# High Power Density Stacked-Coils Based power Receiver for MHz Wireless Power Transfer

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***Abstract*—Wireless power transfer (WPT) is desirable for the charging of consumer electronic devices, such as cell-phones. However, the charging power is still low compared to the conventional plug-in charging, which makes the WPT solution less competitive. This paper proposes a high power density stacked-coil based power receiver for MHz WPT applications. The proposed high power density stacked receiving coil can harvest more power with certain magnetic field for the WPT systems. Detailed circuit model of the proposed stacked-coil based power receiver for WPT system is presented and associated compensation methodology is proposed which is independent of the variation of coil coupling and final loads. Both calculation and simulation are used to validate the proposed design and desired performances. Comparison experiments are also designed and implemented to verify the derivation and the analysis of the stacked-coil based power receiver. Experimental results show that stacked-coil based power receiver can harvest more energy and show improved efficiency compared to the conventional single-coil based power receivers.**

***Index Terms*—Wireless power transfer (WPT), high power density, stacked-coil based power receiver, compensation method.**

## I. INTRODUCTION

Wireless power transfer (WPT) has been considered as a promising candidate for the charging of daily-used electronic devices, including cell-phones, electronic watches, etc [1], [2]. WPT is desirable for its elimination of direct electrical contact, i.e., safer charing solution, water-proof and dust-proof capability, sterile environment application, etc. However, compared to the conventional plug-in charging, WPT still suffers some disadvantages, such as lower efficiency, severer EMI issues and heating problems. All these issues restrict the output power of WPT and it takes longer time for user to fully charging their devices. Since there are regulations for the maximum applicable magnetic field in the environment, such as ICNIRP, the output power can not keep increasing by simply increasing the magnetic field transferring the power. Also, the power receiver mounted at the user terminals can be heated up due to the low efficiency and limited space for heat dissipation. All these issues make the design of power receiver more challenging. The power receiver usually composes of two parts, the receiving coil and rectifier. The receiving coil harvests the power through the time-varying magnetic field and the rectifier converts the AC power to DC power for the charging of final loads. Soft-switching-based rectifiers, such as Class E/EF rectifiers [3]–[5], or synchronous rectification techniques [6]–[8], has been developed and applied to improve the efficiency and reduce the heat dissipation. Meanwhile, the receiving coil can also be well designed to harvest more power with limited magnetic field and further improve the efficiency of the power receivers. For the design of receiving coils, higher inductance is usually preferred to harvest more power with limited magnetic field and higher Q factor is also desirable for less power loss. However, usually there is a trade off between high inductance and high Q factor for a given sized coil because of the proximity effects.

This paper proposes a high power density stacked-coils based power receiver and its compensation method for MHz WPT systems. By using the proposed receiver and its compensation method, the high power density can be achieved in the receiving side of WPT system, which helps to increase the charging power of the final load (e.g., batter) in WPT applications. In the proposed design, multi-layer coils are used to improve the equivalent inductance and Q factor of the receiving coil. Then, a corresponding compensation method is proposed for the stacked-coil based power receiver to achieve the cross coupling compensation and fully resonance under the varying coupling and load. Detailed circuit model of the proposed stacked-coil based power receiver is given and corresponding derivations are presented to explain the working mechanism of the stacked-coil based power receiver. Calculation, simulation and physical experiments are finished to validate the proposed design methodology and desired performance of the stacked-coil based power receiver in MHz

WPT applications.

## II. Fundamental Analysis

### A. Stacked-Coil Based Power Receiver

Here the stacked-coil based power receiver means that using the multi-layer stacked-coil as the receiving coil in the power receiver of WPT system. Fig. 1 shows the configuration of the stacked receiving coils. It comprises multi-layer receiving coils with the same size and layout. These receiving coils are stacked with no misalignment and isolated by the epoxy resin from each other. If the coils are made by enameled wire or covered by the no metallic insulating coating, the epoxy resin layer can be removed. The coils can be various sizes, shapes and structures. Since multiple receiving coils are used simultaneously, the inductance of each receiving coil can be smaller so that higher Q factor can be achieved. The multiple receiving coil can perform as an high-inductance and high-Q factor receiving coil for the power receiver of the MHz WPT system. By using the stacked receiving coils, the power receiver can harvest higher power and achieve higher efficiency than the conventional single-layer coil based design.

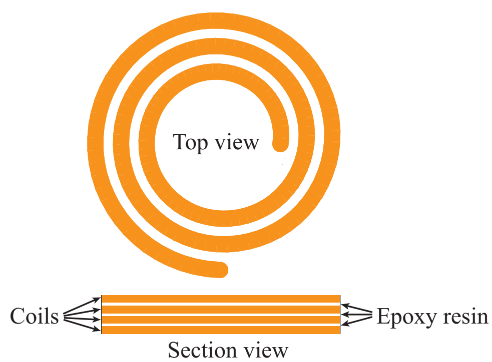



Fig. 1. Configuration of the high power density stacked receiving coils.

Fig. 2 shows the circuit model of the proposed high power density stacked-coils based receiver for WPT system. It comprises $n$ receiving coils ($L_{rx1}$—$L_{rxn}$), $n$ rectifiers, and one dc load $R_L$. Here Class $E$ half-wave rectifiers are applied in this circuit. In this design, the stacked receiving coils are used to pick up the power from the magnetic field simultaneously and charge the same dc load $R_L$ through $n$ rectifiers. $r_{rx1}$—$r_{rxn}$ are the ESR of the receiving coils ($L_{rx1}$—$L_{rxn}$). Since all the receiving coils are identical, the inductances and ESRs of the receiving coils are same and denoted as $L_{rx}$ and $r_{rx}$ in the following derivation. The $n$ compensation capacitors ($C_{rx1}$—$C_{rxn}$) are used to compensate the strong cross coupling and achieve the fully resonance for the $n$ receiving coils. Here $L_{tx}$, $r_{tx}$ and $C_{tx}$ are the inductance, ESR and compensation capacitor of the transmitting coil. Here, the transmitting coil is resonant with the capacitor $C_{tx}$ at the system operating frequency. The transmitting coil is driven by a sinusoidal current source, denoted by $i_{tx}$ in Fig. 2.

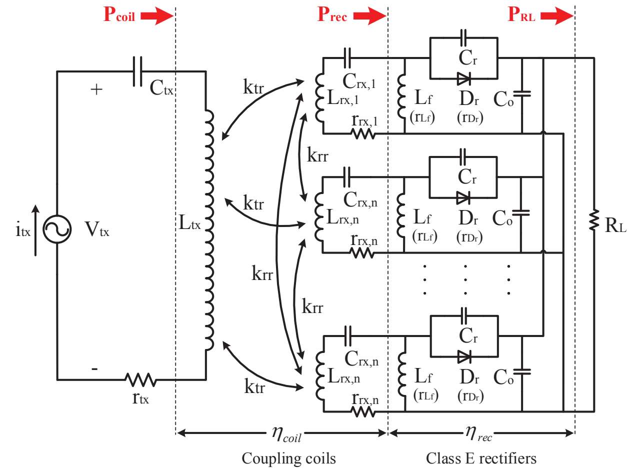



Fig. 2. Circuit model of the high power density stacked-coil based receiver for WPT.

In the proposed high power density receiver, the receiving coils are fixed to be very close to each other and then the coupling among them are strong and fixed. The coupling coefficient between each two receiving coils are assumed to be identical and denoted as $k_{rr}$ in Fig. 2. The transfer distance between transmitting coil and receiving coils are much higher than the gap between the receiving coils. Therefore, the coupling coefficients between transmitting coil and each receiving coil are basically identical and denoted as $k_{tr}$. Detailed derivations are given to present the optimal parameter design and show the improved system performance over the conventional design.

### B. Compensation Design

In following analysis, $M_{tr}$ is the mutual inductance between the transmitting coil and each receiving coil and $M_{rr}$ is the mutual inductance between each two receiving coils, as given in (4) and (5).

$$M_{tr} = k_{tr}\sqrt{L_{tx}L_{rx}}. \tag{4}$$

$$M_{rr} = k_{rr}L_{rx}. \tag{5}$$

Set the input impedance of transmitting coil $Z_{coil}$ (=$V_{tx}/i_{tx}$) to be pure resistive and receiving coils to be fully resonant, the expression of compensation capacitors of the receiving coils can be obtained, as shown in (6).

$$C_{rx} = \frac{1}{\omega^2(L_{rx} + (n-1)\,M_{rr})}. \tag{6}$$

Since the compensation capacitors for each receiving coil are the same, $C_{rx}$ is used here without distinction. It can be seen that the compensation capacitors are independent with the mutual inductances between transmitting coil and receiving coils ($M_{tr}$) and load of receiving coils ($R_{rec}$). It means the stacked-coils based receiver and the compensation method can help WPT systems to achieve the optimal efficiency and power transfer capability under the varying working conditions (varying coupling and load). Note the cross coupling between receiving coils ($M_{rr}$) are fixed in the stacked coils. The input power ($P_{coil}$) and output power ($P_{rec}$) of the stack-based coupling coils can be derived as follows.

$$P_{coil} = \frac{{I_{tx}}^2 r_{tx}}{2} + \frac{n{I_{rx}}^2 \left(R_{rec} + r_{rx}\right)}{2}. \tag{7}$$

$$P_{rec} = \frac{n{I_{rx}}^2 R_{rec}}{2}. \tag{8}$$

Where $I_{rx}$ and $I_{tx}$ are the amplitude of the receiving coil current $i_{rxi}$ and transmitting coil current $i_{tx}$. Then, the efficiency of the stack-based coil can be derived as follows.

$$\eta_{coil} = \frac{P_{rec}}{P_{coil}} = \frac{n{R_{tri}}^2 R_{rec}}{r_{tx} + n{R_{tri}}^2 \left(R_{rec} + r_{rx}\right)}. \tag{9}$$

Where $R_{tr}$ is the ratio of $I_{rx}$ and $I_{tx}$.

$$\begin{aligned} R_{tr} &= \frac{I_{rx}}{I_{tx}} \\ &= \frac{\omega M_{tr}}{\sqrt{(r_{rx}+R_{rec})^2 + \left(\omega L_{rx} - \frac{1}{\omega C_{rx}} + \omega(n-1)M_{rr}\right)^2}} \end{aligned}. \tag{10}$$

When the receiving coils are designed to be fully resonant [refer to (6)], (10) can be simplified as:

$$R_{tr} = \frac{\omega M_{tr}}{r_{rx} + R_{rec}}. \tag{11}$$

In this paper, each receiving coil is followed by a Class E half wave rectifier, as shown in Fig. 2. The relationship of input and output current of the Class E rectifier can be written as [3]

$$I_{R_L} = \sin\phi_{rec} I_{rx}, \tag{12}$$

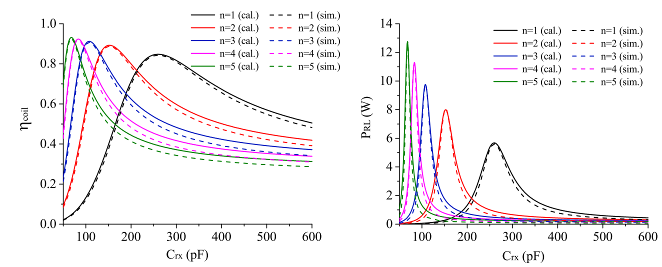
where $\phi$ is the phase of sinusoidal input current of the rectifier. Both $\phi$ and $R_{rec}$ can be determined by the shunt capacitor $C_r$ and the load $R_L$ of the rectifier [3]. Based on(10) and (12), the power received by the final dc load can be derived as

$$P_{R_L} = n^2 {R_{tr}}^2 \sin{\phi_{rec}}^2 {I_{tx}}^2 R_L. \tag{13}$$

## III. Performance Analysis

Based on derivations in section II, the performance analysis of stacked-coils based receiver is provided using both calculation and simulation. Here MATLAB is used to do the calculation and Advanced Design System (ADS) developed by Keysight is used for simulation verification. Both the calculation and simulation are based on the parameters of the final experimental system [refer to Table I].

Firstly, the coil efficiency ($\eta_{coil}$) with different number of receiving coils are calculated versus compensation capacitors $C_{rx}$ [refer to (9)]. The MATLAB calculated results are shown with solid line in Fig. 3 (a). It can be seen that the peak efficiency of $\eta_{coil}$ under the optimal $C_{rx}$ goes higher versus the number of receiving coils. When $n$ grows from 1 to 5, $\eta_{coil}$ is improved from 84.2% to 92.9%. This well demonstrates the improved coil efficiency with the increased number of receiving coils. The dash lines in Fig. 3 (a) shows the simulated $\eta_{coil}$ versus $C_{rx}$ and $n$ in ADS. It can be seen that the simulated results well match the calculated results.




(a) (b)

Fig. 3. System performance versus compensation capacitor $C_{rx}$ and number of receiving coil $n$. (a) Efficiencies. (b) Load power.

Similarly, the load power $P_{R_L}$ with different number of receiving coils are calculated and simulated versus compensation capacitors $C_{rx}$ [refer to (13)]. The calculated and simulated results are shown in Fig. 3 (b). It can be seen that, with the same transmitting coil current, the output power ($P_{R_L}$) increases as the number of receiving coils increases. This well demonstrates that the stacked-coil based power receiver can harvest more power with the same magnetic field. And it can be concluded that the stacked-coil based power receiver shows enhanced power transfer capability with the increased number of receiving coils. Also, the simulated results well match the calculated results, which further validates the derivations in section II-B.

## IV. Experimental Verification

An example 6.78-MHz WPT system is built up with the high power density stacked-coil based receiver [see Fig. 4]. Here the stacked receiving coil is fabricated with a four-layer PCB with three layer of receiving coils. The schematic of the whole experimental system is the same as that shown in Fig. 2. A current-mode (CM) Class E power amplifier (PA) is employed to output desired sinusoidal current driving the transmitting coil. The output of CM Class E PA can keep constant against the variation of the $Z_{coil}$, i.e., the load seen by the Class E PA [9]. Electronic load is employed to emulate the final dc load and measure the output power in the experiment.

For comparison purposes, another two conventional single coil based power receivers are also fabricated and tested in the experiment. Single-layer coil I has the same layout of the stacked coil. Therefore, the inductance and ESR, denoted by $L_{rx'}$ and $r_{rx'}$, are almost the same as that of the stacked coil. Single-layer coil II is fabricated with approximately three times inductance of the three-layer stacked coil, and its parameters are denoted by $L_{rx''}$ and $r_{rx''}$. As shown in Fig. 4, all the three receiving coils have the same dimension, i.e., 30 mm in diameter. All the parameters of the experimental system are listed in Table I. Here $k_{tr}$ equals 0.11 when power transfer distance $H$ is 16 mm.

The three power receivers are tested with the same transmitting coil current, which is fixed as 1.73 A amplitude. then the efficiencies and the output powers are measured under varying $H$. The experimental results are given in Fig. 5. $\eta_{sys}$, $\eta_{sys'}$,

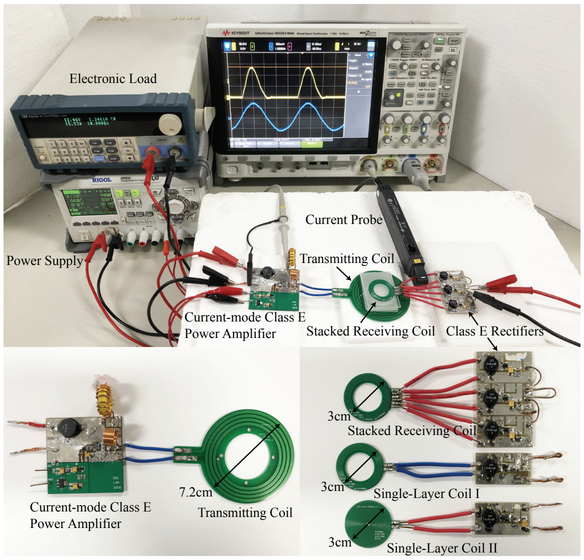
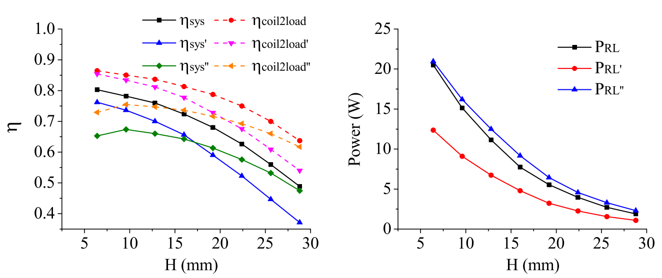



Fig. 4. Experimental setup of the proposed high power density stacked-coil based WPT system.

$\eta_{sys''}$ and $\eta_{coil2load}$, $\eta_{coil2load'}$, $\eta_{coil2load''}$ are the system efficiencies and efficiencies from transmitting coil to the loads of the WPT system with the stacked coil, single-layer coil I and II, respectively.

TABLE I
PARAMETERS OF EXPERIMENTAL SYSTEM

| $I_{tx}$ | $C_{tx}$ | $L_{tx}$ | $r_{tx}$ | $L_{rx}$ |
|---|---|---|---|---|
| 1.73 $A$ | 375 pF | 1.47 $\mu$H | 0.3 $\Omega$ | 2.12 $\mu$H |
| $L_{rx'}$ | $L_{rx''}$ | $r_{rx}$ | $r_{rx'}$ | $r_{rx''}$ |
| 2.13 $\mu$H | 6.28 $\mu$H | 1.5 $\Omega$ | 1.2 $\Omega$ | 3.2 $\Omega$ |
| $k_{rr}$ | $k_{tr}$ | $L_f$ | $C_r$ | $R_L$ |
| 0.85 | 0.11 | 10 $\mu$H | 100 pF | 10 $\Omega$ |




(a) (b)

Fig. 5. Efficiencies and load power versus transfer distances $H$. (a) Efficiencies. (b) Load power.

From Fig. 5 (a) it can be seen that, single-layer coil I can achieve relatively higher efficiency in shorter distances while Single-layer coil II can achieve relatively higher efficiency in longer distances, but the efficiencies of stacked receiving coil can dominate the single-layer coils in all the cases. WPT system with single-layer coil II shows the worst efficiencies performance at high power levels due to the low quality factor of the coil. And the efficiencies of WPT system with single-layer coil I drop quickly due to the low output power at longer distances. Fig. 5 (b) shows the output powers of the receivers versus the vertical distances $H$. It can be seen that, with the same transmitting coil current, namely, the same magnetic field, the stacked coil and single layer coil II can harvest more energy than the single-layer coil I due to the enhanced receiving coil inductance, which validates the analysis in section III.

## V. CONCLUSIONS

This paper proposes a high power density stacked-coil based power receiver for MHz WPT applications. The proposed high power density stacked receiving coil can harvest more power with certain magnetic field and improved efficiency for WPT. Detailed circuit model of the proposed stacked-coil based power receiver for WPT system is presented and associated analytical derivations are given to guide the design for the stacked-coil based power receiver. The proposed compensation methodology for the stacked receiving coil is independent of the variation of coil coupling and final load. MATLAB calculation and ADS simulation are both used to validate the improved performance and optimal parameter design of the stacked-coil based power receiver. Finally, comparison experiments are designed and implemented to validate above derivation and analysis. The experimental results indicates that the proposed stacked-coil based power receiver can harvest more energy with certain magnetic field and shows improved efficiency compared to the conventional single-coil based power receivers.

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