# Determination of Reverse-Current Coil Turns Layout to Mitigate Over-Coupling in Resonant Inductive Power Transfer Links

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***Abstract*** **─** The transfer efficiency of two-coil resonant inductive power transfer links is known to significantly degrade with a reduction of the coil distance, due to an over-coupling at shorter distances. In this work, a simple technique is introduced to determine the spatial layout of reverse-current coil turns, which suppresses the over-coupling-induced transfer efficiency drop. By employing the spatial layout of reverse-current turns as a design parameter, the proposed method provides more generality in its implementation compared to other reverse-current turn methods. Simulation and experimental results validate the method, suggesting a potential for distance-insensitive implementations.

***Index Terms*** **─** Inductive power transfer, mutual inductance, over-coupling.

## I. INTRODUCTION

Two-coil resonant inductive power transfer links have been widely studied in recent times as wireless power transfer implementations [1]. These links typically operate within the low- and high-frequency spectral ranges, with 13.56 MHz being one of the more popular frequencies. Energy is transferred from transmitting to receiving terminals through inductive coupling. Consequently, tuned coil structures are used at the transmitter and receiver terminals to facilitate wireless power transfer. Typical applications of inductive power transfer include wireless chargers for portable household devices, power delivery to biomedical implants, in addition to numerous industrial applications [2].

Inductive coupling-based wireless power transfer links are sensitive to variations in coil positioning [3, 4]. Specifically, bringing a pair of coupled resonant coil terminals closer is known to lead to over-coupling, which is characterized by a drop in the transfer efficiency at the original link frequency, and the appearance of split resonance frequencies [4-7].

High transfer efficiency levels in the over-coupled regime may be maintained through an arrangement to track the new split-resonance frequencies [5, 6], which unfortunately increases link complexity. Alternatively, coil terminals themselves could be designed to mitigate over-coupling. Over-coupling can be controlled by introducing reverse-current turns in the coil structures, thereby providing a reverse mutual inductance to limit the increase in mutual inductance associated with the over-coupled regime [8, 9]. In [8], the required reverse mutual inductance is generated through an appropriate ratio of forward- and reverse-current turns. Nonetheless, this approach requires a rational turns-ratio in order to be physically implementable. Alternatively, the approach in [9] employs one each of forward- and reverse-current turns in a transmit coil, with a lumped capacitance controlling the ratio of currents through these turns. However, the practical performance of the realized energy transfer link using this technique may be constrained by the availability of commercial off-the-shelf (COTS) capacitors with the level of precision determined by the design process. The limitations of these reverse-current turn methods can be surmounted by a more general approach, which uses the spatial layout of reverse-current turns as the over-coupling mitigating parameter.

Consequently, this paper proposes a simple method

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for determining a spatial layout of reverse-current turns to be included in a transmit coil to mitigate over-coupling. The rest of the paper is organized as follows. Section II describes the design method, while results obtained from applying the proposed method to a test scenario are discussed in Section III. The paper is concluded in Section IV.

## II. DESIGN METHOD

A key aspect of the proposed method to mitigate over-coupling is the determination of mutual inductances between coupled coils. The mutual inductance between a pair of multi-turn circular transmit and receive coils separated by a distance $z$ can be calculated using [10]:

$$M = \sum_{i=1}^{i=n_{tx}} \sum_{j=1}^{j=n_{rx}} \frac{\mu_0 \pi a_i^2 b_j^2}{2\left(a_i^2 + b_j^2 + z^2\right)^{3/2}} \left(1 + \frac{15}{32}\gamma_{ij}^2 + \frac{315}{1024}\gamma_{ij}^4\right), \quad (1)$$

$$\gamma_{ij} = \frac{2a_i b_j}{a_i^2 + b_j^2 + z^2}, \quad (2)$$

where $a_i$ and $b_j$ are the radii of the *i*-th and *j*-th turns of the $n_{tx}$-turn transmit and $n_{rx}$-turn receive coils, respectively. Equations (1) and (2) can be rewritten by replacing the $n_{tx}$ and $n_{rx}$ turn-radii in the transmit and receive coils by average radii, such that,

$$\sum_{i=1}^{i=n_{tx}} a_i = n_{tx} a^{(a)}, \quad (3)$$

$$\sum_{j=1}^{j=n_{rx}} b_j = n_{rx} b^{(a)}, \quad (4)$$

where the superscript $(a)$ denotes an average. Consequently, Equation (1) and Equation (2) become:

$$M = \frac{n_{tx} n_{rx} \mu_0 \pi a^{(a)2} b^{(a)2}}{2\left(a^{(a)2} + b^{(a)2} + z^2\right)^{3/2}} \left(1 + \frac{15}{32}\gamma^2 + \frac{315}{1024}\gamma^4\right), \quad (5)$$

$$\gamma = \frac{2a^{(a)} b^{(a)}}{a^{(a)2} + b^{(a)2} + z^2}. \quad (6)$$

The transfer efficiency of the inductive link realized by coupling the transmit and receive coils can be characterized using the s-parameter transmission coefficient as [4, 11]:

$$\eta(\%) = 100 \times |s_{21}|^2. \quad (7)$$

For a given configuration of the receive coil, the first step in the proposed design method is to determine an appropriate transmit coil to realize an adequate transfer efficiency at the operating distance from the transmit coil $z_1$. Bi-conjugate matching of the coupled coils at this distance imposes a critical coupling condition on the link [3, 5]. The next step is to assume an envisaged shortest separation distance between the pair of coupled coils when put into operation, and designate this as $z_3$. Over-coupling between a pair of coils increases the mutual inductance. Consequently, the mitigation of over-coupling requires the introduction of a reverse mutual inductance to counteract the increase in mutual inductance for shorter separation distances [8, 9].

With the incorporation of reverse-current turns, the mutual inductance at the critical coupling distance $z_1$ is a superposition of forward $(M_{f_1})$ and reverse $(M_{r_1})$ mutual inductances, namely,

$$M_1 = M_{f_1} - M_{r_1}. \quad (8)$$

$M_{f_1}$ and $M_{r_1}$ can be calculated with Equations (5) and (6), using the appropriate average radii in the expressions, namely $a_f^{(a)}$ for the forward turns and $a_r^{(a)}$ for the reverse turns. Similarly, at the envisaged shortest distance $z_3$ and a chosen intermediate distance $z_2$, the mutual inductances are:

$$M_3 = M_{f_3} - M_{r_3}, \quad (9)$$

$$M_2 = M_{f_2} - M_{r_2}. \quad (10)$$

To mitigate over-coupling, the average radius of reverse-current turns $a_r^{(a)}$ is determined, such that the function,

$$f\left(a_r^{(a)}\right) = \left(M_2 - M_1\right) - \left(M_3 - M_2\right) = 0, \quad (11)$$

while using the same number of reverse-current turns as there are forward-current turns in the transmit coil. The value of $a_r^{(a)}$ which satisfies Equation (11) is determined by substituting Equations (5)-(6) and (8)-(10) in Equation (11).

A good choice of intermediate distance $z_2$ provides a value of $a_r^{(a)}$ small enough such that the inner diameter of the receive coil just overlaps the inner diameter of the reverse-current turns of the transmit coil. This ensures that the receive coil is always under the influence of a superposition of mutual inductances from the forward- and reverse-current turns throughout the envisaged range of operating distances.

Although the widths and spacings of the reverse-current turns are not used in the approximate expressions given above, they have an impact on the coil quality factor, and thus on the transfer efficiency. A significant spacing between the additional reverse-current turns and the existing forward-current turns conceptually leads to a distributed turns coil, which may lead to a lower coil quality factor [12, 13]. Hence, it may be necessary in a second stage to adjust the spacing and width of the reverse-current turns in a full-wave electromagnetic (EM) solver in order to maintain high transfer efficiency levels. Furthermore, less variation in the transfer efficiency over the range of operating distances can be realized by slightly detuning the link at the critical coupling distance, such that the impedance match conditions are realized at a slightly shorter distance than the critical coupling distance.

## III. RESULTS AND DISCUSSION

To test the proposed design method, an initial configuration of a square transmit printed spiral coil (PSC) was modelled in CST Microwave Studio to provide a transfer efficiency above 80% at 13.56 MHz, when coupled to a square receive PSC at an axial distance of 35 mm. The PSCs were designed on low-cost FR4 substrate boards, with a dielectric constant of 4.7, and copper conductor thickness of 0.035 mm. The design parameters are described in Table 1. Note that both coils are square, which makes this a more stringent test for the technique proposed.

Figure 1 shows the full-wave EM simulation results. As the paired coils were brought closer together, the 13.56 MHz transfer efficiency of 82.63% at a 35 mm separation dropped to 25.32% at 1 mm, due to the over-coupling. The resulting percentage variation $(\eta_{\max}-\eta_{\min})/\eta_{\max}$ is 69.36%. Also, splitting of the resonance frequency is observed in the transfer efficiency profiles at distances less than 35 mm, with an increase in the gap between resonance frequencies as the coils are brought closer together.

To mitigate over-coupling the square coils were conceptually substituted with theoretically equivalent circular coils with the same enclosed area, with $b^{(a)}$ and $a_f^{(a)}$ being the average radii of the equivalent circular receive and transmit coils, respectively. An appropriate value of the average radius of reverse-current turns $a_r^{(a)}$ was then determined using Equations (5)-(6), and (8)-(11).

Table 1: Coil parameters

| Parameter | Value |
|---|---|
| Transmit PSC equivalent average radius $a_f^{(a)}$ | 36.95 mm |
| Receive PSC equivalent average radius $b^{(a)}$ | 19.30 mm |
| Width of transmit PSC forward-current turns $w_f$ | 4 mm |
| Width of receive PSC turns $w_{rx}$ | 0.9 mm |
| Transmit PSC forward-current turn-spacing $S_f$ | 0.5 mm |
| Receive PSC turn-spacing $S_{rx}$ | 0.5 mm |
| Number of forward-current turns in transmit PSC $n_a$ | 2 |
| Number of turns in receive PSC $n_b$ | 10 |
| Operating distance $z_1$ | 35 mm |
| Closest distance $z_3$ | 1 mm |

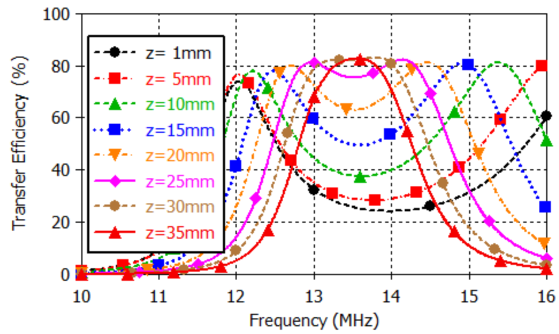


Fig. 1. Link transfer efficiency profiles using initial square transmit coil.

Figure 2 is a study of Equation (11), showing the variation of the function $f\left(a_r^{(a)}\right)$ with the average reverse-current turn radius $a_r^{(a)}$, at various values of intermediate distance $z_2$. It is observed that with $z_2 = 2$ mm, Equation (11) is satisfied with an average reverse-current radius of $a_r^{(a)} = 12.46$ mm. This is small enough to ensure that, using the same spacing as the forward-current turns, the inner diameter of the reverse-current turns is slightly overlapped by the inner side-length of the receive coil.

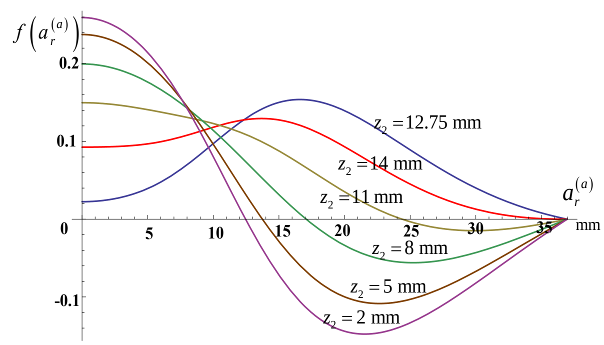


Fig. 2. Study of design Equation (11) for various values of $z_2$, using the coil parameters in Table 1.

For demonstration purposes, $a_r^{(a)}$ was directly used to model circular reverse-current turns in the transmit coil in CST Microwave Studio for full-wave EM simulations. In order to maintain high-transfer efficiency at the critical coupling distance of 35 mm, the width and spacing of the reverse-current turns were then adjusted to achieve a convenient threshold transfer efficiency of 77%, without altering the calculated average radius. The final designed transmit coil, hence consisted of square forward-current turns and circular reverse-current turns, as illustrated in Fig. 3.

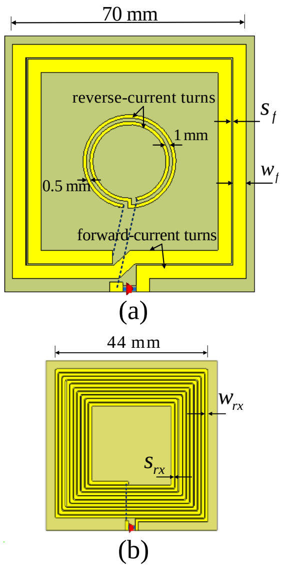


Fig. 3. Physical models of the: (a) transmit and (b) receive coils. The dotted lines show the connection between coil turns behind the substrate board.

Figure 4 shows results of a full-wave EM simulation of the designed transmit coil coupled to the receive coil in CST Microwave Studio. The link resonance condition was realized by bi-conjugate matching the coupled coils using capacitive L-match circuits, as illustrated in Fig. 5. The capacitance values are listed in Table 2. As compared to Fig. 1, the results in Fig. 4 show a marked improvement. Although some frequency splitting can still be observed at distances between 5 mm and 30 mm, the depth of the trough is significantly less than in Fig. 1. The best 13.56 MHz transfer efficiency value of 78.35% occurs at an axial distance of 30 mm, while the lowest value of 52.73% occurs at a distance of 10 mm, implying an improved percentage variation in transfer efficiency of 32.70%. The mitigation of over-coupling has, however, been achieved with a trade-off in the transfer efficiency at the original critical coupling distance of 35 mm. The initial 13.56 MHz transfer efficiency of 82.63% has dropped to 77.29%.

The over-coupling mitigation obtained in Fig. 4 was further improved by slightly detuning the link at the critical coupling distance of 35 mm. As shown in Fig. 6, this adjustment further reduces percentage variation in link transfer efficiency to 20.67%.

To experimentally validate the over-coupling mitigation arising from the inclusion of the analytically determined reverse-current turns in the transmit PSC, s-parameters were measured at different separation distances of the fabricated PSCs using a vector network analyzer, as shown in Fig. 7. The measured s-parameters were used to determine the link transfer efficiency using Equation (7). Due to measurement constraints the shortest measured distance was 5 mm.

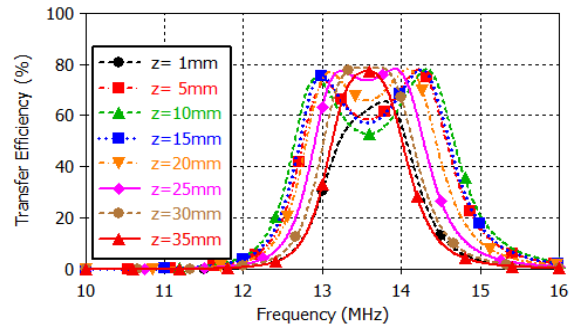


Fig. 4. Link transfer efficiency profile using modified transmit coil.

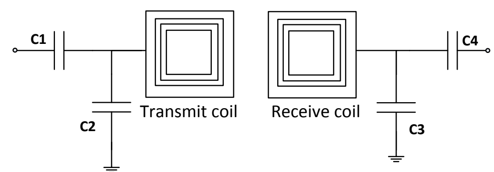


Fig. 5. Schematic representation of impedance match arrangement.

Table 2: Impedance matching capacitance values

| Capacitance | Value (pF) |
|---|---|
| C1 | 57 |
| C2 | 167 |
| C3 | 22 |
| C4 | 2 |

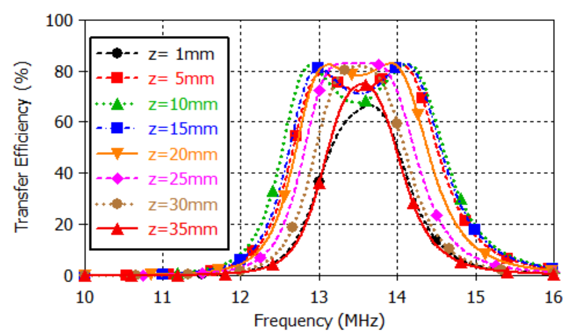


Fig. 6. Link transfer efficiency with adjustment of the critical coupling distance.

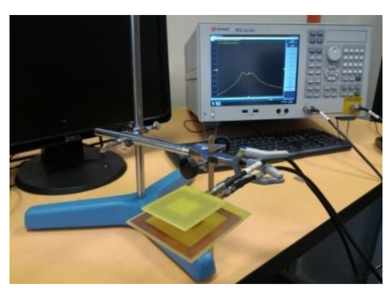

Fig. 7. Measurement set-up.

In Fig. 8, the measured 13.56 MHz transfer efficiency values are compared with the simulated results shown in Fig. 1 and Fig. 6. Trends in measured transfer efficiency using forward and reverse-current turns are in good agreement with the predicted over-coupling mitigation demonstrated by the simulation results. However, the measured transfer efficiency values at each distance were lower than the simulated values, mainly due to losses arising from fabrication inaccuracies.

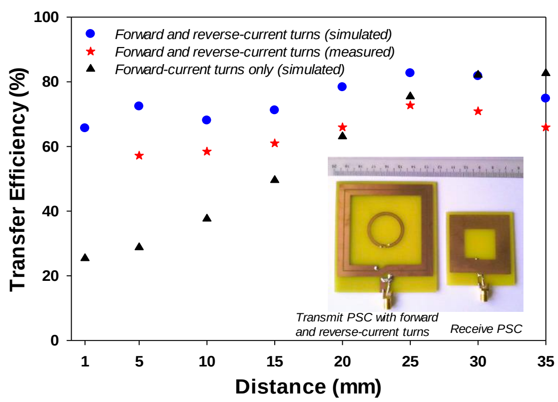


Fig. 8. Comparison of 13.56 MHz transfer efficiencies using transmit coil with forward-current turns only, and transmit coil with forward and reverse-current turns.

## IV. CONCLUSION

This paper has discussed a method to suppress the over-coupling that occurs as the distance between coupled coils in a resonant inductive power transfer link reduces. The simulation and experimental results clearly show that the incorporation of reverse-current turns mitigates over-coupling effects in a resonant inductive power transfer link. The central issue addressed in this paper is the determination of the appropriate coil-turn configuration to provide adequate suppression of over-coupling. By employing the spatial layout of turns as the design parameter, the method proposed in this paper provides more generality than other contemporary reverse-current turn methods, which are either dependent on rational turns-ratios or realizable capacitive current-control.

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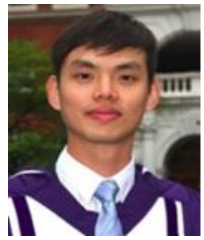

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