Reducing Switching Losses of Resonant Inverter

THESIS SUPERVISER

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Abstract

Inverter is used in different purposes of lives. Inverters are required in a variety of applications including electronic ballasts for gas discharge lamps, induction heating and electrosurgical generators. These applications usually require a sinusoid of tens or hundreds of kHz having moderate or low harmonic distortion. Induction heater is another field where inverter is needed. It is one of the popular techniques of producing high temperature. Since the inverter has been invented long ago now different types of topologies came to light. Resonant inverter is one of them. Voltage and current source inverter was invented before resonant inverter, but resonant inverter has brought something new in engineering society. Now here is a point why resonant inverter is more important than voltage and current source inverter especially for those applications where output power control is needed. A very common term in electrical field is switching loss. In normal inverter circuits when the switches swap their positions they consume some powers, as they conduct their activities when both current and voltage are nonzero. As a result of imperfect switching causes power loss which is strongly unexpected. Moreover with the increase of switching frequencies power loss increases. As expected smaller size filter components needed higher frequencies. So the invented solution for avoiding the power loss is using a new type of inverter which is known as resonant inverter. The most significant part of resonant inverter is, here switching takes place when voltage and current are zero which is known as 'soft switching'. Since switching takes place in zero voltage and current stage there is no possibility of power loss in resonant inverter.

Chapter 1

Resonant Inverter Background

1.1 Introduction

Inverter is now commonly used equipment in our engineering application and also in daily life. In Electrical engineering inverter means an electronic device or circuitry that changes dc power to an ac power at a desired output voltage and frequency. The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. The inverter does not produce any power; the power is provided by the DC source. The classification of inverters is not straight forward. Following is way to classify the inverters.

1.2 Classification of Inverter

There are different ways to classify inverters. [1][2]

(a) According to the semiconductor device used:
(b) According to the input source
(c) According to circuit configuration
(d) According to output waveshape
(e) According to output phases
(f) According to modulation technique
(g) According to application

(a) Semiconductor device Used:

i) Line commutated inverter

ii) Forced commutated inverter

Line commutated inverters operate at line frequency. SCRs are used as switching devices. SCR has large power handling capability. AS a result use of this type is prominent in high power application but not suitable for high frequency generation. This makes the inverters bulkier and costlier.

For low or medium power application forced commutated inverters having gate controlled turn off devices are used. A list of gate controlled devices are BJT,MOSFET,IGBT,GTO,SIT etc.

(b) **According to the input source**:

According to the input source , inverters may be of current source type or voltage source type. For a current source inverter input current is fixed and voltage depend on the load used. Similarly for a voltage source inverter input voltage is fixed and the current depends on the connected load. Use of current source inverter is limited to high power application and not so common. Voltage source inverters are the main concern in this thesis.

(c) **According to circuit configuration**:

Inverters are classified as half bridge or full bridge type. The bridge is constructed by power semiconductor devices. For single phase inverter two legs having two devices in each leg are present. At the output the maximum voltage arises is the connected dc source. For half bridge configuration one of the legs of the bridge is constructed by two equal rating capacitors and maximum output level achieved is half of the input source.

(d) **According to output waveshape** :

According to output waveshape inverters can be classify as square wave inverter, quasi square wave inverter and sine-wave inverter. For low power application square wave inverters may be used but for sensitive loads sine wave inverter is a must. In quasi-square wave inverter switching of the semiconductor devices are made in such a way as between high and low level transition an intermediate zero level exist. As a result THD of the output ave is better than square wave inverter.

(e) **According to the phases**:

Inverters can be classified as single phase or three phase type. Depending upon the load phases single or there phase inverters constructed.

(f) **According to the modulation technique**:

According to the modulating wave used the inverters can be constructed as square wave inverter or Pulse Width Modulated (PWM) inverters. In PWM inverters the output voltage and frequency can be controlled by changing the modulating signal. PWM inverters are also called switch mode inverter.

(g) According to Application:

The most used way to classify inverter according to application is

i. DC power source utilization

ii. Uninterruptible power supplies

iii. Electric motor speed control

iv. Power grid

v. Solar

vi. Induction Heating

vii. HVDC power transmission

viii. Electroshock weapons

1.3 Resonant Inverter

In case of switch mode or PWM technique, imperfect switching is a vital contributor to power loss in converters. Switching devices absorb power when they turn on or off if both voltage and current are nonzero during transition. As the switching frequency increases the transition occur more frequently and switching stress increases and average power loss in the device increases. The steep rise and snap of high current increases Electro Magnetic Interference (EMI) due to large di/dt and dv/dt. This power loss generates heat. As a result heat sink must be designed to drive out heat for proper functioning of the unit.

To keep the switching losses low, fast and quick switching devices is desirable. The increase of switching frequency minimizes the lower order harmonics in PWM type application which in turn reduce the size of reactive component and filter circuits. Nonetheless, the acoustic noise becomes significant. The increase of switch stess and EMI has new design challenge. One way of dealing with stess on switch is to use snubber circuits. Snubbers are included in circuit so that during turn ON/OFF the stess is bypassed through the snubber. As a result stress on switch reduces but not the loss during switching. So no significant improvement on switching loss happens.

Researchers then tried to find out a new solution that can reduce switching losses. Here comes the idea of Resonant converters where the concept of LC resonance is utilized during switching instances. The current and/or voltage of an LC resonant circuit undergo zero level periodically. If the switching of the converters turn on/off is synchronized with zero voltage /current level , the switching losses, stress on devices, EMI generated reduced.[6]

1.4 Classification Resonant Inverter

Like other resonant converters, resonant inverters are classified as:

i. Load resonating or self-commutating
ii. Resonant switch ZVS/ZCS
iii. Resonating dc link
iv. Resonating ac link

In this thesis first two of the inverter categories will be considered. Before going through resonant inverter it should be known what electrical resonance is. Electrical resonance occurs in an electric circuit at a particular resonance frequency when the imaginary parts of impedances or admittances of circuit elements cancel each other. In some circuits this happens when the impedance between the input and output of the circuit is almost zero and the transfer function is close to one. Resonant inverters are electrical inverters based on resonant current oscillation.

i)Load resonating or self-commutating*:*

Both series and parallel LC resonating circuits are used. Oscillating voltage or current due to LC resonance in the tank are applied to the load.The inverter switches can be switched at zero voltage or zero current. They can be

a. Series resonance

b.Parallel resonance

c.Hybrid Resonance (i.e. combination of series and parallel resonance)

a. Series resonant tank circuit: It magnifies the voltage across the work coil higher theno/p of the inverter. Disadvantages of this circuit are it carry same current that flow through the coil.

b. Parallel resonant tank circuit: Magnify the current to work coil higher than current capability of inverter. Inverter has to carry part of the load current.

c. Hybrid Resonance tank circuit: Magnify the current to work coil higher than current capability of inverter. Inverter has to carry part of the load current Power factor is improved because of additional capacitor and inductor in the circuit.

For the selection of resonance circuit series and parallel resonance circuits has their own drawback like in series resonance for higher kW rating the current which passes through the tank coil comes from the inverter this has drawback that switch may not be available or capable of handling this huge power. Whereas in case of parallel resonance inverter has to carry part of load current apart from this advantage the disadvantage of this topology is very poor P.F. and low efficiency.Hybrid resonance circuits have advantage form above two topologies firstly, if LCL load is used in resonant tank circuit than inverter has to carry only part of load current as well as it is not needed not to worry about the rating of switch this third order resonant circuit has advantage that voltage boost up is done with primary inductance and P.F. is corrected by capacitor.

ii) Resonant Switch Converters:

- Resonant convertors are used to reduce the switching losses & reduce stress on device.

- They turn-off & on device at zero voltage & or current.

- Basically two types of resonant converters [5]

a. Zero current switching

b. Zero voltage switching

Zero current switching:ZCS can eliminate the switching losses at turn-off and reduce the switching losses at turn-on.ZCS is particularly effective in reducing switching losses for power devices (such as IGBT, MOSFET or any other controlled switch) with large tail current in the turn-off process.By the nature of resonant tank and ZCS, the peak switch current is much higher than that in a square wave. In addition, a high voltage becomes established across the switch in the off- state after the resonant oscillation. When switch on the capacitor will be discharged through the switch causing significant power loss at high frequency and high voltage. Circuit shown in Fig 1.1

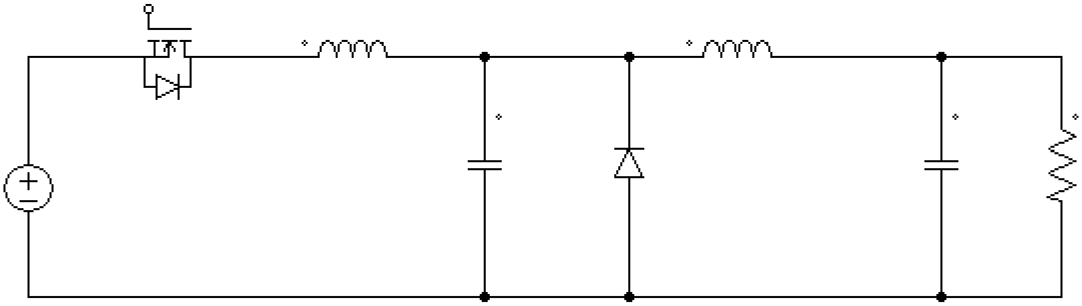


Fig.1.1: Circuit diagram of zero current switching

Zero voltage switching: ZVSuses in frequency conversion circuit and load conversion system. ZVS is more prefers over ZCS at high switching frequency, due to internal capacitance associated with switch.For both ZCS and ZVS, the output voltage control can be achieved by varying the frequency. ZCS operates with a constant on-time control, whereas ZVS operates with a constant off-time constant. Circuit Shown in Fig 1.2

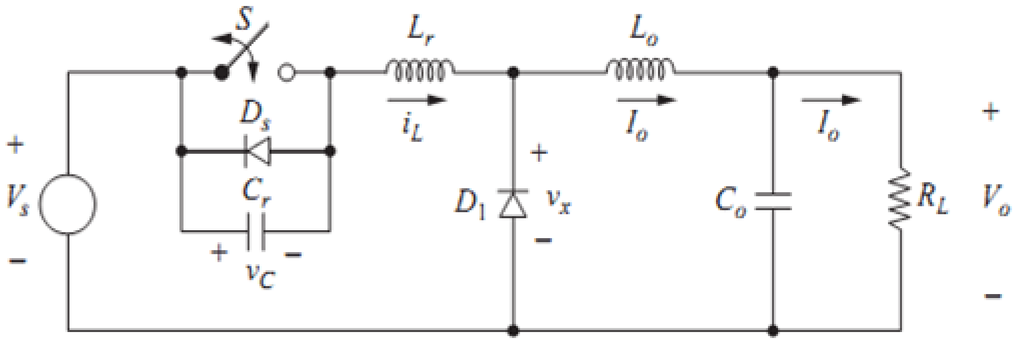


Fig.1.2. Circuit diagram of zero voltage switching

1.5 Analysis of load Resonant Inverter

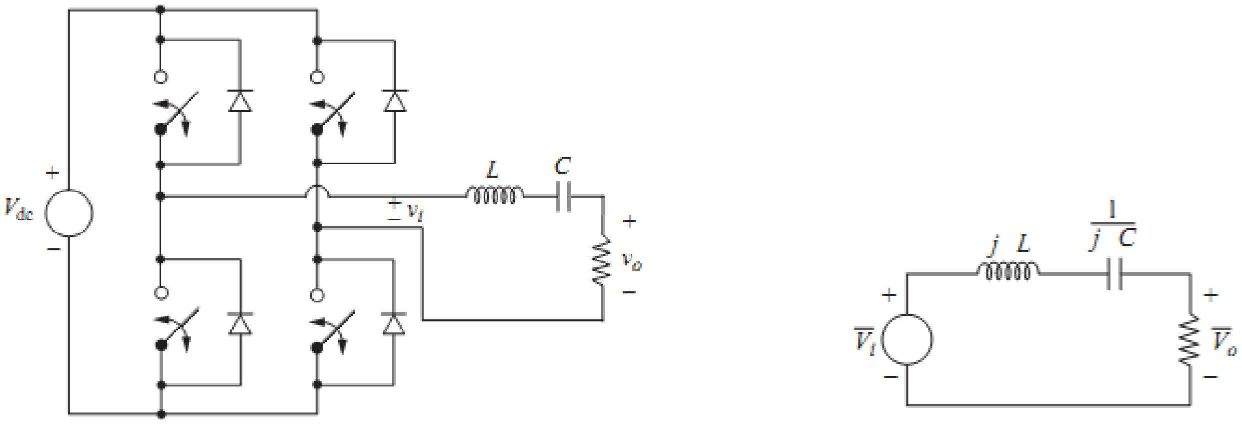
Our topic is resonant inverter so it is time for to go through the background of resonant inverter now. Before going through resonant inverter it should be known what electrical resonance is. Electrical resonance occurs in an electric circuit at a particular resonance frequency when the imaginary parts of impedances or admittances of circuit elements cancel each other. In some circuits this happens when the impedance between the input and output of the circuit is almost zero and the transfer function is close to one. Resonant inverters are electrical inverters based on resonant current oscillation.In series resonant inverters the resonating components and switching device are placed in series with the load to form an under damped circuit. The current through the switching devices fall to zero due to the natural characteristics of the circuit. If the switching element is a thyristor, it is said to be self-commutated.

1.5.1 Series Resonant Inverter Scheme

There are various configurations of series resonant inverters, depending on the connections of the switching devices and load. The series inverters may be classified into two categories:[1]

1. Series resonant inverters with unidirectional switches.
2. Series resonant inverters with bidirectional switches.

Basic Concept: In a series resonant inverter, an inductor and a capacitor are placed in series with a load resistor. The switches produce a square wave voltage, and the inductor-capacitor combination is selected such that the resonant frequency is the same as the switching frequency. Circuits shown in Fig 1.3a and phasor equivalent is shown in 1.3(b).[1]



(a) (b)

Fig 1.3: (a) Resonant Inverter Circuit. (b) Phasor equivalent of series RLC:

In a series resonant inverter an inductor & a capacitor is placed in series with a load resistor. The analysis begins by considering the frequency response of second figure.

$$\frac{V_o}{V_i} = \frac{R}{\sqrt{R^2 + (\omega L - (1/\omega C))^2}} = \frac{1}{\sqrt{1 + ((\omega L/R) - (1/\omega RC))^2}}$$

……………… (1-1)

Resonance is at the frequency

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

……………………………………………………………….. (1-2)

At resonance, the impendences of the inductance & capacitor cancel each other. So the load appears as a resistance. If the bridge output is a square wave at frequency f_0, the LC combination acts as a filter, passing the fundamental frequency and attenuating the harmonics. If the third and higher harmonics of the square wave bridge are effectively removed, the voltage across the load is essentially a sinusoid at the square wave's fundamental frequency.

$$V_1 = \frac{4V_{dc}}{\pi} \qquad \text{……………………………………………………………………..……… (1-3)}$$

Quality factor (Q): The frequency response of the filter could be expressed in terms of bandwidth, which is also characterized by the quality factor Q. THD of the voltage across the resistor is reduced by increasing Q. Increasing inductance & reducing capacitance increase Q.

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 RC} \qquad \text{……………………………………………………………………. (1-4)}$$

$$\frac{V_o}{V_i} = \frac{1}{\sqrt{1 + Q^2((\omega/\omega_0) - (\omega_0/\omega))^2}} \qquad \text{………………………………………………… (1-5)}$$

Switching Losses: The power absorbed by the switches of resonant inverter is lower than nonresonant inverter. If the switching is at the resonant frequency & Q is high, the switches operate when the load current is nearly zero or at zero.

Amplitude control: If the frequency of the load voltage is not critical, the amplitude of the fundamental frequency across the load resistor can be controlled by shifting the switching frequency off of resonance. Power absorbed by the load resistor is thus controlled by the switching frequency. Induction heating is an application. The switching frequency should be higher than resonance when controlling the output. Higher switching frequencies move the harmonics of the square wave higher which increases the effectiveness of the filter.[1]

1.6 Analysis of switched Resonant Inverter:

When the series & parallel resonant inverters are operated below resonance, ZSC (zero currentswitching) phenomenon occurs. Here the circuit causes the switching device's current to go to zero before it is turned off.

InFig.1.4 the switch output voltage $v_s(t)$, and its fundamental component $v_{s1}(t)$, and as well as approximately sinusoidal load current $i_s(t)$ are shown. At frequency below resonance, the input impedance of load/tank network $Z_i(s)$ is dominated by the capacitance of the tank.

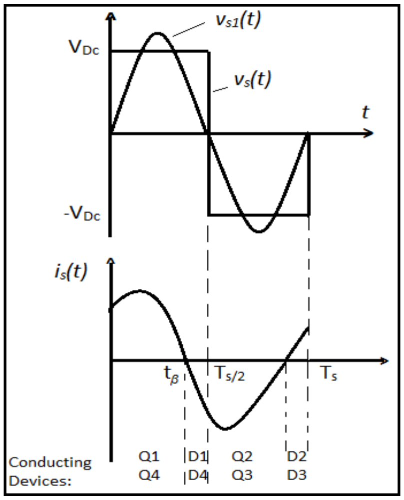


Fig. 1.4: Zero Current Switching

Hence the tank presents an effective capacitive load to the bridge, so the tank current $i_s(t)$ leads the fundamental switch voltage $v_{s1}(t)$. As a result, zero crossing of current waveform occurs before zero crossing of voltage.

For the first half cycle $0<t<T_{s/2}$ the switch output voltage v_s is equal to $+V_{Dc}$. For the time $0<t<t_\beta$ the current $i_s(t)$ is positive & during this time the switches Q1 & Q4 operates. When the current

$i_s(t)$ becomes negative over the interval $t_\beta<t<T_{s/2}$ then diodes D1 & D4 conducts. The situation during $T_{s/2}<t<T$ is symmetrical.

Since the current $i_s(t)$ leads $v_s(t)$ the switches conduct before their respective antiparallel diodes. During $t_\beta<t<T_{s/2}$. When the diode D1 operates at any time by turning off Q1 switching loss is reduced. The circuit naturally causes the switch turn-off transition to be lossless, and a long turn off switching times can be tolerated. Therefore, zero current switching occurs when the resonant tank or load represents an effective capacitive load**.**[2]

1.6.1 ZVS Operation in Full Bridge

Zero Voltage Switching (ZVS) phenomenon occurs when the resonant inverter is operated above resonance frequency of the tank network/load. Then the circuit causes the switch voltage to become zero before the controller turns the switch on. With a minor circuit modification switch turn-off transitions can also be caused to occur at zero voltage. ZVS leads to significant reduction in the switching losses of the inverter based on MOSFETs & diodes. Sometimes to assist the switch turn off process, small capacitors C_{leg} may be introduced in the legs of the bridge. ZVS also reduces the EMI associated with device capacitances. In conventional PWM inverters, and also, to some extent, in zero current switching inverters, significant high frequency ringing and current spikes are generated by rapid charging and discharging of semiconductor device capacitances during turn-on & turn-off transitions. Ringing is conspicuously absent from the waveforms of ZVS inverters. This inverter inherently do not generate this type of EMI.

For the full bridge circuit in Fig.1.3 switch voltage $v_s(t)$,its fundamental component $v_{s1}(t)$ & load or tank's sinusoidal current $i_s(t)$ are plotted in Fig. 1.5 . At frequency greater than the tank resonant frequency, the input impedance $Z_i(s)$ is dominated by the inductor impedance. So, the tank network presents an effective inductive load to the bridge, and the current $i_s(t)$ lags the switch fundamental voltage component $v_{s1}(t)$. As a result, zero crossing of voltage waveform $v_s(t)$occurs before the current waveform $i_s(t)$.

For the first half cycle $0<t<T_{s/2}$ the switch voltage $v_s(t)$ equals to $+V_{Dc}$. For $0<t<t_\alpha$ the current $i_s(t)$ is negative & diodes D1 & D4 conducts. Switches Q1 & Q4 conducts when $i_s(t)$ is positive over the interval $t_\alpha<t<T_{s/2}$. The waveforms during $T_{s/2}<t<T$ is symmetrical. Since the zero crossing $v_s(t)$ leads the zero crossing of $v_s(t)$ leads the zero crossing of $i_s(t)$ the switches conduct after their

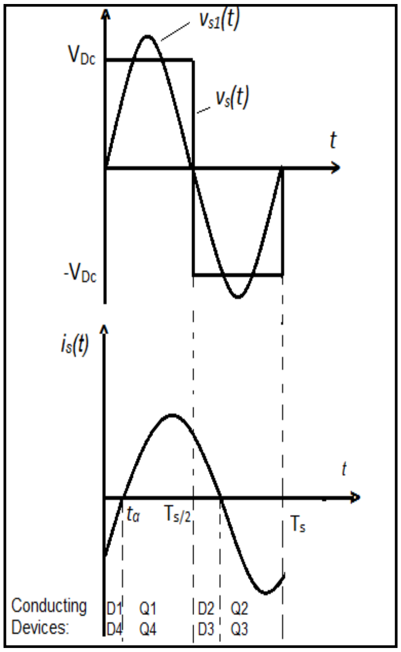


Fig. 1.5: Zero Voltage Switching

respective antiparallel diodes. During the time when D1 conducts over the interval $0<t<t_\alpha$ switch Q1 can be turned off so no switching loss is incurred. The circuit naturally causes the switch turn-on transition to be lossless, and long turn on switching schemes can be avoided. So, in general ZVS can occur when the resonant tank presents an effective inductive load to the switches, and hence zero crossings of switch voltages occur before the switch current zero occurs.[2]

1.7 Motivation of the work

Different types of converter topologies exist for power conversion such as ac-dc, ac-ac, dc-ac, and dc-dc. The circuit schemes for these conversions are pulse width modulation (PWM), square wave & resonant inverter. In PWM and square wave converters, it is required to turn-on & turn-off the switches to control the entire load current. In switch mode operation, the switches become liable to high switching stresses & high switching power losses. This losses increase linearly with switching frequency. It is anticipated that high switching frequency operation will lead to high switching losses but it will lead to increase in size of the converter. Also in PWM & square wave inverter there is EMI (electromagnetic interference) problem due to large *di/dt & dv/dt.* As a result, recently resonant power conversion has become of some interest. Resonant converter is defined as a type of converter in which the topology constitutes of at least one resonant tank circuit as a subcircuit. A resonant tank is subcircuit consisting of at least one inductor and one capacitor. The above mentioned problems can be eliminated by using resonant inverter. The power switches are turned-off under zero current and turned-on with large increase of device current. The resonant converter can be operated either above or below resonance. Also the resonant inverter produces power in sinusoidal form. Therefore, considering reduced component size & weight especially at or above 100kHz, good reliability and reduced EMI/RFI along with the capabilities of zero voltage & current switching (soft switching) resonant converter has become quite popular among power supply designers.

1.8 Organization of the Thesis

In chapter 1 principle of resonant converter along with zero current switching & zero voltage switching will be emphasized. Later in chapter2 some conventional inverter and resonant inverter simulation will be done using power electronics simulation tool PSIM. In chapter 3 a very unique & fundamental method of implementing square wave inverter is introduced & finally in chapter 4 a basic Resonant Inverter will be implemented with scope of future development.

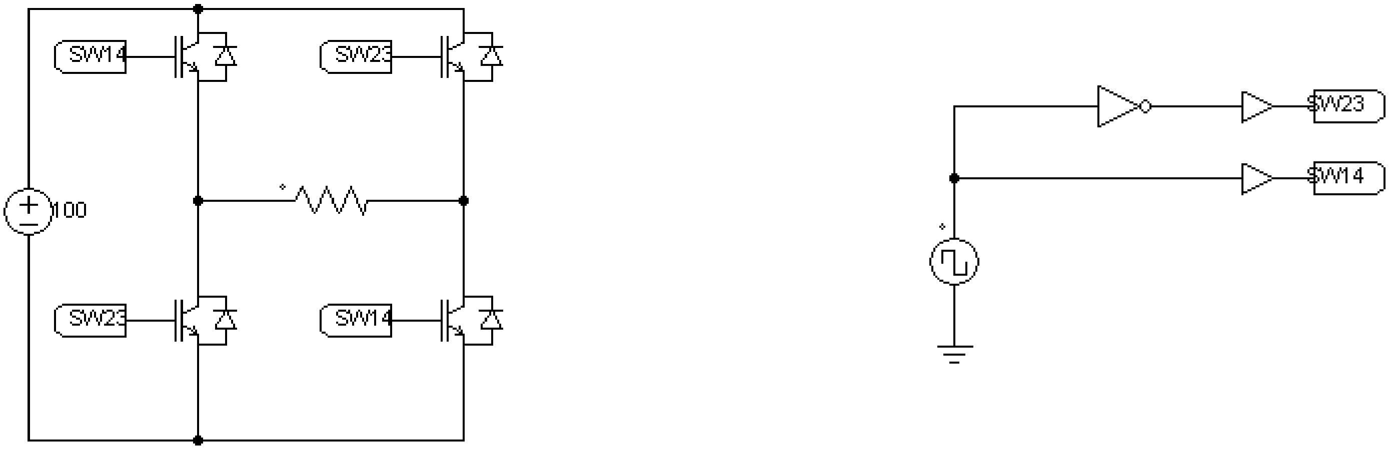
Chapter 2

Simulation of Power Inverters

Chapter 2 includes the simulation of conventional power inverters. In order to validate our project a basic Resonant Inverter simulation is also provided using power electronic simulation tool PSIM. Furthermore, switches, switching frequency, input voltage, load and other aspects are mentioned with their respective schematics & waveforms. The following simulations are included:

2.1 Square Wave

Here is square wave inverter fig: a shows the schematic figure and fig: b shows the control circuit. Fig c shows the wave from where vout is the output and SW14 and SW23 shows the switching. Source voltage was 100v and load was 10ohm[5]



(a) (b)

Fig: 2.1: (a) Square Wave Inverter with IGBT with input level 100V; (b) Control Circuit for gate drives with switching frequency 1000Hz.

Fig: 2.1(c): Simulation of waveform by square wave inverter.

2.2 PWM Inverter with Bipolar Switching

Fig2.2a shows the schematic, fig2.2b shows the control circuit and fig2.2c waveform. In wave shape vout is the output, sw14 and sw23 switching and the first wave shape is showing the control signal.[5]

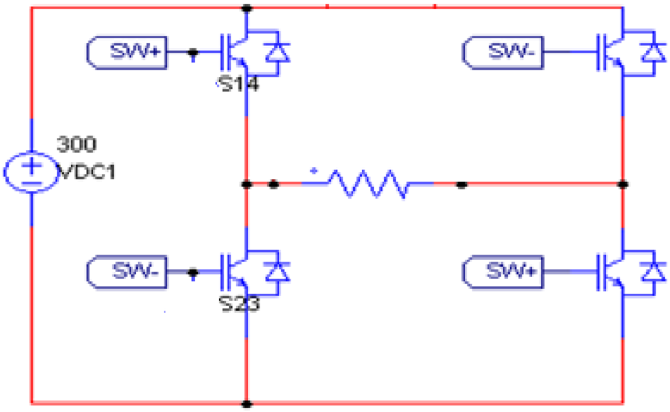


Fig. 2.2: (a) PWM inverter BIPOLAR Switching

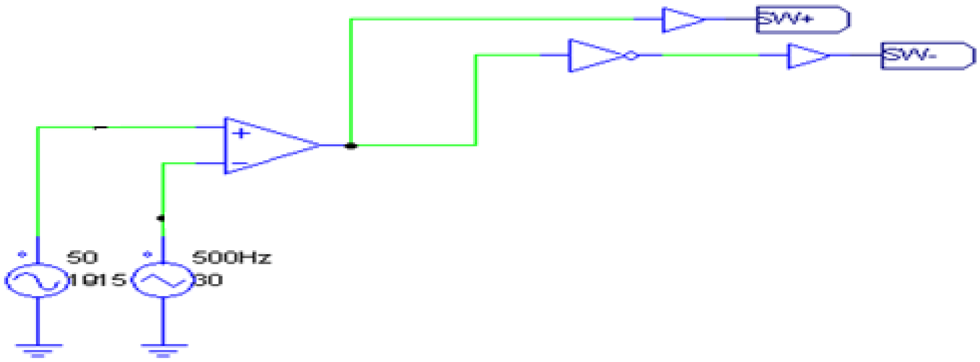


Fig. 2.2b: PWM bipolar control circuit for signal generation

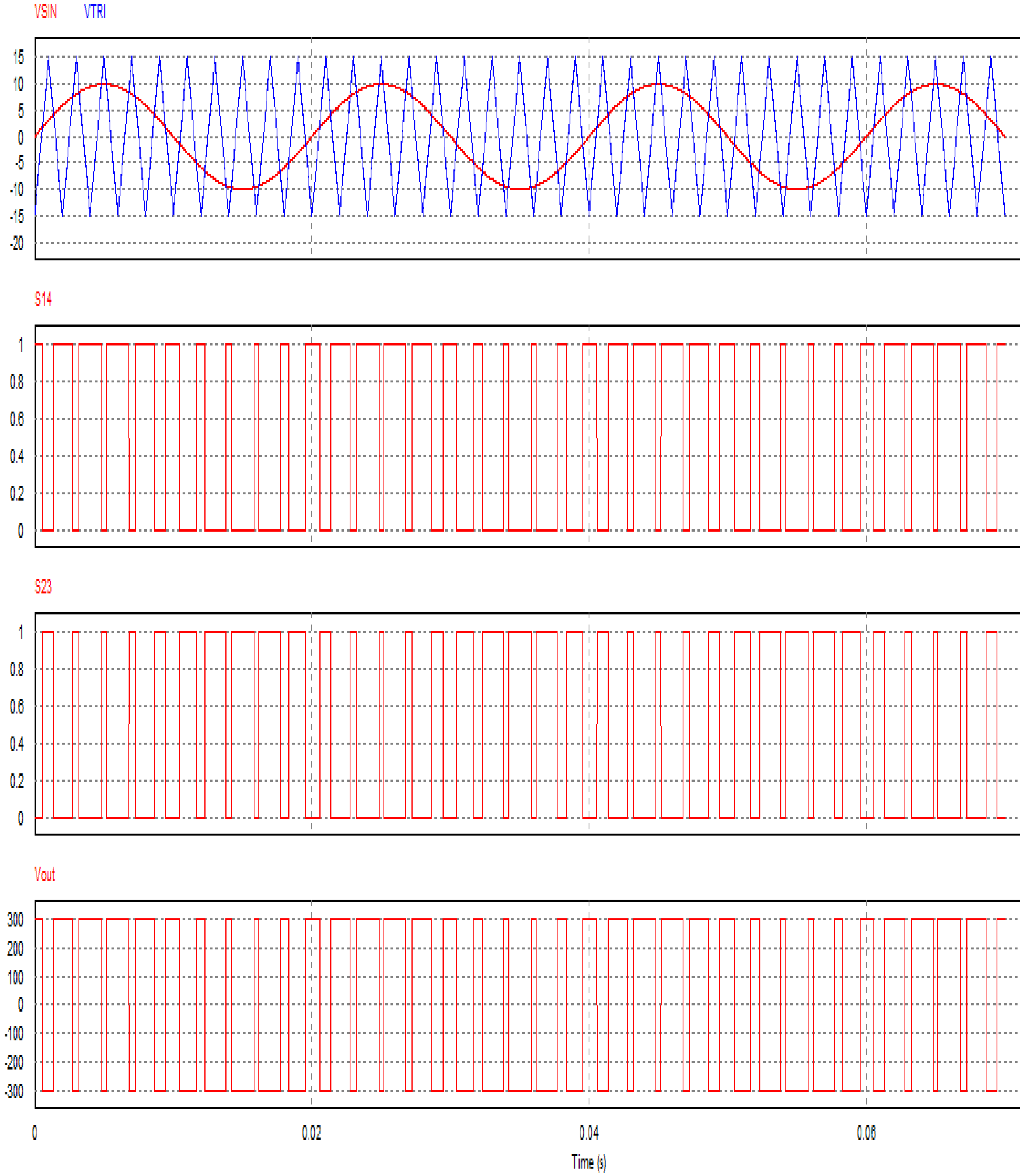


Fig. 2.2(c): PWM Bipolar inverter wave shape

2.3 PWM Inverter with Unipolar Switching:

Fig2.3a shows the schematic, fig2.3b shows the control circuit and fig2.3c waveform. In wave shape vout is the output, sw14 and sw23 switching and the first wave shape is showing the control signal.[5]

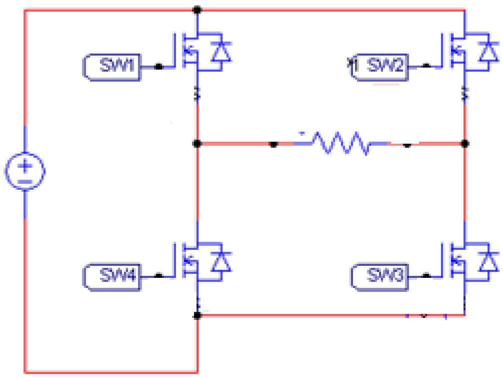


Fig: 2.3(a) Unipolar PWM inverter circuit

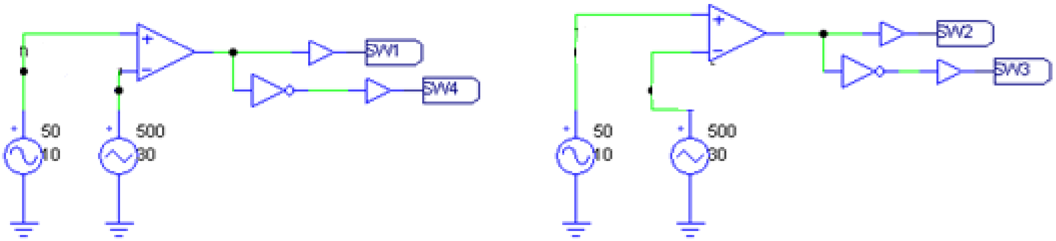


Fig. 2.3(b): Control circuit

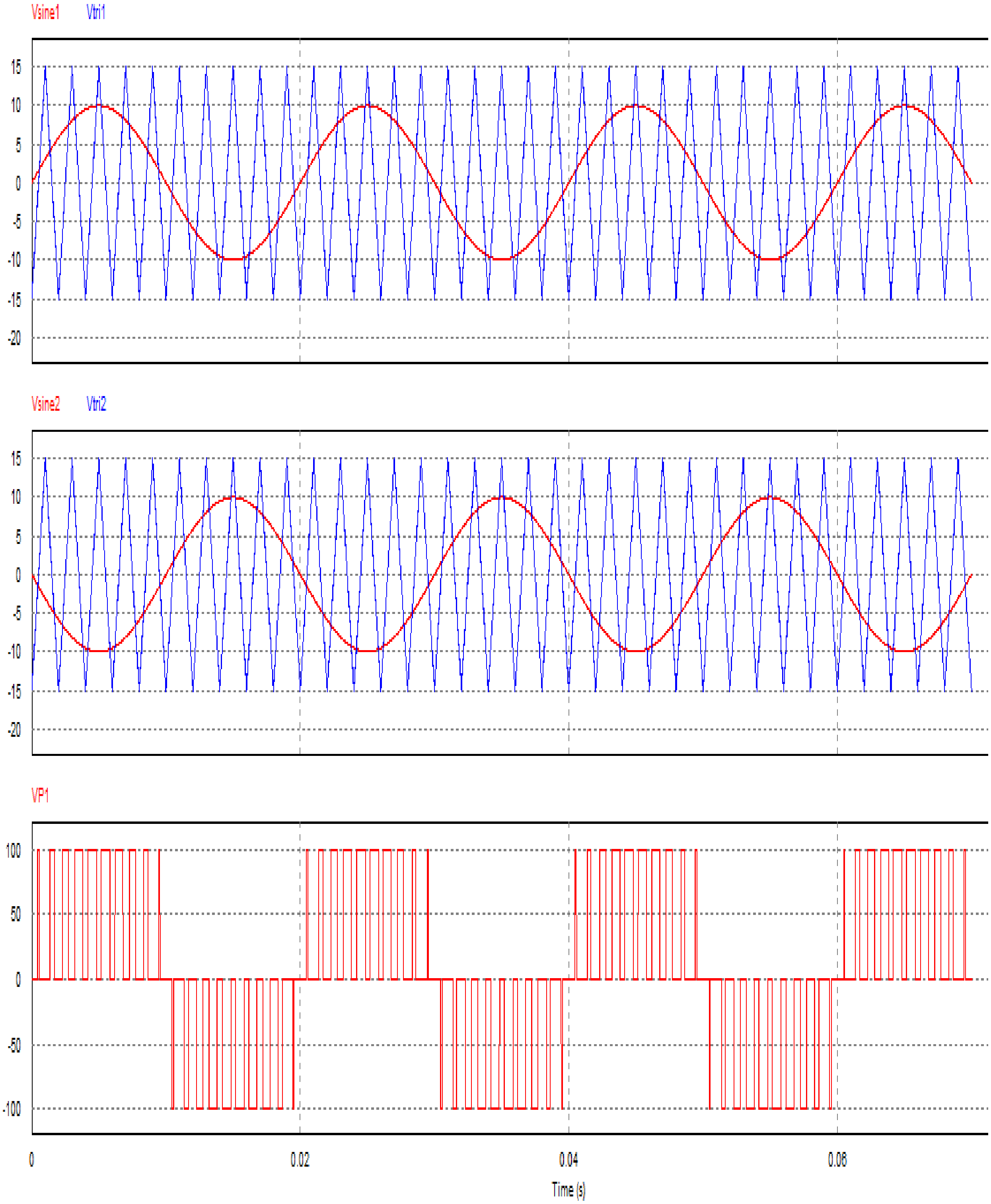


Fig. 2.3(c) Unipolar Wave shape

2.4 Load Resonant Inverter

Fig2.4a shows the schematic, fig2.4b shows the control circuit and fig2.3c waveform. In wave shape vp4 is the output. Two steps of constructing resonant inverter. First is to generate the square wave through rapid turning on & off of the switches. Then the square wave is passed through LC component. From the calculation of LC circuit L=3.93mH & C= 6.44uF switching frequency was chosen 1kHz. The calculations for finding out the values of L & C are detailed in section 4.2 & 4.3.

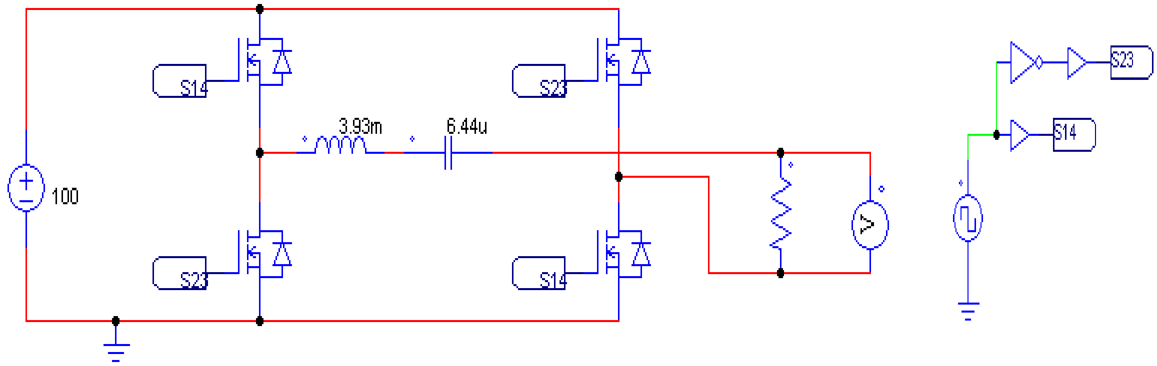
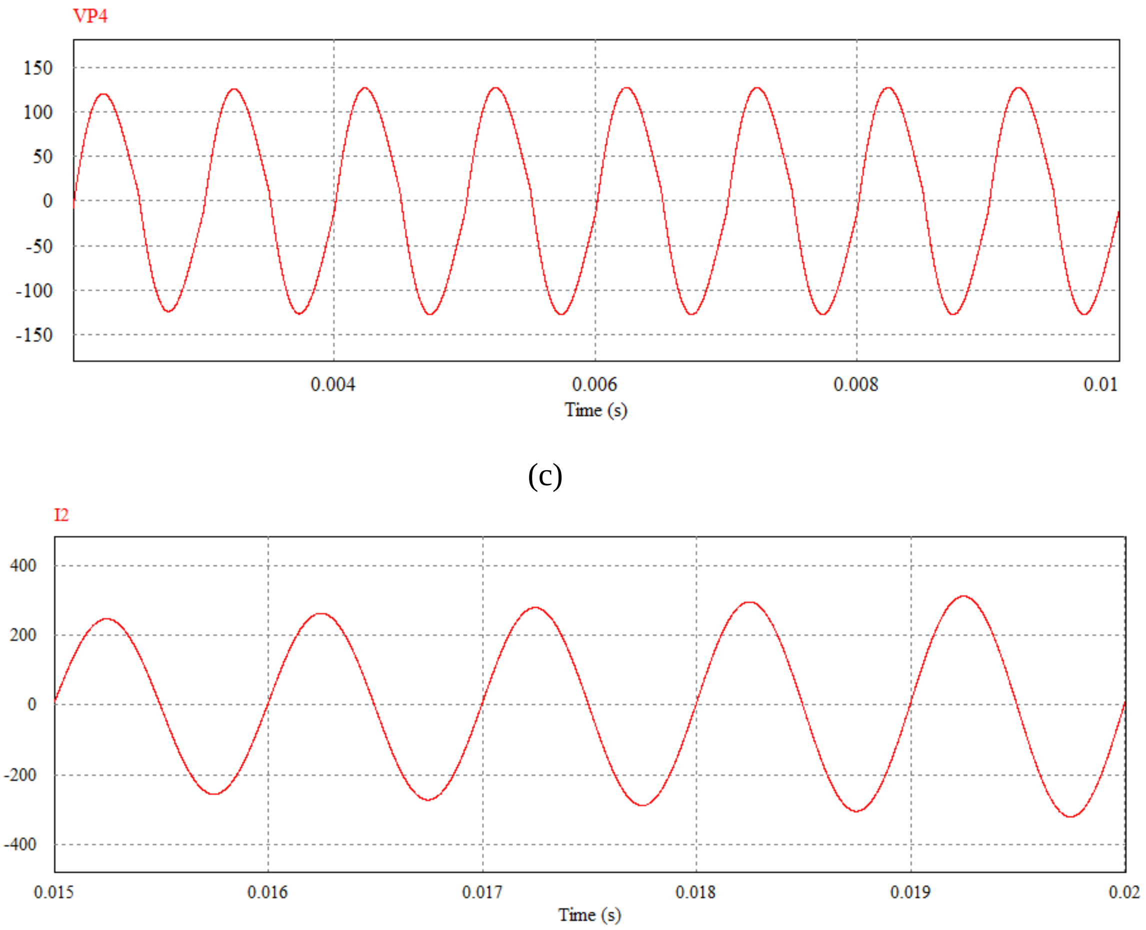


Fig. 2.4: (a) Load Resonant Inverter Schematic; (b) Control Circuit



(c)

(d)

Fig. 2.4: (c) Voltage across Resistor; (d) Current across Resistor

2.5 Zero Current Switching (ZCS)

Following is the dc-dc resonant converter with input voltage of 20V DC. Switching frequency is 30k with an antiparallel diode to ensure reverse recovery of current. The capacitor Cr is 0.01µF, inductor Lr is 40µH. This circuit enables the current across the switch lead the voltage across switching device to reduce switching loss.

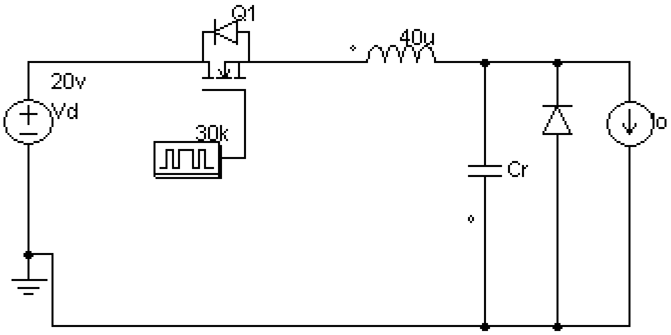


Fig. 2.5(a): Resonant Switching Converter

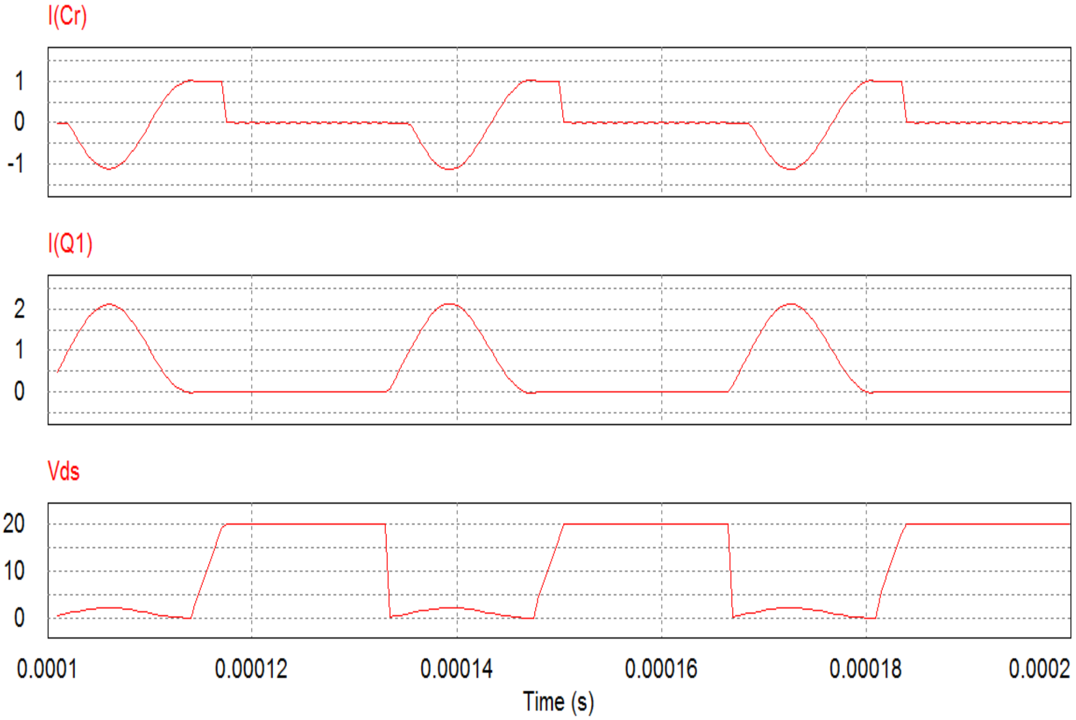


Fig. 2.5(b): Output Current waveform plotted as I(Cr) as load current, I(Q1) as Switch Current & Vds as Switch Voltage.

2.6 Zero Voltage Switching

Following is the dc-dc resonant converter with input voltage of 20V DC. Switching frequency is 30k with an antiparallel diode to ensure reverse recovery of current. The capacitor Cr is 0.01µF, inductor Lr is 0.01m. This circuit enables the voltage across the switch lag the current across switching device to reduce switching loss.

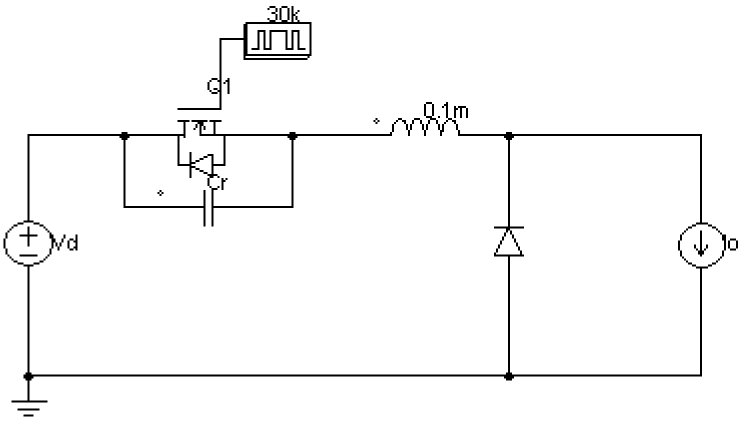


Fig.2.6(a): Zero voltage switching

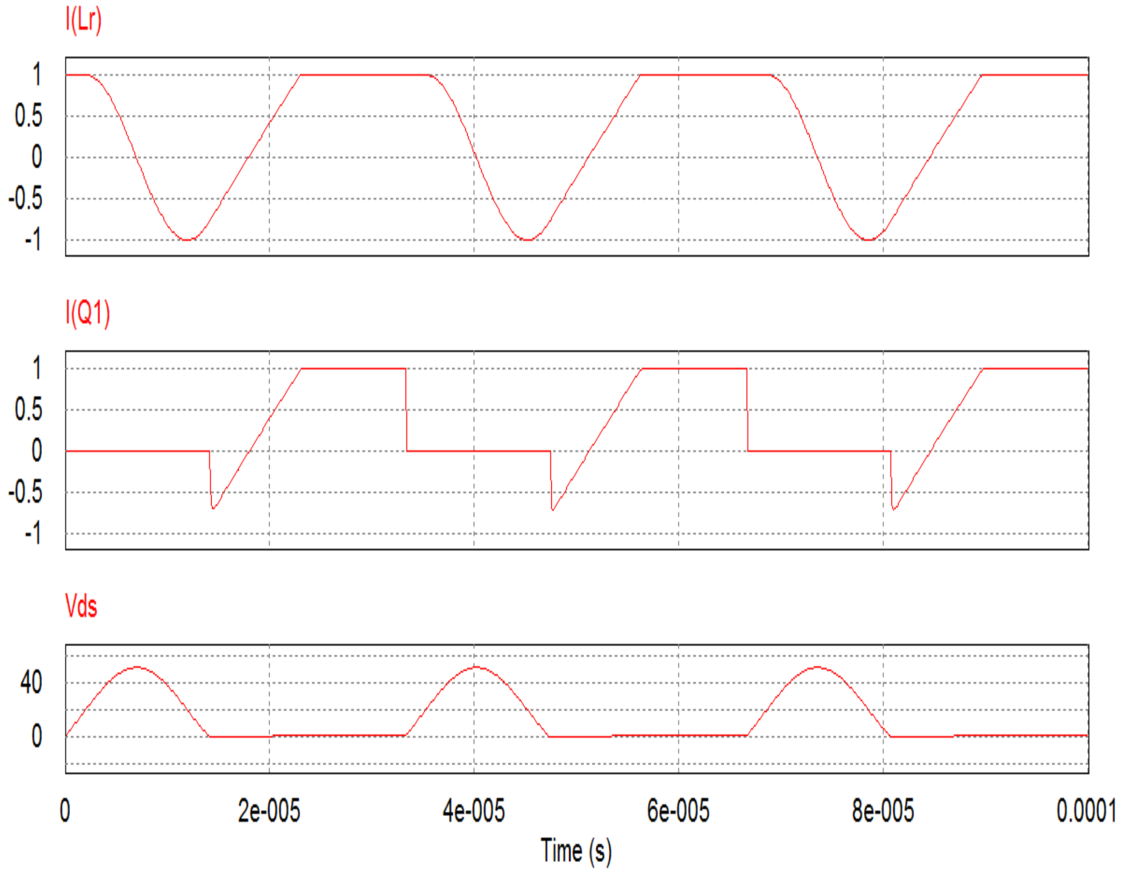
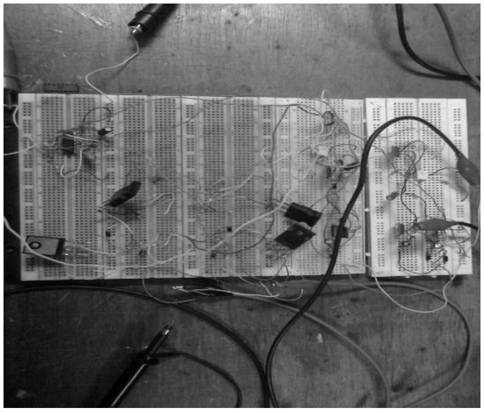


Fig. 2.6(b): Output, Switch Current & Voltage waveform plotted as I(Cr) as load current, I(Q1) as Switch Current & Vds as Switch Voltage.

Chapter 3

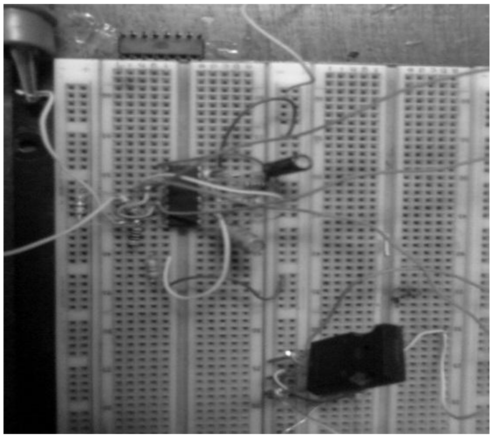
Practical implementation of Square wave Inverter

3.1 Hardware Description



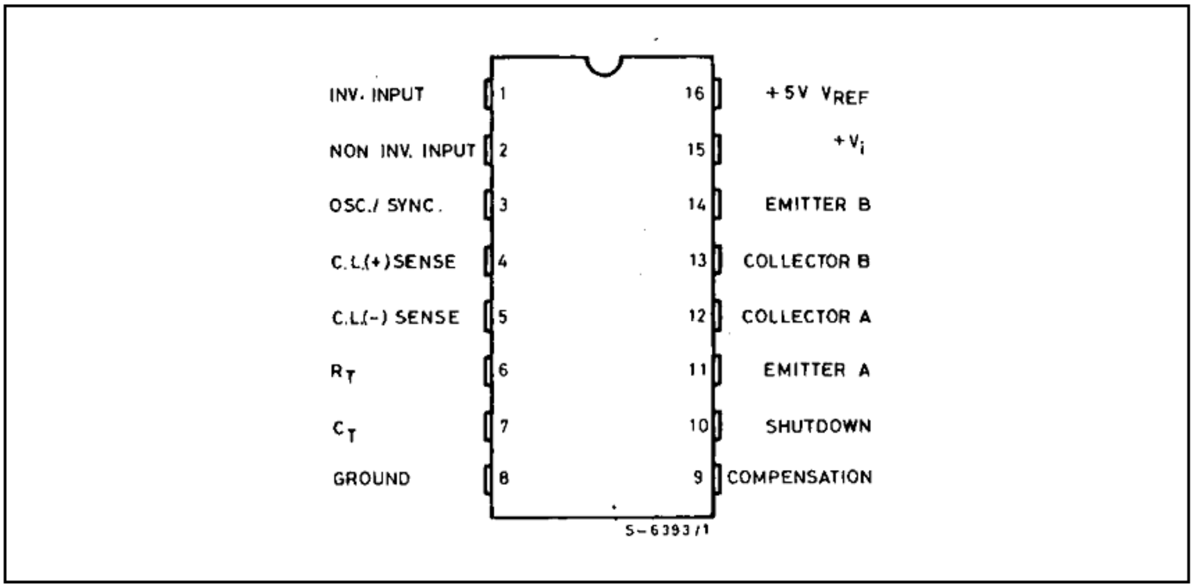
The part of the paper was intended towards design and implementation of a single phase square wave inverter. Primary objective was to develop a square wave Full Bridge voltage source inverter. After successfully simulating the square wave inverter in PSIM next part was to construct it in the laboratory. However driving the switches in the Full Bridge circuit provided a challenge. The control signals for switching devices to be generated with proper time delay so that top and bottom switches on the same leg of inverter are not short circuited due to simultaneous turn on. The progress was made in order such that each step's output can be tested before proceedings to the next. The experiment includes three basic functions: (1) Driving the Switching devices, (2) Charge pump isolation circuit for ground base isolation, (3) Full bridge inverter circuit.

3.1.1 Signal Generation for Driving Mosfets



To generate the gate pulses SG3524 IC based integrated circuit was used. This circuit provided couple of advantages over other processes. It has two outputs especially designed for driving Mosfets. It also provides the option for generating gate drive voltages ranging from +5 to +40 volts. In a single chip it also incorporates

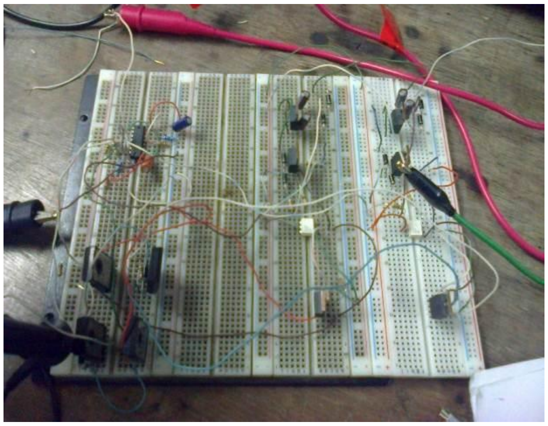
0-90% duty ratio.



SG3524 Pin Connection(Top view)

SG3524 Features

- Regulating power supply.
- Electrical inverter or switching regulator on a single chip.
- Transformer less voltage doublers, and polarity-converter applications employing fixed-frequency, pulse-width modulation (PWM) techniques.
- Uncommitted output for single ended or push pull inverter.
- Operation upto 300 kHz.



Components

1. *Power supply*
2. *Resistors (1k, 4.7kΩ, 6.8kΩ X 2, 8.2kΩ, 15kΩ)*
3. *Capacitors (0.1µF, 0.66µF)*
4. *SG3524 IC.*

Circuit Diagram

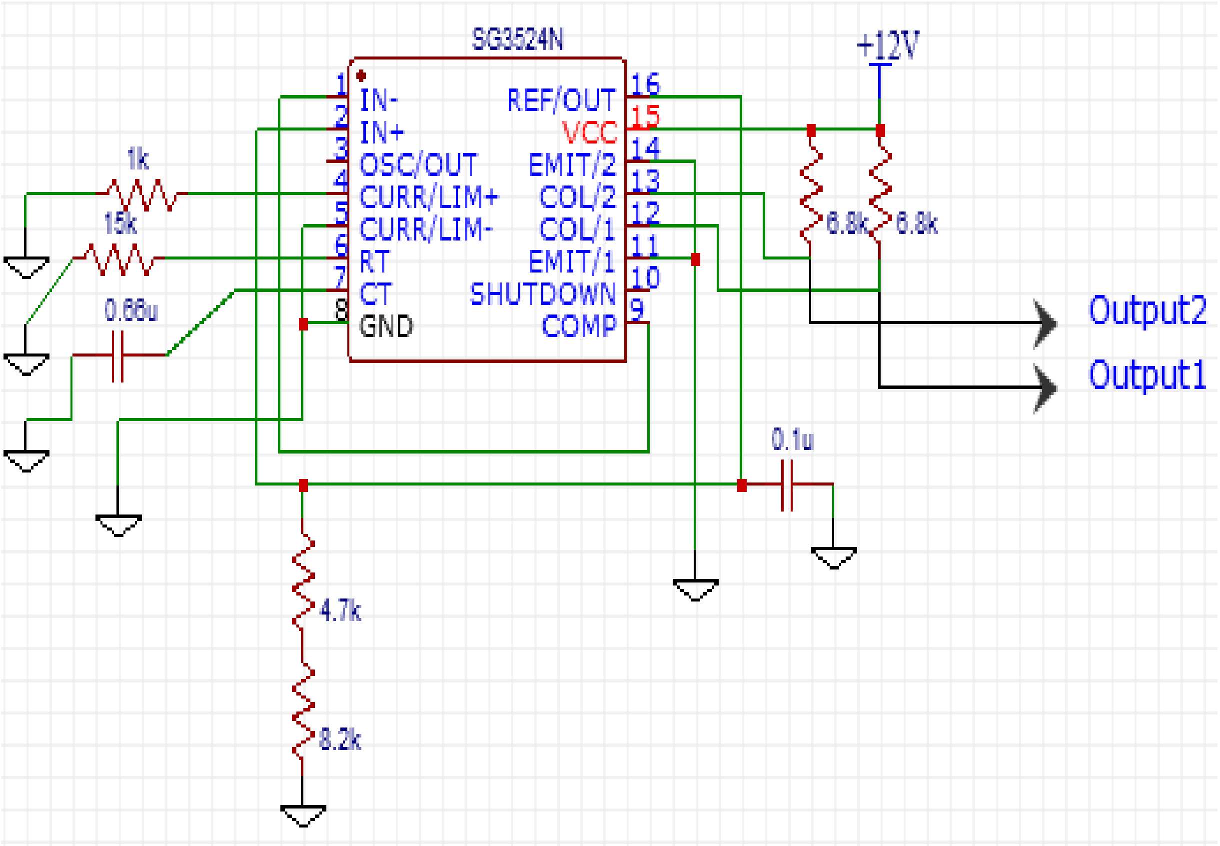


Fig. 3.1: Gate Signal Generation

Application of the Circuit

1. *SG3524 provides an inbuilt oscillation whose frequency was determined by connecting capacitor CT on pin 6 & resistor RT on pin 7.*

   f = 1.3/ (RT CT)
2. *Pin 15 of the IC is connected with +12V supply voltage.*
3. *Outputs were taken from pin 12 & 13 and were connected to the gates of the mosfets & to the charge pump isolation circuit.*

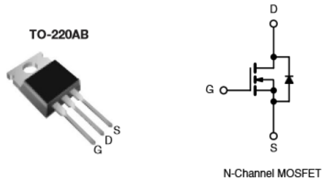
3.1.2 Charge pump isolation Circuit

Next task was to feed the pulses from SG3524 IC’s pin 12 &13 to the full bridge circuit and ensure bipolar switching. As mentioned earlier for full bridge inverter, gates are to be isolated when the control signals are connected to the gates of switching devices. For this purpose isolator circuit was required to prevent shorting during simultaneous turn on. The whole circuit requires input from SG3524 and we connected with the upper switching devices of both legs. Two isolation circuits were made to do the operation. In fig 3.2 and 3.3 isolation circuit is shown

Components (2 sets due to 2 different circuits):

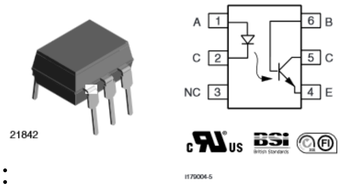
1. 10u capacitor 2pcs
2. Diode 5pcs
3. 100k resistor 2pcs
4. 2.2k resistor 2 pcs
5. 1.2k resistor 2pcs
6. IRF840 MOSSFET 3pcs
7. Optocoupler 4n35 1pcs

Significant parts: IRF840 and Optocoupler.



IRF 840 Features:

1. Dynamic dV/dt Rating
2. Repetitive Avalanche Rated
3. Fast Switching
4. Ease of Paralleling
5. Simple Drive Requirements
6. C1ompliant to RoHS Directive 2002/95/EC



Optocoupler 4N35 Features:

1. Isolation test voltage 5000 VRMS
2. Interfaces with common logic families
3. Input-output coupling capacitance < 0.5 pF
4. Industry standard dual-in-line 6 pin package
5. Compliant to RoHS directive 2002/95/EC and in accordance to WEEE 2002/96/EC

Application of the Circuit:

1. Drive voltages were already generated from SG3524. Main purpose of this isolation circuit was isolation of the gate drives of each leg of the inverter.
2. Few processes can be used for isolation: Pulse transformer isolation and opto-coupler circuit or by charge pump circuits. Pulse transformer isolation can only successfully used in SCR inverters with high frequency ANDing of control signals which is not suitable for BJT, IGBT, MOSFET inverters. So the later process was chosen.
3. Optocoupler allowed the passing of signals through parts of the circuit & at the same time keeps them electrically isolated.
4. Faster switching was achieved by using IRF840.
5. VCC provided the voltage required to work the circuit & optocoupler. Freewheeling paths ensured that optocoupler & mosfets could be driven by same VCC.

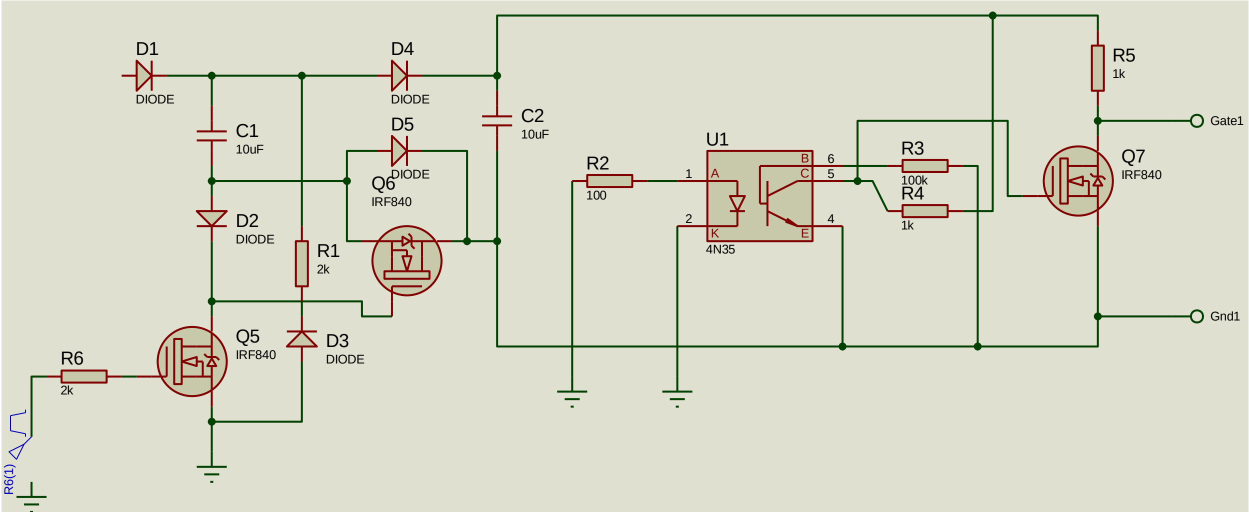


Fig 3.2(a): Charge – Pump isolator Circuit 1

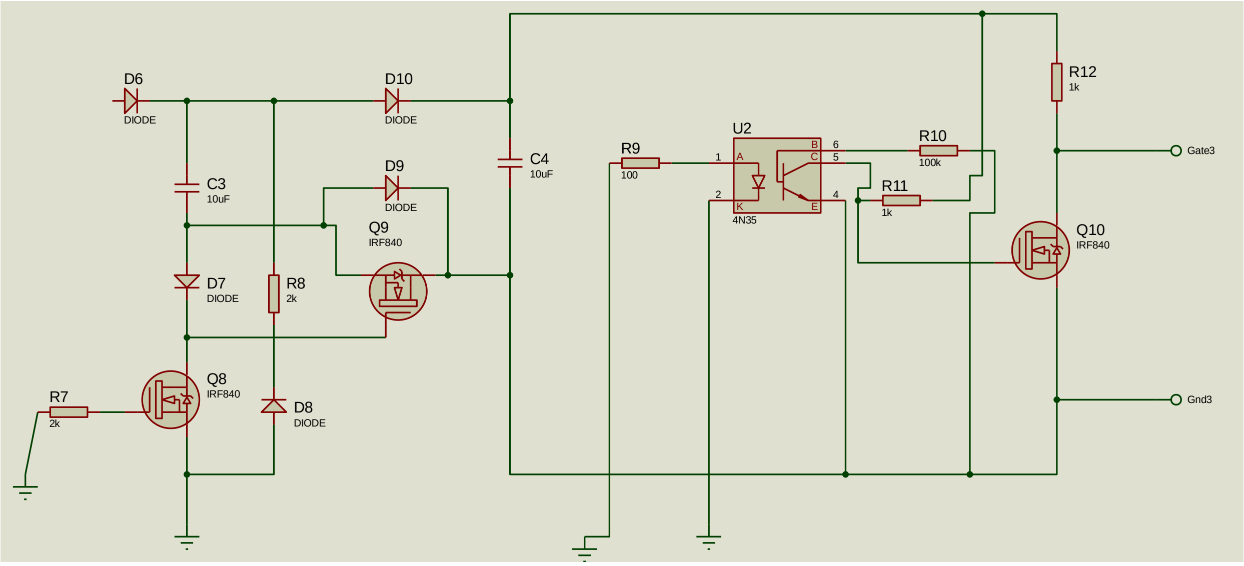


Fig 3.2(b): Charge – Pump isolator Circuit 2

3.1.3 Final Full Bridge Inverter Circuit

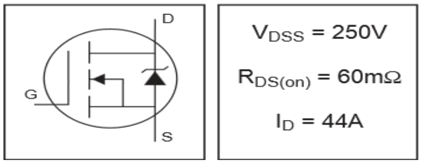
Following circuit incorporates the Full Bridge Inverter. The inverter input was adjusted to 10V.Control signals fed to the gates of the high side switching devices of the inverter through charge pump isolation circuit. Gates of the low side switches were connected directly from pin

12 & 13 of the SG3524 IC. In the circuit freewheeling paths were provided to restrict the switching surge voltage across switches. In Fig 3.4 the circuit is shown

Components:

1. IRF264 Mosfets (4 pcs)
2. Diodes 1N4148 (4 pcs)
3. DC input Vin

IRF264N Features:



$V_{DSS} = 250V$

$R_{DS(on)} = 60m\Omega$

$I_D = 44A$

1. Fast Switching
2. Fully Avalanche Rated
3. Ease of Paralleling
4. Simple Drive Requirements.
5. 175°C Operating Temperature
6. Dynamic dv/dt Rating
7. Advanced Process Technology

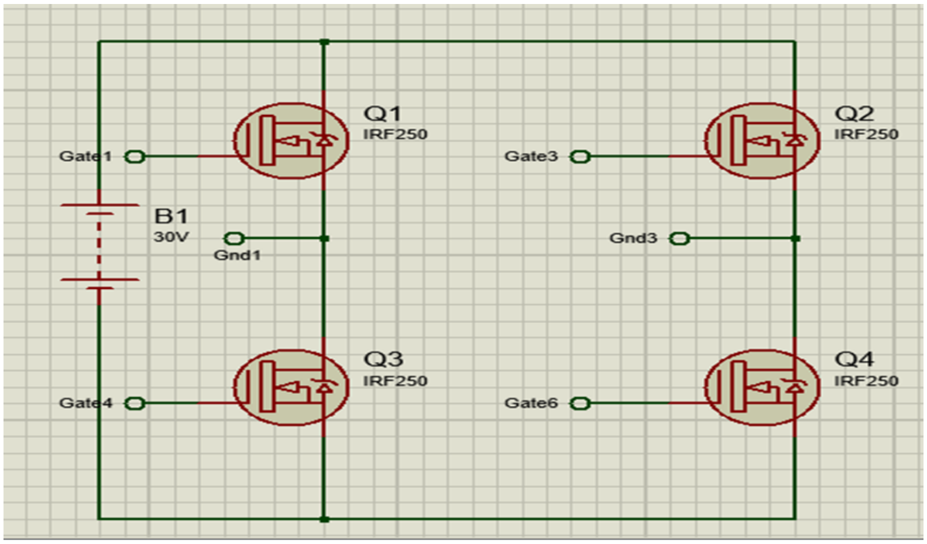
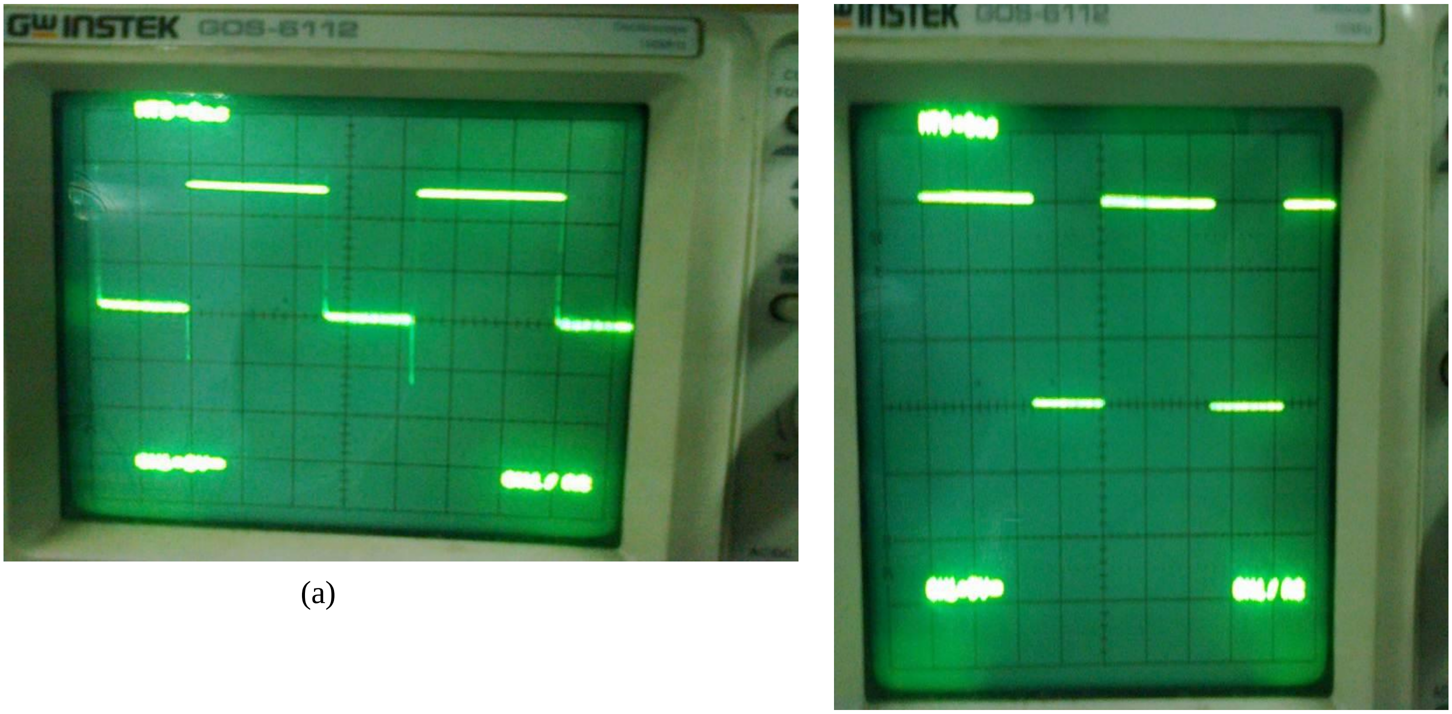


Fig. 3.3: Full Bridge Inverter



(a)

(b)

Fig 3.4: Initial circuit output (a): Pulse ;(b) Pulse 2

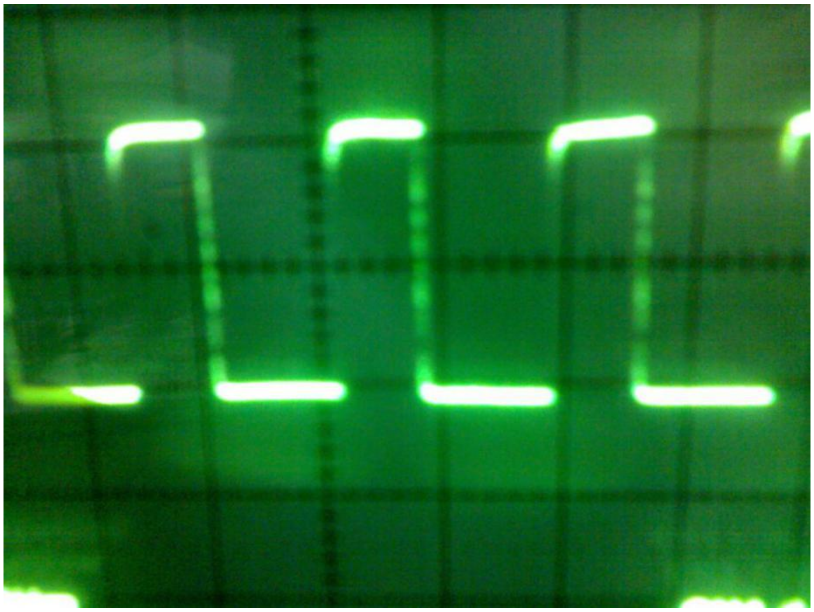


Fig 3.4(c): Square wave output

Chapter 4

Implementing Basic Resonant Inverter

4.1 Fourier analysis of Square Wave

When the French mathematician Joseph Fourier (1768–1830) was trying to solve a problem in heat conduction, he needed to express a function as an infinite series of sine and cosine functions:

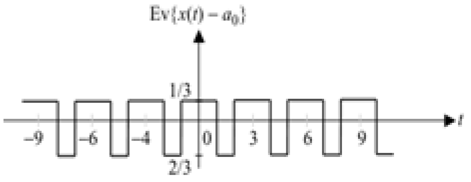
$$f(x) = a_0 + \sum_{n=1}^{\alpha} (a_n \cos nx + b_n \sin nx)$$

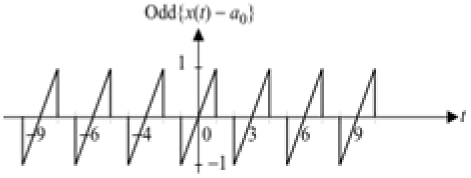
This time our objective is to analyze the square wave inverter output.

First we need to go back to the properties of Fourier to explain this waveform. Particularly we need to understand the effects of symmetry. Unnecessary work can be avoided in determining the series if signal poses any type of symmetry.[7]

Significant symmetries are:

1. Even symmetry x(t)=x(-t)
2. Odd symmetry x(t) = -x(-t)
3. Half wave odd symmetry x(t)=-x(t+T/2)





Suppose we have signal x (t) and having a period T is a Fourier cosine series.

$$x\ (t) = a_0 + \sum_{n=1}^{\infty} a_n \cos \frac{2n\pi}{T}$$

Where $a_0 = \frac{2}{T}\int_0^{T/2} x(t)dt$ and $a_n = \frac{4}{T}\int_0^{T/2} x(t)\cos\frac{2\pi nt}{T}$

Where odd signal is Fourier sine series

Similarly $b_n = \frac{4}{T}\int_0^{T/2} x(t)\cos\frac{2\pi nt}{T}$

From symmetry table we get

Symmetry	a_0	a_n	b_n
Even	Not zero	Not zero	zero
Odd	zero	zero	Not zero

Now we will analyze the square wave. Suppose the Fourier series for a periodic function $V_0(\omega t)$ can be expressed as

$$v_0(\omega t) = a_0 + \sum_{n=1}^{\alpha}(a_n \cos n\omega t + b_n \sin n\omega t)$$

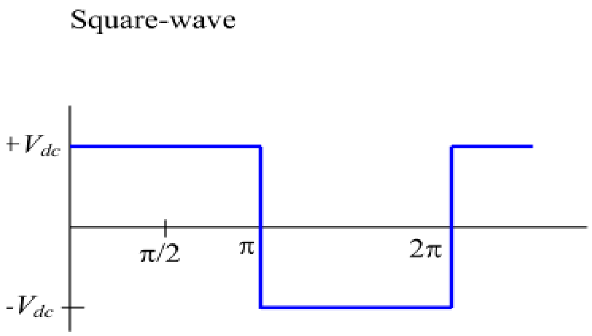
For an odd symmetry a0=an=0

And

$$b_n = \frac{4}{\pi}\int_0^{\pi/2} v_0 \sin(n\omega t) d(\omega t)$$ For odd n

For even it is zero

Therefore we can write $v_0(\omega t) = \sum_{n=odd}^{\infty} b_n \sin(n\omega t)$



$$\begin{aligned} b_n &= \frac{4}{\pi}\int_0^{\frac{\pi}{2}} v_o \sin(n\omega t)d(\omega t) \\ &= \frac{4}{\pi}\int_0^{\frac{\pi}{2}} V_{dc} \sin(n\omega t)d(\omega t) \\ &= \frac{4V_{dc}}{n\pi}\left[-con(n\omega t\right]_0^{\frac{\pi}{2}} \\ &= \frac{4V_{dc}}{n\pi} \end{aligned}$$

………… (4-1)

4.2 Constructing LC Filter from Components

From the Fourier series expansion of the square wave, the fundamental voltage of the square wave is $4V_{DC}/\pi$ which is same as Equation (1-3). Now, in order to extract fundamental component, it is necessary to pass the square wave signal through LC component. Series LC circuit will allow the signal to pass at resonance, and block signal from any other frequencies from getting to the load.

For designing purpose of a series resonant LC filter a particular switching frequency $f_0$is selected. Using Equation (4-1) or (1-3) amplitude V_1 at fundamental frequency is determined. In order to find out quality factor Q Equation (1-5) is used.

$$\frac{V_o}{V_i} = \frac{1}{\sqrt{1 + Q^2((\omega/\omega_0) - (\omega_0/\omega))^2}}$$

……………………………………………… (1-5)

Equation (1-5) relates the input and output amplitude voltages. Using the estimated value of THD next harmonic amplitude V_3 is determined. This V_3 would be third harmonic output voltage $V_{output,\ 3}$.

$$\mathrm{THD} = \frac{\sqrt{\sum_{n\neq 1} V_n^2}}{V_1} \approx \frac{V_3}{V_1}$$
………

…..(4-2)

Again, for the square wave input to the LC combination $V_{\text{input, 3}} = V_1/3$ which is third harmonic input amplitude voltage. Using these magnitudes

$$\frac{V_{\text{output, 3}}}{V_{\text{input, 3}}} = \frac{1}{\sqrt{1 + Q^2((\omega/\omega_0) - (\omega_0/\omega))^2}}$$

For value of ω, it would be $\omega = 3\omega_o$ since magnitude of third harmonic input with magnitude of third harmonic output is used. Value of Q would allow us to find the inductor L & capacitor C value of the LC filter by using equation (1-4).[1]

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 RC}$$
……………………………………………………………………… (1-4)

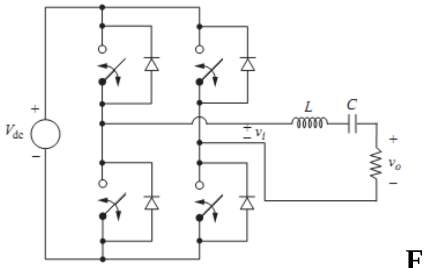


Fig. 4.1: Series Resonant Inverter

4.3 Determining the Values for Resoant tank

As described the process of bulding Resoannt tank in section 4.2, it would be used to determine the values of LC components in the load. Using these values simulation of Load Resonant inverter in section 2.4 was done. So, initially an arbitrary frequency f_o was chosen 1kHz. Using Equation (4-1) or (1-3) amplitude V_1 at fundamental frequency is determined 127.32V.

$$V_1 = \frac{4V_{dc}}{\pi} = \frac{4 \times 100}{\pi} = 127.32V$$

Generally it is estimated that the value of THD is 5%. Using this value $V_{ouput,3}$ is determined.

$$V_{ouput,3} < (.05)(127.32) = 6.366V$$

Since, the input to the LC network is square wave third harmonic input amplitude voltage $V_{input,\,3}$ is $V_1/3$ or 127.32/3 or 42.22V. Now, using these values & equation (1-5) quality factor Q would be determined.

$$\frac{V_{output,\,3}}{V_{input,\,3}} = \frac{1}{\sqrt{1 + Q^2((\omega/\omega_0) - (\omega_0/\omega))^2}}$$

For value of ω, it would be $\omega = 3\omega_o$ since magnitude of third harmonic input with magnitude of third harmonic output is used.

$$\frac{6.366}{42.22} = \sqrt{\frac{1}{1 + Q^2((\frac{3\omega o}{\omega o}) - (\frac{\omega o}{3\omega o}))^2}}$$

Solving this equation Q=2.47. According to equation (1-4)

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 RC}$$

Therefore value of inductor L is 3.93mH & capacitor C is 6.44µF as demonstrated in simulation of section 2.4.[3]

4.4 Application of Resonant Inverter

High frequency operations of PWM converters allow reduction of the size and weight of their magnetic components. However, at high switching frequency, switching losses and EMI emissions become significant and must be reduced. Traditional high frequency switch — mode supplies, which rely on generating an AC waveform have used power transistors to “hard-switch” the unregulated input voltage at this rate. This means that a transistor turning on will have the whole raw input voltage, across it as it changes state. During the actual switching interval (less than 50 microseconds) there is a finite period as the transistor begins to conduct where the voltage begins to fall at the same time as current begins to flow. This simultaneous presence of voltage across the transistor and current through it means that, during this period, power is being dissipated within the device. A similar event occurs as the transistor turns off, with the full current flowing through it. More recently, new power conversion topologies have been developed which dramatically reduce the power dissipated by the main power transistors during the switching interval. The most common technique employed has been a constant frequency resonant switching scheme, which ensures that the actual energy being dissipated by the active device is reduced to nearly zero. This method, commonly called is “Zero Voltage Switching” (ZVS), “Zero Current Switching” or “Soft Switching”. These converters use the LC resonance circuit. When using resonant circuits to reduce switching losses, by resonant inductance connected or disconnected from the resonant circuit at zero current passing through this inductance, or that connects or disconnects the resonance capacity at zero voltage. Leader in this area are quasi-resonant converters, which use the properties of resonant LC circuit, only in moments of commutation switches. Reduction in the steepness of the starting and trailing edge of the output voltage when using resonant inverter also has a favorable influence on the electromagnetic interference.

In fixed frequency operation: Clamped mode series resonant inverters are used in design of magnetic components for resonant tank & filtering because it has an advantage of fixed frequency operation. Above resonant frequency this inverter shows better efficiency.

Induction heating: Most used application of all. In these days when fuel is the other name of scarcity induction heating is one the most prominent solutions. Induction heating is a well known technique to produce very high temperature for applications. A large number of topologies have been developed in this area such as voltage and current source inverter. Recent developments in switching schemes and control methods have made the voltage-source resonant inverters widely used in several applications that require output power control. At high output frequency (20 kHz-100 kHz) resonant inverter produces sinusoidal waveform, reduces switching loss & stress on power components. Therefore it is used in induction heating.

Fluorescent lighting: Current resonant inverter circuit is used in fluorescent light & electronic ballast of gas discharge lamp. If fluorescent light is started by DC supply mercury accumulates at one end of the tube so an inverter circuit is used. The circuit starts operating above resonance frequency & gradually increases voltage ignites the light.

Laser power supply: Laser power supply requires higher charging efficiency since resonant inverter provides that option, series resonant inverter is used in laser power supply.

Accessories: Flat TV panels & ATX PCs require efficiency in power density in switch mode power supply so LLC resonant converter is used.

Ozone generator model: To reduce the size, weight & loss recently basic RLC resonant inverter circuit is used to produce alternating current at high frequency.

Generators & radio frequency: Ultrasonic power generators use resonant inverter & radio frequency generation for electro surgery uses series LCL resonant converter.

Dc-dc energy conversion: Novel loaded-resonant converter is used in dc-dc energy conversion. Novel loaded-resonant converter includes half-bridge series LCL converter with a bridge rectifier with LC filter.

4.5 Future Development

Passive components are often the limitation on volume, and cost of the system. For LLC resonant converter, with integrated magnetic technology, all magnetic components could be integrated into single magnetic structure. With planar magnetic, the resonant capacitors could also be integrated into magnetic structure. This way, all the passive components except output cap could be integrated. This integration will provide many benefits: high density, less interconnection, better electric performance. The most significant benefit of LLC resonant converter for front end DC/DC application is that it could be optimized for high input voltage. In fact, other than this, there are several other benefits. First, the voltage stress on the secondary rectifier is minimized to two times output voltage only. Second, the output rectifier commutates naturally, there is no reverse recovery problem. Third, switching loss of LLC resonant converter could be minimized. Fourth, without output filter inductor, the transient of LLC resonant converter could be very fast. With all these advantages, LLC resonant converter is a possible candidate for other applications like isolated point of load converter too. Higher frequency operation of LLC resonant converter With LLC resonant converter, switching loss could be minimized. By control magnetizing inductance Lm, switching loss could also be controlled. This gave us opportunity to push to higher switching frequency. For some state of the art magnetic material, the optimal operating frequency could be as high as MHz. LLC resonant converter enable us to utilize these new material in front end application. The issue is how to trade off the design between magnetic loss, volume and operating region of the system.

Small Signal modeling of resonant inverter: In this work, the small signal characteristic of LLC resonant converter is been revealed. Still, a simple and easy to use model is not available yet, which is amajor obstacle for people to accept and appreciate this topology. With extended describing function method, it is possible to get an equivalent small signal circuit model when only first order harmonic of switching frequency is considered. Unfortunately, third or even fifth harmonic are needed to model LLC resonant converter. There is still need to develop method to derive simple circuit model for this kind of topologies.

4.6 Conclusion

In this paper, DC-AC a single phase resonant inverter was proposed using basic square wave inverter, and built from simple components and increases the efficiency of the circuit. Its control circuit is simple considering other resonant inverter control circuits & has the capability to operate in different frequencies. Resonant inverter is vastly used in induction heating process for reduced switching loss & converter size. The charge-pump isolation circuit introduced in chapter 4 could also work as snubber circuit to reduce voltage stress. Our topology uses resonant tank and varying the switching frequency, it would be possible to enable soft switching. The proposed inverter's validity is proven through simulation.

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