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Method to Decrease the Vertical Distance in Wireless Charging

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Abstract:

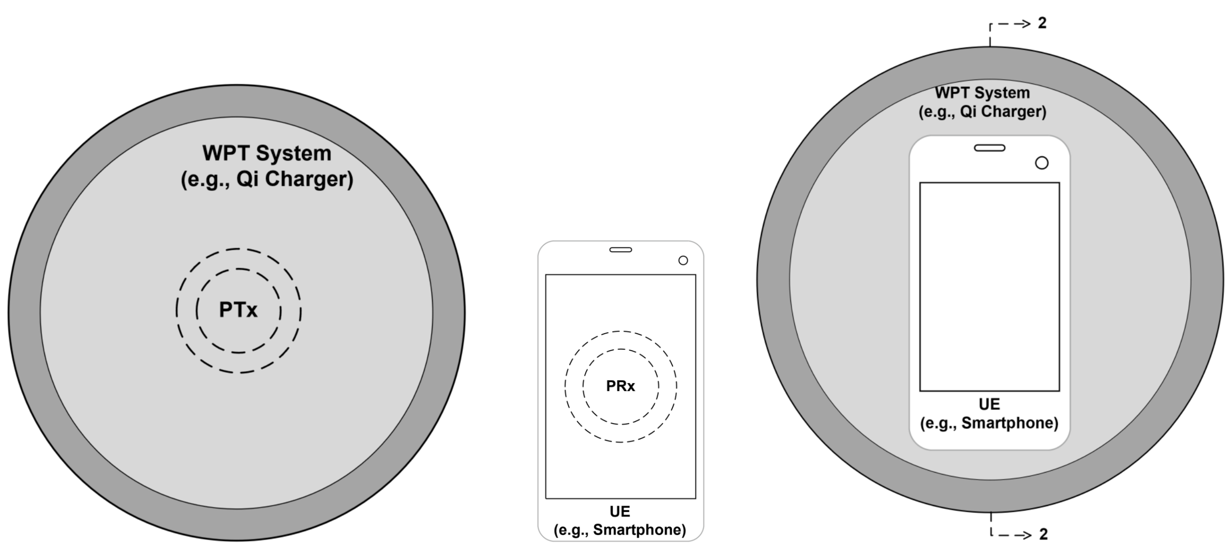
This publication describes methods to accommodate a decrease in the vertical distance between a power transmitter (PTx) of a wireless power-transfer (WPT) system (*e.g.*, wireless-charging pad, Qi charger) and a power receiver (PRx) of a user equipment (UE), such as a smartphone, earphones, a smartwatch, and the like. Original design manufacturers (ODMs) design and build increasingly thinner WPT systems and thinner UE. A decrease in the vertical distance between the PTx and the PRx causes an increase in the PTx-to-PRx inductive coupling coefficient (K_c), where $0<K_c<1$. Subsequently, the input-to-output voltage gain (A_V) is lower, which is not a desirable design. In addition, the range of A_V grows tighter, which translates to a poorer response of the PRx output voltage (V_{OUT}) to a PTx switching frequency (f_{SW}). To maintain the same resonant frequency and to accommodate for a decrease in the vertical distance between the PTx and PRx, an ODM can add an external inductance (L_{Ext}) that is coupled in series with a leakage inductance (L_{Leak}) of the PRx. In addition, by adding an L_{Ext} to the PRx, the ODM of the WPT system can shrink the absolute vertical distance needed between the PRx and PTx and extend the range of the vertical distance needed between the PRx and PTx to maintain the desired output voltage. Therefore, adding an external inductance to the PTx of a WPT system, enables a WPT system ODM and a UE ODM to design and build thinner devices and still maintain, or even increase, the desired output voltage.

Keywords:

Wireless charging, Qi charging, Qi, inductive charging, power transmitter, power receiver, PTx, PRx, Tx, Rx, external inductance, coil-to-coil distance, coil-to-coil z-distance, choke inductance, choke, leakage inductance, resonance frequency, resonant inductive frequency, power transfer, wireless power-transfer, primary-to-secondary coil distance.

Background:

A user may utilize a wireless power-transfer (WPT) system (*e.g.*, wireless-charging pad, Qi charger) to charge user equipment (UE), such as a smartphone, earphones, a smartwatch, and the like. Qi is an open interface standard that defines wireless power-transfer using inductive coupling. Using electromagnetic induction coupling between two coils, WPT systems can transfer power from a power transmitter (PTx) of the WPT system to a power receiver (PRx) of the UE, as is illustrated in Figure 1.



1A **1B** **1C**

Figure 1

Figure 1 illustrates a top view of a WPT system (*e.g.*, a Qi charger), a UE (*e.g.*, a smartphone), and the smartphone on top of the Qi charger. Figure 1A illustrates the top view of the Qi charger and the PTx of the Qi charger. In Figure 1A, the dashed lines indicate that the PTx (not to scale) is located below the pad surface (the mat) of the Qi charger. Figure 1B illustrates the top view of the smartphone and the PRx of the smartphone. In Figure 1B, the dashed lines indicate that the PRx is embedded inside the smartphone. Figure 1C illustrates a smartphone placed on top of the Qi charger mat to charge the smartphone utilizing electromagnetic inductive coupling between the PTx of the Qi charger (Figure 1A) and the PRx of the UE (Figure 1B).

Among other factors, the lateral alignment and the vertical distance between the PTx and the PRx affect power transfer. Figure 1C illustrates lateral alignment of the PRx to the PTx. A user, however, often has no control over the vertical distance between the PTx and the PRx, as is illustrated in Figure 2.

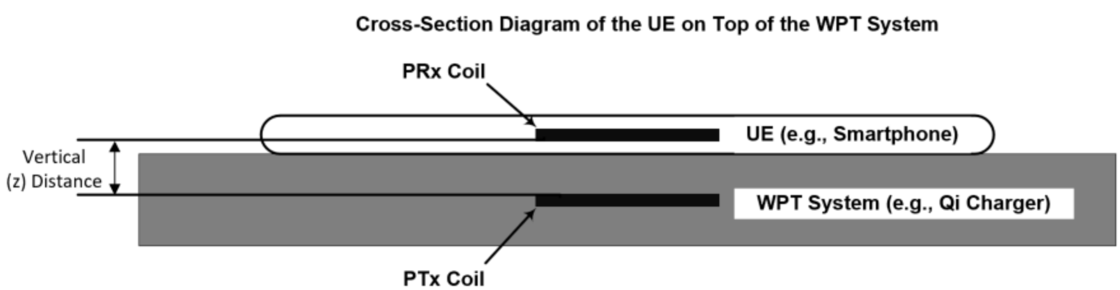


Figure 2

Figure 2 is a cross-sectional diagram of Figure 1C. As the user places their smartphone on top of the WPT system, the vertical distance (z-distance) is fixed and pre-determined by several physical parameters, such as the thickness of the WPT system, the location of the PTx coils inside the WPT system, the thickness of the smartphone, the thickness of a case on the smartphone, and the location of the PRx coil inside the smartphone.

To explain, on a high level, how the z-distance affects power transfer, it is worthwhile to briefly discuss wireless inductive charging by first considering the electrical schematic illustrated in Figure 3.

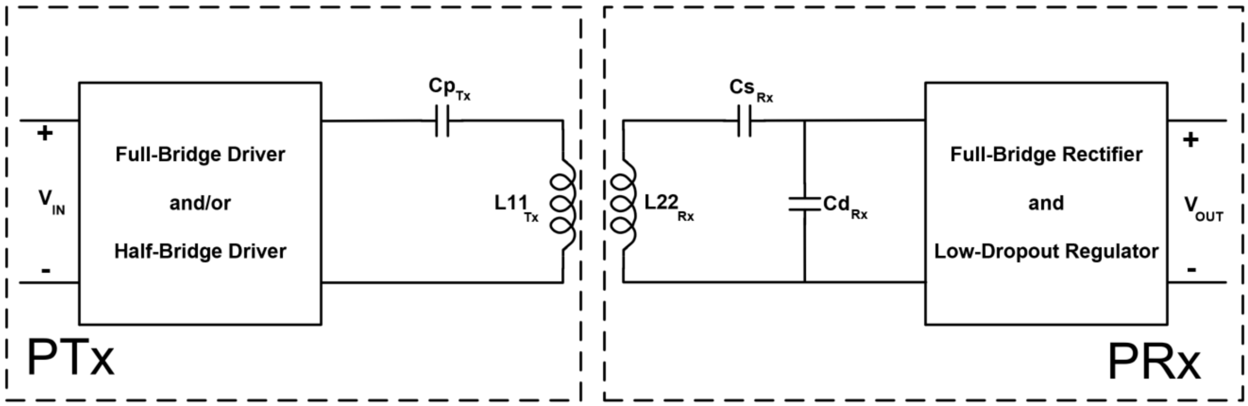


Figure 3

Figure 3 illustrates the PTx and the PRx that enable the electromagnetic induction coupling between the transmitter (primary) coil ($L11_{Tx}$) and the receiver (secondary) coil ($L22_{Rx}$). In Figure 3, the z-distance distance between $L11_{Tx}$ and $L22_{Rx}$ is fixed and depends on the design and build of the WPT system and the UE. On the primary side, $L11_{Tx}$ is coupled in series with a resonance capacitor of the primary circuit (Cp_{Tx}). On the secondary side, $L22_{Rx}$ is coupled in series with a resonance capacitor of the secondary circuit (Cs_{Rx}) and in parallel with a second resonance capacitor of the secondary circuit (Cd_{Rx}). The PTx may incorporate a full-bridge driver and/or a half-bridge driver. In general, the PRx is the master of the PTx, and the PRx controls the power level by changing the operating switching frequency (f_{SW}) of the PTx, the operating duty cycle, and/or the driver supply voltage (V_{IN}); refer to Figure 3.

This publication focuses on controlling f_{SW}. More specifically, the PRx output voltage (V_{OUT}) or the input-to-output voltage gain (A_V), defined in Equation 1, can be regulated by controlling f_{SW}. A decrease in f_{SW} causes an increase in A_V, and vice-versa, an increase in f_{SW}

causes a decrease in A_V. Differently stated, for a given V_{IN}, the PRx (the master) controls V_{OUT} by controlling the f_{SW} of the PTx. Although, this publication focuses on A_V, the same can be said about the transferred power because there is a correlation between A_V and transferred power.

$$A_V = \frac{V_{OUT}}{V_{IN}} \quad \textbf{Equation 1}$$

It is helpful to further explain the electrical schematic illustrated in Figure 3 by representing an ideal transformer between the PTx coil and the PRx coil, as is illustrated in Figure 4.

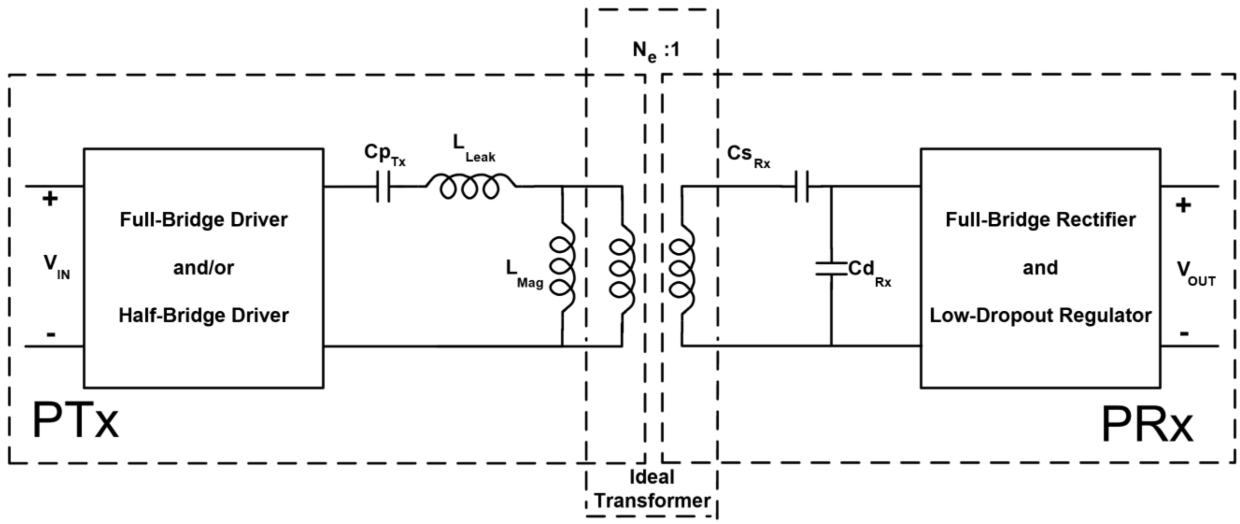


Figure 4

Figure 4 illustrates an equivalent electrical schematic to Figure 3, where the inductive coupling between the PRx coil and the PTx coil is represented with an ideal transformer. In the electrical schematic in Figure 4, L_{Leak} stands for leakage inductance, L_{Mag} stands for magnetizing inductance, N_e represents the equivalent turns ratio between the primary and the secondary coil, and K_c (not illustrated) stands for the coupling inductive coefficient and can range between zero (0) and one (1). $L11_{Tx}$ in the electrical schematic illustrated in Figure 3 can be represented in terms of L_{Leak}, L_{Mag}, and K_c in the electrical schematic illustrated in Figure 4. Equation 2, Equation 3, and Equation 4 define the relationships between some of the parameters in Figure 3 and the equivalent representation in Figure 4.

$$L_{Leak} := (1 - (K_c)^2) \cdot L11_{Tx} \quad \textbf{Equation 2}$$

$$L_{Mag} := (K_c)^2 \cdot L11_{Tx} \quad \textbf{Equation 3}$$

$$N_e := \sqrt{\frac{L_{Mag}}{L22_{Rx}}} \quad \textbf{Equation 4}$$

where ":=" stands for "is defined as."

If the PRx and the PTx are laterally aligned and in a state of resonant coupling, a decrease in the vertical distance (refer to Figure 2) causes an increase in K_c and a decrease in A_V. As original design manufacturers (ODMs) build thinner WPT systems and thinner UE, the vertical distance between the PTx coil and the PRx coil decreases, causing a decrease in A_V. In addition, as UE ODMs embed more hardware and integrate more functionalities, the UE require more power. One way to increase transferred power between the WPT system and the UE, is by increasing the vertical distance between the PTx and the PRx, which increases A_V.

Therefore, it is desirable to have a technological solution that can accommodate a decrease in the vertical distance between the PRx and the PTx, while maintaining or increasing the input-to-output voltage gain.

Description:

This publication describes methods to accommodate a decrease in the vertical distance between a power transmitter (PTx) of a wireless power-transfer (WPT) system (*e.g.*, wireless-charging pad, Qi charger) and a power receiver (PRx) of a user equipment (UE), such as a smartphone, earphones, a smartwatch, and the like. Original design manufacturers (ODMs) build increasingly thinner WPT systems and thinner UE that require more electrical power to support the added computational power. A decrease in the vertical distance between the PTx and the PRx causes a decrease in the PTx-to-PRx coupling inductive coefficient (K_c), where $0<K_c<1$.

Subsequently, the input-to-output voltage gain (A_V) is lower. A very low A_v can result in the inability of the PTx to push power to the PRx causing power-transfer disconnection, which is not a desirable design. In addition, the range of A_V grows tighter, which translates to a poorer response of the PRx output voltage (V_{OUT}) to a PTx switching frequency (f_{SW}) as is illustrated in Figure 5.

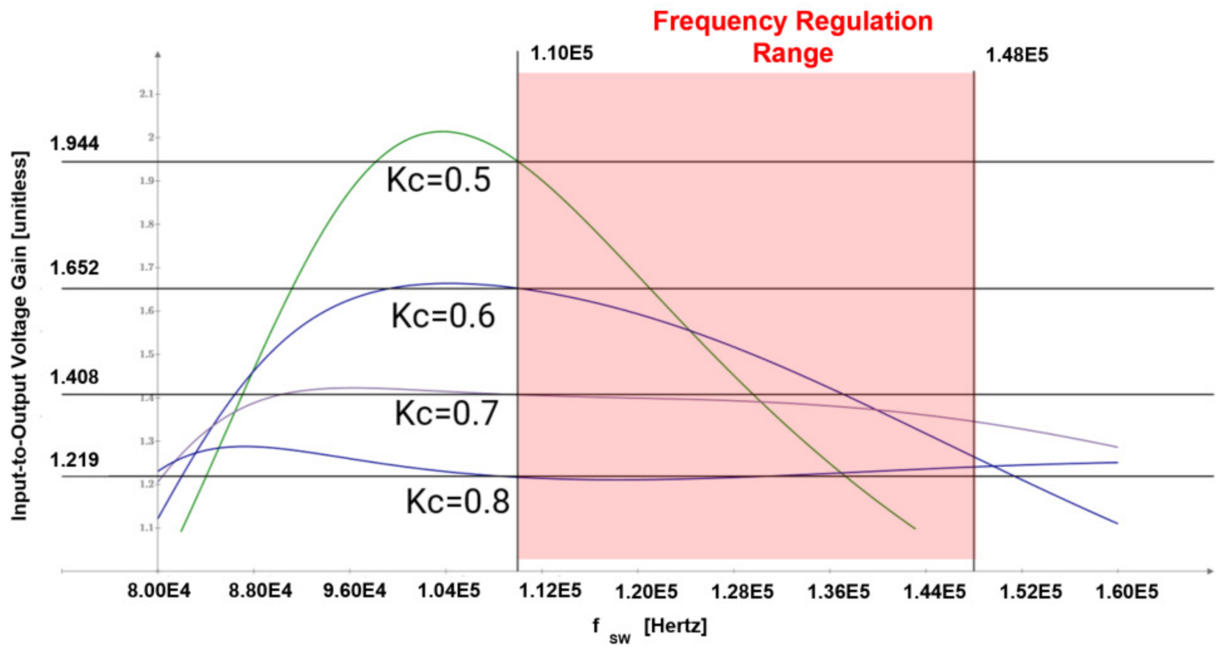


Figure 5

Figure 5 illustrates the input-to-output voltage gain as a function of the f_{SW} of the PTx. In Figure 5, the transmitter (primary) coil ($L11_{Tx}$) is set to 6.3 microhenries (μH), and the resonance capacitor of the primary circuit (Cp_{Tx}) is set to 400 nanofarads (nF), creating a resonant frequency at 100 kilohertz (kHz). Figure 5 illustrates that an increase in K_c causes a decrease in A_V. One cause for an increase in K_c is a decrease in the z-distance the PTx and the PRx. In addition, a higher K_c (0.8>0.7>0.6>0.5) translates to a lower A_V *and* a poorer V_{OUT} response to increases or decreases in f_{SW}, as is illustrated in Figure 5.

To maintain the same resonant frequency and to accommodate for a decrease in the vertical distance between the PTx and PRx, an ODM can increase the leakage inductance (L_{Leak}) by adding an external inductance (L_{Ext}) (*e.g.*, an inductor) as is illustrated in the electrical schematic in Figure 6.

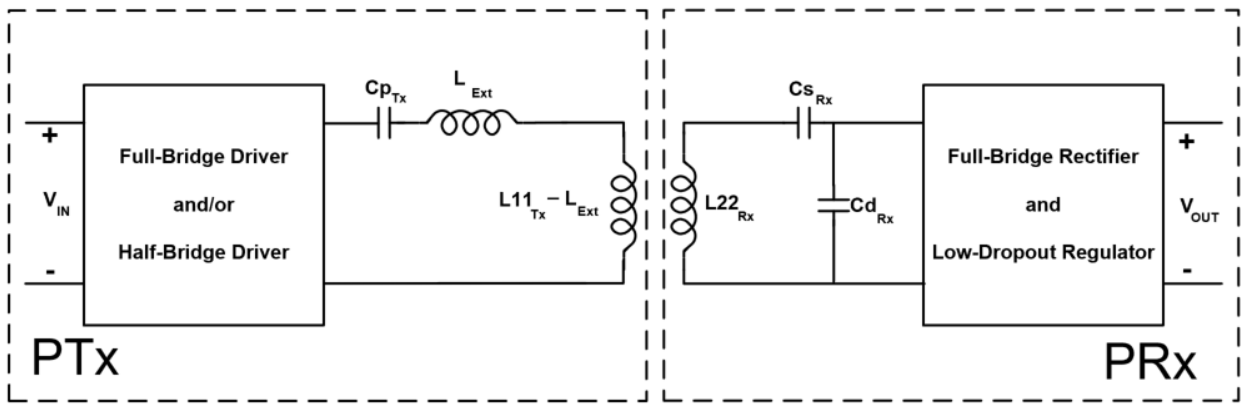


Figure 6

Figure 6 illustrates an added external inductor (L_{Ext}) to the PTx. The added L_{Ext} in Figure 6 is coupled in series with leakage inductance (L_{Leak}) in the electrical schematic illustrated in Figure 3 and the equivalent electrical schematic in Figure 4. In addition, to keep the resonant frequency the same, in this case 100kHz, $L11_{Tx}$ in Figure 3 is reduced by L_{Ext}, as is illustrated in Figure 6. Thus, the total leakage inductance ($L_{Leak_{Total}}$) increases, as is defined in Equation 5.

$$L_{Leak_{Total}} = L_{Leak} + L_{Ext} \quad \textbf{Equation 5}$$

Adding L_{Ext} allows for higher A_V for the same K_c or the same z-distance between the PTx and the PRx, as is illustrated in Figure 7.

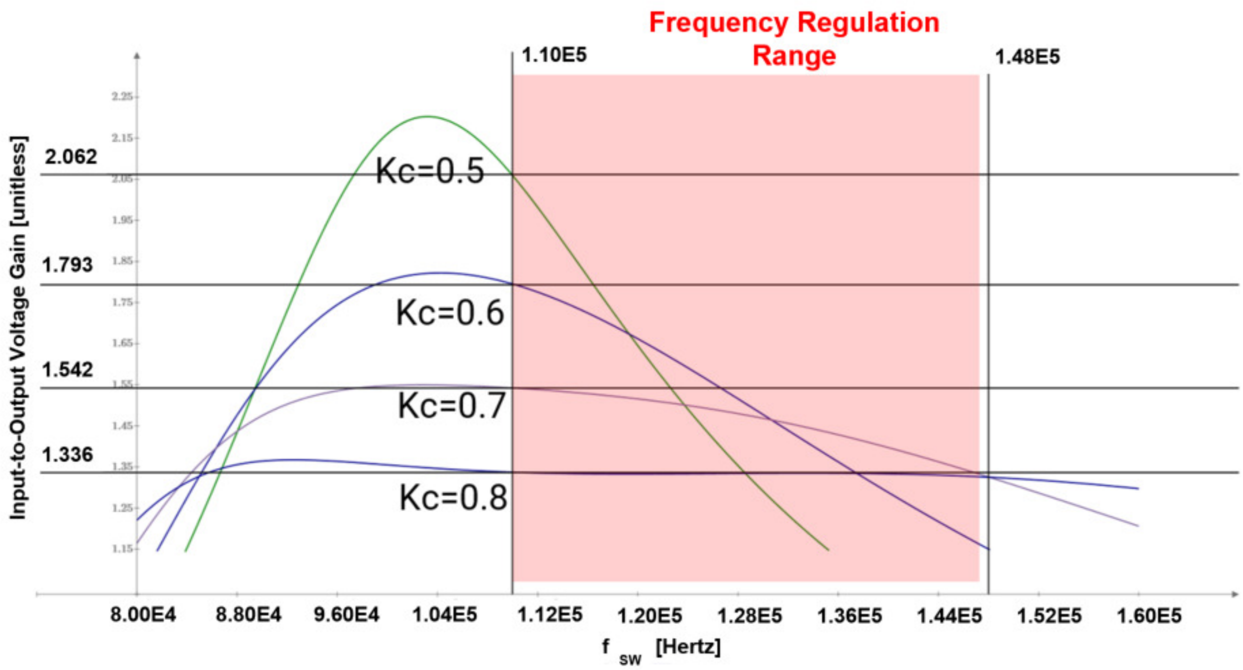


Figure 7

Figure 7 illustrates the A_V responses to f_{SW} for K_c=0.5, 0.6, 0.7, and 0.8, where the PTx has an added external inductance of one microhenry (L_{Ext}=1 μH). Comparing the A_V responses in Figure 7 with the A_V responses in Figure 5 over the same frequency sweep, the A_V responses in Figure 7 are higher at every frequency for a given K_c, indicating that an added external inductance increases V_{OUT}.

In addition, the increase in A_V is proportional to the value of L_{Ext}, as is illustrated in Figure 8.

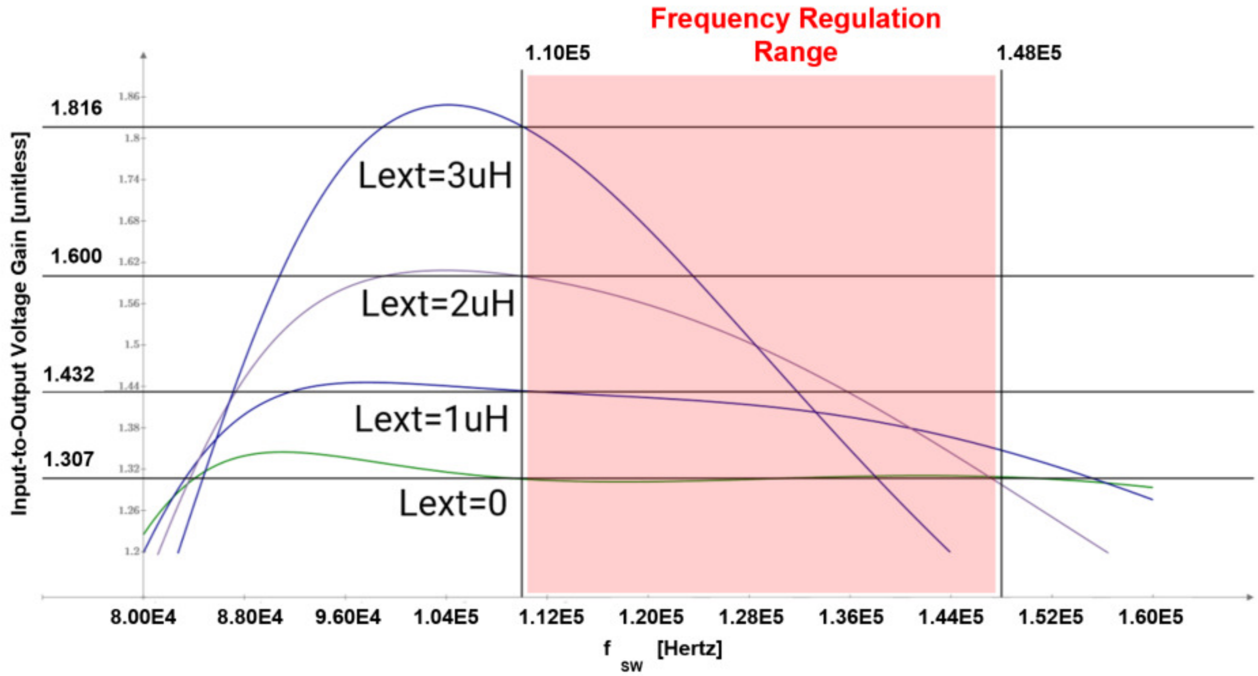


Figure 8

Figure 8 illustrates the A_V responses for the same frequency sweep as in Figure 5 and in Figure 7. In all A_V responses in Figure 8, K_c is 0.75, and L_{Ext} is zero (0) (no external inductance), one (1), two (2), and three (3) μH. Thus, the increase is A_V is proportional to the value of L_{Ext}.

Furthermore, by adding an external inductance to the PRx, the ODM of the WPT system can shrink the absolute z-distance needed between the PRx and PTx and extend the range of the z-distance needed between the PRx and PTx to maintain the desired A_V, as is illustrated in Figure 9.

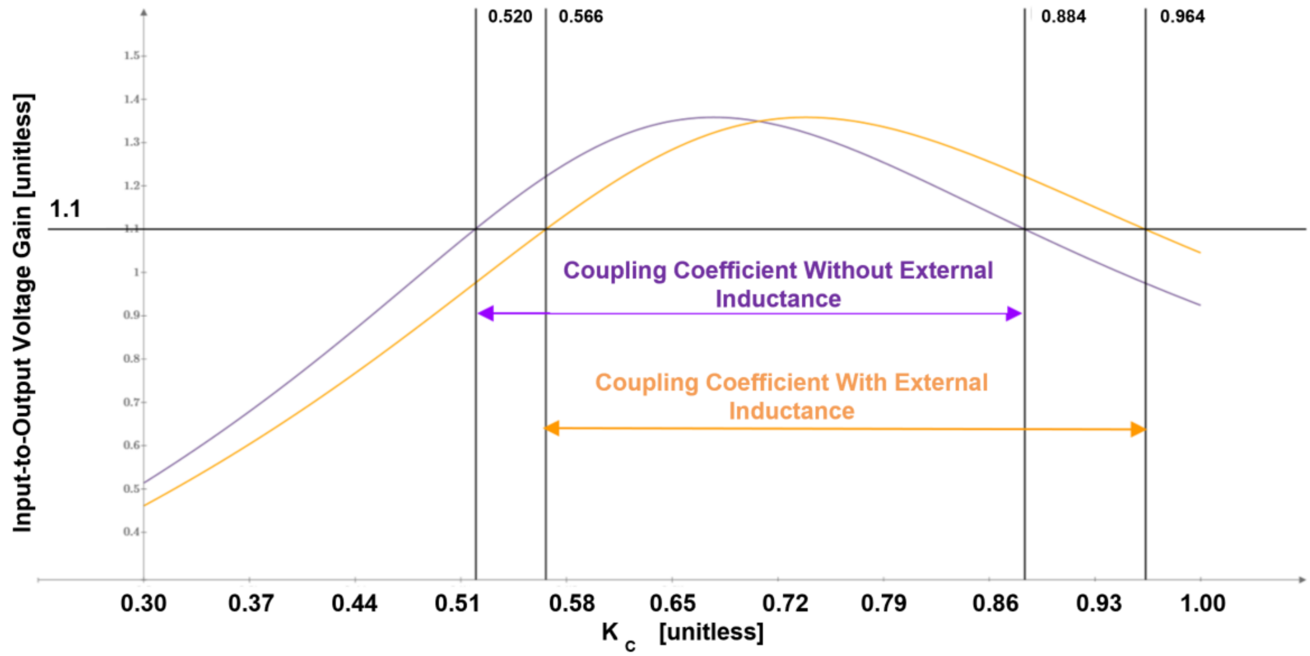


Figure 9

Assume the required A_V is a minimum of 1.1, as is illustrated in Figure 9. Adding L_{Ext} of 1μH in the PTx allows for higher K_c; refer to Figure 9 (0.566>0.520 and 0.964>0.884). Therefore, adding L_{Ext} allows for a smaller z-distance between the PRx and the PTx. Also, adding L_{Ext} in the PTx, extends the range of the K_c, allowing a wider range of vertical distances between the PRx and the PTx; refer to Figure 9.

In conclusion, adding an external inductance to the PTx of a WPT system, enables a WPT system ODM and a UE ODM to design and build thinner devices and still maintain, or even increase, the desired output voltage.

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