CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF ELECTRICAL POWER ENGINEERING

Bachelor Thesis

Multi-coil Qi Charger

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Study Programme: **Electrical Engineering and Computer Science (EECS)**

[July 2019]

BACHELOR'S THESIS ASSIGNMENT

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II. Bachelor's thesis details

Bachelor's thesis title in English:

Multi-coil Qi charger

Bachelor's thesis title in Czech:

Bezdrátová nabíječka Qi s více cívkami

Guidelines:

1) Perform a research of the current state-of-the-art of the Qi wireless charging technology with multiple coils.
2) Design a suitable coil configuration for a demonstration charger with an area of at least 10x20 cm. The field of coils should be simply expandable to a larger area.
a. Analyze what maximum area coverage can be achieved.
b. Analyze the behavior of the coil array in the case of a moving receiver.
3) Design the charger transmitter and receiver electronics.
4) Make a functional sample and measure its properties.

Bibliography / sources:

[1] G. Vigneaux, M. Cheikh, R. Benbouhout and A. Takacs, "Design and modeling of PCB coils for inductive power charging" Wireless Power Transfer, Cambridge University Press, 2015, 2 (2), pp.143 - 152.
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https://www.wirelesspowerconsortium.com/knowledge-base/specifications/download-the-qi-specifications.html

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Date of bachelor's thesis assignment: **11.04.2019** Deadline for bachelor thesis submission: **24.05.2019**

Assignment valid until: **19.02.2021**

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt	Student's signature

Declaration

I hereby declare that this thesis is the result of my own work and that I have clearly stated all information sources used in the thesis according to “Methodological Instructions of Ethical Principle in the Preparation of University Thesis”.

In Prague, 20.05.2019 Signature………………………

Acknowledgments:

I would like to express my very great appreciation to my parents for giving me the opportunity to study and their constant support.

I would like to offer my special thanks to my Supervisor Dr. Pavel Masa for his guidance.

I am particularly grateful for the assistance given by Dr. Vojtěch Petrucha, Jiří Náhlík and Jiří Hospodka.

Abstract:

The present bachelor thesis explores the wireless power transfer systems. The basic example of inductive WPT system may be considered as 2 coupled inductors with air-core and compensating capacitors for setting the resonant frequency of the system to the required range (200 kHz). This paper concentrates mostly on inductive power transfer with compensating capacitors. The purpose of this bachelor thesis is to investigate to what extent the position of receiver effects the coupling of the coils in near field and power transfer. Before the main experiment the prototype design was assembled to obtain the transfer function and faults the system may face. Two-layer PCB was assembled in order to show the coupling between transmitter and receiver coils with power transfer over 60 percent. Major finding of the study is that the overall efficiency decreases when transmitter coil is moved away from receiver coil. Wireless power transfer is only possible in high frequency (more than 87 kHz) and both transmitter and receiver coils should be in resonance.

Keywords:

WPT, Qi, IPT, IC, Inductive power transfer, Qi consortium, inductive coupling, Multi coil Qi charger, PCB.

Abstrakt:

Cílem této bakalářské práce je popsat bezdrátový přenos energie. Základní příklad indukčního bezdrátového přenosu energie jsou dvě vázané cívky se vzdušným jádrem a kompenzujícími kapacitátory kvůli nastavení resonující frekvence na daný rozsah(200 kHz). Tato práce se hlavně soustředí na indukční přenos energie s komoenzujícími kapacitátory. Cílem této bakalářské práce je prozkoumat do jaké míry pozice přijímače ovlivňuje vázání cívek komunikaci a energii. Před hlavním experimentem byl sestaven prototyp na získání přenášecí funkce a chyb na které by systém mohl narazit. Dvojvrstvý plošný spoj byl sestrojen aby se ukázalo vázání cívek s přenosem energie přes 60 procent. Hlavní nález studie je, že efektivita klesá se vzrůstající vzdáleností mezi cívkami. Bezdrátový přenos energie je možný pouze s vysokou frekvencí (více jak 87 kHz) a obě cívky musí resonovat.

Klíčová slova:

WPT, Qi, IPT, IC, Indukční přenos energie, Qi Konsorcium, indukční vazba, Bezdrátová nabíječka Qi s více cívkami, DPS.

List of Abbreviations:

WPT- wireless power transfer

EMF- electromotive force

IPT- inductive power transfer

CPT- capacitive power transfer

MPT- microwave power transfer

HF- high frequency

MRC- magnetic resonant coupling system

NASA- national aeronautics and space administration

PCB- printed circuit board

IC- inductor coil

RMS- root mean square

FOD- foreign object detection

PMOD – parasitic metallic object detection

AC- alternating current

List of symbols:

Tx - transmitter coil

Rx– receiver coil

X1 – Reactance of transmitter coil

X2 – Reactance of receiver coil

LT – inductance of transmitter coil

LR – inductance of receiver coil

C1 – capacitance of transmitter coil

C2 – capacitance of receiver coil

I1- current in the transmitter coil

I2 – current in the receiver coil

V1 – Voltage in transmitter coil

V2- Voltage in receiver coil

M- mutual inductance

k – coupling coefficient

f – frequency

P1 – power in the transmitter coil

P2- power in receiver coil

ω – angular frequency

η – efficiency

d_{in}- inner length of inductor coil

d_{out}- outer length of inductor coil

w_{trace}- length of the trance

$w_{between}$- length between the traces

h_{trace} – height of the inductor trace

h_{pcb}-height of the PCB

D_{edge}- distance of inductor from the edge of PCB

S_{coil}- distance between the coils

η_{system}- efficiency of the system

μ_o – permeability of free space

n – number of turns of the coil

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Introduction:

WPT was first demonstrated by Nikola Tesla in 1898[1]. He approved that the resonant system allows electromagnetic coupling in near-field between transmitter and receiver coils.

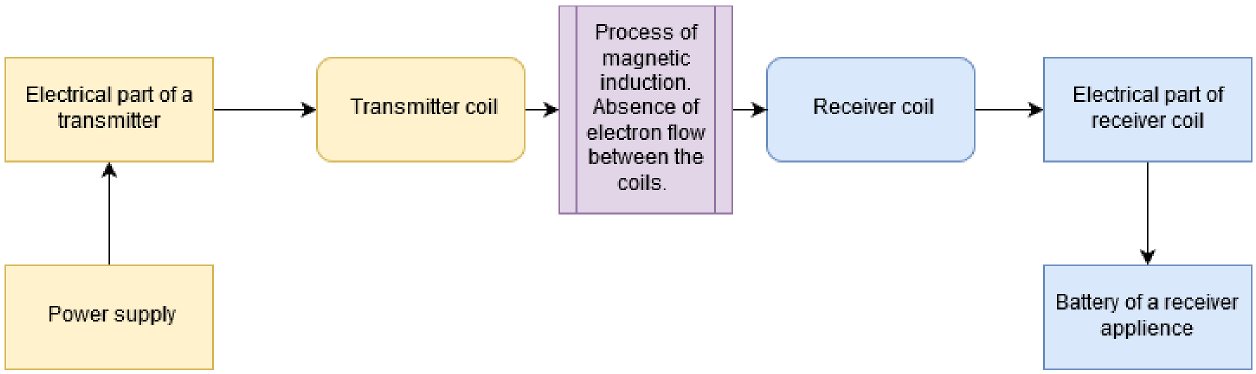


Figure .1 diagram of simple WPT system.

You may observe a detailed diagram above on (Fig.1). Electricity is transferred to the electrical part of the transmitter, and then it is being sent to transmitter coils which transforms electricity to a magnetic field. The magnetic field will induce a current in a receiver coil which will transport electricity to the electrical part of the receiver coil and finally to the battery of the suitable device.

What is WPT:

"The Wireless Power Consortium (WPC) is a worldwide organization that develops and promotes the global interface standard for wireless power transfer Qi(chee). Interface standards ensure the interoperability of devices that conform to that standard. Supported by more than 200 companies and with over 100 registered products, Qi has become the international wireless-charging standard for hand-held consumer electronics" [2]

For high frequency application of WPT, skin effect occurs. In order to reduce that effect in 19 century Litz wire was invented. Furthermore, development of Litz wire allowed to diminish the skin and proximity effects of the wire losses bringing the contribution to WPT systems and making it more efficient.

Recently there is rapid growing attention towards the wireless charging and power transfer, which has sparked my eager to investigate on a problem of wireless energy transfer. I was first introduced to wireless electrical charging when I saw a new toothbrush with wireless charging by an advertisement video on the internet. Since then the technology is multiplying, and now we can see different types of qi charger receivers and phone companies are applying this technology to their products.

The key feature of the wireless energy transfer is the ability to transfer power from a transmitter to a receiver load without any electric and mechanical connections between them. This may provide a lot of advantages for phone companies or any other fields where the certain levels of water and dust insulation are required.

“The WPC actively investigates new applications for wireless power transfer, such as cordless kitchen solution that uses power transmitters installed underneath countertops and tablets that enable a variety of kitchen appliances and smart cookware to operate without power cords” [2]

Most of the previous studies about inductive coupling show that the main contributor to the power loss is the increase in distance between transmitter and receiver coils. Therefore, we will examine to what extent is this statement true and try to design such a transmitter and receiver configuration to minimize power loss.

There are three major solutions to the current state of art problem of wireless charging. One of them is inductive charging, which transfers energy through electromagnetic field between two coils using electromagnetic induction. The second one is Capacitive charging which is thought to work only over small distances and is viewed as very dangerous method of WPT. The third one is microwave method which is used for far- field applications and has very high-power transfer but low efficiency.[2]

Nowadays, we may see basic Wireless charging systems everywhere, starting from Samsung smartphones and finishing at Starbucks where you may now just leave your phone on the table and it will start charging automatically. This rapid growth of technology wouldn’t be possible if the Wireless Power Consortium (WPC) which is a worldwide organization currently working in that field, wouldn’t develop a protocol so called Qi standard. It ensures the interoperability of devices that conform to that standard and now became the international wireless-charging standard for the consumer electronics.[3]

Advantages of WPT systems:

The continued growth of Qi wireless devices and chargers is also reducing the need for product-specific cables[4] which can lead to unified standards for all electronic devices in near future.

Cheap hand-held solutions which leads to fast growth of the market.

Since the wires don’t have to be attached to the electronic devices manually[4], it could potentially lead to an increase in product life.

Both transmitter and receiver coils can be completely sealed[4] which could allow the use of such electronic devices in the places where certain levels of insulation are required.

The continued growth of technology decreases the demand for producing wires, insulation and additional waste materials.

Disadvantages of WPT systems:

Although, the hand-held solutions seem to be cheap some particular solutions for far-field applications require a lot of financing.[5]

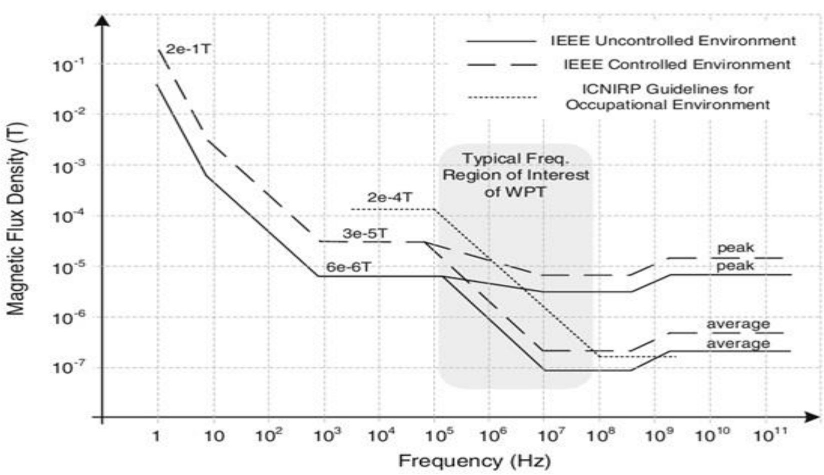
The fastest way to transfer electricity is through conductive wire, that's why the time for charging hand-held devices is greater.

Since power transfer takes place through air a lot of energy is lost to the medium[5].

When the power which is being transferred is high, the approach of WPT might be dangerous for living creatures[5].

Health and safety:

"Although there are still no authoritative international standard dedicated for the wirelessly power transfer for biomedical systems, there are two international electromagnetic standards for public safety that we could take as references. One is the ''IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Field'' from the Institute of Electrical and Electronics Engineers (IEEE). The other is the ''ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, magnetic, and Electromagnetic Fields'' from the International Commission on Non-Ionizing Radiation Protection (ICRIRP)"[6]



Graph 1. maximum permissible exposure of time-varying magnetic field suggested by the IEEE standard and the ICNIRP guideline " [6]

"The IEEE standard covers the frequency in range from 1 Hz to 300 GHz. The ICNIRP guideline applies to frequency in range from 3 kHz to 300 GHz. Both of them cover the typical operating frequency range in the wireless power transfer, which is from 0.1 to 100 MHz"[6]

We may conclude that typical frequency of standard WPT system is safe for health. Although, the article states that it only applies for controlled environments and generally healthy people.

But if we would use this technology for people who are in risk of disease, same approach couldn't be used. Controlled environments mean that the people are aware that they are being exposed to magnetic radiation.

Qi standards:

There are several features which must be taken into consideration before designing any WPT system. All the considerations are specified in Power Class 0 Specification.

First of all, we have to understand at which power levels we would like to proceed in. Power class 0 allows power transfer from 5W and up to 30 W of load power. Actual power transfer can be negotiated depending on the transmitter and receiver designs.

"For example, if the power receiver is designed to be charged by a 15 W power transmitter but is placed on a 5 W power transmitter, the power receiver may allow charging at a slower rate. Conversely, if a 5 W power receiver is placed on a 15 W power transmitter, the power receiver will instruct the power transmitter to send no more than 5 W of power." [7]

Second factor which has to be taken into consideration is operating frequency of the device. Qi standard recommends to use frequency, which ranges from "87 to 205Khz"[7]. Both transmitter and receiver coils should be in resonance in order to transfer the power in most efficient way. For general purposes, it is recommended to set the resonance frequency closer to 205 kHz which would lead to higher transfer rates as a result.

Third factor is charging area of transmitter and receiver coils. Power class 0 is based on 2 coils with transmitter coil (50mm diameter) and receiver coil (40mm diameter). Transmitter coil should be larger or the same as a receiver coil. Although, the paper specifies that the actual designs may differ and could be adjusted for the needs of the specific solution.

"Ideally, the coils should be perfectly aligned for maximum power transfer but misaligning the coils by several millimeters mm (about ¼ inch) should not be a problem." [7]

The reason for perfect alignment is coupling of the coils since the magnetic flux of transmitter coil should cross effective area of receiving coil. Additionally, the Qi standard is developing every day and additional coil alignments could be approved in future.

The fourth factor is Coupling requirements. There are four major requirements which are: the Transmitter Tx and Receiver Rx coils use exactly the same coil, the Tx and Rx are perfectly aligned, the distance between the coils is small (less than the diameter of the coils), the coils are externally shielded by ferrite.[3]

There is a special communication Protocol which is executed by Tx and Rx coils.
"The power receiver uses amplitude shift keying to communicate requests and other information to the power transmitter by modulating its reflected impedance. The power transmitter uses

frequency shift keying (FSK) to provide synchronization and other information to the power receiver by modulating its operating frequency."[7]

The last and one of the most important factors is Foreign object detection. Since we are dealing with alternating current, which transfers energy with the magnetic field, there would also be some eddy currents induced in the materials which are exposed to it. For example: "coins, keys, paperclips, etc." [8] That could lead to unnecessary heating in those materials and cause fire. Power transmitter cannot detect them when these objects are placed with the receiver. However, when for instance keys would be left on the transmitter it could reduce frequency.

Foreign objects must not be presented at a surface or between Tx and Rx. It could potentially cause overheating and damage the circuit. While working, FOD[8] or PMOD protocol is executed between coils to avoid foreign objects . However, some hand held devices could have some metallic shielding which can potentially cause power losses and heating.

Aims of this Bachelor thesis:

There are four main areas to investigate in my bachelor thesis. The first one is to perform a research of the current state-of-the-art of Qi wireless charging technology with Multiple coils. The second one is to design a suitable coil configuration for a demonstration charger with an area of at least 10 x 20 cm. The field should be simply expandable. A) Analyze what maximum area coverage could be achieved B) Analyze the behavior of the coil in case of moving receiver. Then I have to design the charger transmitter and receiver electronics which means I have to make a PCB with qi controller and make a functional sample in order to measure its properties.

In the present bachelor thesis Power ranges from 0 to 8 Watts. The operating frequency for both transmitter and receiver coils are set to 200 kHz. All types of misalignments of coils are examined with a constructed wooden block with a step of 1 cm and the angle between the coils is 0. Transmitter coil is 10x20cm and the receiver is 10x10 cm. The power to transmitter coil was supplied by Power amplifier (Model 800A3).

Any qi compliant receiver electronic design could be adopted since we are only concentrated on transmitter electronic design when examining the maximum area coverage of the WPT device.

Current state-of-the-art of the Wireless Power Transfer systems:

In the current state of art, I would mostly concentrate of a working sample of multi coils array which is offered in bq500410A Free Positioning specification.

Wireless power transfer systems are mainly divided into 2 types depending on radiation pattern which are radiative and non-radiative.[7]

It is worth mentioning some other methods of Wireless power transfer e.g. IPT, CPT and Microwave method.

The standard approach towards the WPT system is to imagine it as a transformer with an air core. Alternating current passes through transmitter coil creating magnetic flux and induces current in the Receiver coil based on Faraday's law. In receiver coil there is a standard diode bridge which transforms alternating current to direct current and a voltage divider, which allows the setting of required V-I characteristics of the load. Based on these studies we know that 4 coils systems give greater efficiency for larger distances than two- coils solution. It is acknowledged fact that the system efficiency is mostly dependent on the number of turns of the system.

Inductive power transfer (IPT)

The first commercial WPT system was introduced by J. Boys in 1994 and intermediate coil was introduced in 1998 it had a great contribution in raising the efficiency over the distance but since it is not cost effective, we shall not consider this solution in our PCB approach.

In 2007 Magnetic Resonant Coupling system (MRC) was introduced by Massachusetts Institute of Technology which came up with adding capacitor to both Transmitter and Receiver coils in order to compensate for leakage inductance of the windings. It is worth to mention that at power transfer of 60 Watts, the distance of 2 meters and frequency of 10 MHz the efficiency of such a system was only 15 percent. However, these results have spiked the interests of researchers to work on this problem more and increase the efficiency of such a wireless transfer system. [9]

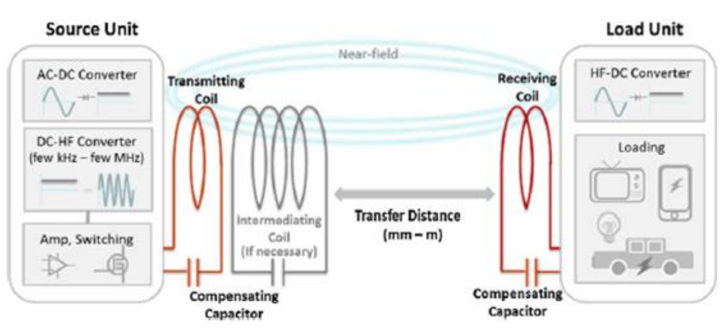


Figure.2 Inductive power transfer with compensating capacitors [9]

Capacitive power transfer (CPT)

Energy transfer can also be achieved by capacitive coupling. Before 2015, CPT method was perceived as methods to be used in low power applications. However, the researchers from Kunming University of science in china conducted the experiment which allowed the power transfer of 700W at the distance of 17 mm to charge the battery of railway vehicle with 300 Volts and 2 MHz Researchers reached the efficiency of 91 percent. Another experiment was conducted in 2017 with power transfer of 1970W over a distance of 150 mm and efficiency of 91.6 percent.[9]

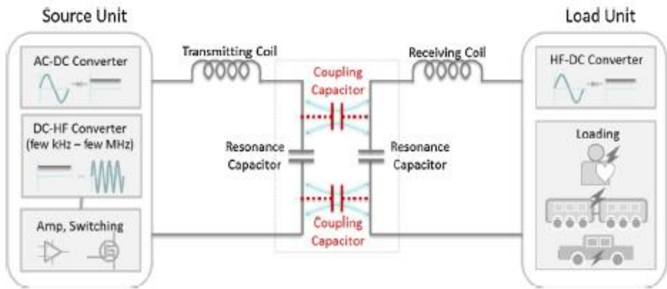


Figure.3 Capacitive power transfer[9]

To sum up, from both of these researches great efficiency over a long distance were reached. However, the problem is that the extreme care is required due to the high voltages of capacitive plates. CPT system doesn't require any considerations of eddy current loss but is dangerous for simple home applications. That's why we shall not consider this method for our PCB design.[5]

Microwave method:

Generally, the microwave method is used in far-field applications. The first ground-to ground MPT was demonstrated in 1975. In the case of this experiment 470kW of electric power was supplied to transmitter with diameter of 26 meters and only 30kW was received by antenna over a 1-mile distance. NASA claimed a free energy transmission from Solar Space Power. They expected to transmit 50 to 250 MW in distance range of 6000 to 12000 km. Efficiency of such a system was only 17 percent at frequency of 2.45 to 5.8 GHz[9]

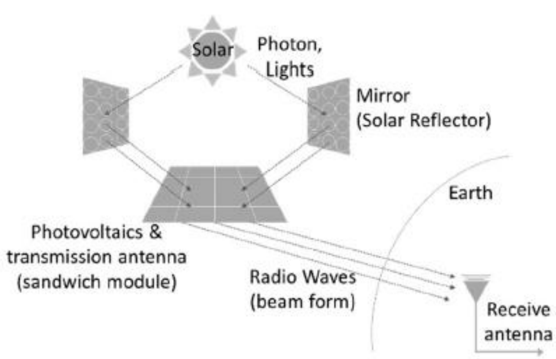


Figure.4 Microwave method for space solar power[9]

The current state-of-the-art of Qi wireless charging technology with Multiple coils:

The bq500410A device is a wireless digital power controller that performs all tasks necessary to execute wireless power transfer with compliant qi receiver. It usually operates with 12 V supply voltage.

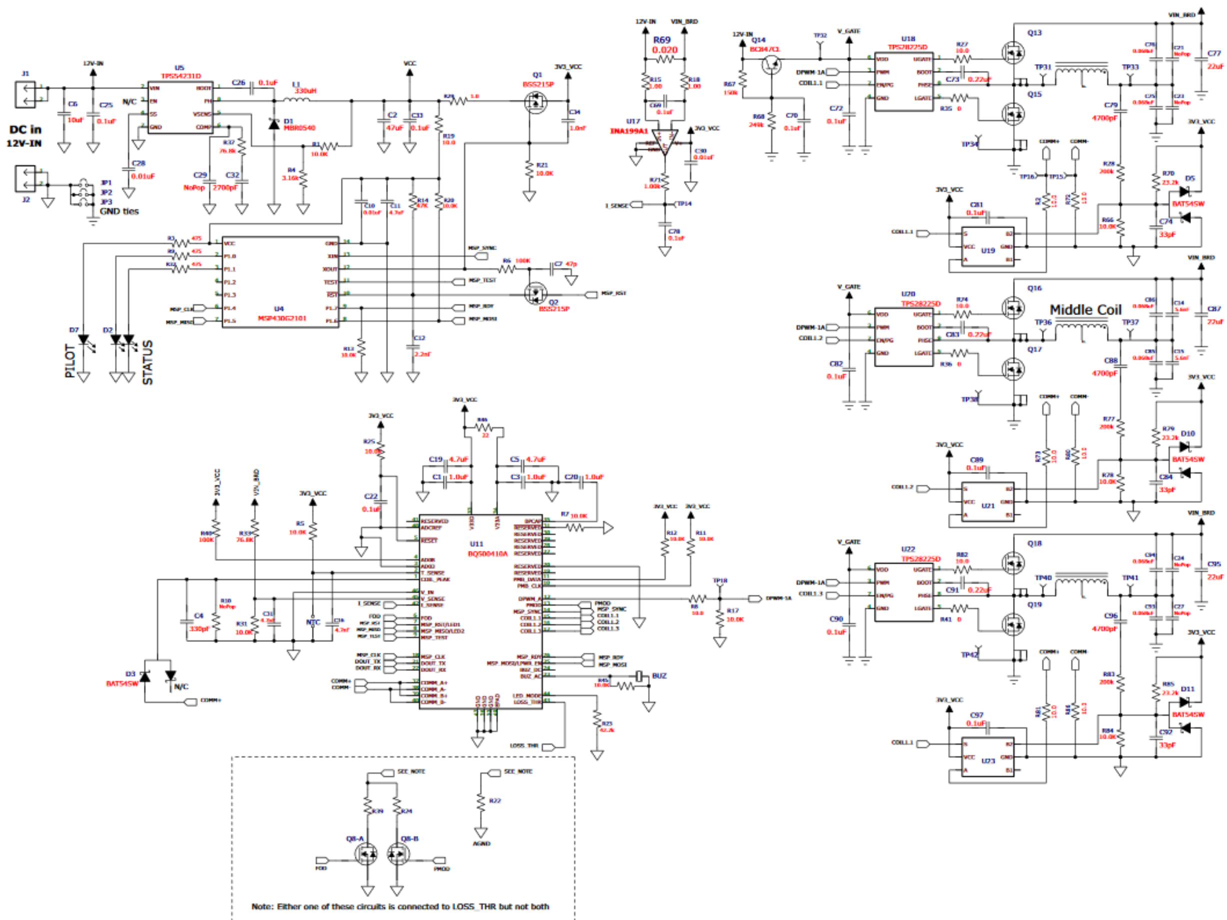


Figure. 5 Transmitter bq500410A Low-Power Application Schematic. [10]

On the image above it may be observed the recommended schematic from Texas Instruments for free positioning Qi wireless transmitter coil. This schematic can be adopted to home or house appliances. We may see on the right that there are 3 coils connected to the main controller, but only one of them is working at a time. The controller pings the surrounding in 400ms intervals and checks the presence of receiver coil. Controller receives the COMM feedback signal pins (37-40) and only the strongest signal switches are sent to digital demodulation block. From demodulation block the signal is sent to Controller. Controller, in turn, sends the signal to DPMW, where it chooses to power required coil.[10]

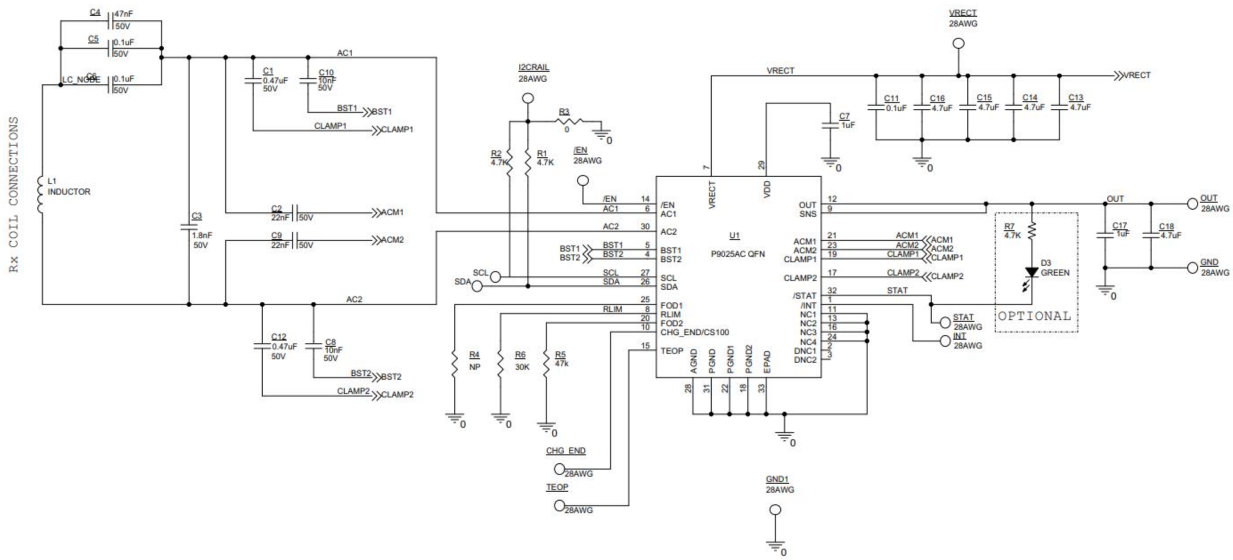


Figure.6 Receiver P9025AC schematic.[11]

Figure above represents the schematic of receiver circuit. Receiver is supplied by AC power signal from a resonant tank which is then transformed to regulated output voltage. This device includes a high efficiency Synchronous Full Bridge Rectifier and has an ability to supply an output current of 1 A. The P9025AC detects the presence of transmitter, which utilizes WPC AC modulation communication protocols with optimal efficiency.[12]

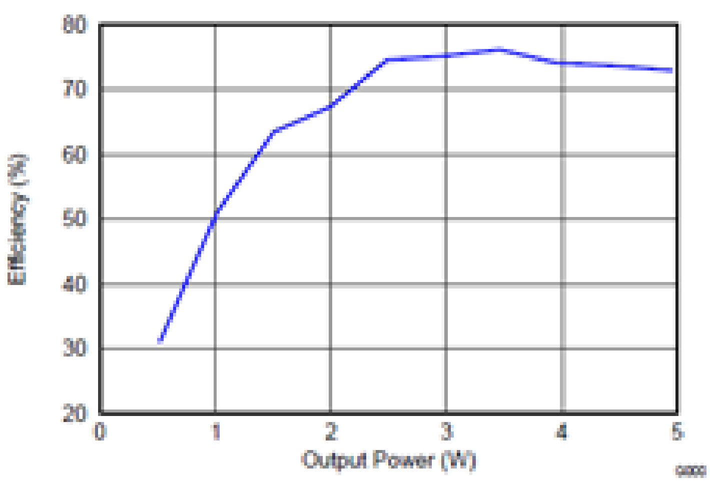


Figure.7 Efficiency Vs System Output Power of bq500410 system [13]

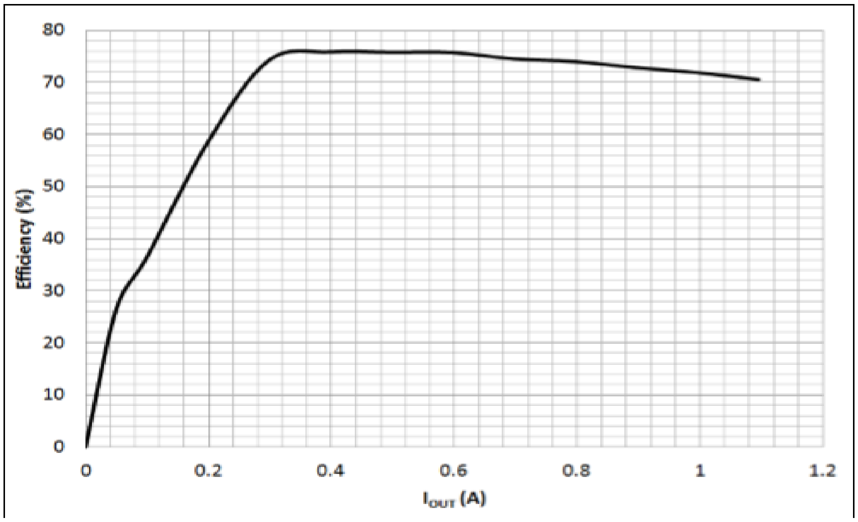


Figure.8 Efficiency vs Output current of P9025AC system [14]

Theoretical description:

Electromagnetic induction is a production of electromotive force in a conductive material due to the changing magnetic field about the conductor. It was first discovered by Michael Faraday and since then found its many applications in electric circuit technologies [15]. Inductance is defined as an intention of an electrically conductive material to oppose a change in current.

Self-inductance is a property of a coil in which a change in electric current leads to production of induced electromotive force in the same coil. When an electric current pass through coil there is magnetic field induced, which could couple with a circuit it is induced from.

Mutual inductance is a phenomenon, where a change in current in one coil creates an electromotive force across the other coil by the alternating magnetic field. [16]

Coupling is the phenomenon that occurs when changes of current in one coil creates electromotive force in the other via magnetic induction. It is known, coupling and power transfer efficiency is highest – with the most efficient power transfer, when the power transmitter coil (Tx) and power receiver coil (Rx) are perfectly aligned or externally shielded by ferrite materials. One of the factors, which could lead to decrease in coupling is mismatching of Tx and Rx coils. Thus, the capacity of one is several times lower than another. Suitable coil sizes indicates that radius of Tx should always be greater than or same to Rx.

"Skin depth is a measure of the distance a high frequency signal can penetrate beneath the surface of a conductor. It is defined as the average depth of the current penetration. "[17]

Solving equations of simple inductors:

Assuming, there are 2 simple inductor coils, that are placed one on the top of another. Coil 1 with number of turns N_1 and the current I_1, which creates magnetic flux Φ and magnetic field B_1. Since both inductors are located close to each other, it can be claimed that magnetic field B_1 also passes through the turns of coil 2. Therefore, there will be Φ_{21} which is magnetic flux through the turns of coil 2 due to the current I_1 in coil 1. Current I_1 will vary due to the time, therefore induces emf in the second coil. The formula for describing this is shown below:

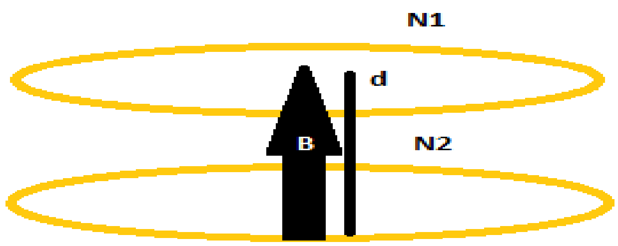


Fig. 9 Example of 2 inductor coils

$$\varepsilon_{21} = -N_2 \frac{d\Phi_{21}}{dt} = -\frac{d}{dt} \iint_{\text{coil2}} B_1 \; dA_2 \text{ [18]} \qquad (1.0.0)$$

The rate of change of magnetic flux Φ_{21} of the second coil will be proportional to the rate of change of the current of the first coil therefore:

$$N_2 \frac{d\Phi_{21}}{dt} = M_{21} \frac{dI_1}{dt} \text{ [18]} \qquad (1.0.1)$$

$$M_{21} = \frac{N_1 \Phi_{21}}{I_1} \qquad (1.0.2)$$

Where M_{21} is constant which is the mutual inductance between the coils. Using the reciprocity theorem which uses both Ampere's Law and the Biot-Savart Law it can be stated that[20]:

$$M_{21} = M_{12} \equiv M \qquad (1.0.3)$$

This states that mutual inductance of Coil 1 on Coil 2 is equal to mutual inductance of Coil 2 on Coil 1.

Also, an inductor has ability of self-inductance. Suppose there is a coil with the N number of turns and alternating current passing through. If the current is steady there will be constant magnetic field, however the current is alternating. Thus, according to Faradays law there has to be back emf ε_{back} induced in the coil in order to oppose the change in current.

$$\varepsilon_{back} = -N\frac{d\Phi}{dt} == -\frac{d}{dt}\iint_{\text{coil}} B\,dA \quad [18] \tag{1.0.4}$$

$$\varepsilon_{back} = -L\frac{dI}{dt} \tag{1.0.5}$$

Combining both of the equations brings us to dependence of the self-inductance to the number of turns, magnetic flux and change in current.

$$L = N\frac{\Phi}{I} \quad [18] \tag{1.0.6}$$

As it is known the formula magnetic field inside a solenoid:

$$\mathrm{B} = \mu_0 I\frac{N}{l} \quad [18] \tag{1.0.7}$$

Where μ_0 is permeability of free space, N is number of turns and l is the length of coil. The magnetic flux for each turn is given by the formulae:

$$\Phi = \mathrm{BA} = \mu_0 I\frac{N}{l}\,A \tag{1.0.8}$$

By combining formulae 1.0.6 with 1.0.8 we end up with the formulae for self-inductance which depends on the physical parameters of coil rather than current and flux.

$$L = N\frac{\Phi}{I} = \mu\mu_0\frac{N^2}{l}\,A \tag{1.0.9}$$

The same has to be done for mutual inductance. Therefore, combining formulas 1.0.2 and 1.0.8

$$M = \frac{\mathrm{N_1} BA}{\mathrm{I_1}} = \mu_0\frac{\mathrm{N_1 N_2}}{l}\,A \tag{1.1.0}$$

The formulae listed above of mutual inductance between two coils which doesn't depend on current but only on the parametric inputs of inductor, where $\mathrm{N_1}$ is number of turns of first coil area and length of first coil and $\mathrm{N_2}$ is number of turns of the second coil.[2]

If we rearrange the formulae of mutual inductance 1.1.0 and substitute self-inductances of transmitter and receiver coils, we may receive the formulae shown below:

$$\mathrm{M} = \sqrt{L_1 L_2} \quad [19] \tag{1.1.1}$$

Now we need to add coupling coefficient and rearrange the formulae:

$$k = \frac{\mathrm{M}}{\sqrt{L_T L_R}} \quad [19] \tag{1.1.2}$$

Coupling coefficient k is one of the most important parameters. It measures an amount of power that was generated by Tx is induced to the Rx. Coupling coefficient varies from 0 to 1. At zero the is no engagement between the coils and 1 is hardly archivable. The formulae which represents k factor is defined by:

where: L_T is an inductance of transmitter coil, L_R is an inductance of receiver coil and M is mutual inductance.

According to Biot-Savart Law [20] : "The magnetic field B due to an element dl

$$B = \frac{\mu_0}{4\pi}\int\frac{Idl\times R}{r^2} \qquad (intergral\ over\ a\ wire\ length) \tag{1.1.3}$$

Where B is magnetic field, μ_0 is permeability of free space, I is current source, element dl is infinitely small wire, R is a unit vector of r and r is the displacement vector.

As already stated we have 2 aligned coils with distance d between them. Therefore, we may say that

$$B = \frac{\mu_0}{2}\frac{NIc^2}{(c^2+d^2)^{3/2}} \tag{1.1.4}$$

Where N is the number of turns, I is a current of the first coil, c is the radius of the first coil and d is the distance between them.

If we recall (1.0.0) then and combine it with (1.2.4):

$$\varepsilon_{back} = -\frac{d}{dt}\iint_{\text{coil}}\frac{\mu_0}{2}\frac{NIc^2}{(c^2+d^2)^{3/2}}\ dA \tag{1.1.5}$$

Simple formulae of alternating current is given by:

$$I = isin(wt) \tag{1.1.6}$$

Where i is peak current, w is angular frequency and t is period. If (1.1.6) is inserted to (1.2.5) the following formula is obtained:

$$\varepsilon_{back} = -\frac{d(\iint_{\text{coil}}\frac{\mu_0 Nisin(\,wt)c^2}{2(c^2+d^2)^{3/2}}\ dA)}{dt} \tag{1.1.7}$$

From this formula it may be deduced, that the voltage, which was induced to the receiving coil depends on the number of turns, the magnitude of current and the radius of the first coil. Also, it may be observed that as greater the separation d between the coils would be, the less back emf would be received on the second coil. Therefore, the coupling and efficiency would drastically decrease.

According to the paper from College of Automation, which came up with the article: "A maximum power transfer tracking method WPT for WPT systems with coupling coefficient identification considering Two-Value problem" the power is given by:

$$P_{out} = \frac{w^2M^2U^2R_l}{(w^2M^2+R_pR_s+R_pR_l)} \quad [21] \tag{1.1.8}$$

Where U is rms value of supplied voltage to primary coil, w is an angular frequency, M is mutual inductance, R_l is load resistance at secondary coil, R_p is resistance of primary coil, R_s is the resistance of secondary coil

System efficiency of such a system would be given by:

$$\eta = \frac{w^2M^2R_l}{R_p(R_s+R_l)^2+w^2M^2(R_s+R_l)} \; [21] \tag{1.1.9}$$

where η is the efficiency of transmission.

Skin effect is the phenomena which may occur when we are dealing with relatively high frequency and relatively thick conductors:

The formulae of calculating skin depth is:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_0 \mu_r}} \; [22]\;[23] \tag{1.2.0}$$

Where ρ is resistivity of the material f is frequency μ_0 is permeability constant and μ_r is relative permeability.

During this experiment skin effect will be completely ignored since the PCB trace which is 2mm compared to its height 35 μm is very large.

“When we are operating in multi gigabit per second range we must bear in mind the skin effect losses”.[7]   In order to observe any significant increase of resistance due to skin effect in PCB trace, the working frequency of the system should be hundreds MHz. [23]

Design of series resonant PCB coil for WPT:

Procedure of assembling PCB coil:

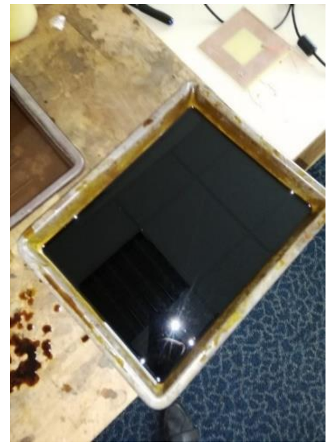


Fig.10 UV light lamp **Fig.11 NaOH bath** **Fig.12 FeCl3 bath**

First of all, the actual design is printed on a transparent plastic sheet. Then the holes were made on PCB in order to place the coil from the both sides easily. The next step aligning the plastic sheet on the top of fotocuprextit material. UV lamp is switched on and place 0.5 meters away from PCB and it was left there for 210 seconds as you may observe form Fig.2. Procedure was repeated for the opposite side of fotocuprextit material. The following step was placing PCB to the NaOH bath until we can clearly distinguish the lines of copper trace. The last step was inserting PCB into FeCl3 bath until all remaining copper was dissolved.

Prototype design:

Before making actual transmitter and receiver prototype PCB was printed in order to assure the calculations of inductance and check the resonance of the circuit. However, a lot of other information were deducted from this experiment.

One of them was that it is important to have distance Dedge-(distance from the edge of the PCB) which may be observed from the Fig. 21 should be at least from 2 – 5 mm because Fig.13 can be discoved that on the bottom part of the coil the whole single trace was missing since the board's edges is damaged while cutting.

The second one was that the glass which keeps the PCB fixed during printing should be cleaned each time before using it for printing the circuit board. As it may be seen from bottom part of Fig.13 there is an open circuit because some water drop was accidentally left and dried on it.

Third consideration is that the printer which was used to print the layout cannot print very precisely. Thus, we technically couldn't make the Wbetween(which stands for width between the turns of the coil) Fig.15 less than 1 mm. Otherwise it short-circuits the inductor. Therefore, it was decided to leave it at exactly 1mm.

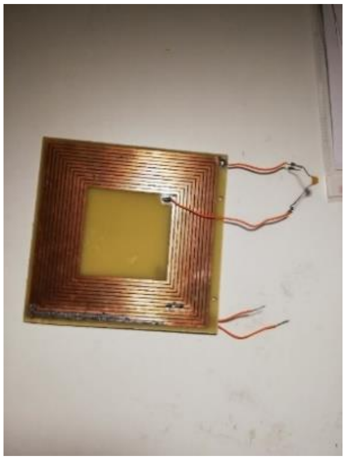


Fig. 13 Prototype design **Fig. 14 transmitter short circuit prevention**

In Fig.14 it might be noted that we checked the whole trace in order to avoid short-circuit in any part of the coil.

Calculation of inductance of a single coil:

According to Fig.15 there is a single rectangular coil with the following parameters d_{out}- vertical outer length of inductor coil, d_{in}- horizontal inner length of the coil, w_{trace}- length of the trace, $w_{between}$- length between traces and n – number of turns of the coil. For the sake of calculation of inductance, h_{trace} is neglected, which may be observed from Fig.16. Since it is only 35µm and the coils are considered to be planar and rectangular.

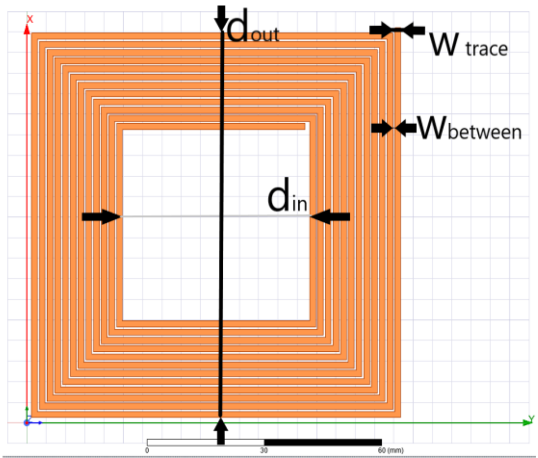
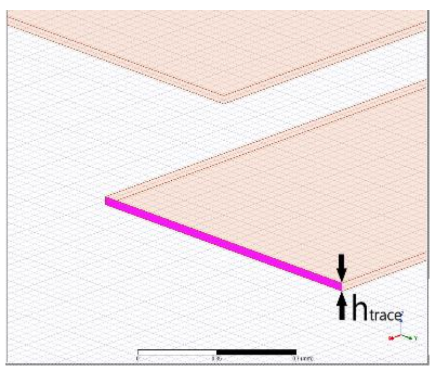


Fig.15 Design of a single coil

This coil was designed in Ansys Maxwell and the length trace of 2mm which can withstand the current of 4 Amperes without heating. Furthermore, the inductance of such a coil was calculated with 2 different methods.



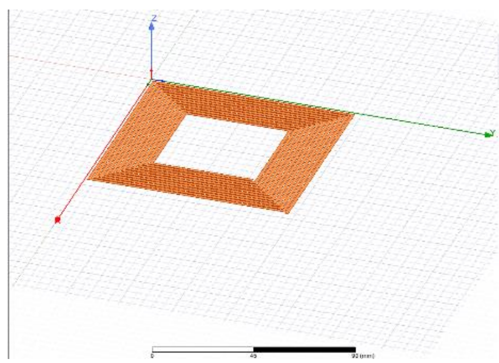


Fig.16 h-trace of a single coil

Fig.17 Trimetric view of a single coil

Before producing the coil, it is necessary to calculate inductance of the coil. From reviewing the current state of the art design, it can be concluded that typical range of inductance of a coil is from 5µH to 100µH for low and medium power transfer. Additionally, from the prototype design it was deduced, that it is necessary to make $w_{between}$ at least 1 mm, in order not to short circuit the inductor. Following this, it was decided to set the parameters in the table 1 .

	d_{in}	d_{out}	h_{trace}	w_{trace}	$w_{between}$	n
[m]	0.030	0.095	0.000035	0.002	0.001	11 turns

Table. 1 Parameters of the single coil.

Modified Wheeler formula[24][25]:

$$L_{mw} = K_1\mu_0 \frac{n^2 d_{avg}}{1+K_2\rho}; \qquad (1.2.1)$$

μ_0 is permeability of free space, n is the number of turns. Where K1 and K2 are depending on the layout of the coil. In that case the coil is a square one, therefore the coefficients are:

$K_1 = 2.34 \qquad K_2 = 2.75$

The ratio ρ is a fill ratio which is defined by the formulae below:

$$\rho = \frac{d_{out}-d_{in}}{d_{out}+d_{in}} = \frac{0.095-0.030}{0.095+0.030} = 0.52\ [ratio] \qquad (1.2.2)$$

d_{avg} is the average value of inner and outer diameters.

$$d_{avg} = \frac{d_{in}+d_{out}}{2} = \frac{0.030+0.095}{2} = 0.0625[m] \qquad (1.2.3)$$

$$L_{mw} = 2.34 \times 1.25664 \times 10^{-6} \times \frac{11^2 \times 0.0625}{1+2.75\times 0.52} = 9.15\mu H \qquad (1.2.4)$$

Expression based on current sheet approximation (geometric mean distance)[24][25]:

$$L_{gmd} = \frac{\mu_0 n^2 d_{avg}\, C_1}{2}\left(\ln\left(\frac{C_2}{\rho}\right) + C_3\rho + C_4\rho^2\right); \qquad (1.2.5)$$

μ_0 is permeability of free space, n is the number of turns. d_{avg} is the average value of inner and outer diameters. Where c coefficients are depending on the layout of the coil. In that, the coil is square, therefore the following coefficients are taken:

$C_1 = 1.27 \quad C_2 = 2.07 \quad C_3 = 0.18 \quad C_4 = 0.13$

$$L_{gmd} = \frac{1.25664\times 10^{-6}\times 11^2\times 0.0625\times 1.27}{2}\left(\ln\left(\frac{2.07}{0.52}\right) + 0.18 \times 0.52 + 0.13 \times (0.52)^2\right) = 9.31\ \mu H \qquad (1.2.6)$$

Measured inductance of a single coil is 9.7 μH. It can be seen the parameters which have been chosen for the coils and predicted results are very accurate and precise.

Receiver coil Rx design:

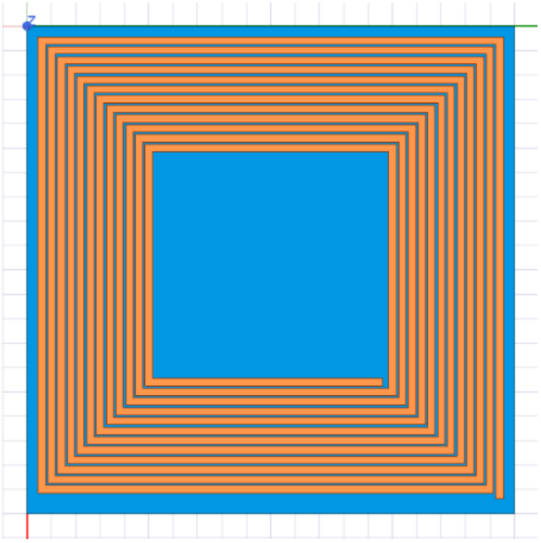


Fig.18 Design of a receiver coil

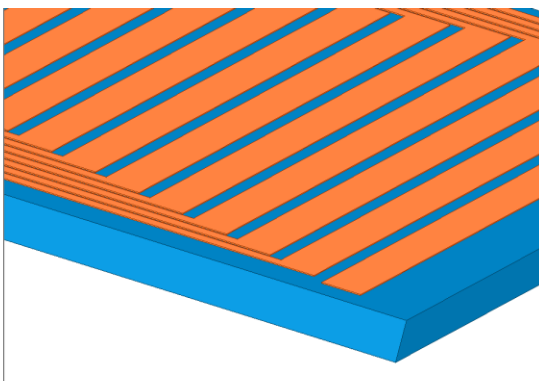


Fig.19 Design of a receiver side view

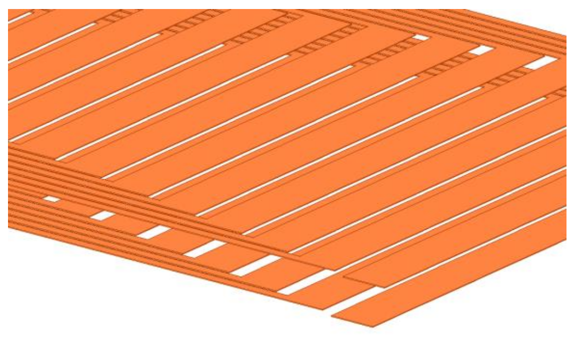


Fig.20 Design of a receiver coils coupled

Total measured inductance of receiver coils was 35.468 μH.

Transmitter coil Tx design:

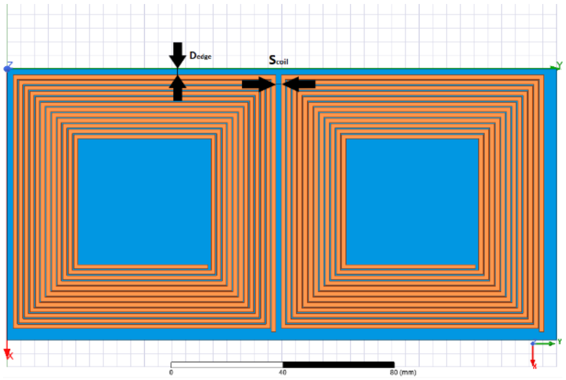


Fig.21 Design of a Transmitter

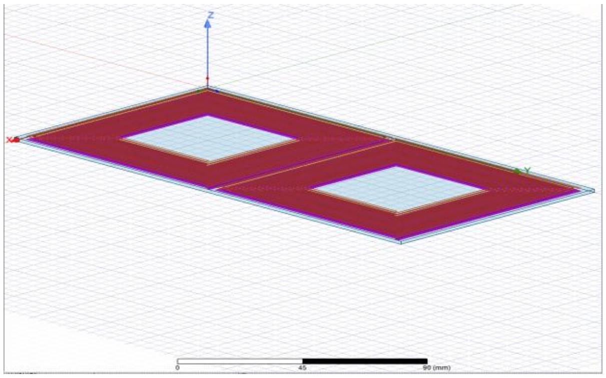


Fig.22Design of a transmitter trimetric view

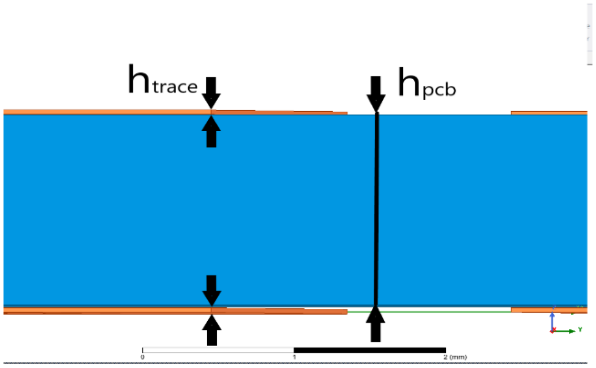


Fig.23 Design of a transmitter side view

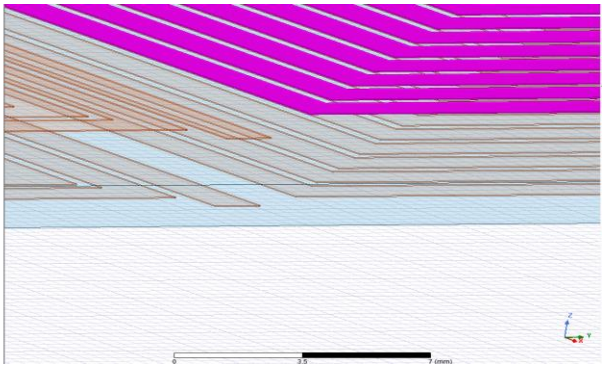


Fig.24 Design of a transmitter close view

Total measured inductance of transmitter coils was 65.2 μH.

Calculation of capacitance and Resonant Adjustment:

One of the most important considerations in the IPT design is setting the resonant frequency of the device. In case of our PCB design first 2 coils were printed, where one of them was on the bottom of PCB and the other one was on the top, with separation between them equal roughly 1.5mm. We connected first one to generator and the second one to the oscilloscope. Inductance of both coils is considered to be the same since they are identical. As it has been already known the natural frequency of the system was set to 200kHz, so it is in the Qi standard range.

As we know the formula of an impedance of an inductor is given by:

$$X_L = 2\pi f L = \frac{2\times\pi\times200000\times10}{1000000} = 12.56\ \Omega \qquad (1.2.7)$$

Impedance of capacitor is [26]:

$$X_C = \frac{1}{2\pi f C} \qquad (1.2.8)$$

Condition of the system in resonance

$$X_L = X_C \qquad (1.2.9)$$

$$2\pi f L = \frac{1}{2\pi f C}$$

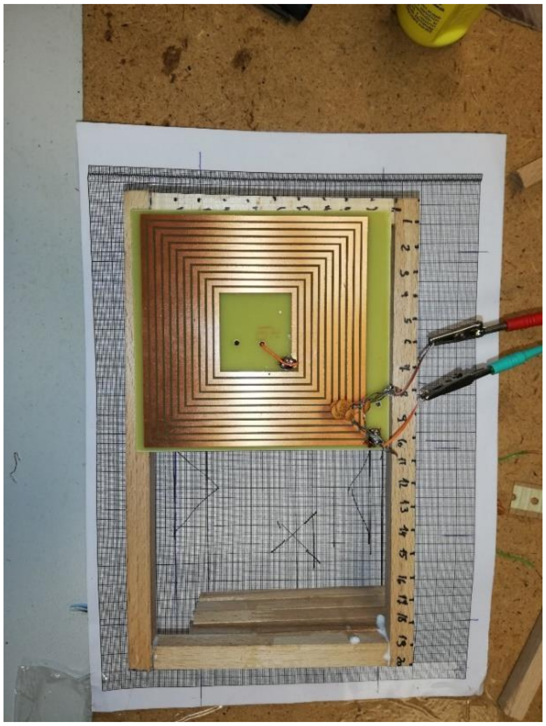
$$C_{receiver} = \frac{1}{4\pi^2 f^2 L} = \frac{1}{4\pi^2\times(200000)^2\times35.468\times10^{-6}} = 18.64nF \qquad (1.3.0)$$

The calculated value is 18.654 nF and then combination of different capacitors were assembled. Measured result was 18.5 nF for receiver circuit.

$$C_{transmitter} = \frac{1}{4\pi^2\times(200000)^2\times65.209\times10^{-6}} = 9.711\ nF \qquad (1.3.1)$$

The calculated value 9.711 nF and then combination of different capacitors were connected in parallel. Measured result was 10.4 nF for transmitter circuit.

Magnetic field experiment:



In magnetic field experiment receiver coil was placed above transmitter coil and the peak to peak voltage value was obtained from the oscilloscope. The Voltage value was measured at a step of 1 cm for x, y, z coordinates. At Z=0 there was some wires which connects the inductors and didn't let us to place it completely at 0 and there was a distance around 2mm which was neglected.

The area was measured for each layer of z and the area of plane was 10 by 20 cm.

While measuring layer of z=0 we placed a paper over the transmitter coil in order to avoid the short circuit of the system.

Fig.25 Magnetic field experiment top view

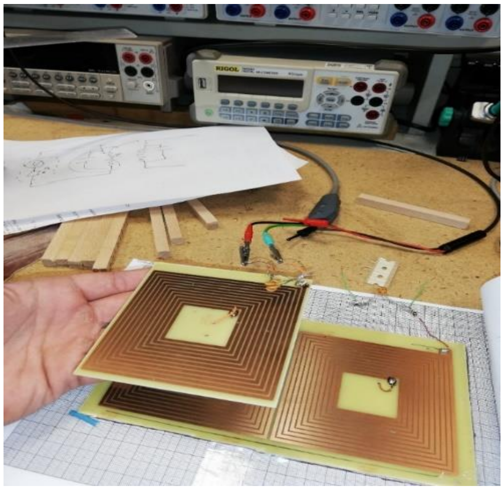


Fig.26 Magnetic field experiment

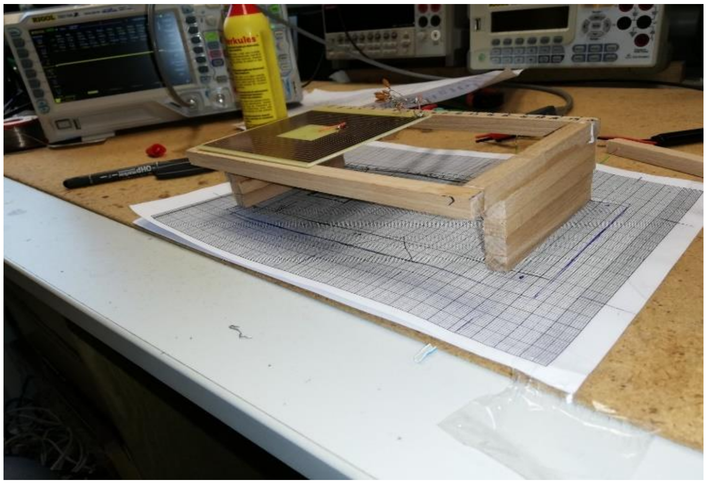


Fig.27 Magnetic field experiment wooden ruler

During magnetic field experiment transmitter was connected to low signal generator with maximum value of 7 V rms. We have set it to be 7 V, and connected Receiver to Oscilloscope. As it was already mentioned the step for each coordinate was 1 cm and the results below were obtained. For each layer the results were different.

Results & Ananlysis:

Magnetic field results (without PCB):

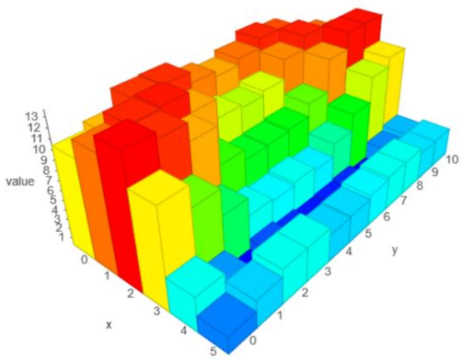


Fig.28 Magnetic field at z0

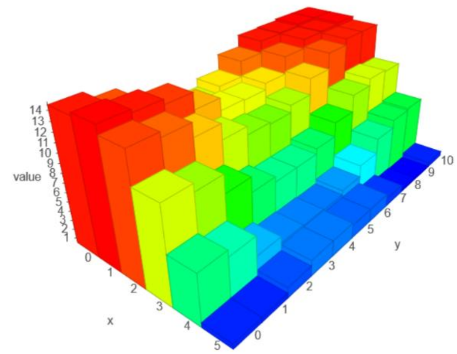


Fig.29 Magnetic field at z1

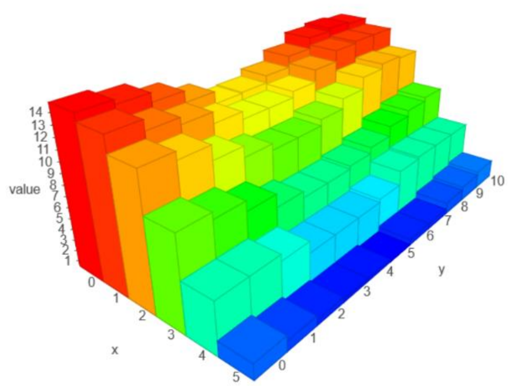


Fig.30 Magnetic field at z2

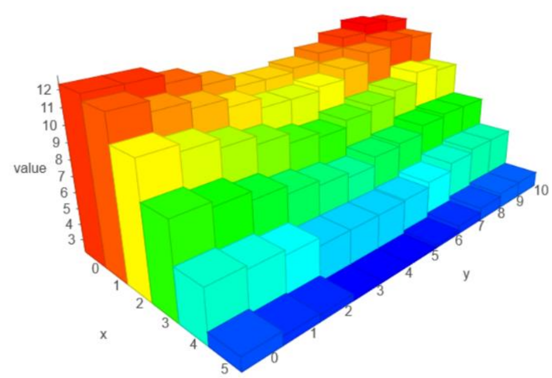


Fig.31 Magnetic field at z3

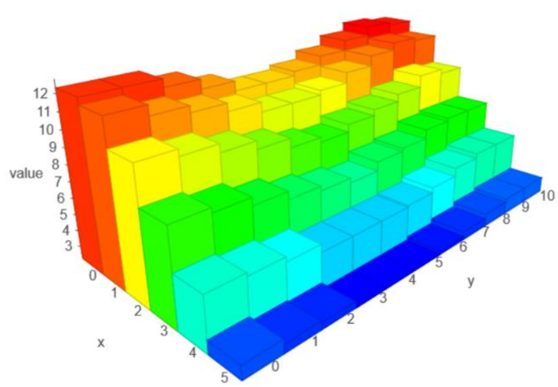


Fig.32 Magnetic field at z4

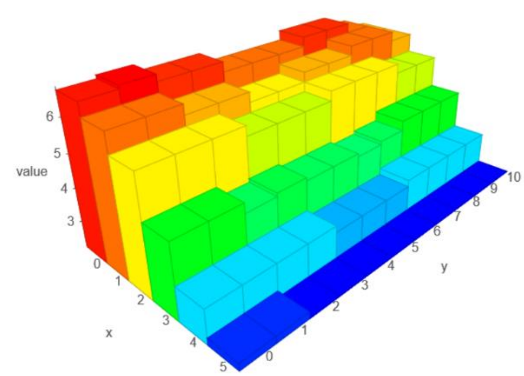


Fig.33 Magnetic field at z5

Red color represents the areas where strongest power transfer was obtained. It is easy to recognize that field is strongest at x=0 y=0 and x=0 y=5. The reason for that is on these points strongest coupling between inductors occur since they overlap one another. While the receiver coil was moved away from x = 0 the signal was weaker.

During magnetic field experiment no load was connected to receiver coil which resulted in very high voltage relatively to voltage on transmitter. This occurred since both coils are in resonance. Therefore, the amplitude of voltage has risen significantly.

If we have to compare the distribution of magnetic field for all different layers, it may be noticed that on z=0 it is very sharp, but when the same points have been checked for any other z coordinate for example z=3 it may be seen that distribution is way smoother.

Through the process of comparing all magnetic field graphs, the general trend is that as z coordinate increases, the value of voltage decreases.

The figure below represents all the voltage values on the same z-scale. It may be stated that it is possible to have a transmitter with the movable receiver for some closed position in space, but if the coils were moved 10 cm apart or the overlap is less than 50 percent, power transfer decreases significantly.

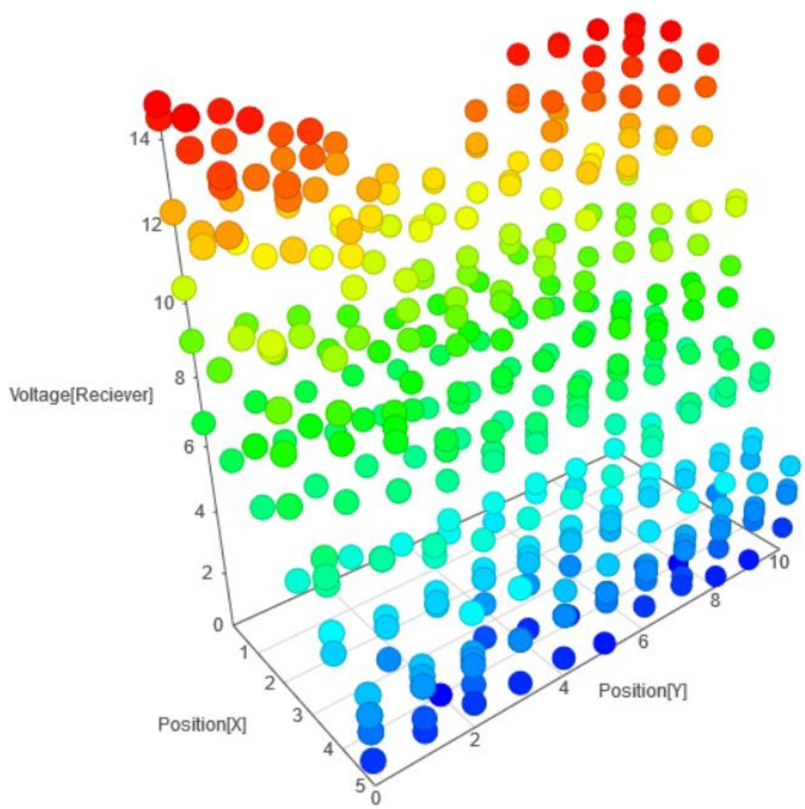


Fig.34 3D graph of Magnetic field for all z layers

Power experiment (without PCB):

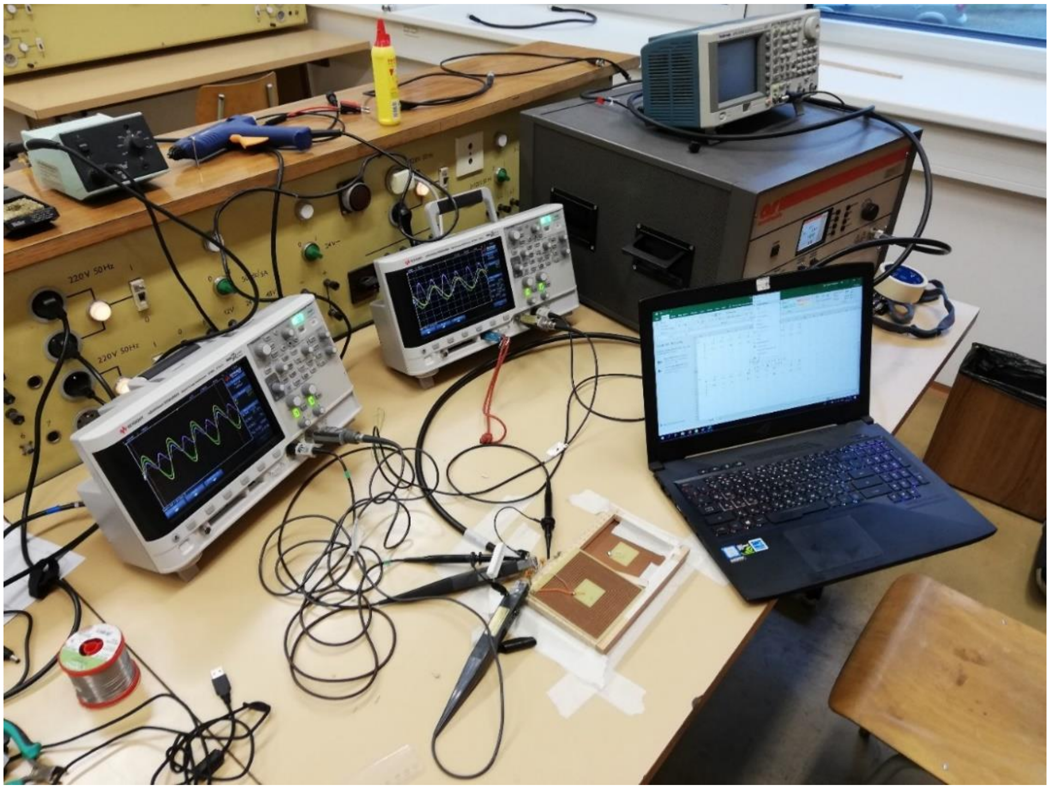


Fig.35 Power transmission experiment overview

In power experiment the transmitter coil was fixed on the table by paper-tape. Two oscilloscopes were placed and each of them measured power. Signal generator was connected to the Power amplifier (Model 800A3).

Oscilloscope at transmitter coil was measuring Voltage across the inductor and current clamp was connected on the wire to measure current supplied.
Oscilloscope at receiver coil was measuring Voltage across the load resistor and current supplied to resistor with Power capacity of 10 Watts.

Oscilloscopes were calculating the resulting power with the special program tool by combining voltage and current signals.

Oscilloscope data (coils without PCB):

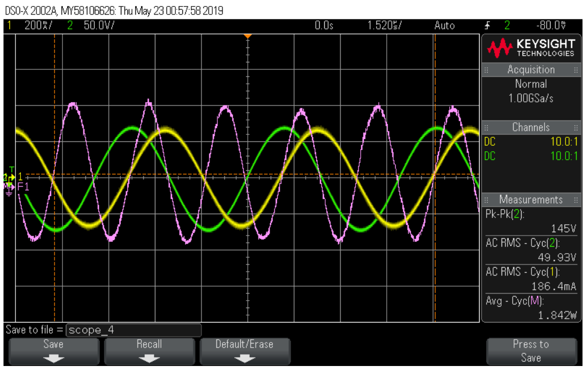
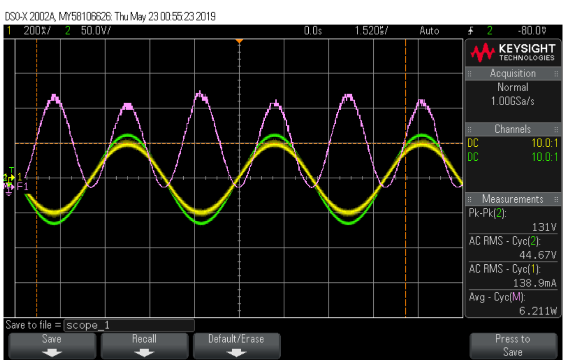


Fig.36 Transmitter without the presence of receiver

On the figure above we may see the readings from the oscilloscope connected to transmitter, where current lags voltage. This happens when the load which draws the current is inductive. When transmitter senses the presence of receiver of the figures 29 and 30, it may be observed that both current and voltage are in phase. Since, the load which is attached to receiver is resistive.



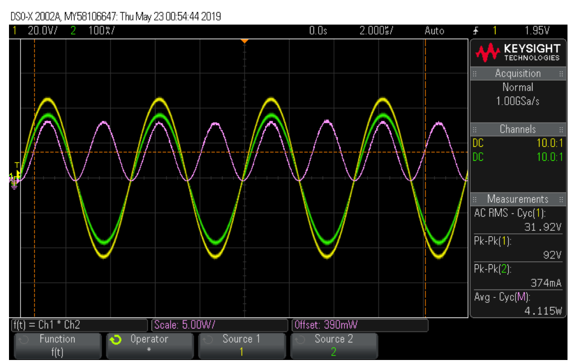
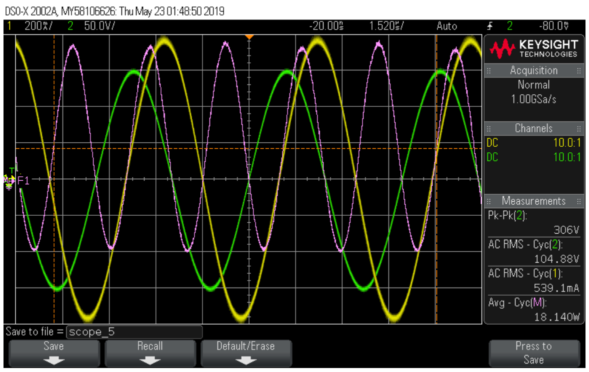


Fig.37 transmitter with presence of receiver **Fig.38 receiver**

Standard Power Position of receiver Position[X]=0 Position[Y]=0 Position[z]=1

However, when power of transmitter is relatively high (18 W) the same phenomenon occurs and current lags voltage again. It is important to note that positions of receiver in both cases (fig. 29, 30) and (fig. 31 and 32) are identical. Thus, we may compare their efficiencies. In first case, the power supplied by transmitter is 6.211 W and absorbed by receiver is 4.115 W, which results in efficiency of 66 percent. In the second, case the power supplied by transmitter is 18.140 W and only 9.349 W is absorbed by receiver, which ends up with efficiency of 52 percent.



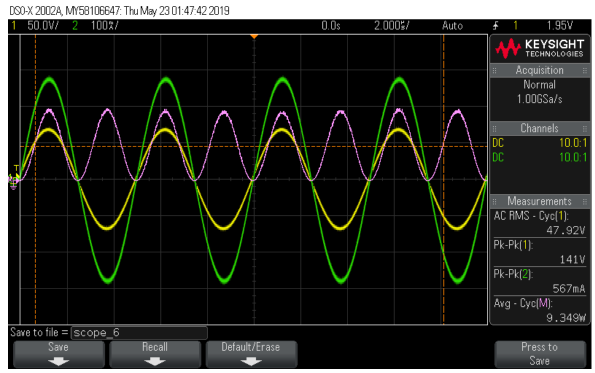
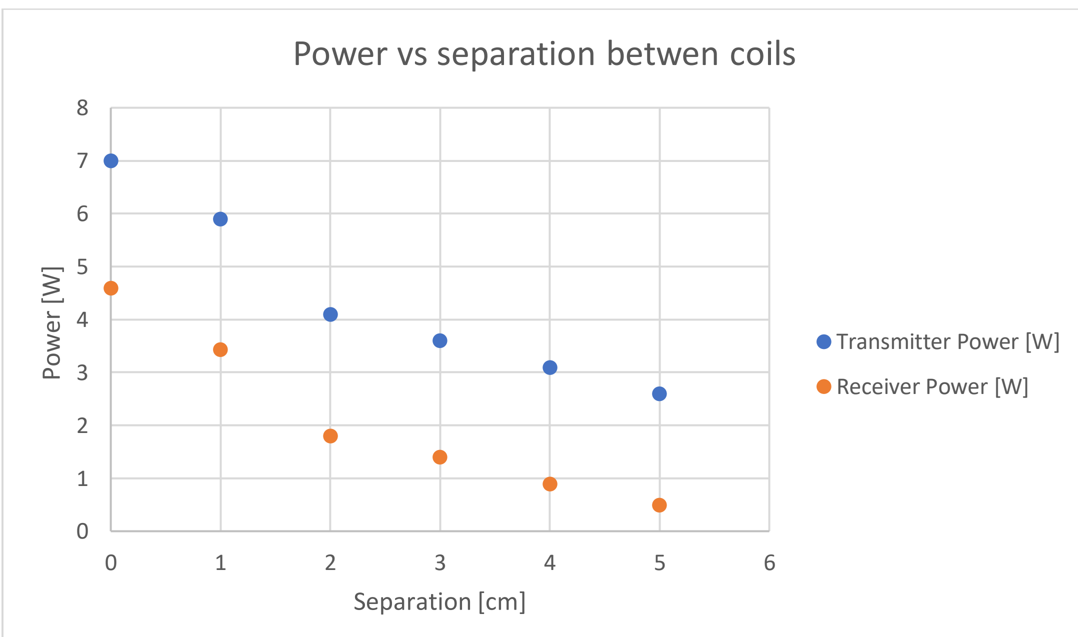


Fig.39 Transmitter **Fig.40 Receiver**

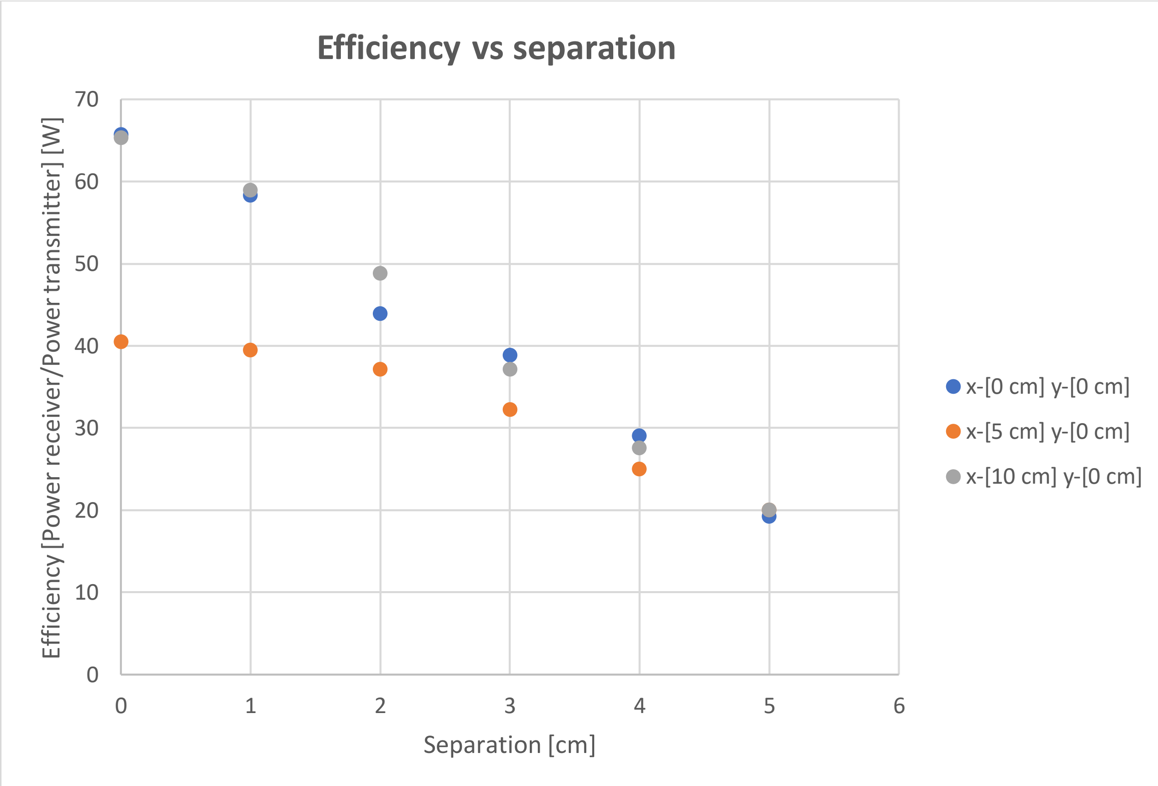
High power Position of receiver Position[X]=0 Position[Y]=0 Position[z]=1

The graph below reflects how the power of transmitter and receiver changes with the separation between them. Horizontal and vertical positions are constant and only z-coordinate is a variable. It is shown that an increase of separation between the coils results in lower power and efficiency, which was predicted by the formulae (1.2.7).



Graph. 1 Power vs separation between coils

However, the power which is supplied to transmitter is strongly dependent on the position of receiver since the main load is attached to receiver and when the coils are closely coupled the inductance increases. The fact that the power supplied is not constant is the main drawback of the experiment.

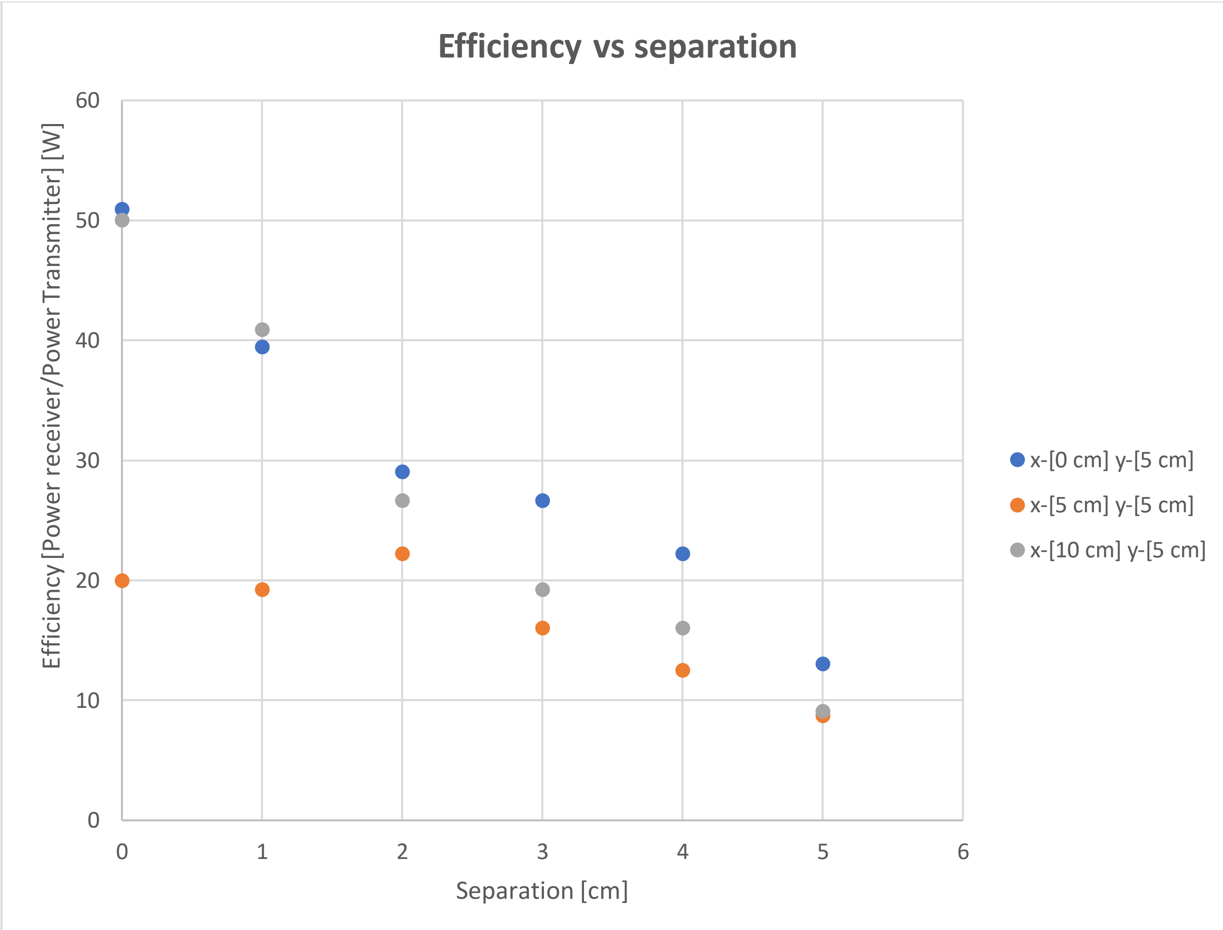


Graph. 2 Efficiency vs separation between coils for different overlaps

The graph above represents correlation between system efficiency and separation between the coils for 3 different overlaps. For all three points the general trend is that as the separation increases efficiency drops down very rapidly.

In first case (x=0 y=0) receiver coil was placed above left coil of transmitter so their edges perfectly overlap, which resulted in highest power transfer efficiency 66.1 percent. Very similar result was obtained when receiver coil was placed above right coil of transmitter (x=10 y=0), which also resulted in power transfer of 66.3 percent. However, when receiver coil is placed exactly between transmitter coils power drops by 30 percent which brings result of only 40 percent efficiency. Also, when separation increases all three different efficiency points are approaching towards each other.

There is standard solution to this problem which was presented in figure 2 bq500410A where the middle coil is introduced. Although, in this bachelor thesis there is precise design specification, that the field coils should be simply expandable to a larger area. In my perspective it is better to increase the resonant frequency and set a standard separation of 2 cm. It will allow us to observe stable field thought the whole area of transmitter.



Graph. 3 Efficiency vs separation between coils for different overlaps

The graph above demonstrates relationship between efficiency and separation. According to this graph it may be obtained that blue line first decreases linearly then it decreases exponentially. The same trend is followed by the grey line. However, orange line increases but then decreases linearly.

Difference between graph 3 and graph 2 is that the receiver coil was placed 5 cm lower. Efficiency of the system is very low when it is set to such conditions. However, in the area of 10x20 the system shows good results. If we were simply to expand the system to 40x20, we would expect an average result of 50 percent throughout the whole system.

Overall the presented system shows very good results compared to other coil configurations.

Conclusion:

The main objectives of this research paper are:

1. Perform a research of the current state-of-the-art of the Qi wireless charging technology with multiple coils.
2. Design a suitable coil configuration for a demonstration charger with an area of at least 10x20cm.
    a. Analyze what maximum area coverage can be achieved.
    b. Analyze the behavior of the coil array in case of a moving receiver
3. Design the charger transmitter and receiver electronics.
4. Make a functional sample and measure its properties.

During this experiment a research of current state-of-the-art of the Qi wireless charging technology was performed. In the process of investigation, many other main ways of WPT were reviewed e.g. Inductive coupling, Capacitive coupling and Microwave method. Key features of Qi consortium were demonstrated. Examples of existing Qi multiple coil chargers and standard efficiency characteristics were shown.

Transmitter coil with an area of 10x20cm and receiver coil of 10x10cm were designed in Ansys Maxwell. Magnetic field of transmitter coil was examined for different positions of receiver. Heat graphs had been modelled in order to show the highest coupling. Power experiment with power amplifier was conducted in order to demonstrate efficiency of the coils.

Charger transmitter and receiver were demonstrated but the actual PCB electronic design wasn't successful due to lack of experience in designing PCB schematics. However, functional sample of coils was designed and the power transfer efficiency results turned out as expected. Even when the separation was 6 cm 20 percent of power transfer were archived.

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