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Resonant Inverter with IGBT for Induction Heating Applications

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Abstract: This paper presents a resonant inverter with IGBT for induction heating (IH) applications. By employing the center tap transformer in the proposed inverter, the switching frequency of the IGBT's is half the load switching frequency. Moreover, the IGBT's in the proposed inverter operate in zero voltage switching during the turn on phase of the switches. The system configuration, operation and the analysis are described to illustrate as to how the load switching frequency of the proposed resonant inverter is twice the switching frequency of IGBT's. The new topology is verified by carrying out the simulation using MATLAB/Simulink software.

Index Terms: Center Tap Transformer, Induction Heating, Resonant Inverter, Zero-Voltage Switching (ZVS).

I. INTRODUCTION

Inverter is an electronic device that converts DC voltage into AC voltage of a desired amplitude and frequency, and commonly used in engineering, domestic and industrial applications. The switching losses and generation of EMI in DC-DC and DC-AC converters can be minimized by the resonant converter which incorporates LC circuit and the switches of resonant converter creates a square wave like voltage and current pulse train. Applications of resonant converters are high frequency electric process heating for induction welding etc. [8]

Induction heating (IH) technology is the choice of heating technology in many home appliances, industrial process and the medical applications due to its practical properties of high efficiency, fast heating, cleanness, safety and accurate power control [1]. The most critical industrial applications of induction heating such as welding and quenching requires high power and high frequency, thus employing induction heating. The heated depth depends on the output frequency, the deeper heating require lower frequencies and surface heating requires higher frequencies.

MOSFET's have been adopted to improve the switching frequency of the inverter in the high frequency resonant inverter for industrial process or home appliances [2]-[4].

MOSFET is a high frequency device but has the weakness of high on-resistance and low power capacity. When compared with MOSFET, IGBT has high power capacity and low on-resistance but has the limitation of switching frequency up to 100 KHz. Meanwhile, in high frequency applications the switching loss especially with tail current, reduces the efficiency of the circuit as well as limits the further expansion of frequency [5].

In many applications, to achieve the goal of high power and high frequency, the method of IGBT's paralleling is applied, which is a more effective way of handling the losses at the particular frequency by distressing the IGBT's, but it has some severe problems like current balance of the device, synchronization of the drive signals and so on [6].

A new multiple frequency IGBT inverter is demonstrated in [7] which makes the load frequency as twice as that of switching frequency and consequently broadens the frequency range of the IGBT. Therefore, the improvement of the output frequency is a significantly technical challenge for the switching frequency of IGBT's.

This paper demonstrates a resonant inverter with IGBT for high frequency induction heating applications, which allows the output resonant frequency to be twice the switching frequency of the IGBT by employing the center tap transformer. The advantage of this design is the switching frequency of the IGBT is reduced thereby reducing the switching losses.

This design of the topology is achieved by combining the two symmetrical half bridge inverters and sharing two equal resonant capacitors. Moreover, the IGBT's in this new topology operates in zero voltage switching condition over the whole process and each IGBT conducts for only a quarter of a switching cycle.

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II. RESONANT INVERTER

A. Circuit Description

For the high frequency induction heating applications, the multiple frequency resonant inverter with center tap transformer is designed. The fig 1 shows the proposed inverter for induction heating applications. The circuit consists of two power stages: input power stage and output power stage. The input power stage consists of a single phase diode bridge rectifier connected to the 220 V/ 50 Hz power line represented as V_{in} which is converted into dc power supply, the dc link capacitor C_d is connected between bridge rectifier and the inverter. The output of the bridge rectifier is given to the inverter.

Single phase voltage source full bridge inverter with four IGBT modules makes the output power stage. The output of the inverter is given to the series resonant circuit, which is composed of two resonant capacitors represented as C_1 and C_2 and have same value C and the center tap transformer, which is matching transformer that will adapt to the load impedance, and IH loads, which is modeled by a series combination of its equivalent resistance R and inductance L.

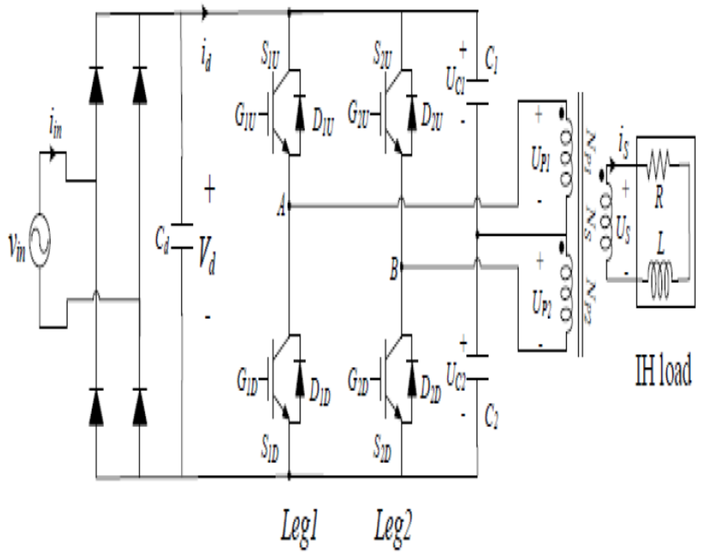

Fig 1: Proposed inverter

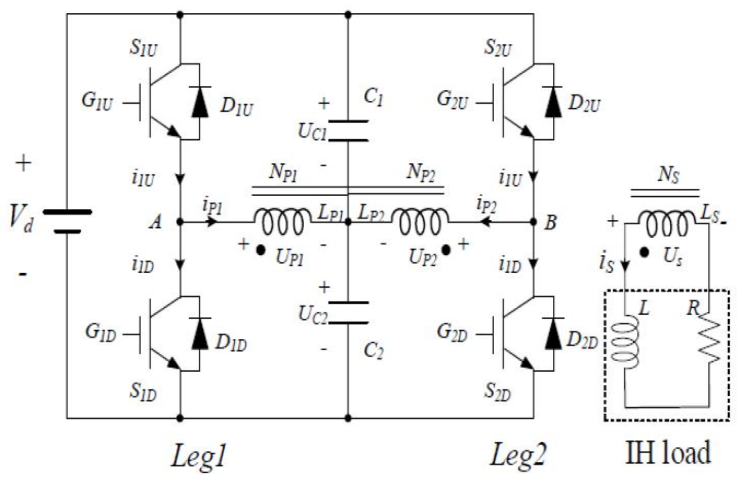

Fig 2: Simplified schematic diagram of multiple frequency resonant inverter

Fig 2 shows the simplified schematic diagram of the proposed inverter where the C_1 and C_2 are relocated and the center tap transformer is transformed. The proposed voltage source full bridge resonant inverter is actually made up of two half bridge inverters which contains two IGBT power modules and they are named as Leg1 and Leg2. The IGBT transistors of Leg1 and Leg2 are represented by $S_{1U} – S_{1D}$ and $S_{2U} – S_{2D}$ and the gate driving signals of each IGBT's are

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represented by $G_{1U} – G_{1D}$ and $G_{2U} – G_{2D}$. For each of four IGBT, there are four antiparallel diodes connected across them and are represented by $D_{1U} – D_{1D}$ and $D_{2U} – D_{2D}$. V_d is the input dc power supply to the proposed inverter. The center tap transformer employed in the proposed inverter has two primary windings and a secondary windings.

The transformer has two primary turns N_{P1} and N_{P2} and a secondary turn N_S, where two primary turns are equal i.e. $N_{P1} = N_{P2}$ and the turn ratio of the transformer is $n=N_{P1}/N_S=N_{P2}/N_S$. The IGBT transistors $S_{1U} – S_{1D}$ and $S_{2U} – S_{2D}$ are commutated in ZVS operation as a result of a resonant by capacitors C_1 and C_2 with the help of L_{P1} and L_{P2}.

B. Modes of Operation

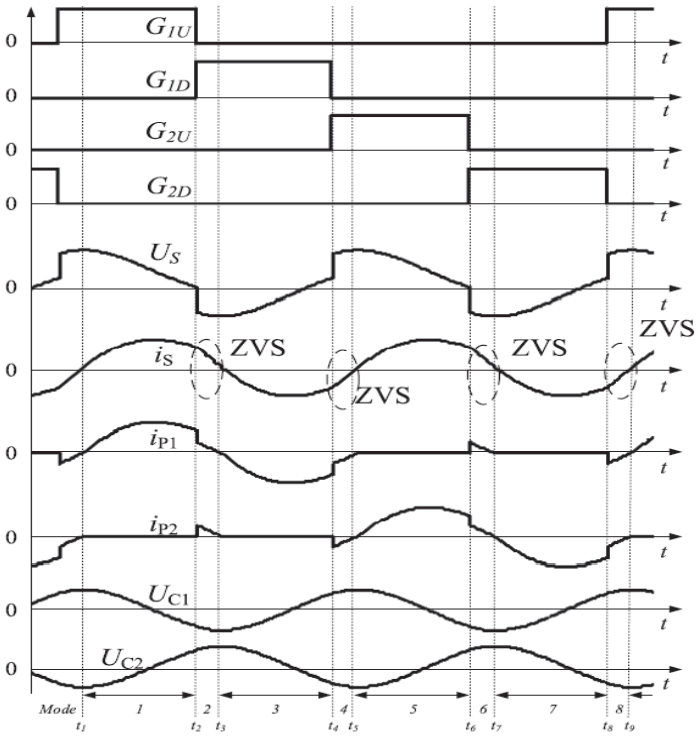

Fig 3: Operating waveforms of proposed inverter

In one switching cycle operation, there are eight modes of operations and is shown in fig 3 and explained as follows:
MODE 1 ($t_1 – t_2$) : In this mode at t_1, the switch S_{1U} is turned ON and switches S_{1D}, S_{2U} and S_{2D} are OFF and primary current i_{P1} and secondary current i_S are zero.

During this mode, two resonant loops exists, i.e. the primary current i_{P1} flows through two loops, where one part of the primary current flows through V_d, S_{1U}, N_{p1} and C_2 and the other part of the primary current flows through N_{P2}, C_1 and S_{1U}, the secondary current $i_S = ni_{P1}$, where turn ratio n is given by N_{P1}/N_{P2}. Fig 4 shows circuit diagram of mode 1. The state equations of this mode are as follows:

$$i_{P1} = \frac{i_S}{n}$$
$$U_{C1} + U_{C2} = V_d$$
$$U_{P1} = U_{P2} = U_{C1}$$
$$L\frac{di_S}{dt} + Ri_S = \frac{1}{n}U_{P1}$$
$$-C_1\frac{dU_{C1}}{dt} + C_2\frac{dU_{C2}}{dt} = i_{P1}$$
$$U_S = \frac{1}{n}U_{P1} = \frac{1}{n}U_{C1} \quad \text{-----1}$$

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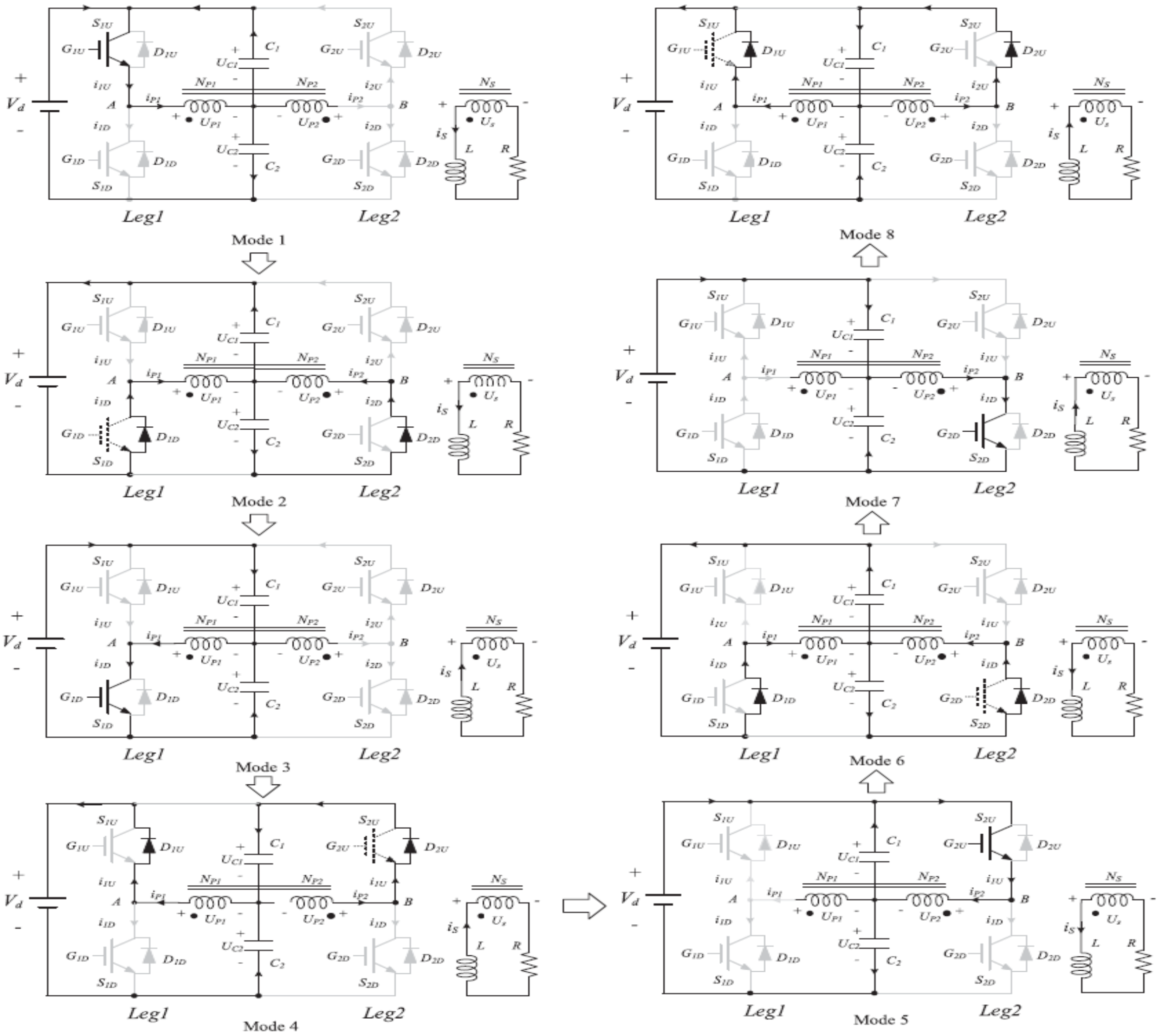

Fig 4: Mode of operation during one switching cycle

MODE 2 (t_2 – t_3): In this mode at t_2, the switch S_{1U} stops conducting and switches S_{2U} and S_{2D} remains OFF. The freewheeling diode D_{1D} starts conducting because the secondary current i_S does not decrease to zero and therefore S_{1D} is turned ON with ZVS. As $U_{P1} = U_{P2}$, freewheeling diode D_{2D} of switch S_{2D} conducts at the same time. The primary current i_{P1} flows through V_d, D_{1D}, N_{P1} and C_1 and the primary current i_{P2} flows through D_{2D}, N_{P2} and C_2. Fig 4 shows the circuit diagram of mode 2. The state equations of this mode are as follows:

$$i_{P1} = i_{P2} = \frac{i_S}{2n}$$

$$U_{C1} + U_{C2} = V_d$$

$$U_{P1} = U_{P2} = -U_{C2}$$

$$L\frac{di_S}{dt} + Ri_S = \frac{1}{n}U_{P1}$$

$$C_2\frac{dU_{C2}}{dt} = i_{P2}$$

$$U_S = \frac{1}{n}\left(U_{P1} + U_{P2}\right) = -\frac{2}{n}U_{C2} \qquad \text{-------2}$$

During this interval, to achieve the completion of ZVS operation, the inductive energy stored in the inductor L_{P1} should be greater than the capacitive energy stored in the capacitors C_1 and C_2, thus ZVS condition in S_{1D} is defined by,

$$i_{P1}(t_2) > 0$$

$$\frac{1}{2} L_{P1} [\, i_{P1}(t_2)]^2 > \frac{1}{4} C V_d^{\,2} \qquad \text{-------3}$$

MODE 3 ($t_3 – t_4$): In this mode at t_3, the switch S_{1D} starts conducting and the switches S_{1U}, S_{2U} and S_{2D} are OFF. The primary current i_{P1} and secondary current i_S decreases to zero. When switch S_{1D} is turned ON, the currents i_{P1} and i_S starts increasing negatively. During this mode, there exists two loops, where one part of the primary current i_{P1} flows through V_d, C_1, N_{P1} and S_{1D} and the other part flows through S_{1D}, C_2 and N_{P1}. Fig 4 shows the circuit diagram of mode 3. The state equations of this mode are as follows:

$$i_{P1} = \frac{i_S}{n}$$

$$U_{C1} + U_{C2} = V_d$$

$$U_{P1} = U_{P2} = -U_{C2}$$

$$L\frac{di_S}{dt} + Ri_S = -\frac{1}{n} U_{P1}$$

$$C_1 \frac{dU_{C1}}{dt} - C_2 \frac{dU_{C2}}{dt} = i_{P1}$$

$$U_S = \frac{1}{n} U_{P1} = -\frac{1}{n} U_{C2} \qquad \text{-------4}$$

MODE 4 ($t_4 – t_5$): In this mode at t_4, the switch S_{1D} stops conducting and switches S_{1U} and S_{2D} are OFF. The freewheeling diode D_{1U} conducts because the secondary current does not increase to zero. Due to $U_{P1} = U_{P2}$, the diode D_{2U} of switch S_{2U} conducts simultaneously, as a result switch S_{2U} is turned ON with ZVS. The primary current i_{P1} flows through V_d, C_2, N_{P1} and D_{1U} and the primary current i_{P2} flows through N_{P2}, D_{2U} and C_1. Fig 5.7 shows circuit diagram of mode 4. The state equations of this mode are as follows:

$$i_{P1} = i_{P2} = \frac{i_S}{2n}$$

$$U_{C1} + U_{C2} = V_d$$

$$U_{P1} = U_{P2} = U_{C1}$$

$$L\frac{di_S}{dt} + Ri_S = -\frac{1}{n} U_{P1}$$

$$C_1 \frac{dU_{C1}}{dt} = i_{P2}$$

$$U_S = \frac{1}{n} (\, U_{P1} + U_{P2}\,) = \frac{2}{n} U_{C1} \qquad \text{------5}$$

During this interval at t_4, to achieve the completion of ZVS operation, the inductive energy stored in the inductor L_{P1} should be greater than the capacitive energy stored in the capacitors C_1 and C_2. Thus, the ZVS condition in S_{2U} is defined by,

$$i_{P1}(t_4) < 0$$

$$\frac{1}{2} L_{P1} [\, i_{P1}(t_4)]^2 > \frac{1}{4} C V_d^{\,2} \qquad \text{------6}$$

Operations during next half switching cycle is similar to the operation explained above.

III. ANALYSIS OF THE PROPOSED INVERTER BASED ON EQUIVALENT CIRCUIT

The proposed inverter is analyzed based on the equivalent circuit by considering the proposed inverter as two symmetrical half bridge inverters sharing two equal resonant capacitors. Hence, it is effective to analyze the characteristics of the half bridge topology of the class D inverter with two resonant capacitors as shown in fig 6. The equivalent circuits of fig 6 is illustrated in fig 7 and fig 8.

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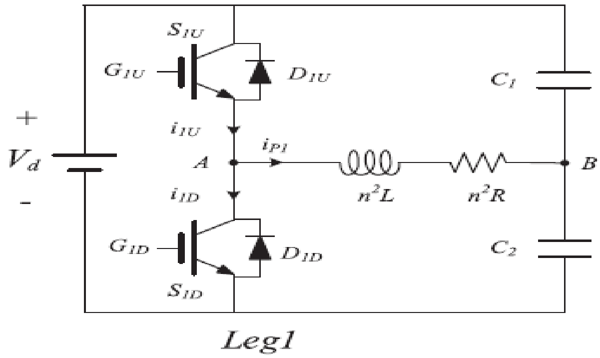

Fig 6: Half bridge topology of class D inverter

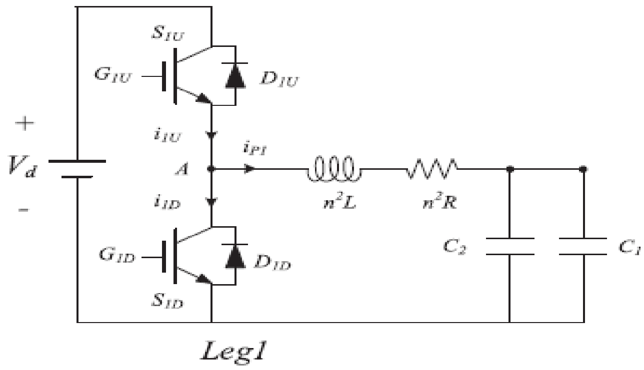

Fig 7: Equivalent circuit of Half bridge topology

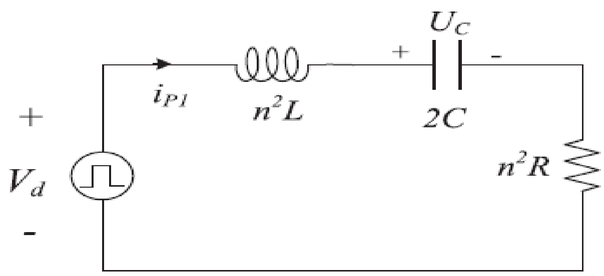

Fig 8: Equivalent circuit of fig 7

The input impedance of the resonant inverter circuit is given by,

$$Z = n^2R + j\left(\omega n^2 L - \frac{1}{2\omega C}\right)$$

$$Z = n^2R\left[1 + jQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)\right]$$

$$Z = |Z|e^{j\Psi}$$

Where,

$$\omega_0 = \frac{1}{\sqrt{2n^2LC}}$$

$$Q = \frac{1}{R}\sqrt{\frac{L}{2n^2C}}$$

$$|Z| = n^2R\sqrt{1 + Q^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}$$

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And

$$\Psi = \tan^{-1}[Q(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega})]$$

Referring to fig 8, the input voltage of series resonant inverter is a square wave and is given as,

$$V = \begin{cases} V_d, \text{ for } 0 < \omega_0 t \leq \pi \\ 0, \text{ for } \pi < \omega_0 t \leq 2\pi \end{cases}$$

IV. SIMULATION RESULTS

To examine the feasibility of the proposed topology, simulation is carried out in MATLAB/Simulink software. Parameters of the system is given in table below.

Table I: parameters of the system

Parameters	Symbols	Value
Input voltage	V_{in}	220 V/ 50 Hz
Resonant capacitors	C_1, C_2	0.1µF
Filter capacitor	C_d	680µF
Resistance	R	0.29Ω
Inductance	L	1.63µF
Switching frequency	f_s	23.2 KHz
Load resonant frequency	f_r	46.6 KHz

Simulation results shows input voltage, IGBT driving signals, current and voltage on the primary winding of the center tap transformer, output voltage and output current.

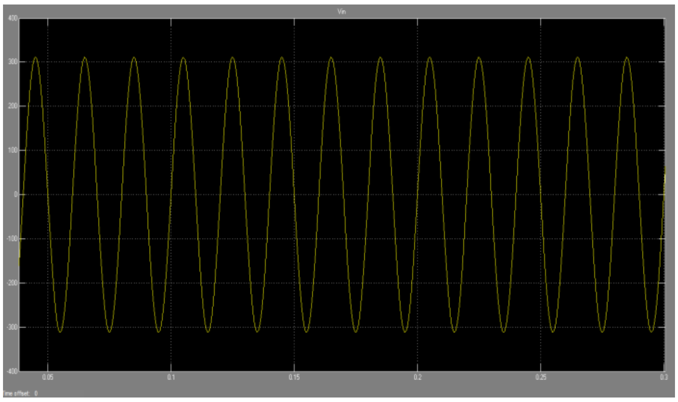

Fig 9: Input voltage waveform

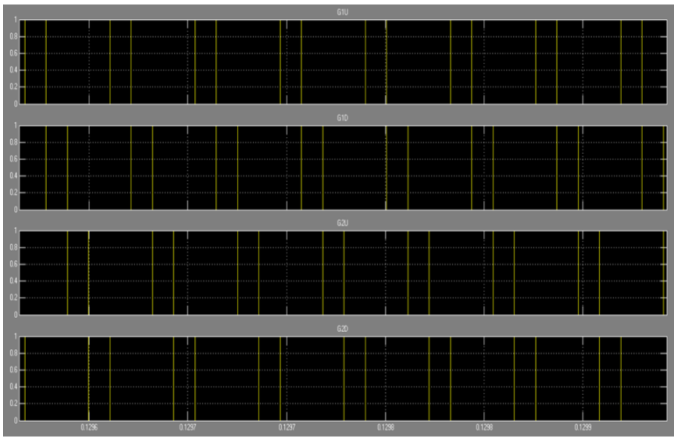

Fig 10: IGBT's driving signals

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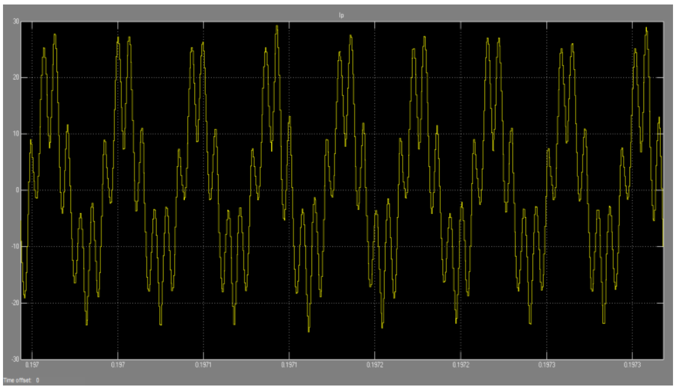

Fig 11: Primary winding current waveform

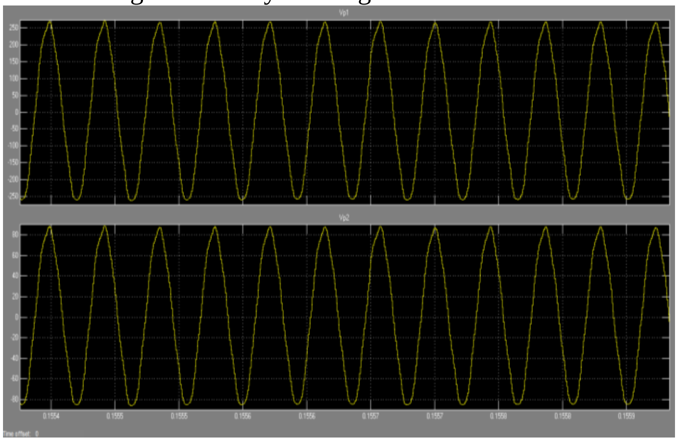

Fig 12: Waveforms of Voltages across primary winding 1 and 2 which shows load resonant frequency is twice the switching frequency

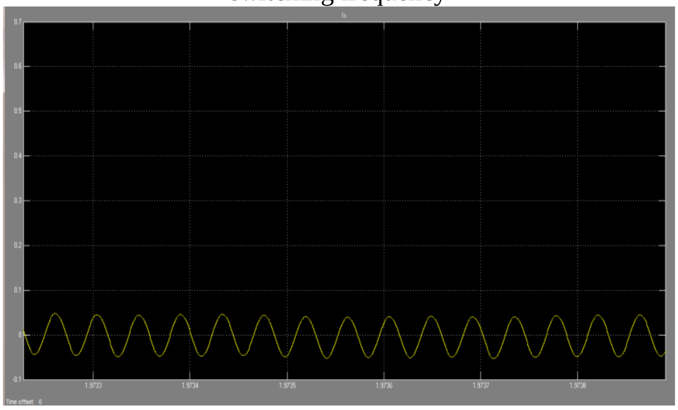

Fig 13: Output current waveform

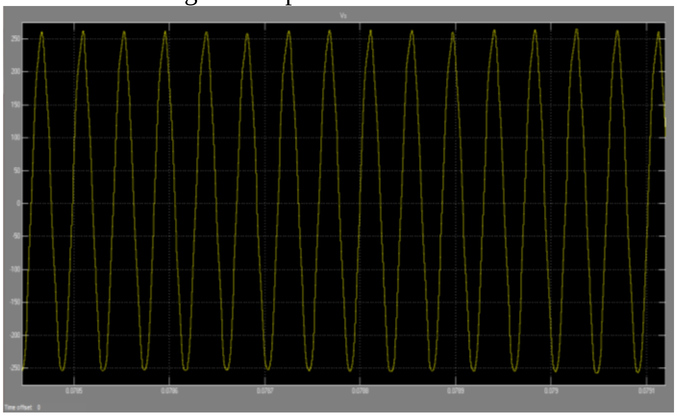

Fig 14: Output voltage waveform

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The input voltage is a sinusoidal waveform with magnitude of 220 V/ 50 Hz. The driving signals to the four IGBT's is of time period of one switching cycle (f=1/T). G1U is initiated with a delay of 12.5% of 'f' and width and amplitude of G1U, G1D, G2U and G2D are 25% of 'f' and 1 V respectively. Each signal start at the end of previous signal. From the time period Vp1 and Vp2 voltages of the primary side of the center tap transformer it can be seen that output frequency is twice the switching frequency and ZVS operation is achieved.

V. CONCLUSION

The analysis and the simulation results of the resonant inverter with IGBT is shown. By adopting a center tap transformer in this proposed inverter topology and by sharing two equal resonant capacitors, the load resonant frequency is twice the switching frequency of the IGBT. Moreover, results show that all the switches operate in ZVS condition during the turn on process.

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