A Loosely Coupled Planar Wireless Power System for Multiple Receivers
Joaquin J. Casanova, Student Member, IEEE, Zhen Ning Low, Student Member, IEEE, and Jenshan Lin, Senior Member, IEEE

Abstract—Wireless power transfer is demonstrated mathematically and experimentally for \( M \) primary coils coupled to \( N \) secondary coils. Using multiple primary coils in parallel has advantages over a single primary coil. First, the reduced inductance of the transmitting coils makes the amplifier less sensitive to component variations. Second, with multiple receiving coils, the power delivery to an individual receiver is less sensitive to changes in the loads attached to other coils. By using a 16 cm by 18 cm primary and a 6 cm by 8 cm secondary coil, going from a 1:2 coupling to a 2:2 coupling, we show an increase in received power from 1.8 to 9.5 W, with only a small change in coupling efficiency. The advantages of the multiple primary coil topology increase the feasibility of charging multiple wireless portable devices simultaneously.

Index Terms—Inductive coupling, wireless power transfer.

I. INTRODUCTION

The large number of battery-operated consumer electronics and the associated tangle of wall-wart chargers have generated interest in designing a single convenient charging platform [1]. Wireless battery charging systems would permit charging many different devices equipped with receiving coils and cut the last wire of portable wireless devices. The approaches to wireless power transfer can be categorized as near field and far field. To date, the latter is still impractical for consumer applications due to the high-power and large-antenna requirement necessary to achieve levels of power comparable to a wall supply [2]. On the other hand, near-field inductive coupling has more promise as a wireless power technology [3]–[6].

Fig. 1 shows a block diagram for a generalized wireless power system. The dc–ac inverter provides the ac power to be transmitted to the receiver. In this study, the inverter is a fixed duty class E amplifier [7] operating at 240 kHz and a supply voltage of 12 V. The switching transistor is an IRLR3410, chosen because of its low output capacitance (typically below 100 pF), much lower than \( C_t \). Following the inverter is an impedance transformation network, the purpose of which is to maximize power transfer and efficiency by transforming the impedance looking into the transmitting coil. In this case, the system was configured with series compensation on the transmitter and parallel compensation on the receiver as described in [8], with an additional series inductor in order to get a \( Q \) within the operating bounds of the driving circuit. After the parallel compensation on the receiver is a rectifying diode (IR10MQ060NPbF) and capacitive filter before the dc load. The circuit diagram is shown in Fig. 2.

If multiple devices are to be charged simultaneously on the same system, the transmitting coil must be large enough to accommodate them. This poses a challenge, as to ensure uniform power delivery to devices, regardless of position, the electromagnetic field distribution must be even. In particular, the distribution of the \( z \)-component of the magnetic field in the plane of the receiving coils must be as uniform as possible. Transmitting coils may be designed to produce such fields; one approach is the optimal hybrid coil design [9], which is demonstrated for as large a coil as 15 cm by 15 cm. A different technique for designing optimal coils and a 20 cm by 20 cm coil is presented in [10]. A technique for widening the power delivery area in an inductively coupled vehicle charging system using three transmitting coils configured in a three-phase delta configuration is detailed in [11].

Regardless of technique, larger transmitting coils require more turns to achieve an even field distribution, raising the inductance. This is a problem because the amplifier operation is sensitive to component variation in the transformation network following the driving circuit. As the inductance of the primary coil increases, the series capacitor in the network needs to be smaller, and the class E becomes increasingly sensitive to small variations in the component values, sometimes severely hindering system performance. To circumvent this problem, the inductance could be lowered by using two or more primary coils in parallel. This reduces the inductance while still allowing a large charging area, because the coils are in parallel. In addition, having multiple transmitting coils in parallel reduces the influence of one load’s power consumption on that of any other load. The phenomenon of one load consuming low power blocking another with high power requirement has been noted and addressed in [12], where their solution was to implement a switch that shorted the receiving coil for lightly loaded receivers. Our multiple transmitting coil system also addresses this issue, but does not require additional components occupying space on the receiver, which, on a portable electronic device, is scarce. This paper derives and verifies the mathematical description of the coupling between \( M \) transmitters and \( N \) receivers and demonstrates the advantages of such a system experimentally.
II. ANALYSIS

The mathematical analysis of power transfer in the $M : N$ case can be performed by applying Kirchhoff voltage and current laws to the circuit shown in Fig. 3. The primary coils are numbered 1 through $M$, and the receiving coils are numbered $M + 1$ through $M + N$. The voltage–current matrix equation is

\[ Z I = V \]  

\[ \sum_{b=1}^{N} Z_{ab} I_b = V_a \]  

where $I_b$ is the current on the $b$th coil and $V_a$ is the voltage on the $a$th coil. $Z_{ab}$ is the $(a, b)$th element of the impedance matrix, defined as

\[ Z_{ab} = \begin{cases} j\omega L_a + R_a, & \text{for } a = b \\ j\omega M_{ab}, & \text{otherwise} \end{cases} \]  

where $\omega$ is the angular frequency, $L_a$ and $R_a$ are the self-inductance and parasitic resistance of the $a$th coil, respectively, and $M_{ab}$ is the mutual inductance between the $a$th and $b$th coils. Relating current and voltage in each of the coils, $V_b$ can be found. For the primary coils (in parallel), the voltage is the same for all, the input voltage ($V_b = V_{in}$). For coils $M + 1$ through $M + N$, $V_b = I_b Z_{Lb}$, where $Z_{Lb}$ is the impedance of the load and any transformation network attached to the $b$th coil. The final constraint is that the sum of the currents in the primary coils must be equal to the input current, $I_{in} = Z_{in} V_{in}$. Applying this to (2),

\[ (Z - Z_L) I = 0 \]  

where $Z$ is defined as before, $I$ is a vector of the currents, and $Z_L$ is defined as

\[ Z_L = \begin{cases} Z_{in}, & \text{for } 1 \leq a \leq M \text{ and } 1 \leq b \leq M \\ -Z_{Lb}, & \text{for } a = b \text{ and } b > M \\ 0, & \text{otherwise}. \end{cases} \]  

Equation (4) can be solved for $Z_{in}$ by splitting it into several submatrices as follows:

\[ Z = \begin{bmatrix} Z^{III} & (Z^{II})^T \\ Z^{II} & Z^{I} \end{bmatrix} \]  

\[ I = \begin{bmatrix} I^{II} \\ I^{I} \end{bmatrix} \]  

where $Z^{III}$ has dimensions $M \times M$, $Z^{II}$ has dimensions $N \times M$, $Z^{I}$ has dimensions $M \times N$, $I^{II}$ has dimensions $M \times 1$, and $I^{I}$ has dimensions $N \times 1$. Defining $Z^{IV} = Z^{III} + Z_{in} \delta_{MM}^1$ (where $\delta_{MM}^1$ is an $M \times M$ matrix of ones) and with some manipulations

\[ Z^{II} I^{I} = -Z^{II} I^{II} \]  

\[ (Z^{IV} - Z_{in} \delta_{MM}^1) I^{II} = -Z^{II} I^{II} - (Z^{IV})^T I^{I}. \]  

Input current $I_{in}$ is the sum of currents in the transmitting coils, stated mathematically as (where $I_{1M}$ is a 1 by $M$ vector of ones)

\[ I_{in} = 1_M I^{I}. \]  

By using (8)–(10),

\[ [Z^{IV} - (Z^{IV})^T (Z^{I})^{-1} Z^{II}] I^{II} = Z_{in} \delta_{MM}^1 I^{II}. \]  

Substituting $V_{in} = Z_{in} \delta_{MM}^1 I^{II}$ and using $Z_{in} = V_{in} / I_{in}$

\[ Z_{in} = \left\{ I_{1M} \left[ Z^{IV} - (Z^{IV})^T (Z^{I})^{-1} Z^{II} \right]^{-1} 1_M \right\}. \]  

Having a closed-form expression for the input impedance allows derivation of the currents in the individual coils. By subtracting $Z_{in} \delta_{MM}^1 I^{II}$ from both sides of (11),

\[ I^{II} = \text{null}(X) \]  

\[ X = Z^{IV} - (Z^{IV})^T (Z^{I})^{-1} Z^{II} - Z_{in} \delta_{MM}^1 \]  

\[ I^{I} = - (Z^{I})^{-1} (Z^{II}) I^{II}. \]
Now knowing the currents in the transmitter and receiver coils, the power received by load b may be computed simply as $|I_b|^2 \Re(Z_{Lb})$. These equations are extensible to different receiver topologies, such as parallel or series capacitors, and nonlinearities (such as rectifiers, or proximity and skin effects on resistance and inductance) may be considered as well, through the use of fixed-point iteration.

III. TESTS RESULTS

To verify the correctness of the preceding equations as well as to demonstrate the benefit of using multiple primary coils in parallel, simulations and tests were carried out for the 1:1, 1:2, 1:3, 2:2, and 2:3 cases. For all except the three-receiver cases, two receiver sizes were considered. In addition, the two-transmitter tests were performed with the transmitting coils adjacent and separated. Fig. 4 shows the 11 different configurations for the test setup.

The primary coil inductance is 34.44 $\mu$H, reduced by half when the two-coil case is considered, because the two coils of 34.44 $\mu$H are in parallel. Component selection procedure for the class E was described in [13], and component values are specified in Table I (for all cases, $L_{dc}$ was 500 $\mu$H and $L_{out}$ was 9.5 $\mu$H). Notably, the values for $C_{out}$ are higher with the two-transmitter system. Higher capacitance means that the impedance will be less sensitive to component variations because of the inverse relationship between capacitance and reactance. The derivative of reactance with respect to capacitance goes as the inverse square of capacitance, so higher capacitance values mean a much lower sensitivity. To mitigate proximity and skin effects, we used 100 AWG/40 strand Litz wire for coil windings. The small receivers were all 4 cm by 5 cm rectangular coils of 6 turns, the large receivers were 7 cm by 8 cm with 6 turns, and the transmitters were 16 cm by 18 cm with 13 turns, designed by the technique described in [10].

For each transmitter/receiver pairing, the resistive load attached to each receiver was swept from 60 to 4000 $\Omega$ by means of programmable electronic loads. The resistive load is an approximation of the charge status of a battery. A fully charged device appears as a large resistive load (thousands of ohms), and an uncharged device appears as a low resistive load (a handful of ohms). A dc received power ($P_{rx}$) flow was measured at the electronic loads.

A. Verification

To verify the accuracy of the equations developed in Section II, simulations were performed using a MATLAB code, implementing the analytical treatment of the class E amplifier by Raab [14] for a load with impedance defined as in (12). $L_a$ and $M_{ab}$ are calculated using a numerical integration of the Neumann formula [15], rather than measured for each case, due to the difficulty of measuring every entry in the inductance matrix for every orientation shown in Fig. 4. Selected inductances and parasitic resistances as measured are given in Table II and as modeled are given in Table III. The measured and predicted $P_{rx}$’s for each of the $M : N$ cases considered in this paper are shown in Fig. 5. The predicted versus observed plots

Fig. 3. $M : N$ block diagram.
show a one-to-one correspondence, aside from some spread due to uncertainty in secondary and primary coil positions. For 1:3, there is a particularly large amount of spread. With three receivers in close proximity to each other, uncertainties in their relative positions have a more pronounced effect on predicted power. In the inductance calculations, a vertical separation of 1 mm center-to-center between transmitting coil and receiving coil is assumed. When only one receiver is on one transmitter,
TABLE I

<table>
<thead>
<tr>
<th>$M$</th>
<th>Rx size</th>
<th>$C_{tx}$ (nF)</th>
<th>$C_{out}$ (nF)</th>
<th>$C_t$ (nF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Small</td>
<td>100</td>
<td>11.5</td>
<td>14.7</td>
</tr>
<tr>
<td>1</td>
<td>Large</td>
<td>53.8</td>
<td>15.3</td>
<td>6.8</td>
</tr>
<tr>
<td>2</td>
<td>Small</td>
<td>100</td>
<td>22.3</td>
<td>27.3</td>
</tr>
<tr>
<td>2</td>
<td>Large</td>
<td>53.8</td>
<td>22.3</td>
<td>18.3</td>
</tr>
</tbody>
</table>

TABLE II

<table>
<thead>
<tr>
<th>Rx size</th>
<th>$L_{tx}$ (µH)</th>
<th>$L_{rx}$ (µH)</th>
<th>$M$ (µH)</th>
<th>$R_{tx}$ (Ω)</th>
<th>$R_{rx}$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>3.38</td>
<td>34.44</td>
<td>1.54</td>
<td>0.086</td>
<td>0.356</td>
</tr>
<tr>
<td>Large</td>
<td>6.59</td>
<td>34.44</td>
<td>4.22</td>
<td>0.114</td>
<td>0.356</td>
</tr>
</tbody>
</table>

TABLE III

<table>
<thead>
<tr>
<th>Rx size</th>
<th>$L_{tx}$ (µH)</th>
<th>$L_{rx}$ (µH)</th>
<th>$M$ (µH)</th>
<th>$R_{tx}$ (Ω)</th>
<th>$R_{rx}$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>4.08</td>
<td>31.84</td>
<td>1.65</td>
<td>0.048</td>
<td>0.286</td>
</tr>
<tr>
<td>Large</td>
<td>6.82</td>
<td>31.84</td>
<td>4.32</td>
<td>0.079</td>
<td>0.286</td>
</tr>
</tbody>
</table>

they are assumed to be centered; when two small receivers are on one transmitter, the receivers are 10 cm center-to-center; and when three small receivers or two large receivers are on one transmitter, the receivers are assumed immediately adjacent. Of course, in reality, the geometry and positions have small variations from the assumed values. This results in deviation of the inductance matrix from the true value and, thus, the spread in the observed/estimated plots. The apparent offset in the plots is largely due to deviation in the calculated parasitics from the true values; the predicted parasitics are lower than those measured. As a result, the predicted values of the received power are generally slightly higher than those observed.

B. Receiver Decoupling

To show that having multiple primary coils reduces the influence of one receiver on the others, we map the loading condition ($R_{l1}, R_{l2}, \ldots, R_{lN}$) to a corresponding received power delivery condition ($P_{rx1}, P_{rx2}, \ldots, P_{rxN}$) using the data from the electronic load sweeps. Although it is impossible to fully explore the power delivery space due to the discrete nature of the tests, looking at this discrete set of loading conditions allows us to outline the physically realizable power values that can be received by multiple loads on the same primary coil or coils.

Figs. 6 and 7 show this for the two-receiver condition. In Fig. 6, 1:2 and 2:2 show similar power spaces because the receivers are small and further apart, so they are weakly coupled. Fig. 7 demonstrates that when the receiver size is large, for 1:2, the power space is squeezed into a much narrower area, while for 2:2, the power space is close to a square 10 W on each side. The constricted power space for 1:2 occurs because when one receiver is lightly loaded (e.g., a fully charged device), it...
“chokes” power delivery to the other high power load (e.g., an uncharged device). This phenomenon can be seen in the blue dots (1:2) in Fig. 7: When receiver 1 has high load resistance and receives low power (less than 0.2 W), receiver 2 is limited to less than 0.2 W. This amounts to the pinched shape of the power space. Such power delivery limitations are unacceptable. The same plot demonstrates that, for 2:2, the power delivered to receiver 2 can still reach about 10 W when receiver 1 has low-power high-resistance conditions. Although a simplification, it can be said that with multiple transmitters, the receivers are essentially in parallel, while with one transmitter, they are essentially in series. With a constant voltage source, power delivery to resistive loads in series is governed by the total resistance, whereas loads in parallel receive independent power delivery. Multiple primary coils parallelize power delivery; however, it does not completely decouple the receivers.

In the same plots, the effect of split transmitter is also demonstrated. The key difference for the split transmitter is a reduction in received power, shown as a shifting of the power
space toward the origin. This is because the fringing fields of
the primary coils dissipate into the nearby environment instead
of into a neighboring coil.

Fig. 8 shows the power space with small receivers for 1:3
and for 2:3 (large receivers could not be considered for 1:3
because of insufficient room on the transmitter). Although
the difference is less pronounced than that of the $N = 2$ condition,
it is apparent that the 1:3 power space is more curved,
with an upward sweep, while the 2:3 power space is a distinct
rectangular prism. When one receiver is in a high-resistance
low-power condition, the power received by the other receivers
is less in 1:3 than in 2:3. Fig. 8 similarly demonstrates the
decoupling effect, only with a split transmitter. The effect is
the same as discussed in the preceding paragraph, and for similar
reasons.

C. Impact on Efficiency and Total Received Power

Transmitted power was measured using a current probe
(Agilent N2783A), a voltage probe (Agilent N2863A), and an
oscilloscope (Agilent DSO 5034A), with measurement ac-
curacies of 1% and 0.5%, respectively. This corresponds to an
accuracy of power measurement of 1.5%. Due to temperature
effects and the effect of transmission delay on the phase of
measurement, the actual accuracy is estimated to be around 5%.

Received power was measured using the dc electronic loads
(BK 8500), which have (worst case) accuracies of 0.4% for
current and 0.38% for voltage, giving a measurement accuracy
for power of about 0.8%.

Fig. 9 shows the total received power $P_{rx}$ and coupling
efficiency ($\eta_c$, defined as the total received power over
the transmitted power) for the two-small-receiver tests. It is clear
from the plot that the impact on efficiency is minimal; the
maximum $\eta_c$ for 1:2 and 2:2 is 0.75 and drops to 0.68 with
split transmitters. With large receivers (Fig. 10), the effect of
changing from 1:2 to 2:2 is seen as an increase in received
power, as the maximum $P_{rx}$ is increased from 1.82 to 9.45.
Likewise, with three receivers, Fig. 11 demonstrates that there
is also an increase in received power, while the maximum
efficiency remains about the same. Using the split transmitter
decreases $\eta_c$ to 0.67. It seems that using multiple transmitters
that are spatially separated from each other reduces efficiency
and received power as the fringing fields are dissipated into the
nearby environment instead of coupling into a neighboring coil.

Table IV gives the maximum $P_{rx}$ and $\eta_c$ for each test.

To investigate the sensitivity to component variation, a Monte
Carlo simulation was run, assuming that the components are
normally distributed, with means given by the derived compo-
nent formulas and with standard deviations $\sigma$ such that
$3\sigma$ is
the component tolerance. These simulations were carried out
at tolerance levels of 5%, 10%, and 20%, for the 1:2 and 2:2
configurations, using the large receivers. One receiver was fixed
at 500 $\Omega$, and the other was swept from 60 to 4000 $\Omega$. Fig. 12
shows the 95% confidence intervals for total received power at
the three tolerance levels. Fig. 13 shows the 95% confidence
intervals for total efficiency at the three tolerance levels. As can
be seen, the power is skewed low, with tighter tolerances for
1:2 than for 2:2. Efficiency is skewed high, with tighter tol-
erances for the 2:2 system than for the 2:1. This skew low in
the power confidence intervals and skew high in the efficiency
confidence intervals show that the system is not optimized for
maximum power delivery but rather efficiency. This makes
sense, as all of the component selection for the system is
done on the basis of efficient operation of the class E. The
2:2 system’s efficiency is less sensitive to component variation
primarily because of $C_{out}$ which governs the phase range seen
by the class E and thus its efficiency. $C_{out}$ is larger in the
2:2 system; therefore, its reactance is less sensitive to variations.
For total received power, the 1:2 system is less sensitive than the
2:2 system to component variations, because the two receivers
in the 2:2 system can vary more independently due to the
decoupling effect.
Inductive wireless power transfer between $M$ primary coils coupled to $N$ secondary coils is derived analytically and demonstrated experimentally for $M = 1, 2$ and $N = 1, 2, 3$. Using multiple primary coils in parallel has advantages over a single primary coil. First, the reduced inductance of the transmitting coils makes the amplifier less sensitive to component variations. Second, with multiple receiving coils, the power delivery to an individual receiver is less sensitive to changes in the loads attached to other coils, decoupling receivers from each other. In addition, using multiple transmitters is shown to increase received power with limited impact on coupling efficiency. The multiple transmitting coil architecture increases the feasibility and effectiveness of simultaneous multiple device charging and makes the amplifier more robust to component variation.

**REFERENCES**


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