Design And Implementation of Class EF2 Circuit Based Wireless Power Transfer

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Abstract- *This paper presents the design and implementation of a Class EF2 inverter and Class EF2 rectifier for two -W wireless power transfer (WPT) systems, one operating at 6.78 MHz and the other at 27.12 MHz's It will be shown that the Class EF2 circuits can be designed to have beneficial features for WPT applications such as reduced second-harmonic component and lower total harmonic distortion, higher power-output capability, reduction in magnetic core requirements and operation at higher frequencies in rectification compared to other circuit topologies. A model will first be presented to analyze the circuits and to derive values of its components to achieve optimum switching operation. Additional analysis regarding harmonic content, magnetic core requirements and open-circuit protection will also be performed. The design and implementation process of the two Class-EF2based WPT systems will be discussed and compared to an equivalent Class-E-based WPT system. Experimental results will be provided to confirm validity of the analysis. A dc–dc efficiency of 75% was achieved with Class-EF2 -based systems*

Keywords- Wireless Power Transfer, category EF inverters, high frequency inverters.

I. INTRODUCTION

Resonant topologies area unit seen to be the foremost appropriate style alternative for a multi-megahertz coil driver in WPT system owing to their reduced switch losses. One explicit topology that has recently been of accelerating interest is that the category E electrical converter. the category E electrical converter is capable of in operation with efficiency at switch frequencies on top of one rate owing to its operation at zero-voltage switch (ZVS) and zero-derivative voltage switch (ZDS) conditions will deliver additional power than alternative categories for an explicit input voltage and is easy to construct owing to its low component-count. category E inverters area unit well documented within the literature and are wide utilized in WPT applications. it's been according in this the potency of the category E electrical converter may be improved and its voltage or current stresses may be reduced by adding a resonant network either in parallel or series to its load network.

The method of adding resonant networks to the load network is employed at school F and sophistication F-1 inverters, and by applying it to the category E electrical converter leads to a hybrid electrical converter that has been brought up because the category EFn or category E/Fn electrical converter. The subscript n refers to the quantitative relation of the resonant frequency of the extra resonant network to the switch frequency of the electrical converter associate degree is an number} number bigger or equal than a pair of. The 'EFn' term is employed if n is a fair whole number and therefore the 'E/Fn' term is employed if n is associate degree odd whole number. The extra resonant network or networks can be within the type of a series LC lumped network that's connected in parallel with the load network as shown, or a parallel LC lumped network that's connected asynchronous with the load network as shown, or a mix of each series and parallel LC lumped networks that area unit connected asynchronous and in parallel with the load network as shown. A $\lambda/4$ conductor inserted between the availability supply and therefore the electrical converter may be used as shown in. The idea of mixing category E and sophistication F or category F-1 inverters was introduced by Kee in 2002. during this paper, kee conferred an summary of the category E/F electrical converter and a generalized frequency domain primarily based analysis technique to see the voltage and current waveforms for any combination of extra lumped LC resonant networks.

A succeeding publication by Grebennikov conferred closed-form analytical equations for the category EF and sophistication E/F inverters with another series LC lumped network in parallel with the load network as shown in Fig. 1. Style equations were derived specifically for the category E/F3 electrical converter supported the belief that the extra series LC resonant network has giant energy storage and therefore the duty cycle is at fifty the concerns. Another publication by Kaczmarczyk conferred a piecewise-linear state-space model for the category EF2 and sophistication E/F3 inverters with a series LC resonant network in parallel with the load network.

The model was resolved numerically to get the elements values for ZVS and ZDS conditions for any desired duty cycle and for any loaded Q's of the extra series LC resonant network and therefore the output network. Kaczmarczyk's model provided the values of duty cycles which will maximise the power-output capability and showed that most power-output capability of the category EF2 and sophistication E/F3 electrical converters is more than that of the category E inverter for a given device rating. Alternative printed papers regarding category EF and sophistication E/F electrical converters use reiterative ohmic resistance standardisation ways and made-to-order RF improvement code to style and optimise the inverter. This paper can gift a category EF2 electrical converter to drive associate degree inductive link at vi.78 MHz.

A piecewise-linear state-space are wont to analyse the circuit and to derive it's performance parameters and components' values for optimum switch operation. the most power-output capability and therefore the voltage and current stresses are investigated and compared to a category E electrical converter. the planning and implementation of the experimental setup of a 25W WPT system are delineate

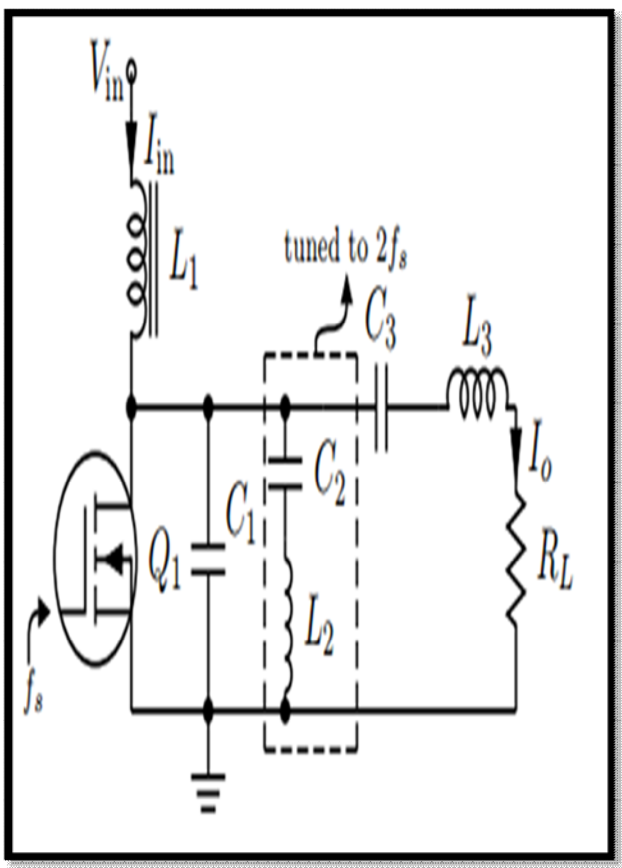

Figure 1. Circuit diagram of the Class EF2 driver

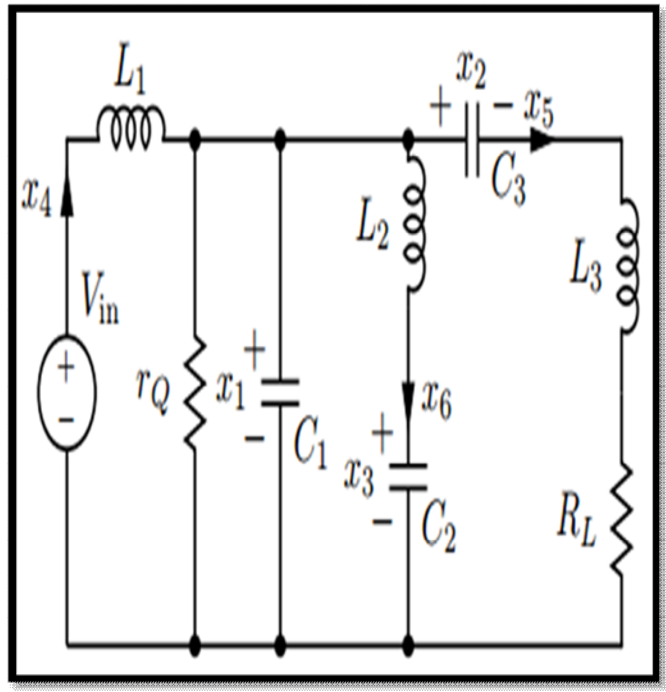

Figure 2. Equivalent circuit diagram of the Semi-resonant Class EF2 driver for state-space modeling

and results will be shown to confirm the accuracy of the analysis and the design

The circuit diagram of the Class EF2 inverter that will be studied is shown in Fig. 1. Inductor L3 represents the inductance of the transmitting coil and resistor RL represents the reflected load seen by the inverter of the receiving side circuitry in addition to the equivalent series resistance (ESR) of the transmitting coil. The inverter can be represented by the equivalent circuit shown in Fig. 2 for state space modelling and the analysis will be based on the following two assumptions:

- Switch Q1 has a zero switching time, a fixed OFF resistance rOFF and a fixed ON resistances rON.
- The shunt capacitance C1 absorbs the output capacitance of switch Q1 and is constant. The equivalent circuit can be analyzed by the following general state-space representation

$$X^{\cdot}(\omega t) = AX(\omega t) + BU(\omega t) \quad (1)$$
$$Y(\omega t) = CX(\omega t) + DU(\omega) \quad (2)$$

where X is the state vector and contains the following seven voltage and current states variables

$$X(\omega t) = [vC1\ (\omega t)\ vC2\ (\omega t)\ vC3\ (\omega t)\ iL1\ (\omega t)\ iL3\ (\omega t)\ iL2\ (\omega t)\ ]^{\wedge}T \quad (3)$$

and U is the input vector equal to a unit step function. Using KVL and KCL, the matrices A, B, C and D maximum switch current, input and output powers as well as the components' values can be obtained for a given coil inductance, reflected load resistance and switching frequency.

The power-output capability is defined as the ratio of the output power to the maximum voltage and current stresses of the switch. It is an indication of the switch utilization for a certain output power.

It can be represented as cp = Po / VDSmax IDSmax . (4)

Although theoretically the values of L2 and C2 could have any value as long as their resonant frequency is tuned to the second harmonic of the switching frequency. It is therefore of interest to find the values of L2 and C2, in addition to the duty cycle, that would allow the Class EF2 inverter to operate at its highest power-output capability point. An exhaustive search was been performed and it was found that the maximum power-output capability is 0.1323 and occurs when the ratio of C1/C2 is 0.867 and the duty cycle is 0.375. In comparison,

Using KCL and assuming lossless components, the MOSFET's drain current is

iDS(ωt) = x4(ωt) − x5(ωt) − x6(ωt). (17)

If the loaded quality factor of the output network L3RL is high enough (>10) the output current can be assumed to be sinusoidal, i.e.

x5(ωt) = io sin(ωt + φ) (18) where io = |x5| and φ = ∠x5. Eq.

can be used to estimate the conduction loss due to the MOSFET's ON resistance as follows

PQ = i 2 DSRMS rON (19) where iDSRMS is the RMS value of the MOSFET's drain current. In order to compare the conduction loss in the MOSFET's ON resistance for a Class EF2 inverter with that of a Class E inverter it is necessary to calculate the normalized conduction power loss which is given by

PQnorm = PQRL PorON = 2 i 2 DSRMS |x5| 2.

By using the values of k and duty cycle that were found previously the normalized conduction loss for the Class EF2 inverter is 0.4542 compared to a value of 1.3648 for the Class E inverter. This means for a given output power and load resistance the conduction loss in a Class EF2 inverter is approximately 66 % less that of the Class E inverter. The reduced conduction loss is due to the fact that the Class EF2 reflects a higher DC resistance to the input voltage source compared to that of the Class E inverter. Consequently the maximum MOSFET drain current is lower than that of the Class E inverter; however the maximum MOSFET drain voltage is increased. Table I compares the Class EF2 inverter and a Class E inverter that are designed to deliver 20W to a 5 Ω load and both having a MOSFET ON resistance of 0.04 Ω and a loaded QL of 12 at 6.78 MHz.

II. RELATED WORK

D. Ahn and P. P. Mercier, "Wireless power transfer with concurrent 200 kHz and 6.78 MHz operation in a single transmitter device," IEEE Trans. Power Electron., vol. 31, no. 7, pp. 5081–5029, Jul. 2016.

The aim of this article is to review of power electronics-based CET systems. Various techniques are divided according to the medium used for energy transfer and are presented as (see Figure 1) acoustics-based CETs, light-based CETs, capacitive-based CETs, and the largest group, inductively coupled CETs. The basic principles and the latest developments in these techniques with a special focus on inductively coupled solutions are systematically described. The advantages and limitations are briefly examined, and the application field where each technique is particularly suited is indicated. Some oscillograms that illustrate properties of these discussed inductive CET techniques

S. Hasanzadeh, S. Vaez-Zadeh, and A. H. Isfahani, "Optimization of a contactless power transfer system for electric vehicles," IEEE Trans. Veh. Technol., vol. 61, no. 8, pp. 3566–3573, Oct. 2012.

A contactless charging system based on a circular coil configuration is presented for electric vehicles. An analytical model of the charging system is derived and used to investigate the effect of system dimensions on the system mutual inductance. The efficiency of the system is then calculated and used as a criterion to optimize the dimensions of transmitter and receiver coils in an uncompensated system, as well as series and parallel compensated systems. As a result, several design rules are presented. Following these rules, it is shown that significant improvement in the system efficiency is achieved by optimizing the coil dimensions while the length and weight of coils are kept constant. The performances of the optimized systems are evaluated using the 3-D finite-element method (FEM) and experiments. The FEM and experimental results are in good agreement, confirming the validity of the analytical model and the optimization approach.

III. PROPOSED SYSTEM

Class-E circuits have a complex principle of operation and are not straightforward to design and implement, however, they can deliver more power for a given input voltage and load than Class-D circuits and at a higher efficiency for high frequency applications. Class-E circuits can be designed to achieve zero voltage switching (ZVS) and zero-voltage-derivative switching (ZDS), which makes them operate efficiently at switching frequencies in the range of tens of megahertz.

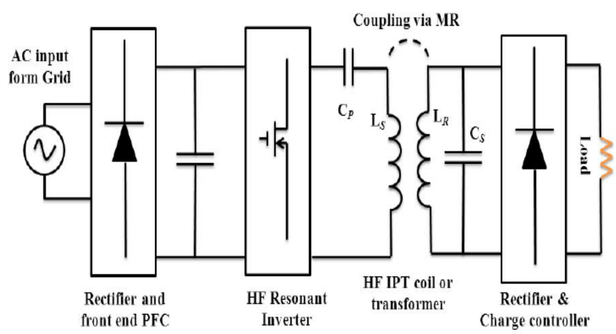

Figure 3. Block diagram

IV. PROPOSED SYSTEM MODULE AND DEVICES

In proposed system used for DC-DC Auto Transformer, DC-to-DC converters, CLASS-EF2 Invertors.

DC-DC Convertors:

DC-DC converters are electronic devices used whenever we want to change DC electrical power efficiently from one voltage level to another. They are needed because unlike AC, DC cannot simply be stepped up or down using a transformer. In many ways, a DC-DC converter is the DC equivalent of a transformer.

Typical applications of DC-DC converters are where 24V DC from a truck battery must be stepped down to 12V DC to operate a car radio, CB transceiver or mobile phone; where 12V DC from a car battery must be stepped down to 3V DC, to run a personal CD player; where 5V DC on a personal computer motherboard must be stepped down to 3V, 2V or less for one of the latest CPU chips; where the 340V DC obtained by rectifying 240V AC power must be stepped down to 5V, 12V and other DC voltages as part of a PC power supply; where 1.5V from a single cell must be stepped up to 5V or more, to operate electronic circuitry; where 6V or 9V DC must be stepped up to 500V DC or more, to provide an insulation testing voltage; where 12V DC must be stepped up to +/-40V or so, to run a car hifi amplifier's circuitry; or where 12V DC must be stepped up to 650V DC or so, as part of a DC-AC sine-wave inverter. In all of these applications, we want to change the DC energy from one voltage level to another, while wasting as little as possible in the process. In other words, we want to perform the conversion with the highest possible efficiency.An important point to remember about all DC-DC converters is that like a transformer, they essentially just change the input energy into a different impedance level. So whatever the output voltage level, the output power all comes from the input; there's no energy manufactured inside the converter.

Class EF2 inversion:

A detailed analysis of Class-EF2 inverters has been performed in three cases of operation were identified based on the values of the duty cycle and k: the maximum power-output capability case, the maximum frequency of operation case, and the maximum power operation case. Here, only the maximum power-output capability case will be considered since it results in the highest efficiency operation for the devices chosen here and only a summary of the analysis and results will be included.

V. SIMULATION CIRCUIT DIAGRAM

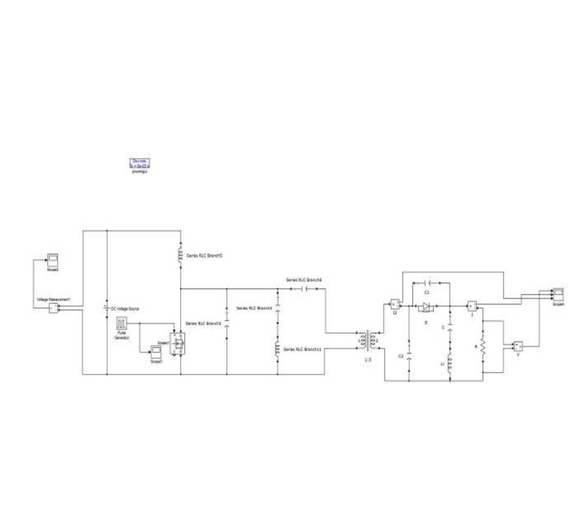

Figure 4.

Step 1: Click on Windows 7 ultimate. To open the Simulink software in MATLAB (R2012B)

Step 2: Start MATLAB, by double clicking on the MATLAB icon In the MATLAB, click the Simulink icon.

Step3: Select New from the File menu which creates a new workspace where the block diagram of the system will be created.

Step4: Connect all the components as per the circuit diagram using the Simulink browser.

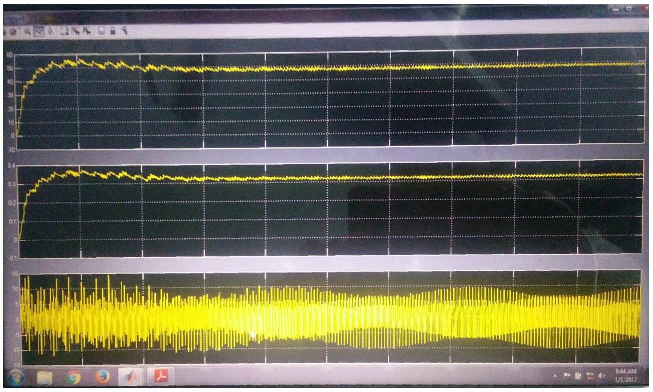

Figure 5.

Step5: Select the simulation parameters and set the start time and stop time.

Step6: Start the simulation and view the waveforms at the respective scope

VI. RESULTS

A Class EF2 inverter capable of delivering up to 25W has been designed and implemented for a 6.78 MHz WPT system. Fig. 4 shows the complete circuit diagram of the implemented WPT system. The inductive link consisted of two coils that were formed of two turns with a diameter of approximately 15 cm and using 4 AWG copper wires. Their inductance was measured to be approximately 1.40 µH and their ESR is approximately 0.21 **Ω**. The coils were aligned with each other and the distance between the coils was 2 in. In order to measure the output power accurately, a current driven Class D rectifier was designed to provide a DC output voltage at the receiver. The Scotty diodes PMEG6030EP (60V, 3A) were used. The load resistance at the output of the rectifier was 58 **Ω**. The MOSFET SiS892ADN (100 V, 28 A) from Vishay (in a surface mount 1212 package) was used and the gate driver was the UCC27321 from Texas Instruments. The maximum gate drive voltage was set at 7.0 V and the input voltage to the inverter was 23 V. Fig. 5 shows the recorded drain voltage waveform of the MOSFET in comparison with the theoretical waveform and excellent agreement can be seen between the two. The measured output power at the load was 20.5W and the input power was 23.5W, therefore the DC-DC efficiency of the WPT system is 87.2 %. A Class E inverter was designed and built for comparison and a lower 84 % efficiency was achieved

VII. CONCLUSION

This paper presented a 6th-order piecewise-linear state space model of Class EF2 inverter for WPT applications. The analysis was performed to investigate the initial reports in literature about their improved efficiency, reduced voltage and current stresses compared to the Class E inverter. It was found that the peak voltage across the MOSFET is about 2.3 times the input DC voltage compared to about 3.56 times the input DC voltage for the Class E inverter. The peak MOSFET current is about 2.4 times the input DC current compared to 2.86 times the input DC current for the Class E inverter. Class EF2 inverters have a higher power-output capability and reduced MOSFET conduction losses than Class E and Class D inverters. It was shown that for a given output power and load resistance, Class EF2 inverters have a lower MOSFET conduction power loss than Class E inverters due to their lower MOSFET peak current. Lower conduction losses can be more beneficial especially in a WPT application since the MOSFET conduction loss can significantly affect the overall efficiency. Class EF2 inverters reflect a higher DC load to the voltage source which means its input voltage is higher than that of a Class E inverter and consequently the voltage stresses of Class EF2 are also higher. However, an increased input voltage might be beneficial because the input DC current and ripple will be lower, and the MOSFET's non-linear output capacitance will have a lower impact of the inverter's performance.

VIII. ACKNOWLEDGEMENT

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