APPLICATION NOTE

Wireless Power Charging Coil Changing Considerations

BY RAGHU NARAYANAN

1. Introduction

Wireless Power Charging is becoming more and more common in new gadgets like smarts phones, tablets and laptops. With this pace of technological growth one can certainly assume in the future that many domestic electronic devices will be charged or powered wirelessly. The number of manufacturers of wireless charging coils and control circuit chips are also expected to grow to meet increasing consumer demand. One may ask, why is the consumer market of interest to us? All known technologies have been mostly driven by the consumer electronic market, subsequently the Industrial and other similar sectors have taken advantages of the "went through learning curve" to lower their design time. The purpose of this document is to explain the methodology on how to change wireless power charging coils manufactured by Würth Elektronik eiSos on a Demo Circuit incorporating receiver control chip LTC4120 manufactured by Linear Technology.

Foreseeing the application demand of wireless charging in various portable gadgets and to help the engineers to develop more end products based on wireless charging technologies, this application note has been prepared explaining the recommended considerations and techniques of changing wireless charging coils.

2. Wireless power transfer principle

The wireless power is transferred from transmitter to receiver coil using more than a century old principle called inductive coupling. However, recent developments prove that when two resonant circuits resonating at the same frequency, designed with minimal loss and absorption (High Q) are brought into close proximity (near field area), that due to evanescent wave coupling the energy transferred from transmitter to receiver are at a high efficiency.

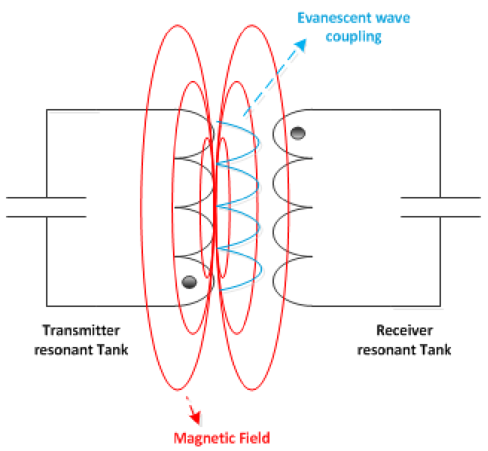

Figure 1: Wireless power transfer principle

In order for a wireless power charging system to work efficiently, the frequency of both transmitter and receiver is required to be tuned to the same frequency. For different inductance value of charging and coupling coil, other associated parts of the circuit are necessary to be changed as well in order to get the same resonant frequency. This document also explains the unique advantage of using Würth Elektronik wireless power charging coils.

3. WE Wireless Power charging coils

Würth Elektronik eiSos is a member of Wireless Power Consortium (WPC) and Alliance for Wireless Power (A4WP) now known as "Rezence" and has been developing various wireless transmitter and receiver coils compliant with Qi standard in proprietary solution. Here are few transmitter and receiver wireless coils.

Figure 2: WE Receiver Coils

Figure 3: WE Transmitter Coils

Following are the Würth Elektronik eiSos transmitter and receiver wireless coils considered for evaluation-

Transmitter coils

1. 760 308 111
2. 760 308 110
3. 760 308 104 113
4. 760 308 101 302

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Receiver coils

1. 760 308 201
2. 760 308 101 303

4. Wireless power charge controller

The wireless charge controller selected for this evaluation is Linear Technology's LTC4120, a wireless power receiver and 400mA Buck battery charger in single chip. This controller is used on demo circuit DC1967A. The resonant tank frequency in receiver board is 127 kHz when tuned and 140 kHz when detuned. The receiver demo board DC1967A is shown in *Figure 4*: DC1967A, receiver demo board*.*

Features of LTC4120:

- DHC (Dynamic Harmonization Control) optimizes wireless charge over wide coupling range
- Wide input voltage range: 4.3 V to 40 V
- Adjustable float voltage: 3.5 V to 11 V
- 50mA to 400mA charge current programmed with a single resistor
- +/-1% feedback voltage accuracy
- Programmable 5% accurate charge current
- No transformer core

The wireless transmitter demo circuit (DC1968A) is a basic transmitter designed using a current fed astable multivibrator with oscillation frequency set by a resonant tank (see *Figure 5: DC1968A, transmitter demo board*). The oscillation frequency set here is 130 kHz. However, the operating frequency would vary depending on the load at the receiver and coupling factor to the receiver coil. Another version of transmitter, manufactured by "Power by proxy" has the added advantage of foreign object detection and low standby power.

The DHC feature of the LTC4120 adjusts the frequency far or close to the transmitters resonant frequency based on the power requirement of the battery (load), when the coupling between transmit and receive coils is high, the frequency will be adjusted in order to limit the power transfer and when the coupling between the transmit and receive coil is low, the frequency will be adjusted to increase the power transfer. The feature "No transformer core" of LTC4120 provides galvanic isolation without transformer core.

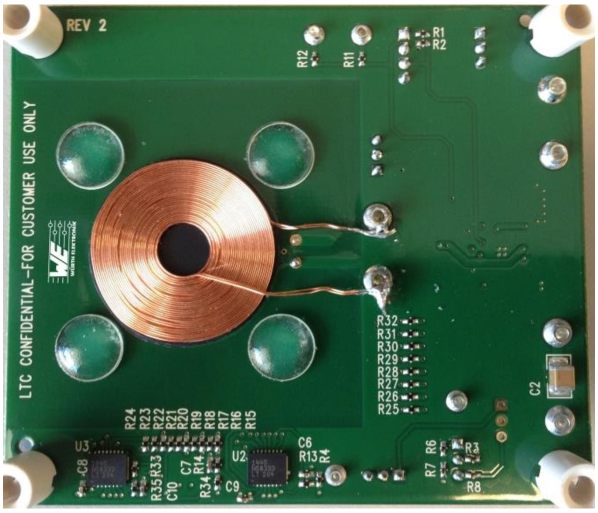

Figure 4: DC1967A, receiver demo board with WE receiver coil # 760308101303

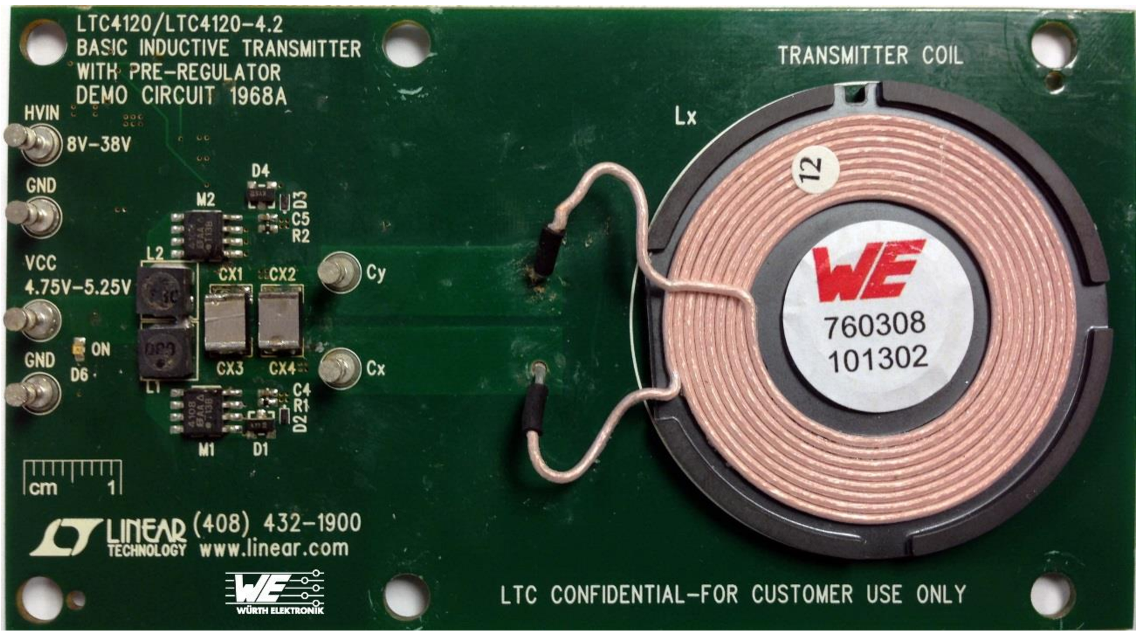

Figure 5: DC1968A, transmitter demo board with WE transmitter coil # 760 308 101 302

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5. Würth Electronik wireless coils and specification

The Wireless coils considered for this evaluation are listed in section 3, the brief specification summary is provided below for further calculations.

5.1. Transmitter coils

Part number	Inductance	DCR	Q	Size	Irated@40°C
760 308 111	6. 3 µH	17 mΩ	80	5353	13 A
760 308 110	24 µH	7 mΩ	180	5353	6 A
760 308 104 113	12 µH	60 mΩ	120	6052	6 A
760 308 101 302	5.3 µH	33 mΩ	100	Ø50	6 A

Table 1: Overview of the transmitter coils

5.2. Receiver coils

Part number	Inductance	DCR	Q	Size	Irated@40°C
760 308 201	10 µH	160 mΩ	50	3737	4.5 A
760 308 101 303	47 µH	460 mΩ	25	Ø26	1.4 A

Table 2: Overview of the receiver coils

6. Parameters to consider

It is important to understand the operation and features of wireless power charge controller LTC4120 and the specification of the coils to fit in the demo circuits. Section *3* has a list of wireless transmitter and receiver coils considered for evaluation on the demo board DC1968A and DC1967A respectively. Section *4* above explains briefly about the demo board's functions and features. The transmitter coil is driven by a current fed source in order to have a good sinusoidal signal transmitted from the transmitter.

As indicated in the datasheet of LTC4120 the selection of Lx (Transmitter coil inductance) and Lr (Receiver coil inductance) is ideally to obtain 1:3 turns ratio. The inductance values may be selected such that the size of the coil required is not too large (In case too small value of capacitor at transmitter end) and circulating current in the transmitter end is not too high (in case too small value of inductance at primary). For the right selection of resonance inductors and capacitors the backward analysis is followed below.

6.1. Receiver coil and frequency

The receiver side coil currently used in DC1969A has 47 µH, it is the embedded 4 layer PCB coil used with a ferrite base. Würth Elektronik eiSos has a coil exceeding the PCB specification by far to achieve better efficiency, the part number is 760 308 101 303, the brief specification has been provided in Table 2. For detailed specification the datasheet can be downloaded from www.we-online.com\wirelesspower

The receiver frequency changes from 127kHz to 142KHz. At tuned condition both C2P and C2S would affect the resonant frequency and at detuned condition only C2S would affect the resonant frequency.

$$Ft \cong \frac{1}{2 * \pi * \sqrt{Lr * (C2P + C2S)}}$$

$$Fd \cong \frac{1}{2 * \pi * \sqrt{Lr * C2S}}$$

When calculated using the above formula for resonant frequency when detuned (*F_D = 142 kHz**)*** the required capacitance will be C2S = 26.7 nF

*Paralleling of 22 nF and 4.7 nF provides the capacitance required.

** The detuned frequency 142 kHz instead of 140 kHz is due to limitation of available capacitance.

Similarly, for the resonant frequency when tuned (*F_T = 127 kHz)*, the required capacitance will be-

C2P = 6.75 nF,

*The closest value for this capacitance is 6.8nF,

Note: The parts used in DC1969A are 1.8 nF and 4.7 nF in parallel and with this value the frequency will be 131 kHz.

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6.2. Transmitter coil and frequency

Now that the receiver coil is selected and its inductance value is 47 µH, the transmitter coil can be selected to meet the turns ratio of 1:3 as recommended in LTC4120 datasheet.

$$n = \frac{nR}{nX} = \sqrt{\frac{Lr}{Lx}}$$

$$3^2 = 9 = \frac{47\ \mu H}{Lx}$$

$$Lx = 5.2uH$$

For the above requirement Würth Elektronik eiSos has a part 760308101302, A brief specification is 5.3 µH, 6 A, 33 mΩ & Q = 100

Frequency of resonance aimed

$$F0 \approx \frac{1}{2 * \pi * \sqrt{Lx * Cx}} = 130\ kHz$$

With the above formula to meet the transmitter resonant frequency of 130 kHz, the Cx required will be 283 nF. As this value is a non-standard part we should be able to choose 180 nF and 100nF to achieve close to the frequency intended for operation. These two capacitors will share the circulating current. More precise values can be selected to achieve the exact resonance frequency desired.

Therefore, the actual capacitance will be 280 nF and for this capacitance the resonant frequency will be:

F_0 = 130.71 kHz,

*F_0 is 0.5% higher than original required frequency.

However, the chosen capacitance value in the DC1969A is 2 x 0.15 µF

The part number = ECHU1H154GX9

The new resonant frequency with the above value will be 126.3 kHz (unloaded)

6.3. Significance of Turns Ratio (n)?

The turns ratio between transmitter and receiver coil suggested in DC1967A is 1:3, here various conditions have been chosen when meeting 1:3 turns ratio is difficult and what effect this would cause in the performance? The circuit has been modified to draw more power from the coil by setting the output voltage to 8.23V while being able to provide as maximum current as possible and maintain highest possible efficiency.

6.3.1. Condition# 1

Tx: 760 308 101 302 (5.3 µH, 33 mΩ, Q: 100, 6 A)

Rx: 760 308 101 303 (47 µH, 460 mΩ, Q: 25, 1.4 A)

$$n = \sqrt{\frac{47\ \mu H}{5.3\ \mu H}}$$

$$n = 3$$

Measurements results:

*V_{CC} = 5 V

*I_{INPUT} = 0.973 A

*V_{IN_LR} = 15.04 V

*I_{IN} = 0.239 A

V_{BAT} = 8.21 V

I_{BAT} = 0.275 A

P_{MAX_BAT} = 4.865 W

Efficiency (η) = $(V_{IN\_LR} * I_{IN})/(V_{cc} * I_{INPUT})$ = 73.9%

6.3.2. Condition# 2

Tx – 760308104113/12 µH/60 mΩ/Q-120/7 A

Rx – 760308101303/47 µH/460 mΩ/Q-25/1.4 A

$$n = \sqrt{\frac{47\ \mu H}{12\ \mu H}}$$

$$n = 1.97\ \approx 2$$

Measurements results:

*V_{CC} = 5V

*I_{INPUT} = 0.224A

*V_{IN} = 11.85V

*I_{IN} = 0.072

V_{OUTPUT} = 8.23V

I_{OUTPUT} = 0.05A

P_{MAX_BAT} = 1.12W

Efficiency (η) = $(V_{IN\_LR} * I_{IN})/(V_{cc} * I_{INPUT})$ = 76.2%

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6.3.3. Condition# 3

Tx – 760308110/24 µH/7 mΩ/Q-180/6 A

Rx – 760308101303/47 µH/460 mΩ/Q-25/1.4 A

$$n = \sqrt{\frac{47\ \mu H}{24\ \mu H}}$$

$$n = 1.4$$

Measurements results:

*V_{CC} = 5V

*I_{INPUT} = 0.1 A

*V_{IN} = 11.65 V

*I_{IN} = 0.025 A

V_{OUTPUT} = 8.23 V

I_{OUTPUT} = **0.013 A**

P_{MAX_IN} = 0.5 W

Efficiency (η) = $(V_{IN\_LR} * I_{IN})/(V_{cc} * I_{INPUT})$ = 58.3%

6.3.4. Condition# 4

Tx – WT-505060-8K2-LT/5.0 µH/30.3 mΩ/Q-80/X A

Rx – 760308101303/47 µH/460 mΩ/Q-25/1.4 A

$$n = \sqrt{\frac{47\ \mu H}{5\ \mu H}}$$

$$n = 3.07$$

Measurements results:

*V_{CC} = 5 V

*I_{INPUT} = 1.159 A

*V_{IN} = 13.16 V

*I_{IN} = 0.314 A

V_{OUTPUT} = 8.21 V

I_{OUTPUT} = 0.275 A

P_{MAX_BAT} = 5.795 W

Efficiency (η) = $(V_{IN\_LR} * I_{IN})/(V_{cc} * I_{INPUT})$ = 71.3%

Note:

*V_{IN} = Voltage at the test point VIN of DC1967A

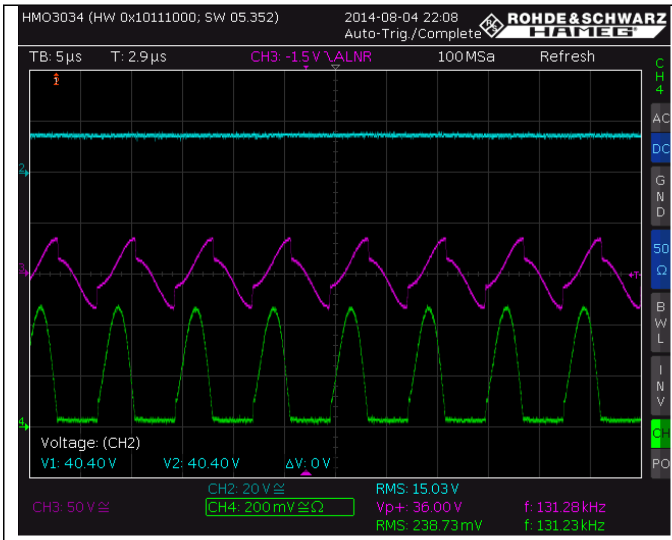
*I_{IN} = Current delivered by the receiver coil

*V_{CC} = Input voltage to transmitter board DC1968A

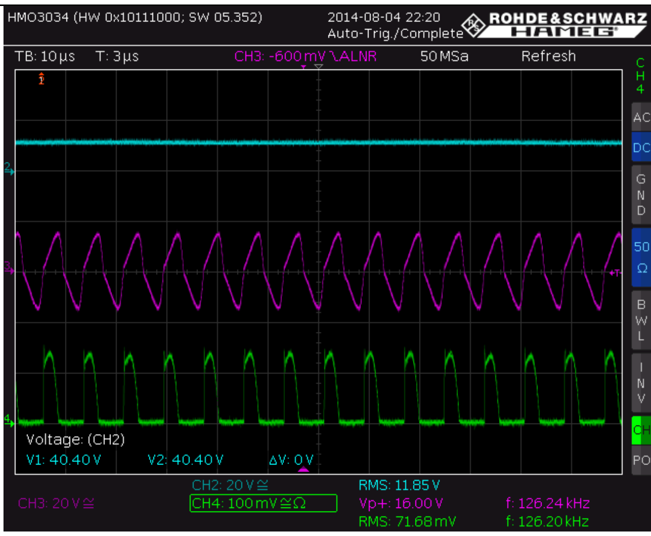
*I_{INPUT} = Current delivered by the VCC voltage source

Scope captures

These scope captures are related to each test cases listed above. In the scope captures Ch1 is the rectified received signal, Ch2 has no signal, Ch3 is receiver signal and Ch4 is rectified receiver current.



6a. Condition# 1, Tx – WE# 760308101302, L – 5.3 µH



6b. Condition# 2, Tx – WE# 760308104113, L-12 µH

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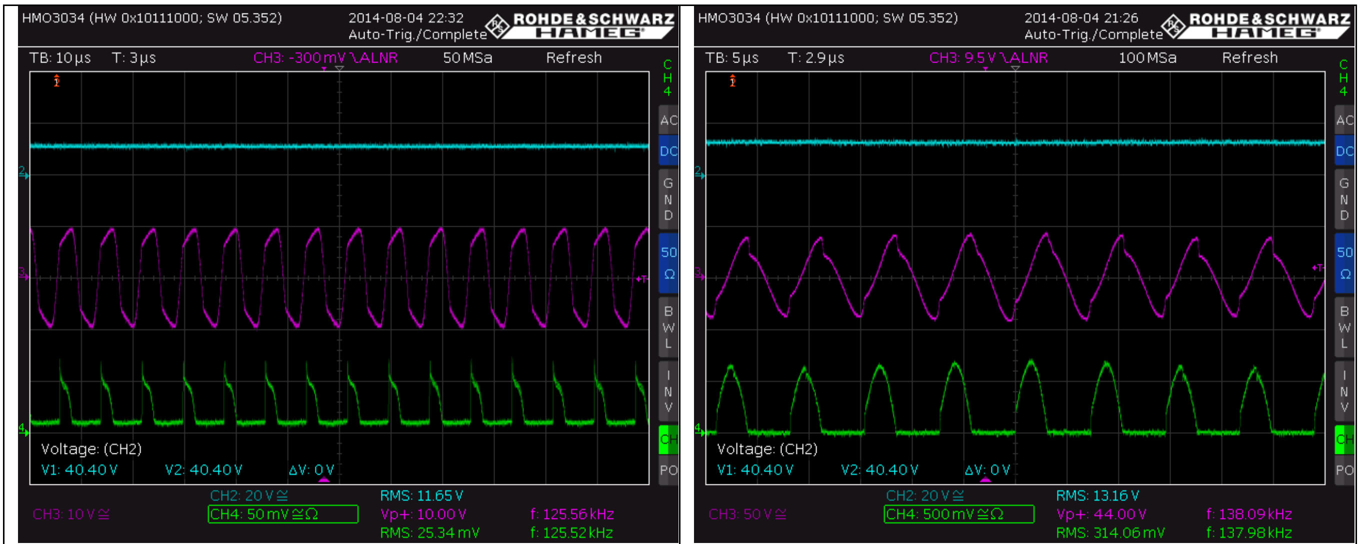

6c. Condition# 3, Tx – WE# 760308110, L – 24 µH

6d. Condition# 4, Tx – TDK# WT-505060-8K2-LT, L- 5.0 µH

Figure 6: Scope captures of various test conditions

By analyzing these signals it can be concluded that condition #1 is exhibiting the best performance. The criteria considered are the coil's efficiency and the ability to support the maximum load current while maintaining as high voltage as possible at the receiver end. It has been observed that the performance of power transfer is better when turns ratio of the Tx coil and the Rx coil is 1:3 but having lower turns ratio will obviously reduce the amount of signal transferred to receiver side and thereby not being able to supply sufficient load current. This is the situation in condition 2 & 3, where the coils are not able to support more than 1.895W & 1.18W respectively.

Therefore, 1:3 turns ratio between transmitter and receiver is significant but not limited to choosing the right size, shape and thickness of ferrite base and the placement of winding on the ferrite base.

6.4. Circulating current

The circulating current in the LC tank of primary and secondary, needed to be estimated for reliable operation of the circuit. The estimated voltage across the primary coil is-

$$Vpk - pk = 2 * \pi * VinDC$$

$$Vpk - pk = 2 * 3.14 * 5$$

$$Vpk - pk = 31.4\ V$$

Therefore,

$$Vpk = 15.7\ V$$

The reactive impedance offered by the 0.3 µF capacitor at frequency 126.3 kHz is –

$$Xc = \frac{1}{2\pi fc}$$

$$Xc = 3.74\ \Omega$$

The above calculated Xc will result in circulating current of approx. 4.2 A pk & RMS current of approx. 3 A.

Therefore, each capacitor 0.15uF should be selected such that it has permissible RMS current of at least 1.5A at 126.3kHz. The chosen capacitor is ECHU1H154GX9 and this has about 1.5Arms permissible current. Likewise, the circulating current is different at different test condition; a short summary is as below-

i. Condition# 1 – 2.07 Arms
ii. Condition# 2 – 0.931 Arms
iii. Condition# 3 – 0.459 Arms
iv. Condition# 4 – 2.14 Arms

6.5. Input Current

The amount of input current drawn to produce enough secondary current is a function of magnetic field produced at the primary coil and the magnitude of magnetic field is directly proportional to the transmitter coil current and its a product of input current and the value of Q.

$$B = Q * I_{Lx}$$

Therefore, while choosing the primary coil one should pay attention to the Q value of the coil. Würth Elektronik eiSos transmitter part 760308101302 has Q of 100, the highest compared to its competitors part to date. The input current required to supply the load current can be optimized or minimized by using transmitter coil with high Q value as possible and the optimized turns ratio. If the turns ratio is high the DHC function will ensure that not too much input power is transferred to the receiver side. Refer to test condition 1 & 2 where condition 1 has higher received signal and the DHC function is active to limit the voltage supplied to DC-DC converter (The Ch2 signal has sharp fall every cycle when the DHC pin is pulled to ground). compared to condition# 2, where the turns ratio is just 1:2 and this does not satisfy the condition (VIN>V_DHC) for DHC pin to pull down. Therefore, the efficiency of the power transfer is highest among four test condition

6.6. R_{DC}

The R_{DC} of transmitter and receiver coils is directly proportional to the resistive loss, therefore lower R_{DC} of the coils is preferred to achieve higher efficiency.

The resistance of secondary coil affects the efficiency of secondary coil, which is given by-

$$\frac{RL}{R2 + RL}$$

The R_{DC} of the Würth Elektronik eiSos transmitter coil (760 308 101 302) is 33 mΩ & the RMS current: 2.2 A

Therefore, the Power loss: I^2 * DCR = 0.16 W

6.7. Reflected impedance

The resonant frequency of both transmitter LC tank and receiver LC tank do change at loaded and unloaded condition. It is important to understand what affects the reflected impedance in resonant coupling circuit and how the effect of reflected impedance affects the performance of the system.

To understand the factors which affect the reflected impedance, following are the explanations.

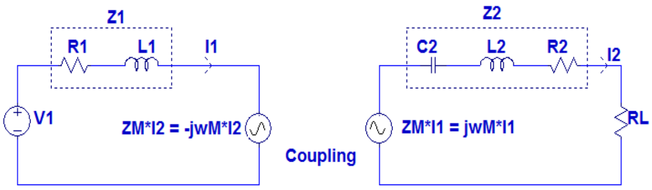

Figure 7: Coupled circuit model

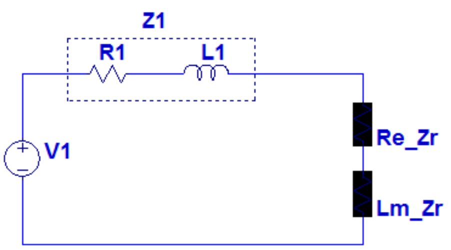

Figure 8: Equivalent primary model with reflected impedance

The reflected impedance, Zr can be expressed with the following equation:

Kirchhoff's equation of primary from figure 6

$I1Z1 + I2ZM = V1$ → Equation 1

Kirchhoff's equation of primary considering shorted load

$$I1ZM + I2Z2 = 0$$

$$I2 = \frac{-I1Zm}{Z2}$$ → Equation 2

Substituting the value of I2 in equation 1

$$Zeq = \frac{V1}{I1} = Z1 - \frac{(Zm)^2}{Z2}$$

Where, Zm = -jωM

M = Mutual inductance between primary and secondary

$$Zeq = Z1 - \frac{\omega^2 M^2}{Z2}$$

Hence, the reflected impedance in the circuit can be expressed as $\frac{\omega^2 M^2}{Z2}$

When the secondary circuit resonates at the same frequency as primary, only the resistive impedance gets reflected at the primary not inductive or capacitive, the resistive impedance of secondary circuit is

$$Z2 = R2 + RL$$

Therefore, the reflected impedance when both the circuits are resonating at the same frequency will be-

$$ReZr = \frac{\omega^2 M^2}{R2 + RL}$$

The efficiency of the system is expected to be more when the ReZr term is higher.

However, substantial decrease in load resistance RL will also affect the secondary efficiency because Rs will dominate with respect to the voltage drop,

Secondary voltage drop factors-

$$\frac{RL}{R2 + RL}$$

6.8. DHC Function

The DHC function of the LTC1967A would move the frequency of resonance to a preset detuned frequency of 140 kHz when the coils have a better coupling factor which means the voltage at VIN is more than 14 V and would be tuned to 127 kHz when coils have low coupling factor that is VIN is below 14 V

Therefore, when the coil for a transmitter circuit is selected it is important to choose the resonant frequency higher than the receiver frequency set at tuned state. This will ensure same frequency at receiver as transmitter resonance and this circuit will work like double tuned resonant circuit thereby chip will ensure full power transfer.

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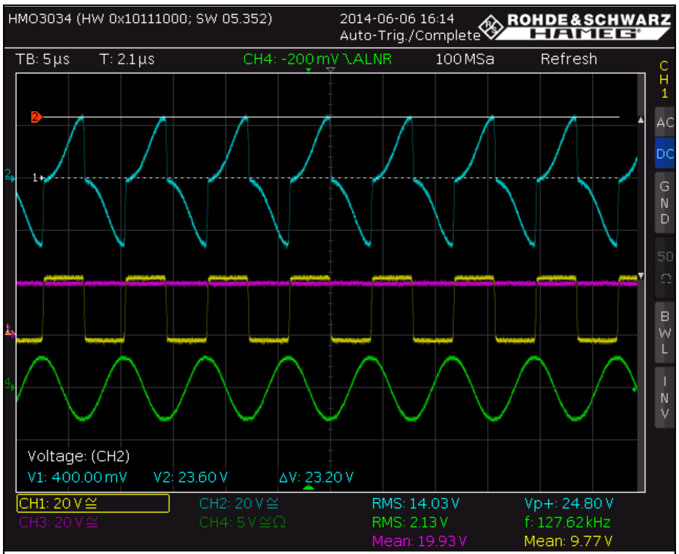
The below scope capture shows the signal at Ch1, a square pulse at the transmitter frequency. Every time the received signal at VIN is higher than voltage at DHC pin, the DHC pin is pulled down to ensure the VIN (Ch3) does not increase further. The CH2 trace is signal across receiver winding and CH4 signal is current through transmitter.



DHC Function verification when VIN>V at DHC pin

Figure 9: DHC function verification

7. Summary

Higher coupling, lower physical distance between transmitter and receiver and higher turns ratio will ensure higher voltage at receiver and so higher VIN. The DHC function will limit the VIN available to DC to DC converter and will ensure the transmitter operating at wide operating voltage. It has been seen from the experiment (Condition # 2) that the efficiency is higher when the signal received is more sinusoidal. Therefore, when the application demands for wider input voltage higher turns ratio (Approx. 3) may be selected and when higher efficiency is demanded the optimized value of turns ratio (when the signal received is sinusoidal) is recommended.

The transmitter and receiver coil must be selected carefully considering all above listed parameters for high efficiency and/or wider input operation performance of the wireless power transfer demo circuit DC1969A. Various transmitter and receiver power charging coils produced by Würth Elektronik eiSos are available with high Q making the power transfer more efficient.

8. Appendix

8.1. Bill of Material

Few parts were changed to see the performance of the coupling and power transfer when the turns ratio is less than 3 and details of the parts modified are provided below:

Designators	Condition 1	Condition 2	Condition 3	Condition 4
Lx	760 308 101 302 (5.3 µH; 33 mΩ; Q-100)	760 308 104 113 (12 µH; 60 mΩ; Q-120	760 308 110 (24 µH; 7 mΩ; Q-180)	WT-505060-8K2-LT (5 µH; 30.3 mΩ; Q-80)
Lr	760 308 101 303 (47 µH; 460 mΩ; Q-25)	760 308 101 303 (47 µH; 460 mΩ; Q-25)	760 308 101 303 (47 µH; 460 mΩ; Q-25)	760 308 101 303 (47 µH; 460 mΩ; Q-25)
CX1	ECHU1H154GX9 (PPS; 0.15 µF; 50 V)	ECHU1H154GX9 (PPS; 0.15 µF; 50 V)	ECHU1H154GX9 (PPS; 0.082 µF; 50 V)	ECHU1H154GX9 (PPS; 0.15 µF; 50 V)
CX2	ECHU1H154GX9 (PPS; 0.15µF; 50V)	Not used	Not used	ECHU1H154GX9 (PPS; 0.15 µF; 50 V)
R_{FB1}	2.0 mΩ	2.0 mΩ	2.0 mΩ	2.0 mΩ
R_{FB2}	825 kΩ	825 kΩ	825 kΩ	825 kΩ

Table 3: Bill of Material

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IMPORTANT NOTICE

USEFUL LINKS

Application Notes:
http://www.we-online.com/app-notes

Component Selector:
http://www.we-online.com/component-selector

Toolbox:
http://www.we-online.com/toolbox

Product Catalog:
http://katalog.we-online.de/en/

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