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High Frequency LLC Resonant Inverter for Induction Heating with Asymmetrical Control

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Abstract— **A high frequency LLC resonant inverter for induction heating is proposed in this paper. This topology is a combination of an H bridge inverter and an LLC load configuration. The load configuration constitutes a series inductor (L_s), dc blocking capacitor (C_{dc}), a matching transformer, parallel resonant capacitor (C_p) and an induction coil (L_c) which is a series combination of an inductor and a resistance. The matching transformer is introduced to ensure maximum power transfer, thus to improve the current gain. It is an effective method of heating and does not contaminate the material being heated since the heat is generated inside the material. The concept of asymmetrical switching helps to control the output power effectively. Moreover the high frequency operation reduces the size of components and thereby the effective cost. Phase loop control (PLL) scheme is used to synchronize the resonant frequency and switching/operating frequency under load parameter variations due to the effect of temperature. The resonance behaviour of the proposed system is analysed for a frequency range of 100 kHz to 110 kHz. PLL closed loop control of the proposed converter is simulated in MATLAB.**

Keywords— asymmetrical control, induction heating, phase locked loop

I. INTRODUCTION

High Frequency Induction heating is a process which is used to bond, harden or soften metals or other conductive materials. For many modern manufacturing processes, induction heating offers an attractive combination of speed, consistency and control. In the most common heating methods, a torch or open flame is directly applied to the metal part. But with induction heating, heat is actually "induced" within the part itself by circulating electrical currents.

The basic requirements of an induction heating system is i) a high frequency electric supply ii) work coil or induction coil and iii) the work piece which is to be heated. Researches on induction heating reveals that LLC resonant inverter offers better performance than traditional SRI and PRI because of its inherent short circuit capability [8]-[13].The most relevant properties of LLC oscillator, its design and equivalency with SRI are discussed in [14]. The requirement of an accurate power control in induction heating applications led to the proposal of Asymmetrical Voltage Cancellation (AVC) method [13] and [14]. In [12] AVC is implemented in a series – parallel resonant inverter. The asymmetrical voltage cancellation concept has the advantage of reduced conduction losses along with the power control capability.

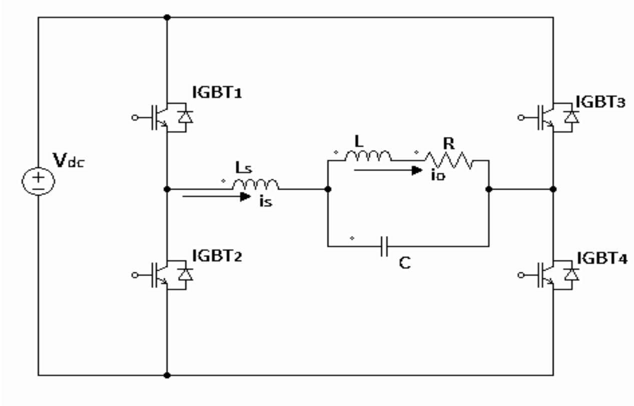

Fig.1 Series Parallel Resonant Converter

The basic series parallel resonant configuration, used for induction heating application is shown in figure 1. It consists of four IGBT switches, a series inductor L_s, parallel capacitor1 C, and an induction coil which is a series combination of an inductor L and resistance R. In this paper a matching transformer is introduced to above circuit, to ensure maximum power transfer to the load. Moreover, instead of IGBT's MOSFET switches are used because of its high input impedance and can operate at very high switching speeds. Finally, the frequency at which the switches are turned on and off will determine the frequency to be applied to the resonant tank. For efficiency purposes, the LLC converter utilizes ZVS to eliminate the switching losses of the MOSFET's.

II. PRINCIPAL OF OPERATION

Figure 2 shows the proposed high efficient full bridge LLC resonant inverter for induction heating applications like induction melting, brazing, hardening etc. It consists of four MOSFET switches SW1, SW2, SW3 and SW4. Antiparallel diodes D1, D2, D3 and D4 are connected across it. The effects of stray capacitances are not considered here. The load configuration section consists of series inductor(L_s), matching transformer, dc blocking capacitor (C_{dc}) to block dc components, parallel resonant capacitor (C_p) and an induction coil which is represented by an inductor (L_c) connected in series with an equivalent resistor(R_{eq}).

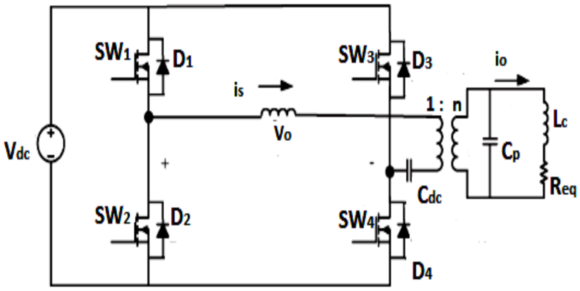

Fig.2 Proposed full bridge LLC Resonant Inverter

Figure 3 shows the equivalent circuit of the proposed system. The asymmetrical voltage from the H bridge inverter is directly given to the LLC load configuration.

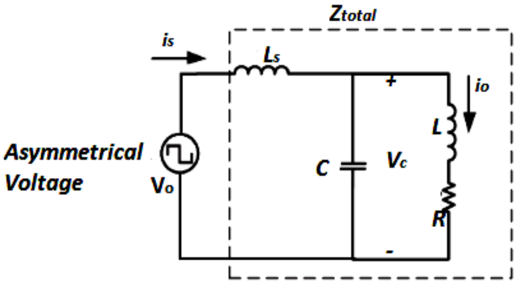

Fig.3 Equivalent Circuit

Modes of Operation:

As shown in figure below there are five basic modes of operation exist in one switching cycle, neglecting the effects of stray capacitances of the MOSFETs. The corresponding waveforms and the circuit operation for each mode is shown in figure (4) and (5) respectively. The analysis is as follows:

Mode 1($t_0 - t_1$)*:* At an arbitrarily chosen time $t_{o,}$ switches SW2 and SW3 are turned off. Gating pulses are applied to switches SW1 and SW4. But SW1 and SW4 are not yet turn on. The energy stored in the inductor get released and it flows in the negative direction through diodes D1 and D4 as shown in figure 4. (a).

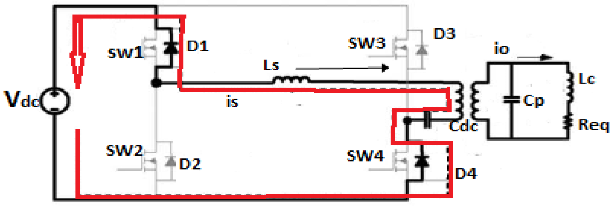

Fig.4.(a): Mode 1 ($t_{o-}t_1$)

Mode 2 ($t_1 - t_2$)*:* During this mode, at t $= t_1$; the energy stored in the inductor is completely released and diodes D1 and D4 are turned off. As soon as antiparallel diodes are turned off switches SW1 and SW4 are turned on and zero voltage switching is achieved. The positive current i_s will flow through V_{dc}, SW1, Ls, primary of the transformer, C_{dc}, SW4 and then back to V_{dc} as shown in figure 4.(b).

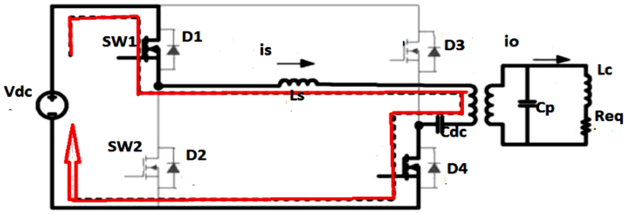

Figure 4. (b): Mode 2 ($t_1 - t_2$)

Mode 3 (t_2 - t_3)*:* At t = t_2, SW4 is turned off, but SW1 still conducts. Once the capacitor C_b is fully charged the diode D3 will conduct and the current will circulate through SW1, Ls and D3. During this mode, output voltage changes from +V_{dc} to 0. After a switch dead time SW3 will receive gating signal.

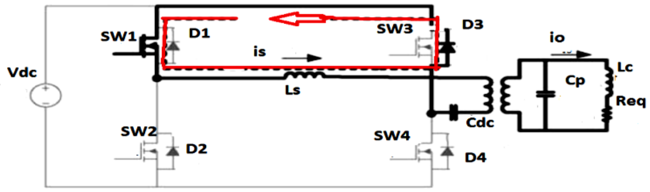

Fig.4 Mode 3 ($t_2 - t_3$)

Mode 4 ($t_3 - t_4$) *:* At this mode S1 is turned off. Similar to Mode 1 , energy stored in inductor Ls starts releasing and diodes D2 and D3 will conducts. S2 will receive positive gating signal in this mode. V_{dc} changes from 0 to -V_{dc}.

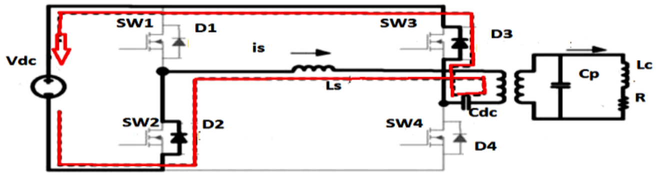

Fig.4 (d): Mode 4 (t_3 - t_4)

Mode 5 ($t_4 - t_5$)*:* The diodes D2 and D3 are turned off in this mode. At t=t_4, switches SW2 and SW3 , which already received gating signals starts conducting and ZVS operation is achieved. The current i_s becomes negative and the modes will repeat for the next switching cycle.

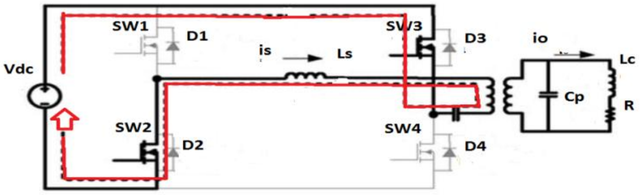

Fig. 4. (e): Mode 5 (t_4 - t_5)

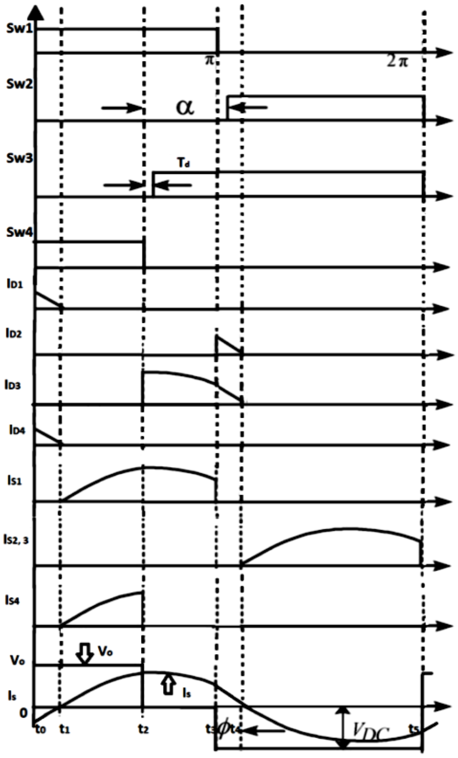

Fig.5 Typical Waveforms of asymmetrical voltage cancellation

III. PHASE LOCKED LOOP CONTROL STRATEGY

A PLL is a feedback system that includes a VCO, phase detector, and low pass filter within its loop. Its purpose is to force the VCO to replicate and track the frequency and phase at the input when in lock. The PLL is a control system allowing one oscillator to track with another. It is possible to have a phase offset between input and output, but when locked, the frequencies must exactly track.

$$\phi_{out}(t) = \phi_{in}(t) + const \qquad (1)$$

$$\omega_{out}(t) = \omega_{in}(t) \qquad (2)$$

Based on figure 3 the resonant frequency can be calculated as:

$$\omega_{out} = \sqrt{\frac{L_S + L}{C.L.L_S}} \qquad (3)$$

The PLL output can be taken from either V_{const}, the filtered (almost DC) VCO control voltage, or from the output of the VCO depending on the application. The former provides a baseband output that tracks the phase variation at the input. The VCO output can be used as a local oscillator or to generate a clock signal for a digital system. Either phase or frequency can be used as the input or output variables.

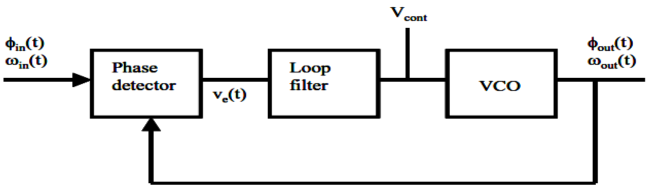

Fig. 6. Basic PLL control

The PLL used in the control scheme has two functions:
1) To control the power of the entire system using asymmetrical voltage cancellation
2) To adjust the operating frequency automatically to the range of resonant frequency under load parameter variations.

The output current i_o, is sensed using a current sensor and it is given to the zero crossing detector to obtain corresponding square pulse. The analogue phase detector in the PLL will compare current signal i_o with the voltage signal to detect the phase difference. The output of phase detector is then filtered using a low pass filter to get an average value proportional to the phase difference at load. The output from VCO is given directly to switch SW1 and its invert signal to SW2. The asymmetrical gate pulse is applied to switch SW4 and its invert pulse to SW3. The output of VCO is given to an integrator to generate corresponding ramp signal and it is compared with a constant $P_{control}$ signal within a comparator. By varying the values of $P_{control}$, we can control the phase shift α.Figure 8 shows the asymmetrical gate pulse generation for switch SW4.

If $P_{control}$ is higher in amplitude than the ramp signal G4 is set to high, and G3 will give invert operation. The gate signal G1 is always on from 0 to Π and G2 will give the invert operation (i.e., from Π to 2Π).

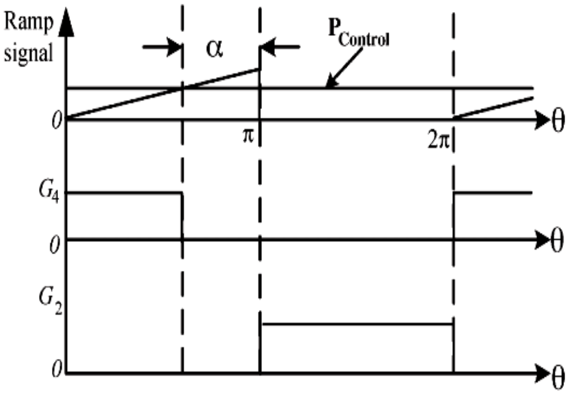

Fig. 7 Waveforms of asymmetrical gate drive signal

IV. SIMULATION RESULTS

The simulations are done in the platform of MATLAB. The simulation parameters of the proposed system are given in Table 1.

TABLE 1: SIMULATION PARAMETERS

SI No	Parameter	Value, specification
1	Input Voltage	150V
2	Switching Frequency	108.7 kHz
3	Series Inductor Ls	4.85μH
4	Dc blocking Capacitor, C_{dc}	3.33μF
5	Transformation Ratio of Transformer, n	5
6	Primary leakage reactance	75μH
7	Parallel Resonant Capacitor ,Cp	2.85μF
8	Induction coil	1.5$\mu H, 100m\Omega$

To confirm the validity of the proposed converter and PLL control scheme, MATLAB simulation is conducted using the parameters in Table 1. Due to the heating effects, the variations in load parameters results in the change in switching frequency. In order to adjust the switching frequency automatically to the resonant frequency, PLL control circuit is used. Using (3), the resonant frequency is calculated as 108.7kHz. The shifted angle α can be varied from 0 to 180°, for the purpose of output power control. As α increases, the inverter output current i_s, output voltage V_o, the induction coil current i_o, and induction coil voltage V_c decreases. Figure 8 shows the simulink model of the proposed control strategy of the resonant converter. The waveforms at full load condition (α=0°) is shown in figure.9 (a) – (e).

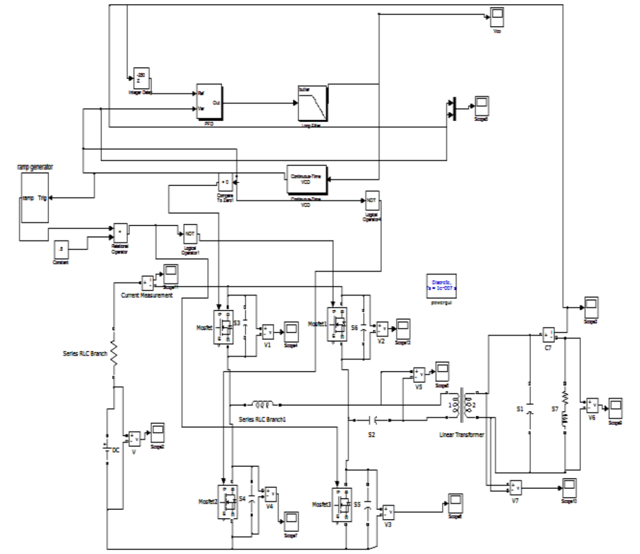

Fig. 8 Simulink model of the proposed converter

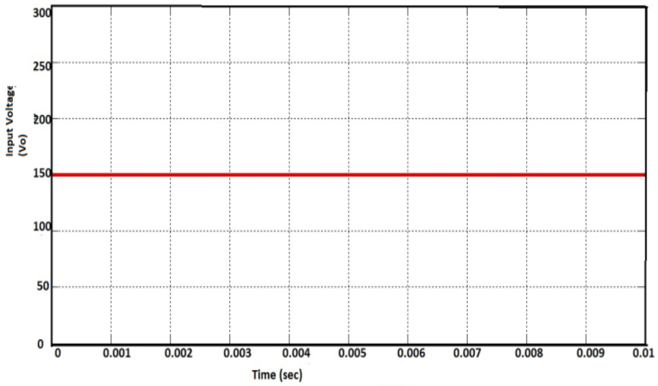

Figure. 9.(a): Input Voltage

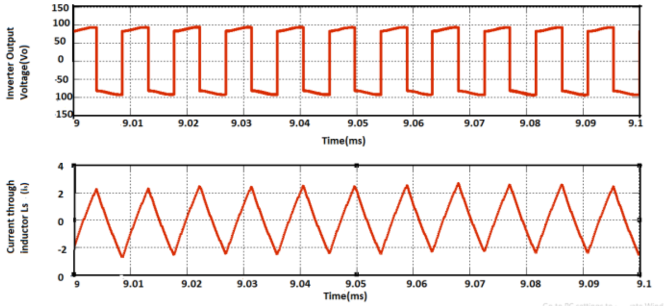

Fig. 9.(b): Output Voltage(V_o) and current of inverter(i_s)

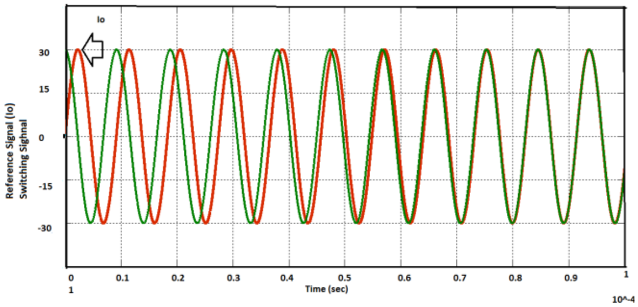

Fig 9.(c) : Synchronized switching and reference signal

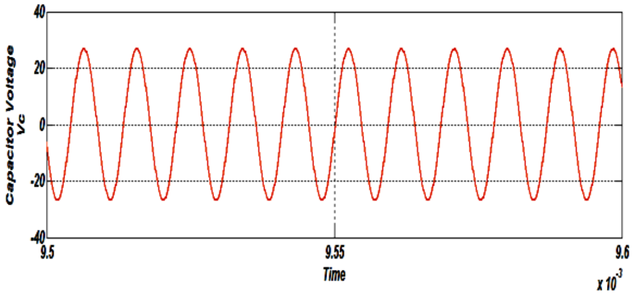

Fig 9.(d): Capacitor Voltage(V_c)

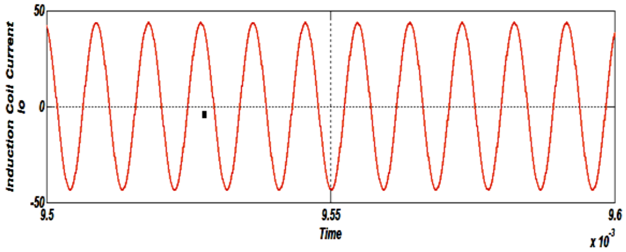

Fig 9.(e): Current through induction coil(i_o)

For an input voltage of 150 volts, the inverter will give an output voltage 90V in the primary of the transformer. The maximum amplitude of current i_s, through the series inductor L_s is 2.5A. The switching signal will automatically tracks the resonant frequency under load parameter variations using PLL, which is shown in fig.9(c). A current of 45A will flow through the induction coil when the phase shift angle α =0. Figure 9.(e) shows the synchronized switching signal and the output current i_o, using PLL closed loop scheme.

Figures10 (a)-(c) shows the waveforms of the proposed converter for a phase shift of $\alpha = 120^{\circ}$. α can be controlled by comparing the ramp signal and the constant value, by varying the constant input term to the comparator α can be varied.

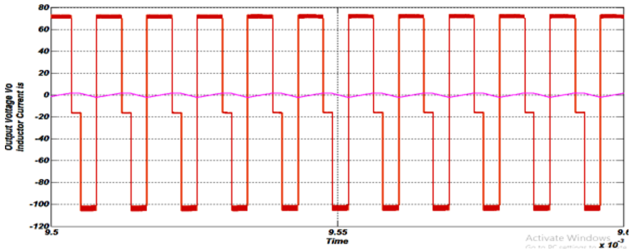

Fig 10.(a:) Output Voltage(V_o) and current of inverter(i_s)

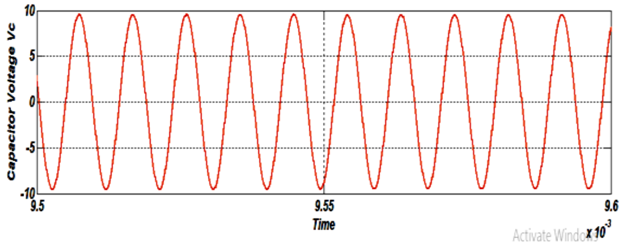

Fig 10.(b): Capacitor Voltage(V_c)

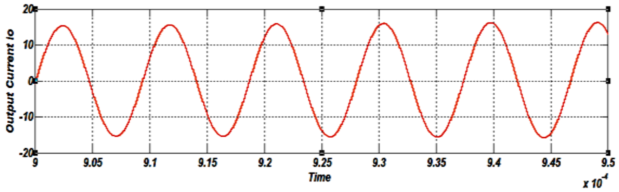

Fig 10.(c:)Current through induction coil(i_o)

For α=120°, the inverter output voltageV_o, the inductor current i_s, the capacitor voltage V_c and induction coil current $i_o$considerably reduces its amplitude. Thus we can conclude that by controlling the phase shift angle α, we can control the power of the proposed induction heating system.

V. CONCLUSION

The proposed LLC resonant inverter for induction heating application is simulated in MATLAB. The matching transformer introduced into the scheme has the advantage of maximum power transfer and improved current gain. In addition the concept of asymmetrical control strategy will considerably reduce the conduction and switching losses along with the power control.

VI. FUTURE WORK

As future work, hardware for the proposed converter can be developed. Using the proposed topology the power of an induction heating system can be controlled by controlling the phase shift angle α̇. The proposed strategy can be easily implemented and the configuration is simple, and therefore can be used for applications that require output power regulation under load parameter variations

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