Efficiency Improvement of Two Coil Wireless Power Transfer System for Biomedical Implants

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***Abstract*—Wireless power transfer system is used to charge the batteries of biomedical implants. This article presents a design of two coil system which is able to transfer the power to the implanted battery without any tissue damage. One module consists of primary coil and alternating signal generator circuit and the other consists of secondary coil, DC-DC converter and control circuit. External coil is used to transfer the power through magnetic link. The whole idea is to recharge the battery of implants. In this research work two coil inductive system with two different strategies, one is field focusing element(repeater) and second is ferrite magnetic core to enhance the magnetic field at same distance and same frequency are compared. In the prototype of two coil power transfer system, 575 kHz and 700 kHz frequency with different signals are used for driving the primary coil with 68 mm diameter and coil distance 10 mm to 50 mm using 18 mm implanted coil diameter and achieved more than 40% efficiency at 30 mm distance which is better results compared by conventional two coil system .**

I. Introduction

Implantable devices are becoming day by day more popular in health and medical field to support the internal organs and make it properly working condition and extend the life of human [15]. The power requirement of biomedical implants depends on their specific application and typically ranges from a few micro watts to a few tens of milliwatts. Some implants use rechargeable batteries for continuous supplying the power to the implantable devices. Because of implant size, batteries are also in small size, but they should be able to supply the power for particular period of time. Li-ion batteries are most preferable in implants, because of their high energy density, safety, and reliability. Li-ion battery or cell in implants, requires constant voltage and constant current for charging [4], [15].

Today inductive coupling is most popular technique in wireless power transfer system, especially powering the implants which requires batteries for long time support the working of implants. Basically inductive power transfer system consists of two coils external coil and implanted coils. External coil is large in diameter and implanted coil is small in diameter because of implant size. Mutual inductance is the basic concept for power transfer in inductive coil system. Coil should be design for which they provide enough power at specific distance to charge the battery of implant for particular time period.

For two coil power transfer system quality factor and coupling coefficient given below,

$$\eta = \frac{k^2 Q_p Q_s}{1 + k^2 Q_p Q_s} \tag{1}$$

where

$$\begin{aligned} \eta &= \text{Two coil system efficiency} \\ k &= \text{Coupling coefficient between two coil} \\ Q_p &= \text{Quality factor of primary coil} \\ Q_s &= \text{Quality factor of secondary coil} \end{aligned}$$

Two coil system has low coupling because of source and load resistance, so efficiency is very low and may $< 40\%$, and generally reduce exponentially with distance $\left(\frac{1}{d^3}\right)$ for $d \gg r_m$ [11],
where

$$\begin{aligned} r_m &= \sqrt{r_p r_s} \\ r_p &= \text{radii of external coil} \\ r_s &= \text{radii of implanted coil} \end{aligned}$$

To recharge the battery of biomedical implants, the system should be able to transfer the power with 60 to 90% efficiency for a distance of 20 mm or more is desired [12]. Strong alternating magnetic field is required for effectively transfer of power at specific distance. Power transfer also depends on frequency. To generate strong alternating magnetic field, high frequency alternative supply required. It may be high frequency sinusoidal wave or square wave or triangular wave or rectangular wave. In this paper, different types of waveform used to compared the results of efficient power transfer. Sine and square wave has two states positive and negative. At same frequency square or rectangular wave is able to generate strong alternating magnetic field in primary coil compared to sine wave.

Fig.1 shows two waves sine and square wave. The green shaded portion shows the excess RMS voltage of typical square wave compared to sine wave RMS, which means that square wave generate more magnetic field compared to sine wave at same distance and same frequency. Because of this reason, sine and square waves are used and compared the results.

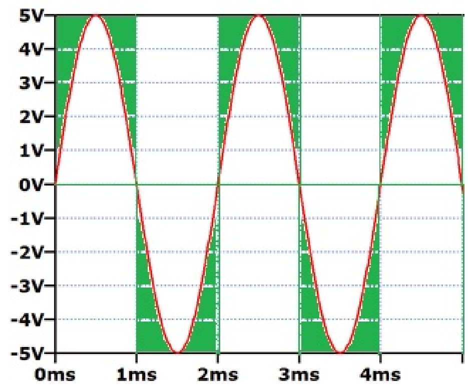

Fig. 1. Sine and Square wave

II. Theory

In two coil power transfer system, power is transferred through the air, so the output power is limited because of distance, coil size of implant, operating frequency, surroundings..etc. But deliver the power to the battery of implants, should be maintain certain level whether misalignment or transverse offset occur between two coil. For this reason system should be efficient and should be able to transfer the power efficiently at large distance. In this article, compared two strategies with two different waves. Comparatively sine wave, square wave has excess RMS voltage, so that it produced more output voltage compared to sine wave. There is another wave, rectangular wave from 555 astable multi-vibrator can produce more effect. Table.I shows RMS values of three waveforms, where A for amplitude and D for duty cycle. RMS value of rectangular wave can be changed according to duty cycle of 555 astble timer. Here repeater is nothing but a coil which is able to enhance the magnetic field. Identifying exact distance of the repeater is also challenge to enhance maximum field strength. As same ferrite core also enhance the magnetic field. In this paper two different signals are used with repeater and core. But the placement of repeater and core at particular distance is depends on frequency, repeater coil dimension, supply voltage, distance between two coils [5].

TABLE I
RMS values of different wavforms

Waveform Type	RMS Values
Sinusoidal	$\frac{A}{\sqrt{2}}$
Square	A
Pulse	A $\sqrt{D}$

III. Design Steps

A. External Circuits Design

1) 555 Astable timer circuit: Basically inductive coil needs alternating supply to generate strong magnetic field with some specific frequency, but tissues absorb magnetic field and generate heat, due to development of eddy current. For frequency range of 100 kHz to 4 MHz band, no biological effect have been reported. There is a frequency band around 100 kHz to 4 MHz, at which no any bodily effect described. To design mobile wireless power transfer system(device), there is an option, 555 timer(wave generator) shown in Fig.2, which requires +5V to +15V dc supply and it is small in size. This paper presents improve the power transfer efficiency in two coil system for implant battery charging system with low input power and reliable and small size power transfer system. In 555 timer, frequency is setting by choosing components R_1, R_2 and C_1 properly so that timer generate required kHz frequency with 5V amplitude. The equations for calculation of frequency are given below,

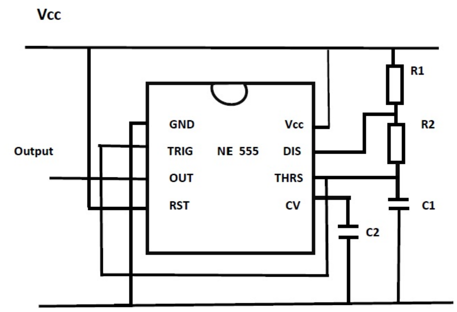

Fig. 2. Astable Mode

$$f = \frac{1.44}{(R_1 + 2R_2)C_1} \tag{2}$$

$$T_{\text{on}} = 0.693 R_2 C_1 \tag{3}$$

$$T_{\text{off}} = 0.693 (R_1 + R_2) C_1 \tag{4}$$

$$\text{Duty Cycle} = \frac{T_{\text{on}}}{T_{\text{on}} + T_{\text{off}}} \tag{5}$$

The components selection for particular frequency generation are given in [1], [2]. The frequency of output of 555 astable timer can very with change in R_1, R_2 and C_1. Here $R_1 = (1k||1k\text{varable}), R_2 = 1.5k$ and $C_1 = 47pf$ chosen for rectangular wave generation at +5 V DC. Here the duty cycle presents mark and space ratio, mark means ON time or pulse and space means no pulse or OFF time. According to duty cycle, output power can be changed. In the Fig.3, there are ringing and overshoot in rectangular wave because of stray capacitance and inductance presents in the circuit causing damping oscillation, which affects the output. Good quality of components reduce these effects and increase the power efficiency.

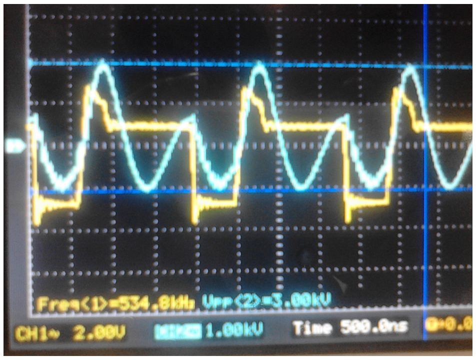

Fig. 3. Output Signals of 555 timer and primary coil

2) Coil designs: Two coil based system has low coupling because of source and load resistance, so the efficiency is very low and is $< 40\%$, and generally reduce exponentially with distance $\left(\frac{1}{d^3}\right)$ for $d \gg r_m$ [10]–[12].

But our aim is to transfer the power at large distance with efficiency more than 40%, so here two techniques used to enhance the magnetic field between the coils. Table II shows coil dimension which are used. Equation for calculation of inductance and capacitance is given below at resonance,

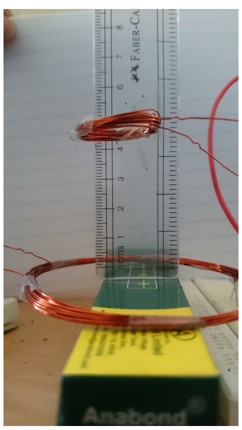

Fig. 4. Two coil system

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

$$C = \frac{1}{4\pi^2 f^2 L} \tag{7}$$

where

$f =$ Operating frequency
$L =$ Coil Inductance
$C =$ Resonance Capacitance of coil

IV. Experiment and Results

To improve the efficiency or enhance the magnetic field, there are two strategies used one is core and second is repeater with sine and square wave.

TABLE II
COIL DIMENTIONS

Dia.(mm)	Turn	Inductance (μ H)
68	20	376
18	20	178

A. Two Coil with ferrite core

A magnetic core is a piece of magnetic material with high permeability used to guide magnetic fields in electrical, electromechanical and magnetic devices. There are different types of magnetic cores, but ferrite has high permeability. The work of core is to concentrate the magnetic field lines in the core material and pass through the core. Simple coil can generate magnetic field, but presence of core can increase the magnetic field. So the placement of core at particular distance is depends on frequency, repeater coil dimension, supply voltage, distance between two coils. At resonance frequency it can enhance magnetic field as high as possible at specific distance from coil. We can use at primary or secondary side coils. In this experiments, core used at secondary coil side, inside the coil. Experimental results shown in Table.III to Table. VIII, which shows that the core enhance the magnetic field and the efficiency of the system more than 40% achieved with different signal waveforms at 30 mm distance [5], [6], [13].

B. Two Coil with repeater coil

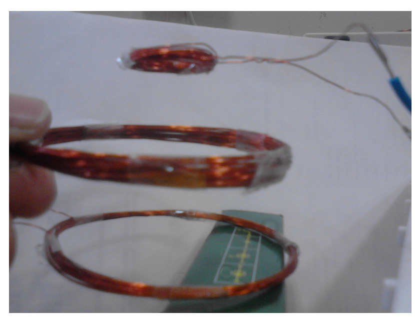

Fig. 5. Two coil with repeater

This is second method to enhance the magnetic field in the system, but placement of repeater between the coil is also a problem, because at what distance to place the repeater, so that it can enhance maximum magnetic field. So the placement of repeater at particular distance is depends on frequency, repeater coil dimension, supply voltage, distance between two coils ...etc. In the experiments, 68 mm diameter with 40 turn coil is used. When a repeater coil without capacitor, placed between two coil system, which enhance the magnetic field, but coil with parallel capacitor at resonance is placed between the two coil system, which reduce the magnetic field. So proper placement and design of repeater is require to enhance the magnetic field and is also depends on coil turn direction, number of turns of repeater coil, distance from primary coil, coil diameter, wire diameter and supply frequency [5], [6], [9].

C. Results

We know that, square wave covers large area compared to sine wave. Because of more RMS value, square wave provide large power compared to sine wave. Electronic circuits consume power, which is average power delivered by the source. Equations are given below,

$$X_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T X^2(t)dt} \tag{8}$$

where

$$X(t) = \text{Voltage or Current} \tag{9}$$

$$P_{\text{avg}} = \frac{V_{\text{rms}}^2}{R_L} \tag{10}$$

or

$$P_{\text{avg}} = I_{\text{rms}}^2 R_L \tag{11}$$

where

$$R_L = \text{Load resistance} \tag{12}$$

$$I_{\text{rms}} = \text{RMS of Current} \tag{13}$$

$$V_{\text{rms}} = \text{RMS of Voltage} \tag{14}$$

TABLE III
EFFICIENCY OF SINE AND SQUARE WAVES AT 10 V_{pp} WITH 575 KHZ FREQUENCY

Distance(cm)	Sinusoidal	Square
1	31.66	46.5
2	24.58	33.33
3	17.08	24.49
4	12.7	18.4
5	8.54	13.04

TABLE IV
EFFICIENCY OF SINE AND SQUARE WAVES AT 10 V_{pp} WITH 700 KHZ FREQUENCY

Distance(cm)	Sinusoidal	Square
1	60.40	73.75
2	31.02	37.50
3	24.89	30.50
4	16.32	20.25
5	11.43	14.37

TABLE V
EFFICIENCY COMPARISON OF SINE WAVES AT 10 V_{pp} WITH 700 KHZ FREQUENCY USING CORE AND REPEATER COIL

Distance(cm)	Repeater	Core
1	No	74.17
2	29	55
3	16.52	43.75
4	10.9	19.17
5	7.3	13.75

TABLE VI
EFFICIENCY COMPARISON OF SQUARE WAVES AT 10 V_{pp} WITH 700 KHZ FREQUENCY USING CORE AND REPEATER COIL

Distance(cm)	Repeater	Core
1	No	84.12
2	27.5	60
3	16.09	40
4	10.9	22.2
5	7.3	16.5

TABLE VII
EFFICIENCY COMPARISON OF SQUARE WAVES AT 10 V_{pp} WITH 575 KHZ FREQUENCY USING CORE AND REPEATER COIL

Distance(cm)	Repeater	Core
1	No	84
2	22.5	76
3	16.85	48.64
4	12.71	36.75
5	5.86	25.13

TABLE VIII
EFFICIENCY COMPARISON OF SINE WAVES AT 10 V_{pp} WITH 575 KHZ FREQUENCY USING CORE AND REPEATER COIL

Distance(cm)	Repeater	Core
1	No	73.2
2	22.97	72.45
3	16.52	45.77
4	12	35
5	6.34	22.64

In the experiment, we have used 575 and 700 kHz frequency with only two coil, two coil with repeater, and two coil with core. We can see that the repeater and the core affects the efficiency, because in the graph, efficiency vary with distance and frequency in the two coil system shown in Fig.6 to Fig.11.

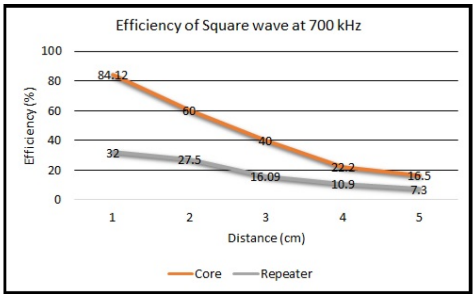

Fig. 6. Efficiency of two coil system using square wave at 700 kHz frequency

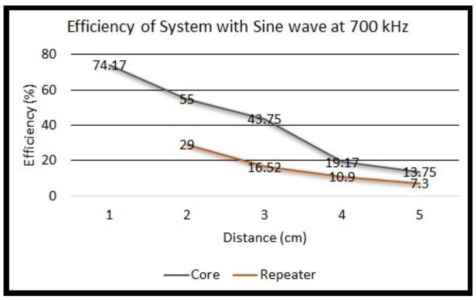

Fig. 7. Efficiency of two coil system using sine wave at 700 kHz frequency

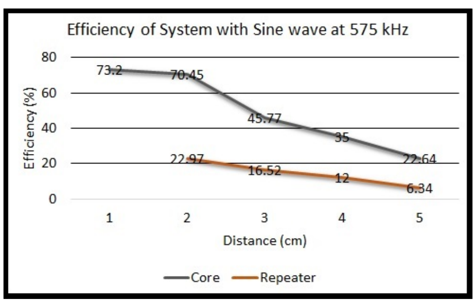

Fig. 8. Efficiency of two coil system using sine wave at 575 kHz frequency

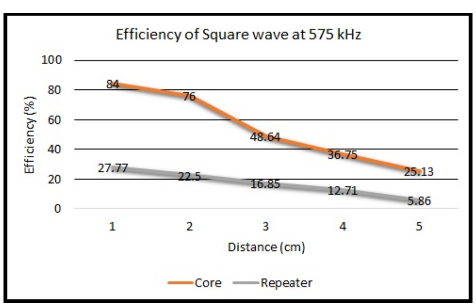

Fig. 9. Efficiency of two coil system using square wave at 575 kHz frequency

V. Conclusion

In this paper, comparison of efficiency of two coil power transfer system with repeater and core with different waveforms are described. The described system is improved to delivered the power to the battery of implants at large distance. Using square wave signal, achieved more efficiency compared to sine wave. To enhance the efficiency, repeater and core

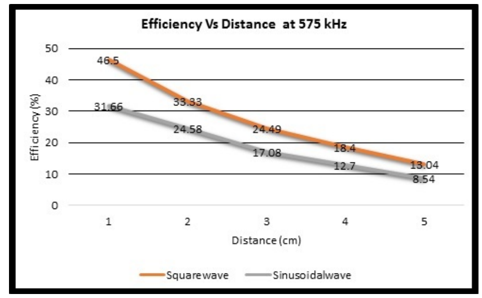

Fig. 10. Efficiency of two coil system using square wave and sine wave at 575 kHz frequency

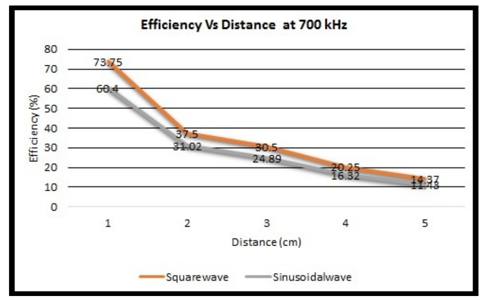

Fig. 11. Efficiency of two coil system using square wave and sine wave at 700 kHz frequency

TABLE IX
Comparison with Previous Work

Ref.	Radii (r_p, r_s) (mm)	Freq. MHz	Efficiency (%)	Dis. (mm)
[3]	(15,15)	4.5	54	10
[7]	(30,10)	0.7	36	30
[8]	(26,5)	6.78	22	15
[14]	(8.5,6)	1	30	7

TABLE X
Comparison with Previous Work

Ref.	Radii (r_p, r_s) (mm)	Freq. MHz	Efficiency (%)	Dis. (mm)
This work	(34,9)	0.575	Square(24.49)	30
This work	(34,9)	0.7	Square(30.50)	30
This work	(34,9)	0.575	Square with core(48.95)	30
This work	(34,9)	0.7	Square with core(40)	30
This work	(34,9)	0.7	Sine(24.89)	30
This work	(34,9)	0.575	Sine(17.85)	30
This work	(34,9)	0.7	Sine with core(43.75)	30
This work	(34,9)	0.575	Sine with core(45.77)	30

used, but using repeater, 15 to 25% efficiency achieved which is not good enough. With coils of 0.4 mm diameter copper wire with 68 mm and 18 mm diameter and 30 mm distance, more than 40% efficiency achieved, which show in Table. X and IX. We can improve the efficiency using high (Q) coil with large distance. For high (Q) coil, litz wire used, because it has low ac resistance at high frequency.

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