Design of Wireless Biotelemetry Powering System for Implanted Sensing Devices in Human Body

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Abstract
In this paper, a wireless power transfer system is used to power the implanted sensors near the skin of the human body. The system consists of an efficient class-E power amplifier and inductive power links based on planner circular spiral coil with rectangular cross sectional area is used as a transmitter and receiver coil. Each of the two coils is symmetrical in geometry and designed with four number of turns and 0.633uH of inductance at inner and outer radii of 1mm and 3mm, respectively. The system is operated with a resonant frequency of 13.56MHz. A digital information with low data rate that has a frequency of 200 KHz and a voltage level of 1V is used with ASK modulation technique. The data transmitted at 1cm separating distance between the transmitter and receiver circuits by directly coupled method with a supplying DC voltage of 2.4V obtained for powering the implanted sensor. The proposed system is designed and simulated on on PSpice in ORCAD 16.6 program.

Keywords: Wireless Transmission, inductive coupling, implanted devices, class E power amplifier,coil design.

الخلاصة
في هذا البحث ، تم تصميم نظام لنقل الطاقة لاسلكي اللحساسات الطبية القابلة للزرع في جسم الأنسان. حيث يتكون النظام من مكبر قدرة من نوع E، مقوم، منظم فولتية ، ودائرة لاسترداد البيانات حيث يعمل النظام بتردد رنين يساوي 13.56MHz. ان هذا النظام مصمم بملف من النحاس في دائرة الأرسال التي تمثل الجزء الخارجي الذي يستعمل في نقل الطاقة لاسلكيا للحساس من خلال جلد الجسم البشري باستخدام طريقة الاقتران الحثي وملف واحد في دائرة الاستلام التيتمثل الجزء الداخلي (الحساس القابل للزرع) والذي بدوره يستلم الطاقة المرسلة . كُلاً من الملفين متماثل في الشكل والابعاد ومصممين بأربع لفات بقيم حث تساوي 0.633nH مع 1mmو3mm للقطرين الداخلي والخارجي بالترتيب. وقد استخدمت طريقة التضمين ASK لتضمين المعلومات الرقمية ذات معدل بيانات منخفض بتردد 200KHz ومستوى فولتية يساوي 1V. البيانات نقلت لمسافة 1cm تفصل بين دائرة المرسل ودائرة المستلم مع تجهيز الحساسات المزروعة 2.4V فولتية مجهزة للحساس. مع عمل دراسة شامله على العوامل المؤثرة في الكفاءة .

الكلمات المفتاحية : الارسال اللاسلكي ، الاقتران بالحث ، الحساسات المزروعة ، مكبر من نوع E، تصميم الملف.

1. Introduction
Heinrich Rudolf Hertz, investigated in the late 1800's that the power could be transferred via electromagnetic waves in free space and performed an experimental proof to Maxwell's Equation. Hertz based on natural resonance phenomena in experiencing many radiating antennas [Faccio and Clerici, 2006].Around 20 years later, Nikolai Tesla, made a return in wireless power transfer fieldand introduceda specific coil called a Tesla coil or Tesla transformer [Prasanth,2012;Williams,2011].

Witricity (Wireless electricity), energy harvesting and wireless power transfer refer to transferring power or electric energy over a distance without the use of wires. This means providing power from a source point to an end-use device without contacts or wires. The space between the power source and the receiving device can range from a centimeter to more than few meters depending on the size of the device, power transfer efficiency, and the amount of power required to be transferred [Mohanram *et.al.*, 2013].

Implantable devices can function as either stimulators or sensors. Sensors are used to extract the bio-signals from inside the human body and transfer data to external devices in order to measure for example blood pressure, body temperature, cardiac pressure disorders, etc... Stimulators receive data from the external world (external units activated by doctors) and stimulate particular nerves. The common implementation of stimulators are the microelectrodes for neural recording, utilized to identify and regulate treatment for brain disorders [Li *et.al.,* 2012]. To decrease the danger of patient discomfort and infection resulted from the transcutaneous wires penetrating the skin, wireless process of implantable microelectronic devices are necessarily utilized for clinical applications. Wirelessly power transfer (WPT) is a clean controllable power to overcome the lifetime of the battery [Islam, 2011].

There are several methods for wirelessly powering the implantable sensors. An inductive link between two magnetically coupled coils is a general method used to transmit power and data wirelessly from the external world to implantable biomedical devices.The inductive power transmission should be good and efficient to overcome tissue heating and inductively minimize the size of the external battery [Li *et.al.,* 2012; Islam, 2011].In a medical system, an inductive link was used for transferring power wirelessly to the implanted sensor with an efficiency of 21.22%. The transmitter coil had 4 turns with a diameter of 4.5cm and 2mm spacing between conductors .The receiver inductance was 0.25µH, which delivered a power of 50mW to the implanted circuit with 3.3V DC voltage. The separation distance between the transmitter and receiver was 1cm and both were tuned to a frequency of 13.56MHz [Sehil *et.al.,* 2005].The printed spiral coil (PSC) was optimized by[Jow and Ghovanloo, 2008] to make transcutaneous inductive power transmission more efficient. It was carried out on two design examples at 1 and 5 MHz for achieving power transmission efficiencies of 41.2% and 85.8%, respectively, at 10mm spacing between transmitting and receiving coils .According to the human electromagnetic exposure limits, a study introduced by [Christ *et.al.,* 2012] provided a recommendations for scientifically sound modes of estimating a compliance of wireless power transfer systems taking modes for both measurements and numerical analysis to measure the specific absorption ratio (SAR) for the human body. For sensors injected near the skin of the human body at distance extremely varied from 1 to 4 cm with two spiral circular coils used as a transmitter and receiver coils, a system was introduced by [Adeeb *et.al.,* 2012]to transfer energy wirelessly to the implanted sensor for obtaining power transmission of 125mW with 12.5% power link transmission efficiency at a coupling coefficient (k) of 0.453.

The biomedical system consists of external device existing outside the human body and transferring power to an implantable device which is generally referred to as any device projected a task inside a living body for either long or short term use as illustrated in Figure1.

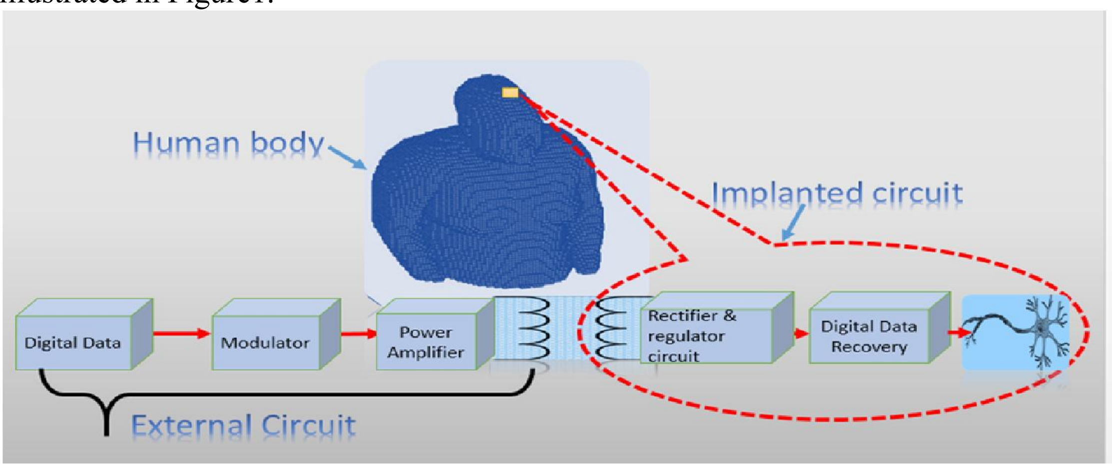

Figure 1. Wireless power transfer system for biomedical applications.

One of the most important parameters of the implantable biomedical system is the wireless link operating frequency, which is also known as carrier frequency. It justifies the following functionalities: inductive power transmission, forward data transmission from the outside world towards the implanted device, and back telemetry from the implanted device outward [Zainuddin *et.al.,* 2013]. In this paper, a design model is introduced for powering sensors that injected near the skin of the human body at distance up to 1cm by direct coupling method between two coils using class E power amplifier at a resonant frequency of 13.56MHz.

2. Analysis of class-E power amplifier and inductive link

Class-E amplifier is a highly efficient switching mode power amplifier, typically used at such high frequencies that the switching time becomes comparable to the duty time [Sokal, 2010;Eswaran *et .al.,* 2014]. The basic schematic of the class-E amplifier and its associated waveforms are shown in Figure 2. The transistor operates as an ideal switch and the shunt capacitor *C* is charged and discharged during its operation. The series combination L_0 and C_0 operate as a filter, thus, the output current and voltage include only the fundamental component and all harmonics are removed [Rogers, and Plett, 2003]. When the transistor is '*on*', the collector voltage is zero, on the other hand, when it is '*off*'', the collector current is zero [Cripps,2006;Eswaran *et.al.*, 2014]. The following assumptions are made during the design process of this amplifier:

1. The RF choke (RFC) is large enough, that only DC current flowing through it.
2. The quality factor *Q* of the series combination L_0 and C_0 is high enough that the output current and voltage are pure sinusoids at the fundamental frequency.
3. The transistor behaves as perfect switch.
4. The output capacitors *C* and C_0 are independent of voltage.

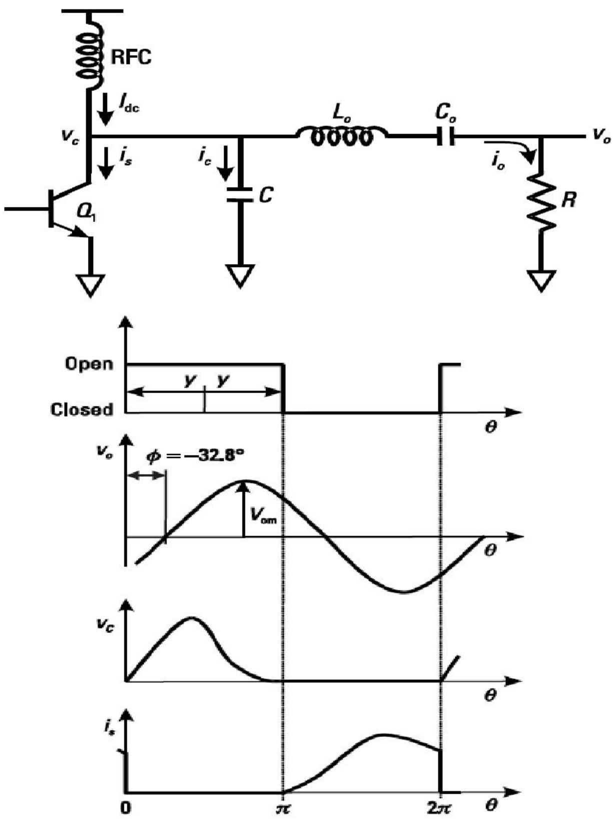

Figure 2. Class-E power amplifier and its associated waveforms [Rogers, and Plett, 2003].

During switching off, the transistor collector voltage $v_C$can be determined as a function of θas [Rogers, and Plett, 2003]:

$$v_C(\theta) = \left[\frac{I_{dc}}{B}\left(y - \frac{\pi}{2}\right) + \frac{V_{OM}}{BR}\sin(\emptyset - y) + \frac{I_{dc}}{B}\theta + \frac{V_{OM}}{BR}\cos(\theta + \emptyset)\right] \tag{1}$$

Where, I_{dc} is the DC input current, V_{OM} is the amplitude of the output voltage v_o, I_{OM} is the amplitude of the output current i_o, $\emptyset$ is the phase of the output voltage measured from the instant at which the switch is open, $2y$ is the switch off angle in radians, B is the admittance of C, and R is the load resistance .Class-E power amplifier is usually designed such that the series combination composed of L_0 and C_0 resonates at a frequency slightly less than the operating frequency f_0 and the parallel combination composed of C and the series combination formed by L_0, C_0, and R resonate at f_0. The capacitor C represents the output capacitance of the power transistor and that of an external one added such that it satisfies the design requirements. The fundamental component of $v_C(\theta)$ is v_1 (θ). The latter is applied to $R + jX$to determine output RF power. Here, jXrepresents the residual impedance of the combination L_0C_0, which resonates slightly below f_0[Rogers, and Plett, 2003].

Equating $v_C(\theta)$ and $\frac{d[v_C(\theta)]}{dt}$ to 0 and substituting for θ by$\frac{\pi}{2} + y$, the following are obtained:

$$\emptyset = -32.48°$$

$$B = \frac{0.1936}{R} \tag{2}$$

$$X = \frac{1.152}{R} \tag{3}$$

It can be proved that [Rogers, and Plett, 2003]

$$V_{OM} = \frac{2}{\sqrt{1+0.25\pi^2}}V_{CC} \approx 1.047V_{CC} \tag{4}$$

Hence, the output RF power can be given by

$$P_{RFout} = \frac{(V_{OM})^2}{2R} \approx 0.577\frac{{V_{CC}}^2}{R} \tag{5}$$

The efficiency of this PA can be 100% in case of perfect circuit elements. The transistor DC current, peak current, and peak voltage are given by [Rogers, and Plett, 2003]

$$I_{dc} = \frac{V_{CC}}{1.734R} \tag{6}$$

$$v_{C,peak} = 3.56V_{CC} \tag{7}$$

$$i_{S,peak} = 2.86I_{dc} \tag{8}$$

With the finite output Q, the following are determined [Rogers, and Plett, 2003]:

$$X = \frac{1.11Q}{Q-0.67}R \tag{9}$$

$$B = \frac{0.1836}{R}\left(1 + \frac{0.81Q}{Q^2+4}\right) \tag{10}$$

$$Q = \frac{\omega_0 L}{R} \tag{11}$$

2.1 Design of class-E power amplifier at 13.56 MHz

The signal required to be transmitted has an amplitude of 1V and a frequency of 200 KHz with 0.1ns for both rise time (TR) and fall time (TF). This signal is used to modulate a 13.56MHz carrier signal that has an amplitude of 2V and pulse width (pw) of 36.87ns with 0.5ns for both TR and TF.

The complete circuit diagram of the proposed class E power amplifier with inductive link is shown in Figure3. This circuit is designed using the PSpice components on ORCAD 16.6 program. In this circuit, a pair of the transistor Q2N2222 with maximum collector current of 800mA is used as a Darlington circuit to accomplish greater current gain. The RFC inductance is adjusted to 500nH to block the high frequency components. The next stage of designing class E power amplifier circuit is the switch device, which is chosen properly to fulfill efficient performance. The BSH103 n-channel high-speed power MOSFET with higher power dissipation and low drain to source on resistance is used.

The input voltage of the power MOSFET is the carrier signal which has an amplitude of 2V and frequency of 13.56MHz resonant frequency. To make the transistor behaves as perfect switch, the circuit is adjusted to operate at a resonant frequency of 13.56MHz. Using Equation(12),the tuned circuit of class E power amplifier is designed such that the shunt capacitor C_1 satisfies the design requirements by setting its value to 0.4647nF andC_2 is designed so as to resonate with L_1 at a frequency slightly less than the operating frequency f_0 (13.56MHz).The capacitor C_2 is calculated to be 0.19554nF.

$$wL = \frac{1}{wc} \qquad (12)$$

The output circuit of the class E power amplifier is designed according to Equations (1) to (10) such that the output current and voltage are pure sinusoids at the fundamental frequency (13.56MHz).

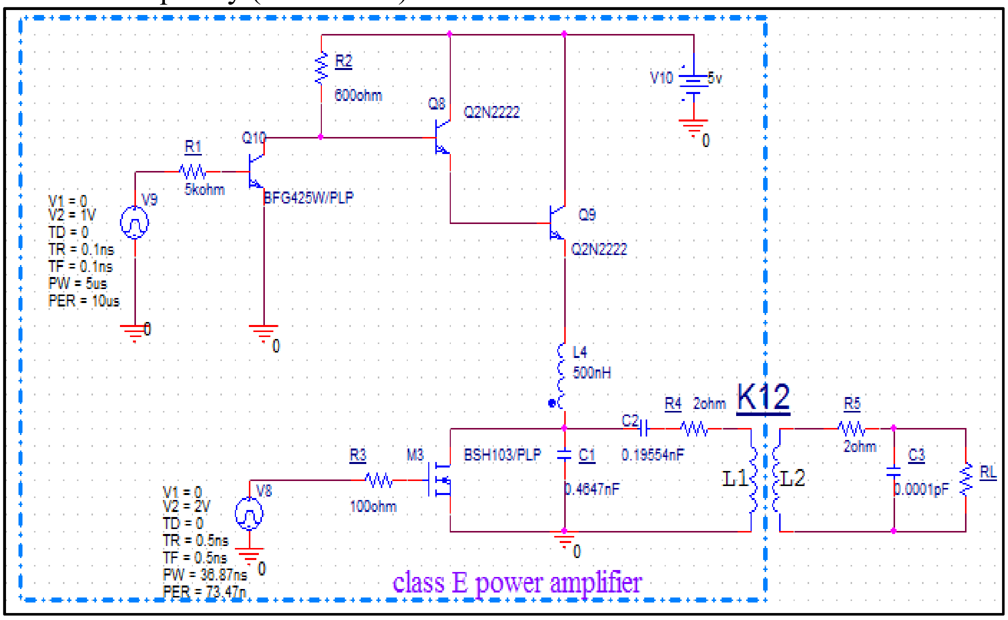

Figure 3. The class E power amplifier circuit with inductive link.

2.2 Inductive Power Link

Presently, the inductive coupling link methods are commonly used in biomedical applications.An inductive link is modelled by a loosely coupled transformer having a pair of coils that are typically located in a coaxial arrangement as shown in Figure 4.

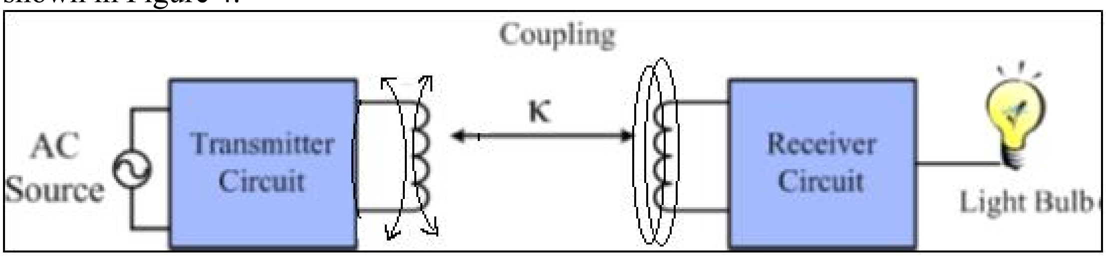

Figure 4. The inductive link produced by an alternating electromagnetic field.

The primary or the external coil is provided by an alternating current. A percentage of the alternating flux lines generated by the primary coil (transmitting coil) links the secondary coil (receiving coil) and produces an induced voltage across the secondary coil terminals. This induced voltage is governed by Faraday's law of electromagnetic induction [Islam, 2011]. If the number of turns of the secondary coil is n and the magnetic flux linking each turn is $\emptyset_m$, then the induced voltage for the circuit can be written as

$$v = n\frac{d\emptyset_m}{dt} \quad (13)$$

In this paper, an inductive link based on a planner circular spiral coil with rectangular cross sectional area is presented. This type of coil is normally used with implantable circuits, which are designed for both transmitter and receiver coils with inductances of both primary (L_1) and secondary (L_2) of 1uH according to the Equation (14) and the inner and outer radii are 1mm and 3mm, respectively for both coils. The structure of this coil is shown in Figure 5.

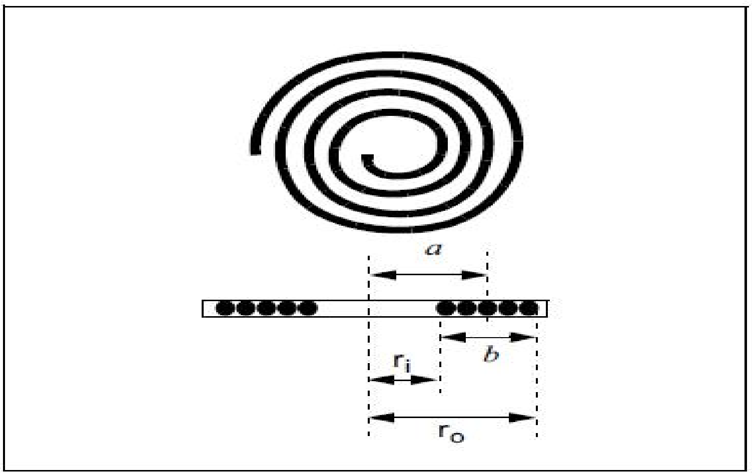

Figure 5.The spiral coil.

$$L = \frac{(0.3937)(aN)^2}{8a+11b} \quad (14)$$

$$a = \frac{(i_r + r_o)}{2} \quad (15)$$

$$b = r_o - r_i \quad (16)$$

Where, $r_i$isthe inner radius of the spiral and $r_o$isthe outer radius of the spiral.There are two factors determining the power transfer efficiency (PTE) of the above inductive link. These two factors are the quality factor Q of each resonator and the mutual coupling (M) between resonators. In [Mou and Sun, 2015],the quality factor for a single resonator is defined by

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{W_0 L}{R} \quad (17)$$

Where, $w_0 = \frac{1}{\sqrt{L\,C}}$ denotes the resonant angular frequency. A higher Q indicates less energy loss. Mutual inductance is a measureable description of the flux coupling of two conductor loops and is defined by

$$M = \frac{K}{\sqrt{L_1 * L_2}} \quad (18)$$

Where, k is the coupling coefficient, which is presented to make a qualitative estimation about the coupling of the conductor loops without mentioning their geometric dimensions, which can be determined by the distance between transmitter and receiver coils. For circular coils, it can be determined by [Mou and Sun, 2015] as

$$K = \left[1 + 2^{\frac{2}{3}}\left(\frac{h}{\sqrt{r_t * r_r}}\right)^2\right]^{-\frac{2}{3}} \quad (19)$$

Where, h denotes the distance between the two coils, and r_t and r_r are the radii of the transmitter and the receiver coils, respectively. The coupling coefficient always fluctuates between the two extreme suitcases$0 \le k \le 1$.

The ratio of the power delivered to the load to the power supplied to the primary coil is called link efficiency. Figure6shows the schematic design of class-E power amplifier withinductive link between two coils. The overall circuit efficiency at resonant frequency is given by [Islam, 2011]

$$\eta = \frac{PO}{Pi} = \frac{k^2 Q_1 Q_2{}^3 R_2\, RL}{(RL + Q_2{}^2\, RL)\{(1 + k^2 Q_1 Q_2)RL + Q_2 R_2{}^2)\}} \quad (20)$$

Where, R_L is the equivalent AC load resistance, which will dissipates an amount of AC power, $Q_1$and $Q_2$are the quality factors of the primary and secondary coils, respectively.

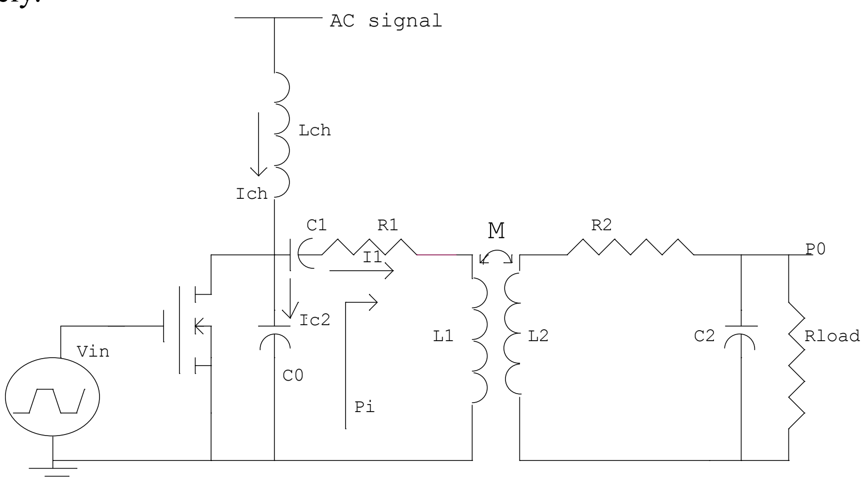

Figure 6. Schematic design of class-E power amplifierwith inductive link between two coils.

The design specifications of the inductive link are listed in Table1.

Table1. Specifications of the designed inductive link

Parameter	Value
primary coil (L_1)	Inductor L_1=0.663uH
	Number of turn N= 4
	Inner radius of coil r_i=1mm
	outer radius of coil r_o=3mm
secondary coil (L_2)	Inductor L_2= 0.663uH
	Number of turn N=4
	Inner radius of coil r_i=1mm
	outer radius of coil r_o=3mm
Shuntcapacitor at the primary side (C_0)	C_0 = 0.4647nf
Series capacitor (C_1) at the primary side	C_1 = 0.19554nf
Shunt capacitor at secondary side (C_2)	C_2 = 0.0001pf
Coupling factor K_{12}	K_{12}= 0.75
Link Efficiency η	60%
Resonant frequency f_0	13.56MHz

3.The proposed system

This model is designed for powering sensors that are injected near the skin of the human body at distance less than 1cm by direct coupling method between two coils .The system consists of two circuits; the first one is the external or the transmitter part that transfers data and power wirelessly to the implantable sensor via the skin by inductive coupling method, while the second part represents the receiver circuit of the system, which is embeded in the implantable sensor and designed to extract the transmitted data and gain the required power from the external part. After transferring the modulated signal to the implanted circuit, a full wave bridge rectifier is used to demodulate the received signal. An Mbreak MOSFET of length of 100nm and width of 500nm is used to design the bridge circuit with common gate biasing method.The rectified signal is stabilized by a regulator for obtaining the DC voltage that is required to supply the implantable sensor. It consists of a zener diode, regulating transistor, and a comparator, which is a wideband low supply voltage OPAMP of the type max998/mxm. After supplying the implanted medical sensor by the stabilized DC voltage produced by the regulator circuit, a data recovery circuit is designed to extract data from the rectified input signal. The overall circuit diagram of the proposed system using direct inductive coupling for powering the biomedical sensors imbedded in human body isshown in Figure 7. This circuit is designed using the PSpice components on ORCAD 16.6.

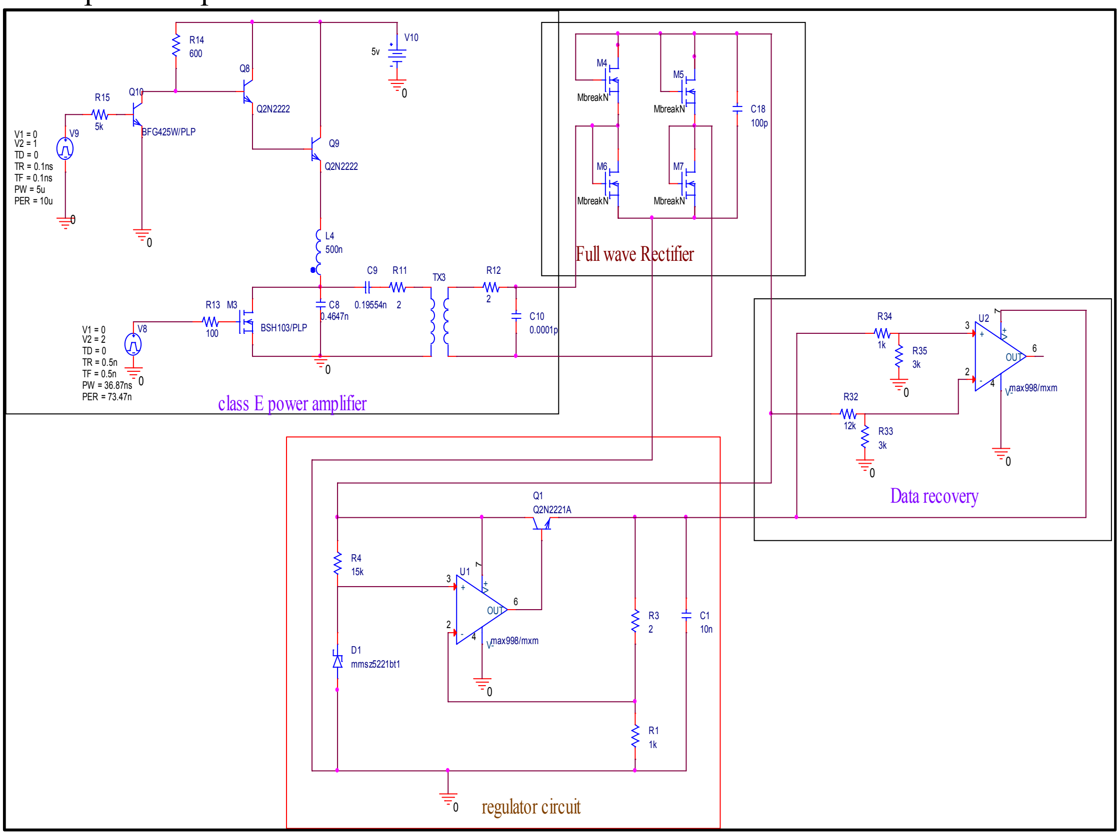

Figure 7. The overall proposed system of direct coupling method.

4. Simulation results

The proposed system shown in Figure 7 was tested on PSpice ORCAD in 16.6 to show its performance. The current out from Darlington circuit and flowing through RF choke (RFC) is 188.701mA.In this design, ASK modulation technique is used for transmitting power wirelessly via magnetic resonant coupling to guarantee efficient power transfer.A sinusoidal voltage of amplitude of 15V asshown in Figure8 and current of amplitude of 174.766mA through the primary coil causes due to magnetic coupling a sinusoidal voltage of amplitude of 14.036V and current of 37.887mA to be induced at the secondary coilwith coupling factor between the primary and secondary coil k of 0.75according to the Equation (19). The quality factor for the primary coil$Q1$ and that for the secondary coil $Q2$ are set equal to 71.519 according to Equation (17).This system is capable of transmitting a power of 40mW with efficiency of class E power amplifier of 60%.The rectified signal obtained by full wave rectifier is of a level of 13.360Vas shown in Figure9.

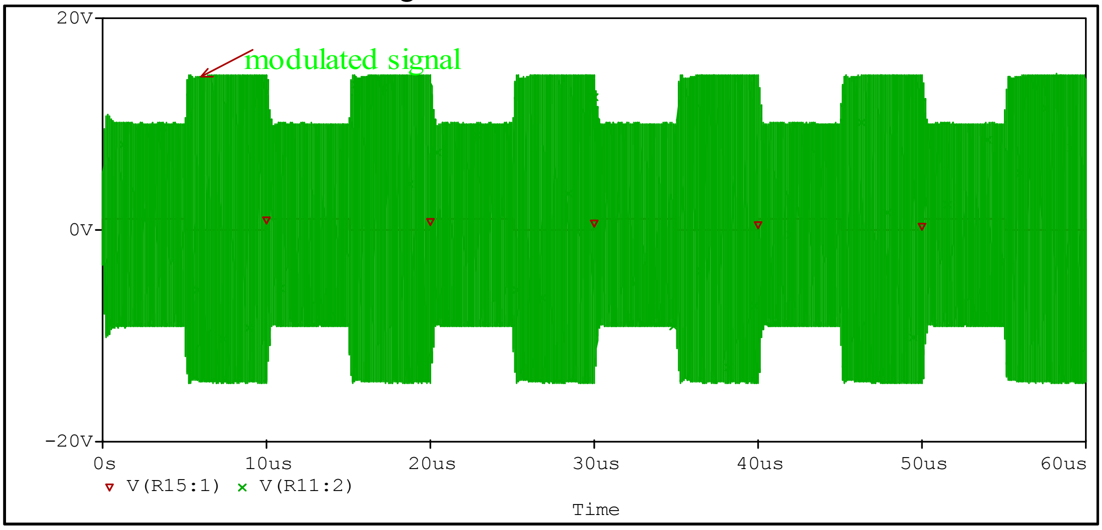

Figure 8. The modulated signal voltage across the transmitter coil.

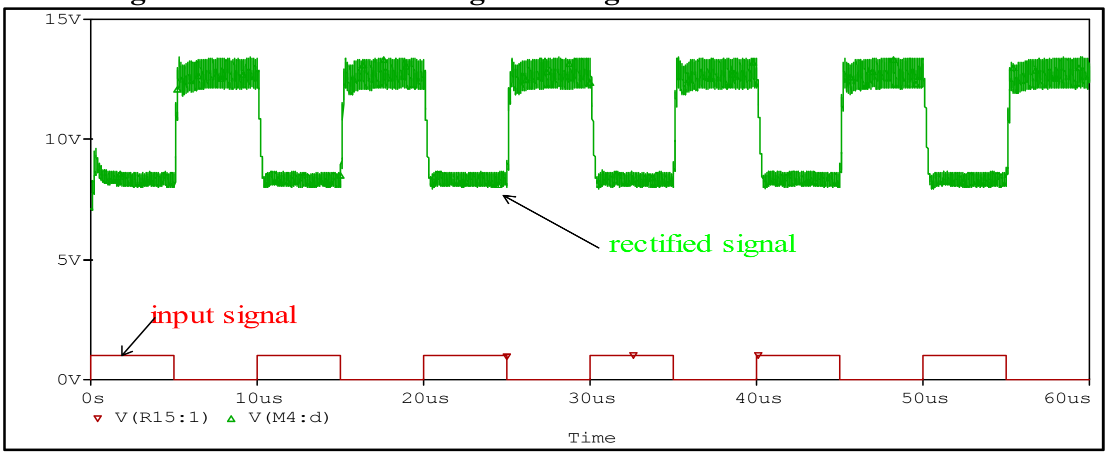

Figure 9. Rectifier output voltage.

A stabilized DC voltage of 2.4V as shown in Figure10 is obtained at the output of the stabilizer circuit.This DC voltage is sufficient to operate any implanted sensor. The comparator makes a comparison between the rectified and stabilized DC voltages after conditioning their voltage levels by using suitable voltage dividers. The output of this circuit is shown in Figure 11. The figure shows approximate compliance in phase for the original digital signal and the recovered digital signal.

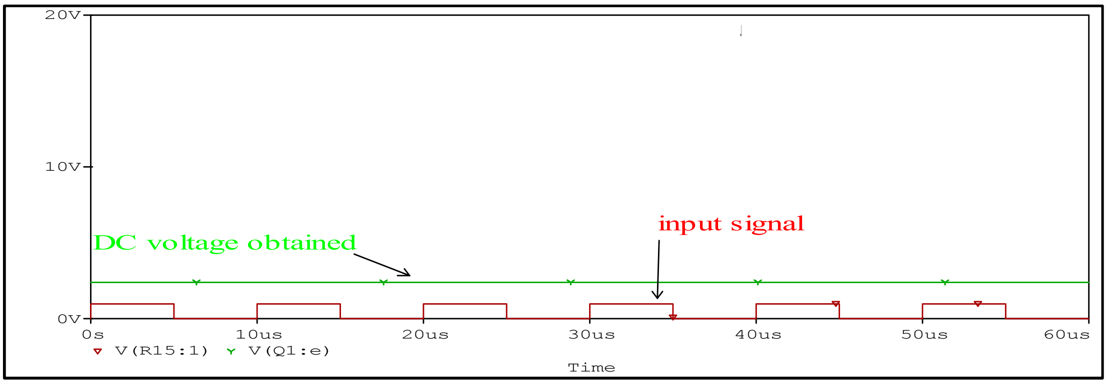

Figure 10. The stabilized DC voltage.

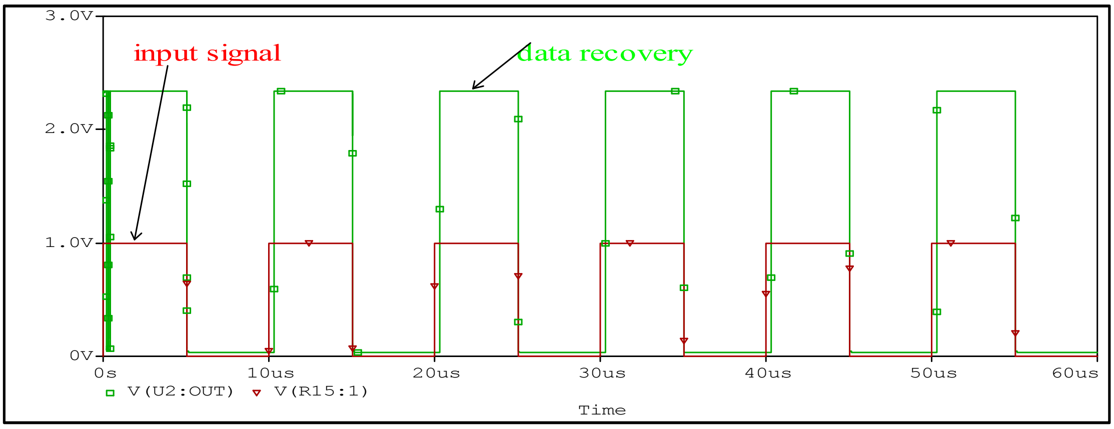

Figure 11. Data recovery signal and the original digital input signal

5.Conclusion

This paper has developed a wireless power transfer system used for powering implantable sensors. The whole systems are composed of a class-E power amplifier, transmitter and receiver coils, rectifier, regulator and data recovery circuit. The geometrical and electrical parameters of the coils are calculated. Simulation results show that the energy can be transferred efficiently for a distance of 1 cm. For a coupling coefficient of 75%,the measured efficiency is about 60%. The system measurement results show that the receiving voltage signal is converted to stable DC output voltage of 2.4V and the data is detected by an efficient circuit of data recovery signal. The whole circuit is designed and tunedat a carrier frequency of 13.56MHz.

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