Analysis and Design of Wireless Power Transmission through Inductive Coupling

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Abstract – *Wireless power transmission is the transmission of electric power through an air gap without the need of wires. This is used to transfer power over a small distance to charge smart phones and other electronic gadgets without the contact of wires. For transmission of power over a small distance inductive power transmission has been used. In this paper, analysis and design of wireless power transmission through inductive coupling has been given. Types of coil structure and factors affecting the inductance of coil have been given for efficient wireless power transmission. Calculation of various parameters like output voltage, output current, self inductance, mutual inductance, coupling coefficient, voltage and current across inductor for different turn ratio have been given for efficient wireless power transmission. Further the experimental results have been verified by simulating the circuit with the help of Proteus software.*

Key Words: **Wireless Power Transmission, Inductive Coupling, Quality Factor**

1. INTRODUCTION

Inductive power transmission is transmission between the coils by a magnetic flux. Two coils are said to be inductively coupled when they are configured in such a manner that change in current through first wire induces voltage across the end of second wire through electromagnetic induction. Inductive power transmission was first employed by Nikola Tesla in the early 20th century using Tesla coils which is employed to generate high AC voltage.

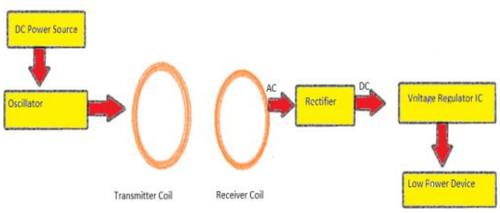

Fig -1: Block diagram of inductive power transmission

Inductive power transmission is often utilized in various applications like recharge drones, cars, smart phones and other electronic gadgets. Inductive power transmission system have two coils i.e. transmitter coil and receiving coil. The power is transmitted to transmitter coil which creates a Changing magnetic field and due to this flux is produced. This flux couples into the secondary coil which induces a voltage in the coil and current start flowing through the secondary coil.

1.1 Merits of Wireless Power Transmission

1. It prevents corrosion and sparking by eliminating mechanical connectors and wired contacts.
2. It eliminates charging cords enables engineers to form compact and watertight devices, thus maximizing on safety and varied use like in deep-sea applications.
3. It provides high charging speed.
4. It reduces cost related to maintaining and replacing mechanical connectors.
5. It will reduce cost of electricity employed by consumer.
6. It is harmless as well as eco-friendly.
7. It reduces cost associated with maintaining and replacing mechanical connectors.

1.2 Demerits of Wireless Power Transmission

1. It is only applicable for shorter and medium distance.
2. Cost of capital for practical implementation of wireless power transmission to be very high.
3. Its efficiency is not high.

2. METHODLOGY

The proposed methodology for designing the wireless

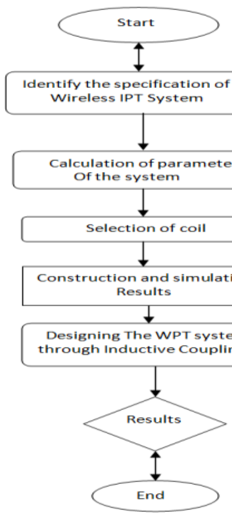

Fig -2: Flowchart for wireless IPT system

Inductive Power Transmission system is given by flowchart in figure 2. For designing the Wireless Power Transfer system through inductive coupling, firstly identify the specification of wireless power transfer system. For this purpose, identify the materials and components used in wireless inductive power transmission system. After identify the specification of wireless power transfer system, the next step is to calculate the parameters of inductive power transmission system. When the parameters are calculated, the next step is to select the coil and construct the wireless inductive power transmission system. When construction is done, the final step is to simulate the circuit and check the system for various applications such as charging.

3. CALCULATION OF PARAMETERS OF WIRELESS POWER TRANSMISSION SYSTEM

The values of parameters are selected according to the system requirements. Input dc voltage of 9V is applied to the system. Calculations are done for different turn ratio. For low power wireless power transmission resonant frequency of 20 kHz is selected.

3.1 Self Inductance

Knowing the value of inductance of a coil is important in the design of wireless IPT system. The inductance of primary and secondary coil is calculated by the equation 1 given below.

1) When turn ratio is 1:1,

$$L = \mu\pi N^2R/2 \quad (1)$$

Where, L = Inductance of coil
N = Number of turns of the coil
$\mu = \mu_0\mu_r$
μ_0 = Absolute permeability having a value $4*10^{-7}$ H/m
μ_r = Relative permeability (equal to unity)
L_1=70.98 µH
L_2=70.98 µH

2) When the turn ratio is 1:2,

For primary coil,

$$L_1 = \frac{\mu\pi N^2R}{2}$$

$$L_1 = \frac{4\pi*10^{-7}*3.14*30^2*0.04}{2} = 70.98\ \mu H$$

For secondary coil,

$$L_2 = \frac{\mu\pi N^2R}{2}$$

$$L_2 = \frac{4\pi*10^{-7}*3.14*60^2*0.04}{2} = 283.95*10^{-6}\ H$$

$$L_2 = 283.95\ \mu H$$

3) When the turn ratio is 2:3,

For primary coil,

$$L_1 = \frac{4\pi*10^{-7}*3.14*30^2*0.04}{2} = 70.98\ \mu H$$

For secondary coil,

$$L_2 = \frac{4\pi*10^{-7}*3.14*45^2*0.04}{2} = 159.72*10^{-6} H$$

$$L_2 = 159.72\ \mu H$$

3.2 Mutual Inductance

From equation 2, mutual inductance is directly proportional to the primary and secondary turns and radius of secondary coil. This means if number of turns is increased then mutual inductance will also increase. Mutual inductance of the 2 coils can be found by using equation (2)

1) When turn ratio is 1:1,

$$M = \frac{\mu n1n2\pi r2^2}{2r1} \quad (2)$$

Where n_1 = Number of primary turns
n_2 = Number of secondary turns
r_1 = radius of primary coil
r_2 = radius of secondary coil

By putting the values in equation 2,

$$M = \frac{4\pi*10^{-7}*30*30*3.14*0.04^2}{2*0.04} = 70.98*10^{-6}H$$

$$M = 70.98\ \mu H$$

2) When turn ratio is 1:2,

$$M = \frac{4\pi*10^{-7}*30*60*3.14*0.04^2}{2*0.04} = 141.97*10^{-6}H$$

$$M = 141.97\ \mu H$$

3) When turn ratio is 2:3,

$$M = \frac{4\pi*10^{-7}*30*45*3.14*0.04^2}{2*0.04} = 106.48*10^{-6}H$$

$$M = 106.48\ \mu H$$

3.3 Coupling Coefficient

The amount of inductive coupling that exist between the 2 coils is expressed between 0 and 1, where 0 indicates no inductive coupling and 1 indicating full inductive coupling. If K is adequate to 1 the two coils are perfectly coupled, if K is greater than 0.5 the 2 coils are said to be tightly coupled and if K is less than 0.5 the two coils are said to be loosely coupled. Coupling coefficient can be calculated by the equation 3.

$$K = \frac{M}{\sqrt{L1L2}} \quad (3)$$

Where K = Coefficient of coupling
M = Mutual inductance of coils
L_1 = Inductance of primary coil
L_2 = Inductance of secondary coil

By putting the values in equation 4.3 -

$$K = \frac{70.98}{\sqrt{70.98*70.98}} = 1$$

$$K = 1$$

3.4 Output Voltage

1) When turn ratio is 1:1,

Output voltage can be calculated by the equation 4.

$$\frac{N1}{N2} = \frac{Vp}{Vs} \quad (4)$$

Where, V_P = Primary Voltage
V_s = Secondary Voltage
N_1 = Primary turns
N_2 = Secondary turns

$$\frac{30}{30} = \frac{9}{V_S}$$

$$V_S = \frac{270}{30} = 9V$$

2) When turn ratio is 1:2,

$$\frac{N1}{N2} = \frac{Vp}{Vs}$$

$$\frac{30}{60} = \frac{9}{V_S}$$

$$V_S = \frac{540}{30} = 18V$$

3) When turn ratio is 2:3,

$$\frac{N1}{N2} = \frac{Vp}{Vs}$$

$$\frac{30}{45} = \frac{9}{V_S}$$

$$V_S = \frac{405}{30} = 13.5V$$

3.5 Output Current

1) When turn ratio is 1:1,

Output current can be calculated by the equation 5

$$\frac{Vp}{Vs} = \frac{Io}{Ii} \quad (5)$$

Where, V_P = Primary Voltage
V_s = Secondary Voltage
I_0 = Output Current
I_i = Input Current

$$\frac{9}{9} = \frac{Io}{0.70}$$

$$I_o = \frac{6.3}{9} = 0.70A$$

2) When turn ratio is 1:2,

$$\frac{Vp}{Vs} = \frac{Io}{Ii}$$

$$\frac{9}{18} = \frac{Io}{0.70}$$

$$I_o = \frac{6.3}{18} = 0.3A$$

3) When turn ratio is 2:3,

$$\frac{Vp}{Vs} = \frac{Io}{Ii}$$

$$\frac{9}{13.5} = \frac{Io}{0.70}$$

$$I_o = \frac{6.3}{13.5} = 0.46A$$

3.6 Resistance

It is calculated by equation 6

$$R = \frac{V}{I} \quad (6)$$

Putting the values in equation 6,

$$R = \frac{09}{0.70}$$

$$R = 12.85\Omega$$

When turn ratio is 1:1, R' will be equal to:

$$R' = 12.85*1^2 = 12.85$$

3.7 Quality Factor

It is calculated by the equation 7

$$Q = \frac{R'}{WL} \quad (7)$$

$$Q = \frac{12.85}{2*3.14*20*1000*70.98\mu H}$$

$$Q = 1.44$$

3.8 Voltage across Inductor

Voltage across inductor can be calculated by the equation 8

$$V_L = V_{in}\sqrt{1+Q^2} \quad (8)$$

Where V_L = Voltage across inductor
V_{in} = Input voltage
Q = Quality factor

$$V_L = 9\sqrt{1+1.44^2}$$

$$V_L = 15.58V$$

3.9 Current across Inductor:

Current across inductor can be calculated by equation 9

$$I_L = \frac{Vl}{L*W} \quad (9)$$

Where, I_L = Inductor Current
W = Operating frequency
L = Inductance
V_L = Voltage across inductor

$$I_L = \frac{15.58}{70.98\mu H*2*3.14*20000}$$

$$I_L = 1.74A$$

Various parameters of wireless inductive power transmission are calculated for different turn ratio. Turn ratio of 1:1 and 2:3 is selected for low power wireless power transmission system according to the system requirement.

At other turn ratio high values of output voltage can damage the system.

Table -1: Calculated parameters of wireless power transmission system.

Calculated parameters of wireless power transmission system			
Self Inductance of primary coil	70.98 μH	Output voltage	9V
Self Inductance of secondary coil	70.98 μH	Output current	0.70A
Mutual Induction	70.98 μH	Voltage across inductor	15.58V
Coupling Coefficient	1	Current across inductor	1.74A

4. COIL DESIGN

4.1 Requirements for the coil construction in Wireless Power Transmission System

The requirements for the coil construction are as follow:
1. The capability of inductance and power must meet the requirements, including the working frequency and power.
2. The mechanical dimension must fit the requirements of the applications, including area and thickness of the coil.
3. The construction of the coil must be durable.
4. The coil must provide the electromagnetic shielding (reducing the electromagnetic field by blocking the field with barriers made of magnetic materials) for the associated electronic device such as the mobile phones.
5. While designing the wireless IPT system, the inner radius of the coil should be smaller because it provide better coupling.
6. The outer radius of the coil should be larger while designing the IPT system because it provide better coupling. By increasing the outer diameter the number of turns also increases which will increase the inductance and hence the quality factor of coil will increase.
7. While constructing the wireless inductive power transmission system, the circular coil is used. Circular coil has advantage of having uniform flux distribution. It provides uniform coupling and helps the power transferred be similar in all the direction.

4.2 Factors affecting Inductance of Coil

1) Quality Factor

Quality factor is the ratio of inductive reactance to resistance at a given frequency. The higher the value of quality factor of an inductor, the more will be its inductance.

2) Spacing between turns

Inductance decreases with the increase of spacing between the coil turns and if the spacing between coils is less then inductance will be increased.

3) Coil Diameter

Diameter of coil affects the inductance of the coil. The greater the diameter of coil, greater will be the inductance. Lesser coil diameter results the less inductance. Greater coil diameter presents less opposition to the formation of magnetic field flux.

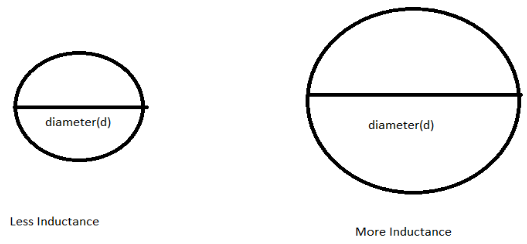

Fig -3: Effect of diameter on inductance

By using equation 1 the inductance for various diameters can be calculated.

Table -2: Inductance for different diameters

Inductance for different diameters	
Diameter (cm)	Inductance (μH)
2	17.66
4	35.32
6	52.98
8	70.65
10	88.31

Fig 4 shows the variation of inductance with various diameters.

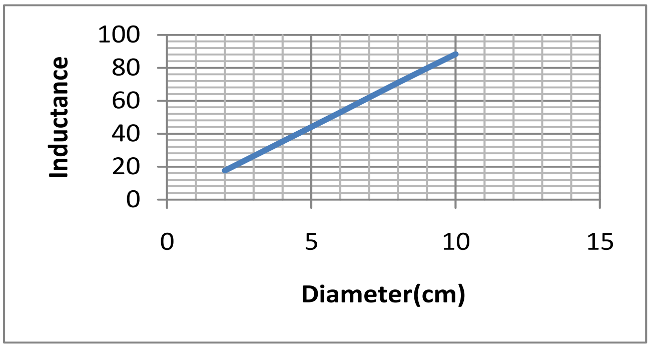

Fig- 4: Variation of inductance for various diameters

4) Number of Turns

Greater the number of turns of the coil, greater will be the inductance. Fewer turns of wire within the coil results the less inductance. Because more turns of coil will generate a greater amount of magnetic field.

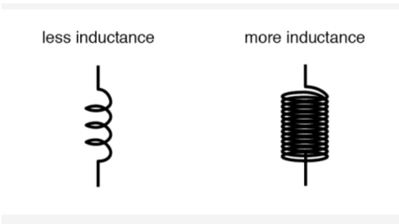

Fig-5: Effect of turns on inductance

By using equation 1 inductance for various turns can be calculated.

Table -3: Inductance for different turns

Inductance for different turns	
Turns	Inductance (µH)
5	1.97
10	7.85
15	17.66
20	31.4

Fig 6 shows the variation of inductance for different turns.

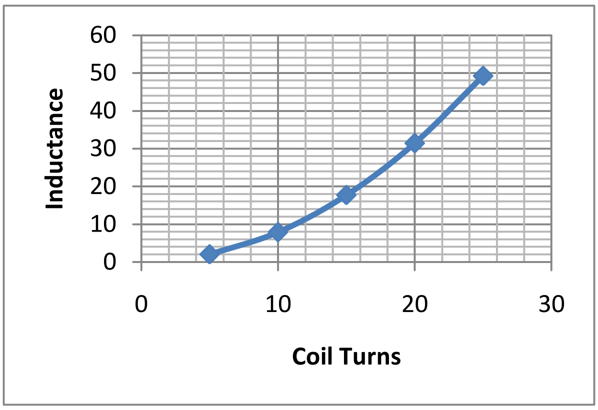

Fig-6: Variation of inductance for different turns

4.3 Types of Coil Structure

1) Circular Coil

These types of coils are non-polarized and having uniform flux distribution. Due to the uniform flux distribution the coupling will be uniform and power transfer will be similar in all directions. For circular coil quality factor is given by:

$$Q = \frac{wL}{R} = \frac{2\pi fL}{R}$$

From above, equation the quality factor is directly proportional to *w* and inductance L. The quality factor can be increased by increasing the value of *w*. When *w* is constant quality factor can be increased by increasing the inductance of the coil or decreasing the resistance.

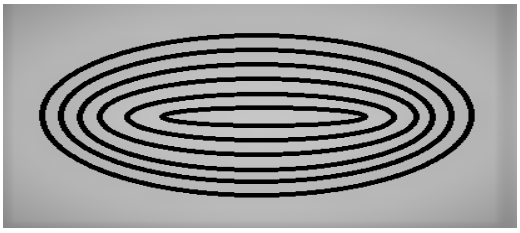

Fig -7: Circular Coil

2) Rectangular or Square Shape Coil

These types of coils form a polarized flux distribution. The advantage of rectangular coil is that the flux path is higher as compared to circular coils. These types of coils are polarized, so they have the highest coupling among all the other types of coils. If the coils are misaligned then the coupling is reduced. The main disadvantage of this type of coil is that it has the highest leakage flux and is hence not suitable for efficient wireless power transmission.

Fig–8: Rectangular Coil

5. CONSTRUCTION OF WIRELESS INDUCTIVE POWER TRANSMISSION SYSTEM

5.1 7805 Voltage Regulator

7805 regulator is the most commonly used voltage regulator IC. For many electronic devices regulated power supply is essential because semiconductor material used in them have fixed rate of current as well as voltage. If there is any deviation then device may get damaged.
Important source of DC supply are batteries. The voltage provided by the batteries is 9V and 12v. This is good for those circuits whose voltage requirements come under this range. But most of the IC's work on 5V and hence we need such kind of mechanism that provide continues 5V supply. So 7805 regulator is used to provide continues 5v supply. This IC comes under the 78XX family that produces regulated 5v supply. Some of the important features of 7805 regulator IC are given below:

1) It has capacity to deliver a current up to 1.5A.
2) It has internal current limiting and thermal shutdown features.
3) For fully functioned it requires minimum external components.

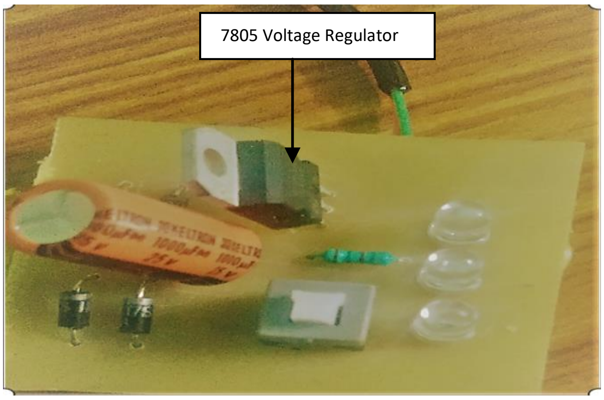

Fig-9: 7805 Voltage Regulator

5.2 Pin Diagram of 7805 Regulator

Fig 10 shows the pin diagram for voltage regulator. The pin description of 7805 is given in table 4.

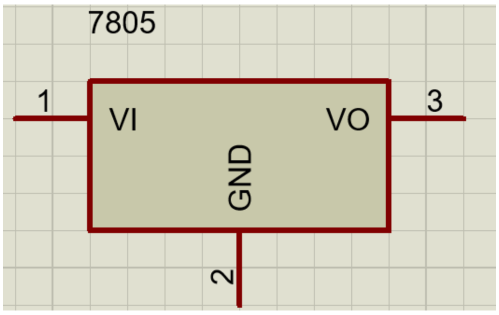

Fig-10: Pin diagram of Voltage Regulator

Table-4: Pin description of 7805 voltage regulator.

Pin description of 7805 voltage regulator		
Pin No	Pin	Pin Description
1	Input	A positive unregulated voltage is given as input to this pin. The voltage range should be 7v to 35v.
2	Ground	Ground is connected to this pin. It is common for both input and output.
3	Output	The output 5v is taken at this pin.

5.3 IRFZ44N MOSFET

It is an N channel MOSFET having high drain current of 49A. It provides low threshold voltage of 4V at which the MOSFET will start conducting. The main features of IRFZ44N MOSFET are:

1) It provides continues drain current of 49A.
2) It provides minimum threshold voltage of 2V and also provides maximum threshold voltage of 4V.
3) Its gate source voltage (VGS) is ±20V (max) and maximum drain source voltage is 55V.
4) It has 60ns and 45ns rise and fall time.

Fig shows pin diagram and symbol of IRFZ44N MOSFET. The pin configuration of IRFZ44N MOSFET is given in table 5.

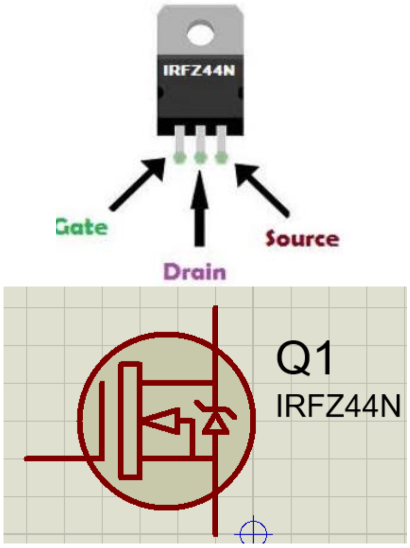

Fig-11: Pin diagram of IRFZ44N MOSFET

Table-5: Pin description of IRFZ44N MOSFET

Pin description of IRFZ44N MOSFET		
Pin No	Pin Name	Pin Description
1	Gate	It controls the biasing of MOSFET.
2	Drain	Current flows in through the drain.
3	Source	Current flows out through the source.

It is a voltage control device. This MOSFET can be turned on and off by supplying the required gate threshold voltage (VGS). It is an n channel MOSFET, when there's no voltage applied to the gate pin drain and source pins will be left open. When voltage is applied to the gate pin, drain and source pins will get closed.

5.4 Diode Full Wave Bridge Rectifier

The diode full wav bridge rectifier produces the same output waveform as full wave rectifier. This type of rectifier uses four individual diodes connected in bridge to produce the desired output. Its main advantage is it does not require special center tapped transformer, so reducing its cost and size.

The four diodes are connecting in series with only two diodes conducting current through each half cycle. During the positive half cycle, diodes 1 and 2 conduct in series and diode 3 and 4 are reverse biased. During the negative half cycle, diode 3 and 4 conduct in series and diode 1 and 2 are reverse biased or switch off. The simulated circuit for diode full wave bridge rectifier is shown in figure 12.

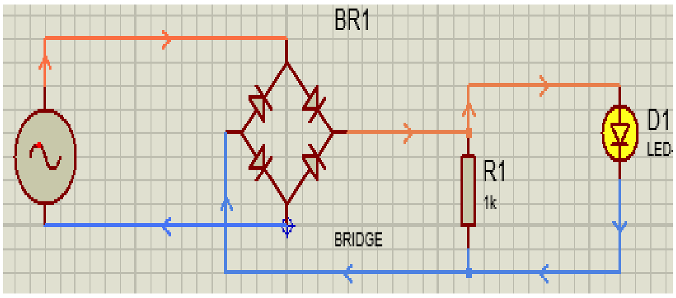

Fig -12: Simulated circuit for full wave bridge rectifier

Figure 13 shows the waveform for diode full wave bridge rectifier.

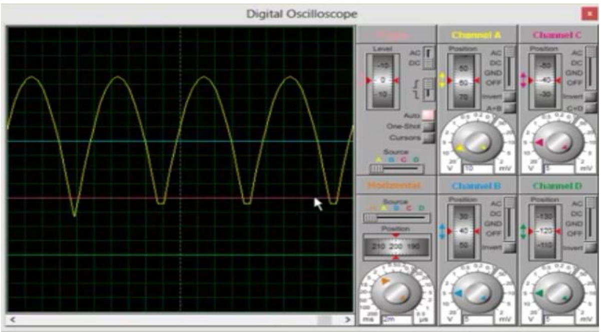

Fig -13: Output waveform for full wave bridge rectifier

6. SIMULATION RESULTS

Figure 14 shows the simulation circuit for wireless inductive power transmission system with the help of Proteus 8 software.

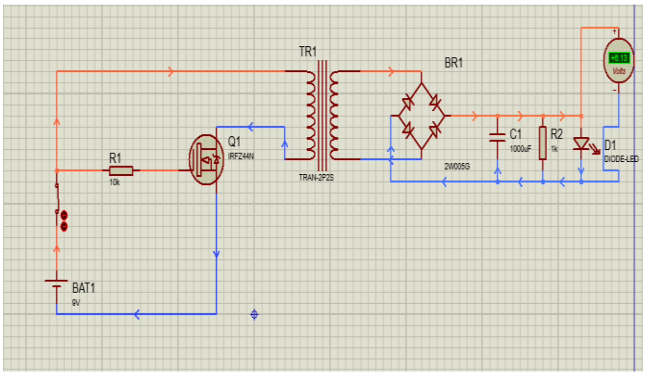

Fig-14: Simulated circuit for WPT system on Proteus

7. HARDWARE EXPERIMENTAL RESULTS

For any system when simulation is complete, hardware implementation is important to bring it practically. The theoretical result obtained is verified by hardware implementation. The system parameters are tested to make sure that they are working according to desired output.

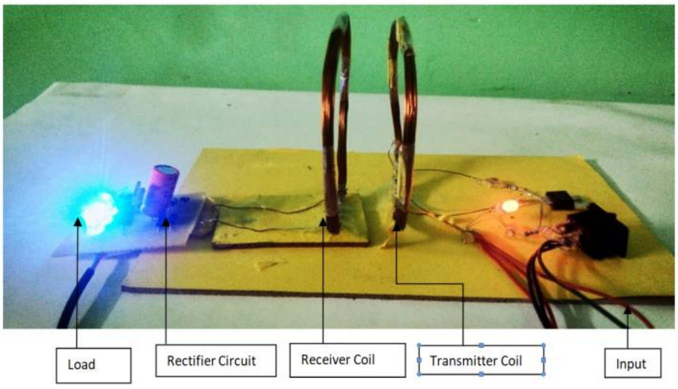

Fig-15: Hardware Setup

Fig 15 shows the hardware setup for the wireless power transmission system through inductive coupling. Firstly the 9V dc input is applied to the system. This 9V is applied to transmitter coil and magnetic field is produced. Secondary coil receives the magnetic field from transmitter coil according to faraday's law of electromagnetic induction. According to this law an EMF must be produced into the receiver coil which is experiencing the magnetic flux generated by transmitter. This generated voltage will be rectified and regulated to get a proper dc voltage. The switch is used to switching the mode from LED to charging mode. Fig 16 shows the experimental setup for inductive coupling when obstacle is applied. When obstacle is applied the power is still transferred wirelessly. There is no effect in wireless transmission when obstacles like books, plastic or any other insulator is applied.

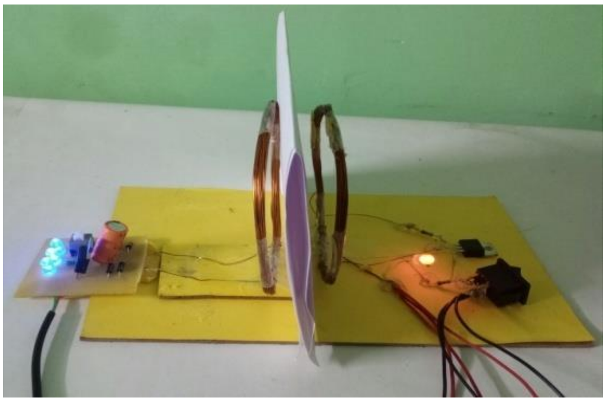

Fig -16: Hardware setup when obstacle is applied

Table 6 shows the experimental values of the system parameters. The experiment has conducted for various distances from 0 cm to 5 cm. From experiment it is concluded that if the distance is increased the efficiency of the system will be decreased as shown in table 6.

Table-6: Experimental values of system's parameters

Experimental values of system's parameters					
Distance (cm)	Output Voltage (V)	Output Current (A)	Input Power (W)	Output Power (w)	Efficiency (ŋ)%
0	6.51	0.50	6.3	3.26	51
1	5.93	0.42	6.3	2.49	40
2	4.01	0.31	6.3	1.26	20
3	3.32	0.14	6.3	0.47	7.5
4	2.21	0.03	6.3	0.066	1.04

7.1 Efficiency versus Distance Graph

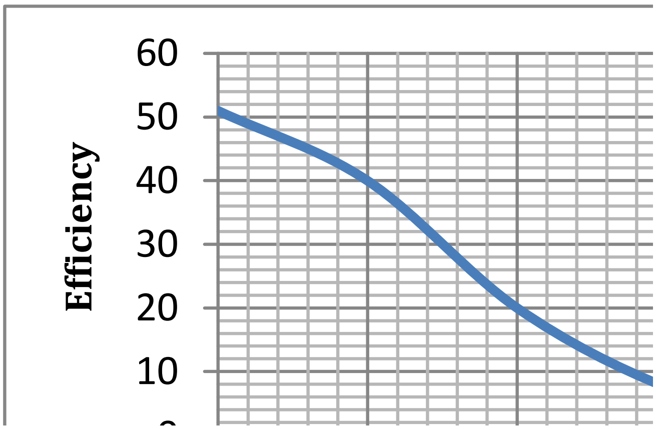

Fig-17: Distance v/s efficiency graph

As shown in figure 17, it is concluded that if the distance is large the efficiency starts decreasing and if the distance is smaller the efficiency will be high.

7.2 Experimental Setup for Phone Charging

Figure 18 shows the experimental setup for phone charging. In the setup, voltage regulator is used to get the dc voltage not more than 5v. When the distance is 0cm to 1cm it can be used for charge the mobile. It takes around 3 hours for charging when distance is up to 1cm. When the distance is 1to 2cm it takes around 7 hours.

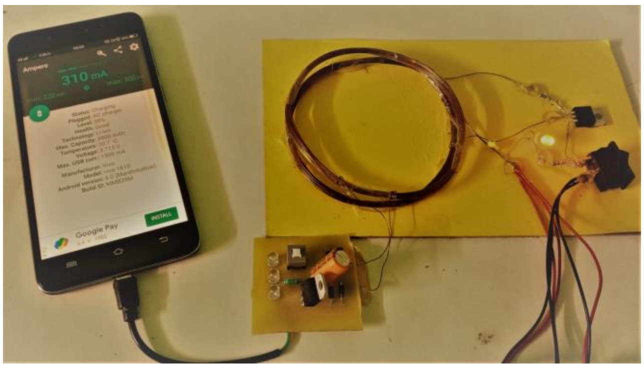

Fig-18: Experimental setup for phone charging

8. CONCLUSIONS

According to the specifications of the system, the design is observed to show good performance at a different turn ratio but turn ratio of 1:1 is selected. At turn ratio of 1:1 the system is perfectly coupled. When the turn ratio is different from 1:1, the efficiency of the system is decreased. Also the voltage on the output side increase which can damage the system. The coupling distance between transmitter and receiver coil also cannot be varied to a long range because the performance of the system is decreased at long distance. It is observed that various factors affecting the inductance of coil. At circular coil shape the maximum efficiency is achieved. Hence, it can be concluded that this proposed system when designed with a turn ratio of 1:1 and at circular coil shape, produced the desired results. It can also be observed that wireless power transmission not much affected when obstacles is applied between transmitter and receiver coils. So this system is useful for practical applications like charging.

Hardware test were done for small distance for charging applications. So future scope should be focus on increasing the wireless power transmission distance and for charging the multiple electronic and electrical equipment at same time.

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BIOGRAPHIES

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