

Original research paper

Wireless Charging System for an Implanted Sensor

ABSTRACT

Increasing the demand for developing implantable devices and sensors promotes the concept of the wireless power transfer. The implanted glucose sensors, for example, shall be built small enough to allow implanting it inside the patients' body [1] to indicate the readings in a non-intrusive way. It grants the patients the ability to read data simply through a receiver out of the body. However, there is a problem in most of these sensors in providing them with the necessary power by using traditional chargers because any direct contact with these devices is impossible. Therefore, scientists and researchers investigate new solutions and methods to maintain transferring enough power to charge the battery of the sensor. Among all of these methods, the inductive coupling proves its ability in transmitting the power wirelessly to the application with high efficiency. This paper presents a wireless charging system to transfer the power from an external charger to an implanted device based on the inductive coupling. It discusses different considerations and possibilities in designing and implementing the proposed charger to provide enough power to the largest possible distance.

Keywords: Wireless charger, induction, inductive coupling, the wireless power transmitting.

1 INTRODUCTION

Wireless charging technology refers to the ability of an energy source in transmitting electromagnetic energy to a load without any connection between the transmitter and receiver [2],[3]. Although the technology of the wireless charging may sound futuristic, it is not a new concept. This notion started in the late of 1800's when Nicolas Tesla proposed theories about wireless energy transmission [4],[5]. His work was impressive, but without particular methodologies for the wireless power transmission [6]. In the early of 1990s, Braun Company used inductive charging to develop Oral-B rechargeable toothbrushes [7]. Then, in 1964 Brown demonstrated "a microwave-powered model helicopter" that uses a microwave beam to transmit the necessary power for the flight [8],[9]. These devices are only some inventions in a long history of development in the idea of the wireless charging during more than a century. So, over these years, many innovations in this field have been discovered and developed, and many researchers have interested in investigating this technology to introduce new methods and techniques. Technological advances over the last century and increasing the demand for reducing the size and the power consumption in electronic devices have promoted the concept of Energy harvesting [10] and its applications in the electronic fields. This development has affected the biomedical field, especially the implantable sensors.

In biomedical instrumentation, the most significant advantage of adopting the wireless charging technology is removing all of the connections between the devices, in particular for the implanted devices. Providing enough energy to these devices is one of the challenges that are associated with making a successful practical application because using the traditional techniques (cables) leads to many problems and disadvantages. In this direction, the wireless power transfer presents convenience and flexible solutions for this problem. The second advantage of the wireless charging is reducing the cost and the hazards of direct connections [11]. With this technology, the transmitter (that is placed in the outside) transfers the power to charge the battery of the implanted sensor and, can receive data from this implanted device at the same time. Uniting the two functions in one system can reduce the cost in through minimize the required instruments. Thirdly, the wireless charger can be more reliable than the traditional wired charger because it can ensure transferring the necessary power efficiently in different environmental conditions [12].

In this trend, the inductive coupling has been classified as an optimal solution to transfer the power wirelessly in the biomedical technologies in a way that can satisfy these demands. This paper aims to design a system that can transfer enough power into the implanted sensor and charge its battery wirelessly by using the inductive coupling. Therefore, two devices will be designed and implemented in this paper. The first one is the transmitter that is placed out of the body and the second is the receiver which is an implanted device.

2. THEORY AND SETUP

2.1 THE INDUCTIVE COUPLING

In electronics and electromagnetism, the inductance refers to the ability of an inductor in storing energy by using the magnetic field [13]. With this capability, Inductors can generate a voltage in opposing to the changing rate of the current[14]. This is also called as self-inductance to discriminate it from the mutual inductance that can occur between two circuits[15]. The equation (1) defines the quantitative definition of the self-inductance L in SI units [16], as follows:

$$V = L * \frac{di}{dt} \quad (1)$$

where 'V' denotes the voltage (in Volt), and 'I' refers to the current (in Amperes). According to (1), a current can change linearly with a constant voltage. Based on Ampere's law, Induction can be caused in response to the magnetic field that is generated by electric currents [17].

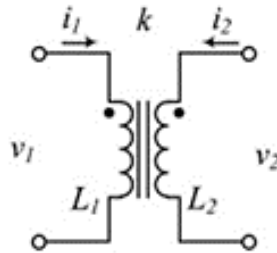


Fig.1. A model of a typical magnetic coupling.

Exchanging an energy between the wires and the magnetic fields is called inductive coupling. It works on the principle of electromagnetism. Therefore, if two circuits are coupled magnetically, a magnetic field can be generated by interlinking two circuits. Then, this will facilitate transferring the energy among these circuits through transmitting the magnetic field. The model of two coupled inductors and resistance is shown in Fig.1 and identified in (2) and (3) [17]:

$$v1 = L1 * \frac{di1}{dt} + M * \frac{di2}{dt} \quad (2)$$

$$v2 = L2 * \frac{di2}{dt} + M * \frac{di1}{dt} \quad (3)$$

where v1, i1 and v2, i2 are the voltage and the current of the primary circuit and the secondary circuit respectively; L1 and L2 are the self-inductance and M refers to the mutual inductance and can be calculated according to (4) [18],

$$M = K * \sqrt{L1 * L2} \quad (4)$$

where K is the coefficient of the coupling of the windings. This coefficient refers to the quality of the magnetic circuit. The power transfer in the wireless charger can work efficiently when the coupling coefficient (k) equal to one or very close to one only. However, in the practical application, this factor cannot reach this value, especially with the large distance between the coils is large, because of the resistance of inductors. Therefore, the quality of the power transmission can be determined based on the value of the "quality factor" that is identified in (5),

$$Q(\omega) = \frac{\omega * L}{R(\omega)} \quad (5)$$

where ω is the resonance frequency and R inductor's series resistance.

2.2 THE DEVICES SETUP

Fig.2 shows a block diagram of the proposed system which includes two separate devices. The first device is the external device which is connected to the power source and located out of the body. The power then will be received by the second device that is called the receiver (the internal device), which will be implanted inside the body and beside the sensor. In order to transfer a power with high efficiency, inductors can be placed in a series resonant LC circuit. Fig.3 demonstrates a typical AC model for the series circuit of the inductive power transfer.

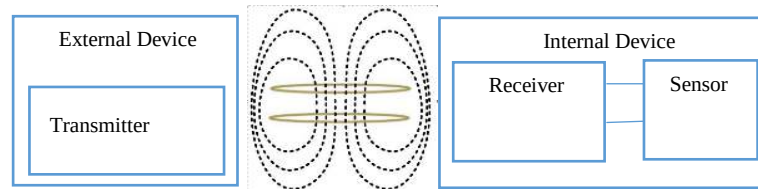


Fig.2. A diagram of the proposed system.

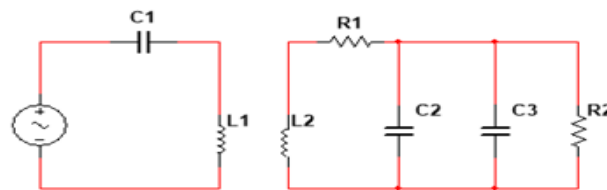


Fig.3. A typical AC model for the series circuit.

Basically, the external device includes four parts: an oscillator, a power amplifier, a coil and an envelope detector. The oscillator generates the carrier frequency, and then the power amplifier will drive the coil. A circuit of an envelope detector and an amplifier chain has been used to facilitating the data transfer. The circuit detects any change in the voltage's amplitude over L1 that may be causing by the data transmission of the implantable device.

Secondly, the implanted device includes a resonator (to receive the power) in addition to a transistor (for load modulation) and a rectifier (to convert the AC voltage to DC voltage). Fig.4 and Fig.5 explain the components of the transmitter and the receiver respectively. The figures illustrate how these components are linked.

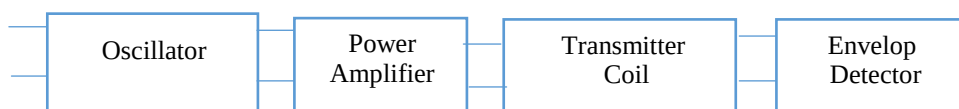


Fig.4. A block diagram to show the components of the Transmitter



Fig.5. A block diagram to show the components of the Receiver

2.3 THE CRYSTAL OSCILLATOR

The Crystal Oscillator is an electronic oscillator that can be designed as a thin slice of quartz sandwiched between two electrodes[19]. It can provide both of the series and parallel resonance. The crystal oscillator has been used in the external device to oscillate the circuit with high frequencies (above 10 MHz). Fig.6 illustrates the design of the circuit that has been used to oscillate this device.

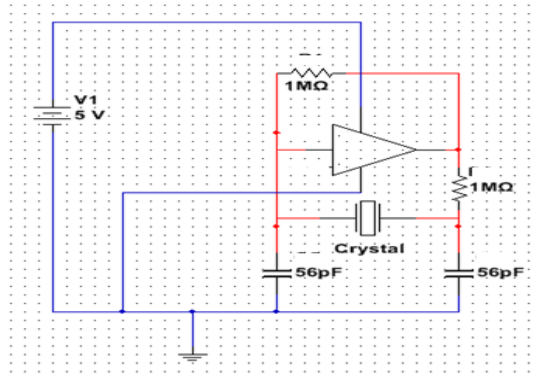


Fig.6. The circuit of the crystal oscillator

2.4 THE CLASS-D AMPLIFIER

The Class-D Amplifier is an amplifier can generate square pulses (square wave). It consists of an inverter and two transistors [20], as shown in Fig. 7. The inverter works as a switch to control the two transistors. The Class-D Amplifier dissipates very little power comparing with the other types of the amplifier. This can lead to decrease the heat and increase the battery life [21]. Therefore, the high efficiency and saving the cost are its main advantages. Two NC7WZ04 transistors have been used to build the amplifier of this system because this type of transistors is able to achieve high speed and high output drive with low power dissipation [22].

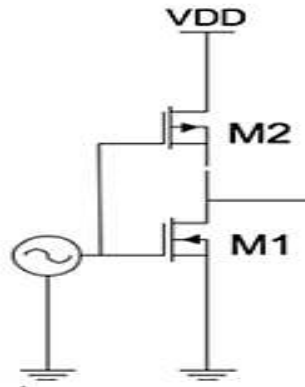


Fig.7. The circuit of a class-D amplifier

2.5 THE RECTIFIER

The rectifier is one of the main components of the receiver (the implanted device). It uses high-frequency power to generate DC power. Two types of rectifiers have been considered and tested in this system. The first type is the full wave rectifier which converts both polarities of the wave to a constant polarity. It can be built by using four Schottky diodes or ultrafast diodes to eliminate the loss effect [23]. The second rectifier is the half wave rectifier which has to be designed by single Schottky diodes. After some investigations and tests, the half wave rectifier has been used instead of the full wave rectifier to reduce the area. The size of the receiver is one of the important issues that have been addressed because it would be implanted inside the human body. Therefore, the half-wave-rectifier replaces the full wave rectifier, and this will be shown in the next section. Finally, Fig.8.a and Fig.8.b illustrate general circuits for a full and half wave rectifiers respectively.

2.6 THE VOLTAGE REGULATOR

The voltage regulator is an essential component to control and stabilize the output voltage of the rectifier in the receiver (the implanted device). In this system, a linear voltage regulator is required to reduce the variation in the output of the rectifier. For this purpose, the Low dropout (LDO) regulator is used. Therefore, there are only small differences between the supplied voltage and the load voltage [24].

3. SYSTEM DESIGN

The system has been proposed to transmit an enough power to charge an implantable glucose sensor without any direct connection between the charger and the implanted sensor. According to [25], the implantable glucose sensors are connected directly to a Microcontroller to facilitate transferring the data from the sensor to the external reader. Therefore, in addition to the power of 18uW that are required by the sensor, an extra power needs to be provided to feed the Microcontroller. Thus, the system has been designed and tested to provide the implanted part with a total of 650 μWatt to maintain an enough power that will be consumed by both of the sensor and the Microcontroller.

It can be concluded from the proceeding that the system includes two devices: a transmitter (external device) and an implantable device (an internal device), as shown in Fig.2. The external device provides and sends the power while the implanted device receives that power. The power will be transferred through the skin from the out of the body to the implanted device by using magnetic induction. Therefore, the receiver has a direct connection with the implantable sensor to feed it with required power.

3.1 THE TRANSMITTER DEVICE

As it explained in the previous sections, this device is responsible for sending the power to the implanted device by using the inductive coupling. In the transmitter device, an RC oscillator has been used to oscillate the circuit by using a network of resistors and capacitors. Because it generates low frequencies, a power amplifier is required to be the second component of the transmitter, as illustrated in Fig.4. The power amplifier is built of two MOSFET transistors (P-MOSFET and N-MOSFET) to establish the class-D power amplifier that is discussed previously.

Two air core coils (L1 in the transmitter and L2 in the receiver) are required to form the inductive coupling that is employed to transfer the power. These coils have actual air inside the windings. The reason for using air core coils is that they have lower inductance than the ferromagnetic core coil. These coils are handmade of a single strand copper with about 2 cm diameters and five turns.

Fig.9 shows the circuit of the transmitter device. In this circuit, the capacitor C5 is inserted to catch the voltage of the envelope detector. The voltage across C5 can be calculated based on the voltage divider rule as it identified in (6).

$$V_{c5} = \frac{R2}{(R1+R2)} * V_{in} = 0.4 * V_{in} \dots\dots\dots (6)$$

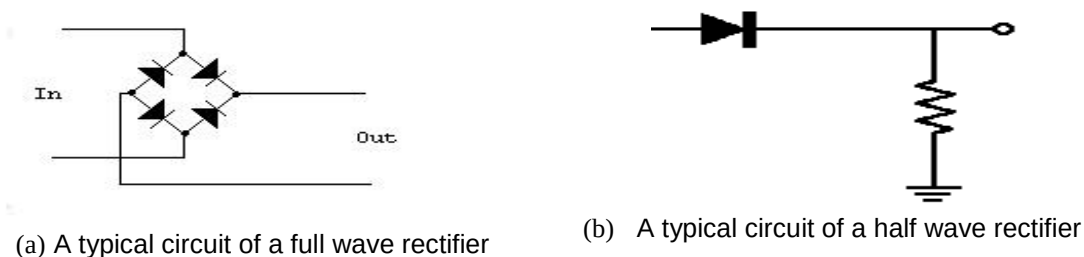


Fig.8. A general design of the rectifier.

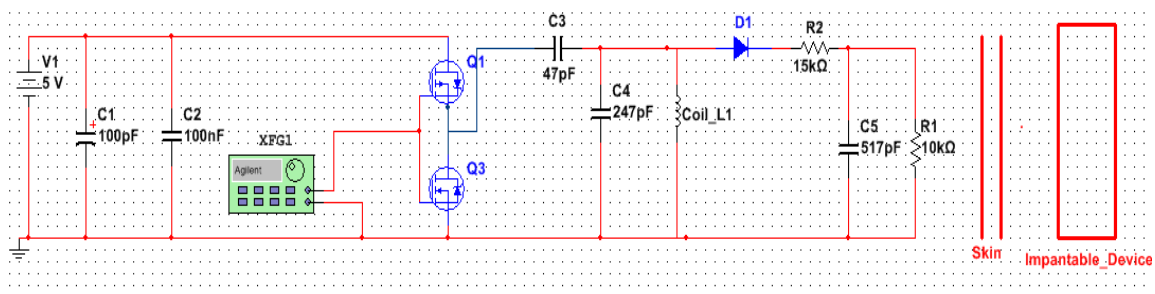


Fig.9. The circuit of the transmitter device

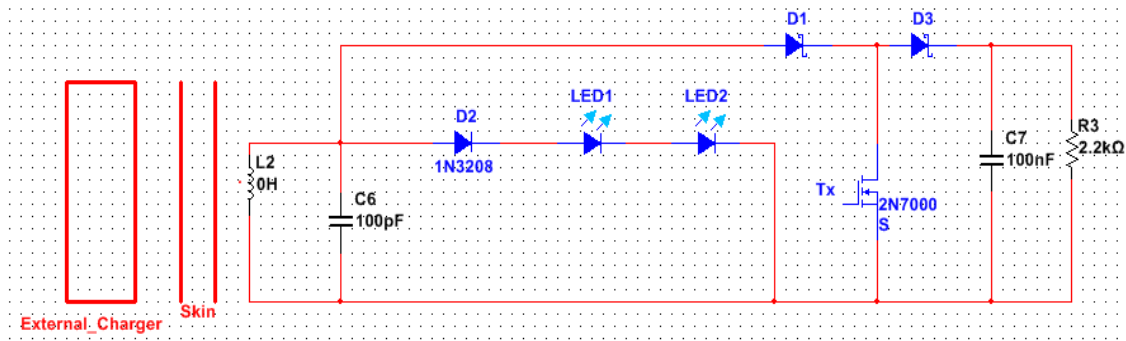


Fig.10.The circuit of the receiver device

3.2 THE RECEIVER DEVICE

The inductive coupling transmits the power that is generated in the first device (the external device) to the implanted device (the receiver). The secondary coils (L2) of the implanted device receives the transmitted power and passes it to the rectifier. The function of the rectifier is converting the received voltage from AC to DC by using Schocky barrier diodes, as it explained in the previous section.

In order to keep the resulted DC voltage stable, C4 will take its responsibility in holding this voltage. With these parts, the output voltage becomes ready to be provided to the sensor. Fig.10 demonstrates the circuit design of the receiver and its configuration. In this circuit, the resistor R1 represents the load to determine the power consumption of the implanted sensor.

Finally, a protection circuit can be added to the circuit to protect it by using two LEDs diodes connected in a series to dissipate any extra or unrequired power once the voltage over the coil become high enough to make the diodes forward-biased. Therefore, it also uses as a voltage limiter.

4. IMPLANTATION AND RESULTS

4.1 IMPLANTATION

The structure of the proposed system and its configuration have been discussed and detailed in the previous sections. Fig.11.a and Fig.12.a illustrate a schematic layout of the transmitter device and the receiver device respectively. They have been schemed by using software which is available online in [26]. In this section, the proposed devices (the transmitter and the receiver) will be implemented on a Vero-board. This version has been made big to some extent (about 12 *4 cm for the transmitter and 4*7 cm for the receiver) because it is the experimental prototype for this project, and making it big and clear can be easier in testing the system and check the connections and the signals. Fig.11.b and Fig.12.b show a photograph of the Veroboards implementation for the devices. During the design phase, the system has been built to do two functions: send power and receive data. However, only the power transmitter has been implemented and tested because this is the aim of this paper and its main contribution.

As an initial implementation, a function generator has been used to oscillate the circuit (with a power amplifier). The function generator has been adjusted to generate a sinusoidal wave with 5 V amplitude to feed the amplifier. For generating DC voltage, a DC power supply is used. Because of the significance effect of the frequency on the output voltage of the rectifier and the transmission distance, it has been examined by changing the frequency of the function generator (from 1MHz to 12MHz) and recording the results. However, the maximum frequency of the function generator is 10MHz. Thus, the crystal oscillator has been used to oscillate the circuit and test its performance with the high frequencies. The circuit of the crystal oscillator that is shown in Fig.6 is used to generate the high frequencies.

Testing the systems with different sizes of coils indicates that increasing the physical area of the coil rises the output voltage. The two coils of this system are implemented as copper handmade square coils with 4*4 cm size and six turns. It has two identical rectangular layers connected in parallel to allow using more turns on each layer.

Additionally, the efficiency (η) of the system can be determining by the following equation,

$$\eta = \frac{P_{out}}{P_{in}} = \frac{v_{out} \cdot I_{out}}{v_{in} \cdot I_{in}} \dots\dots\dots (7)$$

where P_{out} , V_{out} , I_{out} are the output power, voltage and current respectively, and P_{in} , V_{in} , I_{in} are the supplied power, voltage and current respectively.

4.2 THE EXPERIMENTAL RESULTS

During the experiment, the voltage at different nodes is measured by Oscilloscope, and the current is measured by a Millimeter. By applying an input power with 5 Volts and 42 mA current, the transmitter device will be equipped with 210 mW. The output of the power amplifier is about 5.2 peak to peak voltage.

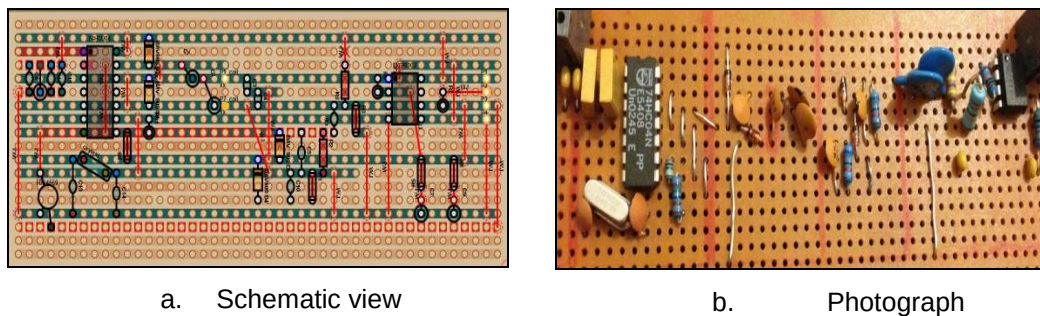


Fig.11. The layout of implementation the transmitter

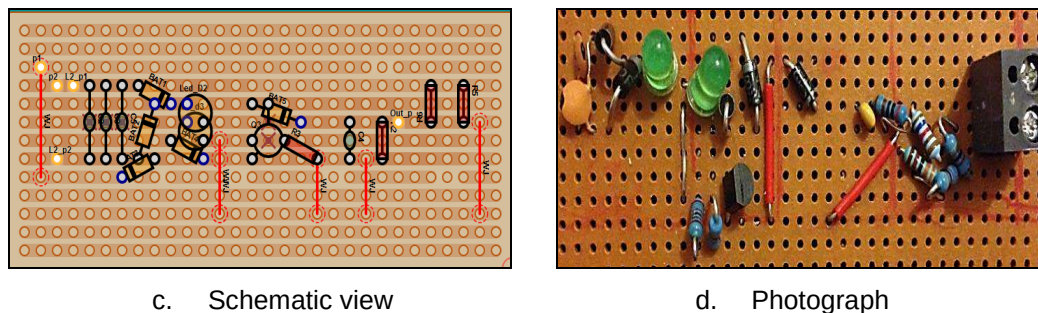


Fig.12. The layout of implementation the receiver

The received current and voltage may vary depending on the frequency of the source of energy. Fig.13 and Fig.14 demonstrate the impact of the frequency on the received power. It can be concluded from Fig.13 that the amount of received voltage can be changing in responding to the changing the value of the frequency. It starts from very low values (about zero Volt) with the frequency below 10.8 MHz. Then, it grows gradually with increasing the frequency to reach its maximum values at a frequency range of 11 MHz to 11.4 MHz. Then, it falls to reach its minimum value again with the frequencies above 11.5 MHz. This slop can identify that the resonant frequency of this circuit is between 11 MHz and 11.4 MHz. Therefore, the circuit becomes in a resonant status with that range. In the same direction, the received current reaches its maximum values within the resonant frequency (from 11.1 MHz to 11.4 MHz) as illustrated in Fig.14.

During the experiment, the system has been tested with various distances (between the sender and the receiver). Therefore, different readings have been recorded from the receiver with these distances. This allows testing the impact of the range on the operation. In order to adjust the matching network, the output voltage of the envelope detector has been examined by Oscilloscope. It is clear from Fig.15 that the highest voltage values are recorded when the distance was below 1.5 cm at 3 volts. Until to 35 mm distance, the output voltage was in the acceptable range (over 1.8V). However, over 36 mm distance, the voltage dropped below the required value, then it went to approximately zero at 70 mm. The received current will take an opposite direction as it is shown in Fig.16.

The purpose of testing the effect of changing the distance is to determine the maximum range between the receiver and the transmitter that can give sufficient power. According to the requirements of the system, 1.8V is enough to charge the battery of the system.

In summary, these measurements indicate that the system can transfer enough power to large distances between the transmitter and receiver (compared with required distances). The amount of the energy that is transferred was sufficient within the range of 35 mm. The voltage regulator dissipates any extra or undesired voltage.

Characteristics of the coils (the primary and the secondary coils) are one of the confusion issues because mathematical calculations cannot give us the final decision about the size and number of turns of these coils. Several coils have been considered and examined during the design phase. All of these coils are handmade spiral square coils. The oscilloscope was connected in parallel to the receiver coil to measure the maximum voltage. The power transmission distance was measured between the closest edges of the coils.

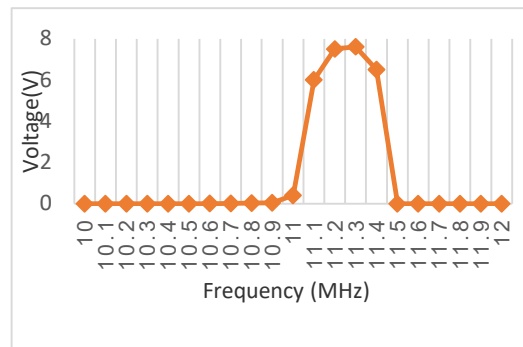


Fig.13. The received voltages with different frequencies

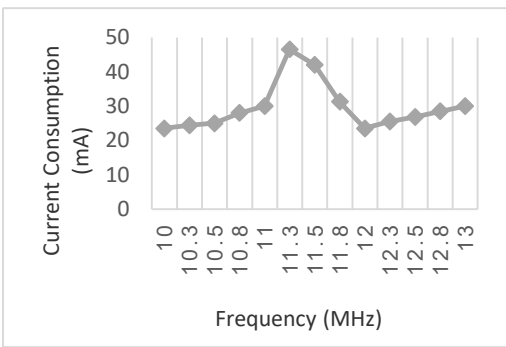


Fig.14. The consumed current with different frequencies

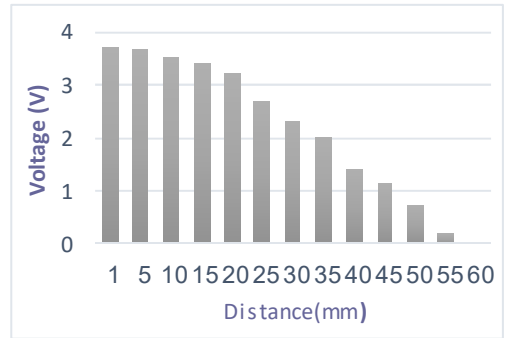


Fig. 15. The received voltage versus distance

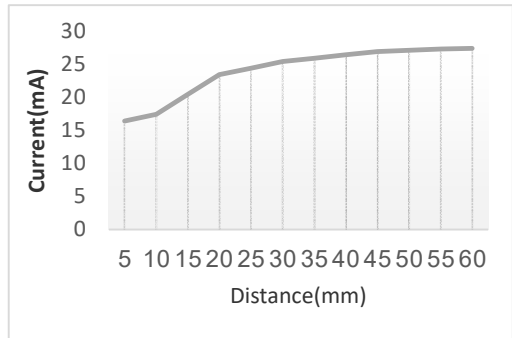


Fig. 16. The current consumption versus distance

5. CONCLUSION

The wireless power transmission is an effective and promising technology to supply the electric power without any direct connection. Nowadays, technological advances in the field of the biomedical promote the idea of the wireless power transfer with the increase of using the implantable devices that require to be powered wirelessly [27]. This paper introduces a system to transfer the power wirelessly by using the inductive coupling. The produced system has two devices: an external device (transmitter) and an implantable device (receiver). The receiver harvests the power to charge an implanted battery with a regulated voltage. This battery is included to supply the implanted sensor that measures the glucose level in the human body and the Microcontroller that is added to control the sensor.

A resistor has been used to represent the desired load (the implanted sensor) to exam whether the system is able to provide them with enough power or not. The previous tests and measurements show that the power that can be harvested is 360 μ A current and 1.8V voltage. The tests prove that the system can transmit the required power until to distance 35mm even with placing an insulator between the sender and the receiver.

The system has been implemented on Vero-boards. This implementation is used for experimental purposes only. It has been designed and implemented to test the core circuit in sending and receiving the power to get the final configuration. It offers high quality and stability, but it has a big size compared with the PCB or ASIC. Therefore, for higher efficiencies and ranges, the implanted device can be implemented by using the Application Specific Integrated Circuit (ASIC), and this can be one of the future directions for this work. Thus, the real implementation of these devices can be done by using an application-specific-integrated-circuit (ASIC).

References

- [1] S. Updike, M. Shults, B. Gilligan, and R. Rhodes, "A subcutaneous glucose sensor with improved longevity, dynamic range, and stability of calibration," *Diabetes Care*, 2000.
- [2] A. Costanzo, M. Dionigi, D. Masotti, M. Mongiardo, G. Monti, L. Tarricone, *et al.*, "Electromagnetic energy harvesting and wireless power transmission: A unified approach," *Proceedings of the IEEE*, vol. 102, pp. 1692-1711, 2014.
- [3] J. Garnica, R. A. Chinga, and J. Lin, "Wireless power transmission: from far field to near field," *Proceedings of the IEEE*, vol. 101, pp. 1321-1331, 2013.
- [4] N. Tesla, "The transmission of electrical energy without wires as a means for furthering peace," *Electrical World and Engineer*, vol. 7, p. 21, 1905.
- [5] T. K. Mandal, "Wireless Transmission of Electricity—Development and Possibility," in *Proceeding of 6th International Symposium Nikola Tesla, Belgrade, Serbia*, 2006, pp. 1-4.
- [6] N. Sekularac and M. Dordevic, "A Survey on wireless power transmission methods," Department of Computer Science, Faculty of Mathematics, University of Belgrade, Serbia, 2011.
- [7] C. Davide, "Wireless energy may power electronics: Dead cell phone inspired research innovation," *Massachusetts Institute of Technology*, vol. 51, 2006.
- [8] S. S. Mohammed, K. Ramasamy, and T. Shanmuganantham, "Wireless power transmission—a next generation power transmission system," *International Journal of Computer Applications*, vol. 1, pp. 100-103, 2010.
- [9] H. Matsumoto, "Research on solar power satellites and microwave power transmission in Japan," *IEEE microwave magazine*, vol. 3, pp. 36-45, 2002.
- [10] J. Olivo, S. Carrara, and G. D. Micheli, "Energy Harvesting and Remote Powering for Implantable Biosensors," *IEEE Sensors Journal*, vol. 11, pp. 1573–1586, 2011.
- [11] T. Kumagai, K. Saito, M. Takahashi, and K. Ito, "A small 915MHz receiving antenna for wireless power transmission aimed at medical applications," *Int. J. Technology (IJTech)*, vol. 2, pp. 20-27, 2011.
- [12] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless charging technologies: Fundamentals, standards, and network applications," *IEEE Communications Surveys & Tutorials*, vol. 18, pp. 1413-1452, 2015.
- [13] K. Y. Kim, *Wireless power transfer: Principles and engineering explorations*: InTech, 2012.
- [14] R. T. Paynter and B. T. Boydell, *Electronics technology fundamentals: electron flow version*: Prentice Hall, 2005.
- [15] F. W. Grover, *Inductance calculations: working formulas and tables*: Courier Corporation, 2004.

312 [16] U. C. Jindal, *Material Science and Metallurgy*: Dorling Kindersley, 2012.

313 [17] K. Fotopoulou, "Inductive Wireless Power Transfer for RFID & Embedded Devices: Coil
314 Misalignment Analysis and Design," Doctor of Philosophy, School of Electronics and Electrical
315 Engineering, The University of Edinburgh, 2008.

316 [18] C. Qiu, K. T. Chau, C. Liu, and C. C. Chan, "Overview of wireless power transfer for electric vehicle
317 charging," in *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, 2013, pp. 1-9.

318 [19] T. Williamson, "Oscillators for Microcontrollers," *Intel Application Note AP-155*, Intel Corp, 1983.

319 [20] A. N. Laskovski, M. R. Yuce, and T. Dissanayake, *Wireless power technology for biomedical implants*:
320 INTECH Open Access Publisher, 2009.

321 [21] E. Gaalaas, "Class D audio amplifiers: What, why, and how," *Analog Dialogue*, vol. 40, pp. 1-7, 2006.

322 [22] F. Semiconductor, "NC7WZ04," ed, 1999.

323 [23] K. Kusaka and J.-i. Itoh, "Experimental verification of rectifiers with SiC/GaN for wireless power
324 transfer using a magnetic resonance coupling," in *Power Electronics and Drive Systems (PEDS), 2011
325 IEEE Ninth International Conference on*, 2011, pp. 1094-1099.

326 [24] G. A. Rincon-Mora, "Current efficient, low voltage, low drop-out regulators," School of Electrical and
327 Computer Engineering, Georgia Institute of Technology, 1996.

328 [25] F. Fereydouni_Forouzandeh, "Ultra Low Energy Communication Protocol for Implantable Wireless
329 Body Sensor Networks," Doctor of Philosophy, Electrical and Computer Engineering, Concordia
330 University, Canada, 2010.

331 [26] 3electronics. *electronics blog, forum, schematics and PCB layouts*. Available:
332 <http://www.3electronics.com>

333 [27] T. d. S. Motta, "Transmissão de energia sem-fio: método de acoplamento indutivo ressonante," 2016.

334