New Design for Class - E^T Isolated Resonance Inverter with Ability of Producing Variable AC Output Voltage in Wireless Power Transfer Technology

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***Abstract*:** *This paper presents new design, analyses, and simulation for an isolated resonance inverter. This inverter produces adjustable AC output voltage at fixed switching frequency based on magnetic resonant coupling in wireless power transfer (WPT) technology. It consists of a new design for resonance inverter circuit based on class-E inverter and a high-frequency transformer with tap-changer. Steady-state output voltage waveforms of are obtained via PSPICE simulation. The results illustrate up to 3 times increase in output voltage level. The state-of-the-art of class-E resonant inverter is discussed in this paper called class-E^T resonant inverter afterwards. Steady-state output voltage waveforms equations validate the simulation results. Finally, th results are compared with waveforms produced by conventional class-E inverter in order to confirm the trust ability of suggested design for class-E^T inverter.*

Keywords*: Isolated resonance inverter, Variable output voltage, Wireless power transfer (WPT), Zero voltage switching condition (ZVS).*

1. Introduction

Regarding to class-E inverter operation with high conversion efficiency at very high-frequency, and also daily increase in use of sensitive loads and applications, considerable attentions on isolating and optimizing on resonance inverters such as class-E inverter in wireless power transfer (WPT) technology, have received [1]. Usually, wireless power transfer technology (WPT) is divided in three approach: inductive coupling approach or inductive power transfer (IPT) or capacitive power transfer (CPT), magnetic resonant coupling approach, and electromagnetic radiation approach [2]. Electromagnetic radiation approach has an advantage of long power transfer distance, on the other hand, there are many concerns about environmental issues. In inductive coupling approach (IPT), transmission distance is very short but, transmission efficiency is much more than two other approaches. Capacitive power transfer (CPT) system has advantages of transmit through metals, reducing energy losses, and has anti-interference ability of the magnetic fields [3]. In resonant coupling approach by using resonant inverters such as, class-E inverter with high quality factor (Q), and increase resonance frequency, transmission distance can be increased [4]. Some actions are taken in order to enhance efficiency and transfer distance, such as some designs for reducing power losses of inverter, and coupling parts, or increase switching frequency up to 30 MHz to increase transfer distance by overcoming air gap loss [5], [8]. Because of using MOSFET transistor as a switch, including MOSFET-body-diode effects in analyses can help to achieve more accurate results in output power conversion and efficiency but generally transistor body-Diode effects cannot be mentioned because of fast and autonomous turning on and off in switch [6]. Because of increasing power losses on switch by increasing switching Frequency, in higher frequency (more than 1 MHZ), new COOLMOS transistors with high quality and optimized for low conduction losses from Infineon Technology can be applied [7]. Design a resonant inverter with low voltage stress on switch can result in low switch power losses and increase output power in the inverter [8], [9]. In [10], steady-state equations for class-E inverter at high-frequency (1MHz) by consideration of COOLMOS transistor effects are given.

Increasing distance in inductive power transfer system (IPT) to almost 10 inches by changing the number of turns of transmitter and receiver coils in [11] are discussed. In [12], design of DC-DC converter with class-E oscillator by consideration of low quality factor (Q), and finite DC-feed inductor in order to minimize the scale of circuit with low efficiency is presented. Analyses and design of isolated DC-DC converter using class-E rectifier in [1] is illustrated. In [1], the purpose is regulating DC output voltage and isolating inverter from rectifier. Some researches over transmitter and receiver coils like, electromagnetic radiated emissions, optimal number of turns of coils, dimension of transmitter and receiver coils, in order to obtain the highest performance in wireless power transfer system in [13], [14] are mentioned. New approach to make integrated coils as an IC in order to minimize circuits in low power applications such as, medical equipment in [15] is studied. Finally, comprehensive study on wireless power transfer via strongly coupled magnetic resonance, resonant inverters, equations, and usage of this type of power transfer system in some industrial issues like electrical vehicles (EV) in [16], [17] are discussed. Comprehensive design equations for Class-E inverter for highest efficiency and satisfied ZVS switching conditions at switching frequency in [18], [19] are given.

In This paper, analytical design of isolated resonant inverter with capability of having variable AC output voltage with fixed DC input voltage at fixed switching frequency that can be used in some applications that need adjustable AC voltage and also for equipments that require reliability and isolation is presented. In this circuit by changing in class-E topology, increasing in output voltage in comparison with conventional class-E inverter is accessible. To achieve the new topology for enhance output voltage extra resonant filter in complicity of high-frequency transformer is applied. The method of designing for extra resonant filter is as same as fundamental resonant filter for conventional class-E once at frequency 25 KHz. Due to using of high-frequency transformer to isolate output from input. State equations for both class-E and class-E^T resonant inverter in order to illustrate differences in voltage values in both topology, are given. In proposed topology, IGBT transistor as a switch is used and the transistor-body effects are not considered in this paper.

2. Circuit Description And Principle Operation

A. Class-E Inverter:

Fig.1. shows a circuit topology of class-E (ZVS) inverter. It consists of DC-supply voltage source, MOSFET (FET) transistor as a switching device, shunt capacitance C_s, and series-resonant filter L-C Plus a resistor R as load. Switch will be driven by pulse voltage source v_g . When switch is on, the current i_s flows through the switch and inductance current is constant. When switch is off, the current difference through inductance and resonant filter (load part) flows through shunt capacitance. Fig. 2. Presents the example of waveforms for Class-E inverter with a duty cycle of 0.5. The ZVS conditions can be shown by the equations below [6]:

$$v_s(\theta) = 0, \frac{dv_s(\theta)}{d\theta} = 0 \quad (1)$$

$$\theta = 2\pi D \quad (2)$$

Where v_s is the voltage across the switching device (shunt capacitance), and D is switch-off duty ratio at the switch.

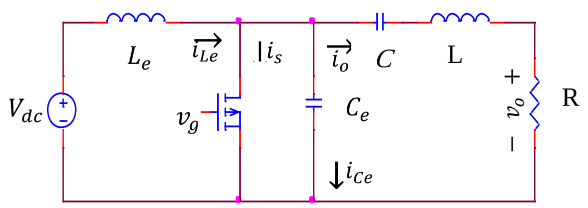


Fig. 1. Class-E inverter circuit

By consideration of this fact that, class-E inverter usually has a resonant filter with high quality factor (Q), the output current i_o is a sinusoidal waveform [1]. Additionally, the resonant filter produces a phase-shift φ in the output current, as shown in Fig. 2. [6].

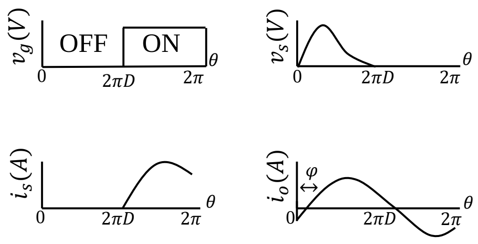


Fig. 2. Samples of waveform in the class-E Inverter for D=0.5.

In order to design Class-E and inverter and compute optimal components (C_e, L-C filter), below equations are used in this paper [18-19]:

$$L_e = 0.4001(\frac{R}{2\pi f_s}) \quad (3)$$

$$C_e = \frac{2.165}{2\pi R f_s} \quad (4)$$

$$(2\pi f_s)L - (\frac{1}{2\pi C_e f_s}) = 0.3532R \quad (5)$$

$$L = (\frac{QR}{2\pi f}) \quad (6)$$

$$2\pi f_0 = (\frac{1}{\sqrt{LC_e}}) \quad (7)$$

According to above equations the highest efficiency and providing ZVS switching conditions are provided.

B. Proposed new topology of Class-E^T Inverter

Fig. 3 shows new topology of isolated resonant inverter which is called class-E^T in this paper. In new topology of resonant inverter that will be proposed, three aims are following:

1. Isolating output (load) and input (source).
2. Increase output voltage (in compare with conventional Class-E inverter).
3. Gaining variable output voltage.

Usually, class-E resonant inverter is used to create constant AC output voltage at fixed switching frequency [18]. In proposed topology some actions are taken in order to satisfy three mentioned goals. For isolating and gaining variable output voltage high-frequency transformer equipped with tap-changer is used. It should be noted that, because of transformer's primary inductance complicity in resonance state, the amount of this inductance can change in a specified rang to change output voltage and fix it, and the secondary inductance must be fixed in order to preclude of unwilling interference effects. Adding extra and same series resonant filter, causes enhancement in rank of resonant circuit and increase two extra poles in frequency response diagram near two extant poles of conventional class-E inverter on imaginary axis [20]. As it is clear, existence of double pear of poles at the same frequency on imaginary axis, increase the amount of energy or can say increase voltage and current. Existence of resistant load insures damping ratio ($\delta \leq 0.07$) for stability and amplitude fading of the waveform for preventing instability because of double resonant filter [18-19]. In this paper the method for increasing output voltage is using extra series resonant filter. To achieve this aim, extra shunt capacitor (C_{e1}), and extra series capacitor (C_r), that makes resonant filter by complicity of primary inductance of high-frequency transformer are added into conventional class-E resonant inverter. C_{e1} is acting exactly as same as shunt capacitor in class-E inverter in order to make a path for current when the switch is off, and C_r is used to make resonant state with transformer's primary inductance. The load part of new proposed resonant inverter is as same as load part in class-E inverter. It consists of capacitance (C_{r2}) and inductance (L_r) as resonance filter and also capacitance (C_{e2}). In order to minimize the unwilling effects of C_{e2} capacitor in resonant state, secondary inductance of transformer can be set experimentally. Gaining variable output voltage by changing the primary inductance of transformer is involved in resonance state, is possible. As it was noted in past, the amount of primary inductance can change in a specified rang. By changing the tap-changer can change the position of double pear of poles in frequency response diagram and as a result can change output voltage and current continuously. It should be noted that, equations (3)-(7) are used to find out both class-E and class-E^T resonant inverter's optimal elements. Fig.3. shows proposed resonant inverter.

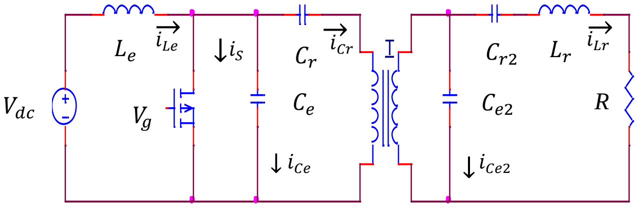


Fig. 3. New topology of class-E^T
Resonant inverter

In the next section, state equations for both class-E and class-E^T resonant inverters in order to calculate output voltage-current equations and waveforms for comparison and validate the proposed idea in this paper, are presented.

4. Class-E Steady-State-Space Equation

For achieving the steady state space equations for class-E and class-E^T inverter, duo to switching modes (on-off), the following assumptions to obtaining more accurate equations will be useful:

- When transistor is on, the switch resistance is R_{Ton}, and in case of switch off mode, the resistance is infinite.
- The shunt capacitor C_e includes transistor input capacitor.
- All passive elements are ideal with no loss.
- Switching frequency is f and duty cycle D is defined as switch-on time divided by the switching period (T=1/f).
- Switch works as an ideal element with no loss.

Fig. 4 shows class-E circuit for on and off mode to carry out steady-state-apace equations.
State equations are defined as follow[20]:

$$\frac{d\overline{X}}{d\theta} = A\overline{X} + B\overline{U}$$

$$Y = C\overline{X} + D\overline{U} \qquad (8)$$

Where: A is state matrix, B is input matrix, C is output matrix, D is input-output matrix and U is input vector (input voltage). For circuit in Fig .4, the state-equation in time domain is as follow [7]:

$$\begin{bmatrix} V_C \\ V_{Ce} \\ I_L \\ I_{Le} \end{bmatrix}^* = \begin{bmatrix} 0 & 0 & 1/C & 0 \\ Z & 0 & -1/C_e & 1/C_e \\ -1/L & 1/L & -R/L & 0 \\ 0 & -1/L & 0 & 0 \end{bmatrix} \begin{bmatrix} V_C \\ V_{Ce} \\ I_L \\ I_{Le} \end{bmatrix}$$

And also the input matrix (B) for Class-E inverter is as follow:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1/L_e \end{bmatrix} V_{dc}$$

For output:

$$v_0 = \begin{bmatrix} 0 & 0 & R & 0 \end{bmatrix} \begin{bmatrix} V_C \\ V_{Ce} \\ I_L \\ I_{Le} \end{bmatrix}$$

It should be noted that in case of switch on or off the amount of Z is different. When swith is off Z=0 and when switch is on $Z = -1/R_T \omega C_e$. so by consideration of this fact steady-state-space equations for both on-interval and off-interval is achievable.

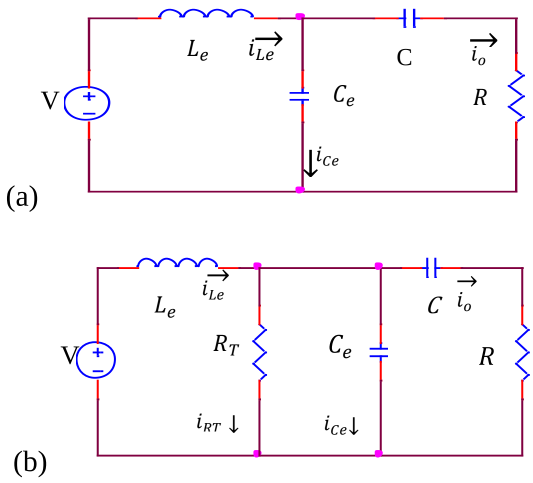


Fig. 4. Equivalent circuit for class-E inverter.
(a) switch off, (b) switch on

5. Class-E^T Steady-State-Space Equation

To obtain the steady state space equation for Class-E^T resonant inverter below premises are mentioned:

- Switch resistant interval on is R_T.
- Transformer turns ratio is $a=N_1/N_2$. Where N_1 refer to primary side and N_2 refer to secondary side.
- All elements of load part in Class-E^T inverter are transferred to primary side.
- All elements are ideal with no loss.
- Shunt capacitor C_{e1} includes transistor input capacitor.

Fig .5 shows the Class-E^T circuit in both on-interval and off-interval to calculate steady state equations matrix. As like as class-E inverter and using equation (8), the class-E^T steady state matrixes by transferring the components in secondary side of high- frequency transformer to primary side, in order to simplify calculation process, are carried out as below:

$$\begin{bmatrix} I_{Le} \\ I_{Lr} \\ V_{Ce} \\ V_{Ce2} \\ V_{Cr} \end{bmatrix}^* = \begin{bmatrix} 0 & 0 & -1/L_e & 0 & 0 \\ 0 & -R/L_r & 0 & D & -D \\ (1/AC_e + C_{e2}/BC_e) & -1/AC_e & 0 & 0 & 0 \\ (1/AC + C_{e2}/BC) & -1/AC & 0 & 0 & Z \\ 0 & (a^2/C_{r2}) & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{Le} \\ I_{Lr} \\ V_{Ce} \\ V_{Ce2} \\ V_{Cr} \end{bmatrix} + \begin{bmatrix} 1/L_e \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{dc}$$

Also for output:

$$v_0 = \begin{bmatrix} 0 & (a^2 R) & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{Le} \\ I_{Lr} \\ V_{Ce} \\ V_{Ce2} \\ V_{Cr} \end{bmatrix}$$

Where:

$$A = (1 + \frac{C_{e2}}{a^2 C_e} + \frac{C_{e2}}{a^2 C_r}) \qquad (9)$$

$$B = Aa^2 C_r \qquad (10)$$

$$C = C_r + (\frac{C_{e2}}{a^2}) \qquad (11)$$

$$D = \frac{1}{a^2 L_r} \qquad (12)$$

In case of switch on or off the amount of Z is different. When switch is off Z=0 and when switch is on $Z = -1/R_T \omega C_r$. By consideration of Z, the steady state equation is obtaining like Class-E inverter for both on-interval and off-interval.

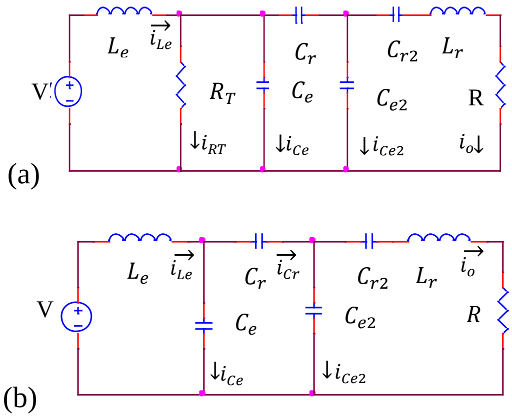


Fig. 5. Equivalent circuit for class-E^T inverter.
(a) switch on, (b) switch off.

In Fig. 5 the load part of circuit is transferred to the primary side of transformer.

6. Circuit Analyses

In this section analysis of both Class-E and Class-E^T resonant inverter are carried out. For this analysis some assumptions should be mentioned.

A. Assumptions

The system analysis is based on following assumptions for simplicity:

- The power transistor operates as an ideal switching device in both circuits.
- The DC-feed inductance (L_e in Class-E and in Class-E^T) is high enough so the current through DC-feed inductance is constant.
- The Q-factor for both inverters is high enough to insure sinusoidal waveforms for current and voltage.

- All the passive components are working as linear components.

B. Class-E inverter

In this paper, output voltage is carried out by steady state space matrixes components in previous section. Regarding to Class-E circuit steady state matrix and topology of this inverter in Fig.1 the output voltage is calculating as below [1],[4]:

$$V_0(t) = V_{Ce}(t) - V_C(t) - V_L(t) \tag{13}$$

Where:

$$V_{Ce}(t) = \int_0^T \left(ZV_C(t) - \frac{V_{Ce}(t)}{C_e} + \frac{I_L(t)}{C_e} \right) dt \tag{14}$$

$$V_C(t) = \int_0^T \left(\frac{I_L(t)}{C} \right) dt \tag{15}$$

$$V_L(t) = \int_0^T \left(V_{Ce}(t) - V_C(t) - RI_L(t) \right) dt \tag{16}$$

With equation (13) and put equations (14)-(16) in (13) the output voltage for Class-E inverter based on DC-feed inductance current and output current component is as below:

$$V_0(t) = \left[\int_0^T \left(\frac{I_{Le}(t)}{C_e} \right) dt + \int_0^T \left(V_{Ce}(t) + ZV_C(t) - V_C(t) \right) dt \right]$$

$$+ \left[\int_0^T \left(\frac{I_L(t)}{C} - \frac{I_L(t)}{C_e} - RI_L(t) \right) dt \right] \tag{17}$$

In equations (13)-(17), $T = 1/f_S$. In (17), the first bracket is consists of voltage parameters and DC-feed current component and the second bracket is consists of output current component in this paper the first bracket is called α , and the second one is called β to simplify comparison in output voltage for both Class-E inverter and Class-E^T inverter.

C. Class-E^T inverter

The output voltage of Class-E^T inverter by steady-state equations is as follow:

$$V_0(t) = V_{Ce2}(t) - v_{Cr2}(t) - V_{Lr}(t) \tag{18}$$

Where:

$$V_{Ce2}(t) = \int_0^T \left(\frac{1}{AC} + \frac{C_{e2}}{BC} \right) I_{Le}(t) dt + \int_0^T \left(\frac{-1}{AC} \right) I_{Lr}(t) dt$$

$$+ \int_0^T ZV_{Cr}(t) dt \tag{19}$$

$$V_{Cr2}(t) = \int_0^T \left(\frac{1}{C_{r2}} \right) I_{Lr}(t) dt \tag{20}$$

$$V_{Lr}(t) = \int_0^T \left(\frac{D}{L_r} \right) V_{Ce2}(t) dt - \int_0^T RI_{Lr}(t) dt$$

$$- \int_0^T \left(\frac{D}{L_r} \right) V_{Cr}(t) dt \tag{21}$$

By combination (19)-(21) in (18) the output voltage is as below:

$$V_0(t) = \int_0^T \left(\frac{1}{AC} + \frac{C_{e2}}{BC} \right) I_{Le}(t) dt + \int_0^T \left(Z - \frac{D}{L_r} \right) V_{Cr}(t) dt$$

$$- \int_0^T \left(\frac{D}{L_r} \right) V_{Ce2}(t) dt +$$

$$\int_0^T \left(R - \left(\frac{1}{AC} \right) - \left(\frac{1}{C_{r2}} \right) \right) I_{Lr}(t) dt \tag{22}$$

For comparison Class-E output voltage equation with class-E^T output voltage equation, in (22) the first three components are called γ and the last component is called δ. By consideration of transformer's turn ratio parameter (a) in A, B, C, D (defined in Class-E^T steady-state equation) in (22) and comparison γ in (22) with α in (17) and also δ in (22) with β in (17), it is clear that due to turn ratio of transformer in Class-E^T inverter and also same passive elements in both inverters, and regarding to $a \gg 1$, the output voltage is variable and by changing the turn ratio of transformer the output voltage can be increased or decreased. The proposed steady-state-space analysis verifies obtaining aims 2 and 3 (increase output voltage and gaining variable output voltage). In the next section the PSPICE simulation results of both inverters are proposed. The simulation results will validate steady-state-space analyses conclusion.

7. Conceptual Design

In this section, a step-by-step design process for Class-E and Class-E^T is presented. The circuit design specifications were given as follow:

Operation frequency $f_s = 25KHz$, dc-supply voltage $V_1 = 6V$, load resistance (output) $R_L = 10\Omega$, gate voltage $V_g = 12V$, duty-cycle of the inverters is $D_s = 0.5$, $Q = 7$.

A. Class-E design

Regarding to equations (3)-(7), the design process for Class-E inverter is as follow:

$$L_e = 0.4001\left(\frac{R}{2\pi f_s}\right) = 25.47\mu H$$

$$C_e = \frac{2.165}{2\pi R f_s} = 1.38\mu F$$

$$L = \frac{QR}{2\pi f_s} = 445.63\mu H$$

And by (5)

$$C = 0.0958\mu F$$

By (7) the resonance frequency is:

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 24.35KHz$$

B. Class-E^T design

As it was mentioned in section II, the formulation and also the amount of passive components and load resistance (output) R_L for both inverters are same so Class-E^T inverter's elements are:

$$L_e = 25.47\mu H$$

$$C_r = C_{r2} = C = 0.0958\mu F$$

$$L_r = L = 445.63\mu H$$

$$C_e = C_{e2} = 1.38\mu F$$

For setting high-frequency transformer's primary and secondary inductance two experimental facts should be noted: 1) because of secondary inductance and electromagnetic coupling between primary and secondary inductance, the amount of primary inductance for making resonant filter with capacitor C_r is not as same amount as L_r (calculated above). Because of electromagnetic coupling in primary and secondary inductances, the amount of primary inductance for resonance with capacitor C_r at frequency 25 KHz should be less than L_r that is calculated above. This fact refers to T equivalent circuit of transformers [20].

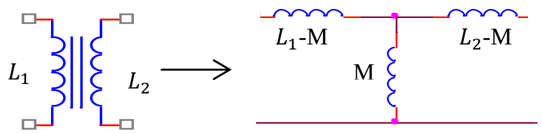
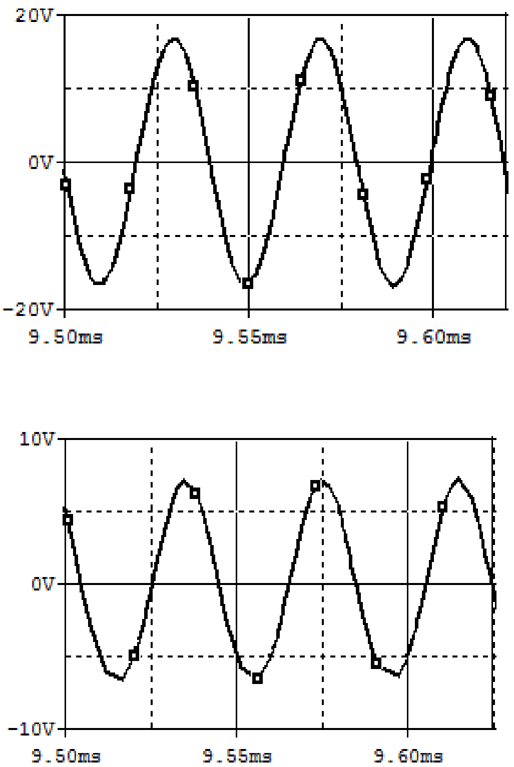


Fig. 6. T equivalent circuit of transformer

In Fig.6. M refers to electromagnetic coupling phenomenon that cause decrease in primary (L1) and secondary (L2) inductances [20]. 2) In order to preclude unwilling effects on resonant filter on load part of transformer $(L_r - C_{r2})$, the amount of secondary inductance experimentally should be set in order to make shunt resonant filter with capacitor C_{e2} at frequency 4 or 5 times higher than switching frequency f_s. Regarding to these two facts, the secondary inductance is set in $1\mu H$ and the primary one is set in rang of $380\mu H$ – $420\mu H$ to gain the highest performance. In Class-E^T transistor IRG4PH50U IGBT (1200V, 45A), and in Class-E transistor IRFP460 MOSFET (500V, 20A) is used as switch for simulation via PSPICE.

8. PSPICE Simulations Results

In this section PSPICE simulation results for both inverters are given. Simulation results show achieving all three aims (increase output voltage, make variable output voltage, and isolating output and input) as mentioned in section II. In Fig.7.(b) the output voltage for conventional Class-E inverter is shown and in Fig.7.(a) the output voltage of Class-E^T inverter by transformer primary inductance 410 μH is shown. Increasing in output voltage level in Class-E^T inverter is shown in Fig.7.



(a)

(b)

Fig. 7. output voltage. (a) Class-E^T with transformer primary inductance 410 μH .(b) Class-E.

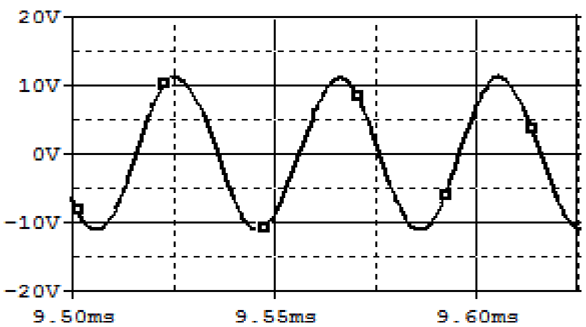


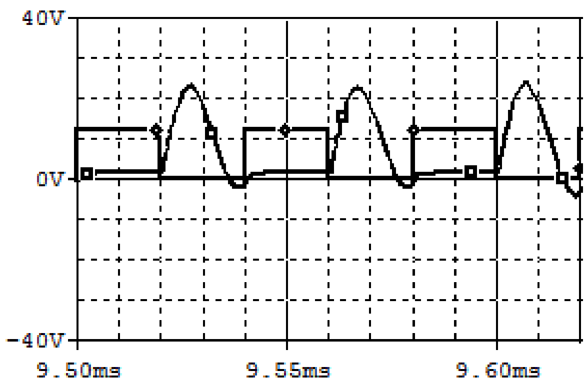
Fig. 8. Class-E^T output voltage with transformer primary inductance 383 μH.

Fig. 8. Shows Class-E^T inverter output voltage with transformer primary inductance 383μH. Simulation results comparison shows that by changing turn ratio in transformer, variable output voltage and increasing output voltage in Class-E^T resonant inverter in comparison Class-E inverter is achievable. In table I, PSPICE simulation result for output voltage of Class-E^T inverter by changing the primary inductance between 370μH-445.63μH and fixed secondary inductance in 1μH and 10μH for transformer is shown.

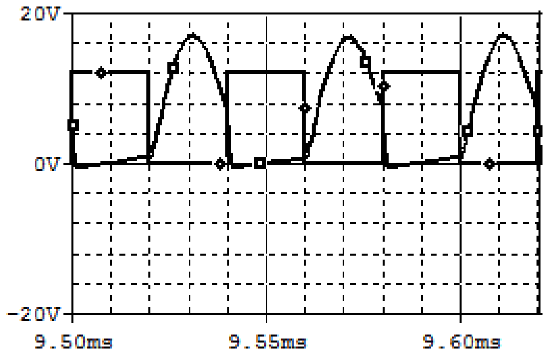
TABLE
Class-E^T output voltage

Primary inductance (μH)	Secondary Inductance (μH)	Output voltage (peak-V)	Secondary Inductance (μH)	Output voltage (peak-V)
370	1	6.04	10	8.23
375	1	7.82	10	8.39
380	1	9.717	10	8.29
385	1	15.82	10	8.59
388	1	16.09	10	8.65
390	1	15.614	10	8.63
395	1	16.92	10	8.53
400	1	19.35	10	8.5
405	1	18.159	10	8.6
410	1	17	10	8.78
420	1	17.7	10	8.72
440	1	16.5	10	8.506
445.63	1	15	10	8.4

As it was mentioned in section II and regarding to table I, by increasing secondary inductance of transformer, the output voltage is constant and less than situation when secondary inductance is fixed at 1μH. As it was noted, by increasing secondary inductance, the resonance frequency for shunt capacitor C_{e2} and this inductance is near the resonace frequency of series resonant filter (L_r, C_{r2}), and result in disturbance in series resonance filter operation and destroyed output voltage[19-20]. Table I shows that primary inductance for resonance with series capacitor $C_r$is less than inductance calculated by (6) due to T equivalent circuit of transformer and electromagnetic coupling. In Fig.9 switch voltages for both inverters are shown. It shows ZVS switching condition for both Class-E and Class-E^T inverter.



(a)



(b)

Fig. 9.switch voltage.(a) Class-E^T inverter.(b) Class-E inverter.

9. Conclusion

This paper has presented new design of resonant inverters in order to be used in different applications in wireless power transfer (WPT) technology that requires variable output AC voltage and also having isolated output. Analytical expressions for steady-state waveforms, based on Class-E inverter outside the Class-E ZVS switching conditions were proposed. Steady-state-space equations for Class-E and new topology (Class-E^T) as well as output voltage equation for both inverters in time domain have been presented. Usage of high-frequency transformer with tap-changer in primary side and fixed secondary inductance, satisfied aims of isolating and creating adjustable output voltage in Class-E^T inverter. Extra series resonant filter causes enhancement in output voltage in new topology compared to classical Class-E resonant inverter. It is also shown that the results obtained by analytical expressions agree within less than 5% error with the simulation outcomes. Additionally, simulation results verify ZVS switching conditions for switching pattern in new topology regarding to the usage of extra resonant filter and high-frequency transformer.

References

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