Wireless Power Transmission by Magnetic Resonance Circuits

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1. Abstract
Since the advent of electricity and start using it, the transmission from the source to the consumer has always been existed. Meanwhile, wireless power transmission was an issue that was in the minds of the scientists from the beginning of generation of electricity. Until now, many efforts have been made in this regard and scientists have discovered several methods so far.
The subject of this paper is to transmit the electricity wirelessly by magnetic resonance circuits. In this paper, first of all the performance of magnetic resonance method would be described, then the relevant circuits are studied in more details, and finally the effect of each quality parameters in this method of transmission is measured by some examinations.

Keywords: wireless power transmission, magnetic resonance

2. Introduction
The initial idea of wireless power transmission by magnetic resonance method was introduced by Nikola Tesla. In 1899, Tesla achieved a great progress by designing a resonance transformer that was recognized as Tesla coil and transmitted 100 million volts of electrical energy to a distance of 26 miles and lit 200 lamps and turned on an electric motor. Unfortunately, Tesla's experiments were halted due to lack of financial resources and he failed to finish his plans.

Despite the antiquity of this method of transmission is more than a century, but the scientists didn't do so much research in this regard for a long time. One of the reasons of that break was this method was not economically commodious. Because even with today's technology the highest yield were recorded in about 40%, which was conducted by researchers at MIT University and 60 W of electrical energy transmitted to a distance of about 2 meters and a 60 watts light bulb was lit. Today with the rapid growth of science and technology, this issue has become one of the up to date issues. More articles and studies published in this issue are related to after the year 2008 and in 2009 the number of these papers is considerable. Topics such as reliability, security, being cheaper than other methods of wireless power transmission and ... Increased attention of the researchers to this method. Transferring the energy is always embedded with issues like efficiency and quality. For further investigation in this regard, in this paper the influence of parameters such as operating frequency, the diameter of the transmitter and receiver coils, the diameter of the wire of the coils, the distance between the transmitter and the receiver coils and the coils turns will practically be evaluated on the performance of designed power transmission system.

3. Theory

3.1. The concept of magnetic resonance
In physics, resonance is the tendency of the system (usually a linear system) to oscillate with maximum amplitude at certain frequencies named resonant frequency or natural frequency. If you consider an oscillating system (like a swing), we can have the maximum amplitude if we blow it with a frequency equal to its natural frequency. The main function of this method is that two separate coils with a same resonant frequency can form a resonant system and have energy exchange, while the effect of coupling between the coils with different natural frequencies would be less, so this causes the effective distance range in the case of

resonant system would increase comparing to the non-resonant mode.

The effective performance distance in this manner, depending on the factors such as operating frequency, the accuracy rate for the circuits at the desired resonant frequency and the transmitter and receiver coils size, can increase to several times of the size of the coils.

3.2. The resonance circuit

Consider a circuit comprising a capacitor and an inductor. Each of the inductor and capacitor has impedance which can be calculated as follows:

$$Z_L = j\omega L \qquad (1)$$

$$Z_C = \frac{1}{jC\omega} \ ; \ \omega = 2\pi f \qquad (2)$$

Now if the working frequency of the circuit is such that the absolute value of Z_L and Z_C is the same, we can say that the circuit is at resonant mode and the working frequency of the circuit in this mode is called the resonant frequency. If we equate the absolute values of Z_L and Z_C we will have:

$$Z_L = Z_C \Rightarrow j\omega L = \frac{1}{j\omega C} \Rightarrow f = \frac{1}{2\pi\sqrt{LC}} \qquad (3)$$

The last equation is used to calculate the resonant frequency of an LC circuit. When an LC circuit is in resonant mode, the inductor and the capacitor constantly exchange energy together. This energy is stored as electric field the capacitor and magnetic field in the inductor and constantly by charging and discharging their energy exchange causing an AC current flowing in the circuit. If the circuit doesn't disturb, the energy oscillation (due to the absence of losses) will continue. If we put a resistor in the circuit above, the energy exchange in the absence of a power supply will be damped and finally stops.

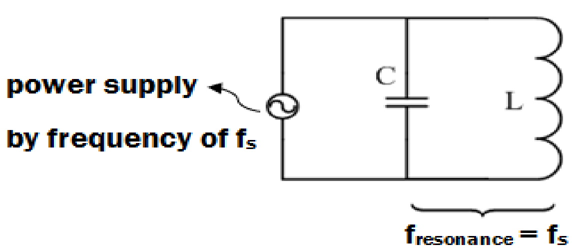

Figure (1): a resonant LC circuit

3.3. Wireless Power Transmission

In wireless power transmission by resonance method, we have two coils with a determined selfish capacity, each coupling to a capacitor with a determined capacity and meantime they have mutual inducting effects with each other. They play the role of our transmitter and receiver. One of the coils is connected to the AC power supply and the other is connected to the load. The performance of this system is that when the AC source is connected to the transmitter coil, an AC current is established. The AC current in the transmitter coil establishes an AC flux with the same frequency. The frequency of the source must be equated to resonant frequency of the transmitter and receiver circuit. Alternating flux produced by the transmitter coil, would be received by the receiver coil by mutual induction and since its frequency is equal to the resonant frequency of the receiver circuit, the maximum energy transfer amount occurs. Overview of such system is shown in figure (2).

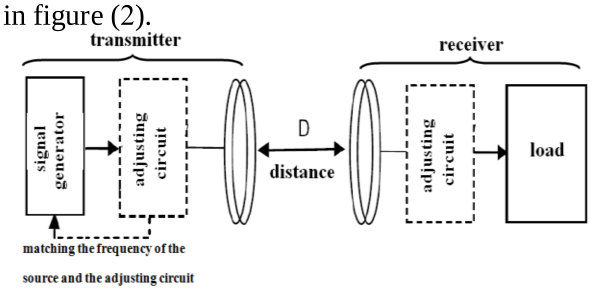

Figure (2): overview of the dismounted system

In the next section, the circuit of the system for the experiments is presented.

3.4. The overall circuit of the experiments

The overall circuit that was used for the experiments is shown in Figure (3).

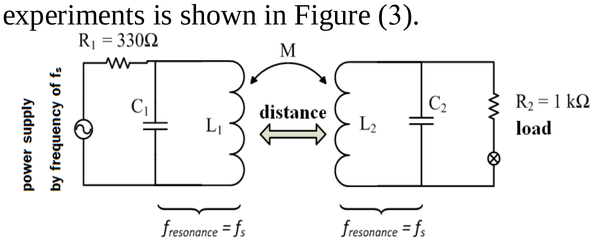

Figure (3): The overall circuit of the experiments

As shown in Figure (3), the amount of L_is and C_is (i = 1 , 2) must be configured such that the resulting resonance frequency is the frequency of the source.

4. Case Studies

In this section, the system that was closed during the tests and its theory was discussed in the previous section would be explained further.

First, a signal generator with a frequency of 1 MHZ and voltage amplitude of 23 V (peak-peak) was considered as a power supply of the circuit. The exact waveform of this signal generator is given in the test results. To dismount the circuits, a breadboard was used (one for the transmitter and one for the receiver) and any part of the circuit was mounted on the breadboard. For the transmitter and receiver, it is used of coils that were made of different materials at different dimensions which also are the selfish capacity of the circuit (Although the number of turns of coils was less but winding by a machine caused the coils to have a smooth shape and take the form of a loop). For the capacitors of the circuit, it is used of several capacitors to form a desired total capacitance. It is used of a digital oscilloscope to measure and capture the transmitting and receiving waveforms. For maintaining a constant distance between the coils and also having the coils concentric and to maintain the annular shape of the coils and have no geometrical distortion, it is used of a cardboard tube. The value of inductance, capacitance and resistance of the coils was measured using an RLC meter. Measuring the coils resistance was for calculating the power. The resistance of the coils comparing to the resistance which is placed in the circuit (either in the transmitter and the receiver) was very low, so it was ignored. (Coil resistance was about 0.1 to 0.2 ohms). In the receiver, it is used of a 1 kΩ resistance for the circuit load. It should also be added that changing the 1 kΩ resistance with the 1 MΩ, 8.2 MΩ, 16.4 MΩ and 32.8 MΩ, the amount of the received voltage in the output remained unchanged with good approximation. The amount of the capacitors and the inductors of both sides of transmitter and receiver were taken the same (I.e. in the experiments: C1 = C2 and L1 = L2).

Before presenting the results of the experiments, two points are necessary to express:

- ✓ The presented experiment is probably one of the first experiments in this regard in Iran.
- ✓ Improving the current circuit is part of future research goals.

The aim of the implemented experiments, was to measure the influence of parameters such as distance between the coils (d), the radius of the coils (r), the diameter of the wire used in the coils (D), the number of turns of the coils and power supply frequency (f) on the system performance.

Case 1:

Table (1): parameters amounts

Parameter	Amount
Frequency (f) - kHZ	1042
Cross section diameter of the wire (D) – mm	0.5
Number of turns of the coils (N)	4
Radius of the coils (r) – cm	15
Distance between coils (d) – cm	50
Coil's self-inductances (L) - µH	16.1
Capacity of the capacitors (C) - nF	1.5

Figure (4) shows the overview of the dismounted system.

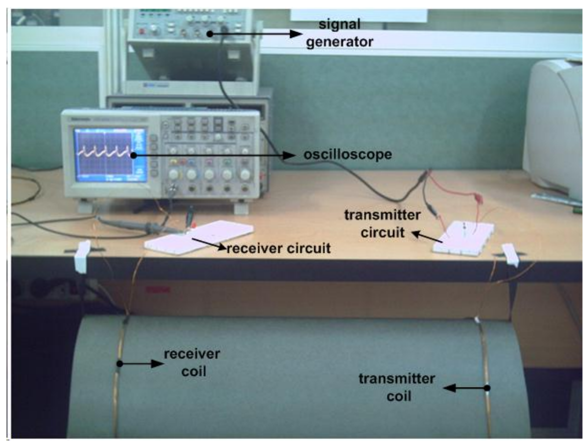

Figure (4): Overview of the dismounted system

The equation of the resonance frequency is:
(f_r is the resonance frequency of the circuit and f_s is the frequency of the power supply)

$$f_s = 1042000\ HZ \quad (4)$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{16.1\times10^{-6}\times1.5\times10^{-9}}}$$

$$= 1024100\ HZ \quad (5)$$

This difference between the resonance frequency of the circuit, from the calculating methods and the one in the experiment, is for the reasons like not assuming the exact amount of equivalent impedance of the coils and the breadboard itself, approximations like to assume the coils to be exactly the same and issues like this.

In the figures (5) to (8) the waveform of the power supply (signal generator) and the output waveform related to the terminals of the 1 kΩ resistance are shown.

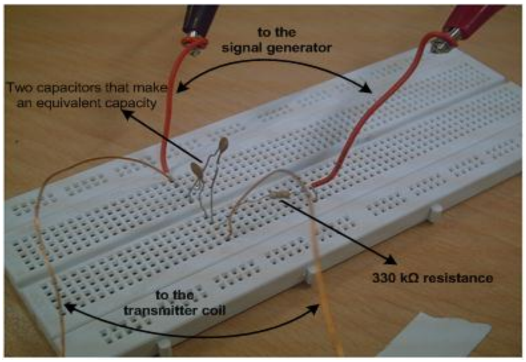

Figure (5): the transmitter circuit of case1

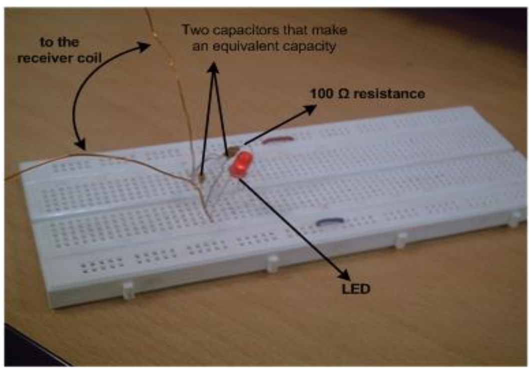

Figure (6): the receiver circuit of case1

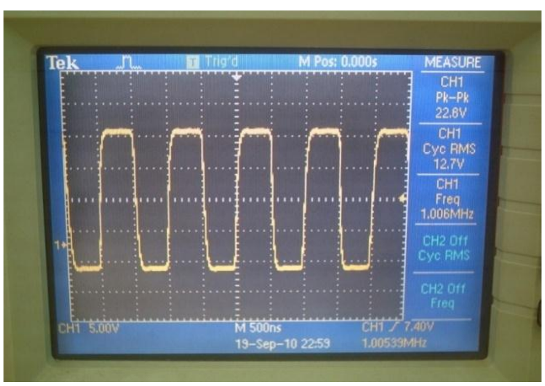

Figure (7): waveform of the signal generator

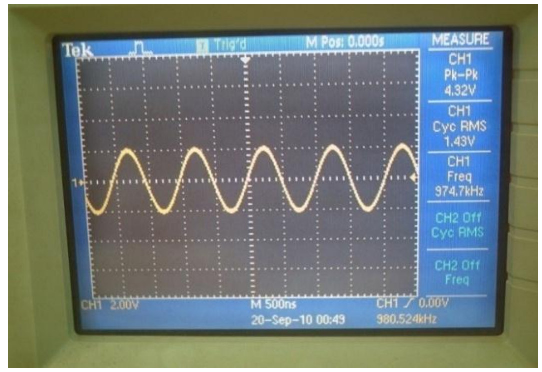

Figure (8): the output waveform

The measured quantities in this experiment are shown in the table (2):

Table (2): measured quantities of case1

Quantity	Amount
V_s (voltage of the signal generator)	12.6 V (RMS)
V_{R1} (voltage of the 330Ω resistor)	7 V (RMS)
V_{R2} (voltage of the 1 kΩ resistor)	1.43 V (RMS)
Phase difference of the voltage and the circuit of the source (φ)	180 degrees

We have:

$$I_s = \frac{V_{R1}}{R_1} = \frac{7}{330} = 21.2\ mA \qquad (6)$$

$$P_{in} = V_s . I_s . cos\varphi = 12.6 \times 21.2 \times (-1)$$

$$= 267.12\ mW \qquad (7)$$

$$P_{R1} = \frac{V_{R1}^2}{R_1} = \frac{7^2}{330} = 148.5\ mW \qquad (8)$$

$$P_{out} = P_{R2} = \frac{V_{R2}^2}{R_2} = \frac{1.43^2}{1\times10^3} = 2.1\ mW \quad (9)$$

$$\eta = \frac{P_{out}}{P_{in} - P_{R1}} = \frac{2.1}{267.12-148.5} = 1.77\% \quad (10)$$

Case 2:

Table (3): parameters amounts of case2

Parameter	Amount
Frequency (f) - kHZ	1014
Cross section diameter of the wire (D) – mm	0.5
Number of turns of the coils (N)	4
Radius of the coils (r) – cm	15
Distance between coils (d) – cm	25
Coil's self inductances (L) - µH	16.1
Capacity of the capacitors (C) - nF	1.5

The measured quantities in this experiment are shown in the table (4):

Table (4): measured quantities of case2

Quantity	Amount
V_s (voltage of the signal generator)	12.6 V (RMS)
V_{R1} (voltage of the 330Ω resistor)	7 V (RMS)
V_{R2} (voltage of the 1 kΩ resistor)	1.43 V (RMS)
Phase difference of the voltage and the circuit of the source (φ)	180 degrees

We have:

$$\eta = \frac{P_{out}}{P_{in}-P_{R1}} = \frac{10.89}{236.73-116.5} = 9.06\% \quad (11)$$

Case 3:

Table (5): parameters amounts of case3

Parameter	Amount
Frequency (f) - kHZ	1050
Cross section diameter of the wire (D) – mm	0.5
Number of turns of the coils (N)	10
Radius of the coils (r) – cm	15
Distance between coils (d) – cm	50
Coil's self inductances (L) - µH	93
Capacity of the capacitors (C) - nF	0.15

The measured quantities in this experiment are shown in the table (6):

Table (6): measured quantities of case3

Quantity	Amount
V_s (voltage of the signal generator)	12.6 V (RMS)
V_{R1} (voltage of the 330Ω resistor)	7.12 V (RMS)
V_{R2} (voltage of the 1 kΩ resistor)	1.71 V (RMS)
Phase difference of the voltage and the circuit of the source (φ)	180 degrees

We have:

$$\eta = \frac{P_{out}}{P_{in}-P_{R1}} = \frac{2.924}{272.16-153.6} = 2.47\% \quad (12)$$

Case 4:

Table (7): parameters amounts of case4

Parameter	Amount
Frequency (f) - kHZ	1066
Cross section diameter of the wire (D) – mm	0.5
Number of turns of the coils (N)	4
Radius of the coils (r) – cm	8
Distance between coils (d) – cm	25
Coil's self inductances (L) - µH	7.2
Capacity of the capacitors (C) - nF	3.1

In this experiment it is necessary to explain that with this coil with the diameter of 8 cm, when the distance between the coils was 50 cm, the amount of power loss was so that the received voltage at the receiver was very low and noisy. So, the distance was edited to 25 cm. The measured quantities in this experiment are shown in the table (8):

Table (8): measured quantities of case4

Quantity	Amount
V_s (voltage of the signal generator)	12.6 V (RMS)
V_{R1} (voltage of the 330Ω resistor)	5.2 V (RMS)
V_{R2} (voltage of the 1 kΩ resistor)	1.2 V (RMS)
Phase difference of the voltage and the circuit of the source (φ)	180 degrees

We would have:

$$\eta = \frac{P_{out}}{P_{in}-P_{R1}} = \frac{1.44}{199.08-81.9} = 1.23\% \quad (١٣)$$

Case 5:

Table (9): parameters amounts of case5

Parameter	Amount
Frequency (f) - kHZ	526
Cross section diameter of the wire (D) – mm	0.5
Number of turns of the coils (N)	4
Radius of the coils (r) – cm	8
Distance between coils (d) – cm	5
Coil's self inductances (L) - µH	7.2
Capacity of the capacitors (C) - nF	12.4

The measured quantities in this experiment are shown in the table (10):

Table (10): measured quantities of case 5

Quantity	Amount
V_s (voltage of the signal generator)	12.6 V (RMS)
V_{R1} (voltage of the 330Ω resistor)	6 V (RMS)
V_{R2} (voltage of the 1 kΩ resistor)	4.33 V (RMS)
Phase difference of the voltage and the circuit of the source (φ)	180 degrees

We would have:

$$\eta = \frac{P_{out}}{P_{in} - P_{R1}} = \frac{18.75}{299.1 - 109.1} = 9.87\% \quad (14)$$

Case 6

Table (11): parameters amounts of case 6

Parameter	Amount
Frequency (f) - kHZ	2119
Cross section diameter of the wire (D) – mm	0.5
Number of turns of the coils (N)	4
Radius of the coils (r) – cm	8
Distance between coils (d) – cm	5
Coil's self inductances (L) - µH	7.2
Capacity of the capacitors (C) - nF	0.75

The measured quantities in this experiment are shown in the table (12):

Table (12): measured quantities of case 6

Quantity	Amount
V_s (voltage of the signal generator)	12.6 V (RMS)
V_{R1} (voltage of the 330Ω resistor)	6.2 V (RMS)
V_{R2} (voltage of the 1 kΩ resistor)	6.81 V (RMS)
Phase difference of the voltage and the circuit of the source (φ)	180 degrees

We have:

$$\eta = \frac{P_{out}}{P_{in} - P_{R1}} = \frac{46.38}{236.7 - 116.5} = 38.6\% \quad (15)$$

Case 7:

Table (13): parameters amounts of case7

Parameter	Amount
Frequency (f) - kHZ	1048
Cross section diameter of the wire (D) – mm	1.1
Number of turns of the coils (N)	4
Radius of the coils (r) – cm	15
Distance between coils (d) – cm	50
Coil's self inductances (L) - µH	15
Capacity of the capacitors (C) - nF	1.603

The measured quantities in this experiment are shown in the table (14):

Table (14): measured quantities of case7

Quantity	Amount
V_s (voltage of the signal generator)	12.6 V (RMS)
V_{R1} (voltage of the 330Ω resistor)	6.5 V (RMS)
V_{R2} (voltage of the 1 kΩ resistor)	1.48 V (RMS)
Phase difference of the voltage and the circuit of the source (φ)	180 degrees

We have:

$$\eta = \frac{P_{out}}{P_{in} - P_{R1}} = \frac{2.2}{248.22 - 128} = 1.83\% \quad (16)$$

5. Acknowledgment

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6. Conclusion

As described before, the goal of performing the experiments in this paper is to evaluate the amount and the way of influence of the different parameters of the system on its performance. Table (15) shows the effect of the different parameters by comparing the experiments results.

Today, by the rapid improving of the technology, the issue of wireless power transmission, especially by the resonant circuits has become an up to date issue in the world.

In this paper, first of all, the concept of resonance had been explained, then the resonant circuits proposed, then some dismounted systems in the laboratory were assessed and at last the effect of each of the parameters in the system has been evaluated. A brief summary of the experiments conclusion is shown in table (15).

Table (15) The effect of the different parameters by comparing the experiments results

Experiment No.	Evaluating parameter	conclusion
1 , 2	d (distance between the coils)	The distance between the coils in examination #1 was equal to 50 cm and in examination #2 decreased to 25 cm. we can see that the efficiency increased from 1.77% to 9.06%. This means by halving the distance, efficiency increased more than 5 times.
1 , 3	(N) number of turn of the coils	In the examination #1, the number of turns of the coils was equal to 4, but in the examination #3 it increased to 10. We can see that the efficiency increased from 1.77% to 2.47%. So, by increasing the number of turns of the coils, the efficiency increases by a normal coefficient.
1 , 4	(r) radius of the coil	The radius of the coils in the examination #1 was equal to 15 cm, but in the examination #4 was decreased to 8 cm. As we can see, it had a notably effect on the system because although the distance was decreased to 25 cm, the efficiency just had been equal to 1.23% (and even we didn't have the efficiency of examination #1)
5 , 6	(f) working frequency	The working frequency of the examination #5 was equal to 526 kHZ that it increased to 2119 kHz in the examination #6. it can easily be seen that the working frequency has an enormous effect on the efficiency an increased it from 9.87% to 38.6% (that means more than 7 times)
1 , 7	(D) diameter of the wires	In the examination #7 the diameter of the wire was almost equal to two times of that in #1. By comparing the results we can see that increasing the wire diameter would just poorly increase the efficiency.

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