Analysis and Simulation of Power Inverter for Induction Heating Applications by Phenomenon of Resonance

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Abstract— Electromagnetic induction refers to the phenomenon by which electric current is generated in a closed circuit by the fluctuation of current in another circuit placed next to it. Induction heating is that when AC current flowing through a primarily circuit induces a current in the load (the secondary circuit) located near it and heating the load. Heat loss occurring in the process of electromagnetic induction can be turned into productive heat energy in an electric heating system by applying electromagnetic induction principle. The intent of this paper is to present Induction Heating principles and the details of half-bridge power inverter (i.e. Series Resonant Inverter) via a comprehensive analysis with operation equations of the circuits and its various operating modes and finally do simulation of power inverter using MATLAB and verify effect of resonance phenomenon.

Key words: Induction Heating Applications, Electromagnetic Induction and Skin Effect, Resonant Converter, Inverter

I. INTRODUCTION

All induction heating (IH) applied systems are developed using electromagnetic induction, first discovered by Michael Faraday in 1831. Electromagnetic induction refers to the phenomenon by which electric current is generated in a closed circuit by the fluctuation of current in another circuit placed next to it. [1] The basic principle of induction heating is that AC current flowing through a primarily circuit induces a current in the load (the secondary circuit) located near it and heating the load. Heat loss, occurring in the process of electromagnetic induction, can be turned into productive heat energy in an electric heating system by applying this law [2]. If a conductive object e.g. the container of a rice cooker, is put inside the magnetic field, the induced voltage and an eddy current are created on the skin depth of the container as a result of the skin effect and Faraday's Law. This generates heat energy on the surface of the container. Rice is cooked by using this heat energy. The main goal of the paper is to show Induction Heating principles and analysis of half-bridge power inverter (i.e. Series Resonant Inverter) via a comprehensive study with operating equations of the circuits and its various operation modes and Simulation of power inverter using MATLAB to verify resonance effect.

The paper is organized as follows. Section II shows basic principle of Induction heating with its various applications. Section III explains principles of electromagnetic Induction and skin effect. Section IV shows converter topology review. Section V shows resonant converter topology with IH Rice Cooker as Induction Heating Application. Section VI explains half-bridge series resonant inverter with simulation. Section VII gives conclusion.

II. BASICS OF INDUCTION HEATING

Induction heating is a non-contact heating process. 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 [3]. Induction heating is comprised of three basic factors: (1) Electro-magnetic Induction, (2) Skin Effect and (3) Heat Transfer.

Induction heating is the principle that the magnetic field induced in the coil when energized, causes eddy currents to occur in the heating load and these give rise to the heating effect, as shown in fig.1 [4]

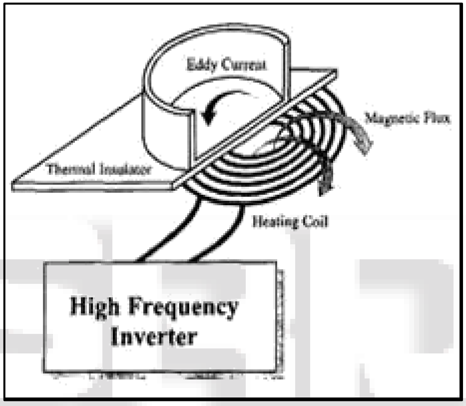


Fig. 1: Principle of Induction Heating

The most of the heat, generated by eddy currents in the heating load is concentrated in a peripheral layer of skin depth δ which is given by following equation 1 [4]:

$$\delta = \sqrt{\frac{1}{4\pi^2 X 10^{-7}}} * \sqrt{\frac{\rho}{\mu_r f}} \qquad \text{------ (1)}$$

Where μ_r = Relative Magnetic Permeability of the material,

ρ = Electrical Resistivity of the material,

f = operating frequency.

It is also important factor to determine operating frequency for induction heating applications. Electromagnetic induction and the skin effect will be described briefly. For that Figure 2 illustrates a basic system, consisting of inductive heating coils and current to explain electromagnetic induction and the skin effect. However, the fundamental theory of IH is similar to that of a transformer.

Figure 2-a shows the simplest form of a transformer, where the secondary current is in direct proportion to the primary current according to the turn ratio. The primary and secondary losses are caused by the resistance of windings. When the coil of the secondary is turned only once and short-circuited, there is a substantial

heat loss due to the increased load current (secondary current). This is demonstrated in Figure 2-b.

Figure 2-c shows the concept of induction heating where the energy supplied from the source is of the same amount as the combined loss of the primary and secondary. In these figures, the inductive coil of the primary has many turns, while the secondary is turned only once and short-circuited.

The inductive heating coil and the load are insulated from each other by a small aperture. Because the primary purpose of induction heating is to maximize the heat energy generated in the secondary, the aperture of the inductive heating coil is designed to be as small as possible and the secondary is made with a substance featuring low resistance and high permeability (Non-Ferrous Materials).

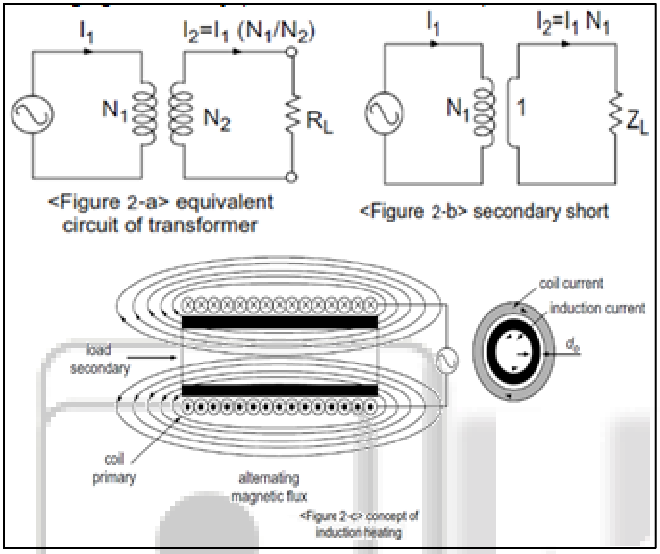


Fig. 2: Basics of Induction Heating With Equivalent Circuits

Induction heating allows the targeted heating of an applicable item for applications including surface hardening, melting, welding, quenching, brazing, soldering etc. Iron and its alloys respond best to induction heating due to their ferromagnetic nature. Induction heating has been also used to heat liquid conductors (such as molten metals) and also gaseous conductors.

Major Applications of Induction Heating are as follows: Induction furnace, Induction welding, Induction cooking, Induction brazing, Induction sealing, Heating to fit, Plastic processing, Heat treatment.

III. ELECTROMAGNETIC INDUCTION & SKIN EFFECT

A. Electromagnetic Induction:

According to Ampere's Law as [2] as shown in fig. 2, when the AC current enters a coil, a magnetic field is formed around the coil, calculated as in (2):

$$\int Hdi = Ni = f \qquad \text{------ (2)}$$
$$\phi = \mu HA$$

According to Faraday's Law [2], the current on the surface of the object generates an eddy current, calculated as in (3):

$$E\frac{d\lambda}{dt} = N\frac{d\Phi}{dt} \qquad \text{----- (3)}$$

As a result, the electric energy caused by the induced current and eddy current is converted to heat energy, as shown in Equation P = $I^2R = E^2/R$.

B. Skin Effect:

The higher the frequency of the current administered to the coil, the more intensive is the induced current flowing around the surface of the load [2]. The density of the induced current diminishes when flowing closer to the center, as shown in (4) and (5) below. This is called the "skin effect" or "Kelvin effect."

From this effect, one can infer that the heat energy converted from electric energy is concentrated on the skin depth (surface of the object):

$$i_x = i_0\, e^{-\frac{x}{d_0}} \qquad \text{------ (4)}$$

Where, i_x = current density at x, distance from the skin (surface) of the object;

i_0 = current density on skin depth (x=0); &

d_0 = a constant determined by the frequency (current penetration depth or skin depth);

Equation (5) could be used to find d_0 which states that the skin thickness is determined by the resistivity, permeability, and frequency of the object.

$$d_0 = \sqrt{\frac{2\rho}{\mu\omega}} \qquad \text{------ (5)}$$

Where, ρ = resistivity;
μ = permeability of the object; and
ω = frequency of the current flowing through object

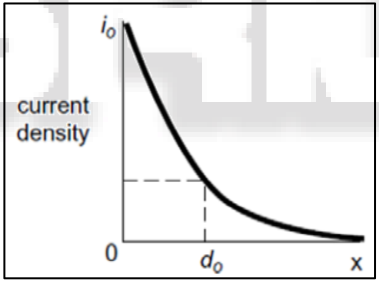


Fig. 3: Distribution Chart of Current Density & Skin Thickness

IV. CONVERTER TOPOLOGY REVIEW

Generally, semiconductor switching devices operate in Hard Switch Mode in various types of Pulse Width Modulation (PWM) DC-DC converters and DC-AC inverter topologies. In this mode, a specific current is turned on or off at a specific voltage whenever switching occurs, as shown in Figure 3. This process results in switching loss [2].

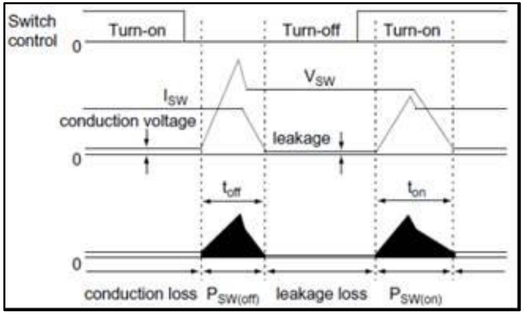


Fig. 4: Waveform of a Switching Device

The higher the frequency, the greater the switching loss, which obstructs efforts to raise the frequency. Switching loss can be calculated as shown in (6) below [2].

$$P_{SW} = \frac{1}{2} V_{SW} I_{SW} f_S (ton + toff) \qquad \text{-----}\ (6)$$

Where,
P_{sw} = switching loss (W), V_{sw}= switching voltage (V)
Isw = switching current (A), f_s = switching frequency (kHz)
t_{on} = switching turn-on time (sec)
t_{off} = switching turn-off time (sec)

Limitations: (1) Devices are turned on and off at the load current with high $\frac{di}{dt}$ value, (2) Switches are also subjected to a high voltage stress, (3) Switching power loss of a device increases linearly with switching frequency, (4) So, the turn-on and turn off loss could be a significant portion of the total power loss [5], (5) Switching also causes an EMI problem, because a large amount of $\frac{di}{dt}$ and $\frac{dv}{dt}$ is generated [5].

As we know, raising the switching frequency reduce the size of a transformer and filter, which helps to build a smaller and lighter converter with high power density. But switching loss decreases the efficiency of the entire power system in converting energy, as more losses are generated at a higher frequency [6]. Switching loss can be partly avoided by connecting a snubber circuit parallel to the switching circuit. However, the total amount of switching loss generated in the system remains the same. Because the loss avoided has been moved to the snubber circuit [2].

Above limitations can be minimized by, employing Higher energy conversion efficiency at high-frequency switching can be obtained by manipulating the voltage or current at the moment of switching to become zero. This is called "soft switching" which can be sub-categorized into two methods: Zero-Voltage Switching (ZVS) & Zero Current Switching (ZCS).

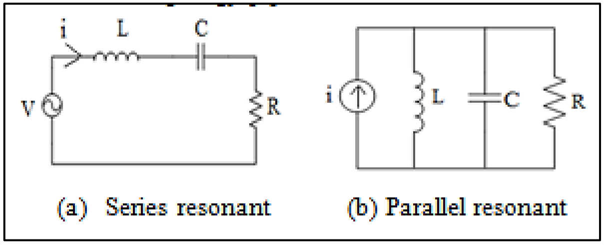
ZVS refers to eliminating the turn-on switching loss by having the voltage of the switching circuit set to zero right before the circuit is turned on. ZCS avoids the turn-off switching loss by allowing no current to flow through the circuit right before turning it off. [2]. The voltage or current administered to the switching circuit can be made zero by using the resonance created by an L-C resonant circuit. This is a "resonant converter" Topology. [5]

V. RESONANT CONVERTER

This topology constitutes of at least one resonant tank circuit as a sub-circuit. A resonant tank is a sub-circuit consisting of at least one inductor and one capacitor [6]. As a resonant converter provides most of the energy conversion efficiency in a power system by minimizing switching loss, so it is widely used in a variety of industries. This is also the reason the converter is adopted in the Induction Heating (IH) power system Topology, which is described in detail in this paper. Power systems for home appliances, such as electronic rice cookers, generally employ a ZVS resonant converter. ZVS converters can be classified into two major types: Half-bridge series resonant converter and Quasi- resonant converter.

A. *Resonant Inverter:*

High frequency currents required in IH Application which are obtained using resonant converters viz. series or parallel resonant topology [3].



(a) Series resonant (b) Parallel resonant

Fig. 5: Resonant Converter

When power is connected, electric energy, as shown in Equation (8), is stored in the inductor and transferred to the capacitor. Equation (9) simplifies the calculation of the amount of energy stored in the capacitor sent to the inductor.

$$i = \sqrt{2}\, I\, sin\omega t\ (A) \qquad \text{-----}\ (7)$$

$$E_L = \frac{1}{2} Li^2 = LI^2 sin^2\omega t\ (\mathrm{J}) \qquad \text{-----}\ (8)$$

$$E_C = \frac{1}{2} CV^2{}_C = \frac{I^2}{\omega^2 C} cos^2\omega t = LI^2 cos2\omega t\ (J) \ \text{-----}\ (9)$$

Resonance occurs while the inductor and the capacitor exchange the energy. The total amount of energy stored in the circuit during resonance remains unchanged. This total amount is the same as the amount of energy stored at peak in the conductor or capacitor.

$$V_C = \frac{1}{C}\int idt = -\frac{\sqrt{2}I}{\omega C} cos\omega t\ (V) \qquad \text{-----}\ (10)$$

$$E_L + E_c = LI^2(sin^2\omega t cos^2\omega t) = LI^2 \frac{I^2}{\omega^2 C} \ \text{-----}\ (11)$$

As some energy is lost due to resistance in the resonance process, the total amount of energy stored in the inductor decrements in each resonant exchange. The resonance frequency, which is the speed of energy transfer, is determined by capacitance (C) and inductance (L), as shown in further Equations.

The inductive reactance and capacitive reactance is given by (12) and (13) respectively and the size of impedance in a series resonant circuit is determined by (14),

$$X_L = j\omega L = j2\pi f L\ \ (\Omega) \qquad \text{-----}\ (12)$$

$$X_C = \frac{1}{j\omega C} = \frac{1}{j2\pi f C}\ (\Omega) \qquad \text{-----}\ (13)$$

$$|Z| = \sqrt{R^2} + \left(\omega L - \frac{1}{\omega C}\right)^2 (\Omega) \qquad \text{-----}\ (14)$$

At the resonance frequency, the inductive reactance X_L of (12) and the capacitive reactance X_c of (13) become the same, i.e. the voltage of the power source and the current in the circuit stay at the same level. The resonance frequency can be summarized as shown in (15).

$$2\pi f L = \frac{1}{2\pi f C} \Rightarrow f_0 = \frac{1}{2\pi\sqrt{LC}}\ \mathrm{Hz} \qquad \text{----}\ (15)$$

The current in the circuit reaches its peak when the source frequency becomes identical to the resonance frequency. It decrements when the source frequency gets higher or lower than the resonance frequency [2].

The selection ratio of a half-bridge series resonant circuit is as shown in (16),

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR} = \frac{Z_0}{R} \qquad \text{-----}\ (16)$$

As shown in (17), the smaller the resistance is than the inductance, i.e. when the source frequency gets closer to the resonance frequency, the sharper the frequency curve of Fig. 6 and the bigger the value of Q.

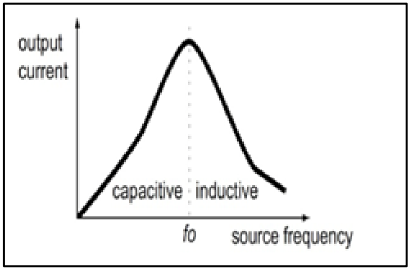


Fig. 6: Frequency Curve

The frequency curve demonstrates the relationship between current/output energy and source frequency when the source voltage of the resonant circuit is set at equal. The current and output energy reaches its maximum value at resonance frequency. In the area where the switching frequency is lower or higher than the resonance frequency i.e. in induction or capacitive region, we get less value of current than maximum.

B. *Induction Heating Application (IH Rice Cooker):*

Induction heating (IH) plays a great role in industry and home applications [7]. IH systems have many positive properties including Cleanliness, CO less than the fossil burners, Safety, High thermal efficiency. Generally, efficiency of IH rice cooker is 84% compared to non-induction electric cookers which has 74.2 % for the same quantity of heat energy. It simply consist of an inverter, an IH coil, a heating object as shown in fig. 7. AC current flows through the surface of a conductor and home IH systems produce heat based on eddy current and skin effect resistance of the coil and metal pots [7]. The operation Theory of IH rice cooker shown in block diagram form as in fig. 8.

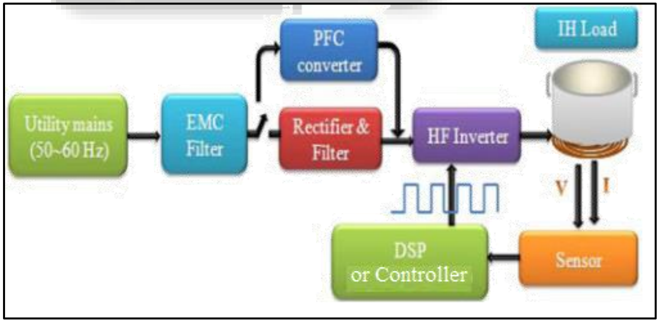


Fig. 7: Block Diagram for IH Rice Cooker

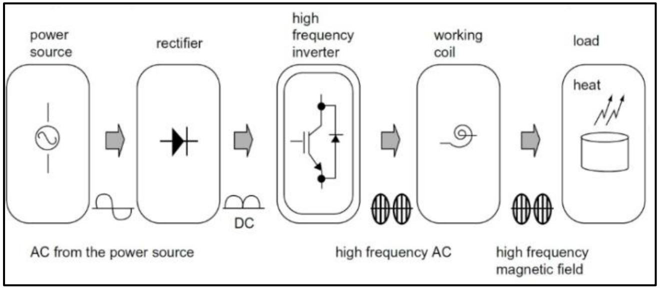


Fig. 8: Operating Theory of IH Rice Cooker

Firstly Rectifier used to convert from mains AC to DC, then connect this DC current to a high-frequency switching circuit (Inverter) and finally high-frequency current applied to the heating coil. According to Ampere's Law, a high-frequency magnetic field is created around the heated coil.

If a conductive object e.g. the container of a rice cooker, is put inside the magnetic field, the induced voltage and an eddy current are created on the skin depth of the container as a result of the skin effect and Faraday's Law. This generates heat energy on the surface of the container. Rice is cooked by using this heat energy.

VI. HALF-BIRDGE SERIES RESONANT INVERTER

This system is comprised of an AC power supply, main power circuit, control circuit, input current detection circuit, resonant current detection circuit, and gate operation circuit. It does not contain the heater and cooling fan. The operation for the whole system is illustrated in the Fig.7

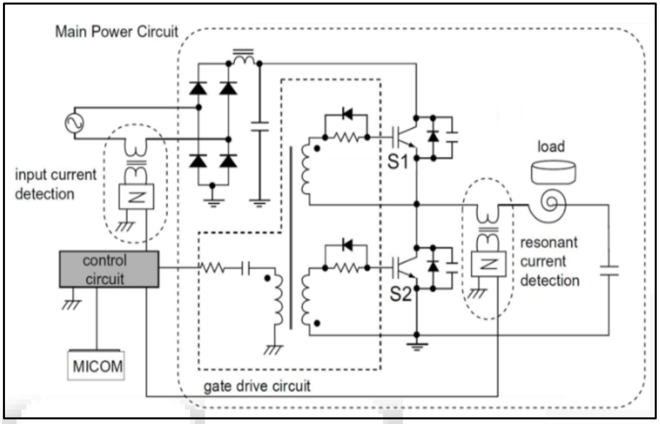


Fig. 9: Block Diagram for Whole IH System.

In recent years, with remarkable advancements of power semiconductor devices and electronic control systems, much attention has been focused on the research and developments of high-frequency resonant inverters capable of supplying high-power to induction heating loads.

The main features of half-bridge power inverters includes (1) Switches like MOSFETs, IGBTs, MCTs, SITs offer reduced power device switching losses , (2) So by means of soft-switching technique and attractive possibilities in developing higher frequency of operation, (3) Higher efficiency, lightweight and overall system simplicity in inverter control, (4) Half-bridge series resonant inverter is the most used topology due to its appropriate balance between performance, complexity, and cost, (5) It is used to design converters with up to 3.5-kW output power.

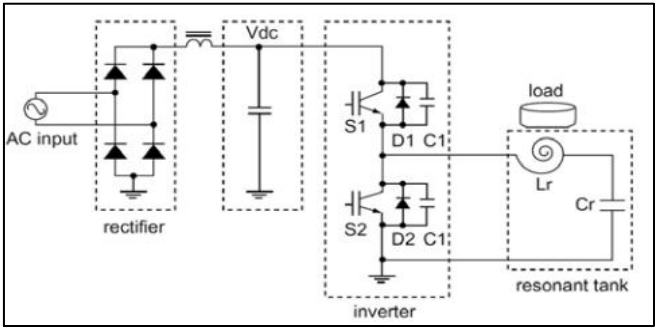


Fig. 10: Main Power Circuit

As shown in fig. 10, the resonant circuit comprises of resonant inductance (Lr) and resonant capacitance (Cr). The capacitors, C1 and C2, are the lossless turn-off snubbers for the switches, S1 and S2.

A. Equivalent Circuits [2]:

A circuit equivalent to a resonant circuit is described in Fig. 11. The load in circuit (a) is equivalent to the circuit in (b) where the transformer has resistance connected to the secondary circuit. This can be simplified as in the circuit (c), where R*, L*, and Cr are directly connected. R* in (c) indicates the resistance of the primary circuit of the transformer converted from the secondary. L* means the inductor on the primary side of the transformer (Lr), which is a resonant inductor combining the leakage inductor and the secondary inductor.

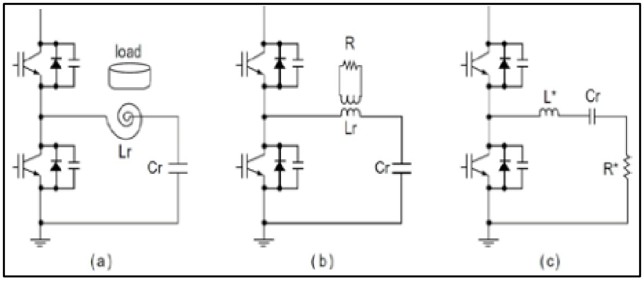


Fig. 11: Equivalents of the Resonance Circuit

B. Operation Theory [2]:

By connecting the IGBT switching circuit, S1 and S2, in parallel to diodes D1 and D2; current loss is minimized. When S1 is turned off, D2 helps S2 stay on zero voltage /current before being turned on, substantially reducing current loss (the same is the case with S1). There is no reverse-recovery problem as the voltage on both sides remains zero after the diode is turned off. However, as the switching circuit is turned off at around the upper limit of voltage and current, some switching loss results on turn-off. Capacitors C1 and C2, acting as turn-off snubbers connected in parallel to S1 and S2, keep this loss to a minimum. Upon turn-on, the switching circuit starts from zero voltage / current, so these turn-off snubbers operate without loss. The configuration of a half-bridge series resonant inverter in fig. 10 can be simplified as an equivalent circuit illustrated in fig. 12. Figure 13 is a waveform of a frequency cycle in each part of the main power circuit. Turn on S1 when the current of the L*-Cr resonant circuit flows in the opposite direction through D1 (S1 and S2 remain off). Until t<t0, the resonant current flows in the opposite direction through D1, rather than passing directly through S1.

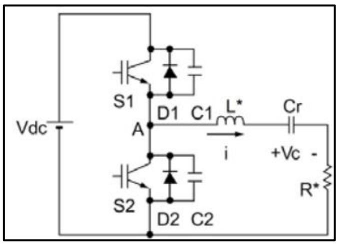


Fig. 12: Equivalent of Main Power Circuit

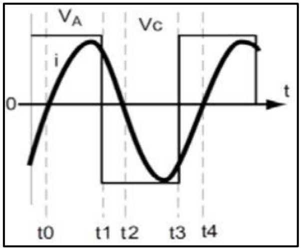


Fig. 13: Waveform of Main Power Circuit

C. Simulation of Power Inverter with Results & Discussion:

Simulation of half-bridge resonant inverter with MOSFET as switching devices are used with input DC of 325 V. To obtain maximum value of current, it is required to set switching frequency which should be equal to resonance frequency.

Here, we have chosen values of resonant components as of L and C as 55 μH and 0.799 μF respectively to get resonance frequency of 24 kHz. So, by adjusting same values of switching and resonance frequency we are getting maximum value of current as 32.5 A as due to cancellation of inductive and capacitive reactance by resonance principle as drop in only resistance which is set to 10 Ω.

Adjusting values of switching frequency other than resonance frequency gives inductive or capacitive effect as discussed in earlier sections with frequency curve.

Here, from simulation study inductive effect is obtained by setting switching frequency as 40 kHz which higher than resonance frequency and we are getting current lags voltage with decrease in magnitude. Capacitive effect is obtained by setting switching frequency as 17 kHz which is lower than resonance frequency and we are getting current leads voltage with decrease in magnitude.

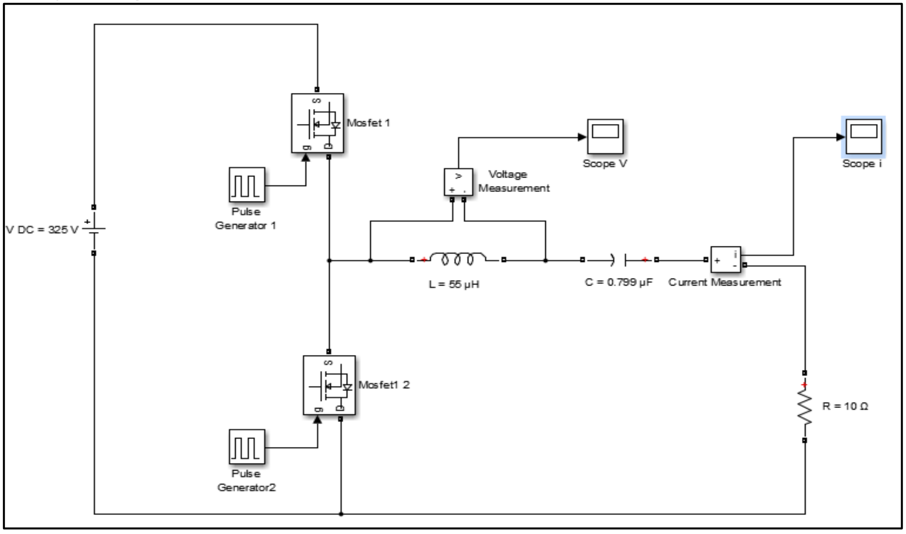


Fig. 14: Simulation Diagram for Half-Bridge Power Inverter

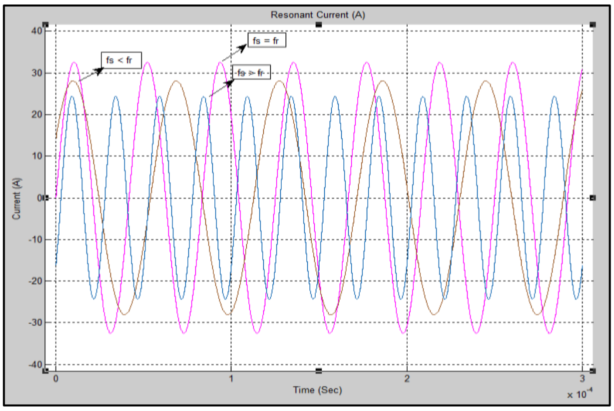


Fig. 15: Waveform of Load Current by Selecting Different Values of Frequencies to Verify Resonance Phenomena

VII. CONCLUSION

From the analysis & simulation of power inverter , we can conclude that For Induction Heating Applications, Maximum Heat Energy is required i.e. maximum power loss is required in the form of I2R loss. In half bridge power inverter, at the time when resonance frequency is the same as switching frequency, we get maximum value of current & so that maximum I2R loss i.e. maximum power loss in form of Heat Energy. While in the case where switching frequency is higher or lesser than the resonance frequency, we get more inductive or capacitive effect & so that we are getting lesser value of current depending on switching frequency.

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