Optimum Mode Operation and Implementation of Class E Resonant Inverter for Wireless Power Transfer Application

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***Abstract*—This paper proposes the design of ZVS class E resonant inverter to be used in a wireless power transfer (WPT) system. Since the Class E inverter satisfies the zero voltage switching (ZVS) and zero derivative voltage switching (ZDS) condition, high conversion efficiency at high frequency can be achieved. All the components of the circuit are designed for optimum mode of operation and the inverter is made to operate at optimal switching conditions. The designed circuit is simulated in PSPICE environment and experimentally verified at a frequency of 333 kHz. The system is also tested for the WPT application and the transferred power is found out with different coupling coefficients.**

***Keywords*- Class E resonant inverter, wireless power transfer, zero voltage switching, zero derivative voltage switching.**

I. Introduction

In recent years, wireless power transfer (WPT) has gained its popularity over the conventional wired counterpart due to various advantages [1]-[2]. Inductive coupled coil is one of the coupling methods used for WPT system. In a magnetically coupled wireless power transfer system, high frequency resonant dc-ac inverters are mainly used [3]–[5]. Class E resonant inverters can achieve high efficiency at higher frequency due to its zero voltage switching (ZVS) and zero derivative voltage switching (ZDS) conditions [6].

A detailed analysis of class E amplifier is discussed in [7]. The circuit contains only one capacitor and an inductor at the load and designed for optimum condition and variable duty ratio. In [8], the class E resonant amplifier is designed for any value of quality factor (Q) and duty ratio. Laplace transforms method and a regulated current through the choke coil is considered for analyzing the operation of the circuit. For all values of quality factor (0.1 to 10) and at frequency 2 MHz, 96% efficiency is achieved. A class E circuit is designed for low frequency application where thyristor is used as a switch without any parallel capacitance [9]. The circuit is designed in such a way that it mainly depends upon the quality factor. The design and optimization of class E amplifier for wireless power system has been discussed in [10]. In [11], a ZVS class E resonant inverter is designed by considering the nonlinearity of gate to drain capacitance and drain to source capacitance. It is seen that the resonant inverter achieves the ZVS and ZDS condition with the nonlinear parasitic capacitances.

The ZVS condition of the class E inverter is analyzed with the variation of the resonant components [12]. With the variation of resonant components the angle of the load current is shifted with respect to the drain-source voltage. The shifting angle is used to analyze the ZVS operation of the circuit. The application of class E resonant inverter in wireless power transfer is discussed in [13]. It is observed that, as the distance between the coupling inductor of the WPT system varies, class E inverter can be operated in optimum condition by controlling the duty ratio and dc feed inductance.

This paper presents the design of class E inverter used in wireless power transfer. Load parameter is chosen in such a way that losses across the switch are reduced. A detailed analysis of the circuit has been done for the optimum mode of operation and all the components of the circuit are designed for optimum condition. In PSPICE environment, the circuit is simulated at a frequency of 333 kHz. The dependency of the power transfer capability on the coupling coefficient is observed. The experimental results indicate the validity of the proposed design.

II. Class E Inverter for WPT System

A. Class E Inverter

A ZVS class E resonant inverter constitutes a dc-feed inductor L_1, a series resonant circuit $L - C$, a shunt capacitor C_s, a load resistance R_O and MOSFET as a switching device as shown in Fig. 1. The switch is used at a duty cycle of 50% periodically. When the switch is turned off, the difference of current flowing through the $L - C$ resonant circuit and dc-feed inductor flows through the shunt capacitor. The current flowing through the shunt capacitor produces the voltage across the switch which increases from initial zero to peak and decreases to zero again. When the switch voltage is zero it will turn on as the circuit is satisfying the ZVS condition.

The ZVS and ZDS condition of class E resonant inverter is given by

$$V_{SW}(2\pi) = 0 \tag{1}$$

$$\left. \frac{dV_{SW}(\omega t)}{d(\omega t)} \right|_{\omega t = 2\pi} = 0 \tag{2}$$

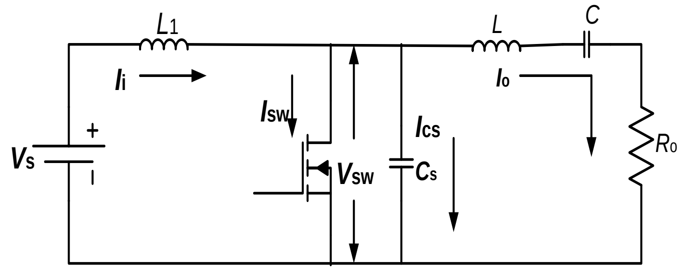

Fig. 1. Class E inverter circuit topology

The theoretical waveforms of the gate pulse, current through the switch, load current and voltage across switch are shown in Fig. 2.

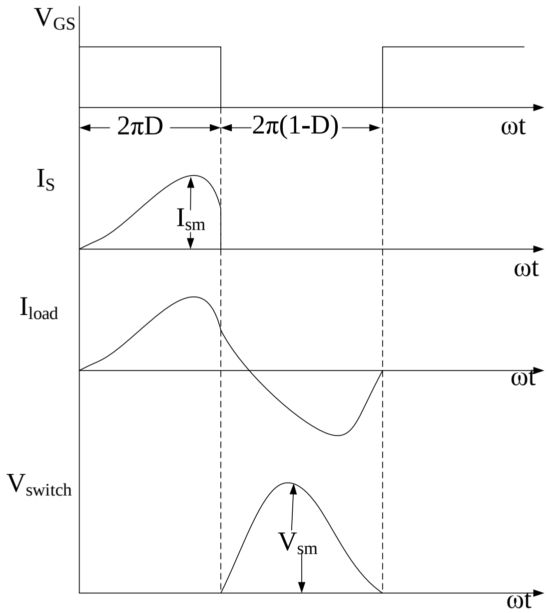

Fig. 2. Theoretical waveforms of Class E inverter

B. Wireless Power Transfer System

The WPT system mainly consists of DC to AC inverter, coupling inductor, and AC to DC rectifier if the power is used for DC load as shown in Fig. 3. By applying the switching scheme of class E inverter to the transmitter, high power delivery efficiency can be achieved for the proposed WPT system.

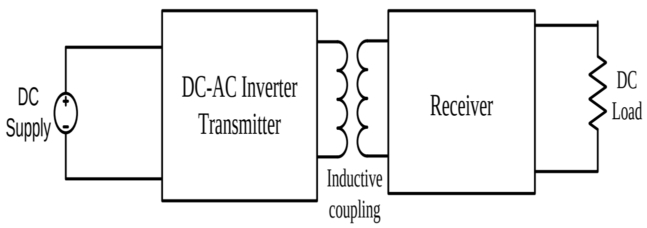

Fig. 3. Inductive coupled wireless power transfer system

The induced voltages in the coupled coils can be expressed as

$$v_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \tag{3}$$

$$v_2 = L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} \tag{4}$$

Where Mutual inductance, $M = k\sqrt{L_1 L_2}$

k is the coupling coefficient.

The elementary resonant inductive coupled circuit consists of a resonant circuit on the primary side and an inductive coil on the secondary side. If the primary coil and the secondary coil are resonant at a same frequency and each coil is connected in such a way that it forms a tuned LC circuit, a major power is transferred between the coil over a range and efficiency is also improved.

III. Circuit Design

To design class E inverter circuit, the following assumptions are made.

The load current is assumed to be sinusoidal and expressed as:

$$I_o = I_m \sin(\omega t + \phi) \tag{5}$$

When switch is ON, $0 < \omega t < 2\pi D$

$$\left.\begin{aligned} I_{CS} &= 0 \\ I_{SW} &= I_i - I_m \sin(\omega t + \phi) \\ V_{SW} &= 0 \end{aligned}\right\} \tag{6}$$

When switch is OFF, $2\pi D < \omega t < 2\pi$

$$\left.\begin{aligned} I_{CS} &= I_i - I_m \sin(\omega t + \phi) \\ I_{SW} &= 0 \\ V_S &= \frac{1}{\omega C_S}[I_i(\omega t - 2\pi D) + I_m\{\cos(\omega t + \phi) - \cos(2\pi D + \phi)\}] \end{aligned}\right\} \tag{7}$$

By applying ZVS and ZDS condition, the basic equations can be derived as

$$\tan\phi = \frac{\cos(2\pi D) - 1}{[2\pi(1-D) + \sin(2\pi D)]} \tag{8}$$

$$C_S = \frac{2\sin(\pi D)\sin(\pi D + \phi)\cos(\pi D + \phi)[(1-D)\pi\cos\pi D + \sin\pi D]}{\pi^2(1-D)\omega R_o} \tag{9}$$

$$C = \frac{1}{\omega R_o\left[Q - \frac{\pi(\pi^2 - 4)}{16}\right]} \tag{10}$$

$$L = \frac{QR_o}{\omega} \tag{11}$$

$$L_{1(\min)} = 2\frac{R_o}{f}\left(\frac{\pi^2}{4} + 1\right) \tag{12}$$

For designing the Class E inverter for open loop operation in optimum condition, it is desirable to keep the duty ratio D as 50%. With D = 0.5, input voltage V_s = 20 V and f = 333kHz, the circuit parameters are obtained as given in Table I.

The value of the coupling inductor in the secondary side is same as the class E resonant inductor.

TABLE I. CALCULATED CIRCUIT PARAMETERS

Parameter	Values
C_S	0.01 µF
L_1	300 µH
L	32 µH
C	0.01 µF
R_o	8 Ω

IV. SIMULATION RESULTS

The class E resonant inverter circuit is simulated to achieve zero voltage switching across the switch which increases the system efficiency. The parameters of the class E resonant inverter are given in Table I for optimum mode of operation. The simulation is carried out with PSPICE software. MOSFET IRFP460 is used as a switch in the resonant inverter. The waveforms are analyzed during both the switching interval on and off period. Fig. 4 shows the simulated waveform of the gate pulse and the voltage across the switch. It is seen from the waveform that the switch voltage turns to zero before turning on the switch. Zero voltage switching is achieved in this circuit. Fig. 5 shows the simulated waveforms of load voltage and load current. The maximum current is 1.7 A and maximum output voltage is 13V. The load output power is 11.05 W. The simulated waveforms of gate pulse with load voltage and load current are shown in Fig. 6 and Fig. 7 respectively. The efficiency of the inverter is 92 %.

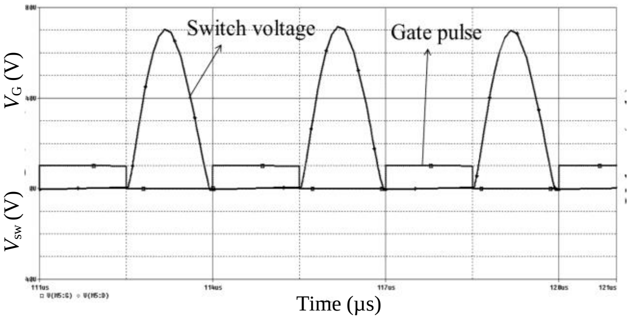

Fig. 4. Simulation waveforms of gate pulse and switch voltage

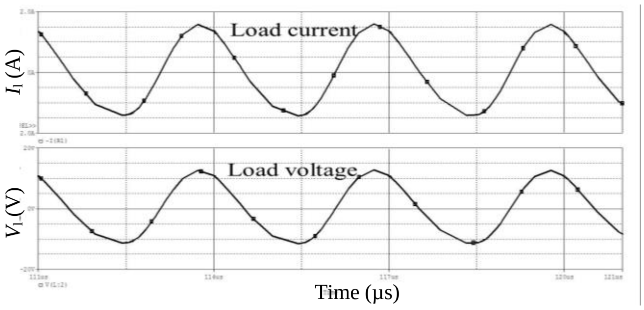

Fig. 5. Simulation waveforms of load current and load voltage

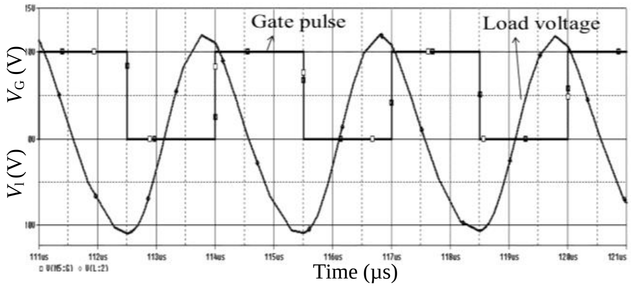

Fig. 6. Simulation waveforms of gate pulse and load voltage

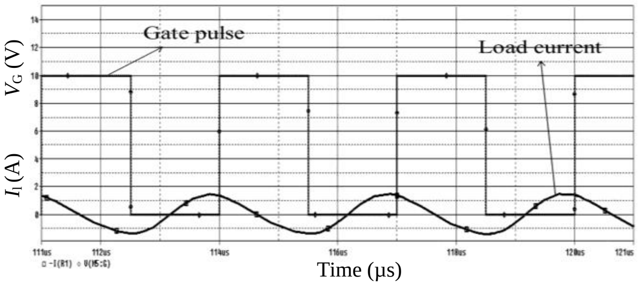

Fig. 7. Simulation waveforms of gate pulse and load current

The simulation for WPT system has been done with ZVS class E resonant inverter circuit. A mutually coupled inductor is used for the wireless power transmission. The simulation is performed in the PSPICE environment at a frequency of 333kHz. All the parameter for this circuit is taken from the class E circuit. From the simulation, it has been shown that the power is transferred through the coupled inductor. By varying the coupling coefficient of inductor, simulated waveforms of load voltage and load current are shown which are alternating in nature. The simulated waveforms of output current and load voltage are shown in Fig. 8 at a coupling factor of 1. The peak current of 0.5 A and a peak voltage of 24 V appear across the load. The total power of 6 W is transferred to the load. Fig. 9 shows the waveforms of load current with 300 mA peak and load voltage of 24 V peak at a coupling factor of 0.7. The load power transferred is 3.6 W.

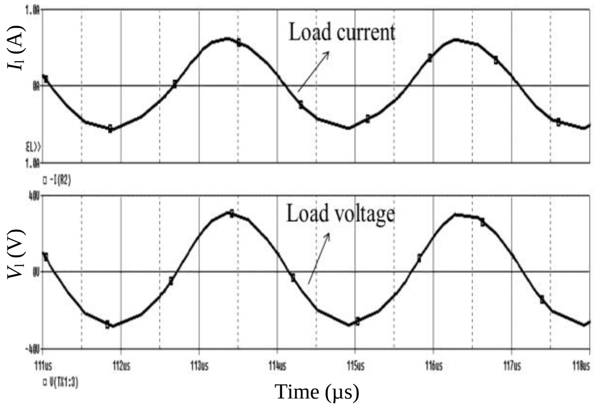

Fig. 8. Load current and voltage for power transfer at a coupling factor of 1

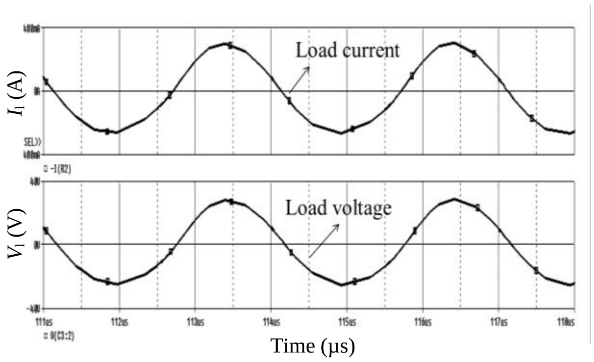

Fig. 9. Load current and voltage for power transfer at a coupling factor of 0.7

V. EXPERIMENTAL VALIDATION

Implementation of class E resonant inverter circuit for open loop operation is shown in Fig. 10. Here 20V dc source is used as a main power supply for the inverter circuit. MOSFET 'IRFP460' is used as a switch. For triggering the MOSFET, 10 V gate to source pulse is required. Here in this circuit, a 5 V pulse is generated from the Arduino at a switching frequency of 333 kHz. For triggering the MOSFET 'IRFP460', the 5 V gate pulse is boosted to 10 V using a MOSFET driver IR2110. Ceramic type capacitor of rating 100 V is used in this circuit as it is connected across the switch. To verify the zero voltage switching (ZVS) condition of the class E resonant inverter, the experiment is performed with the almost same parameters for the optimum mode of operation.

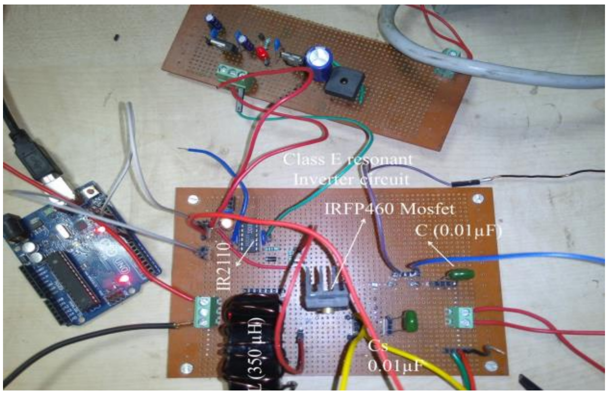

Fig. 10. Experimental setup for Class E resonant inverter

Fig. 11 shows the waveforms of the switch voltage and the gate pulse. The switching frequency is taken as 333 kHz for the operation of the resonant inverter. Zero voltage switching occurs at the switching instant. The resistance of 8 ohm is taken as a load. The maximum current of 1.76 A is flowing through the load and the voltage appears across it is 12.4 V as shown in Fig. 12. The output power is 10.77 W and the Class E inverter efficiency is 89.7 %.

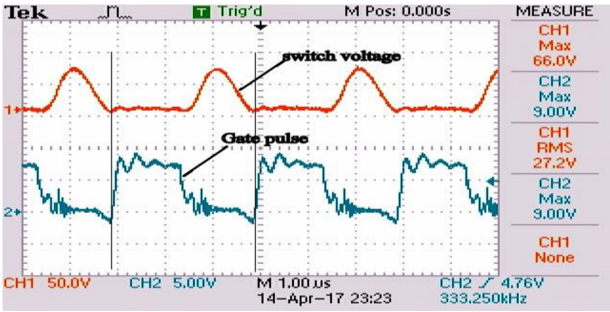

Fig. 11. Experimental waveforms of switch voltage and gate pulse

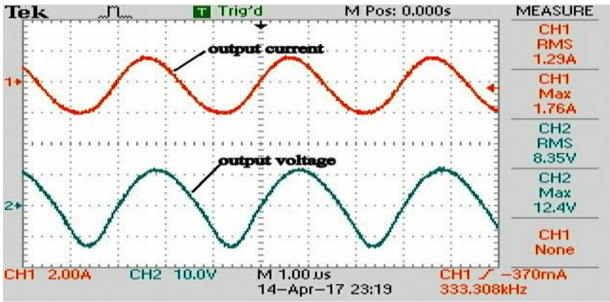

Fig. 12. Experimental waveforms of load voltage and load current

To verify the simulation of the WPT, implementation of the wireless power transfer system has been done. Fig 13 shows the experimental setup of the wireless power transfer circuit. An inductor is coupled with the resonating inductor of class E inverter circuit. The value of the coupling inductor is same as the class E resonating inductor. A ceramic capacitor of value 10 nF is connected in parallel to the coupling inductor. A load of 10 ohm is connected to verify the transferred power.

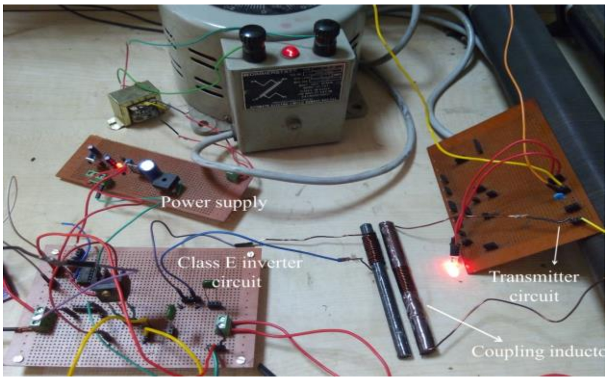

Fig. 13. Experimental setup for wireless power transfer

The results with different coupling co-efficient are taken by changing the distance between two coupling inductors. Fig. 14 shows the waveforms of load current and load voltage at a distance of 0.5 cm. The corresponding maximum current and voltage are 520 mA and 9.8 V respectively.

Fig. 15 shows the load current and voltage waveforms after changing the distance between the coupled inductor to 1 cm.

The output current and voltage decrease to 300 mA and 5.4 V as the distance is increased.

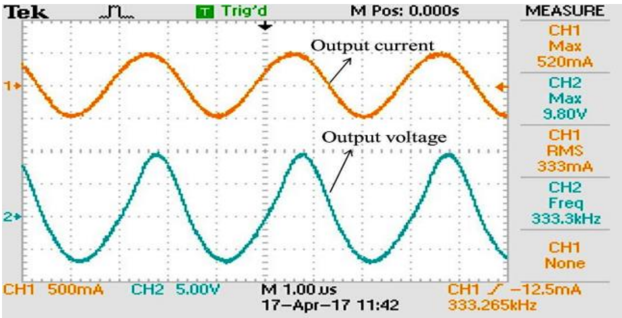

Fig. 14. Experimental waveforms of load current and voltage at 0.5 cm

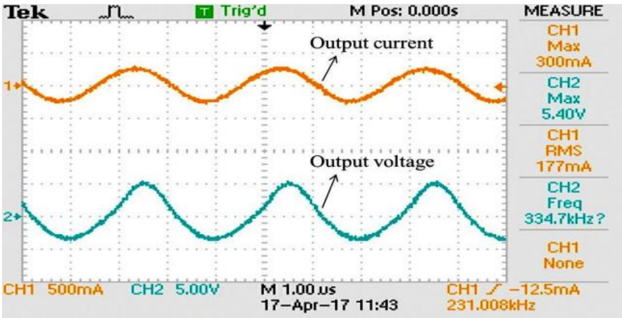

Fig. 15. Experimental waveforms of load current and voltage at 1.0 cm

VI. CONCLUSION

In this paper, a wireless power transfer system with class-E resonant inverter is proposed along with its design procedure. Simulation of the class E resonant inverter has been done by choosing the appropriate value of the parameters. The results show that the MOSFET works in ZVS condition. ZVS is achieved for open loop operation so that the switching loss is reduced and efficiency of the inverter is also improved. The simulation result done in PSPICE environment is validated by the hardware implementation. Class E resonant inverter for the high-frequency wireless power transmission system is designed and fabricated. It is seen that power transfer capability of the WPT system depends on the various parameters, such as the value of the capacitor, inductor used and the coupling coefficient etc. The main aspect in WPT system is to design the coupling inductor uniquely. As it is known that the coupling coefficient mainly depends on the distance between the two inductors, from where the power is transferred from one circuit to another. The dependency of the coupling coefficient with power transfer capability is tested by varying the distance between the two inductors.

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