Designing a Qi-compliant receiver coil for wireless power systems, Part 1

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Overview

The implementation of the Wireless Power Consortium's (WPC's) Qi standard[1] brings wireless power to many different end applications. The receiver (Rx) coil for each application may have different geometries and/or power requirements. Since the Rx coil is a key component in a successful and efficient design of a Qi-compliant Rx and there are many design options and trade-offs to consider, the designer must take a careful and methodical approach when realizing a solution. This article provides the technical insight needed to realize a successful Rx-coil design. It covers the Qi-compliant system model as a basic transformer; Rx-coil measurements and system-level influences; and methods of qualifying a design for successful operation. It is assumed that the reader has a general understanding of the Qi-compliant inductive power system. Background information can be found in Reference 2.

Qi-compliant system as a transformer

For many near-field wireless power systems such as the one specified by the WPC, the behavior of the magnetic power transfer can be modeled by a simple transformer. A traditional transformer usually has a single physical structure with two windings around a core material that is highly permeable compared to air (Figure 1). Since the traditional transformer uses a highly permeable material to carry the magnetic flux, most (not all) of the flux produced by one coil couples to the second coil. This coupling, which can be measured through a parameter known as the coupling coefficient, is denoted as k (a measure that can have a value between 0 and 1).

Three parameters define a two-coil transformer:

L_{11} is the self-inductance of coil 1.

L_{22} is the self-inductance of coil 2.

L_{12} is the mutual inductance of coils 1 and 2.

The coefficient for coupling between the two coils can be formulated as

$$k = \frac{L_{12}}{\sqrt{L_{11}L_{22}}}. \tag{1}$$

The ideal transformer then can be modeled by using a coupled inductor as shown in Figure 2.

Using the voltage and current relationship of an inductor can provide the nodal equations of this two-coil transformer:

$$V_1 = L_{11}\frac{di_1}{dt} + L_{12}\frac{di_2}{dt} \tag{2a}$$

$$V_2 = L_{22}\frac{di_2}{dt} + L_{12}\frac{di_1}{dt} \tag{2b}$$

For circuit analysis, the model in Figure 2 can be represented by what traditionally is referred to as a cantilever model, shown in Figure 3. Here the magnetic coupling and mutual inductance are simplified to leakage and magnetizing inductances. This allows the physical nature of the

Figure 1. Traditional transformer with one physical structure

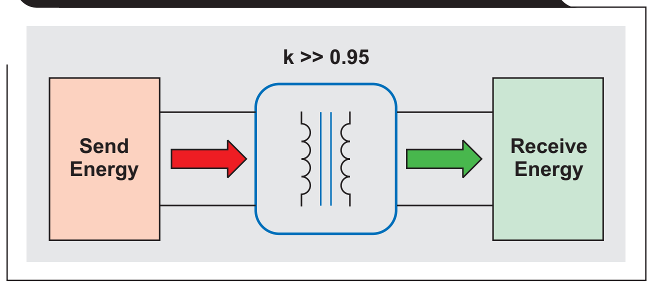


Figure 2. Ideal model of a traditional transformer

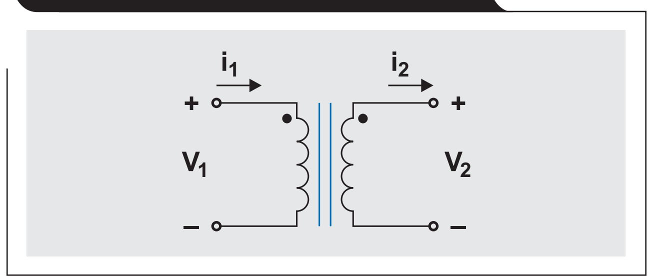
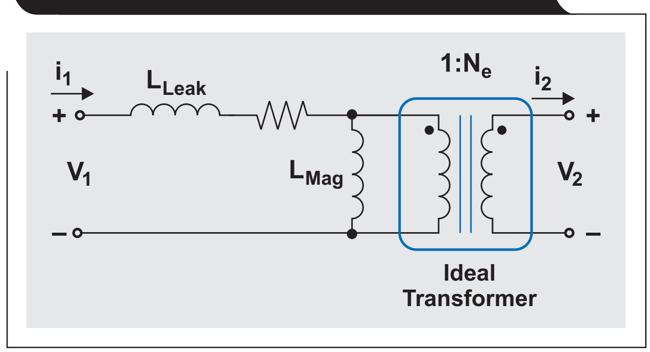


Figure 3. Cantilever model of a traditional transformer



coupling to be understood through a circuit implementation. For the ideal transformer, the turns ratio is calculated by using the following equations:

$$N_e = \frac{1}{k}\sqrt{\frac{L_{22}}{L_{11}}} \quad \textbf{(3a)}$$

$$L_{Mag} = k^2 L_{11} \quad \textbf{(3b)}$$

In a tightly coupled system, the leakage inductance is a small percentage of the magnetizing inductance, allowing this parameter to be neglected for a first-order approximation. In addition to high coupling, the series resonant capacitors utilized in the Qi-compliant system reduce the effect of leakage inductance. Therefore, the voltage gain from the primary coil to the secondary coil can be approximated for the first order as

$$\frac{V_2}{V_1} \propto k\sqrt{\frac{L_{22}}{L_{11}}}. \quad \textbf{(4)}$$

The transformer in a Qi-compliant system consists of two separate physical devices, the transmitter (Tx) and the receiver (Rx), each with an isolated coil. When a Tx and Rx are placed near one another, they form a coupled-inductor relationship, simply modeled as a two-coil transformer with an air core (Figure 4). The shielding material on both sides serves as a magnetic-flux short. This allows the magnetic field lines (flux) to be contained between the two coils. Figure 5 illustrates a 2D simulation of the magnetic field lines found during typical operation.

For a typical Qi-compliant system, the coupling coefficient (k) is much lower than for a traditional transformer. A traditional transformer has coupling in the range of 0.95 to 0.99. For example, 95 to 99% of the magnetic flux couples to the secondary coil; whereas, for a Qi-compliant system, the coupling coefficient is on the order of 0.2 to 0.7, or 20 to 70%. For the most part, the Qi standard attempts to mitigate this lower coupling with a series resonant cap on the Tx and Rx that can compensate for the leakage inductance at resonance.

Electrical requirements of the Rx coil

In some Rx ICs, the target voltage of the dynamically controlled rectifier varies as a function of the output current. Since the rectifier output dictates the voltage gain needed across the transformer, the highest output voltage on the rectifier must be considered along with the output load, or demand for output power. As shown in Figure 6, the rectifier output varies from ~7 to 5 V over a 1-A load, which sets the required voltage gain across the transformer. It is important to ensure that the Rx coil, when tuned per the WPC specification (see the section "Tuning the Rx coil" later in this article), can achieve this voltage demanded by the Rx IC.

Figure 4. Simple inductively coupled transformer with an air core

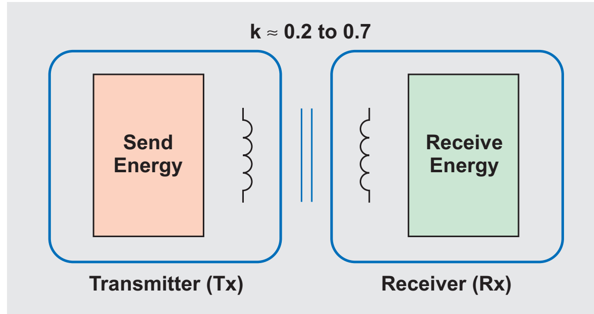


Figure 5. Example magnetic field lines between two mutually coupled coils

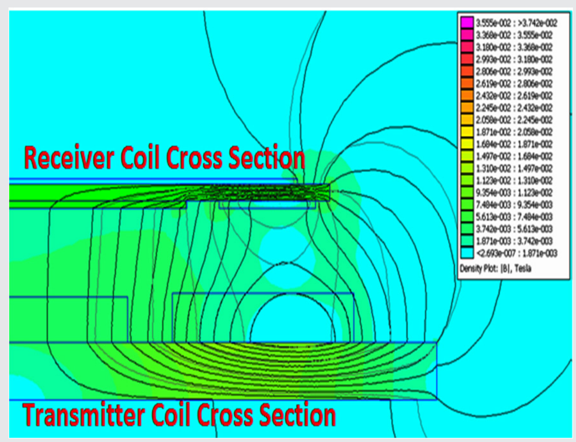
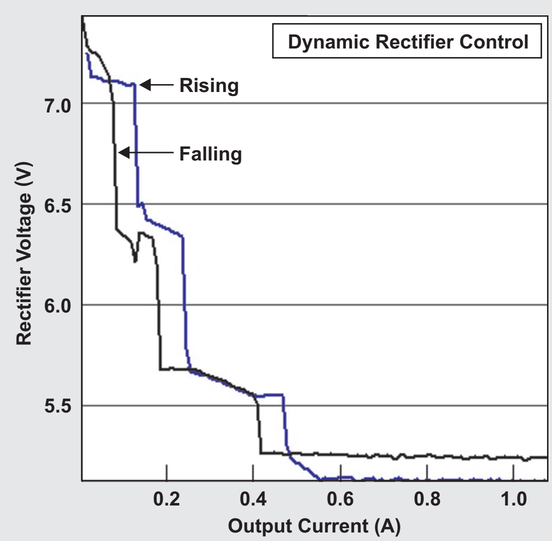


Figure 6. Rectifier output versus load



The flowchart in Figure 7 illustrates a recommended approach for specifying a new Rx coil. The design flow has limited choices for the shield, the wire gauge, and the number of turns. Each of these will be discussed next.

The shield

The shield has two primary functions: (1) providing a low-impedance path for the magnetic flux so that very few flux lines impinge upon surrounding metallic objects, and (2) permitting a higher-inductance coil to be realized with fewer turns so that excessive resistance is not introduced (from additional turns).

Thick shields, which can absorb a large amount of magnetic flux (i.e., they have a high flux saturation point), can be used to prevent heating in the material behind the Rx coil. Thick shields also are less susceptible to drops in efficiency than thinner shields when they encounter a Tx or Rx with a magnet used for alignment. (See the section "Measuring the Rx-coil inductance" later in this article for details on this effect.) Typical materials from vendors such as Vishay, TDK, Panasonic, E&E, Elytone, and Mingstar can help minimize efficiency degradation. Note that high-permeability ferrite materials, such as powdered iron, don't always perform better than distributed-gap materials. Although ferrite materials have a high permeability, they exhibit a lower flux saturation point when the shield thickness is reduced. This factor must be carefully considered.

The Rx-coil wire gauge

The choice of wire gauge for the Rx coil is based on cost versus performance. Large-diameter wire or bifilar wire (two parallel wires) can provide high efficiencies but is costly and can result in thick Rx-coil designs. For instance, a PCB coil might be cheaper in overall cost but incurs a much higher equivalent series resistance than a bifilar counterpart.

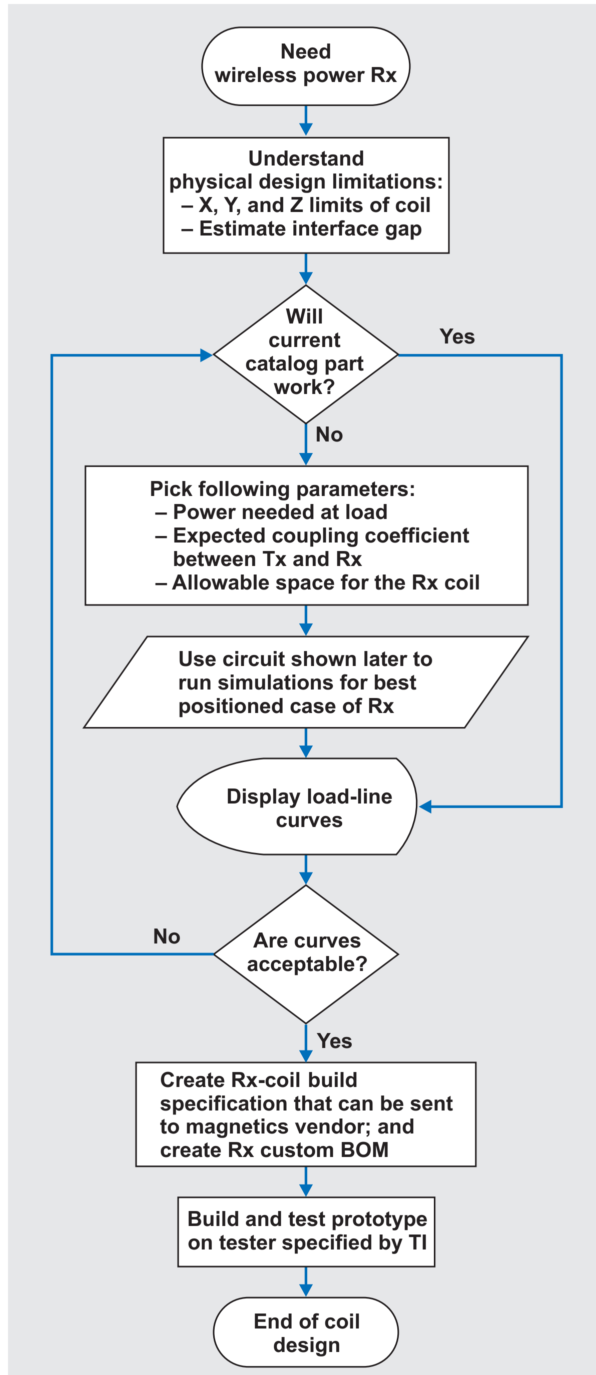
The number of turns

Once the wire and shield have been chosen, the number of turns determines the Rx-coil inductance. Coil inductance and coupling determine the voltage gain observed at the Rx's rectifier output as well as the total available power to the Rx. This voltage-gain target is shown in Figure 6.

Three procedures offer a general approach to determine the inductance target:

1. The Tx's type-A1 coil should be used as the basis for the primary coil's characteristics (for example, 1500-mm^2 area, 24-µH inductance, and 19-V primary voltage).
2. When a shield material with a permeability significantly higher than air (>20) is used, the coil area is a good proxy for the coupling coefficient. Note that this only applies to planar coils with either a single layer or two layers of turns. Exotic coil structures do not utilize this principle. In order to ensure a reasonable coupling and high efficiency, an Rx coil can be used with an area approximately 70 to 80% of the area of A1 coil for a 5-W system. This ensures a coupling coefficient of approximately 50% for most reasonable designs with a distance, d_Z, of up to 5 mm between the Tx and Rx coils as specified by the WPC.
3. The desired voltage gain is determined based on the average expected rectifier voltage—for example, 6 V found in the plot in Figure 6. In this example case, the voltage gain is ~0.32 (6 V/19 V).

Figure 7. Flowchart of methodology for Rx-coil design



A typical design for a 5-V/5-W output-voltage system shows that with the coupling coefficient around 0.5, a secondary inductance of about 10 µH is sufficient to produce the target voltages required. There are two relationships to consider in the system design:

$$V_2 \propto kV_{IN}\sqrt{\frac{L_{22}}{L_{11}}} \tag{5a}$$

$$L_{22} \propto N_2^{\,2} \tag{5b}$$

Therefore, if the coupling coefficient is changed from 0.5 to 0.4, the inductance for the same power output can increase by up to 1.6 times the previous inductance. This means that the new inductance is ~16 µH. As shown in Equation 5b, coil inductance is proportional to the number of coil turns squared.

Table 1 shows the secondary inductance and coupling for some common coils designed for the system.

Table 1. Examples of typical coils

COIL DIMENSIONS (mm)	TURNS	V_{OUT} (V)	P_{OUT} (W)	L_{22} (µH)	k
48 × 32	15	5	5	12	~0.6
28 × 14	24	5	2.5	33	~0.25
35 × 35	24	7	5	22	~0.5

One caveat is that these rules of thumb apply to general planar coils and are preliminary, meant to serve as a starting point for a design. The actual design is best optimized by using simulation tools, as shown in the flowchart in Figure 7.

Measuring the Rx-coil inductance

The Rx-coil inductance is a very important parameter that dictates the electrical response (such as voltage gain and output impedance) of the Rx AC/DC power stage. To preserve a consistent response, the inductance must minimally vary in different system scenarios. Due to the interoperability nature of the Qi standard, the Rx coil can be placed on many different types of Tx's that may influence the Rx-coil inductance—and hence the electrical response.

Per Section 4.2.2.1 of the WPC specification,[1] the Rx-coil inductance, L'_S, is measured with the test configuration in Figure 8. The spacer and Tx shield provide a reference to emulate Tx components near the Rx coil. In this test configuration, the Tx shield is a 50 × 50 × 1-mm piece of ferrite material (PC44) from TDK Corporation. The gap d_Z is set to 3.4 mm by means of a nonmetallic spacer. The Rx coil is then placed on the spacer, and L'_S is measured with a stimulus of 1-V RMS and 100 kHz. In addition, the free-space Rx-coil inductance, L_S, is measured without the Tx shield.

What is not detailed in the WPC specification is the influence of common system scenarios on the L'_S and L_S measurements. The most common influence on these parameters is the presence of a battery behind the Rx coil. Due to the casing material and the battery cell's makeup, the Rx-coil inductance generally is reduced when the battery is placed behind it. In addition to the battery, the presence of a magnet on a Tx-coil structure influences the inductance. (See Section 3.2.1.1.4 of the WPC specification.[1]) The magnet functions as a stressor on the Rx-coil shielding material where the shield's magnetic saturation point is of key interest. If the Rx-coil shielding material saturates when a magnet is present, the coil inductance drops dramatically. Because the Qi standard specifies Tx coil assemblies with and without a magnet, the designer needs to understand how the inductance varies in both scenarios, as any shift in inductance will shift the resonant tuning of the Rx. Note that the test configuration in Figure 8 does not include a magnet. When a magnet is included, its flux density should be between 75 and 150 mT and its diameter should be a maximum of 15.5 mm. This means that the typical 30-mT magnetic field of the Tx coil during power transfer is about 20% of the magnet's field strength.

Figure 8. Test configuration for measuring Rx-coil inductance (L'_S)

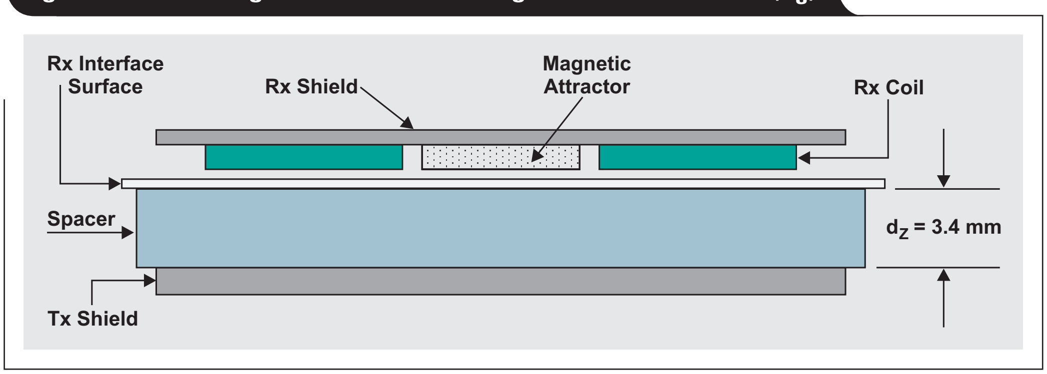


Table 2. Rx-coil-inductance parameters to be measured during development

PARAMETER	Rx COIL WITH Tx SHIELD	Rx COIL WITHOUT Tx SHIELD	BATTERY	MAGNET	SUMMARY
L'_S	Included	—	—	—	Standard L'_S measurement
L'_S_m	Included	—	—	Included	Exposes the effect of the magnet
L'_S_b	Included	—	Included	—	Exposes the effect of the battery
L'_S_m_b	Included	—	Included	Included	Exposes the effect of the battery and the magnet together
L_S	—	Included	—	—	Standard L_S measurement
L_S_b	—	Included	Included	—	Exposes the effect of the battery

For the purpose of understanding the performance of the Rx-coil inductance, Table 2 defines parameters in addition to the recommended measurements of L'_S and L_S. When the battery is introduced into the measurement, it should be placed in the same orientation/location as it will be in the final system. Note that the materials used in the final industrial design could also influence the final inductance measurement. Therefore, when the tuning circuit is configured, all components of the final industrial design of the mobile device should be used for the final measurement. The measurements found in Table 1 can be used to screen and qualify potential Rx coils.

Table 3 summarizes the measured inductances from an acceptable coil design and the resonant frequency with a fixed series and parallel resonant capacitor. Here L'_S_b was used for the capacitor calculations. (See the next section, "Tuning the Rx coil," for details.) Note that the variation could be linearly scaled as a percentage of L'_S and used as a reference for acceptance of a prototype coil.

Table 3. Measured inductances of a sample coil

	L'_S	L'_S_m	L'_S_b	L'_S_m_b	L_S	L_S_b
Inductance (µH)	12.9	13.1	10.5	10.6	10.9	9.52
Resonance (kHz)	90.15	89.63	100	99.72	98.15	105.02

Tuning the Rx coil

The simplified Rx-coil network consists of a series resonant capacitor, C_1, and a parallel resonant capacitor, C_2. These two capacitors make up the dual resonant circuit with the Rx coil (see Figure 9) and must be sized correctly per the WPC specification.

To calculate C_1, the resonant frequency of 100 kHz is used along with L'_S:

$$C_1 = \frac{1}{(100\text{ kHz} \times 2\pi)^2 \times L'_S} \tag{6}$$

To calculate C_2, a secondary resonance of 1.0 MHz is used along with L_S. This calculation requires that C_1 be determined first and used in Equation 7:

$$C_2 = \frac{1}{(1.0\text{ MHz} \times 2\pi)^2 \times \left(L_S - \dfrac{1}{C_1}\right)} \tag{7}$$

Finally, the quality factor must be greater than 77 and is calculated as

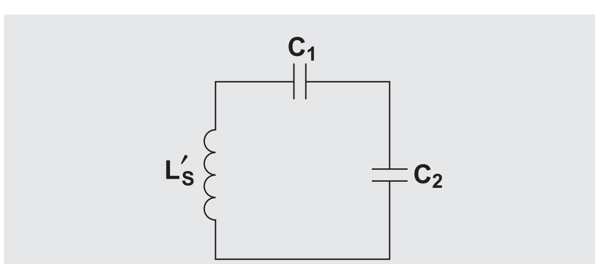
$$Q = \frac{2\pi \times 1.0\text{ MHz} \times L_S}{R}, \tag{8}$$

where R is the DC resistance of the coil.

Load-line analysis of the Rx coil

When choosing an Rx coil, a designer needs to understand the transformer characteristics by comparing the primary and Rx coils via load-line analysis (I-V curves). This analysis captures two important conditions in the Qi-compliant system: (1) operating-point characteristics and (2) transient response. These will be discussed next.

Figure 9. Dual resonant circuit with Rx coil



Operating-point characteristics

An example test configuration for conducting load-line analysis is shown in Figure 10, whose parameters are defined as follows:

V_{IN} is an AC power source that should have a peak-to-peak operation of 19 V.

C_P is the primary series-resonant capacitor (100 nF for type-A1 coil).

L_P is the primary coil of interest (type A1).

L_S is the secondary coil of interest.

C_1 is the series resonant capacitor chosen for the Rx coil under test.

C_2 is the parallel resonant capacitor chosen for the Rx coil under test.

C_B is the bulk capacitor for the diode bridge. C_B should be at least 10 µF at 25 V.

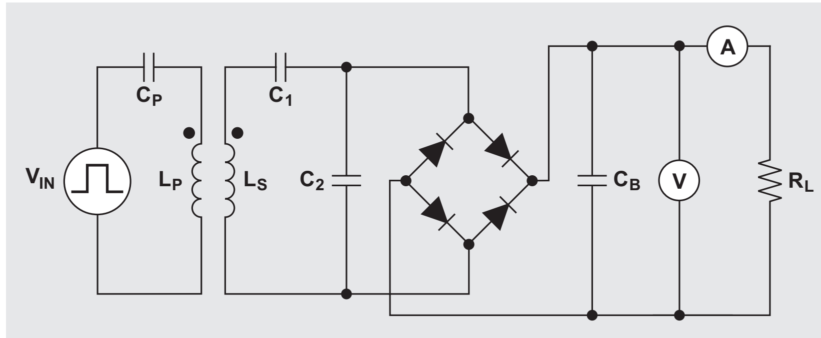
V is a Kelvin-connected voltage meter.

A is a series ammeter.

R_L is the load of interest.

The diode bridge should be constructed of Schottky diodes in either a full bridge or a synchronous half bridge with low-side n-type MOSFETs and high-side Schottkys. Three test procedures are used for the analysis:

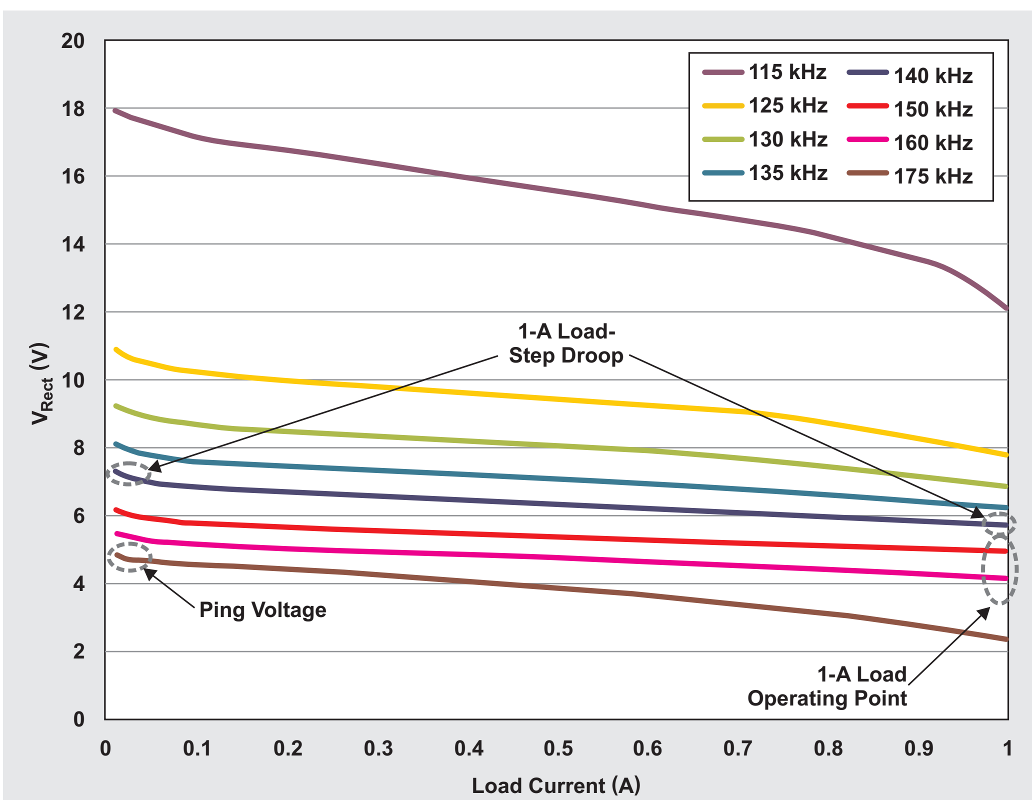
Figure 10. Test setup for load-line analysis



1. A 19-V AC signal is supplied to L_P, starting at a frequency of 200 kHz.
2. The resulting rectified voltage is measured from no load to the expected full load.
3. The preceding two steps are repeated for lower frequencies, stopping at 110 kHz.

An example load-line analysis is shown in Figure 11. The plot conveys that specific load and rectifier conditions result in a specific operating frequency. For example, at

Figure 11. Results of example load-line analysis



1 A, the target for the dynamic rectifier is 5.15 V. Therefore, the operating frequency is between 150 and 160 kHz, which is an acceptable operating point. If the operating point falls outside the WPC-specified frequency range of 110 to 205 kHz, the system will never converge and will become unstable.

Transient response

For transient analysis, there are two major points of interest, shown in Figure 11: (1) the rectifier voltage at the ping frequency (175 kHz), and (2) the rectifier voltage droop from no load to full load at the constant operating point.

In this example, the ping voltage is ~5 V. This is above the V_{UVLO} of the chip. Therefore, start-up in the Qi-compliant system can be guaranteed. If the voltage is near or below the V_{UVLO} at this frequency, start-up may not occur.

If the maximum load step is 1 A, the droop in this example is ~1 V with a voltage of 6 V at the 140-kHz load line in Figure 11. To analyze the droop, the 140-kHz load line that starts at 7 V at no load is followed to the maximum load current expected. Droop voltage is the difference between the voltages at the ends of the load line. Acceptable full-load voltage at the selected operating frequency should be above 5 V. If it descends below 5 V, the power-supply output also droops to this level. This type of analysis for transient response is necessary due to the Qi-compliant system's slow feedback response. The analysis simulates the step response that would occur if the system did not adjust the operating point of the resonant transformer.

Note that coupling between the primary and secondary coils worsens with Rx-coil misalignment. Therefore, an additional analysis of the load lines at multiple misalignments is recommended to determine where in the planar space the Rx discontinues operation.

Conclusion

This article has shown that traditional transfer fundamentals can be employed to simplify the design of Rx coils for wireless power systems. However, the nature of interoperability and mobile-device characteristics can impose unique deviations from standard magnetics design practices. Identifying and addressing coil-design details up front increases the probability of greater success on the first pass. The evaluation methods introduced allow specification and characterization of a custom Rx coil in a very methodical approach.

Part 2 of this article series will provide design details of different types of custom Rx coils. The results will exercise the methods and theory presented in Part 1.

References

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