Analysis of Push-Pull Class-E Inverter for Induction Heating

[1]Kamlesh Kumar Bhartiya, [2] Mr. K.P. Singh, [3]Dr. A. N. Tiwari

1. M.Tech(Power Electronics & Drives), Electrical Engineering Department, Madan Mohan Malaviya Engineering College Gorakhpur U.P. India- 273010

2. Associate Professor, Electrical Engineering Department, Madan Mohan Malaviya Engineering College Gorakhpur U.P. India-273010

3. Associate Professor, Electrical Engineering Department, Madan Mohan Malaviya Engineering College Gorakhpur U.P. India-273010

Abstract:

Push-pull Class-E series-parallel resonant inverter based induction heaters proposed in this paper, having high efficiency switching mode tuned circuit consist of two parallel inductor and two capacitor. DC is converted into high frequency AC using Class-E inverter. This proposed topology utilizes a push-pull scheme to realize sinusoidal output voltage. Close loop system is modelled and simulated using Matlab simulink. However, the simplified circuit is only appropriate for applications in which the harmonic content of output is not an important criterion. The complementarily activated configuration will provide continuous high-ripple frequency input current waveform.

Keywords:

Induction Heating, High Efficiency Power Amplifier, Simulink, Zero Voltage Switching(ZVS).

INTRODUCTION:

In high efficiency Class-E power amplifier (PA) [2]-[9], the transistor has been used as switch. The resonator L_0,C_0 are used to block high frequencies and DC content, forcing the output current to approximate a sine wave at the fundamental frequency.This paper present a new switched-mode inverter which utilizes a specially-tuned resonant network to achieve zero voltage switching(ZVS) and low voltage stress. This new design also realizes small passive components, fast dynamic response and a high degree of design flexibility. These characteristic also make the proposed topology advantageous in application requiring very high frequency and duty ratio. The shrinking size of electronics equipment demands ever – increasing power densities at high switching frequencies and a nominal part for the circuit technology. In attempt to minimize the part count with Class-E operation, the one inductor one capacitor Class-E high efficiency switching-mode tuned PA [1] provides a more simplified circuit. Nevertheless only for applications in which the harmonic content and the phase modulation noise of output are not important criteria. It is therefore desirable to retain the function of the conventional Class-E features; i.e that the amplifier can be operated with high efficiency at very high frequencies and provides a sinusoidal output waveform and power-handling capability without increasing the complexity of power circuits.

The proposed push-pull Class-E amplifier and the conventional single-ended circuit configuration include one inductor and one capacitor. As expected, the harmonic content of output-voltage is significantly reduced in the proposed push-pull amplifier. However, the amplitudes of the positive and negative half-cycle in the output voltage waveform are not symmetrical, which may cause a small second-harmonic component characteristics differ appreciably, the appearance of even harmonic must be expected. The approaches presented here can be applied to the analysis and design of other Class-E amplifier configurations or with more complicated circuit in exact designs. Further, it should be noted that for this topology, the circuit described in this paper has to operational points that are performed by the ZVZS and ZVZC switching. Unlike the single ended Class-E amplifier [1], the push pull architecture is able to achieve a sinusoidal output waveform and high power handling capability. For instance a symmetrical driven push-pull Class-E amplifier has been proposed for high power applications as shown in Fig.1.

With the symmetrical gate-driving signals, theoretically, the even harmonics are entirely cancelled at the load, and thus there are few harmonic distortions (HDs). However the doubled-part count configuration incurs penalties on overall efficiency and the design cost. Fortunately, there is more elegant way to further reduce the switching loss, if the switch current increases gradually from zero after switch are closed.

This paper is proposes a push-pull Class-E resonant PA with a simple LC load network and a load resistor R_L in each half-amplifier, as shown in fig.1. An overlap capacitor-voltage waveform is utilized to achieve the nominal Class-E conditions without increasing the complexity of the power circuits.

II. PRINCIPLE OF OPERATION PUSH-PULL CLASS-E INVERTER

The basic schematic of the proposed push-pull Class-E series-parallel LCR resonant PA is shown in fig.1. It contains two transistors [these can be bipolar junction transistors (BJTs) or MOSFETs], two inductors, two capacitors, and a load resistance. Switches S_1 and S_2 are complementarily activated to drive periodically at the operating frequency $f = w/2\pi$ as in push-pull switching PA [27], i.e. the switch waveforms are identical, except that the phase-shift between S_1 and S_2 are π with an on duty ratio D of less than 50%. The simplest type of half-amplifier as shown in fig1. Is series-parallel resonant circuit, which consists of an inductor L in series with a parallel capacitor C and resistor R. The resistor R_L is the load to wich the AC power to be delivered, with neither end connected to a ground. It is suitable for a load that is balanced to ground, but most RF-power loads have one end connected to a ground.

The switching sequence and theoretical waveforms for the steady-state operation of proposed amplifier are illustrated in fig.2.

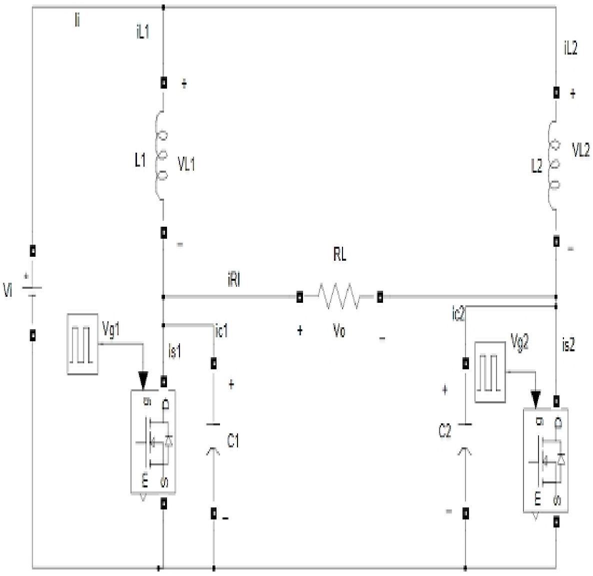

Fig.1. Proposed push-pull Class-E inverter

To reduce the transistor turn-on power losses, the switch current i_S increase gradually from zero after the switch is closed. The proposed push-pull Class-E PA uses a pair of LC resonant networks with an overlapped capacitor-voltage wave form; this offers additional degrees of freedom, and thus there are two operational points that can validly achieve this situation:

Case 1: [Zero-Voltage Zero-Slope switching (ZVZSS)]:

In this case, the nominal operating conditions of ZVS and zero-voltage-slope switching (ZVSS) are simultaneously satified. Namely

$$v_{C1}(\pi\text{-}2\pi D) = 0 \tag{1}$$

$$dv_{c1}\,(\pi - 2\pi D)/dt = 0 \tag{2}$$

Case2: [Zero-Voltage Zero-Current switching (ZVZCS)]:

The operation principle in the communication of this case is solved by the following simultaneous equation:

$$v_{C1}\,(\pi - 2\pi D) = 0$$

$$i_{L1}(\pi\text{-}2\pi D) = -v_{c1}\,(\pi - 2\pi D)/R_L \tag{3}$$

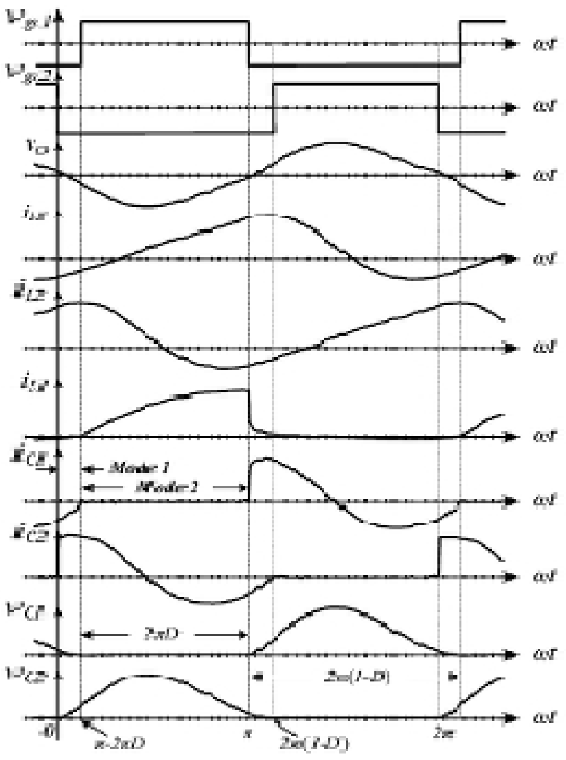

Fig.2 Theoretical waveforms

In order to satisfy both cases 1&2, it is necessary to find the current i_{L1} = - i_{R_L} by which the switch current i_{s2} increases gradually from zero a time t = $(\pi - 2\pi D)/\omega$, asshown in fig. 1&2. The duty ratio D must be kept at less than 50% so that the capacitor-voltage waveforms v_{C1} and v_{C2} can be overlapped.

III. OPERATING PRINCIPLE OF INDUCTI-ON HEATING

The induction heating is mainly based on two well-known physical phenomena:

1. Electromagnetic Induction
2. The Joule Effect

1. Electromagnetic Induction

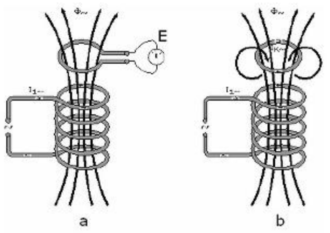

Fig.3 a&b : Induction Law of Faraday

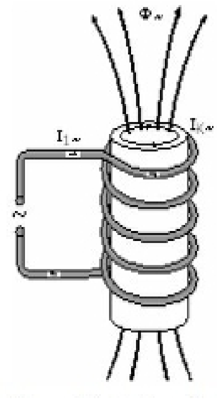

Fig.4: Induction of eddy current

The energy transfer to the object to be heated occurs by means of electromagnetic induction. It is known that in a loop of conductive material an alternating current is induced, when this loop is placed in an alternating magnetic field as shown in fig. 3. The e,m.f. equation is given as:

E = $\frac{d\phi}{dt}$ Where E: Voltage [V], ϕ: Magnetic flux [Wb], t : time [s], (4)

When the loop is short circuited, the induced voltage E will cause a current to flow that opposes its cause – the alternating magnetic field. This is Faraday – Lenz's law see in fig.3b.

If a "massive" conductor (e.g. a cylinder) is place in the alternating magnetic field instead of short-circuited loop, then eddy current (Foucault Currents) will be induced here as shown in fig.4. The eddy current heat-up the conductor according to the joule effect.

2. Joule-Effect:

When a current I[A] flows through the conductor with resistance R[Ω], power is dissipated in the conductor,

$$P = I^2 \times R \text{ Watt}, \qquad (5)$$

In most applications of induction heating the resistance can-not be just like that. The reason is the non-uniform distribution of current in the conductor.

IV. SIMULATION AND RESULTS:

Class-E power amplifier is shown in fig.5a. High frequency AC input voltage is given to the circuit is shown in fig.5b. Driving pulses and switch voltages are shown fig.5d. The pulse given to the second switch is shift by 180^0 with respect to the pulse of switch 1.

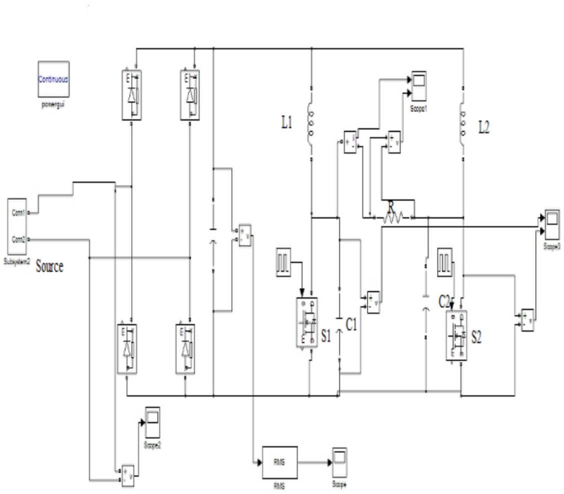

Fig.5a. Open loop Class-E Inverter in Induction heating.

In this model the input given to rectifier is high frequency AC, which is converted from DC to AC with the help of single phase inverter. The output of rectifier is DC which is input for Class-E inverter. The output of Class-E inverter is high frequency AC which requires for Induction heating. The output voltage of rectifier has been shown in fig.5c and the output current and voltage across the load of push-pull inverter has been shown in fig.5e, the wave form of current and voltage similar to sine wave.

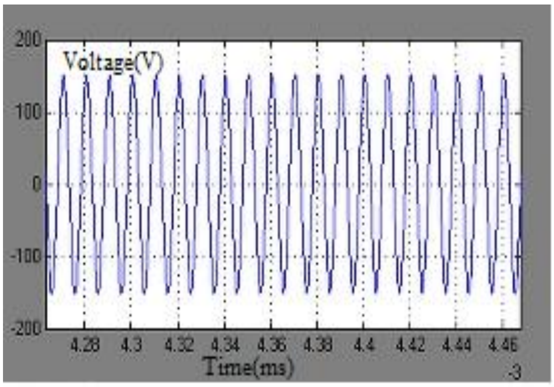

Fig.5b: Input Voltage to the circuit

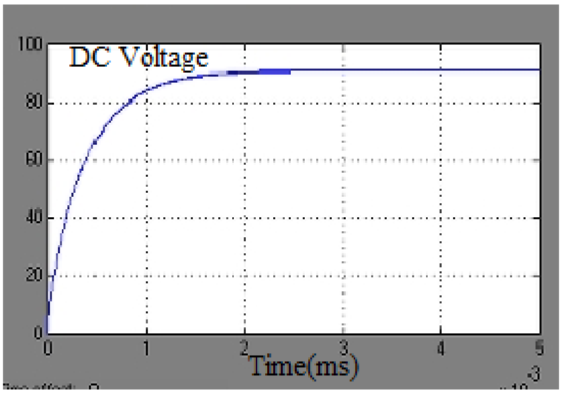

Fig.5c. DC Output of Rectifier

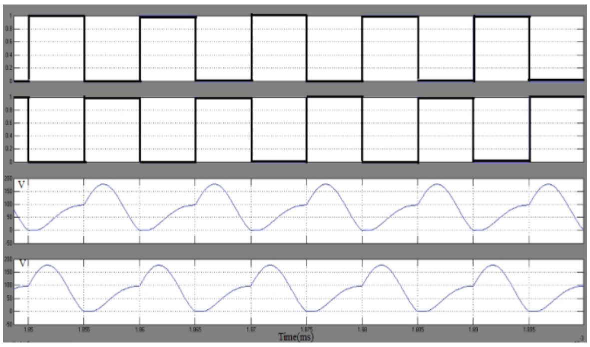

Fig.5d Switching Pulses and Voltages of S1 & S2

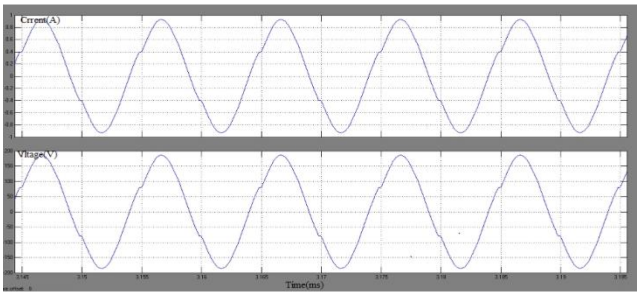

Fig.5e: High Frequency Current and voltage across Load.

Close loop circuit model is shown in fig.6a. Dc voltage is sensed and it is compared with the reference value. The output of PI controller adjusts the pulse width such that the output is brought back to the constant value. Close loop system uses a semi converter to maintain constant amplitude at the output. The output of the rectifier in the close loop system is shown in fig.6b. The switching pulses and switching voltages are shown in fig.6.c. AC output voltage and current across the load are shown in the fig.6d which is similar in sine wave of high frequency.

V. CONCLUSION:

A Class-E inverter fed induction heater is studied and simulated using Matlab Simulink. This system has advantages like low switching losses, reduced stress and high power density. In Closed loop model developed, the steady state error in the output is reduced. The simulation results are in line with the predictions.

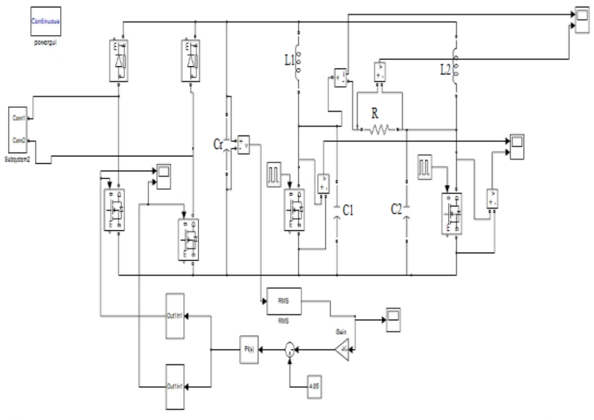

Fig6.a: Close loop Class-E inverter

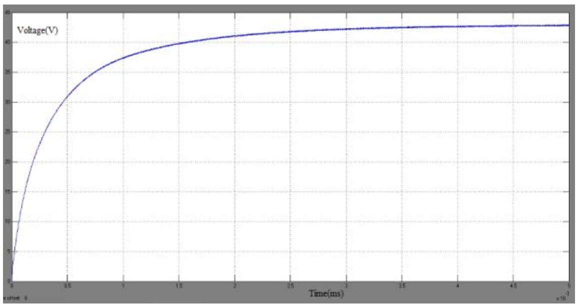

Fig.6b: DC output of Rectifier

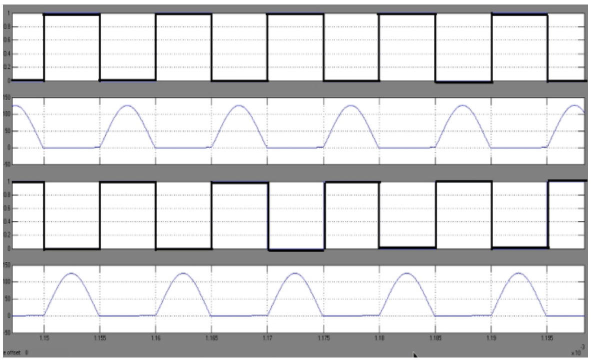

Fig.6c: Switching Pulses & Voltages across S1&S2

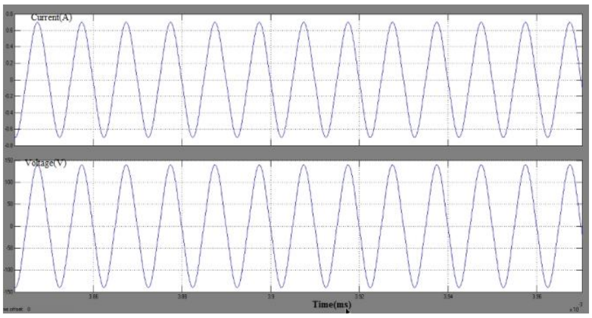

Fig.6d; Voltage and Current across the load

REFERENCES:

[1] N.O.Sokal, “Class-E high Efficiency switching-mode tuned power amplifier with only one inductor and one capacitor in load network-approximate analysis”. IEEE J. Solid-State circuits, SC-16, no. 4, pp, 380-384, Aug, 1981.

[2] N.O. Sokal and A.D. Sokal, “Class-E a new class of high efficiency tuned single-ended switching power amplifiers”, IEEE J. Solid-State circuits, vol. SC-10, no 3, pp. 168-176, june, 1975.

[3] F.H. Raab, “Idealized operation of the Class-E tuned power amplifier,” IEEE Trans. Circuit syst, vol. CAS-24, no. 12, pp.725-735, Dec.1977.

[4] M.K. Kazimierczuk and K. Puczko, ”Exact analysis of Class-E tuned power amplifier at any Q and switch duty cycle,” IEEE trans. Circuit syst. Vol. CAS-24, no.12, pp 149-159, Feb. 1987.

[5] M.K. Kazimierczuk and D. Czarkowski, Resonant Power Converter. New York: Wiley 1995.

[6] D.J. Kessler and M.K. Kazimierczuk,” Power losses and efficiency of Class-E power amplifier at any duty ratio,” IEEE trans. Circuit syst.I Reg. Papers, vol. 51, no.9,pp.1675-1689, Sept. 2004

[7] V. Yousefzadeh, N. Wang, Z. Popovic, D. Maksimovic,” A digitally controlled DC/DC converter for an RF amplifier IEEE Trans. Power Electron,vol 51.

[8] T. Suetsugu and M.K. Kazimierczuk, “Design procedure of Class-E amplifier for off nominal operation at 50% duty ration. IEEE Trans. Circuits syst.I Reg. Papers, vol. 53, no.7, pp.1468-1476, Jan.2006.

[9] S.C. Wang and C.K. Tse,”Design of symmetrical Class-E power amplifiers for very low harmonic-content applications,” IEEE Trans. Circuits syst. I Reg. Papers, vol. 52, no.8, pp. 16684-1690, Aug.2005.

[10] W.A. Davis and K.K. Agrawal, “Radio Frequency Design. New York: Willey, 2006,