A REVIEW: AN IMPROVED LLC RESONANT INVERTER FOR INDUCTION FREQUENCY USING DIFFERENT ELECTRICAL APPLICATIONS

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Abstract- In this paper, A simple power-control scheme for high frequency an LLC resonant inverter with asymmetrical control technique is proposed. The aim is to control the output power for high-temperature applications like steel melting, brazing, and hardening, where the load parameters and resonant frequency vary substantially throughout the system operation. The operating frequency is controlled using phase locked loop to track for the resonant frequency. The output power is controlled by adjusting the switch duty cycle. The LLC resonant tank is designed with a matching transformer in between the series inductor and paralleled LC resonant tank. The important advantage of the proposed topology is the short-circuit protection of the transformer and the induction coil. The validity of the proposed method is verified through computer simulation using MATLAB.

1. INTRODUCTION

In the realm of power electronics, the LLC resonant inverter stands as a cornerstone technology, offering efficient and reliable solutions for a myriad of electrical applications. Among its many utilities, one of the most critical functions of the LLC resonant inverter is the control of induction frequency. This control plays a pivotal role in applications ranging from induction heating to renewable energy systems and electric vehicle charging. However, conventional LLC resonant inverters often encounter challenges in achieving optimal performance, efficiency, and controllability in regulating induction frequency. A novel soft-switching technique to give high input power factor and low current distortion on the rectifier side and provide clean and stable ac voltage on the inverter side, is presented. The proposed converter uses a zero-voltage switching (ZVS) strategy to get ZVS function. Besides operating at constant frequency, all semiconductor devices operate at soft switching without additional voltage stress. The phase-shift (PS) control technique varies the output power by shifting the phase of the switch conduction sequences. The asymmetrical duty-cycle control technique employs an unequal duty-cycle operation of the switches in the converter. The asymmetrical voltage-cancellation (AVC) proposed, which describes the voltage cancellation for conventional fixed-frequency control strategies AVC is implemented in a full -bridge series resonance inverter. A significant reduction in the conduction losses is achieved, since the circulating current for the soft switching flows only through the auxiliary circuit and a minimum number of switching devices is involved in the circulating current path. The rectifier in the proposed converter uses a single converter instead of the conventional configuration composed of a four-diode front-end rectifier followed by a boost converter. The systematic project of high performance and high frequency induction heating power supply a theoretical and simulation validation for parts of the system, including three-phase current source PWM rectifier, LLC resonant inverter and alternate control scheme of inverters are carried out. In this paper , time domain and frequency domain models of three-phase current source rectifier is used in three-phase static coordinate system, the generation and distribution mode of PWM modulation signal was presented; and on the basis of analyzing control strategies for three-phase current source PWM rectifier, indirect current control strategy is emphatically studied, control system is designed and feasibility condition of unity power factor on line-side is presented. The current transformation capacity and adaptability for malfunction of LLC resonant inverter are discussed by analyzing its structure and properties. It is proved that the use of LLC resonant circuit could make inverters paralleled easily and also make alternate control scheme implemented easily by comparing the output difference of two inverter units such as output voltage amplitude error, phase error, and trigger asynchrony when the inverters are paralleled. Then the parameter selective principles of LLC resonant inverter are summarized and the parameters calculation completed Note that the closed-loop PFM method presented may sacrifice the efficiency due to switching losses at high-frequency operation. However, the LLC resonant load offers better performance with high-quality factor ($Q > 30$) and only requires a small series inductance in the circuit configuration. This implies that the output transformer can be omitted. The disadvantage of the LLC resonant load is that the output current may no longer be sinusoid in the case of low Q ($Q < 10$) . The current in the induction coil is unavoidably small and distorted. Therefore, system efficiency is a price to pay. The requirements for the system are given as follows:

- high frequency switching.
- high power factor.
- wide load range.
- high efficiency.

- low cost.
- reliability.

This research endeavors to present an improved LLC resonant inverter design tailored specifically for efficient and precise control of induction frequency in various electrical applications. Through a comprehensive design methodology, encompassing component selection, circuit topology optimization, and advanced control strategies, the proposed design aims to address the shortcomings of conventional inverters and unlock new levels of performance, reliability, and controllability.

By leveraging state-of-the-art simulation tools and experimental validation techniques, the effectiveness of the proposed improved LLC resonant inverter design will be rigorously evaluated. Detailed analysis and comparison with existing approaches will provide valuable insights into the potential advantages and applications of the proposed design.

This research seeks to contribute to the advancement of power electronics by offering a novel solution for enhancing induction frequency control in LLC resonant inverters. Through innovation and experimentation, it is anticipated that the proposed design will not only overcome existing limitations but also pave the way for new possibilities in a wide range of electrical applications, from industrial processes to renewable energy integration and beyond.

2. LLC RESONANT INVERTER

Three traditional resonant topologies are analyzed in chapter 2. From the results, we can see that all of them will see big penalty for wide input range design. High circulating energy and high switching loss will occur at high input voltage. They are not suitable for front end DC/DC application. Although above analysis give us negative results, still we could learn something from it: For a resonant tank, working at its resonant frequency is the most efficient way. This rule applies to SRI and PRI very well. For SPRI, it has two resonant frequencies. Normally, working at its highest resonant frequency will be more efficient.

For this application, we are not able to design the inverter working at this resonant frequency. Although the lower frequency resonant frequency is not usable, the idea is how to get a resonant frequency at ZVS region. By change the LCC resonant tank to its dual resonant network, this is achievable. As shown in Figure 2.1, by change L to C and C to L, a LLC resonant inverter could be built. The DC characteristic of

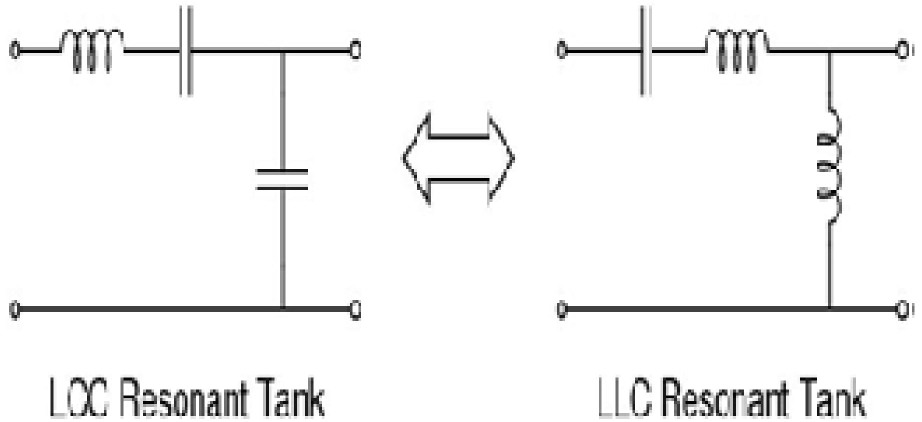

Fig. 2.1 LCC and LLC Resonant Tank

LLC inverter is like a flip of DC characteristic of LCC resonant inverter. There are still two resonant frequencies. In this case, Lr and Cr determine the higher resonant frequency. The lower resonant frequency is determined by the series inductance of Lm and Lr. Now the higher resonant frequency is in the ZVS region, which means that the inverter could be designed to operate around this frequency. As a matter of fact, LLC resonant inverter existed for very long time. But because of lack of understanding of characteristic of this inverter, it was used as a series resonant inverter with passive load. Which means it was designed to operate in switching frequency higher than resonant frequency of the series resonant tank of Lr and Cr. When operating in this region, LLC resonant converter acts very similar to SRC. The benefit of LLC resonant converter is narrow switching frequency range with light load and ZVS capability with even no load. In this dissertation, some unexplored operating region of LLC resonant converter will be investigated. Within these operating regions, LLC resonant converter will have some very special characteristic, which makes it an excellent candidate for front end DC/DC application

3. OPERATION OF LLC RESONANT INVERTER

An LLC inverter is made up of 4 blocks: the power switches, resonant tank, transformer, and diode rectifier. First, the MOSFET power switches convert the input DC voltage into a high-frequency square wave. This square wave then enters the resonant tank, which eliminates the square wave's harmonics and outputs a sine wave of the fundamental frequency. The sine wave is transferred to the secondary of the inverter through a high-frequency transformer, which scales the voltage up or down, according to the application. Lastly, the diode rectifier converts the sine wave into a stable DC output.

As load getting heavier, the resonant frequency will shift to higher frequency. The two resonant Frequencies are

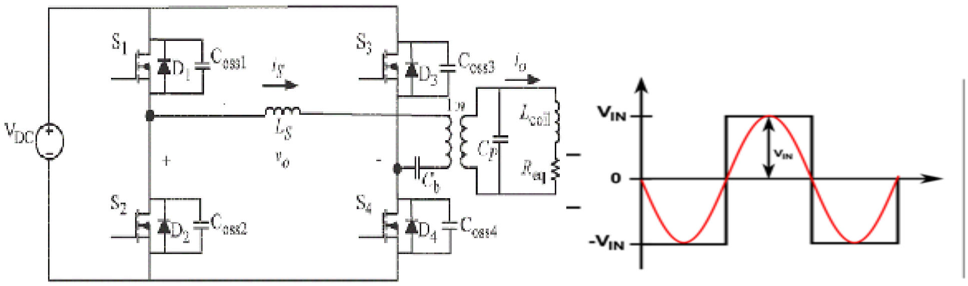

Fig. 3.1 Full bridge LLC resonant Inverter

$$Fr = \frac{1}{2.\pi.\sqrt{Lr.Cr}}$$

$$Fr2 = \frac{1}{2.\pi.\sqrt{(Lm+Lr).Cr}}$$

With this characteristic, for 400V operation, it could be placed at the resonant frequency of fr1, which is a resonant frequency of series resonant tank of Cr and Lr. While input voltage drops, more gain can be achieved with lower switching frequency. With proper choose of resonant tank, the inverter could operate within ZVS region for load and line variation. There are some interesting aspects of this DC characteristic. On the right side of fr1, this converter has same characteristic of SRC. On the left side of fr1, the image of PRC and SRC are fighting to be the dominant. At heavy load, SRC will dominant. When load get lighter, characteristic of PRC will floating to the top. With these interesting characteristics, we could design the converter working at the resonant frequency of SRC to achieve high efficiency. Then we are able to operate the converter at lower than resonant frequency of SRC still get ZVS because of the characteristic of PRC will dominant in that frequency range.

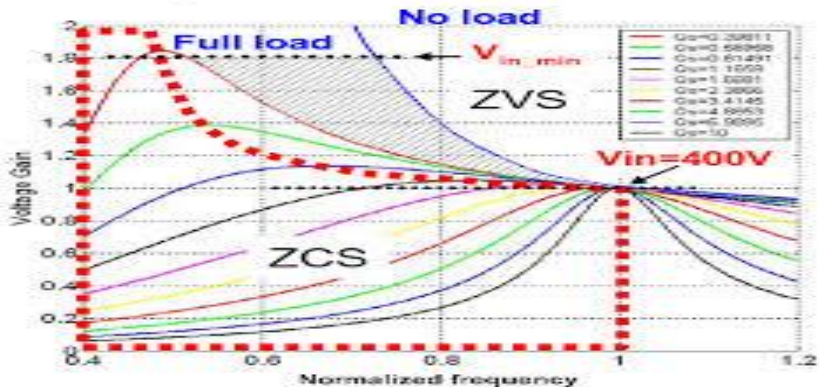

Fig. 3.2 DC characteristic of LLC resonant Inverter

4. MODES OF OPERATION OF INVERTERS

Five different operating modes of the inverter are discussed below.

- MODE 1 (Soft Switching mode)
- MODE 2 (Zero Voltage Switching)
- MODE 3 (Zero Current Switching)
- MODE 4 (Resonant Frequency Control)
- MODE 5 (Burst Mode Operation)

5. PROPOSED CONTROL STRATEGY

The work piece geometry, conductivity, and permeability of different metals have various effects on the inductance of the heating coil. In addition, the coil inductance is also changed when heated. This is due to the fact that beyond the Curie temperature, the relative permeability (μr) of the work piece decreases when the temperature increases. This results in the reduction of the equivalent inductance of the work piece which in turn reduces the coil inductance. On the contrary, when the work piece temperature is lower than the Curie temperature, the relative permeability of the work piece decreases with temperature. Therefore, the coil inductance exhibits a change in the opposite direction.

Considering the fact that the resonant capacitance is fixed, therefore, the resonant frequency is varied throughout the heating process. The phase-locked loop integrated-circuit (IC) device for load-adaptive resonant-frequency tracking is introduced to the resonant inverter to drive the operating frequency to the new resonant frequency.

The proposed control scheme of the full bridge LLC resonant inverter consists of following parts:

5.1 **Pulse Width Modulation (PWM) Control**

Utilize PWM control to adjust the duty cycle of the switching signals to regulate the output voltage. The duty cycle is adjusted based on the feedback signal from the output voltage sensor.

5.2 Frequency Control for ZVS Operation

Implement a frequency control scheme to adjust the resonant frequency of the LLC tank circuit. This can be achieved by varying the timing of the switching signals or by adjusting the values of the resonant components (inductors and capacitors).

5.3 **Phase Shift Control**

Employ phase shift control between the switching signals of the upper and lower arms of the full bridge to achieve ZVS (Zero Voltage Switching) operation. Phase shift control ensures that the turn-on and turn-off transitions of the switching devices occur at zero voltage, reducing switching losses and improving efficiency.

5.4 Current Limiting Control

Implement current limiting control to protect against overcurrent conditions. This involves monitoring the current flowing through the switching devices and reducing the duty cycle or frequency if the current exceeds a predetermined threshold.

5.5 Voltage Regulation

Incorporate voltage regulation feedback loops to maintain a stable output voltage despite changes in the load or input voltage. This can be achieved by adjusting the duty cycle or frequency of the switching signals based on the difference between the actual and desired output voltages.

5.6 **Protection Mechanisms**

Implement protection mechanisms such as overvoltage and overcurrent protection to prevent damage to the inverter and connected loads. This involves monitoring the output voltage and current and triggering shutdown sequences or fault protection mechanisms if abnormal conditions are detected.

5.7 Digital Control Implementation

Utilize digital control techniques, such as microcontroller-based control or digital signal processing (DSP), to implement the control algorithms and enhance flexibility and accuracy in controlling the inverter.

The controller comprises a current sensor, zero-crossing detector, phase detector, and voltage-controlled oscillator, as shown in Fig. 5.1. The 4046 phase-locked loop IC is used for frequency control at slightly higher than the resonant frequency. In typical voltage-fed inverter, the gate drive signal is in phase Fig5.2.

Waveforms of the asymmetrical gate drive signal with the asymmetrical inverter output voltage vo. Therefore, we can use the gate drive signal instead of the load-voltage pulse for phase detection. The current signal io is compared with the voltage signal in order to detect the phase difference. The output signal of the digital phase detector is filtered by an RC low pass filter to get an average value that is proportional to the phase difference at the load. The generation of asymmetrical gate drive signals for power control is shown in Fig.5.2.

The Pcontrol signal is compared with the ramp signal from the 4046 IC to generate the gate signal G4.

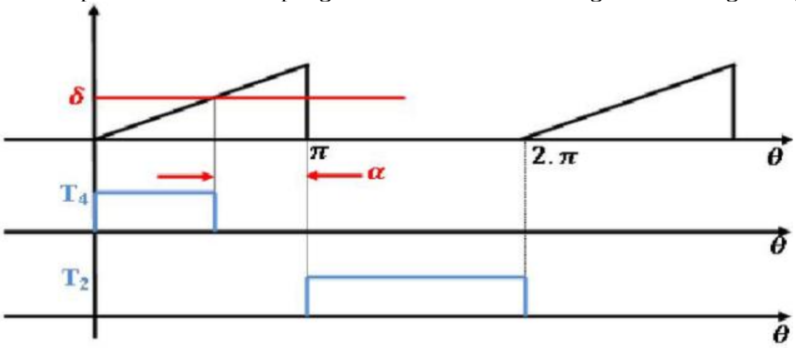

Fig. 5.1 Waveforms of the asymmetrical gate Drive Signal

If the Pcontrol signal is greater than the ramp signal, the gate signal G4 is set to high. Otherwise, it is set to low. In this way, α is dependent on the Pcontrol signal. The gate signal G2 is always on from π to 2π. The G1 and G3 signals are the inverse of G2 and G4 signals, respectively. Note that the ramp signal is generated from the phase detector. Therefore, its frequency is automatically adjusted to track the resonant frequency and turns on as ZVS operation is obtained. The gating signals G1, G2, G3, and G4 are sent into the dead-time circuit where the dead-time setting is adjusted through the pairs R1–C1, R2–C2, R3–C3, and R4–C4. A phase-protection circuit with a limiter is used where the Vphase signal, a dc signal proportional to the phase, is put through a limiter . This allows an operation in the desired frequency range for the ZVS mode. If the phase lies in the region that is out of the predetermined limits, an active signal is sent out to turn the transistor Q on and ground all gate signals S1 to S4.

6. SWITCHING LOSS

Switching losses comprise turn-on and turn-off losses.

During turn-on, as the semiconductor device transitions from off-state to on-state, there's a rapid increase in current, leading to turn-on losses primarily due to the on-state resistance (RDS(on)) of the device. Turn-on losses can be minimized by ensuring an efficient gate drive circuit, with appropriate voltage and current levels to swiftly switch the device on.

Conversely, during turn-off, the device transitions from on-state to off-state, discharging its stored charge, resulting in turn-off losses. These losses stem from the reverse recovery charge (QRR) and the forward voltage drop (VF) across the device during recovery. Minimizing turn-off losses involves reducing the reverse recovery time and optimizing the recovery process. In LLC resonant inverters, employing soft-switching techniques such as zero-voltage switching (ZVS) and zero-current switching (ZCS) helps mitigate switching losses by ensuring that the devices switch states when the voltage or current across them is close to zero. Additionally, careful design and optimization of the resonant tank circuit and control strategy can further minimize switching losses, thereby enhancing the overall efficiency and reliability of the inverter.

To maintain the operation under ZVS conditions, the power angle φ must be kept greater than both the dead time and charging time of the stray capacitors. This is to allow sufficient time for the diodes to conduct while keeping the voltage across the switch at zero. For the operation at the frequency above resonance, the turn-on switching loss of all switches is zero, but there still is a turn-off switching loss for every switch. It is seen in Fig. 3 during the t3–t4 interval that the switch S4 turns off at a larger current as α becomes larger. This results in a higher switching loss. To consider the switching loss in details, the current and voltage transition at turn off are shown in Fig. 6. are shown in fig.6.1 and 6.2 represented. Thus, the turn-off loss is decreased. The dead time must be increased to maintain approximately zero turn-off loss. Clearly, the snubber capacitor can always be included. However, there is a tradeoff for adding a snubber capacitor because the power angle φ must cover the switch dead time and the capacitor charging time. Therefore, the increased power angle φ results in a reduced range of the angle α (αmax = φ − 180), and therefore, the range of power adjustment will be reduced.

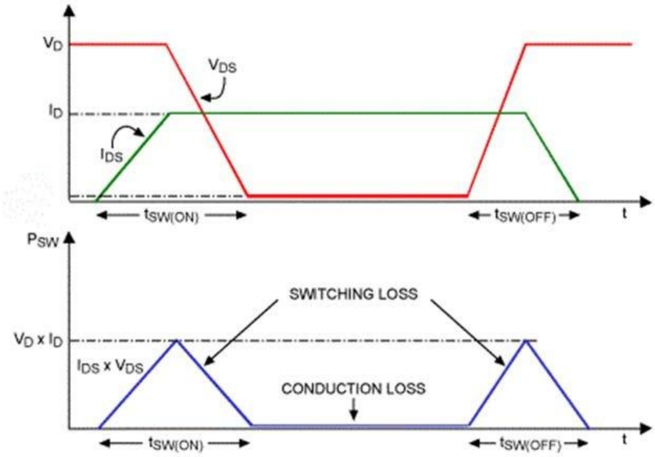

Fig. 6.1 Typical switching and conduction Loss

6.1 Conduction Loss

These losses occur during the on-state operation of the semiconductor devices, when they conduct current from the input source to the output load. Conduction losses primarily consist of two components: static losses and dynamic losses. Since the intervals t2–t_2 and t5–t_5 in Fig. 6.1 representing the charging and discharging periods of the stray capacitors are small compared with the overall conduction times, both intervals are neglected in the following calculation. Taking the switch conduction loss into account, the current and voltage at switches S3 and S4 from t0 to t5. Switches S1, S2, and S3 carry the same current and conduction loss through the intervals t1–t2 and t4–t5, respectively. Since the inverter current is is given as

$$is(t) = IS,peak \sin(\omega t - \varphi)$$

The aforementioned conduction losses can be calculated by substitution of the currents Next, the diode conduction loss is considered. Clearly, diodes D1–D4and D2–D3 conduct during the t0–t1 and t2–t4 intervals, respectively. In addition, the conduction loss of diodeD3 includes the forward conduction during the t2–t3 interval, similar to the current.

Therefore, the current contribution to the conduction loss of diode D3. The conduction loss of switch S3 and switch S4.

At the frequency above resonance, there is always a positive power angle φ (i.e., lagging current operation). A high efficiency inverter with LLC topology can be achieved by introducing a small positive switching angle and high current gain in the desigC it is deduced that a suitable load would be applications with high quality factor (Q) such as brazing, surface hardening, and tube welding. For applications with low Q (less than ten), it is very difficult to obtain both high current gain and resonant operations at the same time. One of the possible solutions would be to increase the power angle φ. This means that the operating frequency must be adjusted further away from the resonant frequency, which results in the operation of the inverter under low efficiency

This is where the high-frequency transformer is introduced to match the output current and power. In addition to improving the system efficiency, the important advantage of the inclusion of the transformer is the inherent current-limiting capability in case of transformer saturation. The inductor Ls carries low current because it is located on the primary side. Therefore, it is easier and cheaper to construct such an inductor.

7. CIRCUIT ANALYSIS

7.1Analysis of the Output Power

The steady-state analysis of the full-bridge LLC inverter is based on the following assumptions.

- All circuit components are ideal.
- The dc input voltage VDC is constant.
- The effects of stray capacitance are neglected.

7.2 Operating Principle:

During one half of the switching period, two diagonal switches (upper left and lower right or upper right and lower left) are turned on, allowing current flow from the DC input through the resonant tank and to the load.

During the other half of the switching period, the other two diagonal switches are turned on, reversing the direction of current flow through the resonant tank and the load.

7.3 Steady-State Analysis

In steady state, the inductor current (IL) and the capacitor voltage (VC) will be periodic waveforms due to the resonant behavior of the LLC tank.

The switching frequency (fsw) is determined by the switching frequency of the control signals driving the switches.

The resonant frequency (fres) is determined by the values of inductance (L) and capacitance (C) in the LLC tank.

7.4 Load Voltage and Current

The output voltage (Vout) across the load (R) will be the voltage across the resonant tank during the ON state of the switches.

The output current (Iout) through the load can be calculated using Ohm's law (Vout=Iout×R).

7.5 Control Strategy

The switches are controlled using pulse-width modulation (PWM) to regulate the output voltage and current.

The duty cycle of the PWM signals determines the ON time of the switches and thus the average output voltage.

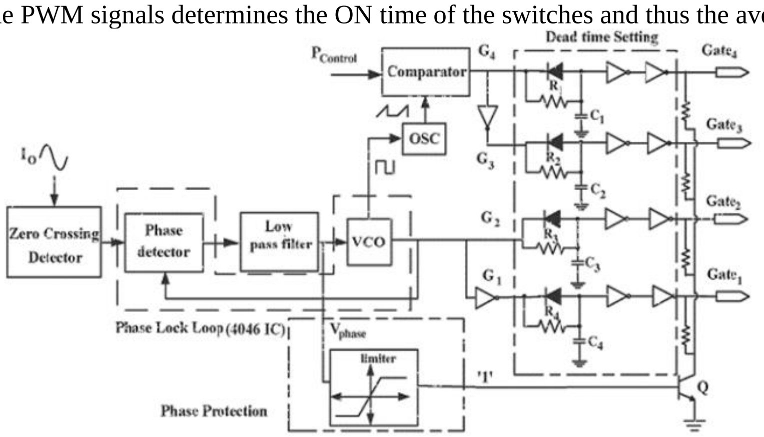

Fig. 7.1 Proposed control block diagram of the LLC resonant Inverter

8. SIMULATION ANALYSIS

This simulation models for the different blocks and derived as shown in Fig. 8.1.

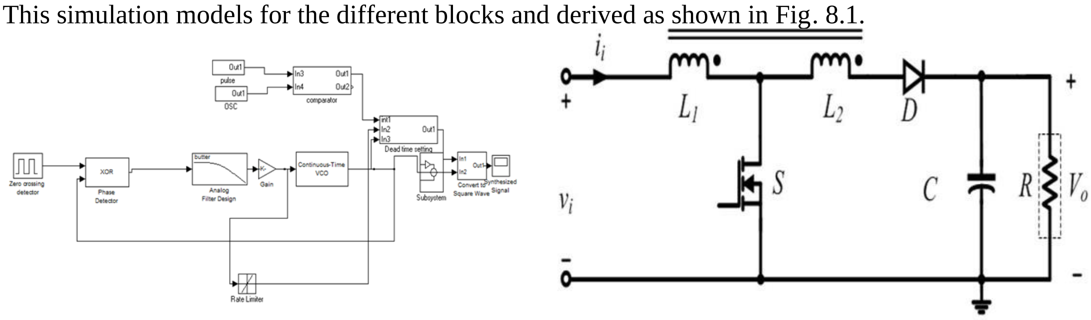

Fig. 8.1 Proposed control diagram of the LLC resonant inverter Simulation Model

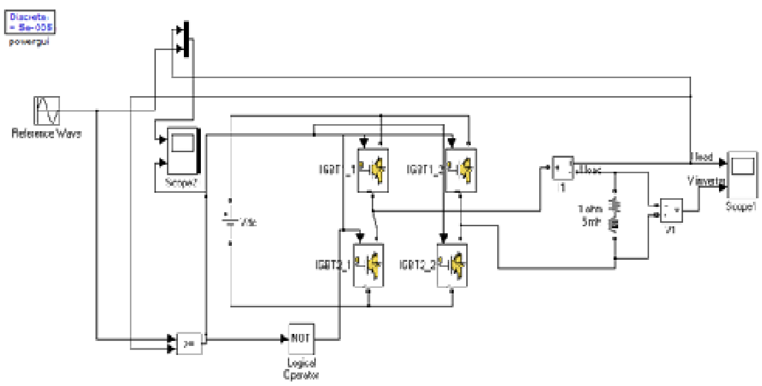

Fig. 8.2 Control circuit and Power Circuit

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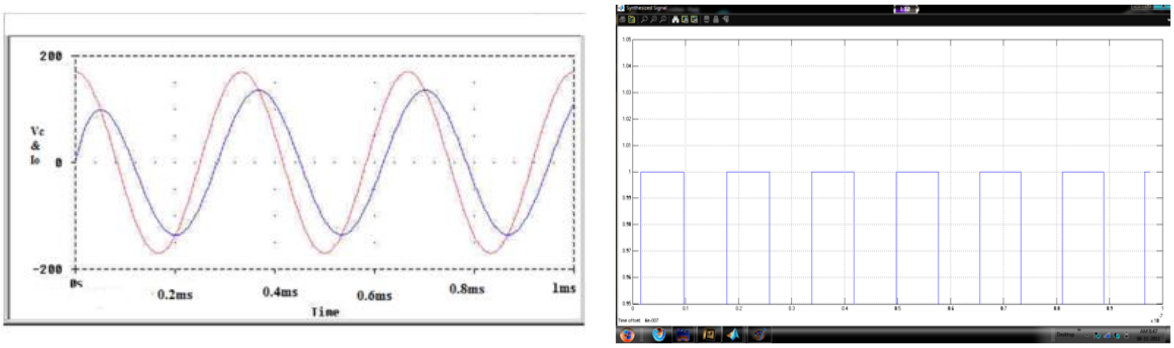

Fig. 8.3 Induction coil-current Ic and Induction coil-voltage Vc waveform with respective time under full Load

CONCLUSION

An improved full-bridge LLC resonant inverter topology for induction-heating application has been proposed. The validity of the proposed asymmetrical control scheme is verified through simulation and experimental results. It can be concluded that the presented work control technique has the following advantages.

- The asymmetrical control can be used to control the output power to the induction coil for the LLC resonant tank.
- The control scheme is in a simple configuration and easy to implement.
- The resonant-frequency tracking together with the adjustment of the pulse voltage ensures maximum power transfer to the load throughout the heating cycle with minimal loss.
- The placement of the inductor on the transformer's primary results in a small inductor due to the low current on the transformer's primary.

Therefore, the presented circuit configuration and proposed control scheme can also be used for other applications that require output-power regulation under load-parameter variation.

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