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Modelling of Closed Loop Class E Inverter Based Induction Heater

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Abstract: This study presents simulation of class E inverter based induction heater system using simulink. DC is converted into high frequency AC using class E inverter. This high frequency AC is used for induction heating. Closed loop systems are modeled and they are simulated using Mat lab Simulink.The results of closed loop systems are presented. The proposed amplifier with two series-parallel resonant load networks will allow sinusoidal output voltage to be achieved by associating with the positive and negative quasi-sinusoidal waveforms. The complementarily activated configuration will provide continuous high-ripple-frequency input-current waveforms; this approach significantly reduces electromagnetic interference and requires very little filtering. With the symmetry of the push-pull Class-E Circuit, there is the additional benefit that the even harmonics are suppressed at the load, and thus there are fewer harmonic distortions.

Key words: Harmonic Distortion (HD), Induction Heating (IH), Power Amplifier (PA), Zero-voltage Switching (ZVS)

INTRODUCTION

In the high-efficiency Class-E power amplifier (Ma *et al*., 2002; Aoki *et al*., 2003; Asbeck *et al*., 2001; Albulet and Zulinski, 1998; Huijsing and Sokal, 2002; Kazimierczuk and Kessler, 2004). The transistor is used as a switch. The resonator L_0, C_0 is used to block the harmonic frequencies and DC component, forcing the output current I0 to approximate a sine wave at the fundamental frequency, with harmonic content as discussed in (Raab and Sokal, 1977). The radio frequency choke LRF is assumed to be ideal such that it conducts only the DC current. The current into switch S and capacitor Cs must be a DC -offset sine wave, with some harmonic content as discussed in (Raab and Sokal, 1977). By appropriately adjusting the amplitude and phase of the load current.

This results in a switching waveform with zero voltage and zero voltage slopes at turn-on. The conditions are those of the well-known Class-E switching (Ma *et al*., 2002; Chen *et al*., 2005). This allows high-efficiency operation at frequencies up to 10 GHz, Additionally, the Class-E topology can be implemented with fewer components because the power MOSFETs' parasitic capacitors can be incorporated into the circuit. These benefits have allowed the Class-E topology to achieve high power density, thus reducing the size and weight of the equipment. However, a blocking filter L_0, C_0 is needed to block the harmonic frequencies and DC component, but also introduces loss (Raab and Sokal, 1977; Rivas *et al*., 2006). The shrinking size of electronic equipment demands ever-increasing power densities at high switching frequencies and a minimal parts count for the circuit technology. In an attempt to minimize the parts count with Class-E operation, the one-inductor one-capacitor Class-E high-efficiency switching-mode tuned PA (Toumazou and Tu, 2000; Kazimierczuk *et al*., 2005) provides a more simplified circuit. Nevertheless, this simplified single-ended circuit is appropriate only for applications in which the harmonic content and the phase-modulation noise of the output are not important criteria. It is therefore desirable to retain the functions 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 the power circuits. Unlike the single-ended Class-E amplifier (Toumazou and Tu, 2000) the push-pull architecture is able to achieve a sinusoidal output waveform and high power-handing capability. For instance, a symmetrically driven push-pull Class-E amplifier has been proposed for high-power applications (Matsuo *et al*., 1998, Huijsing and Sokal, 2002) as shown in Fig. 1a. With the symmetrical gate-driving signals, theoretically, the even harmonics are entirely cancelled at the load, and thus there are fewer harmonic distortions (HDs). However, this doubled parts-count configuration incurs Penalties on the overall efficiency and the design cost. Recently, the Class-E/F (Matsuo *et al*., 1998) and the current-mode Class-D (Tse and Wong, 2005; Boonyaroonate *et al*., 2006), with low peak voltage and low rms current, have been implemented

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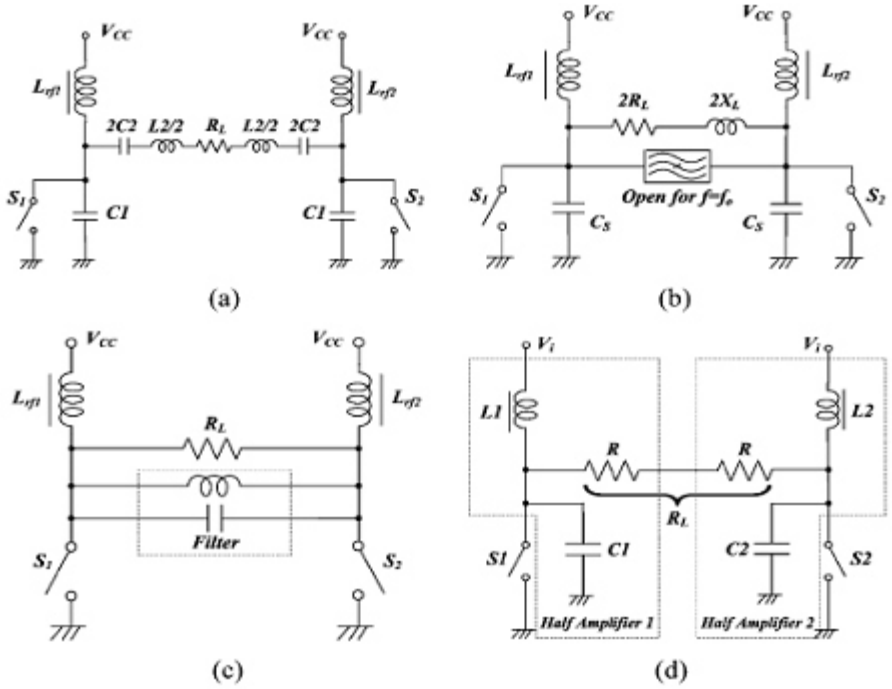

Fig. 1: Four classic push-pull amplifiers; (a) Dual-type original Class-E amplifier topology; (b) Class-E/F amplifier; (c) Class-D amplifier; (d) Proposed topology with a symmetrical arrangement of one inductor and one capacitor in the load network

as a high-frequency amplifier, as shown in Fig. 1b, c. Fortunately, there is a more elegant way to further reduce the switching loss, if the switch current increase gradually from zero after the switch is closed. Power loss and efficiency of class E power amplifier at any duty ratio is given (Kazimierczuk and Kessler, 2004).

This study suggests a push-pull Class-E resonant PA (Popovic *et al*., 2006; Kazimierczuk and Suetsugu, 2006) with a simple LC load network and a load resistor R_L in each half-amplifier, as shown in Fig. 1d. An overlapped capacitor-voltage waveform is utilized to achieve the nominal Class-E conditions without increasing the complexity of the power circuits. For nominal operation, the following performance parameters are determined: the current and voltage waveforms, the peak values of drain current and drain-to-source voltage, the output power, the power-output capability, and the component values of the load network .The above literature does not deal with modeling of closed loop controlled class E amplifier. The objective of this study is to model the closed loop system using simulink.

Design procedure of class E Power oscillator is given (Kazimierczuk *et al*., 2005). Digitally controlled Dc to Dc converter for RF amplifier is given (Popovic *et al*., 2006). Design procedure for class E amplifier for off nominal operation is given by (Kazimierczuk and Suetsugu, 2006).

MATERIALS AND METHODS

The basic schematic of the proposed push-pull Class-E series- parallel LCR resonant PA is shown in Fig. 2 and 3.

It contains two MOSFETs, two inductors, two capacitors, and a load resistance. Switches S1 and S2 are complementarily activated to drive periodically at the operating frequency f = ω/2Π as in a push-pull switching PA, i.e., the switch waveforms are identical, except that the phase shifts between S1 and S2 are Π with an "on" duty ratio D of less than 50%. The simplest type of half-amplifier, as shown in Fig. 1d, is a series-parallel resonant

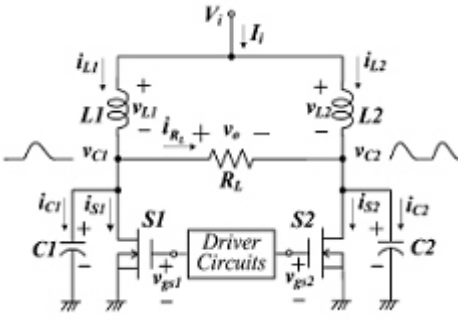

Fig. 2: Basic push pull class- E power amplifier

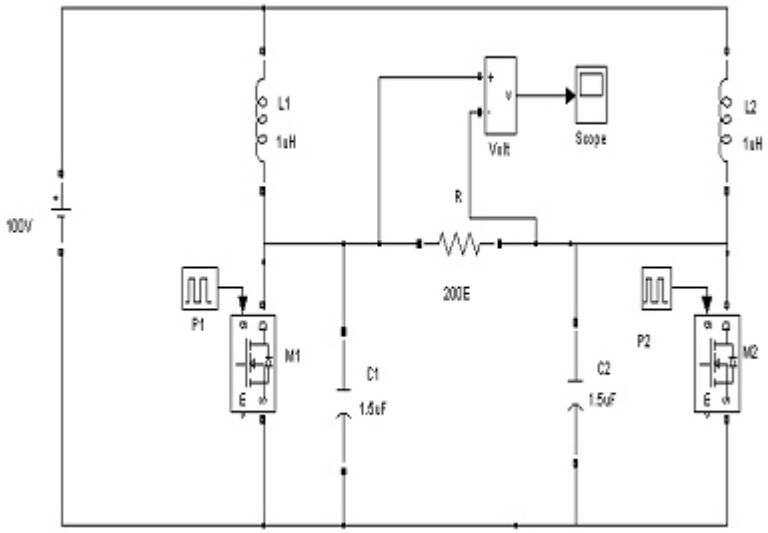

Fig. 3: Proposed simulation model

circuit, which consists of an inductor L in series with a paralleled capacitor C and resistor R. The resistor R_L is the load to which the AC power is to be delivered, with neither end connected to a ground. It is suitable for a load that is balanced to a ground, but most RF-power loads have one end connected to a ground.

To accommodate grounded loads, the proposed topology needs to add one of the following: a balun that can be used to provide the interface with the amplifier or a two-winding transformer (that has V_i connected to a center-tap on the primary winding), between the grounded load (on the grounded secondary winding) and the drains of S1 and S2 (connected to the ends of the center-tapped primary winding). 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 waveform; this offers additional degrees of freedom, and thus there are two operational points that can validly achieve this situation, it is necessary to find the current $i_{L1} = -i_{RL}$ by which the switch current increases gradually from zero at time $t = (\Pi - 2\Pi D)/\omega$. The duty ratio must be kept at less than 50% so that the capacitor-voltage waveforms V_{C1} and V_{c2} can be overlapped.

RESULTS AND DISCUSSION

Class E inverter system is simulated using simulink and the results are given here. Class E inverter circuit is shown in Fig. 4a. DC input voltage is shown in Fig. 4b. Driving pulses are shown in Fig. 4c. The pulse given to the second switch is shifted by 180º with respect to the pulse of Switch 1. Voltage across M1 is shown in Fig. 4b.

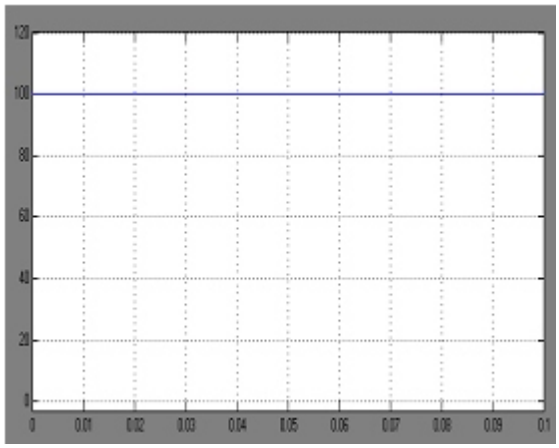

Fig. 4a: DC input voltage

Voltage across M2 is shown in Fig. 4e. Voltage across the inverter is shown in Fig. 4f. It can be seen that the output voltage is almost sine wave and the spectrum for the output is shown in Fig. 4g. The THD value is 3.3%.

The closed loop circuit model is shown in Fig. 5a. The output is sensed and it is compared with the reference voltage. The error is given to a PI controller; the output of PI controller adjusts the pulse width to bring the voltage to the set value. The rectifier output is shown in Fig. 5b. AC output voltage is shown in Fig. 5c.

CONCLUSION

This work has presented analysis, modeling and simulation of class E inverter based induction heater system. This system has advantages like low switching

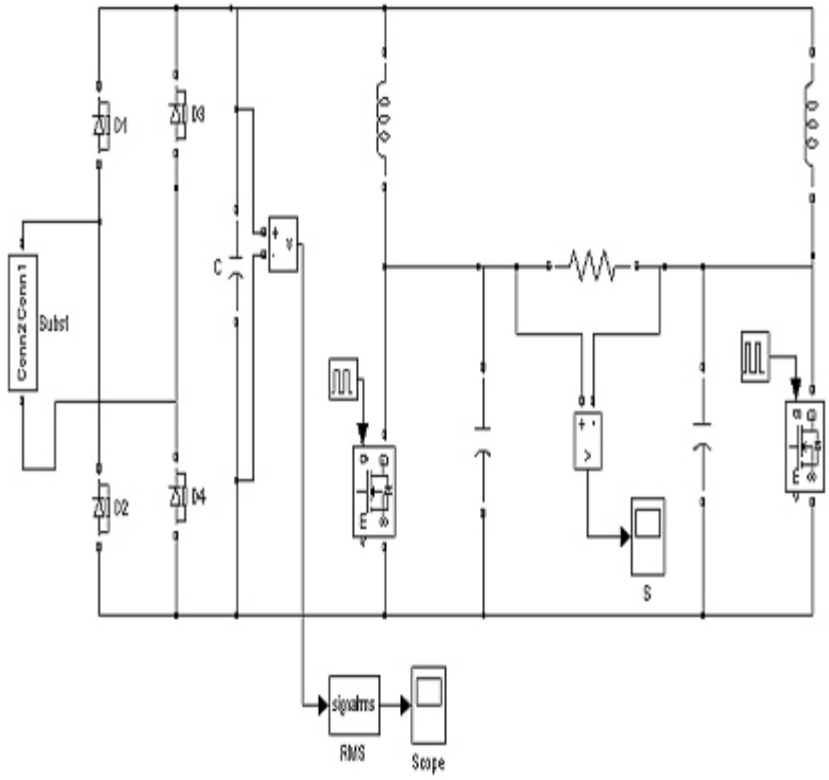

Fig. 4b: Matlab simulation circuit

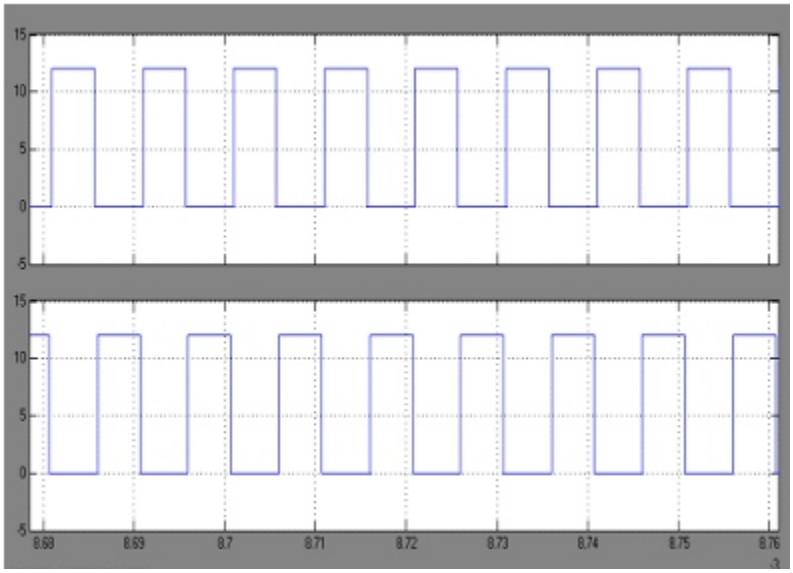

Fig. 4c: Driving pulses

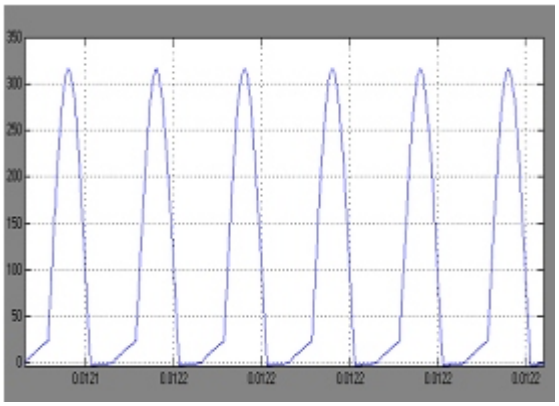

Fig. 4d: voltage across switch 1

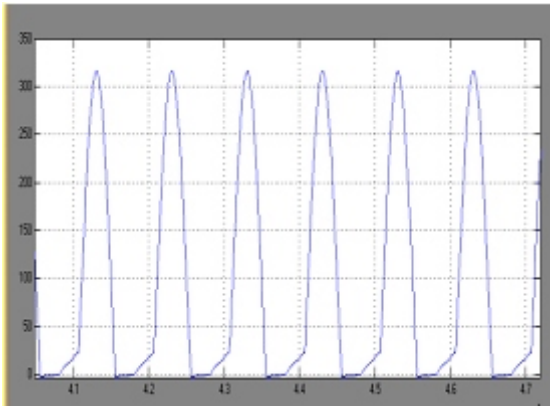

Fig. 4e: Voltage across switch 2

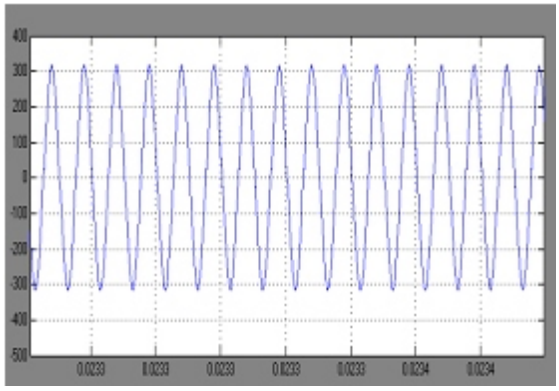

Fig. 4f: Output voltage

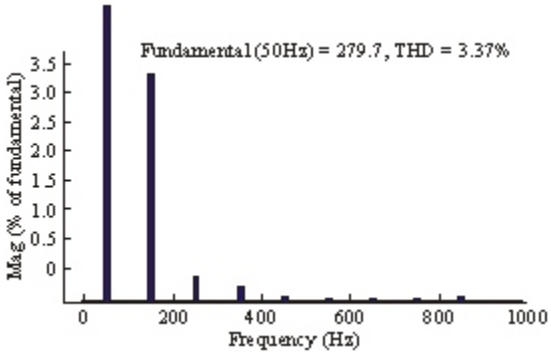

Fig. 4g: FFT Analysis for output voltage

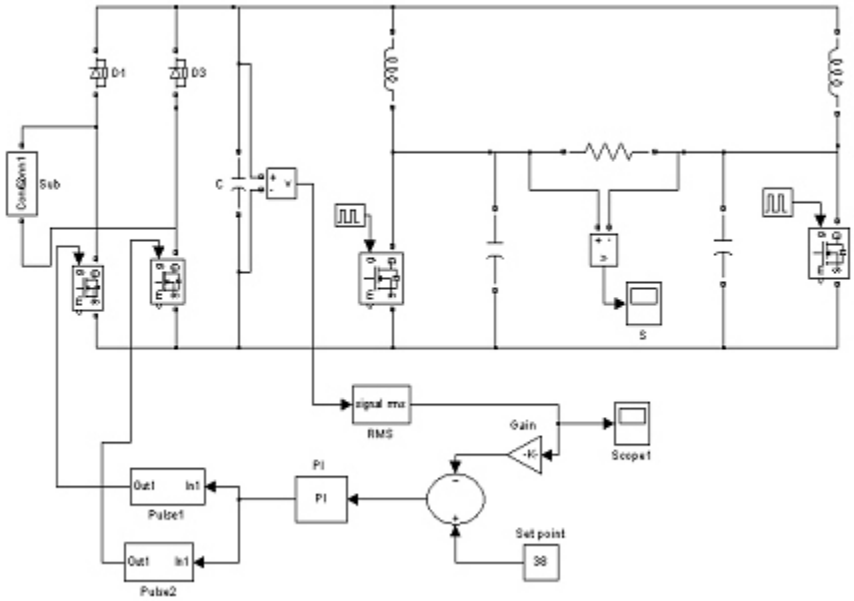

Fig. 5a: Closed loop circuit model

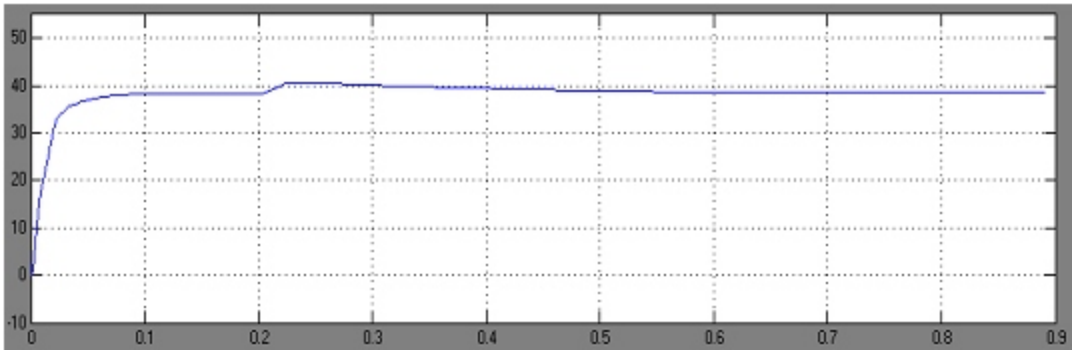

Fig. 5b: Rectifier output voltage

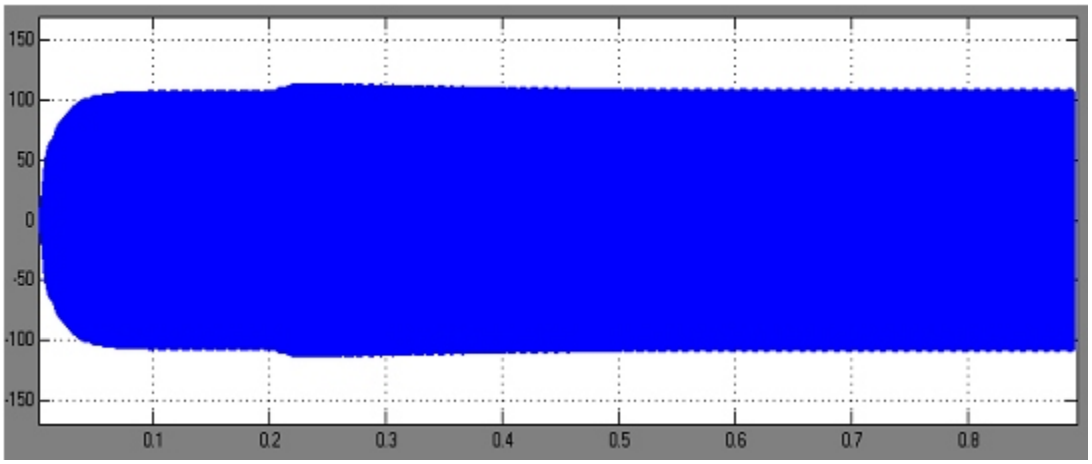

Fig. 5c: Inverter output voltage

losses, reduced stress and increased power density. Closed loop models are developed and they are successfully used for simulation studies. The simulation results are in line with the predictions. The proposed push-pull amplifier accomplishes the following:

- It provides a continuous, high-ripple-frequency input-current waveform.
- Due to its symmetry and the duty ratio D<0.5, the proposed amplifier achieves a significantly decreased level of THD (<17.827%).
- The narrower operating frequency variation of ratioA (f_o/f) changes to realize nominal amplifier performance for values higher than Q_{min}.
- The voltage and current stresses on the switches are lower than those of the original Class-E amplifier with the same output voltage and power. The approaches presented here can be applied to the analysis and design of other Class-E amplifier configurations or with more complicated circuits in exact designs. Further, it should be noted that for this topology, the circuit described in this paper has two operational points that are performed by the ZVZS and ZVZC switching. In future work the author plans to research how to control these operational points.

The steady state error in the output is reduced by using the closed loop system.

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