Field Containment in Dynamic Wireless Charging Systems Through Source-Reciever Interaction

Kibok Lee, *IEEE Student Member* , Zeljko Pantic, *IEEE Student Member*, Srdjan Lukic, *IEEE Member*

Department of Electrical and Computer Engineering
North Carolina State University
Suite 100, Keystone Science Center
1791 Varsity Drive
Raleigh, NC 27606
Email: {klee10}{zpantic}{smlukic}@ncsu.edu

Abstract— **This paper presents a new topology appropriate for dynamic wireless charging of electric vehicles. We propose a source coil made from multiple lumped coils powered by a single inverter, with the receiver coil mounted on the vehicle. The proposed system uses the reflected reactance from the receiver to automatically limit the field strength in uncoupled portions of the source-receiver system, thus allowing the system to more easily meet the electromagnetic field emission standards without complex shielding circuits, switches, electronics and communication systems. The power transfer is at its peak when the source-receiver coils pair is strongly coupled resulting in improved system-level efficiency. The analysis is supported by simulation and experiments.**

Keywords—Inductive Power Transfer (IPT), Resonant Coupling, Roadway-Powered Electric Vehicles

I. INTRODUCTION

Wireless power transfer (WPT) via magnetic coupling is seen as an effective way to transfer power over relatively large air gaps. Numerous applications of the technology have been considered, including charging batteries of portable electronics and electric vehicles. Stationary charging systems have been demonstrated to have a relatively high efficiency (above 90%), if the source and the receiver are well aligned (i.e. if the coupling coefficient is reasonably high) [1]. In the case of dynamic charging systems, the issue of alignment becomes more challenging. One approach is to have an elongated source coil coupled by a small receiver [2]. This system results in fairly constant coupling as the vehicle moves along the length of the elongated coil. The issue is that the resulting coupling coefficient is fairly low, due to the relatively large self-inductance of the elongated source coil. Another issue is that the field emitted in the uncoupled sections of the track needs to be contained to ensure that emission standards are met.

A potential solution is to use sectionalized (we will call them lumped) source coils that are commensurable with the receiver to maintain the high coupling coefficient [3]. This approach may solve both the efficiency and the emission challenges in dynamic charging applications. The proposed system is presented diagrammatically in Fig. 1. The source track is composed of multiple unloaded coils that cover the entirety of the area where the receiver is expected to be placed with each unloaded coil commeasurable with the receiver coil. Source track coils are compensated so that the coil resonance occurs at a frequency offset from the operating frequency of the system in uncoupled portion of the source-receiver. The result is a relatively weak field in the uncoupled sections. When the receiver is strongly coupled with the source track, the magnetic field of the source track is automatically increased to transfer the power required from the receiver, since the resonance of the source track is brought to the operating frequency through the reflected reactive load from the receiver. The remainder of this paper describes the concept in more detail. In Section II the proposed receiver design is discussed while the source design is presented in Section III. The system efficiency is discussed in section IV. Experimental results and conclusions are outlined in Sections V and VI respectively.
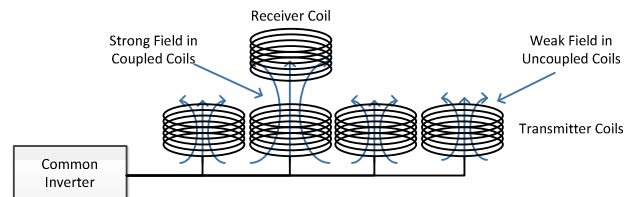

Fig. 1: Conceptual visualization of the proposed system.

II. RECIEVER DESIGN

In wireless power transfer systems, the parallel compensated receiver has been widely used since it boosts the voltage to the load and it is easy to decouple with source track by controlling the switch of the receiver driver. The load impedance reflected back onto the source track by the parallel compensated receiver can be described as [4]:

$$Z_r = \frac{V_r}{I_s} = \frac{\omega_0 M^2}{L_2}(Q - j) \qquad (1)$$

Typically, the reflected reactance results in higher power supply VA rating, and therefore, increased inverter current, without contributing the real power to the load. This is considered as the disadvantage of the parallel compensated receiver. In order to overcome this disadvantage, the *LCL* compensated receiver, which reflects purely a real load onto the source track and has unity input power factor, is suggested by [5]. Our goal in this paper is to design a system that has a substantial reactive power reflected onto the source, and to use this property as a way to tune the source circuit.
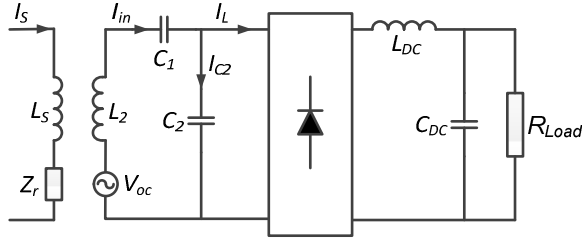

Fig. 2: The source track and series-parallel compensated *LCC* receiver.

Fig. 2 shows the proposed series-parallel compensated *LCC* receiver. The receiver consists of the series-parallel compensation, a rectifier circuit and a *DC* load represented by a resistor connected to the rectifier through an *LC* filter. The *DC* resistance R_{Load} can be replaced by the effective load R_{eq} seen by resonant tank before the rectifier. The value of R_{eq} is determined by:

$$R_{eq} = \frac{\pi^2}{8} R_{Load} \qquad (2)$$

The proposed series-parallel compensated *LCC* resonant tank consists of the coil inductance and two compensation capacitors C_1 and C_2. The values of two capacitors are chosen for the resonance of receiver to occur at the operating frequency of system as described in (3)-(5):

$$C_1 = \frac{n}{n-1} \cdot C \qquad (3)$$

$$C_2 = n \cdot C \qquad (4)$$

$$C_1 \parallel C_2 = C \qquad (5)$$

The resonant frequency of the receiver is derived as:

$$\omega_0 = \frac{1}{\sqrt{L_2 C}} \qquad (6)$$

Here, the value of an auxiliary variable C is determined from (6), and ω_0 is the resonant frequency of the circuit. The ratio of C_1 to C_2 is $n - 1$. We name the parameter n the *tapping coefficient*, realizing that this coefficient represents the fictitious tapping of the parallel compensation capacitor. The quality factor of the system can be calculated by finding the

current and voltage boost factor (Q_I and Q_V). The current boost factor of receiver (Q_I) can be defined as [6, 7]:

$$Q_I = \frac{I_L}{I_{sc}} = \frac{L_2}{L_2 - \frac{1}{\omega_0^2 C_1}} = \frac{C_2}{C_1} + 1 = n \qquad (7)$$

where I_{sc} of the receiver coil short circuit current and I_L is the input current of rectifier. The voltage boost factor of receiver (Q_V) can be defined as:

$$Q_V = \frac{V_{ac}}{V_{oc}} = \frac{R_{eq}}{\omega_0 L_2} \cdot n = Q \cdot n \qquad (8)$$

where V_{ac} is the input voltage of the rectifier, and $Q = R_{eq}/(\omega_0 L_2)$ is the quality factor of the parallel compensated receiver. The quality factor (Q_{total}) of the *LCC* receiver is obtained by multiplying Q_I and Q_V:

$$Q_{total} = Q_I \cdot Q_V = \frac{R_{eq}}{\omega_0 L_2} \cdot n^2 = Q \cdot n^2 \qquad (9)$$

From (9), we determine that the quality factor of the series-parallel compensated *LCC* receiver depends on the tapping coefficient n, and it is different from that of a traditional parallel compensated receiver, where the quality factor is defined as Q.

To find the reactance reflected by the proposed receiver into the source track, we calculate the impedance ($Z_{receiver}$) of the *LCC* receiver seen by the open circuit voltage is calculated as:

$$Z_{reciever} = j\omega_0 L_2 + \frac{1}{j\omega_0 C_1} + (R_{eq} \parallel \frac{1}{j\omega_0 C_2}) = \frac{\omega_0 L_2}{n} \frac{Q_V + j}{1 + Q_V^2} \qquad (10)$$

The load impedance reflected back onto the source track by the *LCC* receiver can be defined by:

$$Z_r = \frac{(\omega_0 M)^2}{Z_{receiver}} = \frac{\omega_0 M^2}{L_2}(Q_{total} - n \cdot j) \qquad (11)$$

It is noticed that if n is chosen to be greater than one, the amount of reflected reactive load from the *LCC* receiver can be larger than that of the parallel compensated receiver obtained in (1). It means that the *LCC* receiver can shift the resonant frequency of the source track more than the parallel compensated receiver.

III. SOURCE DESIGN

The proposed source coil design consists of a band-pass filter formed by L_F and C_F, a parallel compensation capacitor C_{comp}, and a source coil connected in parallel (see Fig. 3). The impedance of a single source coil is formed by the coil inductance L_s and the compensation capacitor C_s.
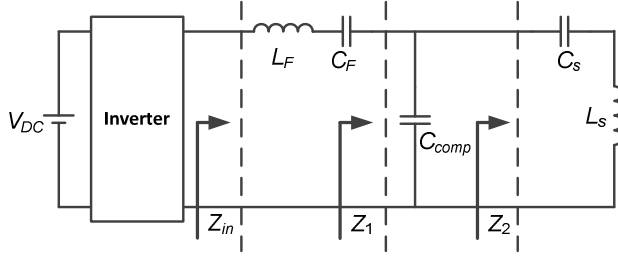
Fig. 3: The new proposed source track.

The reactive load reflected onto the source coil was found in the receiver design procedure, and summarized in (11). The compensation capacitor C_s is, therefore, designed for resonance at a pre-determined coupling coefficient M_0:

$$j\omega_0 L_s + \frac{1}{j\omega_0 C_s} = \frac{\omega_0 M_0^2}{L_2} n \cdot j = j\Delta X \qquad (12)$$

Here M_0 is a constant mutual inductance and is determined before designing the source coil. ΔX is the amount of reactive load which will be reflected from the LCC receiver in the pre-defined coupled condition. Note that the reflected reactance from (11) is the function of the mutual coupling M between the source and the receiving coil. Therefore, the target value of reflected impedance ΔX is only achieved for a pre-defined coupling, which we define as "perfectly coupled" condition. Based on (11) and (12), when the source coil is perfectly coupled with the LCC receiver, the series compensated source coil becomes purely resistive:

$$Z_2 = j\omega_0 L_s + \frac{1}{j\omega_0 C_s} + Z_r = \frac{\omega_0 M_0^2}{L_2} Q_{total} = R_r \qquad (13)$$

Here R_r is the resistive load reflected from the receiver, and it is equal to the real part of (11). This is because all reactive components are cancelled out by the reflected reactive load at the operating frequency.

The reflected load from both the LCC receiver and parallel compensated LC receiver is summarized in Table I. When using a parallel compensated LC receiver, the current in the uncoupled segment of the source coil is determined by the uncompensated reactive component and the voltage applied to the segment. In contrast, the current in the perfectly coupled source coil segment is determined by the real load reflected from the receiver. The current gain of the source track in case of using the parallel LC receiver is calculated as:

$$Gain[dB] = 20\log_{10} \frac{|V_s / \text{Re}(Z_r)|}{|V_s / \text{Im}(Z_r)|} = 20\log_{10} \frac{1}{Q} \qquad (14)$$

Parasitic resistances of the source coil and compensation capacitor are neglected to simplify the analysis. V_s is the *rms* value of the voltage applied to the coil. As shown in (14), the current gain is always a negative value since a quality factor in wireless power transfer systems is chosen to be greater than

one. In contrast, the current gain of the LCC receiver can be a positive value if the tapping coefficient n is chosen to be larger than the quality factor. The current gain of the source track in case of using the LCC receiver is described as:
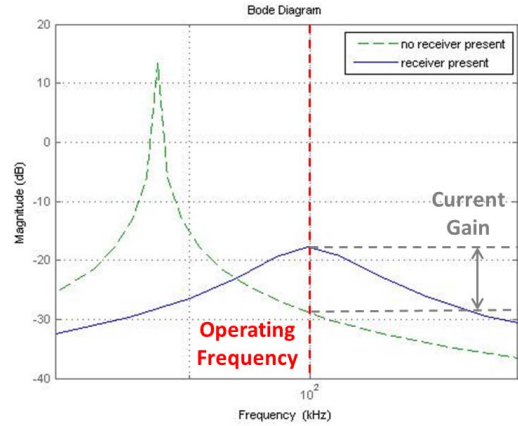
$$Gain[dB] = 20\log_{10} \frac{n}{Q_{total}} = 20\log_{10} \frac{1}{Q_V} \qquad (15)$$

TABLE I
THE LOAD REFLECTED TO THE SOURCE

	Real load	Reactive load
LC Receiver	$\dfrac{\omega_0 M^2}{L_2} Q$	$-\dfrac{\omega_0 M^2}{L_2} j$
LCC Receiver	$\dfrac{\omega_0 M^2}{L_2} Q_{total}$	$-\dfrac{\omega_0 M^2}{L_2} n \cdot j$
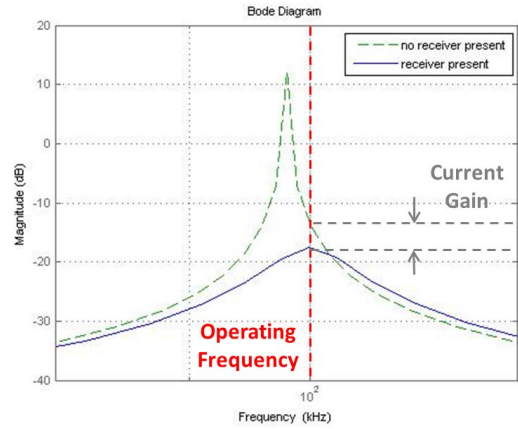
(a) Parallel compensated receiver.

(b) Series-parallel LCC compensated receiver.

Fig. 4: Current gain for the series compensated source coil.

As shown in Fig. 4(a), the current gain of parallel LC receiver is a negative value. In contrast, Fig. 4(b) shows that the current gain in case of using the LCC receiver is a positive value. As a result, the electromagnetic field emission can be limited since the current flowing in the source track is reduced in the

uncoupled condition. However, the tapping coefficient n cannot be increased up to very high value because the efficiency of the receiver decreases due to the increase of a circulating current by n. Therefore, all parameters of circuit should be chosen to maximize the current gain of source track while the system satisfies the expected overall efficiency.

The new source track is suggested to reduce the switching loss of inverter switches generated by the reactive current of the uncoupled source tracks when multi source tracks are connected to the inverter in parallel. The configuration of the proposed source track is shown in Fig. 3. The basic principle is to make the input impedance (Z_{in}) to be very high in the uncoupled condition with the receiver. A LC series filter and parallel capacitor are added to the series compensated source track. This resulting impedance is:

$$Z_{in} = j\omega_0 L_F + \frac{1}{j\omega_0 C_F} + \frac{1}{\frac{1}{j\Delta X} + j\omega_0 C_{comp}} \qquad (16)$$

The value of C_{comp} is chosen to make the denominator of the last term to be zero at the operating frequency. Therefore, the value of C_{comp} at the operating frequency equates to:

$$C_{comp} = \frac{1}{\omega_0 \Delta X} \qquad (17)$$

Here ΔX is the impedance of source coil as defined in (12). Then, the impedance seen by the inverter becomes very high. An additional bandpass LC filter (formed by L_F and C_F) is added to eliminate the high order harmonics. Therefore, the inverter current will be almost zero. When the source track is coupled with the receiver, the impedance (Z_2) will be changed as a pure real load by the reflected load from the receiver. At this condition, the inpedance (Z_1) is defined as:

$$Z_1 = \frac{R_r}{1 + (\omega_0 C_{comp} R_r)^2} - \frac{\omega_0 C_{comp} R_r}{1 + (\omega_0 C_{comp} R_r)^2} j \simeq R_r - j\omega_0 C_{comp} R_r^2 \qquad (18)$$

Here, R_r is the reflected real load from the receiver. In (18), the impedance has a little capacitance component. This can be removed as making the LC series filter to have a little indutance component at the operating frequency. As a result, the coil current as well as the inverter current can be automatically controlled by using the proposed source track because the impedance (Z_1, Z_2) is changed as the coupling condition.

IV. SYSTEM EFFICIENCY CONSIDERATION

An important aspect of the system design is to consider overall system efficiency. To determine system design parameters, we analyze a single coil segment in the coupled and uncoupled condition.
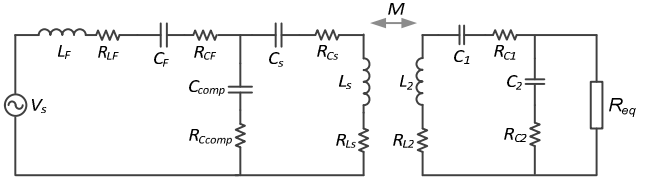

Fig. 5: Equivalent circuit of the system with compensation circuit losses included.

Looking at the uncoupled condition first, the "idle" loss will be the result of the circulating currents in the source compensation circuit, and it is defined as:

$$P_{loss} = (R_{LF} + R_{CF}) I_s^2 + R_{Ccomp} I_{Ccomp}^2 + (R_{Cs} + R_{Ls}) I_t^2 \qquad (19)$$

with the parasitic resistances presented in the Fig. 5. I_s is the input source current, I_t is the source coil current, I_{Ccomp} is the current of parallel capacitor. The source current I_s will be relatively small for the uncoupled condition, allowing the losses of LC filter to be neglected. We note that the losses are minimized by increasing the reactive component ΔX, which is proportional to the parameter n, as shown in (12).

Similarly for the perfectly coupled condition, efficiency can be calculated by evaluating the losses in the parasitic resistances of the source and the receiving coils. Calculating the source efficiency first:

$$\eta_{source} = \frac{\omega_0 M_0^2}{L_2} Q_{total} I_t^2 \bigg/ \left[\begin{array}{c} (R_{LF} + R_{CF}) I_s^2 + R_{Ccomp} I_{Ccomp}^2 \\ + \frac{\omega_0 M_0^2}{L_2} Q_{total} I_t^2 + (R_{Ls} + R_{Cs}) I_t^2 \end{array} \right] \qquad (20)$$

The receiver efficiency is:

$$\eta_{receiver} = \frac{n^2 R_{eq}}{n^2 R_{eq} + Q_{total}^2 R_{C2} + (n^2 + Q_{total}^2)(R_{L2} + R_{C1})} \qquad (21)$$

The overall system efficiency is obtained by multiplying (20) and (21):

$$\eta_{total} = \eta_{source} \cdot \eta_{receiver} \qquad (22)$$

Fig. 6(a) shows the efficiency of the proposed system using the parameters given in Table II as a function of the load resistance (which controls the voltage gain). We conclude that a larger voltage gain would be beneficial. On the other hand, as shown in Fig. 6(b) it is apprarent that with the increase in Q_{total} the current gain reduces, making the difference in current between the coupled and uncoupled sections ever smaller for higher quality factors. Therefore, a tradeoff between efficiency and current gain is needed.
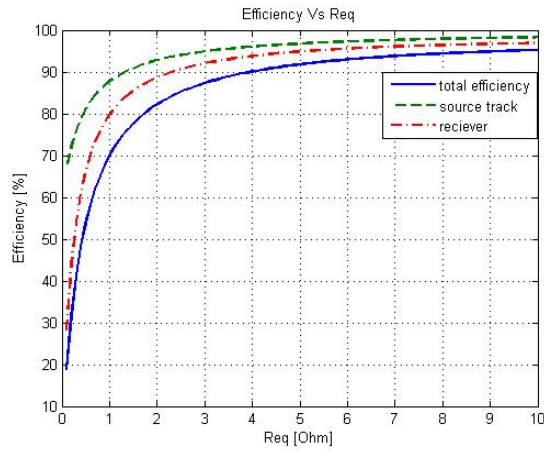
(a) Efficiency vs R_{eq}.
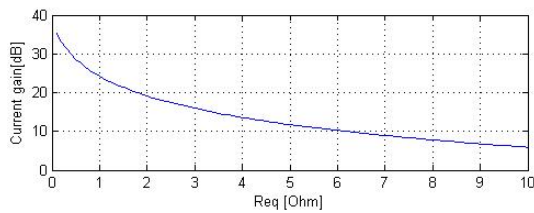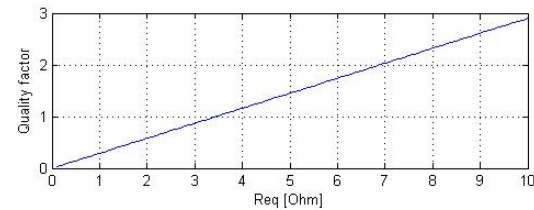
(b) Q_{total} & current gain vs R_{eq}.

Fig. 6: Efficiency, Q_{total} and current gain in relation to the effective load.

TABLE II
THE SYSTEM PARAMETERS

	Parameter	Value
Source track	L_S	191 uH
	C_S	19.32 nF
	C_{comp}	42.29 nF
	L_F	30.80 uH
	C_F	85.95 nF
Receiver	L_2	191 uH
	C_1	15.97 nF
	C_2	78.25 nF
	n	5.9
	R_{Load}	4.2 Ω

Fig. 8 shows the current of the series-compensated source track at the load resistor (4.2 Ω). The current in the coupled condition is 9.25 A, and the current in the uncoupled condition is 2.82 A. The current gain of the source track coil is 10.32 dB at the coupling factor (k=0.224). The quality factor of the receiver is 1.50. The overall efficiency of system is 82.03 %. When the load is changed to 6.24 Ω, the current in the coupled condition is 6.62 A, and the current in the uncoupled condition is 2.72 A. The current gain of the source track coil is 7.73 dB at the same coupling factor. The quality factor is 2.23. The efficiency of system is 84.77 %. This means that the efficiency can be improved as increasing the quality factor, even though the current gain is decreased.

Fig. 9 shows the input current of inverter and source track coil in case of using the new proposed source track. In the uncoupled condition, the inverter current is reduced up to 511 mA. The current gain of source track coil is 10.46 dB. The efficiency of system is 80.45 %. It is decreased a little compared to the series compensated source track because of additional capacitors and inductor even though the switching loss of the uncoupled source track is reduced.

V. EXPERIMENTAL RESULTS

The experiment was implemented so as to validate the effect of proposed system. As shown in Fig. 7, the practical prototype consists of the source power supply, the source track, the *LCC* receiver and the load. The parameters are selected as listed in Table II. The operating frequency of the source power supply is 100 kHz. The experiment was implemented at the output power of 300 W. To validate the effect of using the series-parallel *LCC* receiver, the coil current of source track was measured under both the uncoupled and coupled condition with the receiver.
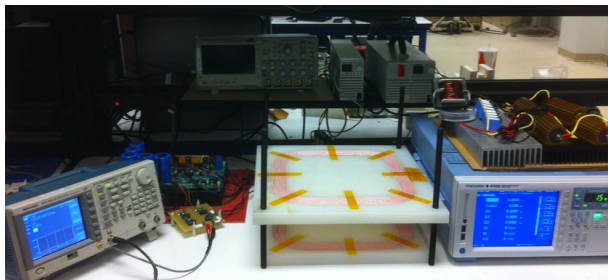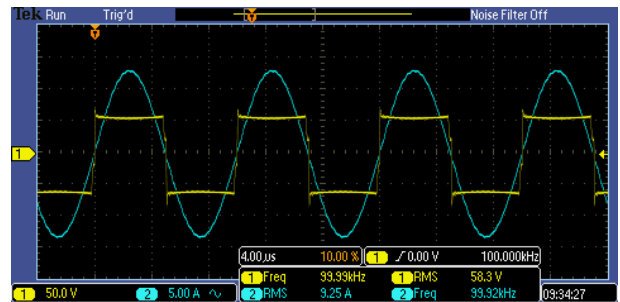

Fig. 7: The system configuration.

(a) Coupled condition with the receiver
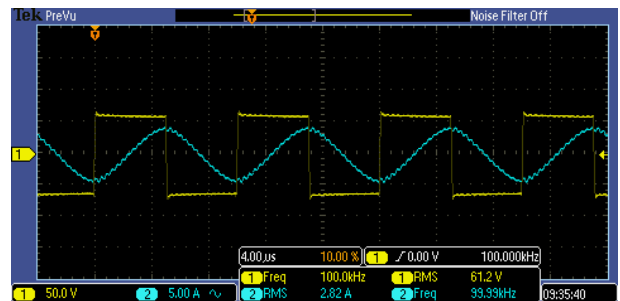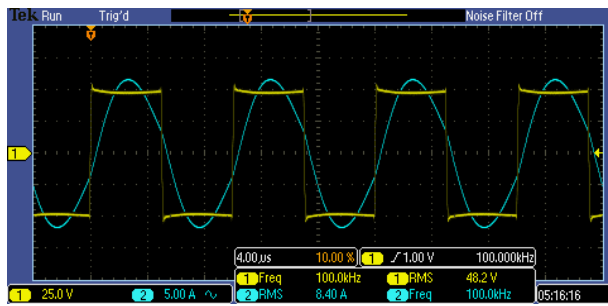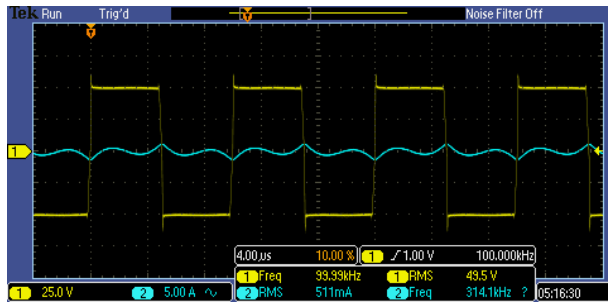

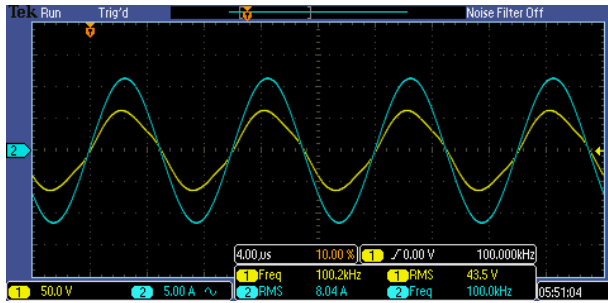(b) Uncoupled condition with the receiver

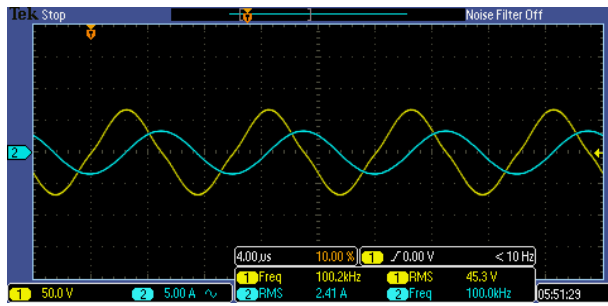Fig. 8: The current and voltage of the series compensated source track

(a) Coupled condition (inverter)

(b) Uncoupled condition (inverter)

(c) Coupled condition (source track coil)

(d) Uncoupled condition (source track coil)

Fig. 9: The current and voltage of the new proposed source track

VI. CONCLUSIONS

A new WPT system has been designed by using a series compensated source track and a series-parallel compensated *LCC* receiver. The advantage of using the *LCC* receiver has been described and compared to parallel compensated receiver in terms of reflected load to the source track. In addition, the new source track is developed to reduce the switching loss of the inverter switches generated by the reactive current of the uncoupled source tracks when multi source tracks are connected to the inverter. The experimental results have

verified that this proposed system can control automatically the current of the source tack coil and inverter by the strength of coupling with receiver.

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