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Contactless Self-Tuned Capacitive Coupled Power Transfer System Using Series Resonant Inverter and MPPT Controller

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***Abstract* - Inductive Power Transfer (IPT) has received most of the interest until now; new researches on Capacitive Power Transfer (CPT) have led to proposals for high power, long distance applications, such as electric vehicle charging or handheld devices. So the traditional conception of capacitive wireless transmission only for low power and short distances is slowly changing. Here the proposed CPT system can track the maximum power transfer capability over a wide load variation even when the resonant circuit is not fully tuned. The maximum power transfer is achieved by designing a DC-DC buck-boost converter with duty cycle control for dynamic impedance matching. In the inductively coupled power transfer (ICPT) method, the power is transferred wirelessly between separated coils via MF, while the CPT relies on the electric field (EF) to transfer power between two pairs of metal plates. By applying capacitive coupling by means of electric field, wireless power transfer can be realized between a transmitter and a receiver. The presented capacitive link design can reduce the receiver to the bare minimum, the capacitance plates and the load. All tuning for variable coupling occurs at the transmitter side, therefore lowering the costs and making data communication no longer necessary. State of the art of CPT converters includes a significant variety of resonant topologies, including different number of switches in the inverter, from single switch to a half or full bridge, different resonant tanks and impedance adaptation networks. This work is focused on simplicity, using as simple high frequency inverter and series resonant tank. Bearing in mind that the goal of this research was to achieve efficiency as high as possible, and that a high switching frequency is needed to compensate for the low capacitance value and to select the resonant tank and the inverter best suited for the application.**

Keywords: Contactless, Self-Tuned, Capacitive Coupled, Power Transfer System, Series Resonant, Inverter, MPPT Controller.

I. INTRODUCTION

Wireless power transfer has been gaining interest in the latest years due to some advantages over conventional power transmission, such as position independence, no need for physical connectors, capability to work even when metals are present, etc. Wireless power transfer allows for the charging of electronic devices without the need of a power cord, from high power electric and automatic guided vehicles, to low power biomedical implants and consumer applications. For the latter, the main advantage is the improvement of user friendliness; the user can simply put the device on a charging pad without the need to connect a wire. Additional benefits are the improved, clutter-free aesthetics by using no wires, and increased durability, since the regularly connecting and disconnecting of the wire wears the cable down. For industrial uses, the most important benefit is the improved safety.

As a result of the extensive research in WPT, various categories have arisen. WPT can be categorized in terms of efficiency, distance of transmission, power level and size. Classification based on distance of transmission however is more relevant. For any electromagnetic source both electric (E-fields) and magnetic (H-fields) fields are generated around it. These fields are characterized by the radiative and non-radiative components. Depending on the distance from the source they can either be near field, transition zone or far field. The transition zone possesses characteristics of both the near and far field transfers.

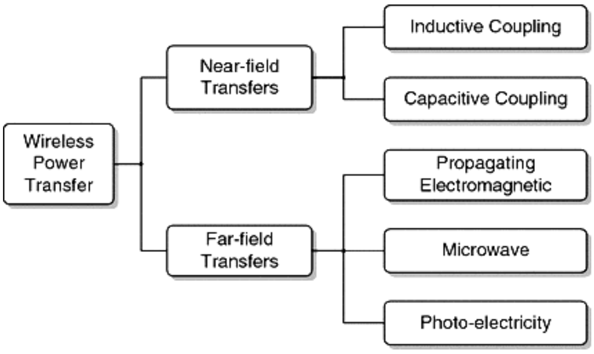

Figure 1: Classification of WPT

The near field transfers have all the polarization types i.e. vertical, horizontal, elliptical and circular while the far field transfer only has one type. This far in research the near field transfer has been found to have a higher efficiency during transfer of power. This can be attributed to the decrease in both electric and magnetic fields proportionally to the distance from the source. In addition, the near-field region allows higher diffraction of the wave, resulting in stronger penetrability and weak directivity on a short range. In light of all these, more research is being focused on development of the near field transfers as compared to far field transfer.

1.1 Inductive and Capacitive Power Transfer

Wireless charging is a spark-free and totally waterproof procedure, often desirable properties in hazardous or moist industrial environments. The IPT system uses magnate fields to transfer power, which has made remarkable achievements. The transfer power can be up to megawatt level, and the transfer efficiency can reach 96%. The development of the IPT system has paved the way towards various applications, such as electric vehicle charging, biomedical applications, track-moving system, mobile communication devices etc. Both near field transfer and far field are further categorized based on the method of operation of the transfer.

Applications on the market that offer wireless charging are all based on inductive charging: the magnetic field between coupled inductors is used to transfer energy wirelessly. However, research and development on capacitive (or electric) coupling, that uses the electric field to transfer power wirelessly, is steadily increasing. Drawbacks are the higher voltages, frequencies and field strengths compared to inductive wireless power transfer. Besides acoustic power transfer, optical power transfer, and microwave power transfer, there are two effective methods to achieve WPT, the inductive power transfer (IPT) and capacitive power transfer (CPT).

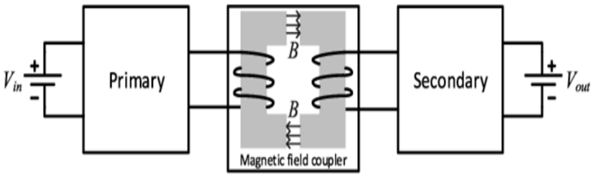

Figure 2: Inductive Power Transfer (IPT)

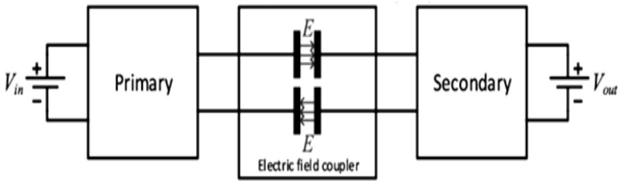

Figure 3: Capacitive Power Transfer (CPT)

Wireless power transfer (WPT) can be used to transfer electric power from the input source to the output load without direct physical wires or conductors solving the problems of traditional cable connection such as wear, breakdown, and complex structure. In addition, an IPT system may generate large electromagnetic interference (EMI) which can cause health and safety concerns.

II. EXISTING SYSTEM

In this system a zero-voltage soft-switching (ZVS) high-frequency resonant converter for inductive power transfer (IPT) applications is presented. By adopting the burst mode pulse-density-modulation (PDM) scheme with resonant frequency tracking, the load power can be continuously regulated under the conditions of full-ranges of soft switching due to the undamped resonant currents through the coils, there by the current surges which appears with the conventional PDM scheme can be eliminated effectively. The essential performances on the output power regulation and soft-switching operations are demonstrated in experiment using a 500kHzprototype.

2.1 Drawbacks

- A fully tuned inductive power transfer (IPT) system operating at its maximum power can only obtain a power efficiency of 50% or less.
- The detuning factor of an LC resonant circuit reduces the power transfer capability.
- An IPT system may generate large electromagnetic interference (EMI) which can cause health and safety concerns.
- IPT cannot be used to transfer energy across metal barriers.
- Significant increase in weight due to bulk coils.
- Hardware cost is high.

III. PROPOSED SYSTEM

A novel Capacitive Power Transfer (CPT) system which can track the maximum power output using a DC-DC converter is proposed. At the same time aimed to achieve a high-power efficiency when the circuit is not fully tuned. The method is applied to a voltage fed inverter at series tuned off-resonance operation for reduced power losses. A prototype system is built with a half-bridge inverter to drive the capacitively coupling circuit, and a buck boost converter is designed for impedance matching. A perturb and observe algorithm is developed for controlling the duty cycle of the DC-DC converter to track the maximum power against load variations.

3.1 Advantages

- CPT exhibits better tolerance to receiver misalignment.
- Requires simpler hardware design than Inductive Power Transfer (IPT)
- CPT provides a good potential for transferring power for short-range, compact WPT applications
- Simpler design, light weight and lower cost.
- CPT systems will not generate the eddy current loss in the nearby metal.

3.2 Block Diagram

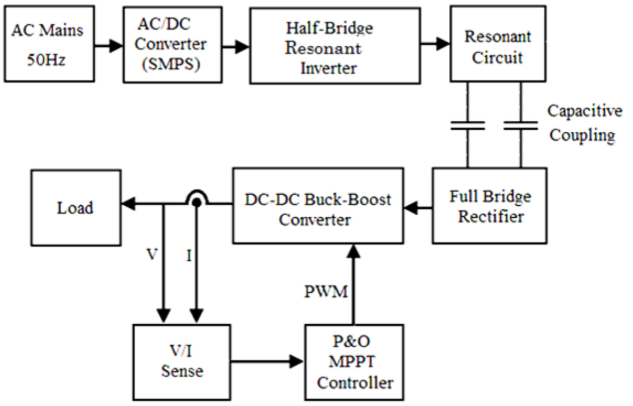

Figure 4: Block Diagram of Proposed System

The block diagram of the proposed system is shown in figure which consists of transmitter and receiver side components. The main power supply is obtained from a AC 220v 50Hz power supply which is converted into DC by means of a AC-DC converter or by using a switching mode power supply (SMPS). Then it is converted into high-frequency AC supply using a half-bridge voltage source inverter and given to a resonant circuit. The receiver side is connected to a full-bridge rectifier and DC-DC buck-boost converter. A perturb and observe (P&O) algorithm based maximum power point tracking (MPPT) controller supplies gate pulses to the buck boost converter switch which operates the converter in MPPT mode. The V/I feed back is given to the input of MPPT controlled for tracking load current and voltage.

The circuit diagram of the proposed system is shown in figure the first section of the circuit is the Inverter which converts the DC source voltage into high-frequency AC output. Here a half-bridge series resonant voltage source inverter is implemented. It operates in the frequency range of 80-120 kHz. The resonant circuit consists of a series LC circuit connected in series to the output of the half-bridge inverter. A pair of capacitor plates acts as coupling device at the output of the LC circuit through which the power is transferred by means of static electric field.

3.3 Circuit Diagram

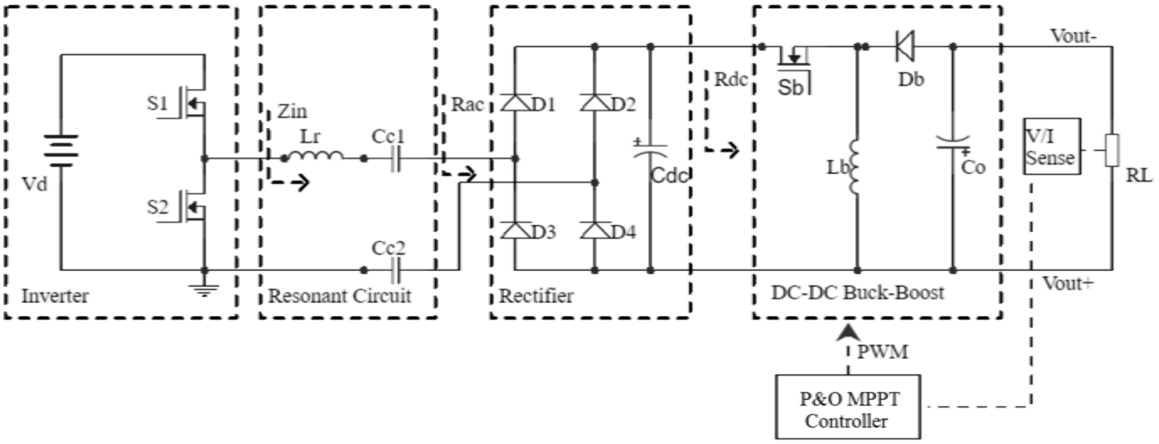

Figure 5: Circuit Diagram of Proposed System

Transmitter side has one conducting metallic plate that acts as one pole of capacitor while the other plate in the receiver side acts as other pole of a capacitor. When both the plates are kept near each other a with a minimum air gap a electric field is generated between the plates and power gets transferred from transmitter to the receiver. Receiver gets a high frequency AC current which is converted into DC by the bridge rectifier and then maximum power is extracted by the MPPT circuit and the output of DC-DC buck boost converter will be a constant regulated DC output supplied to the loads.

IV. PROPOSED METHODOLOGY

Figure shows a typical series tuned, voltage-fed inverter based CPT system based on a half-bridge inverter. It consists of a half-bridge with switches S1, S2 operating at frequency fs, coupling capacitors CC1, CC2 compensated by series

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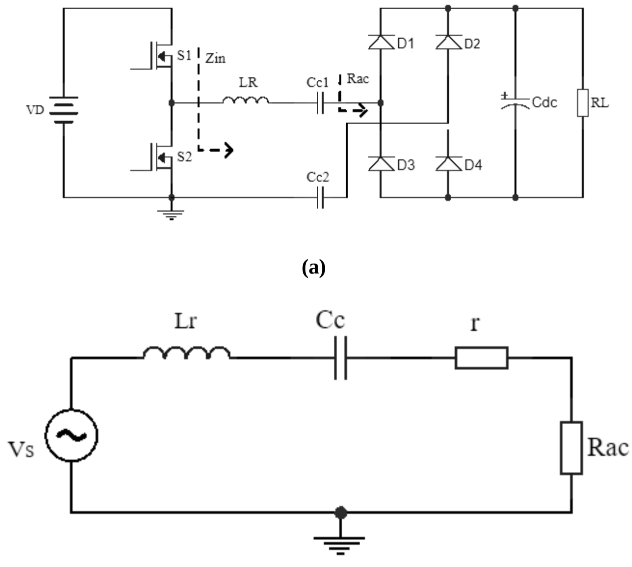
inductor Lr, a full-wave rectifier formed by D1-D4, and a resistive load RL. If the harmonic components at the inverter output and the switching losses are ignored, the system can be simplified to an RLC equivalent circuit as in Figure 2.3(b) using the Fundamental Harmonic Approximation (FHA) method. In this simplified model, VS is the fundamental component of the converter output voltage, resistor r reflects the total conduction losses of inductor, capacitors, and wiring to the LC resonant tank, Rac is the load reflected by the rectifier Rac, and the equivalent coupling capacitance Cc.



(a)

(b)

Figure 6: Typical CPT System Configuration

RLC Equivalent Circuit

For a half-bridge inverter operating at the angular operating frequency, ω=2πfs, the fundamental component of the switch node voltage VS (1) can be expressed as follows:

$$V_s(t) = \frac{2V_D}{\pi}\sin(\omega t + \varphi) \qquad (1)$$

The total impedance seen at the inverter output:

$$Z_{in} = j\omega L_r + \frac{1}{j\omega C_C} + R_{ac} + r \qquad (2)$$

Resolve the LRC equivalent circuit, the power output and efficiency can be expressed as below:

$$\begin{cases} P_o = \left(\dfrac{\sqrt{2}V_D}{\pi}\right)^2 \dfrac{1}{\left(j\omega L_r + \dfrac{1}{j\omega C_C}\right)^2 + (R_{ac} + r)^2} R_{ac} \\ \eta = \dfrac{R_{ac}}{R_{ac} + r} \end{cases} \qquad (3)$$

The optimal reflected load value, Rac, Max-Po (3), which receives maximum output power can be determined as:

$$R_{ac,Max-Po} = \sqrt{\Delta X^2 + r^2} \qquad (4)$$

Where

$$j\Delta X = j\omega L_r + \frac{1}{j\omega C_C} \qquad (5)$$

From (3) and (5), the maximum output load power and the corresponding power efficiency can be expressed as:

$$\begin{cases} P_{o,Max} = \dfrac{V_S^2}{2(\sqrt{\Delta X^2 + r^2} + r)} \\ \eta = \dfrac{\sqrt{\Delta X^2 + r^2}}{\sqrt{\Delta X^2 + r^2} + r} \end{cases} \qquad (6)$$

If the compensation network is fully tuned, or all reactive impedance is canceled ΔX = 0 , from (4), the maximum power is archived atr ac, Max Po (3) and the output load power with the corresponding efficiency are:

$$\begin{cases} P_{o,Max}\big|_{X=0} = Max(P_o) = \dfrac{V_S^2}{4r} \\ \eta_{P_o\,\max}\big|_{X=0} = 50\% \end{cases} \qquad (7)$$

It should be noted that Max(Po) = Vs^2 / 4r is the maximum power output which can be archived based on the fundamentals of power electronics of an RLC circuit.

If the compensation network is not fully tuned, it is clear that

$$|\Delta X| > 0 \text{ and } R_{ac,Max-Po} = \sqrt{\Delta X^2 + r^2} \qquad (8)$$

Which is greater than the total loss r (8). Therefore, the power efficiency at maximum power transfer condition of an off-resonant CPT system (9) can be higher than 50%

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$$\eta = \frac{1}{1 + r / R_{ac}} \quad (9)$$

However, the maximum power transfer Po-Max will be less than Max(Po). Therefore, when the system is operating off-resonance, tracking for maximum power transfer can become important.

4.1 Maximum Power Point Tracking Algorithm

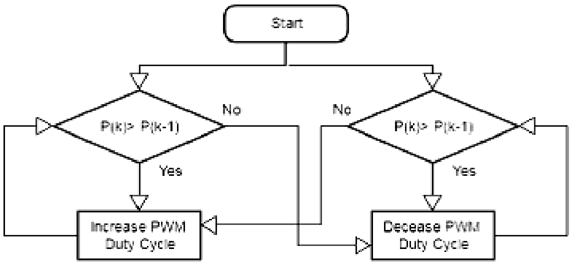

Figure 7: Perturb and Observe algorithm

Fig. 3 shows the maximum power point tracking (MPPT) algorithm. The algorithm is commonly known as perturb and observe in PV systems. The tracking process starts with increasing the converter PWM duty cycle by a predetermined step. If the output power increases then the controller will increase the duty cycle, otherwise the duty cycle is decreased with the same step. The process continues until the output power is around the maximum point. It needs to mention that at the steady state, the system will slightly oscillate around the maximum power point. And this fluctuation effect can be reduced by reducing the duty cycle step.

4.1 Capacitive Wireless Power Transfer System

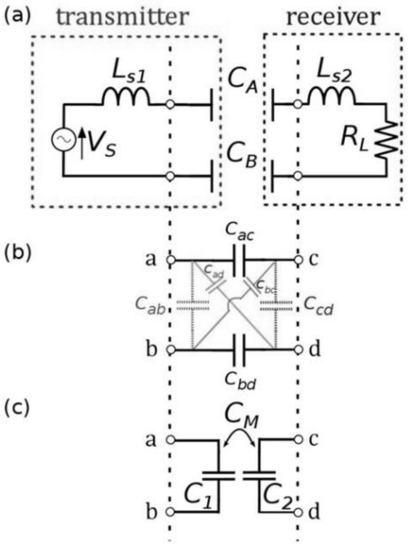

Figure 8: Overview of a capacitive wireless power transfer system with capacitances CA and CB

A basic wireless capacitive link consists of two capacitances CA and CB (Figure 4.1a). One plate of each capacitor is part of the transmitter, the other one belongs to the receiver part. Cross-capacitances are present between the plates as indicated in Figure 4.1b and are named through their subscripts, e.g., Cab is the capacitance between the two transmitter plates.

In order to obtain an efficient power transfer at the working angular frequency ω 0, the default strategy is to realize a resonant circuit, as well at the transmitter as at the receiver side. Generally, this is done by adding a resonant coil in series or in parallel. More complicated compensation circuits include a PWM converter, a power amplifier, LC or LCLC based topologies.

Figure shows the circuit where an inductor is added in series at the transmitter and the receiver side to construct the resonant circuits. In practice, a real capacitive wireless power transfer system will include other network elements as e.g., a rectifier-stabilizer, supply regulator, power conditioner. For this work, we neglect those systems because we want to study the properties of the wireless power transfer link itself, without the influence of other network elements. For an excellent overview of the different compensation techniques that takes into account the remote electronics.

At variable coupling, either due to varying vertical distance or due to lateral alignment changes, the value of the compensation network or operating frequency would have to change for each position to obtain optimum power transfer at the transmitter and the receiver side. This not only requires an impedance matching system or frequency tuning mechanism at the transmitter and receiver side, but also data communication between both sides.

4.4 Capacitive Power Transfer (CPT) Topology

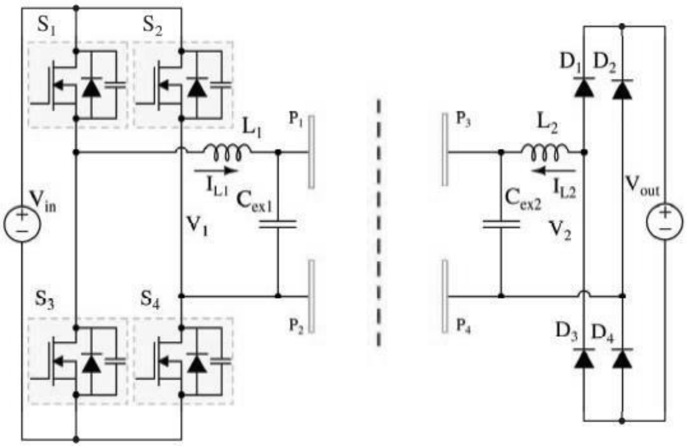

Figure 9: A CPT with LC compensation topology

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The CPT is another way to transfer power wirelessly from a source to a load. In the past, this method was dedicated to applications requiring low power and short distances. Recently with the effort of researchers, high power levels can be transferred across a large air gap distances and the CPT can be applied in the EV battery charging applications. Compared to the ICPT, the CPT is a cost-effective way; expensive coils used to transfer power in the ICPT can be replaced by cheaper metal plates. In the CPT, the power is transferred using the EF; this last has some advantages that are desired in EV applications such as a large misalignment tolerance and insensitivity to conductive objects. The fig. 10 shows a CPT where P1 and P2 are the transmitting plates while P3 and P4 are the receiving ones.

In the case of EV applications P1 and P2 are embedded in the ground while P3 and P4 are installed in the bottom chassis of the EV. One can see in the fig. 11 that in such a system several parasitic capacitances can occur, therefore they must be taken into consideration in order to well design the system for achieving high efficiencies.

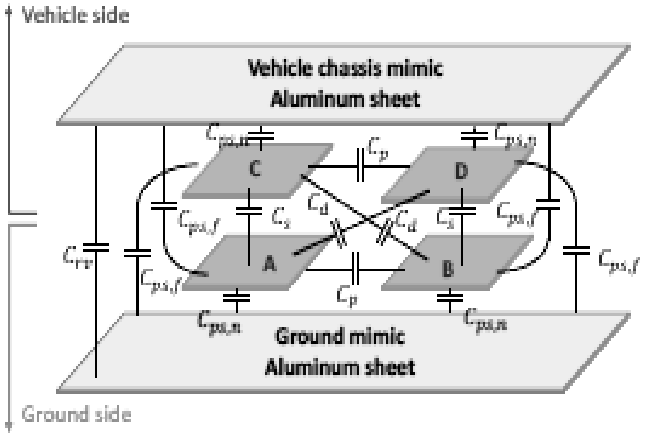

Figure 10: Parasitic capacitances in an EV charging application based CPT

Similar to the ICPT, CPT systems need compensation networks, the large distance between the plates result in a low coupling capacitance, therefore the reactive power must be compensated. In most cases an inductor is used to resonate with the coupling capacitance which create a high voltage in the plates to transfer power, however, this topology requires a high inductance value due to the low coupling capacitance, therefore the operating frequency is increased but it is limited by both the power losses in the inverter and the self-resonant frequency (SRF) of the inductor. The LC topology is addressed, it consist of adding an external capacitor with a very high value in parallel with the plates to increase the coupling capacitance so that the required compensating inductance value becomes low.

V. RESULTS AND DISCUSSION

5.1 DC-DC Buck Boost Converter Schematic in PSIM

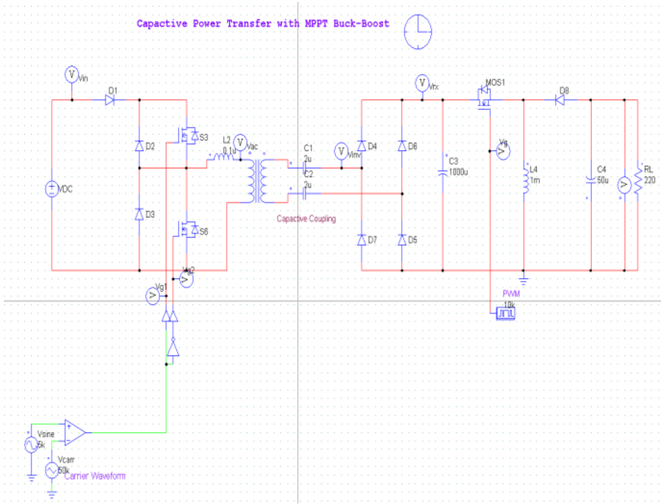

Figure 11: Series Resonant Voltage Source Inverter and DC-DC Buck Boost Converter Schematic in PSIM

The simulation for the series resonant half-bridge voltage source inverter and MPPT controlled DC-DC buck-boost converter has been done using capacitive coupling between transmitter and receiver side and the result waveforms are plotted. The transmitter DC voltage input, Inverter AC output and receiver AC input, Rectifier DC output and MPPT DC output were observed.

5.2 PSIM Simulation Outputs

5.2.1 Transmitter Side

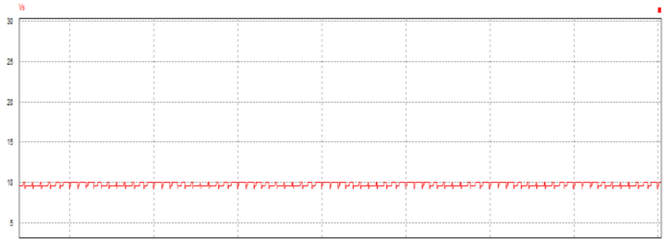

Figure 12: DC Source Voltage

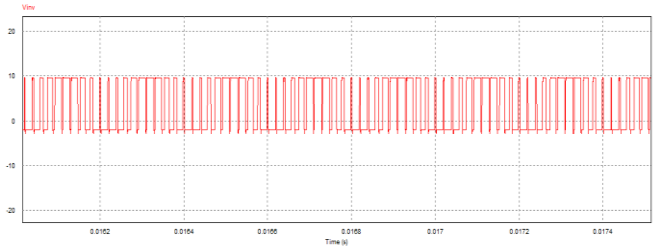

Figure 13: Inverter Output

5.2.2 Receiver Side

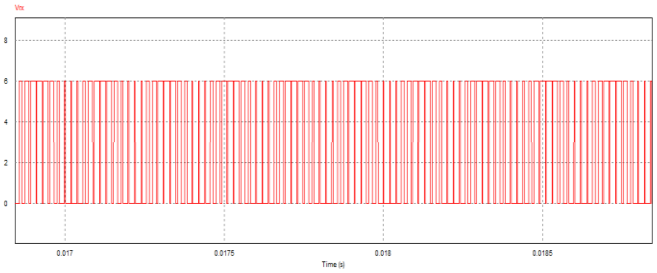

Figure 14: Receiver Voltage Output

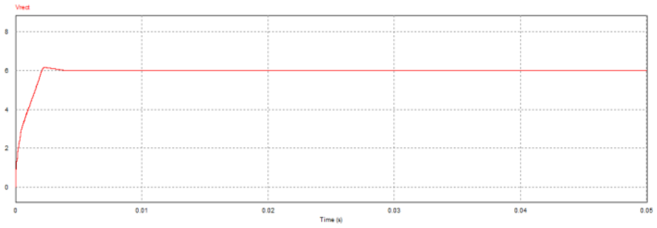

Figure 15: Bridge Rectifier Output

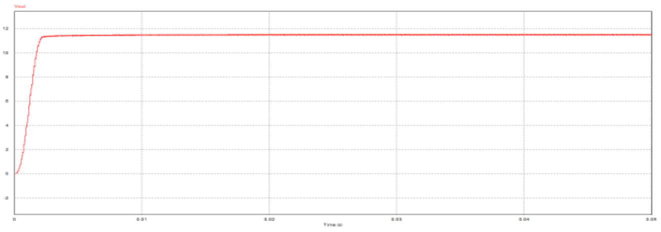

Figure 16: Buck-Boost Converter Output

VI. CONCLUSION

In this work the design for a series-tuned CPT system with a DC-DC converter which can track for the maximum power point when the load changes with high power efficiency is done. A buck-boost converter was designed with perturb and observe algorithm which can dynamically track for the maximum power output with high efficiency even when the circuit is not fully tuned. A simulation circuit was built with a half-bridge inverter at the primary side driving the capacitive coupling circuit and a buck-boost converter at the secondary side matching the load to the optimal value where the output power is maximum. The simulation for the same has been done using PowerSim (PSIM) software and the observed results are plotted in graph.

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