ ratio where g is the diameter or half-width of the work.

Magnetic permeability is constant (~ 1.0) for non (para) magnetic materials. Hence, μ has no effect on the heating of materials such as copper, aluminum, or nonmagnetic steels.

For ferromagnetic materials (common carbon and low alloy steels) the permeability is high and decreases with temperature. At a temperature higher than Curie temperature (~ 760°C) the permeability vanishes. Thus the depth of penetration for ferromagnetic material will be very low initially and will increase as temperature increases. It will stabilize at $\tau = t$ curie.

Resistivity ρ and δ are directly proportional. Hence, copper or aluminum will have a larger δ than brass, steels, and other alloys.

BLOCK SCHEMATIC OF INDUCTION HEATER

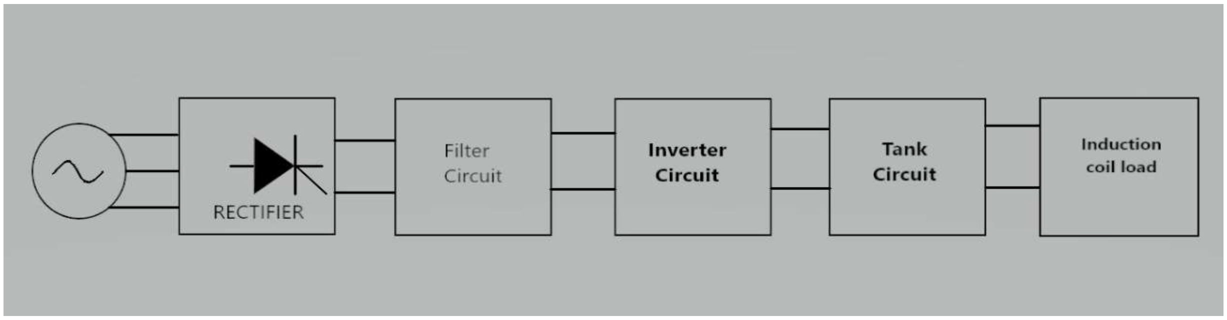

Figure 1: Block diagram of Induction heating

The power is derived from 50 Hz, 3 phase AC mains and rectified by a suitable rectifying circuit (full wave bridge). The rectifier is a thyristor based fully controlled circuit whose output is passed through an LC filter. Then we get an almost pure DC signal.

The DC supply passes through an inverter where it is switched at a high frequency producing a square wave switched DC (i.e., non-sinusoidal AC).

It is then fed to a tank circuit which acts as a buffer between the inverter and the coil. The tank matches the load and generator impedances, corrects the power factor, and produces a resonant condition to derive maximum power. There is usually an output transformer to lower the coil voltage. The load (coil) is connected to the tank output. There may be an extra correction capacitor in parallel with the coil to suit individual load demands. The output frequency is adjusted (often automatically) by adjusting the thyristor switching frequency.

ADVANTAGES OF INDUCTION HEATING

1. Like other electrical heating processes this is a “clean” process, i.e., there are no combustion gases and attendant problems.
2. The heat is produced directly in the job. Hence, no enclosure of furnace is required.
3. As there is no contact between the coil (the inductor) and the job, the two can be located at a (reasonable) distance from each other. Hence, the process can be used in a vacuum or protective environment. A very wide coil-job spacing lowers the efficiency.
4. The process uses very high-power densities (~ 0.01 to 2 kW/cm^2), therefore the heating is very fast (~ a few seconds).
5. Quick heating virtually eliminates oxidation of the work-piece. There is also no distortion and oxidation.
6. There is excellent control on the power input and time, hence, the heating temperature and depth can be accurately controlled. Fast heating and good control makes the process suitable for automation by using proper fixtures.
7. The heating effect is located on the surface opposite the coil. This makes it possible to restrict heating only at a desired location.
8. There is no temperature limit. With proper design and adequate power, any desired temperature can be attained.

INDUCTION HEATING CONVERTER

In IH, the heat is generated by eddy currents which are originated by a varying magnetic field that is obtained by means of a varying current circulating in an inductor. So, in induction heating, the work piece can be considered analogous to the secondary of the transformer.

The operating frequency used for an induction heating system is dictated by the work piece to be heated and the material it is made from. And to understand the reasons for different operating frequencies let's look at a characteristic known as the "skin effect." When the electromagnetic field induces a current in the part, it flows primarily at the surface of the part. The higher the operating frequency the shallower the skin depth and the penetration of the heating effect. Skin depth or penetrating depth is dependent on the operating frequency, material properties and the temperature of the part.

It is important to use an induction system that delivers power over the range of frequencies appropriate for the application so naturally a variable frequency source is most suitable for induction heating applications.

The operating frequency of the induction heating system is a factor to consider based on the size of the work piece to be heated. Smaller work pieces require a higher frequency for efficient heating, and larger work pieces benefit from a lower frequency and more penetration of the heat generated.

The power required is determined by:

- The type of material
- The size of the work piece
- The required temperature increase
- The time to temperature

So, a natural choice of converter suitable for above application is an AC to DC to AC converter, which we will also focus upon. With this, we can easily vary frequency, DC voltage for the inverter, PWM output of the inverter, & power flow by phase control.

THREE-PHASE RECTIFIER

The first stage of conversion used is the AC-DC rectification followed by a DC link capacitor and a filter to smoothen out the output voltage, minimizing the output ripple voltage. So, for a three-phase supply side, three-phase full converter is considered here providing two quadrant operations as required for our application.

As shown in the figure, the upper halves of the legs have thyristors numbered 1, 3, &5. And similarly 4, 6, & 2 in the lower halves. The current commutates to another thyristor every 60 degrees. Thyristors in each half are fired at an interval of 120 degrees of the fundamental wave and for the numbering as shown in the adjacent figure the firing sequence is 1-2, 2-3, 3-4, 4-5, 5-6, & 6-1. Here, the frequency of the output ripple voltage is 6f (where f is the fundamental frequency). So, the filter size is also smaller as compared to other rectification schemes.

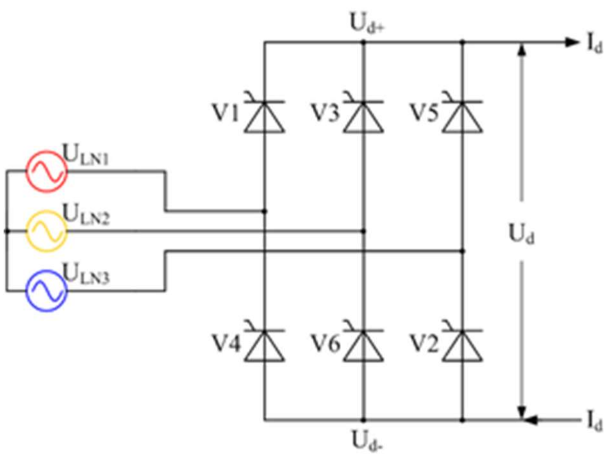

Figure 2 Basic circuit of three-phase full-wave controlled rectifier using thyristors

This rectification scheme introduces harmonics on the source side. In many applications, a filter circuit is required at the source side to reduce the harmonic content introduced in the supply due to rectification action.

The whole circuit can be studied in two sections:

- Power Circuit of the rectifier
- Triggering Circuit of the rectifier

POWER CIRCUIT OF RECTIFIER

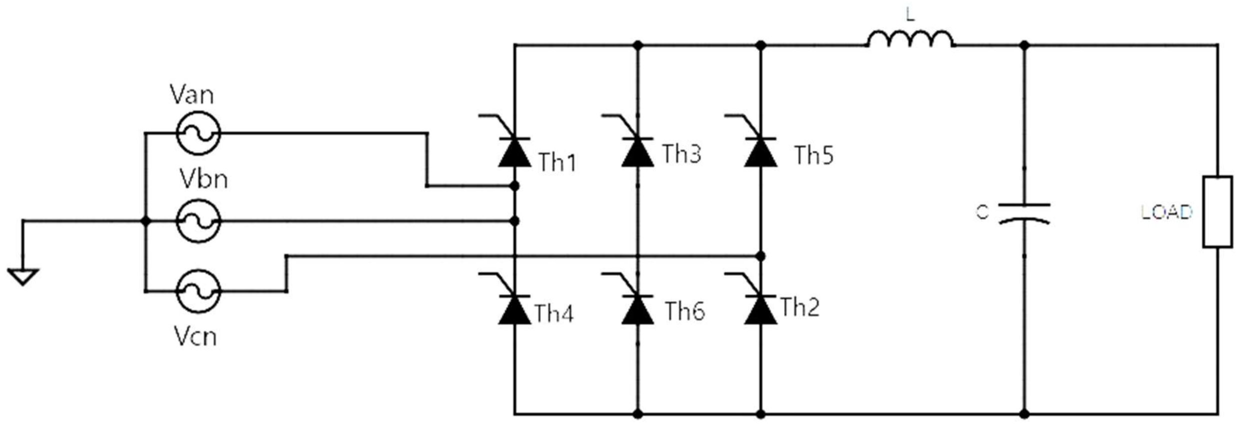

Figure 3: Thyristorized three-phase full wave rectifier with LC filter

The above figure shows the Power circuit of the rectifier with LC filtering to smoothen the voltage and current output of the rectifier.

NOTE: FULL CIRCUIT USED FOR SIMULATION IS ATTACHED IN THE APPENDIX.

Let's consider the line to neutral voltages at the input of the rectifier as:

$$v_{an} = V_m \, sin \, \omega t$$

$$v_{bn} = V_m \, sin(\omega t - 120°)$$

$$v_{cn} = V_m \, sin(\omega t + 120°)$$

So, the corresponding line-to-line voltages are:

$$v_{ab} = v_{an} - v_{bn} = \sqrt{3} V_m \sin{(\,\omega t + \pi/6)}$$

$$v_{bc} = v_{bn} - v_{cn} = \sqrt{3} V_m \sin{(\,\omega t - \pi/2)}$$

$$v_{ca} = v_{cn} - v_{an} = \sqrt{3} V_m \sin{(\,\omega t + \pi/2)}$$

For the above the average output voltage is given by:

$$v_{dc} = \frac{3\sqrt{3}V_m}{\pi} cos\alpha$$

So, maximum average output for α=0.

$$v_{max} = \frac{3\sqrt{3}V_m}{\pi}$$

And the rms output voltage is given as:

$$v_{rms} = \sqrt{3}V_m \left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi} cos\ 2\alpha\right)^{1/2}$$

Here, the voltage may go for certain value of α in case of inductive load, but the load current can't be negative. Figure 4 as attached below clearly shows the amount of ripple present in the output of the rectifier, which needs to be suppressed before feeding it to the inverter.

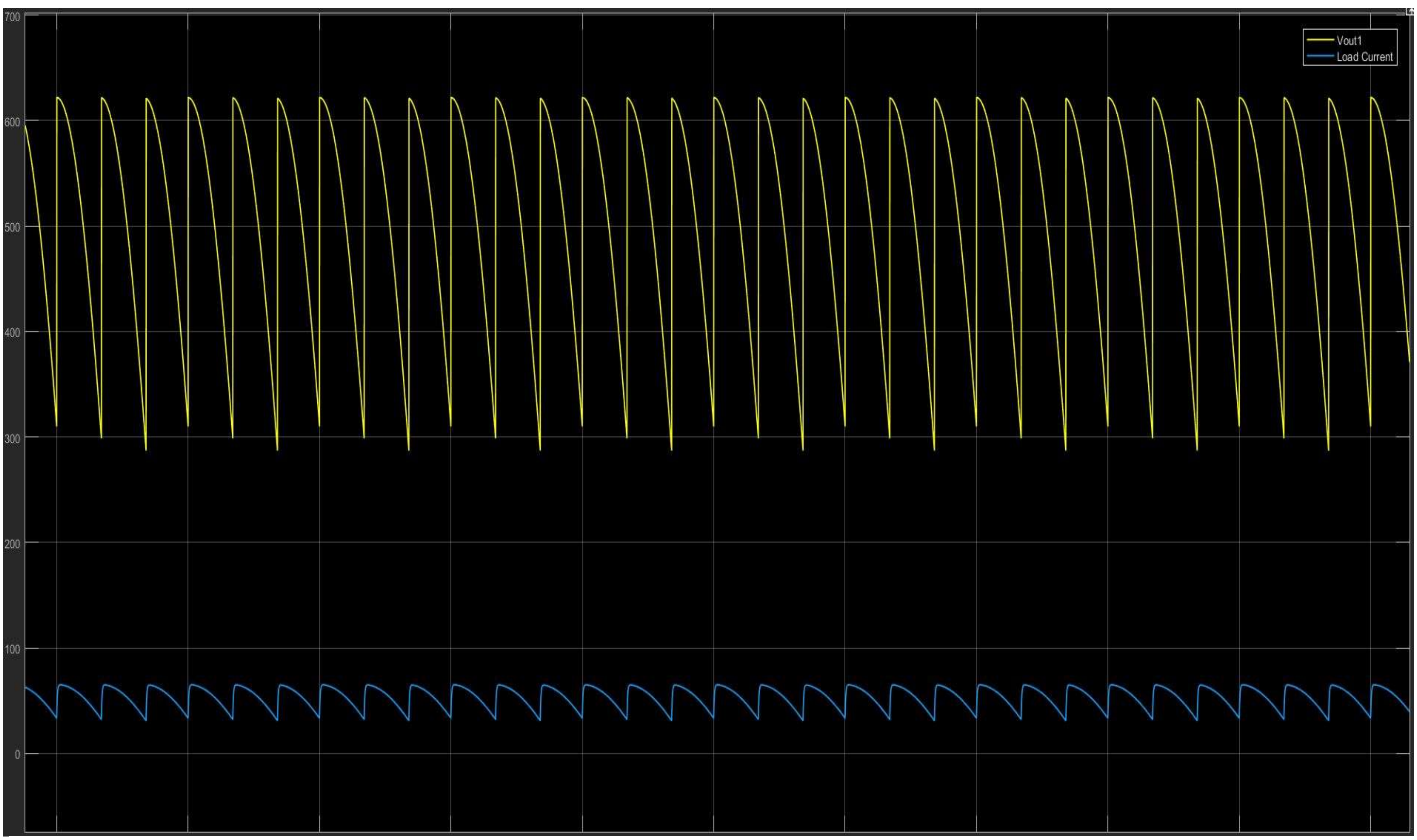

Figure 4: Rectifier output without using the LC filter at α=30°

POWER CIRCUIT OF RECTIFIER WITH LC FILTER

As we have discussed earlier, the output obtained is not smooth DC but it contains harmonics. Filters can be used to smooth out the dc output voltage of the rectifier using filters which are usually of L, C, and LC type. These are called dc filters. Filter capacitance performs the action of limiting the ripple in the output voltage while Inductance limits the amount of ripple current.

Also due to the rectification action, harmonics are introduced on the supply side also. AC filter is used to filter out some of the harmonics from the supply system. Although, here, we have only used LC filter at the output side of the rectifier.

In the below output of the simulation, it can clearly be seen that after LC filter we are able to reduce the ripple current and voltage to desired minimum value.

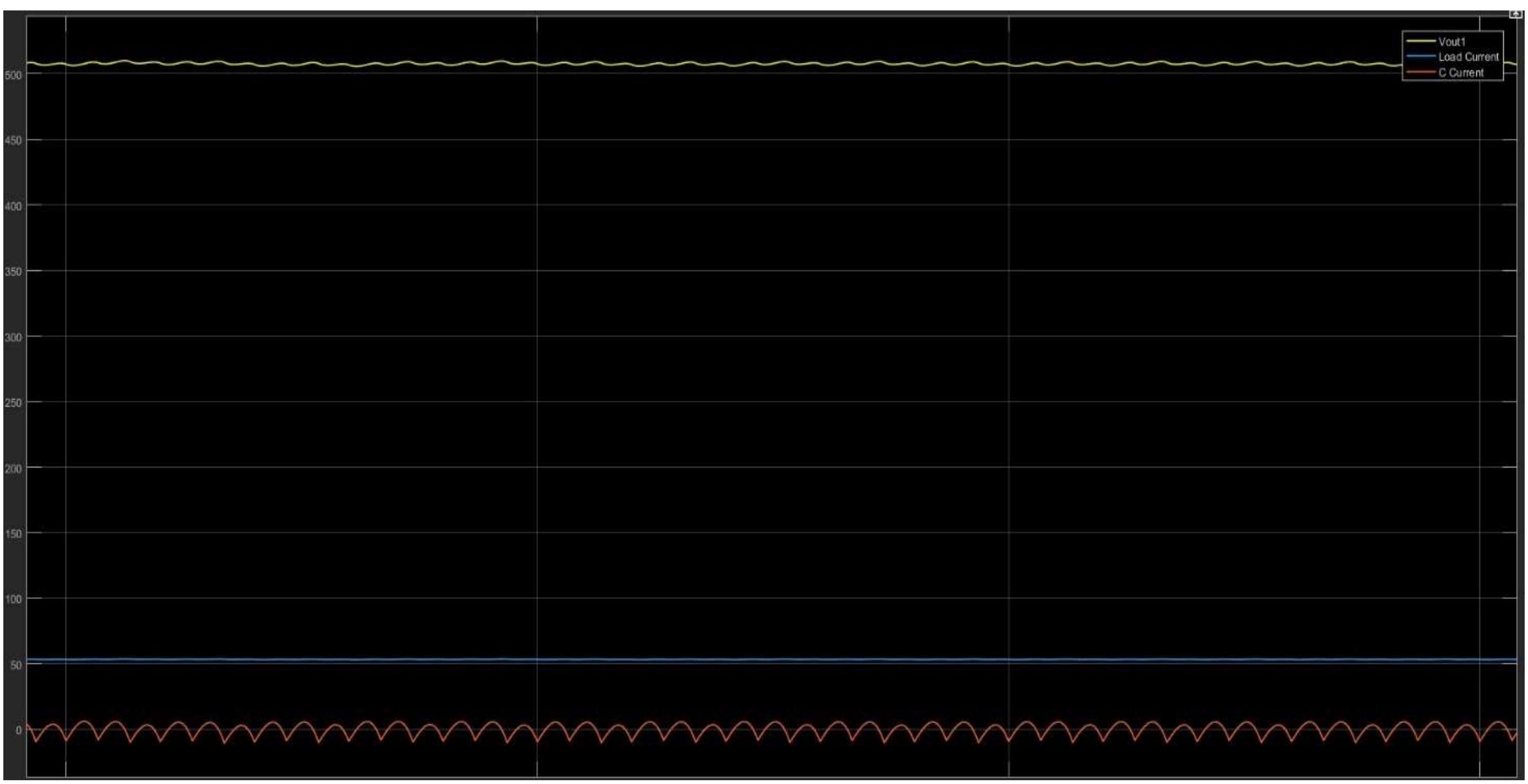

Figure 5: Steady state output of the rectifier for RL load with LC filter at α=30^0

TRIGGERING CIRCUIT OF RECTIFIER

The pulse circuit is required to trigger thyristor T1, T3, and T5 shifted by 120° and similarly T2, T4, and T6. As discussed earlier, the gating sequence for the circuit considered is 1-2, 2-3, 3-4, 4-5, 5-6, & 6-1. Since, we are working on inductive load, so pulse train is most suitable to trigger each thyristor. It is considering that the load current may include some ringing, the load current may temporarily drop below the hold current and the SCR may release (before the zero cross). Additionally - especially with inductive loads - the load current is phase shifted. The SCR doesn´t release at zero cross of voltage but at zero cross of current. So, here our strategy is to generated a 120° pulse train for each thyristor.

The logic followed to generate each gate triggering pulse train is as follows:

- Using a zero-crossing detector, generate a 180° pulse of uniform magnitude.
- Pass it through an integrator to generate a ramp signal.
- Compare it with a suitable voltage level control signal and generate a uniform magnitude signal for the duration it remains higher than the control signal.
- And the signal with high frequency clock signal to generated the final output signal to be connected to the gate of the thyristor.
- Reset the integrator before the next signal.

Following the same Logic G1, G2, G3, G4, G5, and G6 are produced each shifted by 60° from

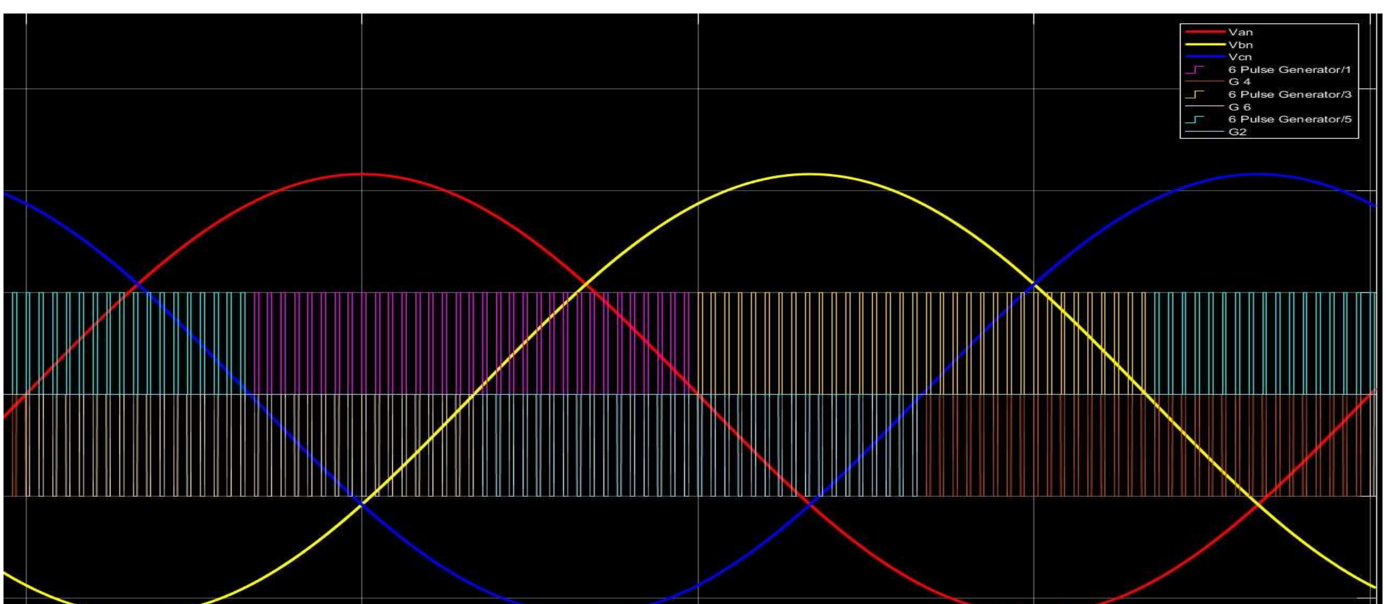

Figure 6: Pluses triggering the thyristors gate at α=30⁰

each other as shown in the figure below:

INVERTER

Here we used a single phase SPWM (Single pulse width modulation) inverter whose frequency and rms value of the output can be determined by manipulating external factors. Figure attached below explains basic working of inverter.

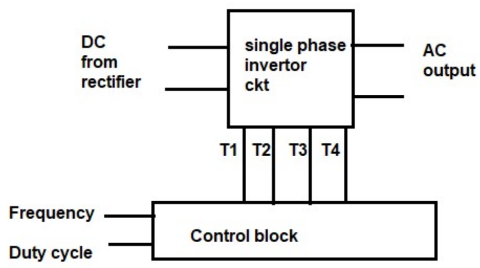

Figure 7: Basic block diagram of single phase inverter with PWM control

Single phase inverter working

Circuit Diagram:

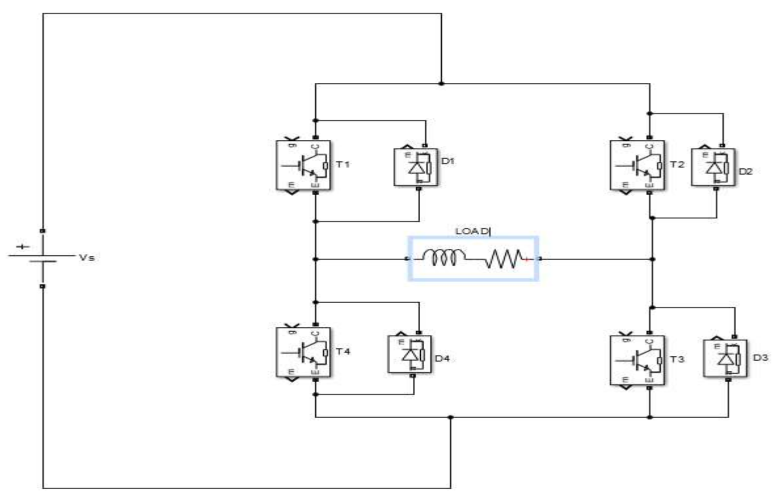

Figure 8: Circuit diagram of the single phase inverter feeding from DC source

The power circuit of a single phase full bridge inverter comprises of four thyristors T1 to T4, four diodes D1 to D1 and a two wire DC input power source V_s. Each diode is connected in antiparallel to the thyristors viz. D1 is connected in anti-parallel to T1 and so on. The power circuit diagram of a single phase full bridge inverter is shown in the figure.

Working principle:

The working principle of single phase full bridge inverter is based on the sequential triggering of thyristors placed diagonally opposite. This means, for half of time period, thyristors T3 & T4 will be triggered while for the remaining half of time period, T1 & T2 will be triggered. Only two thyristors are turned ON in half of the time period.

Carefully observe the waveform of the gating signal. You will notice that thyristors T1 & T2 are triggered simultaneously for a time T/2. Therefore, load is connected to source through T1 & T2 and hence, the load voltage is equal to the source voltage with positive polarity. This is the reason; the load voltage is shown positive & equal to V_s in the output voltage waveform.

As soon as the gate signal (i_{g1} & i_{g2}) are removed, T1 and T2 gest turned OFF. However, at the same instant gate signal (i_{g3} & i_{g4}) are applied and hence, T3 & T4 are turned ON. When T3 & T4 are conducting, load gets connected to the source. The load voltage magnitude is again V_s but with reverse polarity. This is the reason; the output voltage is shown negative in the voltage waveform.

SPWM (Single Pulse width Modulation):

In this project we have used single pulse width modulation as per controlling rms value of AC output of inverter. In brief what is done in SPWM technique, pulse width of every pulses in every cycle is to be changed symmetrically in order to achieve desired rms value. In many ways this control strategy can be implemented.

Our method of generating SPWM is explained later in ‘Pulse generation’ portion.

PULSE GENERATION OF INVERTER

In the block diagram attached below the pictorial overview of the pulse generation process will be clear.

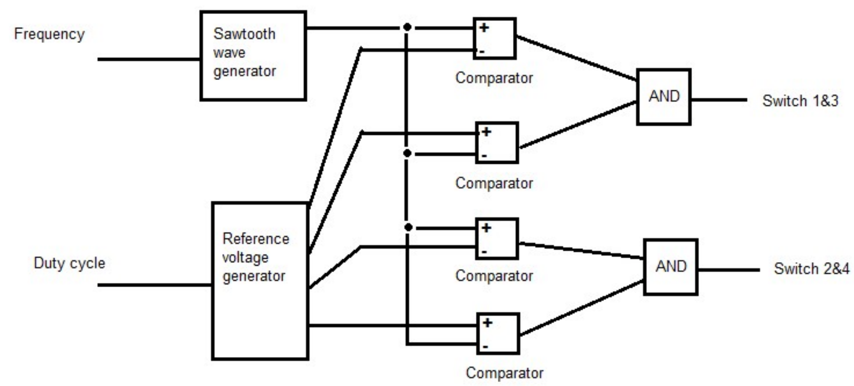

Figure 9: Pictorial representation of the circuit generating the pulses to trigger BJTs

Sawtooth wave generator:

In this block we are generating sawtooth wave of maximum value 1 of particular frequency (kHz). In order to generate the wave we have using an integrator with a gain of 1000 and the integrator gets reset as soon as output reaches 1. Thus the sawtooth wave of desired frequency is generated.

Reference voltage generator:

Let us take we are generating reference voltage for duty cycle 1. In this case for switch 1 & 3, if the ST wave gets compared with upper limit 0.5 and lower limit 0, we get desired pulse. Similarly for switch 2&4 these two limits are 0.5 and 1.

Now let us think for different duty cycle. If the duty cycle is 0.8 i.e. 80% of its one half cycle pulse will be high. In this case for switch 1&3 the band width should be less than 0.5. The following upper and lower limit will be 0.4 and 0.1. This logic is implemented in this block and it generates different reference voltages for different duty cycles and this is how SPWM is implemented.

Comparator & AND gate:

This two are together are used for bandwidth comparison. Output of AND gate will be true only when both of the comparator will be high.

❖ **Note:**

Dead time: We have chosen a dead time of 4 us.
4us is enough for switching off of a standard IGBT.

TANK CIRCUIT

Firstly, an electromagnetic compatibility (EMC) filter ensures that the power converter complies with the electromagnetic standards. After that, an ac-dc converter provides a dc-bus to supply the inverter block. The rectifier stage can be either a non-controlled stage, i.e. diode rectifier, or a controlled one. The latter implementation is used to provide an additional degree of freedom for the control system, and can be implemented either as a controlled rectifier or as a diode rectifier plus a dc-dc converter. Depending on the applications, some IH systems also include a power factor corrector block in order to increase voltage and ensure sinusoidal input current. The dc-ac power converter, also known as inverter, is the most important one and has to supply medium frequency currents to supply the inductor. The operating frequency is usually higher than 20 kHz in order to avoid audible noise and rises up to 1 MHz depending on the application. Currently, most IH systems feature either voltage source or current source resonant inverters in order to obtain efficient and high-power-density implementations. The induction heating load is usually modelled as an equivalent resistor R_{eq} and inductor L_{eq} (Fig. 3 (a)), which may be connected in series or parallel, depending on the model, and additional external inductors and/or capacitors are added to complete the resonant tank. The resonant inverter topology used can be classified either considering the type or resonance used or the number of switching devices. Considering the resonant tank, the most used configurations are the second-order series resonant (Fig. 3 (b)) and parallel resonant circuits (Fig. 3 (c)), and the third-order LLC series-parallel resonant circuit (Fig. 3 (d)). The series resonant RLC circuit, is commonly used in voltage source inverters and ensures zero mean current through the inductor, due to the series capacitor, and zero voltage switching (ZVS) conditions above the resonant frequency, i.e. zero voltage across the device during the switching process that ideally leads to zero switching losses. By contrast, the parallel-resonant RLC circuit is used in current source inverters, achieving reduced current through the switching devices and zero current switching (ZCS), i.e. switching with zero current through the device that leads to ideally zero switching losses. For this reason, this topology is chosen when high inductor current is demanded in order to reduce stress in the power devices. Finally, the series-parallel LLC circuits combines the benefits of parallel resonance with additional load short-circuit protection, making it one of the most used topologies for high power industrial applications.

Series resonant tank circuit:

The work coil is made to resonate at the intended operating frequency by means of a capacitor placed in series with it. This causes the current through the work coil to be sinusoidal. The series resonance also magnifies the voltage across the work coil, far higher than the output voltage of the inverter alone. The inverter sees a sinusoidal load current but it must carry the full current that flows in the work coil. For this reason the work coil often consists of many turns of wire with only a few amps or tens of amps flowing. Significant heating power is achieved by allowing resonant voltage rise across the work coil in the series-resonant arrangement whilst keeping the current through the coil (and the inverter) to a sensible level.

This arrangement is commonly used in things like rice cookers where the power level is low, and the inverter is located next to the object to be heated. The main drawbacks of the series resonant arrangement are that the inverter must carry the same current that flows in the work coil. In addition to this the voltage rise due to series resonance can become very pronounced if there is not a significantly sized workpiece present in the work coil to damp the circuit. This is not a problem in applications like rice cookers where the workpiece is always the same cooking vessel, and its properties are well known at the time of designing the system.

The tank capacitor is typically rated for a high voltage because of the resonant voltage rise experienced in the series tuned resonant circuit. It must also carry the full current carried by the work coil, although this is typically not a problem in low power applications.

Parallel resonant tank circuit

The work coil is made to resonate at the intended operating frequency by means of a capacitor placed in parallel with it. This causes the current through the work coil to be sinusoidal. The parallel resonance also magnifies the current through the work coil, far higher than the output current capability of the inverter alone. The inverter sees a sinusoidal load current. However, in this case it only has to carry the part of the load current that actually does real work. The inverter does not have to carry the full circulating current in the work coil. This is very significant since power factors in induction heating applications are typically low. This property of the parallel resonant circuit can make a tenfold reduction in the current that must be supported by the inverter and the wires connecting it to the work coil. Conduction losses are typically proportional to current squared, so a tenfold reduction in load current represents a significant saving in conduction losses in the inverter and associated wiring. This means that the work coil can be placed at a location remote from the inverter without incurring massive losses in the feed wires.

Work coils using this technique often consist of only a few turns of a thick copper conductor but with large currents of many hundreds or thousands of amps flowing. (This is necessary to get the required Ampere turns to do the induction heating.) Water cooling is common for all but the smallest of systems. This is needed to remove excess heat generated by the passage of the large high frequency current through the work coil and its associated tank capacitor.

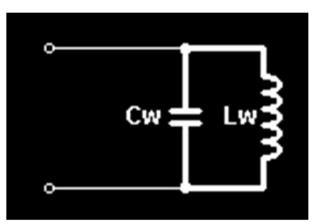

Figure 10: Parallel resonant tank circuit

In the parallel resonant tank circuit the work coil can be thought of as an inductive load with a "power factor correction" capacitor connected across it. The PFC capacitor provides reactive current flow equal and opposite to the large inductive current drawn by the work coil. The key thing to remember is that this huge current is localised to the work coil and its capacitor, and merely represents reactive power sloshing back-and-forth between the two. Therefore the only real current flow from the inverter is the relatively small amount required to overcome losses in the "PFC" capacitor and the work coil. There is always some loss in this tank circuit due to dielectric loss in the capacitor and skin effect causing resistive losses in the capacitor and work coil. Therefore a small current is always drawn from the inverter even with no work piece present. When a lossy work piece is inserted into the work coil, this damps the parallel resonant circuit by introducing a further loss into the system. Therefore the current drawn by the parallel resonant tank circuit increases when a work piece is entered into the coil.

Impedance matching

Or simply "Matching". This refers to the electronics that sits between the source of high frequency power and the work coil we are using for heating. In order to heat a solid piece of metal via induction heating we need to cause a TREMENDOUS current to flow in the surface of the metal. However this can be contrasted with the inverter that generates the high frequency power. The inverter generally works better (and the design is somewhat easier) if it operates at fairly high voltage but a low current. (Typically problems are encountered in power electronics when we try to switch large currents on and off in very short times.) Increasing the voltage and decreasing the current allows common switch mode MOSFETs (or fast IGBTs) to be used. The comparatively low currents make the inverter less sensitive to layout issues and stray inductance. It is the job of the matching network and the work coil itself to transform the high-voltage/low-current from the inverter to the low-voltage/high-current required to heat the work piece efficiently.

We can think of the tank circuit incorporating the work coil (L_w) and its capacitor (C_w) as a parallel resonant circuit. This has a resistance (R) due to the lossy work piece coupled into the work coil due to the magnetic coupling between the two conductors.

See the schematic opposite.

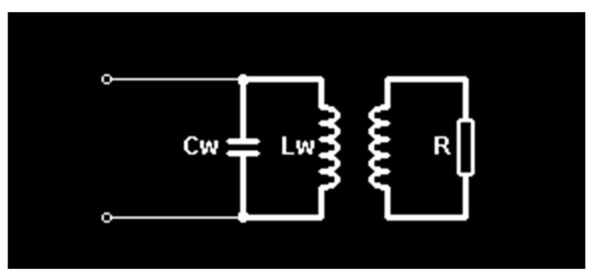

Figure 11: Impedance matching through transformer

In practice the resistance of the work coil, the resistance of the tank capacitor, and the reflected resistance of the work piece all introduce a loss into the tank circuit and damp the resonance. Therefore it is useful to combine all of these losses into a single "loss resistance." In the case of a parallel resonant circuit this loss resistance appears directly across the tank circuit in our model. This resistance represents the only component that can consume real power, and therefore we can think of this loss resistance as the load that we are trying to drive power into in an efficient manner.

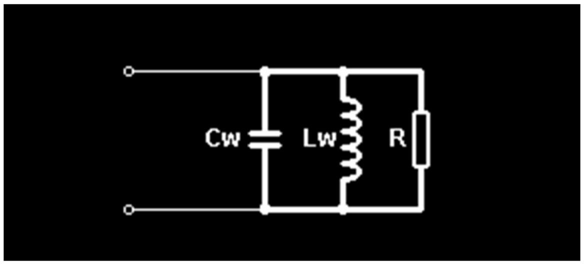

Figure 12: Impedance matching with Loss Resistance

When driven at resonance the current drawn by the tank capacitor and the work coil are equal in magnitude and opposite in phase and therefore cancel each other out as far as the source of power is concerned. **This means that the only load seen by the power source at the resonant frequency is the loss resistance across the tank circuit**. (Note that, when driven either side of the resonant frequency, there is an additional "out-of-phase" component to the current caused by incomplete cancellation of the work coil current and the tank capacitor current. This reactive current increases the total magnitude of the current being drawn from the source but does not contribute to any useful heating in the workpiece.)

The job of the matching network is simply to transform this relatively large loss resistance across the tank circuit down to a lower value that better suits the inverter attempting to drive it. There are many different ways to achieve this impedance transformation including tapping the work coil, using a ferrite transformer, a capacitive divider in place of the tank capacitor, or a matching circuit such as an L-match network.

In the case of an L-match network it can transform the relatively high load resistance of the tank circuit down to something around 10 ohms which better suits the inverter. This figure is typical to allow the inverter to run from several hundred volts whilst keeping currents down to a medium level so that standard switch-mode MOSFETs can be used to perform the switching operation.

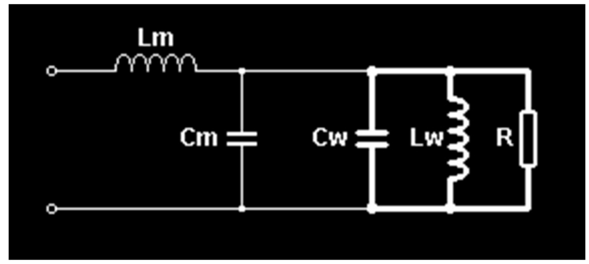

Figure 13: L-match Network

The L-match network consists of components Lm and Cm shown opposite.

The L-match network has several highly desirable properties in this application. The inductor at the input to the L-match network presents a progressively rising inductive reactance to all frequencies higher than the resonant frequency of the tank circuit. This is very important when the work coil is to be fed from a voltage-source inverter that generates a square wave voltage output. Here is an explanation of why this is so…

The square wave voltage generated by most half-bridge and full-bridge circuits is rich in high frequency harmonics as well as the wanted fundamental frequency. Direct connection of such a voltage source to a parallel resonant circuit would cause excessive currents to flow at all harmonics of the drive frequency! This is because the tank capacitor in the parallel resonant circuit would present a progressively lower capacitive reactance to increasing frequencies. This is potentially very damaging to a voltage-source inverter. It results in large current spikes at the switching transitions as the inverter tries to rapidly charge and discharge the tank capacitor on rising and falling edges of the square wave. The inclusion of the L-match network between the inverter and the tank circuit negates this problem. Now the output of the inverter sees the inductive reactance of Lm in the matching network first, and all harmonics of the drive waveform see a gradually rising inductive impedance. This means that maximum current flows at the intended frequency only and little harmonic current flows, making the inverter load current into a smooth waveform.

Finally, with correct tuning the L-match network is able to provide a slight inductive load to the inverter. This slightly lagging inverter load current can facilitate Zero-Voltage-Switching (ZVS) of the MOSFETs in the inverter bridge. This significantly reduces turn-on switching losses due to device output capacitance in MOSFETs operated at high voltages. The overall result is less heating in the semiconductors and increased lifetime.

In summary, the inclusion of an L-match network between the inverter and the parallel resonant tank circuit achieves two things.

1. Impedance matching so that the required amount of power can be supplied from the inverter to the work piece,
2. Presentation of a rising inductive reactance to high frequency harmonics to keep the inverter safe and happy.

In practice the resistance of the work coil, the resistance of the tank capacitor, and the reflected resistance of the work piece all introduce a loss into the tank circuit and damp the resonance. Therefore it is useful to combine all of these losses into a single "loss resistance." In the case of a parallel resonant circuit this loss resistance appears directly across the tank circuit in our model. This resistance represents the only component that can consume real power, and therefore we can think of this loss resistance as the load that we are trying to drive power into in an efficient manner.

OPEN LOOP CONTROL STRATEGY

As of now the two converter circuits are not attached we are describing here individual control strategy of them.

1. Three Phase Controlled Rectifier Circuit

This converter is converting a three phase supply into an almost constant dc output whose amplitude can be varied by triggering thyristor gates at particular time. Firing the thyristor gates at different instants is called “Firing Angle or α Delay”. The firing circuit gives a triggering pulse to gate of thyristor to switch it ON. There are 6 thyristors and each thyristor pair is ON for 120°. So, by varying the value of α between 0° to 120° we can get required DC output (using filters).[1]

2. Single Phase Inverter

This converter is converting the DC output of rectifier taking it as input and giving single pulse periodic AC signal as output. By this converter we will be controlling the final AC output frequency and the duration of pulse in one period in output (or indirectly RMS value of output signal).

Here the semiconductor switches used are IGBT. So, it will remain ON for only that period for which gate signal of IGBT is ON. By this gate signal control the pulse duration of output can be controlled and eventually the RMS value can be controlled. The frequency of inverter output signal determines the depth of penetration of heat in the workpiece. So, it is also necessary to control the frequency of inverter output. There is a circuit employed for this purpose in the control circuit of inverter that controls the output frequency. We just need to give the value of frequency and get the desired output (frequency) signal.[2]

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[1] Control strategy is fully elaborated in Appendix.
[2] Control strategy is fully elaborated in Appendix.

CLOSED LOOP CONTROL STRATEGY

Here we will be describing the closed loop control scheme of the two circuits independently.

1. Three Phase Controlled Rectifier Circuit

In this converter output is the DC signal. So, there is a constant block in the simulation circuit which takes the required DC signal amplitude value which is passed to the circuit like a feedback control system using a Proportional-Integrator (PI) controller.

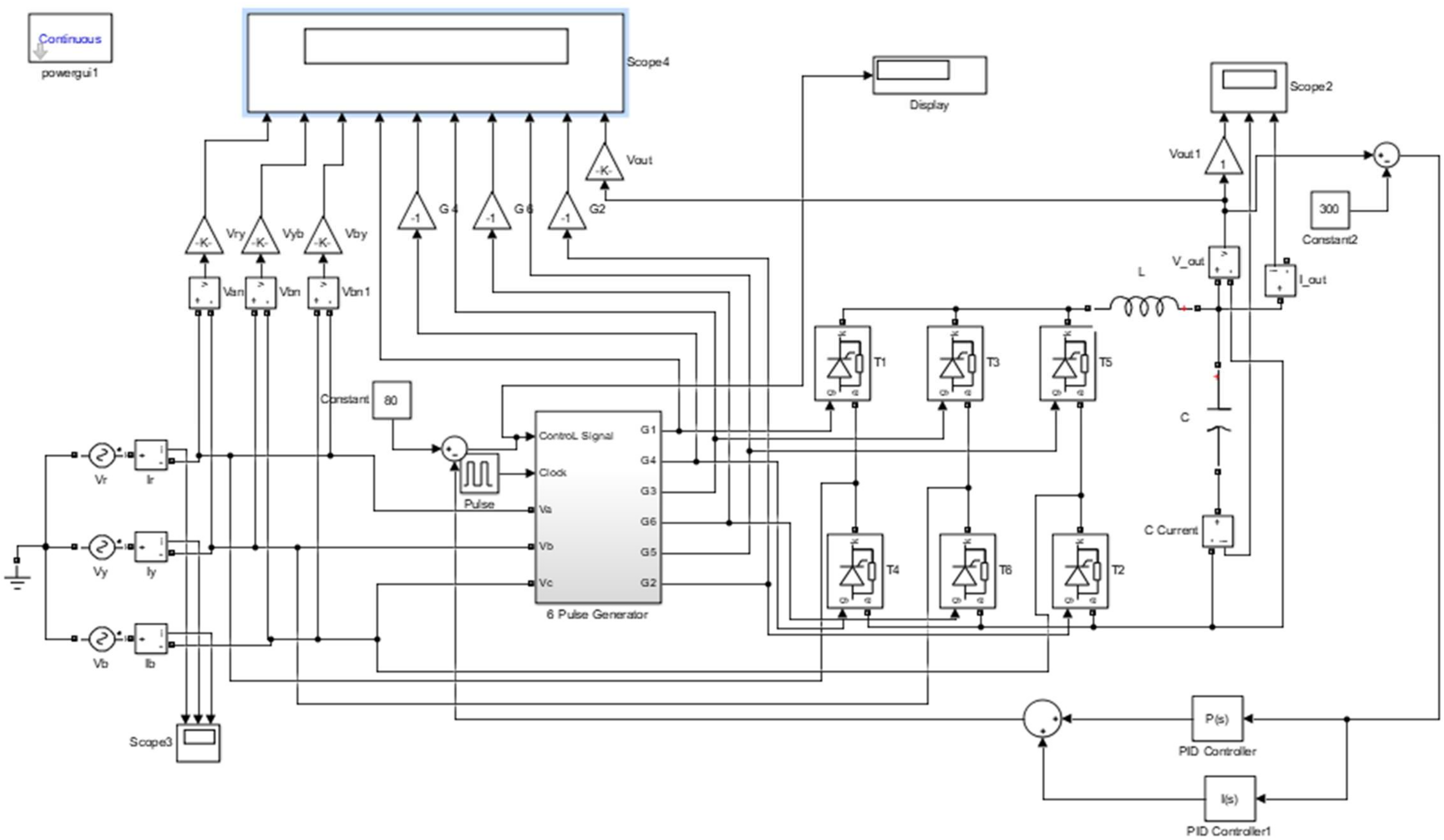

Figure 14: Rectifier Circuit with Closed Loop Control

2. Single Phase Inverter

In this converter the required signal is the RMS value of output AC signal which is first compared to the inverter output signal's RMS value and then that error signal is fed back to the inverter circuit pulse duration control signal using an adder. The feedback path contains a Proportional-Integrator (PI) controller which determines the transient and steady state response of the output signal.

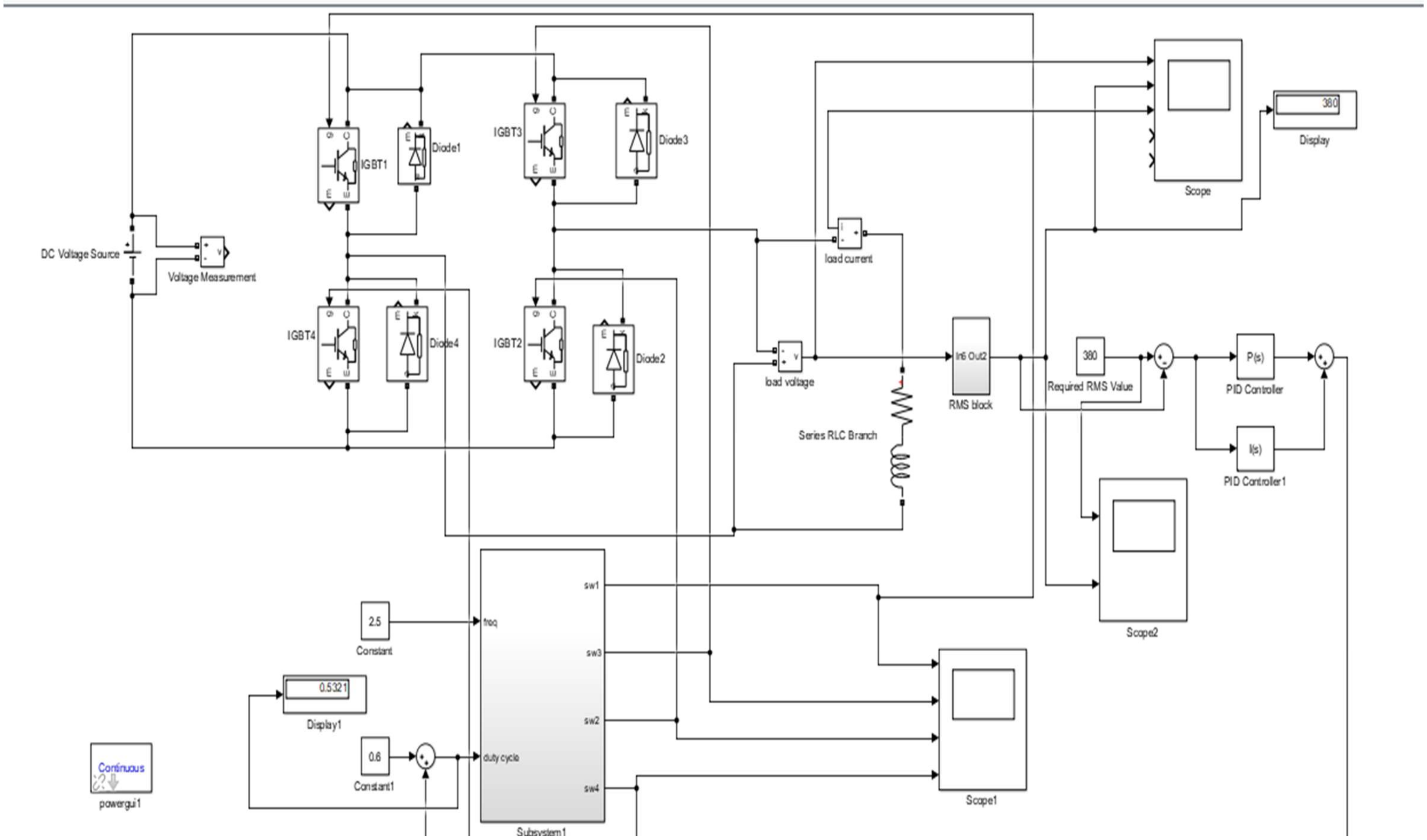

Figure 15: Inverter Circuit with Closed Loop Control

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APPENDIX

1. Firing Angle Control of Rectifier:

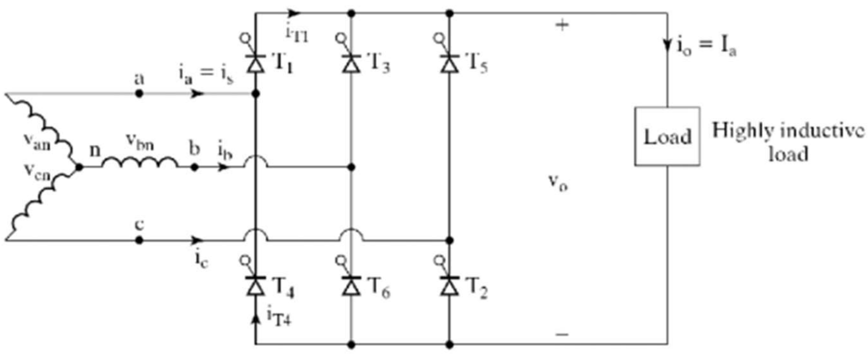
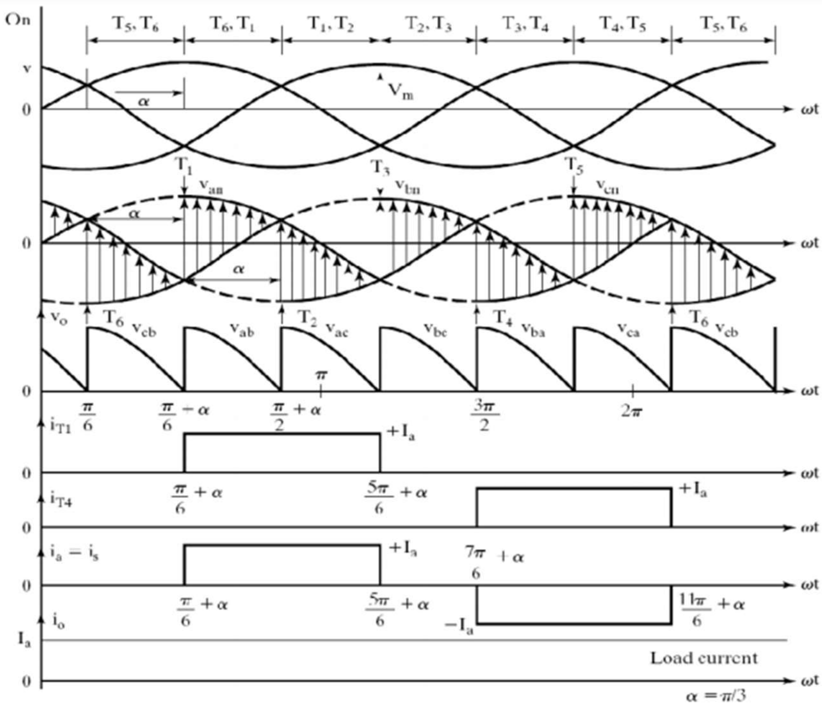


Figure 16: Power Circuit of Rectifier

At ωt = (π/6+α), thyristor T6 is already conducting when the thyristor T1 is turned on by applying the gating signal to the gate of T1. During the time period ωt = (π/6+α) to (π/2+α), thyristors T1 and T6 conduct together and the line to line supply voltage v_{ab} appears across the load. At ωt = (π/2+α), the thyristor T2 is triggered and T6 is reverse biased immediately and T6 turns off due to natural commutation. During the time period ωt = (π/2+α) to (5π/6+α), thyristor T1 and T2 conduct together and the line to line supply voltage ac v appears across the load. The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23, and so on.



The output load voltage consists of 6 voltage pulses over a period of 2π radians, hence the average output voltage is calculated as

$$V_{O(dc)} = V_{dc} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_O.d\omega t \qquad ;$$

$$v_O = v_{ab} = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right).d\omega t$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha = \frac{3V_{mL}}{\pi}\cos\alpha$$

Where $V_{mL} = \sqrt{3}V_m =$ Max. line-to-line supply voltage

The maximum average dc output voltage is obtained for a delay angle α = 0,

$$V_{dc(\max)} = V_{dm} = \frac{3\sqrt{3}V_m}{\pi} = \frac{3V_{mL}}{\pi}$$

The normalized average dc output voltage is

$$V_{dcn} = V_n = \frac{V_{dc}}{V_{dm}} = \cos\alpha$$

The rms value of the output voltage is found from

$$V_{O(rms)} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_O^2 .d(\omega t)\right]^{\frac{1}{2}}$$

$$V_{O(rms)} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_{ab}^2 .d(\omega t)\right]^{\frac{1}{2}}$$

$$V_{O(rms)} = \left[\frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} 3V_m^2 \sin^2\left(\omega t + \frac{\pi}{6}\right).d(\omega t)\right]^{\frac{1}{2}}$$

$$V_{O(rms)} = \sqrt{3}V_m\left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}\cos 2\alpha\right)^{\frac{1}{2}}$$

2. Simulink firing Circuit of the three-phase rectifier:

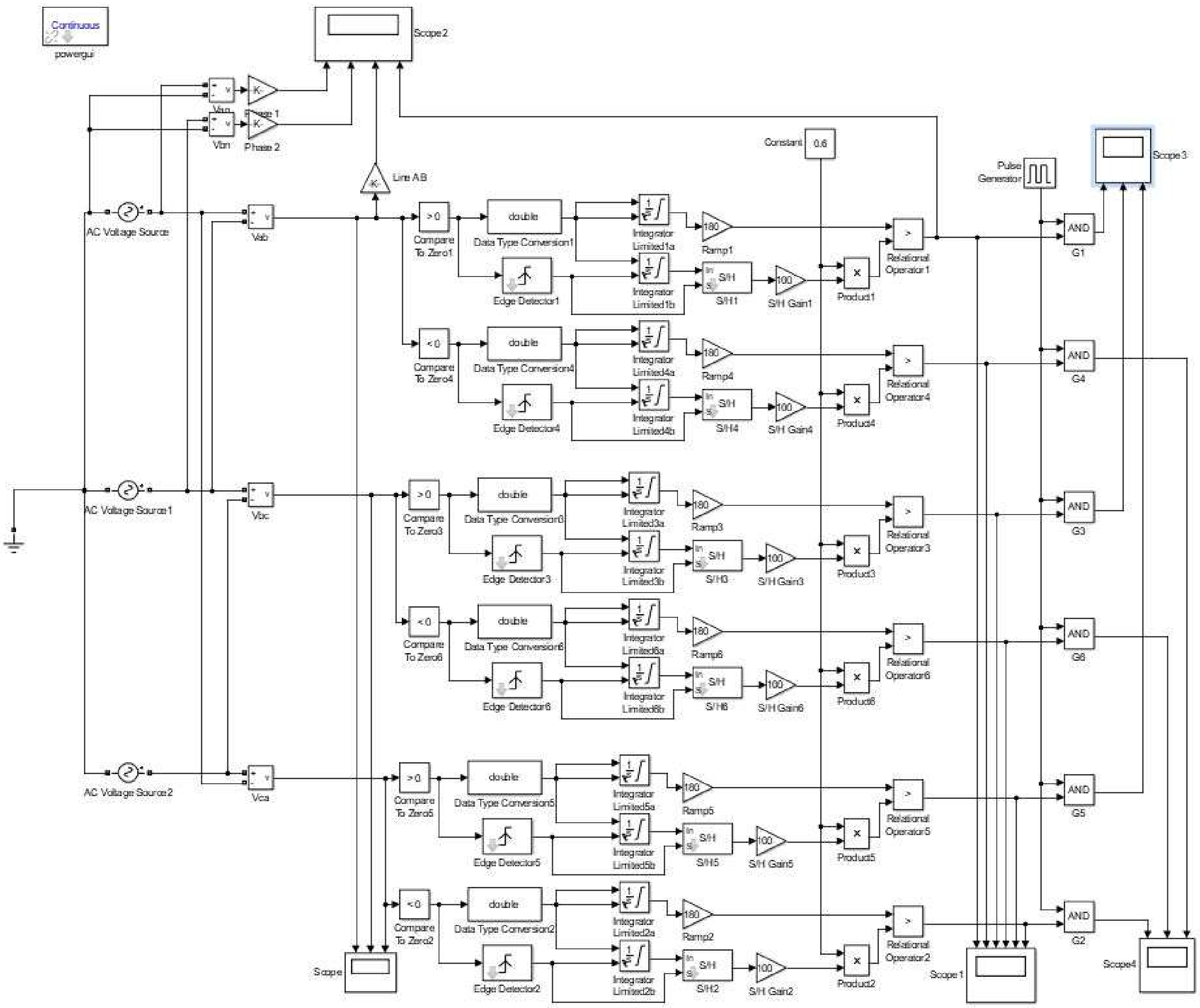


Figure 17: Rectifier Firing Circuit

3. Rectifier Circuit: Closed Loop configuration:

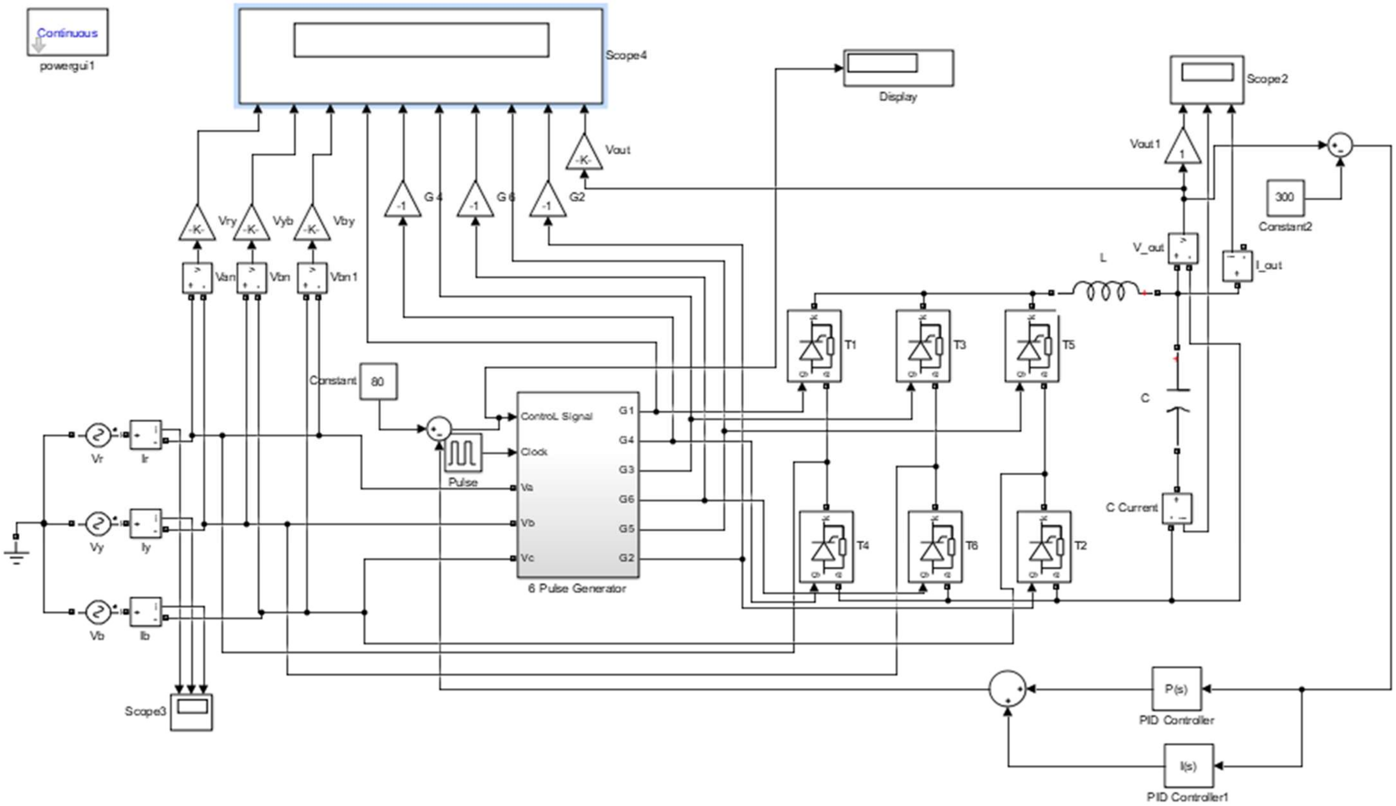


Figure 18: Rectifier Circuit Closed Loop Control

4. Rectifier Output Waveforms (Open Loop)

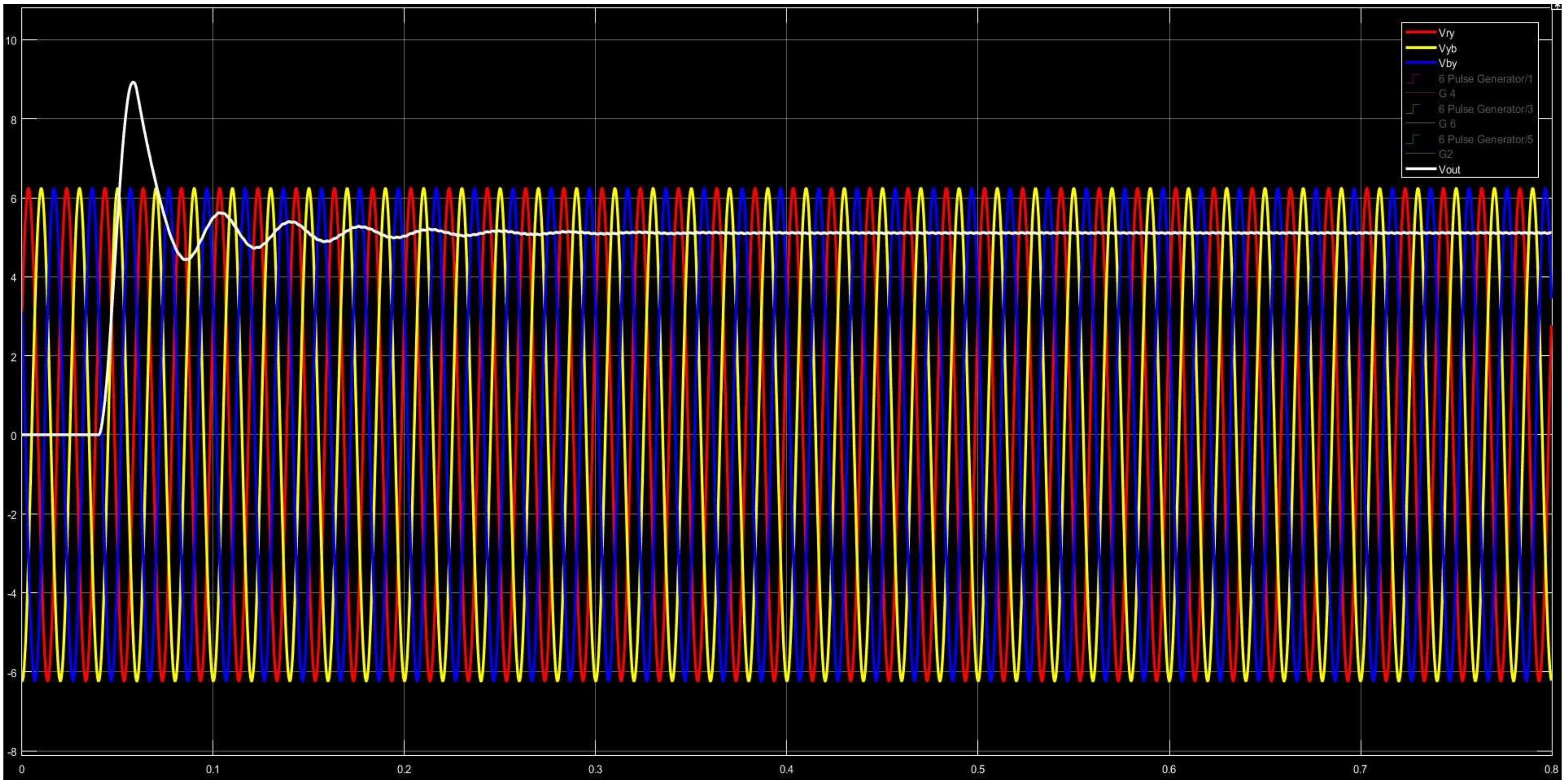


Figure 19: Plot of rectifier output voltage, load current, and capacitor current at α=30⁰

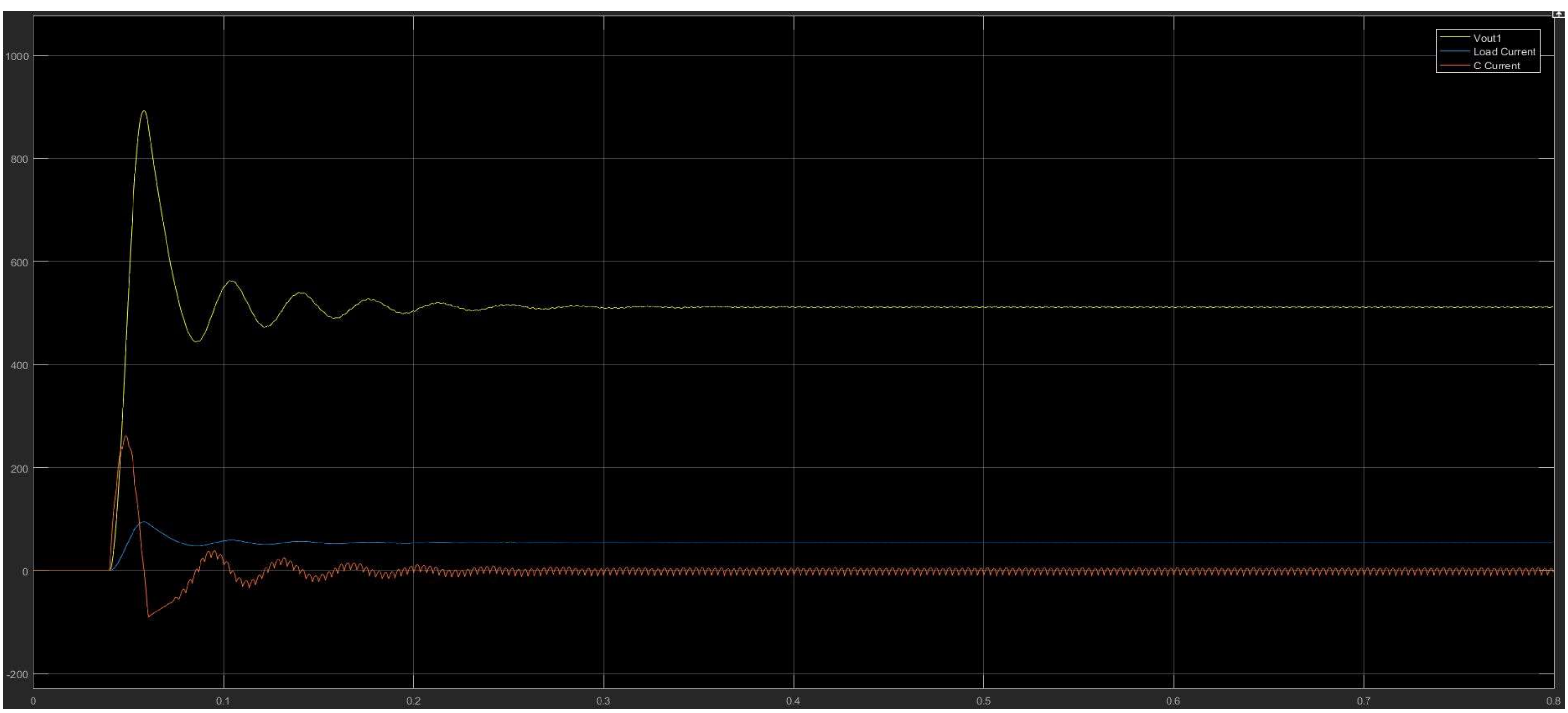


Figure 20: Plot of line voltages and output voltage of the rectifier at α=30⁰

5. Single Pulse Width Modulation of inverter:

   In this technique the gate of the IGBT switch is triggered for the required interval with respect to required frequency of output of inverter. Let's say we need the duty cycle to be 50% then the gate signal will be ON for only half of the time and in other half it will be OFF.

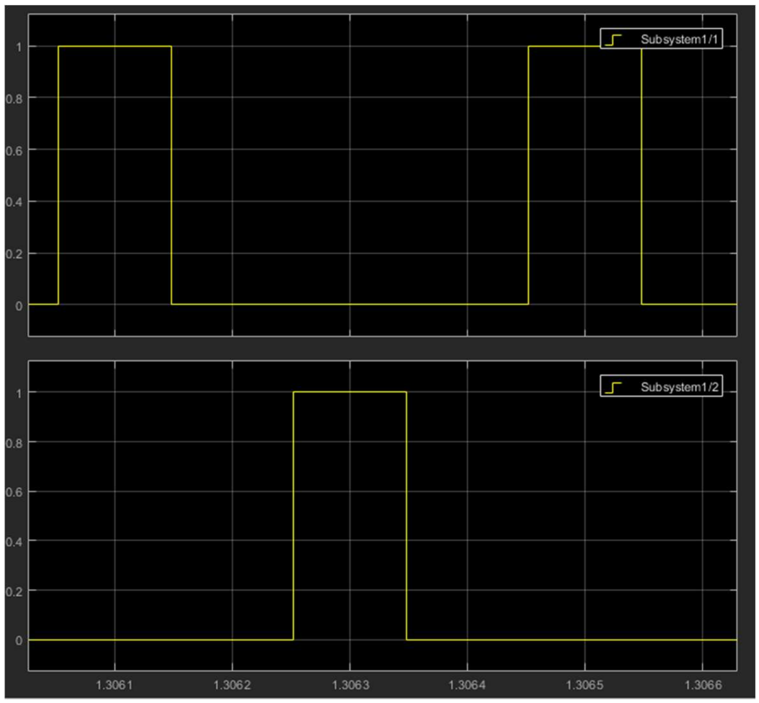


Figure 21: Gate Signals of two same branch switches of Inverter

This waveform is for 50% duty cycle (almost) for frequency 2.5kHz, i.e. , for 1 half period(2 x 10^{-4} sec), the pulse duration is 10^{-4} sec. Here the duration for which signal is high is 10^{-4} sec. Both frequency and pulse width are controlled simultaneously in inverter.

6. Inverter Circuit:

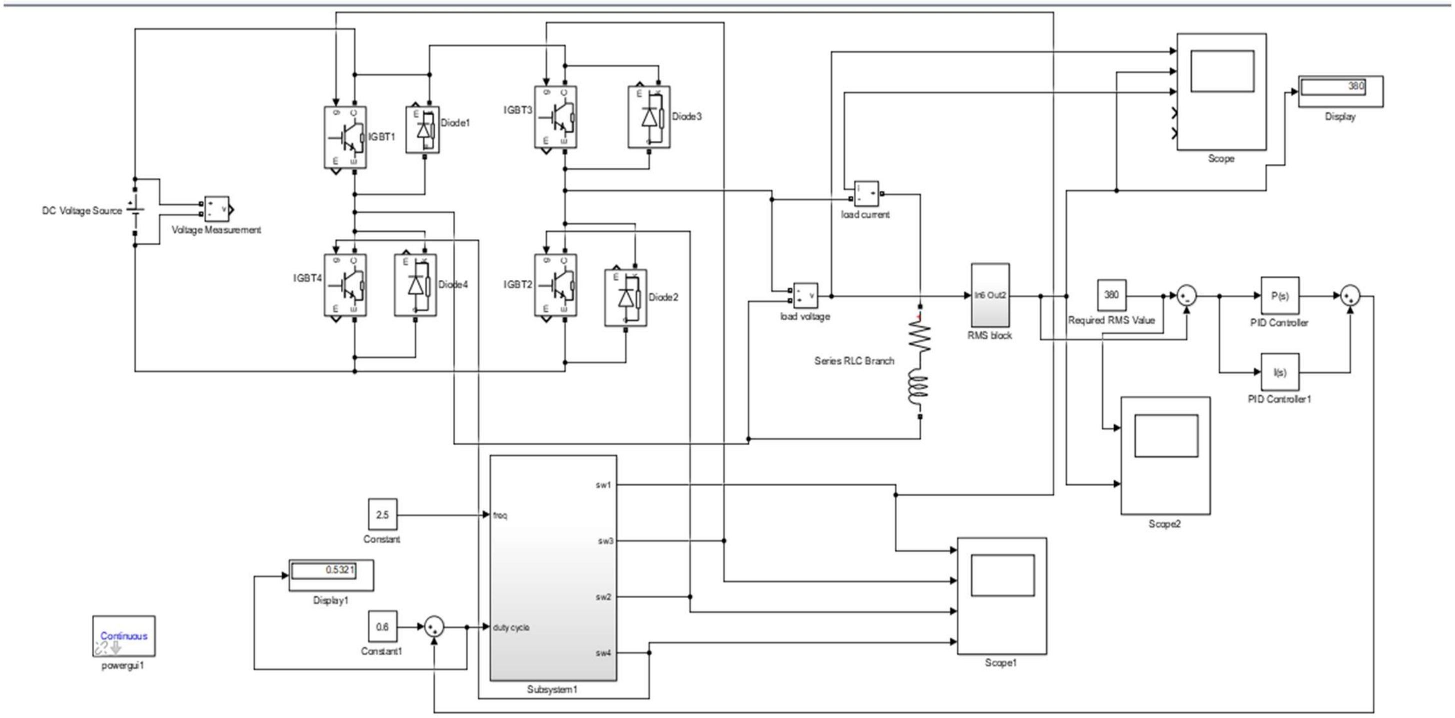


Figure 22: Inverter Circuit with Closed Loop Control

7. Inverter Output Waveforms (Closed Loop):

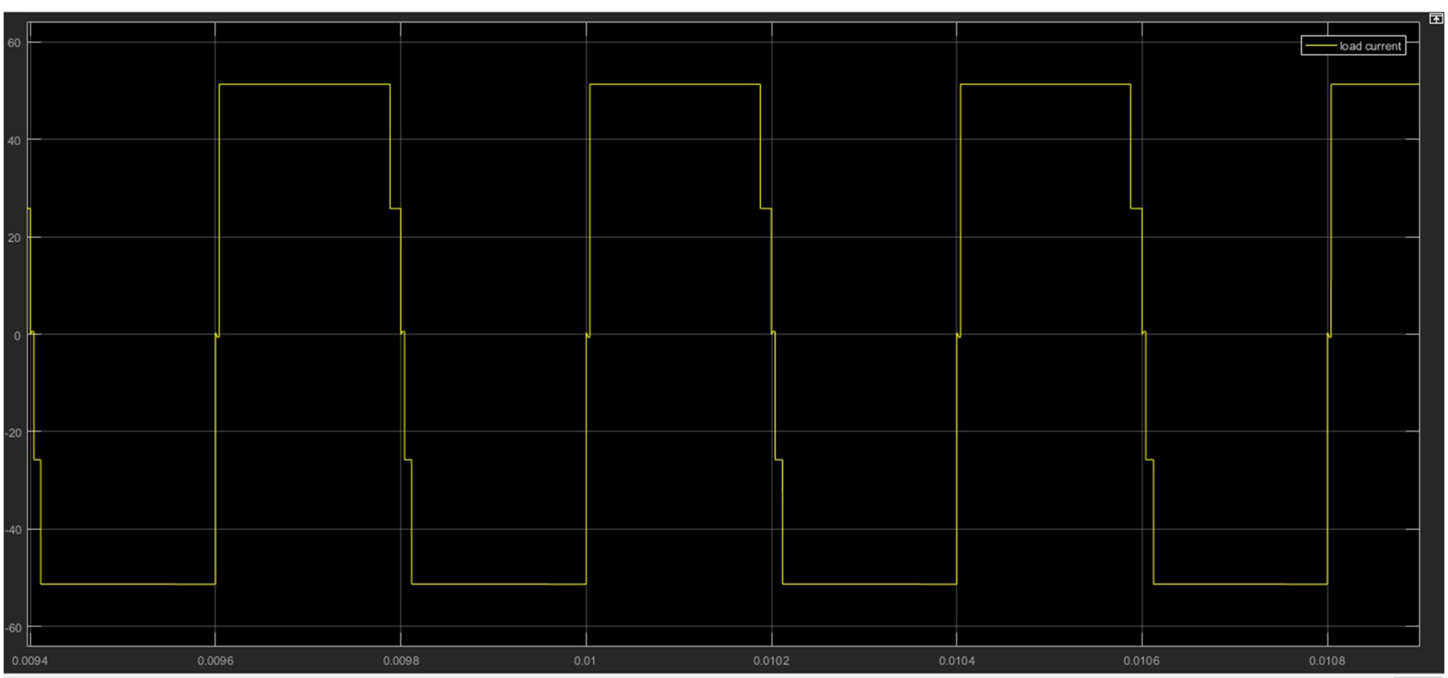


Figure 23: Load Voltage

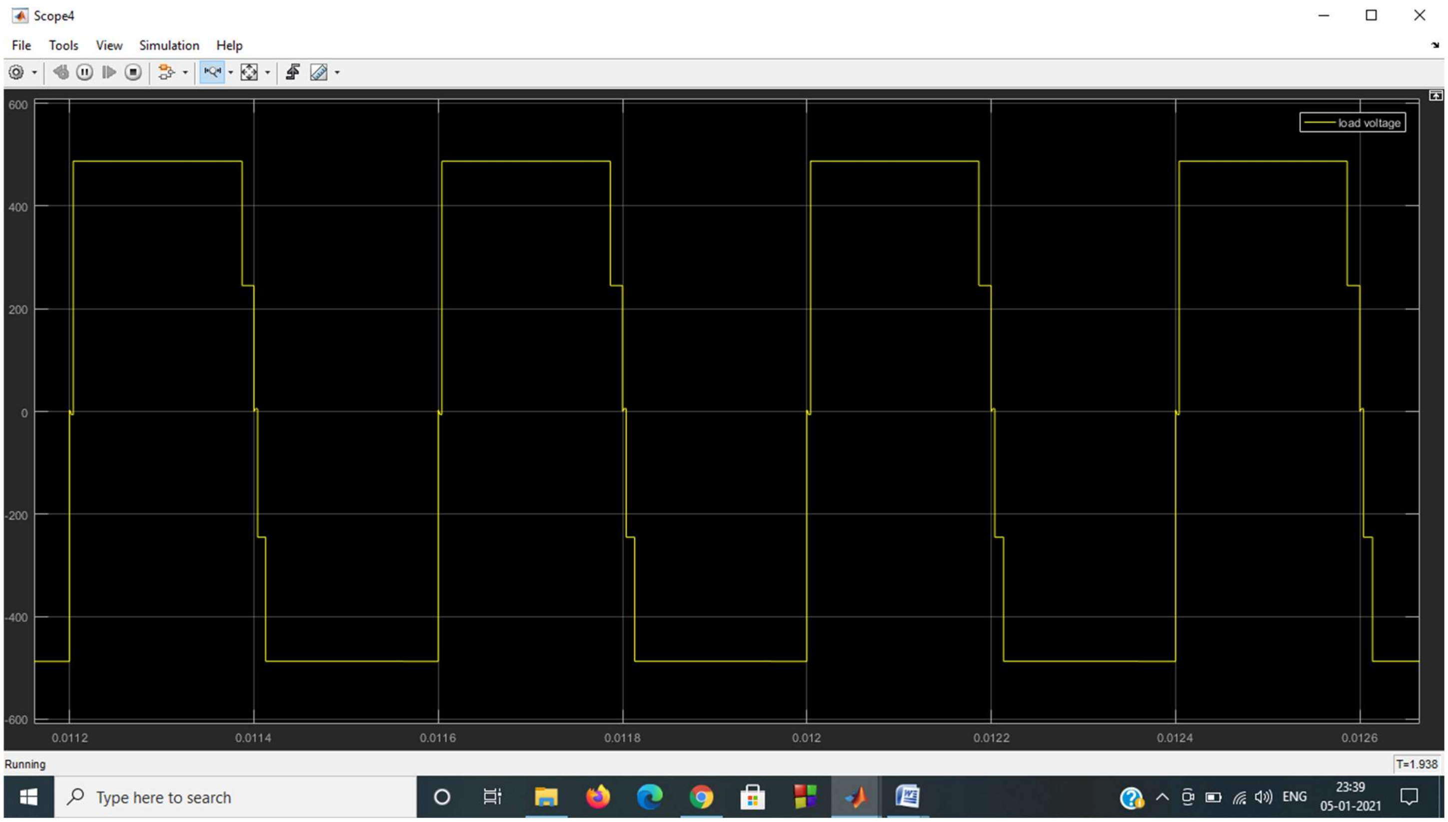


Figure 23: Load Current

Figure 24: RMS of Inverter Output Signal