Wireless power transfer coil design

Introduction

The primary function of a wireless power transfer system is usually to provide a reliable power supply across a distance. A commonly used mechanism (including by the Qi standard) is the near-field inductive coupling, which works in principle as a transformer with additional capacitive compensation. The fundamental parameters involved in the design of such system are:

- Mechanical:
  - Available space for the transmitter and receiver coils
  - Separation distance between the transmitter and receiver coils
- Electrical:
  - Input and output voltages and currents
  - Operating frequency range
  - L-C-R values of the components

Depending on the application, some parameters can be considered as hard constraints, while others are variables to maximize. Further considerations can include more parameters such as range of positioning, materials, thermal effects, interoperability, etc.

The large numbers of parameters would give rise to many possible ways one could approach the design of such a system.

This document aims to provide a simple approach as a starting point to designing a pair of wireless power transfer coils.

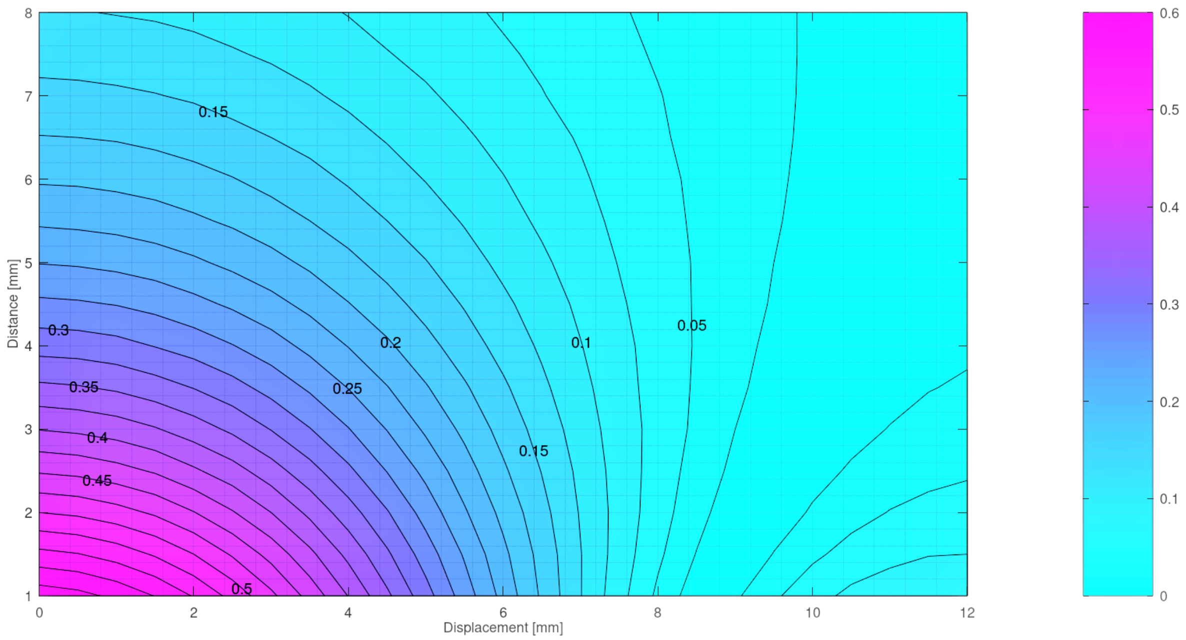
1 Coupling factor considerations

The coupling factor between transmitter and receiver coils is one of the most critical parameters in the design of a wireless power transfer system and it may significantly vary due to many reasons.

Applications with some alignment assistance (e.g. magnets, mated surfaces, etc.) on the transmitter and receiver coils would lead Figure 1 to a more controlled and predictable operation of the system. On the other hand, larger freedom in positioning of the coils would require larger margins to ensure power transfer reliability.

The shows how the coupling factor between two commercial coils, specifically designed for wearable applications, varies as a function of separation distance (coil-to-coil) and relative displacement (center-to-center).

Figure 1. Coupling factor versus coils distance and radial displacement



In Figure 1, a perfect alignment and 1 mm distance give a maximum coupling factor of about 0.6. The coupling factor then quickly drops with distance and displacement.

In real applications, the minimum distance would be dictated by the distances of both the transmitter and receiver coils to the external surfaces of their enclosures and the best-case coupling factor could be relatively low. A coupling factor that is too low negatively impacts the overall power transfer efficiency due to higher power losses in the transmitter.

The two coils used in Figure 1 are listed in Table 1 as the transmitter coil L1 and the receiver coil L2.

Table 1. Transmitter and receiver coils examples

Ref.	Coil PN (WE)	Inductance	DCR	Dimensions
L1	TX: 760308101104	6.8 µH	125 mΩ	20 mm diameter
L2	RX: 760308101219	11.8 µH	750 mΩ	15 mm diameter
L3	TX: 760308104113	12 µH	72 mΩ	60 x 46 mm
L4	RX: 760308102207	8 µH	80 mΩ	40 x 40 mm

The Figure 2 and Figure 3 similarly show the coupling factor of another pair of TX-RX coils, L3 and L4. Because of the rectangular shape of the transmitter coil, the coupling factor slightly differs between X-axis and Y-axis displacements. The larger size of both coils also results in significantly higher coupling factors over a wider misalignment area.

Figure 2. **Coupling factor versus coils distance and X-axis displacement**

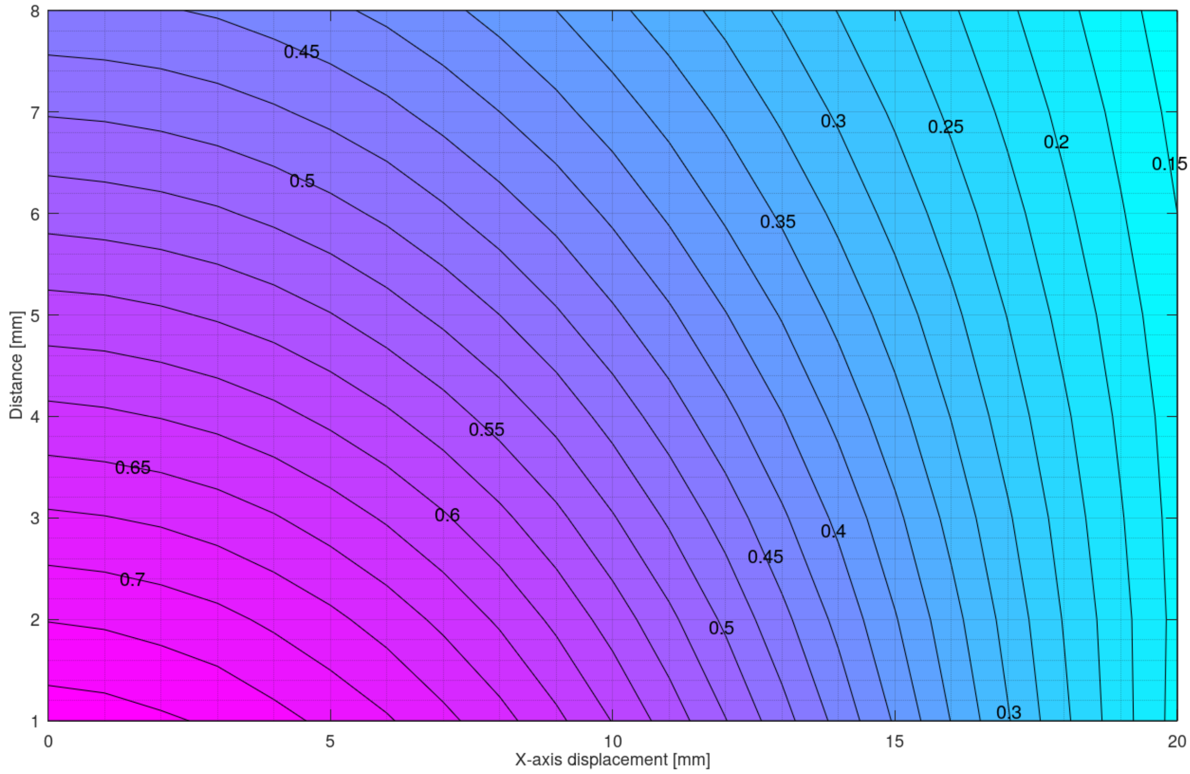
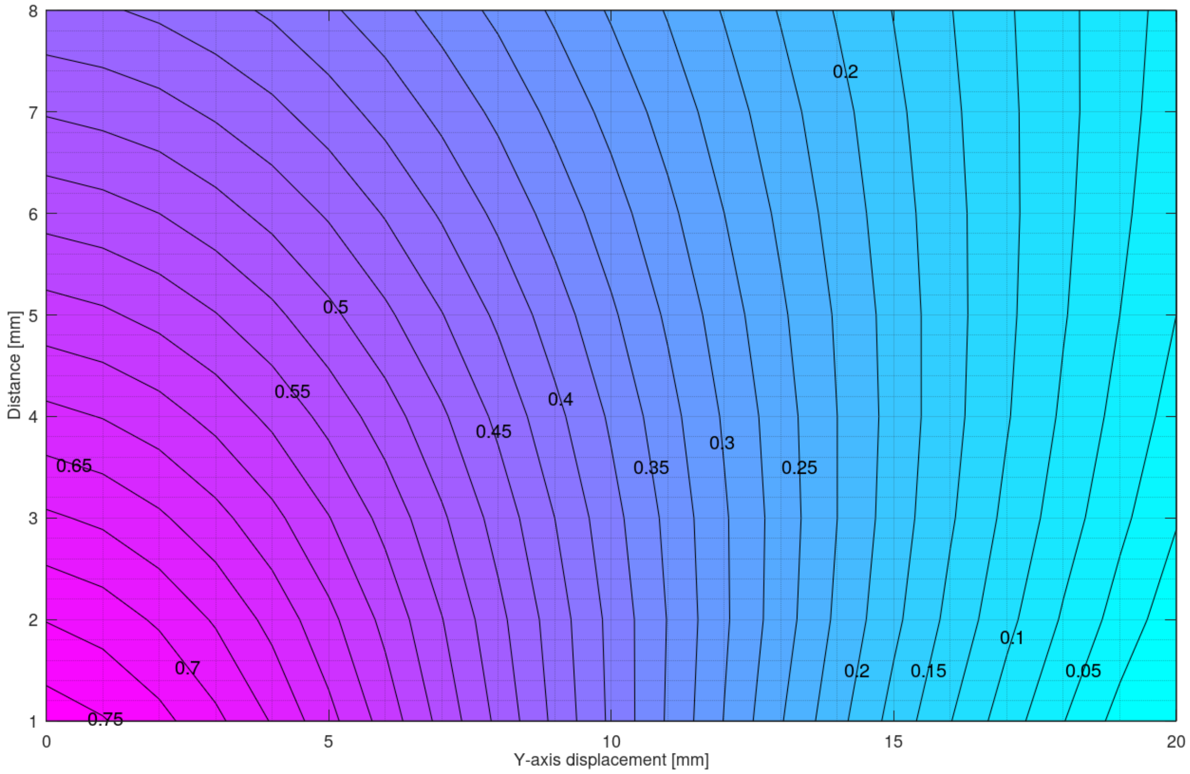


Figure 3. **Coupling factor versus distance and Y-axis displacement**



2 Designing the receiver coil with the GUI

The **Coil Selection** tool in the STSW-WPSTUDIO GUI (Figure 4. Operating point selection) approaches the coil design from the power receiver side. This is because many RX applications usually have a need to be interoperable with existing TX products in the market, while the TX products are usually based on just several TX reference designs.

Some applications such as wearable products might be designed with a dedicated charging cradle and so do not require such compatibility. These applications would have more freedom in designing the whole system and in the selection of coils with unusual shapes.

The design procedure provided here has some limitations:

- The calculations assume that all coils are circular planar shaped. The standard TX coils, even if rectangular, are approximated as circular.
- The loss model is not the most accurate. For example, it’s not using the loss-split model, and there is no loss model for power ferrite or other shielding materials.
- Coupling estimation neglects the effect of shielding.
- Only the series-series compensation topology (Figure 13. Circuit model) is supported.
- Only the AC model is considered. Conversions between AC and DC values use the First Harmonic Approximation, which is less accurate at high coupling factors.
- Since the tool is intended to help with practical coil designs for mobile device charging applications, the results may not be suitable for designs using very large or very small values.

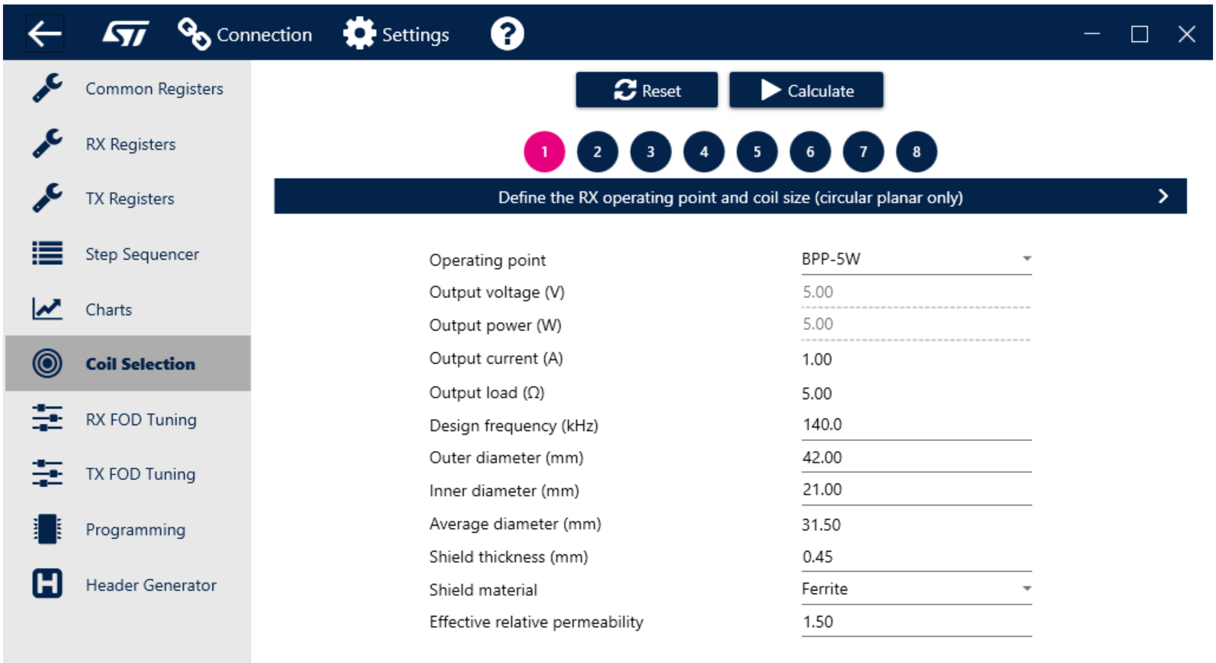
The tool is divided into several pages for ease of navigation. It’s recommended to go through the pages in sequence for the first design pass.

Underlined values are meant for user input, which are greyed out when they are locked. Values with no underlining are calculated values.

The “Calculate” button is used to process the entered values. It should be used at every page change, even though most of the values will be recalculated automatically. In case there are improper values or unexpected results encountered, a notification will pop up to alert the user.

2.1 Page 1

Figure 4. Operating point selection



The first page (Figure 4) begins the coil design process with the definition of the operating point with the lowest output load impedance. For example, an application targeting both output loads of 20V/1A and 5V/1A, 5V/1A should be used as it means a lower load impedance.

There are two preset operating points for BPP 5W and EPP 15W, and a user-defined operating point.

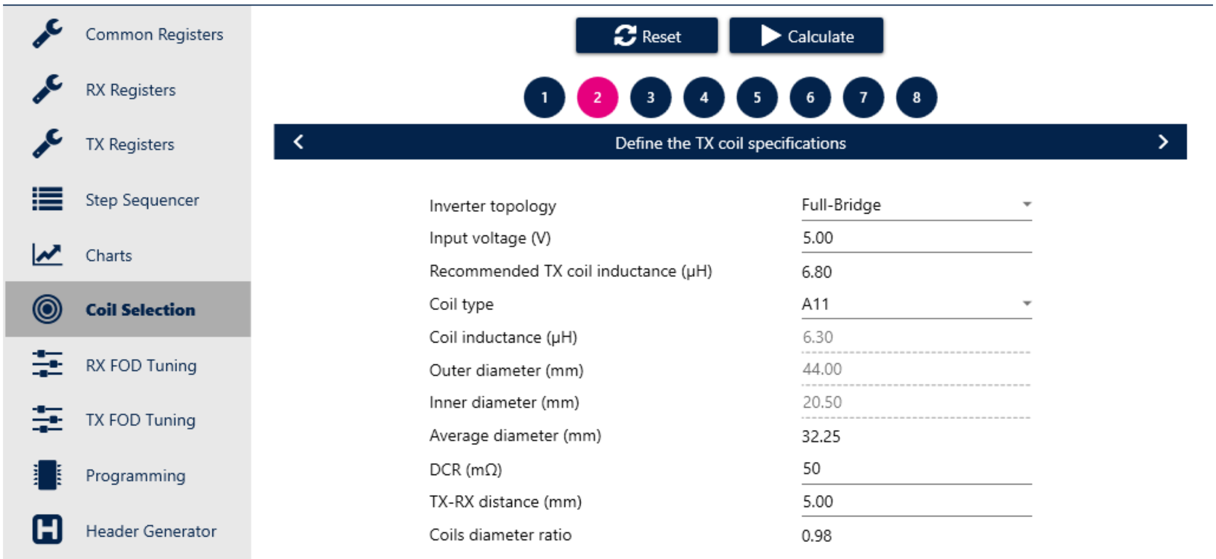
The design frequency helps to locate the appropriate inductance value of the receiver coil, as smaller inductance is needed for higher frequency and vice versa. The design frequency is usually set within the desired operating frequency range.

Next is the dimensions of the receiver coil. The outer diameter would be constrained by the space available to the coil. The inner diameter is usually at most half of the outer diameter to achieve good coupling. The coil thickness has not much impact in the first iteration. It is, however, important in many applications and should be considered in subsequent iterations by summing the winding and shielding thicknesses.

Effective relative permeability represents the effect of the shielding material (if present), typically ferrites, or magnetic nanocrystalline sheets, on the inductance of the coil. The effective relative permeability is difficult to estimate since the shielding only partially forms the magnetic flux path around the coil and the reluctance of the air is much higher than that of the shielding. The preset value of 1.5 is a good starting point.

2.2 Page 2

Figure 5. Transmitter details



Page 2 (Figure 5) is dedicated to the transmitter.

A TX coil inductance value is recommended based on the operating point, inverter topology, input voltage, and the estimated coupling factor. After the coupling is calculated on page 4 (Figure 7. Coupling factor and coil inductance estimation), a second look may be warranted.

The recommended value is the TX coil inductance when coupled with the RX coil, as this is the effective value in circuit. At this point however, there is no indication on what the relationship between coupled inductance and self-inductance is like. A good starting point would be a TX coil with a self-inductance around 1.5x lower than the recommended value.

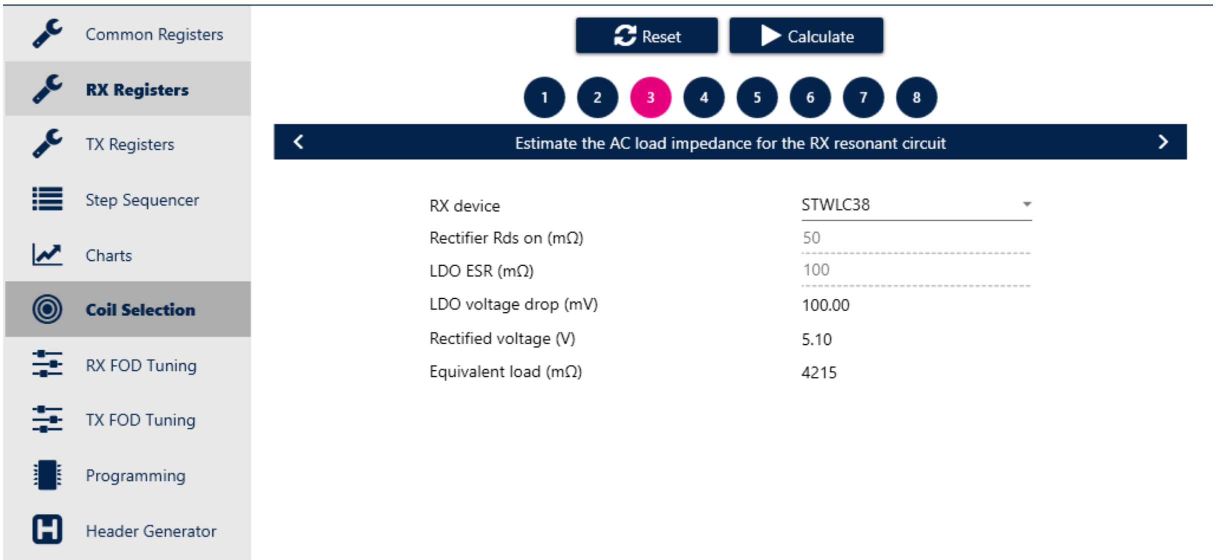
The desired TX coil can be chosen from a set of pre-loaded standard TX coils. Outer and inner diameters, nominal inductance and DC-resistance of the coil are shown. If the required coil is not listed, a custom coil can be specified by the user.

The expected distance between the transmitter and receiver coils is required next. This parameter has a significant impact on the coupling factor.

Finally, the ratio between the average diameters of the transmitter and receiver coils is shown. This ratio serves as a preliminary indication of the coupling between the transmitter and the receiver. For example, a ratio much lower than unity means that the selected transmitter coil is probably oversized for the receiver coil. For this reason, the suggested starting point is a ratio between 0.8 to 1.0. (When this condition is not met, a pop-up message will appear to highlight this.) Lower values are usually considered when larger misalignment tolerance is desired, but it would result in a lower coupling factor.

2.3 Page 3

Figure 6. **Resonant circuit load impedance**

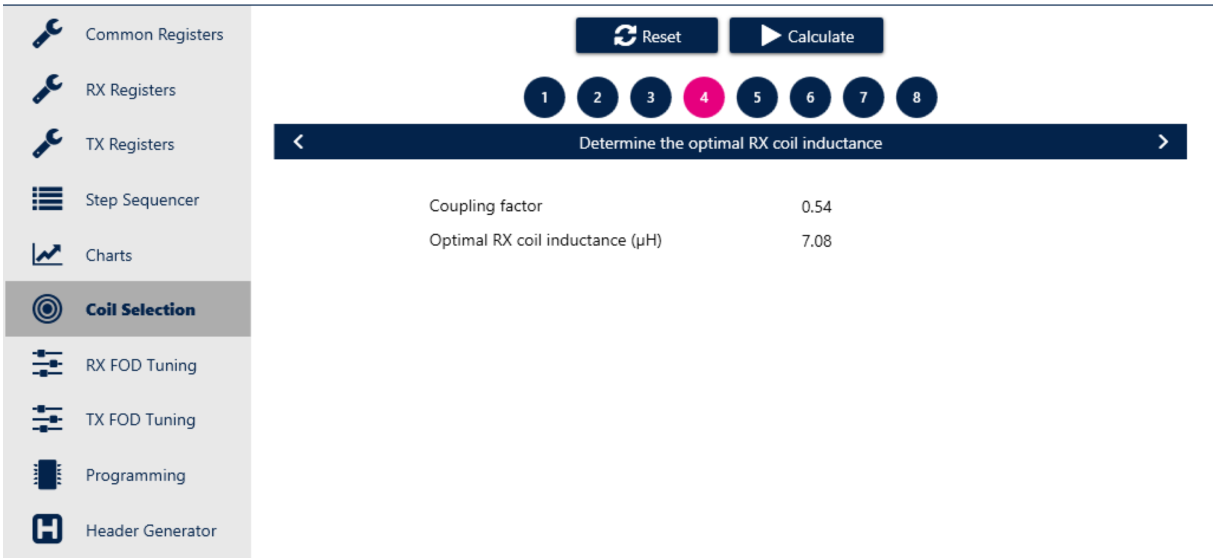


Page 3 (Figure 6) translates the selected operating point into the equivalent AC impedance seen by the L-C series resonant circuit of the receiver.

Once an RX device is selected, the internal resistances of its rectifier, current sensing resistor and main low-dropout regulator are used to calculate the voltage at the VRECT pin (output of the rectifier) and the equivalent load impedance at the AC1-AC2 pins.

2.4 Page 4

Figure 7. **Coupling factor and coil inductance estimation**



In page 4 (Figure 7), the coupling factor and inductance of the receiver coil are determined.

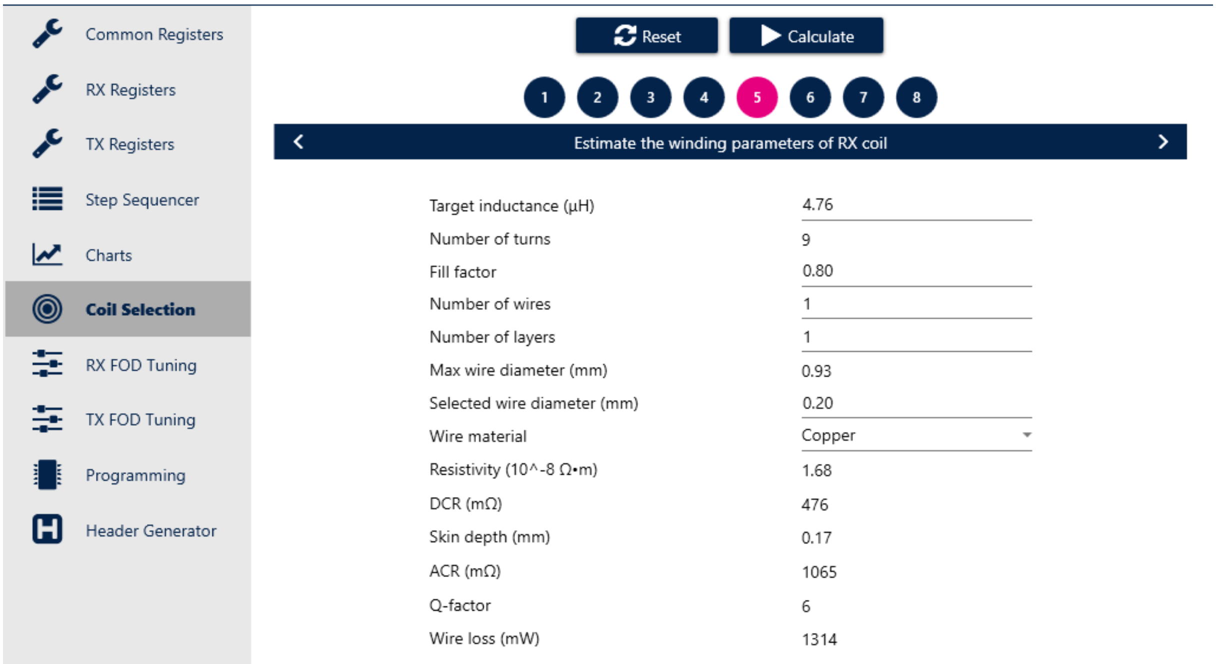
The coupling factor is estimated using Neumann’s formula from the previously defined characteristics of the TX and RX coils. This method doesn’t account for any shielding, so it tends to underestimate the coupling with decreasing distance between TX and RX coils.

The “Calculate” button needs to be pressed to perform the coupling calculation.

The optimal inductance value is estimated from the equivalent load impedance, design frequency, and the estimated coupling factor. This is the RX coil inductance when coupled with the TX coil, similar to the recommended TX coil inductance in page 2 (Figure 5. Transmitter details).

2.5 Page 5

Figure 8. Coil winding specifications



Page 5 (Figure 8) aims to present all the information needed to build a prototype RX coil.

The target coil inductance is first required. Again, there is no indication on what the relationship between coupled inductance and self-inductance is like, and a good starting point would be an RX coil with a self-inductance around 1.5x lower than the optimal inductance value from the previous page.

An estimation of the number of turns follows from the target inductance. The fill factor of the winding is preset to 0.8, but it can be changed as necessary. The winding would fit the available span between the outer and inner diameters previously defined. This includes the number of wires in parallel (which is assumed to stack horizontally) and the number of layers in series (which is assumed to stack vertically). The maximum wire diameter is then calculated.

Note: *Note: a notification will pop up if the selected wire diameter exceeds the max wire diameter when the "Calculate" button is pressed in any page.*

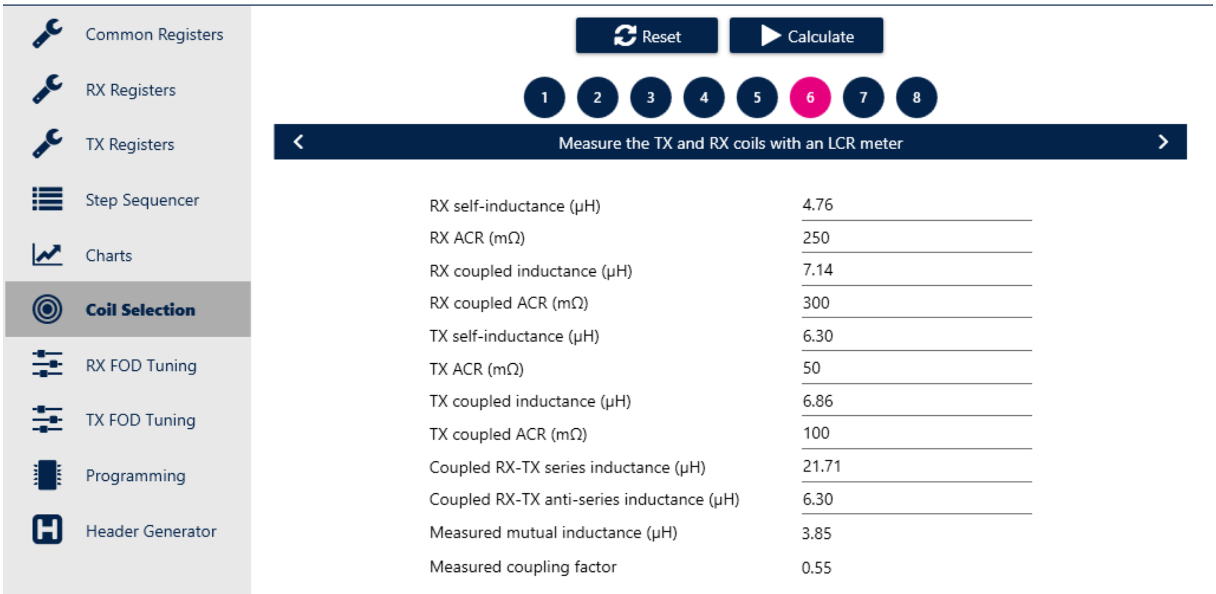
With the above inputs and resistivity from the selected wire material, a rough estimation of the DC and AC resistances, the associated wire loss and quality factor of the coil (at the operating point) are shown.

At this point of the coil design procedure, a prototype RX coil can already be built. Some iterations may be required:

- To reduce the resistance, thicker and/or multiple wires in parallel should be considered together with the constraint on the total thickness.
- When adjusting the number of turns to obtain the desired inductance value, the actual number of turns does not need to be an integer value and can be in a fraction of a loop.

2.6 Page 6

Figure 9. **Measured coil characteristics**



Page 6 (Figure 9) provides a space to record the measured electrical parameters of the TX and RX coils. Measurements should be done using an LCR meter near the design frequency. Optionally, if a coil prototype is not available, calculated results from previous sections can be entered instead.

For each of the TX and RX coil-pair, several sets of values are measured.

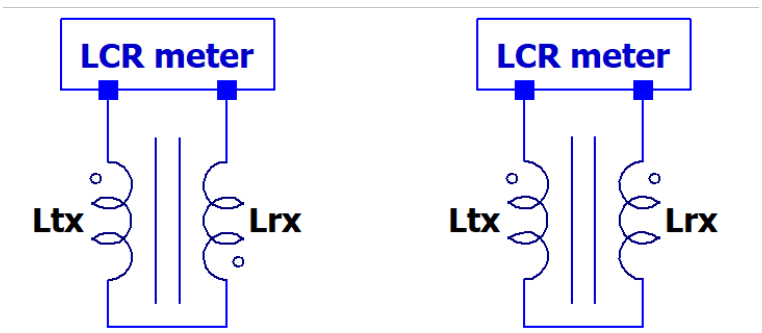
First is the self-inductance and AC resistance in free air. These measurements provide a correlation and a basis for adjustment to the coil construction parameters.

Then the inductance and AC resistance are measured when coupled as a pair. For a single coil, the proximity of the shielding of the other coil when coupled significantly reduces the reluctance of its magnetic flux path, therefore increasing the self-inductance of that coil. Additional losses that would occur in this flux path are also reflected as an increase in its AC resistance. These coupled inductances and resistances are the values used in subsequent circuit analyses.

To calculate the mutual inductance and coupling factor, couple the TX-RX coils, connect them in series (the same winding direction), and measure the combined inductance. To connect them in anti-series, swap the terminals of one coil (opposite winding direction). The connections are illustrated in Figure 10.

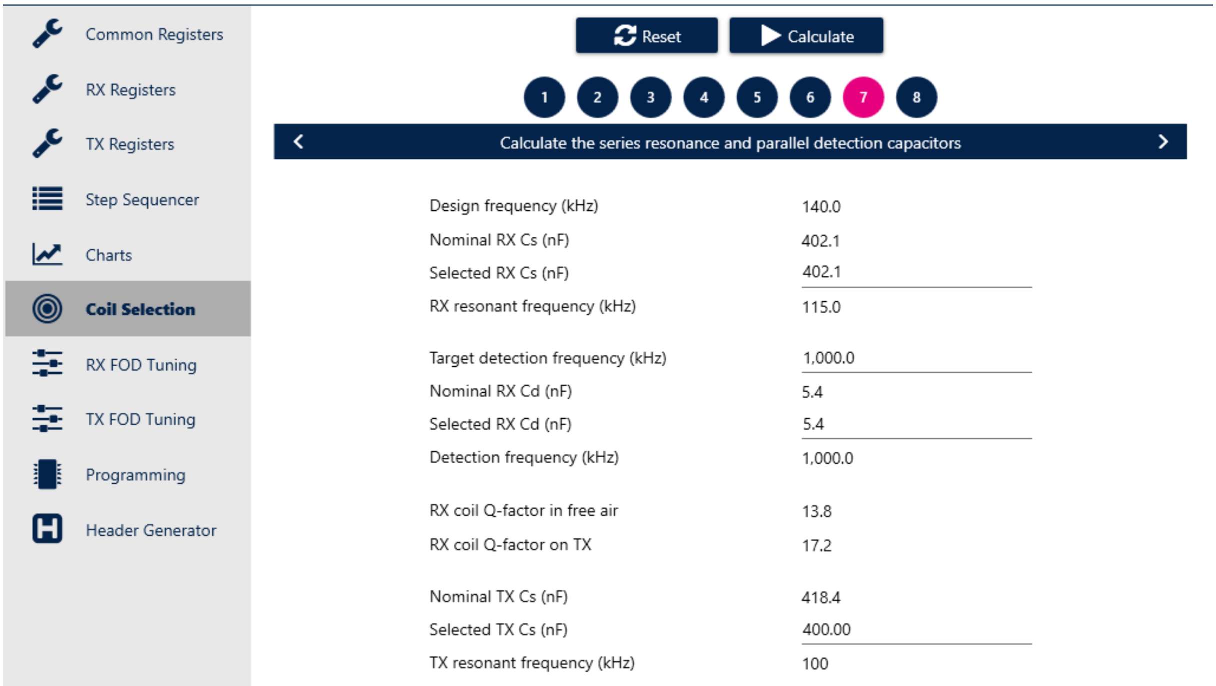
Figure 10. **Connection for measuring mutual inductance**

(a) Series connection **(b) Anti-series connection**



2.7 Page 7

Figure 11. **Cs and Cd capacitors**



Page 7 (Figure 11) calculates the capacitors to be used.

The design frequency follows the value entered in page 1, and the target detection frequency is preset as per Qi specification.

The nominal RX series and TX series capacitor values are calculated using the design frequency, the respective coupled inductances, and the measured coupling factor.

The nominal detection capacitor value is calculated using the design frequency, RX self-inductance, and nominal RX series capacitance.

For reference, the RX resonant frequency, the detection frequency and the TX resonant frequency are calculated based on the selected capacitances and the measured coil inductances in free air. It's recommended to select values close to nominal for the first design pass. And it's normal that the self-resonant frequencies would seldom coincide with the design frequency.

RX coil Q-factors in free air and on TX are also displayed for reference.

A few suggestions regarding the capacitors:

- NP0/C0G/U2J (Class 1) dielectric type is preferable whenever possible (usually indispensable on the TX side)
- The capacitance of temperature sensitive X5R/X7R (or similar Class 2) dielectric types will vary as heat is generated during power transfer. Care should be taken to limit this capacitance variation to ensure adherence to Qi specifications.
- Multiple capacitors in parallel are preferable to reduce the Equivalent Series Resistance (ESR) and increase the heat dissipation ability. Combinations of E6 or E12 values are usually the most economical.
- Excessive RMS currents easily stress the capacitors, especially if densely packed on a PCB with poor cooling.

See also datasheet of STWLC devices for additional considerations on external components.

2.8 Page 8

Figure 12. **Output current and transfer function plots**

The last page of the design tool (Figure 12) generates several frequency-sweep plots from the circuit analysis.

The circuit parameters used are listed on the left side of the plots. All parameter names correspond to the names used in the preceding pages and are directly editable apart from the rectified voltage from page 3, which is calculated from the operating point in page 1.

In the top subplot, the RX output current is estimated given a constant rectified voltage, with the corresponding coil-to-coil efficiency.

The bottom subplot provides the TX-to-RX gain (transfer function magnitude) and RX coil quality factor based on the equivalent load in page 3.

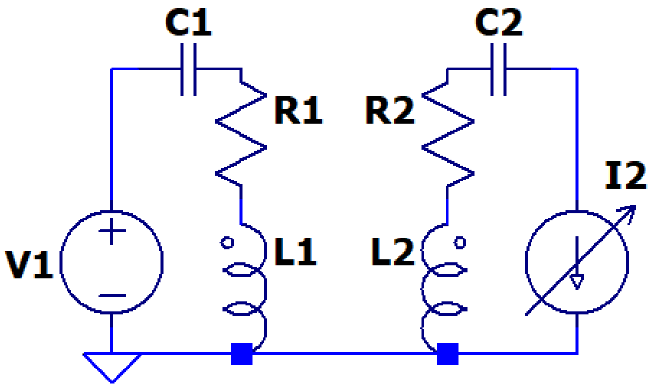
The “Calculate” button needs to be pressed to generate the plots.

The plots also have built-in navigations:

- Click and drag the right mouse button within the graph, on the horizontal or either of the vertical axes to pan.
- Scroll within the graph, on the horizontal or either of the vertical axes to zoom.
- Click and drag the middle mouse button within the graph to zoom into an area.
- Double-click the middle mouse button to reset the view.
- Click the left mouse button along the data points to see detailed values.

The circuit model used is shown in Figure 13. L1 and L2 are the measured TX and RX coupled inductances, coupled by the measured coupling factor; R1 and R2 are the measured TX and RX coupled AC resistances; C1 and C2 are the selected TX and RX series capacitors, respectively. The input voltage is converted to AC as V1. The rectified voltage is converted to AC as the voltage across I2. The resulting I2 is converted to DC as the RX output current and plotted.

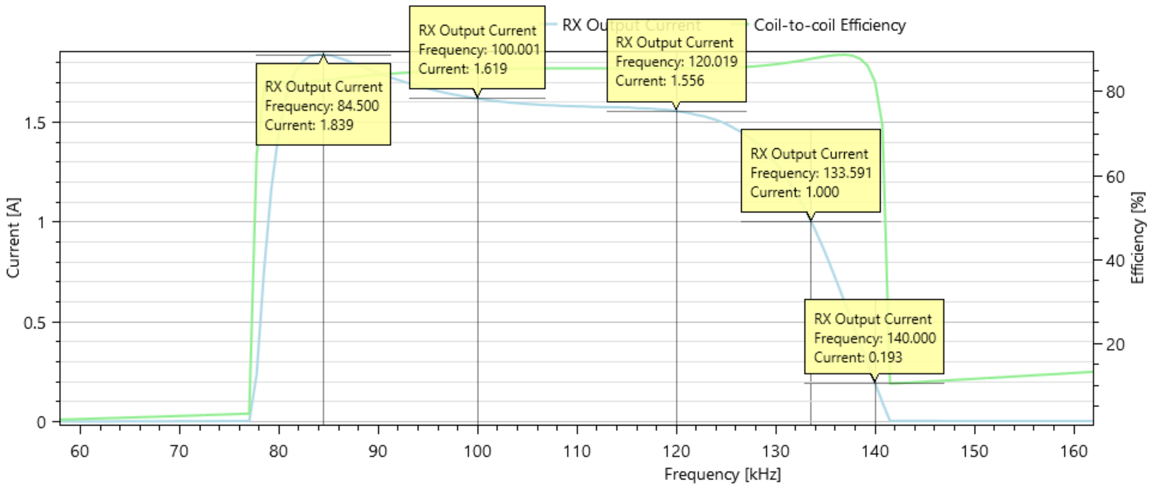
Figure 13. **Circuit model**



TX control logic commonly operates by decreasing frequency to increase the power output. Therefore for such a system, a good plot would show that the system can provide the required maximum RX output current at the lower end of the operating frequency range, and the minimum current at the upper end.

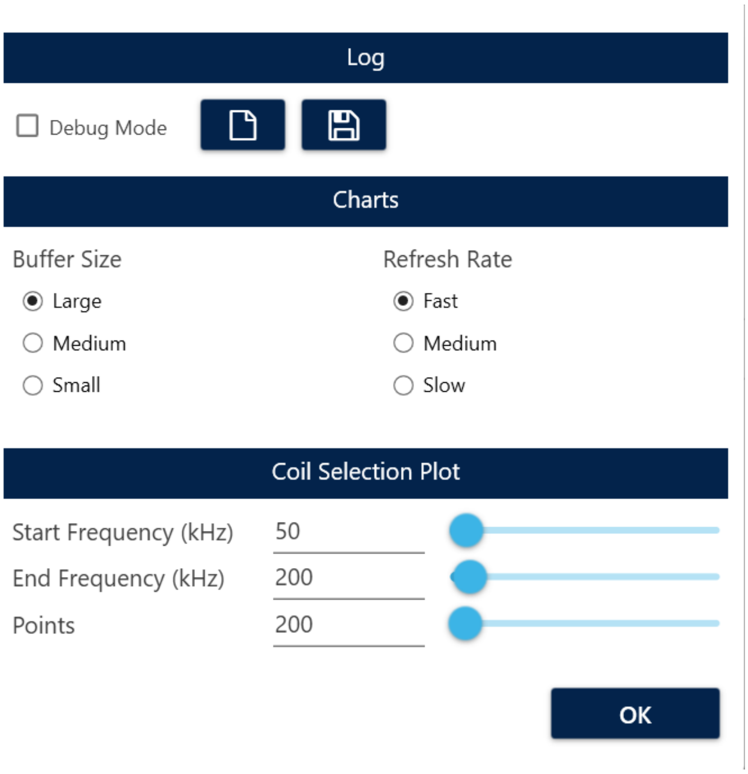
For example, the plot in Figure 14 shows that the system would output 193 mA at 140 kHz, rising to the peak of 1.839 A as the frequency is swept down to 84.5 kHz.

Figure 14. **Example plot**



2.9 Plot settings

Figure 15. Plot settings



The “Settings” menu of the GUI (Figure 15) has a section to modify the frequency range and coarseness of the coil selection plot.

The start and end frequencies are selectable from 1 to 10000 kHz. The number of points is selectable from 200 to 10000.

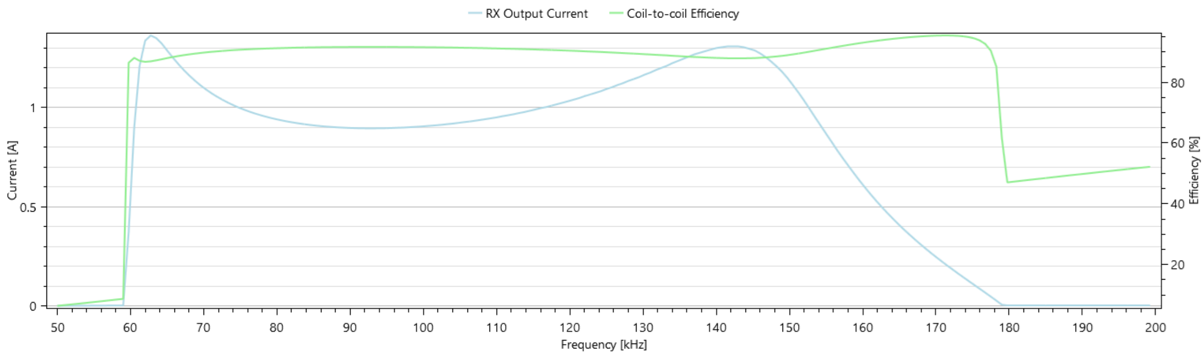
3 Tips for tuning the design

The plots predict how the circuit will behave across frequency. To explore the circuit behavior for a given input and output, the selected coil and capacitor values can be freely changed in pages 6 and 7 without any consideration for the coil construction or the actual measured values.

For example, the input-output voltage ratio or the gain of a wireless charging circuit can be thought to be proportional to the square-root of the TX-RX inductance ratio like that of a transformer. The coil inductance values can be explored accordingly.

In wireless power transfer, as the coupling increases between two resonant circuits having similar resonance, the singular peak gain at the resonant frequency may start to "split" into two peaks: one at a frequency lower and one at a frequency higher than the resonant frequency. This peak-splitting could result in a peak current in the middle of the operating frequency range. The example plot in Figure 16 shows that the output current would decrease when decreasing the frequency below 140 kHz. This would result in control failure or instability for a TX control logic that expects the opposite.

Figure 16. Peak-splitting example



One workaround is to shift the operating frequency range to avoid the problematic trough. The design frequency can also be redefined.

When peak-splitting is unavoidable and the RX output current magnitude is sufficiently high, changing the series capacitor values can help. It tends to have the following effect on the RX output current magnitude:

Table 2. Effect of Cs change on output current peaks

Capacitance change	At the low frequency peak	At the high frequency peak
Increasing Tx Cs	magnitude is increased	magnitude is decreased
Decreasing Rx Cs	magnitude is increased	magnitude is decreased

Decreasing the Tx Cs also tends to increase the frequencies of both peaks.

In case there is an insufficient or excessive RX output current, the input voltage can be changed to let the tool calculate for different gain values, as a higher gain would usually give a higher output current, and vice versa. The resulting inductance and capacitance values are then used with the original input voltage to check the final behavior.

Similarly, the TX-RX distance value can be changed to easily let the tool calculate for different coupling values. One common example is inputting a smaller distance to compensate for when the tool underestimates the coupling compared to the measurement. If the coupling in the application has a range, a circuit designed using a lower coupling usually performs better in a higher coupling condition than the other way around.

TX coil construction may be estimated using the same sections of the tool that estimate the construction of RX coil (in pages 1, 4 and 5).

For further analyses such as parametric sweep or transient analysis, circuit simulators such as LTspice may be used in conjunction with this tool.

Electromagnetic simulators such as FEMM could also help with inductance and coupling estimates.

4 Concluding remarks

Once the design of the whole wireless power received is completed, it is good practice to perform validation tests by sweeping over the full frequency range for different operating conditions. Important items to monitor, for example, are the communication between RX and TX, power transfer capability and efficiency, temperature rise which would affect the battery and user comfort.

It is also recommended to test with many different certified transmitters having various coil-types and architectures (half-bridge/full-bridge, etc.) in order to verify the robustness of the designed receiver.

Revision history

Table 3. Document revision history

Date	Revision	Changes
24-Jul-2023	1	Initial release.

Contents

List of tables

List of figures