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Design and Analysis of Class EF_2 Inverter for Driving Transmitting Printed Spiral Coil

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Abstract: This paper studies a high frequency inverter for low power applications at a short distance. Class EF_2 inverter is selected and designed as a transmitting driver. A printed spiral coil is designed as a transmitting coil and is connected to the high frequency inverter. Experimental results are obtained to compare with simulation results. The experiment and simulation are in good agreement and the circuit design is verified. Operating frequency is 2.75 MHz. Maximum flux density is generated by transmitting coil is measured 149uT.

Key words: High frequency inverter, Class EF_2 , transmitting coil, experiment, simulation.

1. Introduction

Resonance coupling and microwave radiation are common methods which are used in wireless power transfer applications. Need for large metal plates to generate electric field is a disadvantage of capacitive coupling method. Microwave radiation method has lowest efficiency among mentioned techniques and is used in long-range wireless power transfer systems [1]. Inductive coupling can be used as an appropriate and reliable method in short-range wireless transmission [1]. This technique is selected in this work. Compensation capacitors are used to boost power transfer efficiency by reducing reactive power. The connection of capacitors are divided into four categories based on the connection between capacitor and coil: Series-Parallel, Series-Series, Parallel-Series and Parallel-Parallel [1]. Wireless power transfer technique has been applied in the numbers of technologies including; charging electric vehicle, charging mobile and medical implants [3]. Exact design of circuit, system modelling and energy transfer efficiency are important issues in this field [3]. Various types of drivers are applied in wireless power transfer systems such as, Class D, Class E, Class F and other novel hybrid inverters such as EF and EF_2 . Characteristic of Class D driver is a push-pull configuration. The output of this amplifier is voltage-type and series-resonant primary is suitable for inductive link. The duty cycle of 50% is defined for driving switches. This driver generates voltage regardless of load and this feature is in contrast with Class C driver. Class D drivers are able to drive resistive, inductive and capacitive loads [2]. Reference [3] has used Class E amplifier as a

transmitting driver for a wireless power transfer system. In that work, effect of load resistance variations due to changing of distance between transceivers is analysed and operating frequency for Class E amplifier is considered 125 kHz. Adding resonant network to load network is applied in Class F inverters and also Class F^{-1} . By using this method in the Class E inverter Class EF_n inverter can be achieved. The ratio of the resonant frequency of added resonant network is shown by subscript n [5]. Reference [5] used Class EF_2 as a driver in transmitting side for a wireless power transfer system. The advantage of class E and Class F is efficient switching and improved switch voltage and current waveforms, respectively. By combination of these two classes, both advantages are achievable. This combination leads to a reduction of switch voltage and current stresses and improvement of power output efficiency. Class EF_2 is a suitable amplifier in wireless power transfer systems [5]. Class EF_2 inverter is designed in this work. A spiral printed coil is designed to connect to the high frequency driver. This coil is designed according to the procedure which is presented in [6]. The inner diameter and the outer diameter are 10 mm and 45.2 mm, respectively. Resonant configuration leads to reduction of high frequency switching effect so a capacitance which is tuned to switching frequency is connected in parallel with transmitting coil.

2. Theoretical analysis of Class EF_2

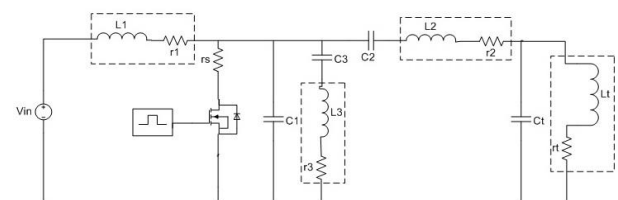


Fig1. Class EF_2 inverter.

Theoretical analysis of Class EF_2 performs in this section. This analysis is based on the procedure which is presented in [7, 9].

The configuration of Class EF_2 is shown in Fig1. To simplify the analysis, some assumptions are considered.

- The MOSFET is driven under several assumptions: zero saturation voltage, zero saturation resistance, infinite off-resistance, and the switching is ideal.
- The capacitance C is linear.
- The impedance of resonant circuit $L_n C_n$ is zero at the resonant frequency and infinite at other frequency.
- The loss of circuit elements is neglected.

To analyze the circuit and to obtain equations, the equivalent circuit of Class EF₂ can be shown as Fig2. Switch voltage of ideal Class E has below conditions:

$$v(\omega t)|_{\omega t=2\pi} = 0 \quad (1)$$

$$\frac{dv(\omega t)}{d\omega t}|_{\omega t=2\pi} = 0 \quad (2)$$

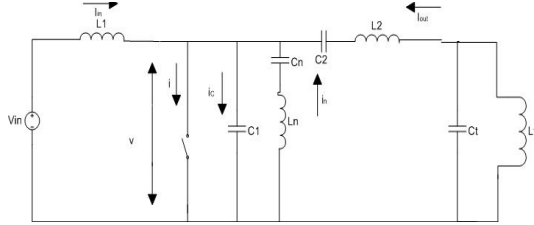


Fig2. Equivalent circuit of Class EF₂.

The output current and the current i_n are considered as sinusoidal:

$$i_{out}(\omega t) = I_{out} \sin(\omega t + \varphi) \quad (3)$$

$$i_n(\omega t) = I_n \sin n\omega t \quad (4)$$

There is no current through capacitance C during the time that switch is on:

$$0 < \omega t < \pi,$$

$$i_c(\omega t) = \omega C \frac{dv(\omega t)}{d(\omega t)} = 0 \quad (5)$$

Switch current can be written as below equation (6):

$$i(\omega t) = I_{in} + I_n \sin n\omega t + I_{out} \sin(\omega t + \varphi) \quad (6)$$

Initial switch current is considered zero $i(0) = 0$ and the equation (6) can be rewritten as equation (7):

$$1 + \frac{I_{out}}{I_{in}} \sin \varphi = 0 \quad (7)$$

There is no current through the switch during the time that switch is off and current through capacitance C can be written:

$$\pi < \omega t < 2\pi,$$

$$i_c(\omega t) = I_{in} + I_n \sin n\omega t + I_{out} \sin(\omega t + \varphi) \quad (8)$$

Charging of capacitance C produces switch voltage:

$$v(\omega t) = \frac{1}{\omega C} \int_{\pi}^{\omega t} i_c(\omega t) d\omega t$$

$$= \frac{I_{in}}{\omega C} \left\{ \omega t - \pi - \frac{1}{n} \frac{I_n}{I_{in}} (1 + \cos n\omega t) - \frac{I_{out}}{I_{in}} [\cos(\omega t + \varphi) + \cos \varphi] \right\} \quad (9)$$

By applying zero voltage switching (ZVS) condition (equation (1)) which is a feature of an ideal class E inverter, the equation (9) can be rewritten as below equation:

$$\frac{\pi}{2} - \frac{I_n}{n I_{in}} - \frac{I_{out}}{I_{in}} \cos \varphi = 0 \quad (10)$$

The relative amplitude of resonant circuit $L_n C_n$ for any n can be obtained as below:

$$I_n = \frac{1}{\pi} \int_0^{2\pi} i(\omega t) \sin n\omega t d\omega t = \frac{2 I_{in}}{n\pi} (1 - \cos n\pi) \quad (11)$$

For even n:

$$I_n = 0 \quad (12)$$

By employing Fourier-series, dc input voltage can be achieved:

$$V_{in} = \frac{1}{2\pi} \int_0^{2\pi} v(\omega t) d\omega t$$

$$= \frac{I_{in}}{2\pi\omega C} \left[\frac{\pi^2}{2} - \frac{\pi}{n} \frac{I_n}{I_{in}} - \frac{I_{out}}{I_{in}} (2 \sin \varphi + \pi \cos \varphi) \right] \quad (14)$$

By substituting (7) and (12) into equation (10):

$$\cot \varphi = -\frac{\pi}{2} \quad (13)$$

$$\varphi = -32.48^\circ \quad (18)$$

$$\frac{I_{out}}{I_{in}} = -\frac{1}{\sin \varphi} = 1.8620 \quad (19)$$

3. Design procedure 3.1 Driver design

Reference [8] has presented a method for designing Class EF₂ and Class E/ F₃ inverters. Initial driver design is performed according to the technique which is presented in [8]. Table1. shows component values.

Table1.Component values.

Element	Value
L_1 (μH)	8.4
L_2 (μH)	8
L_3 (μH)	7.3
L_t (μH)	1.58
C_1 (nF)	20
C_2 (nF)	27
C_3 (nF)	10
C_t (nF)	2
r_1 (Ω)	0.3
r_2 (Ω)	0.125
r_3 (Ω)	0.66
r_t (Ω)	0.1
r_s (Ω)	1
V_{in} (v)	2
$f_{switching}$ (MHz)	2.75

3.2 Coil design

In this section, the design of the spiral coil is described and coil specifications for the effective permeability are presented. The proposed coil is shown in Fig. 3.

The variables that parameterize the shape of the coil are the wire thickness (t), inner diameter (d_{in}), outer diameter (d_{out}), number of turns (N), and the space between turns (s). Transmitting coil specification can be seen in Table 2.

Several equations have been proposed for approximating L [11].For designing the mentioned method, we adopted (1) from [12].

$$L = \frac{\mu_0 n^2 d_{avg}}{2} \left[\ln \left(\frac{2.46}{\gamma} \right) + 0.20\gamma^2 \right] \quad (1)$$

$$\gamma = \frac{d_{out} - d_{in}}{d_{out} + d_{in}} \quad (2)$$

Where n is the number of turns, d_o and d_i are the outer and inner diameters of the coil, respectively.

$d_{avg} = \frac{d_{out} + d_{in}}{2}$ and γ is a parameter defined as fill factor [11].

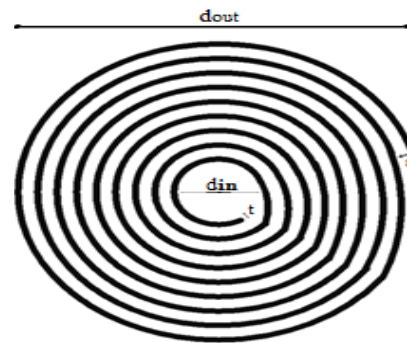


Fig3.Printed spiral coil [10].

Table2. Transmitting coil specification.

Parameter	Value
Inner Diameter (d_{in})(mm)	10
Outer Diameter (d_{out})(mm)	45.2
Turns	8
Trace Width(t)(mm)	0.8
Spacing (s)(mm)	1.4

4. Experimental and simulation results

In this section, the simulation results are investigated as well as experimental results to verify design accuracy. The experimental results are in a good agreement with the simulated ones. The circuit components are selected as used in [5]. The MOSFET is SiS892ADN from Vishay and the MOSFET DRIVER is UCC27321 from Texas Instruments. The gate driver is from the family of high speed drivers. The experiment setup is shown in Fig4.

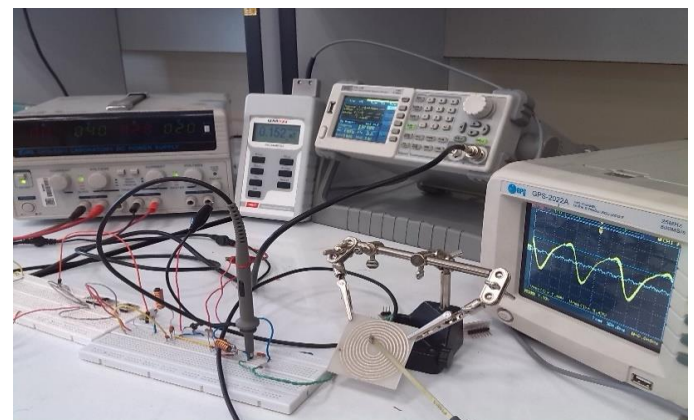


Fig4.Experiment Setup.

Fig5 (a) shows the pulse that drives MOSFET in simulation and Fig5 (b) shows the pulse that is generated by a function generator and is sent to the input port of MOSFET driver.

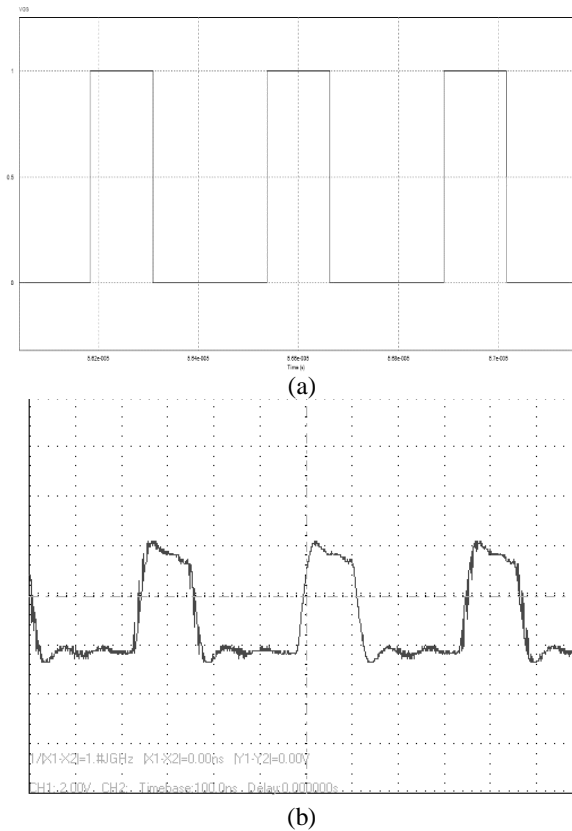


Fig5. Input pulse (a) Simulation (b) Experimental.

A set of simulation results and experimental results are presented to evaluate design accuracy. The duty cycle (d) is changed from 20% to 45% to investigate circuit operation. Fig6. illustrates input current. Fig7 and Fig8 show drain voltage (d=20%) and output voltage (d=20%), respectively.

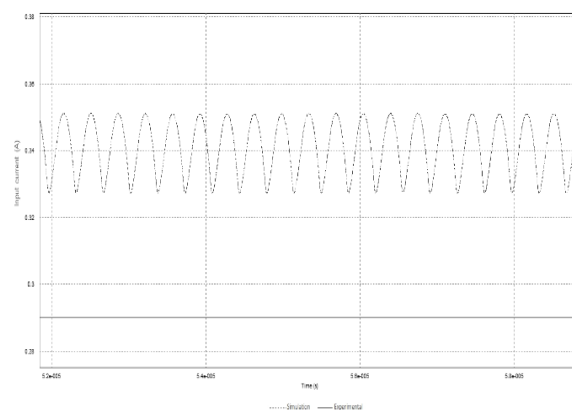


Fig6. Input current.

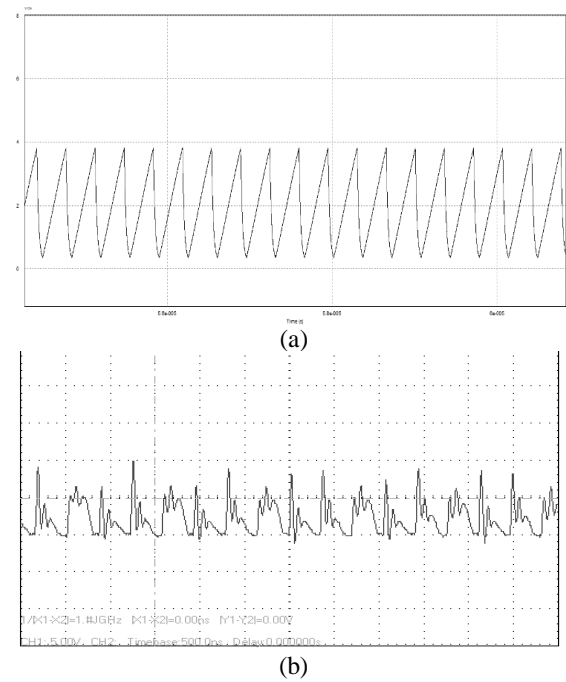


Fig7. Drain voltage (a) Simulation (b) Experimental.

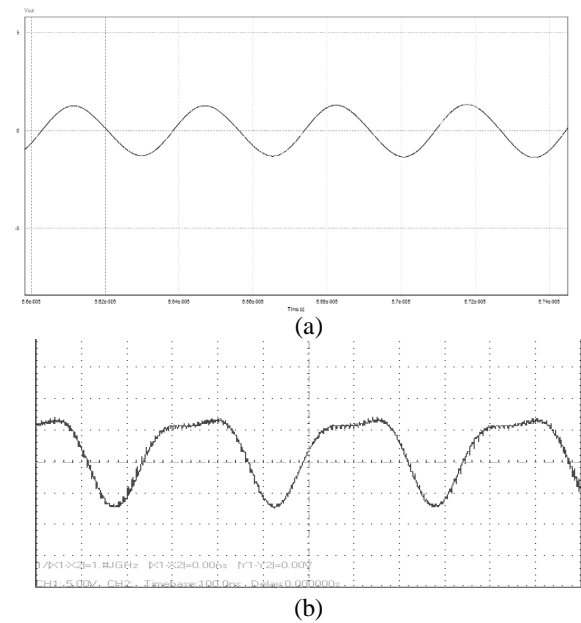


Fig8. Output voltage (a) Simulation (b) Experimental.

The duty cycle (d) is considered 45% to measure the output voltage and maximum drain voltage. These measurements are compared with simulation results and can be shown in Table3. Fig.9. illustrates maximum drain voltage versus changing duty cycle.

Table3. Comparison of simulation via calculated values.

Parameter	Simulation	Experimental
Duty cycle (%)	45	45
Output voltage (V)	1.27	1.90
Maximum drain voltage (V)	4.70	3.96
Voltage gain (Vout/Vin) at 2.83 MHz	1.495	1.450

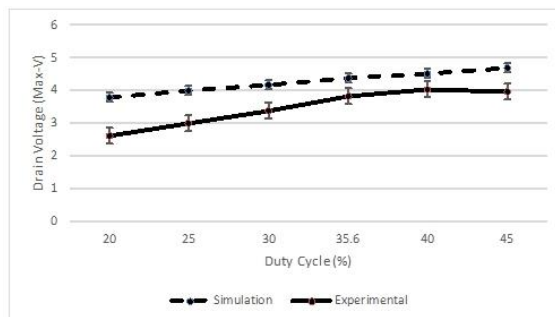


Fig9. Maximum drain voltage versus changing duty cycle (20%-45%).

5. Conclusions

This paper has studied Class EF₂ inverter that can be used as a driver in transmitting side for wireless power transfer applications. This high frequency inverter is designed and simulated. Operating frequency is considered 2.75 MHz. A printed spiral coil is designed and connected to the inverter. Maximum flux density is measured 149uT. The design accuracy is verified by simulation and experimental results.

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