Design of ZVS Half-Bridge Series Resonant Inverter with Improved Efficiency for Induction Heating Applications

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***Abstract*— Nowadays, the induction heating market is continuously growing due to its benefits including precise output power control, high efficiency, reduced heating times, and cleanness. The maximum output power and efficiency are achieved at the resonant frequency, and if the switching frequency is increased the output power will get reduced. As a consequence, in these converters, the efficiency is also reduced in the low-medium output power range appliances. Most of the circuit structures in large capacity devices were adapted with Full-bridge structures in Inverter. Because of the high power density and the reduced cooling capabilities, efficiency becomes critical in this application.**

In this study, a half-bridge series resonant inverter driven by a variable -frequency was implemented in an inductive heating-facility in which the circuit was adapted Resonant-Transition in Zero-Voltage-Switching (ZVS). The proposed variable frequency duty cycle (VFDC) control is intended to improve the efficiency in the medium and low output power levels because of the decreased switching frequencies.

This paper presents a new Design circuit topology and its digital control scheme for a ZVS Half-Bridge Series Resonant Inverter circuit with improved efficiency for Domestic induction heating appliances. The proposed circuit is implemented and simulated by using MATLAB software.

***Keywords*—Induction Heating, Zero-Voltage-Switching (ZVS), Series Resonant Inverter, Variable frequency duty cycle (VFDC).**

I. INTRODUCTON

Induction heating system can be applied for many applications like induction hardening, induction melting, induction cooking etc. [1]. Induction heating is a non-contact heating process, which uses to heat materials that are electrically conductive by applying electricity with a high frequency. Where the induction pan is directly heated by the induced currents, which are generated by varying magnetic fields in the range of 20-100 kHz. This magnetic field is generated by an inductor coil system supplied by a resonant power inverter [2]. Fig. 1 shows the block diagram of a domestic induction cooking appliance. The Supply AC voltage is rectified and filtered. Afterward, the resonant inverter supplies power to the induction coil with a variable frequency of 20– 75 kHz. This current produces an alternating magnetic field, which causes eddy currents and magnetic hysteresis heating up the pan.

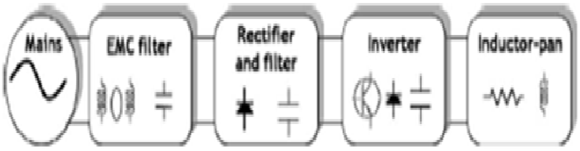

Fig. 1 Domestic induction cooking appliance

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 [3]. The various resonant inverters using MOSFETs, IGBTs, MCTs, SITS offer reduced power device switching losses by means of soft-switching technique and attractive possibilities in developing higher frequency of operation, higher efficiency, lightweight and overall system simplicity in terms of inverter control, protection and maintainability [4], [5]. Domestic induction heating application is suitable for the use of VFDC strategy due to its special load characteristics. The main advantage of this converter is to improve the efficiency even at the low output power range by reducing switching losses.

This paper presents the simulation model for a new circuit topology which improves the efficiency of the half-bridge series resonant inverter with is driving an induction heating appliance as a load. The simulation results have been validated for an induction heating inverter with a specially designed load by using MATLAB/SIMULINK.

II. CHOICE OF CONVERTER

The most used topologies have been the full bridge [6], half-bridge [7] and two single-switch inverter topologies [8] with zero voltage switching and zero current switching operations. Pulse-width modulation (PWM) and pulse-frequency modulation (PFM) methods are also used to control the output power of the resonant inverter [9].

For higher output power levels, the full-bridge inverter is used and half bridge ZVS series resonant inverter is the mostly used topology, for medium high output power applications like Induction Heating. Because of having small number of switching devices, low conduction losses, high efficiency and low voltage stress across the switching devices half bridge series resonant inverter is most preferred than the other circuit topologies [10]. Fig 2 represents the schematic diagram for the half bridge series resonant inverter.

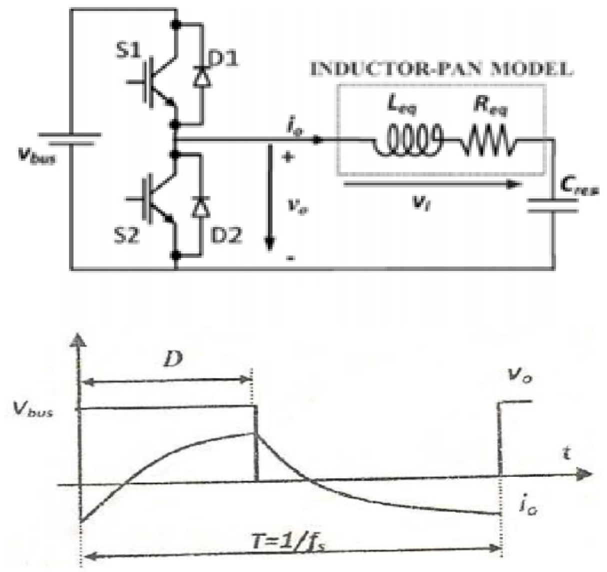

Fig. 2 Half bridge series resonant inverter schematic Diagram with waveform.

The resonant load consists of the pan, the induction coil, and the resonant capacitor. Induction coil and pan coupling is modelled as the series connection of an inductor and a resistor, based on its analogy with respect to a transformer, and it is defined by the values of L_{eq} and R_{eq}. Traditional square wave (SW) modulation implies operation at high switching frequencies to deliver low-medium power. This entails inverter efficiency reductions, which is a basic fact to ensure reliability, maximize output power capabilities, and minimize heat sink and fan size. In the past, pulse density modulation (PDM) has been proposed to improve the efficiency. However, it has some limitations regarding flicker emissions and user performance.

The half-bridge, series resonant converters were selected above the single-switch topologies due to the following reasons [7]:

- The voltage across the semiconductors is clamped. Even though two switches are needed, at least half the voltage blocking capability is required.
- Due to switching is done at a duty ratio of *50%,* feedback is not needed.

Considering the classical frequency-based continuous modulation scheme, there are two resonant soft-switching operation modes, which are shown in detail in Fig. 3. On the one hand, the zero current switching (ZCS) soft-switching turn-off is achieved for switching frequencies below resonance whereas on the other hand, for frequencies up to the resonance, the zero voltage switching (ZVS) turn-on soft-switching is achieved. Nonetheless, in both resonant operation modes a hard switching transition occurs in the opposite transition, i.e. the turn-on in the ZCS and the turn-off in the ZVS operation mode.

The switching losses play an important role in the efficiency of the power electronics converter for domestic induction heating. As a result, a loss-less snubber networks are used to reduce the voltage and current overlap in the transitions, i.e. a series inductance to reduce current slope or a parallel capacitance for reduce the voltage slope in the ZCS and the ZVS operation modes, respectively. As a consequence of that, the ZVS operation mode featuring capacitive loss-less snubber networks is usually selected, reducing the required volume and cost.

Fig 3 shown below represents the turn-on and turn-off soft switching characteristics of both ZCS and ZVS for switching frequencies below resonance and up to the resonance frequency.

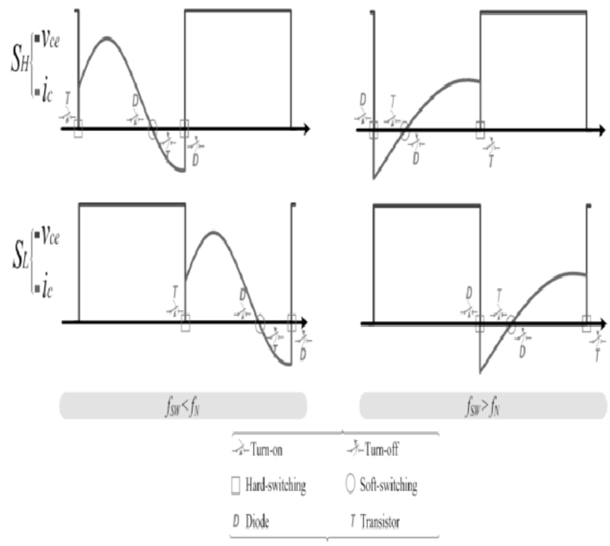

Fig. 3 Modes of Operation for the half-bridge series resonant inverter.

Therefore, zero-voltage switching (ZVS) and zero-current switching (ZCS) techniques are used to reduce the stress of switching devices As a consequence; the converter efficiency is significantly improved. This results in an increase of the net efficiency of the induction heating system.

III. EFFICIENCY ANALYSIS

An efficiency analysis has been carried out by considering the contribution of conduction (P_{ON}) and switching losses (P_{SW}) to total losses (P_{loss}). Conduction losses analysis has been computed by modelling the switch as the series connection of a resistance (R_{ON}) and a voltage source (V_{ON}). Thus power losses are calculated as follows: This loss term can be modelled as a function of the on-state voltage drop, *von*, during the device conduction, *Ton*, and the load current level i_o.

$$P_{ON}=V_{ON}I+R_{ON}I^2_{rms} \quad (1)$$

$$P_{ON} = \frac{1}{Tsw}\int_0^{Tsw} io\,(t)von(t)dt \qquad (2)$$

Where I and I_{rms} are the device average and rms currents respectively.

Switching losses depend on the converter operation mode, i.e. ZCS or ZVS for the half-bridge inverter, and the device switching times. Considering its linear dependence with frequency, this term is usually modelled as a function of the turn-on and turn-off energy losses, E_{on}, E_{off}, respectively.

$$P_{sw}=f_{sw}(E_{on}+E_{off}) \qquad (3)$$

$$P_{sw=}\ \ 0.5 f_s V_{bus} t_{fall} \sum_j (ifall.j\psi j(qj)) = f_s E_{OFF} \qquad (4)$$

$$\psi j(qj) = (1-\frac{4}{3}qj+\frac{qj^2}{2});\ where\ q_j = \frac{\sqrt{2CsVbus}}{Tfall.ifall.j} \qquad (5)$$

Where: Tsw=1/fsw is the switching period.

T_{fall} = fall time in transient state.

i_{fall} =fall current in transient state.

VFDC control scheme achieves power loss reduction by decreasing switching frequency. The power loss have been normalized with the value operating with D=0.5 to provide a clear evaluation of VFDC control scheme.

Fig 4 shows the block diagram for the proposed Resonant Inverter with an induction heating system as a load unit.

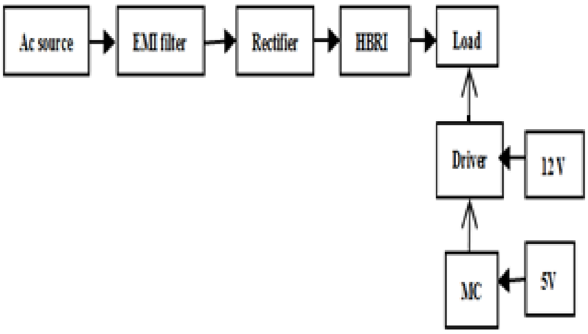

Fig. 4 Block diagram representation for the proposed Model.

Fig 5 represents the EMI input voltage & output voltage wave forms with high frequency noise. It is observed that the input voltage to the EMI has the high frequency noise but after it passed through the EMI unit high frequency noise Effect is reduced.

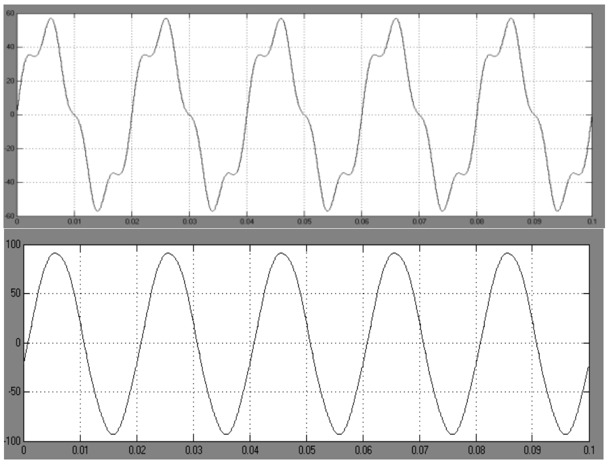

Fig. 5 EMI input and output voltage wave forms.

IV. SIMULATION RESULTS

The proposed ZVS half bridge series resonant inverter is simulated for both open loop and closed loop Configurations with a domestic induction healing application as a load using Matlab Simulink and their results are presented here. Single phase 230 V, 50Hz AC supply is applied as input to the diode bridge rectifier and the system parameter are followed as; V_{Bus}= 230 V, $f_{s,min}$=20 kHz, $f_{s,max}$=100 kHz, Max. Output Power =3500 W, C_s=15nF, C_r=1440 nF, R_{eq}=3 ohm, L_{eq}=25x10^{-6} H.

Fig 6 shown below represents the simulation model for the proposed half bridge series resonant inverter circuit for Induction heating application in open loop configuration with improved VFDC control strategy.

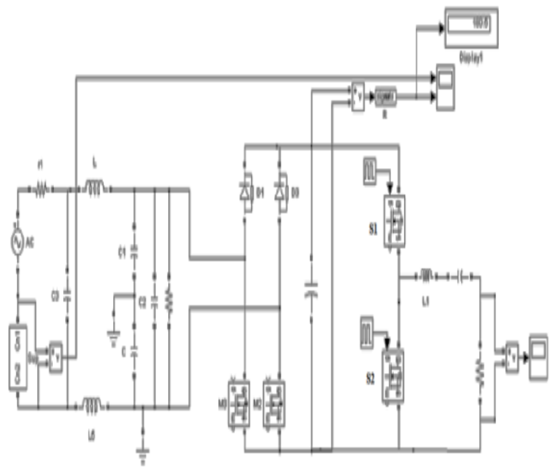

Fig. 6 Simulation Model for the Proposed Inverter Circuit in Open Loop.

Fig 7 shown below represents the Simulation wave forms for the input and output voltage levels of the rectifier circuit.

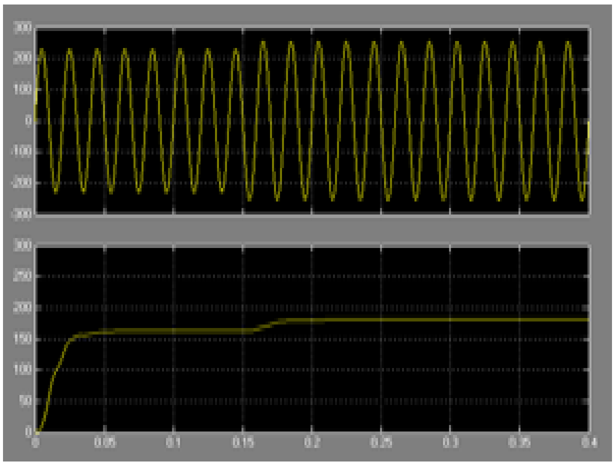

Fig. 7 Input and output voltage of rectifier for open loop.

Fig 8 represents the simulation model for the proposed half bridge series resonant Inverter circuit fed induction heater with improved VFDC control strategy in closed loop configuration.

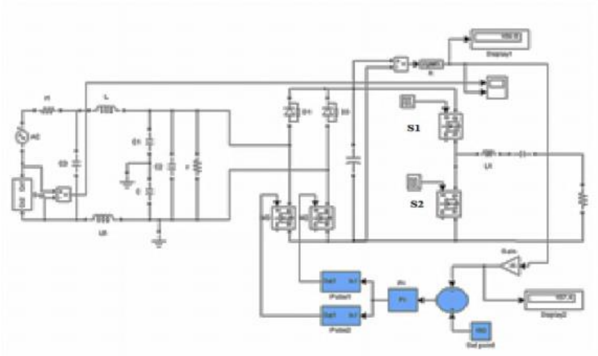

Fig. 8 Simulation Model for the Proposed Inverter Circuit in closed loop.

Fig 9 shown below represents the Simulation wave forms for the input and output voltage levels of the rectifier circuit.

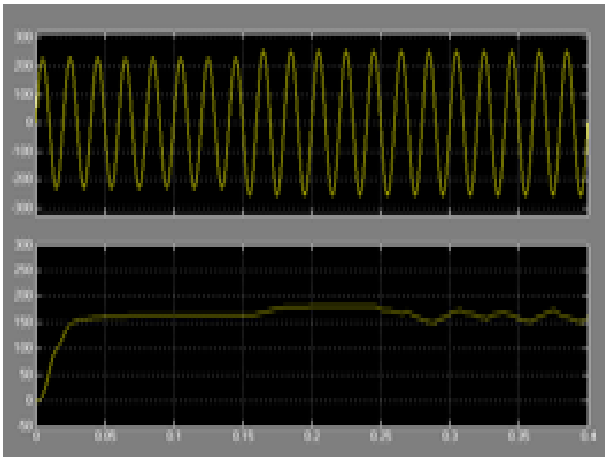

Fig. 9 Input and output voltage of rectifier for closed loop.

Fig 10 shown below represent the simulation wave forms of switching pulses and voltage levels across the switches S1 and S2 .for the proposed system, Fig 11 gives the output voltage of the EMI filter and Fig 12 represents the Output voltage, current and power wave forms for the proposed system.

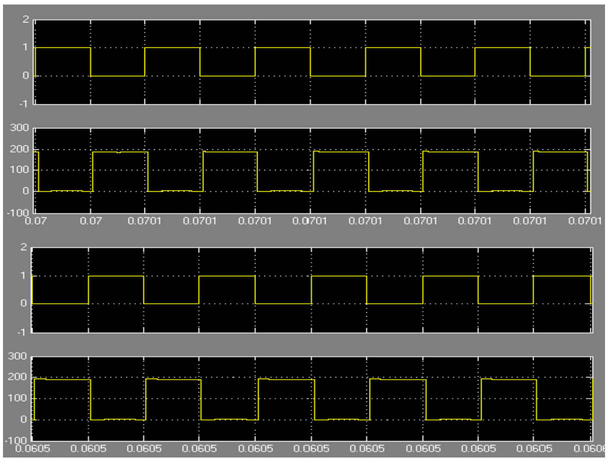

Fig. 10 Switching pulses and voltage Wave forms across the switches S1&S2.

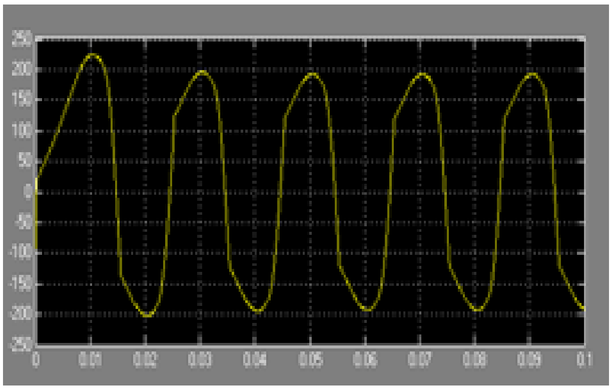

Fig. 11 EMI filter output voltage.

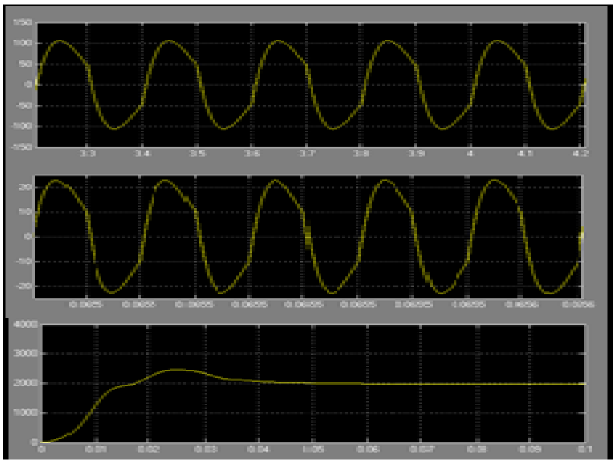

Fig. 12 Output voltage, current and power of the proposed system.

Fig 13 shows the Efficiency analysis for the proposed ZVS half bridge series resonant inverted with induction heating appliance with and without proposed VFDC control strategy for both open loop & closed loop configurations. This analysis results in increase of efficiency about 13-15% in each case for different duty cycle variations.

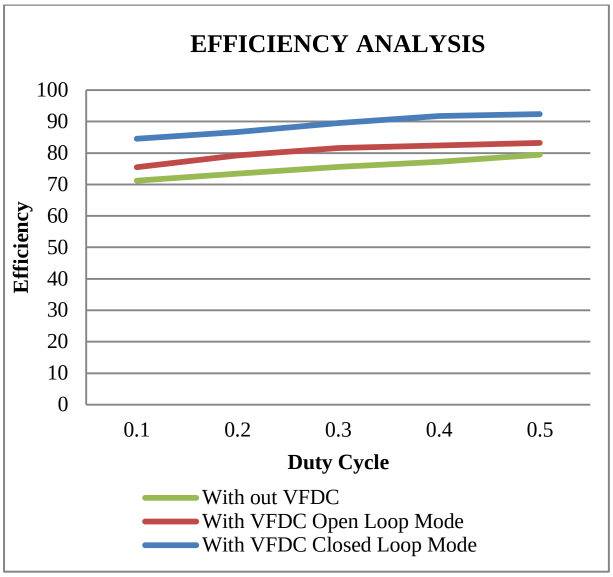

Fig. 13 Efficiency analysis for the proposed inverter Model.

V. CONCLUSION

In this paper a new control strategy for ZVS half bridge series resonant inverter applied to domestic induction heating applications is proposed. An analytical analysis has been performed in order to obtain the equations and operation modes that describe the proposed converter. The inverter can operate with zero-voltage switching during both turn-on and turn-off commutations. Besides, the output voltage is doubled compared to the classical half-bridge, reducing the current through the switching devices. As a consequence, the power inverter efficiency is improved in the whole operating range.

Therefore, the proposed control strategy can ensure reliability of .the inverter system and be expected to be effectively applied to different induction heating applications. The results analysed on then MATLAB/ SIMULINK platform shows that with this proposed control strategy the efficiency of the Induction heating system can be increased to about 13% without Effecting the cost of the system.

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BIOGRAPHIES

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