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ORIGINAL PAPER

Contactless Power Transfer System for Low Power Medical Devices

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ABSTRACT

Currently, contactless power transfer system is being implemented to power up the medical devices. Those medical devices can either power by transcutaneous cable or batteries. However, the power driven for medical devices via transcutaneous cable might lead to infection due to breach on the skin. The battery replacement surgery for cardiovascular patients also can lead to infection. Therefore, a contactless power transfer system is effectively solving the problem by transmitting power in a safe and non-invasive manner and has mitigated effect to patient health, yet efficient in the power transmission process. Magnetic coupled resonant is being designed since magnetic field cannot be shielded by biological tissues. Resonant power transfer technique can minimize the power scattering on the non-resonant objects such as human body. Impedance matching technique is utilized to improve the overall power transmission efficiency. The system consists a pair of transmitter and receiver coil, transmitter and receiver circuit, and a pair of transformer as impedance matching purpose. The system is capable to achieve a transfer efficiency of over 60%. Contactless power transfer technology does offer the advantages of safety, non-invasive and no significant effect on patient health. Eventually, bacterial infection on the skin breach is prevented.

INTRODUCTION

The energy supply is crucial in the functionality of medical devices. Hence, an efficient, continuous and stable supply of energy is required. These devices must receive energy supply externally or harvest the ambient energy. However, the batteries in implantable medical devices can only be replaced or recharged by surgery. An alternative method to use is the transcutaneous power cable. Generally, the percutaneous link across the body skin is used to recharge the internal battery (RamRakhyani et al, 2011). This may pose infection risks to the patients (Samad et al, 2006 & Si, P., et al, 2007). The power cord also restricts the patient to perform activities related to water. Therefore, an alternative solution such as wireless power charging may be a viable solution (Chandrakasan et al, 2008).

Magnetic resonant coupling is being proposed to apply into mid-range wireless power transfer application. The advantage of using this magnetic resonant coupling transfer technique is to improve the transfer efficiency. When this technology is used, a pair of primary and secondary coils which act as transmitter and receiver is capacitively loaded to form tuned LC circuit. If the transmitter and receiver coils are resonant at the same frequency, the power can be transmitted between the coils over a range of the transmitter coils diameter with reasonable efficiency. In addition, if any obstables (non-magnetic materials) is placed between the transmitter and receiver, the transmitted power will still pass through the obstable without and power lose.

Wireless power transfer can be achieved using magnetic field couplings that are non-radiative. On the other way, the radiation emitted can be negligible. These mutual coupling between transmitter and receiver circuit has been researched over a decade (Mur-Miranda et al, 2010, Imura et al, 2011 & Liu et al, 2017). Transcutaneous energy transmission (TET) system has been introduce by a group of researchers to power LVAD (Slaughter et al, 2010 & Wang et al, 2013). The technique used during for the TET system is inductive coupling within transmitter and receiver coils. The size of the transmitter and receiver are 5cm. The TET system was able to power 10 watt across a 1cm distance with an efficiency of 65 percent. During the experiment, the temperature of the transmitter and receiver coils increase. Therefore, it is not suitable to use for the implantable device.

Four coils wireless power transfer system refer to the wireless power system consist of transmitter and receiver coils pair (two coils wireless power system) and added two coil resonators into the system (Hui et al, 2014). This two coil resonator aid as the input and output impedance matching function for the wireless transfer system in order to achieve the maximum transfer efficiency. Free-Range Resonant Electrical Energy Delivery (FREE-D) system is introduced by a group of researchers in year 2012 (Waters, Benjamin H., et al, 2012 & 2014). The FREE-D system adopted the four coils wireless power transfer system to power LVAD. The frequency used during the experiment was 13.56MHz. It can transfer 70cm with a 75 percent of transfer efficiency. The transmitter and receiver coils size are 9.5cm and the resonator coils used are 59cm.

Two coils wireless power transfer system consist of transmitter and receiver coils. Four coils wireless power transfer system is modified from two coils wireless power transfer system, and sending resonator and receiving resonator were added in between the transmitter and receiver coils. However, four coils wireless power transfer system is more complex than two coils wireless power transfer system due to the mutual coupling coefficient within the pairs of coils. Four coils wireless power transfer system consist more coils than two coils wireless power transfer system. The distance of resonators put between the transmitter and receiver coils had to be fixed due to the frequency tuning technique used achieved maximum power transfer. But two coils wireless power transfer system are

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flexible within the transmission range. Other than that, more coils on the system result the frequency splitting phenomenon occur often. It will affect the transfer efficiency of the system.

In order to solve the safety problem regarding the wireless power transfer, a group of researchers face the problem regarding the electromagnetic field issues in the four coils wireless transfer system. The electric field and magnetic field were measured when the power of 60 watt had been transfering from transmitter coil to receiver coil with the frequency of 10MHz at the distance of 2 meters (Bawa et al, 2008 & Badr et al, 2017). The electric field measurement was recorded at the middle of the two resonators which electric feild = 210V/m and magnetic field = 1A/m. The researcher repeat the measurement at the point of 20cm near the resonator coil surface and recorded the reading. It shows that the value of the electric field and magnetic field gradually increased. Now the new electric field = 1400V/m and magnetic field = 8A/m. The new reading had higher than expected value as the regulation stated. In order to feed the IEEE regulations, the researchers modify the coil and lower the operating frequency from 10MHz to 1MHz. This caused the transmission range for the system decreases. Therefore, the low resonance frequency which lower than 1MkHz was chosen for this contactless power transfer system for safety reason.

MATERIALS AND METHOD

Hardware Prototype

This system will be divided into two main parts. First is the transmitter circuit and second is the receiver circuit. In order to increase the efficiency the system, an impedance matching method by adding two transformers into the system was implemented. A step-up transformer is added into the transmitter circuit and a step-down transformer is added into the receiver circuit. This impedance matching method ensures that system always operates in its best performance. In designing this receiving circuit, space constraint is another issue besides the power limitation. The size of the receiving module is reducing, leading to the decreased space available for the receiving coils. As a result, the frequency of the power transmission has to be increased proportionally.

Impedance Matching

An impedance matching method is designed by adding the transformer into the two coils wireless power transfer system. As mention in the introduction, the most suitable way to implement this project is the two coil system. Therefore, an analysis of two coil system with and without transformer was carried out using Matlab. The analysis aims to maximize the transfer efficiency of the contactless power transfer system. Several conditions were considering into the analysis which is the coupling coefficients between the coils, critical coupling point between two resonant coils and purely resistive impedance for transmitter and receiver circuit. At the end of the analysis results into two simplify equations which represent the step-up and step-down transformer gain in below.

$$n_2 = \sqrt{\frac{L_1 R_1 R_2}{R_L\left(L_1 R_2 + L_2 R_1\right)}} \tag{1}$$

$$n_1 = \sqrt{\frac{1}{2}\left(\frac{L_1}{L_2}\right)\left(\frac{R_L}{R_S}\right)} \tag{2}$$

Rs is the source impedance and R_L is the load. R_1 and R_2 are the parallel resistance of the resonant coils on the transmitting side and receiving side respectively. L_1 and L_2 are the inductance value for the transmitting side and receiving side. n1 represents the step-up transformer gain and n2 represent the step-down transformer gain in the system. Equation 1 and 2 then apply into the transformer impedance modelling to optimize efficiency of the system.

Figure 1 shows the steps to implement the transformer base impedance modeling into the two coils wireless power transfer system.

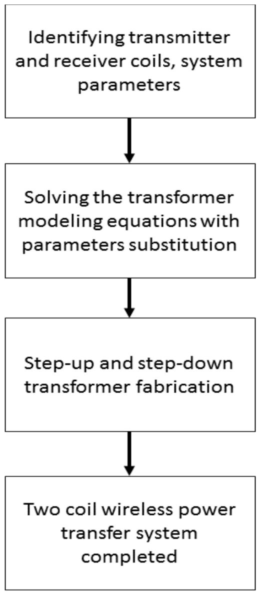

Fig. 1 Flows for transformer impedance modeling.

Firstly, the quality factor, resistance, inductance of the transmitter and receiver coils were measured using LCR meter. The resistance and the inductance of the transmiter and receiver circuit will also be measured. After identified the parameters, the parameters are then substituted into the equations (1) and (2). n1 represent the step-up transformer and n2 represent the step-down transformer in the system. Once the values of n1 and n2 is obtained, the transformer can be fabricated. When the step-up transformer and step-down tranformer are adding to the transmitter and receiver circuit, the two coil wireless power transfer system is completed.

Experimental Setup

The transmitter circuit was connected to the power source and function generator as shown in figure 2(a). The transmitter circuit was then connected to a step-up transformer and to the transmitter. Another side of the receiver circuit consists of the receiver coil, capacitor, step-down transformer and load. The load was connected to the LCR meter to undergo result measurement. Figure 2(b) shows the setup for receiver circuit with receiver coil and connected load with an oscilloscope. The result was recorded every centimeter starting from 5cm up to 70cm. After the result have been measured and recorded, it is compared with the simulated result using Agilent Advance Design System to verify the efficiency.

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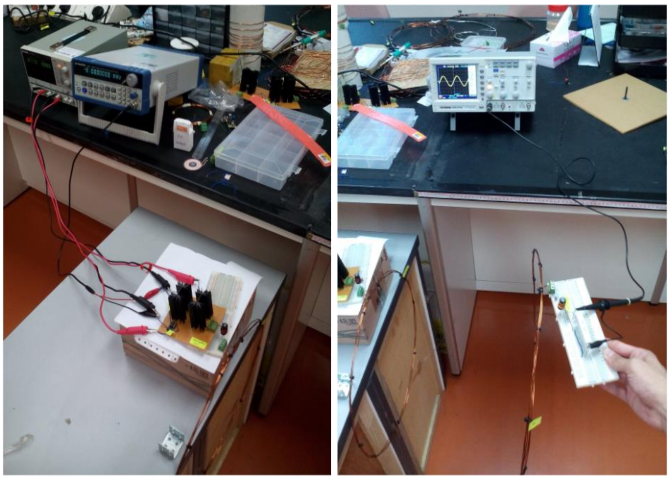

(a) **(b)**

Fig. 2 (a):Transmitter circuit connect to function generator and power source, (b): Receiver circuit connect to oscilloscope.

RESULTS AND DISCUSSION

Qualify Factor of The Transmitter and Receiver Coils

This section describes the design of the transmitter and receiver coils pair been designed. Several numbers of turns of the coils had been fabricated and the quality factor had been measured to obtain the number of turns with the best quality factor of the coils. Figure 3 shows the quality factor for the different number of turns of the coils during different resonant frequencies. The thickness of the coil is approximately 1.5mm. The results are measured and recorded using LCR meter. These results serve as references during the fabrication process of transmitter and receiver coils pair. The quality factor is divided into four different category which is 250kHz, 500kHz, 750kHz and 1MKhz to be measured.

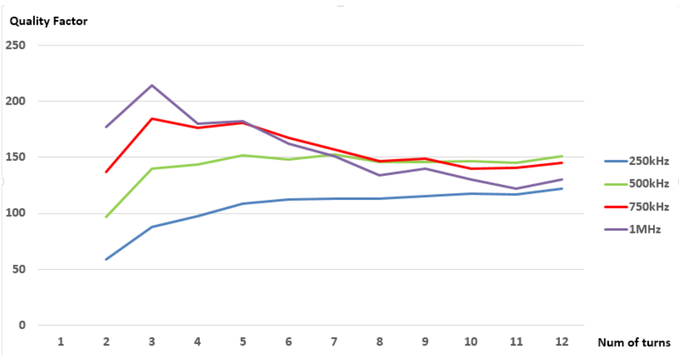

Fig. 3 Quality factor versus number of turns of 30 cm coils.

For different categories of frequency resonance, the turns of coils will be different. For resonant frequency at 250kHz and 500kHz, the twelve turns of coil show the highest quality factor. For resonant frequency at 750kHz and 1MHz, three turns of coil show the highest quality factor. During the experiment, the resonant frequency used for the 30cm diameter coils pair was 784kHz. The graph shows the highest quality factor was 184.5 when the number of turns of coil equal to three. The graph also shows the quality factor of the coil decreased when the number of turns of the coil increased. So, three turns of coils provided the best performance for the transmitter and receiver pair for the 30cm diameter.

Comparison of Experimental Result and Simulation Result for 30cm Coil Diameter

Figure 4 shows the comparison of the experimental result and the simulation result using Agilent Advance Design System.

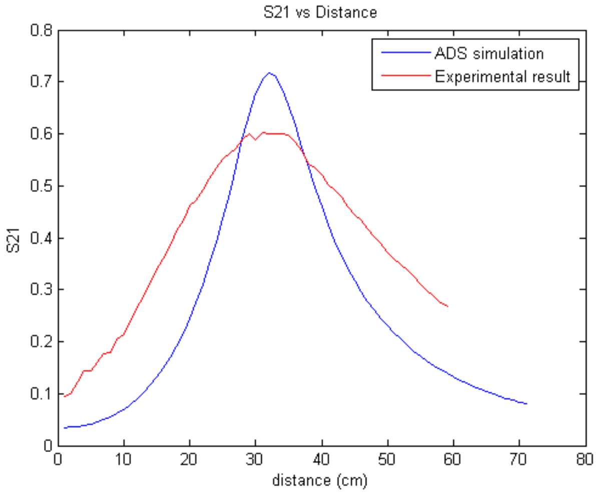

Fig. 4 Comparison for the experimental and simulation results for 30cm diameter coil.

Based on Figure 4, a transfer distance of 46cm is achieved using the magnetic coupling with two resonance coils of 30cm diameter and able to yield an energy transfer up 50 percent (experimental result) which is approximately 1.5 time of the coil diameter. However, it means that the contactless power transfer system can only maintain its high efficiency at limited distances. The simulation result shows the highest efficiency of 70 percent at a distance of 32cm and the experimental result shows the highest efficiency of 60 percent at a distance of 35cm. The performance of this system decreases when the distance between transmitter and receiver coils increases. At a distance of 60cm, the system can achieve 33 percent of transfer efficiency. The experimental result shows lower performance as compared to the simulated result. There are few reasons contributing to this difference which are impedance mismatch and power losses in the transformer.

The step-up and step-down transformers with gain, n1=24.8 and n2 =19.6 respectively are designed manually. Therefore its gain will be slightly different from the simulation value. The difference in the transformers gain caused the impedance of the system to be slightly unmatched and the manually designed transformers cannot achieve the simulation ideal state. The second reason is the power loss from the transformer during the experiment. The temperature of the step up transformer in the transmitter circuit increased and changed the transformer resistance. The connection of the wires and connectors used in the transmitter and receiver circuit also caused the loss of power during the experiment which lead to the difference between the experimental result and simulation result.

However, this contactless power transfer system demonstrates the approach for matching the system impedance correctly without any aid of the multiple resonators to optimize the performance of the system. In addition, the temperature of transmitter and receiver remain unchanged throughout the experiment. Therefore this two coil wireless power transfer system can be implemented to other practical medical charging devices.

CONCLUSION

A study of contactless power transfer system for low power medical devices with magnetic coupling technique has been demonstrated. The contactless power transfer system adopted the two coils wireless power transfer system to operate. It successfully transmitted the power wirelessly through the transmitter circuit to the

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receiver circuit. The transfer distance achieved by the coils with diameter with 30cm with highest transfer efficiency recorded approximately 1.1 time its coil diameters (32cm). An innovative impedance matching for both transmitter and receiver circuit by adding a step-up and step-down transformers has been proposed. From the simulation, it shows that the impedance matching method improved the transfer efficiency and distance of the contactless power transfer system for low power medical devices. This impedance matching method is universal and can be applied to all the two coil contactless power transfer system. This impedance matching method also help to reduce the size of the contactless power transfer system because it can work without any help of the resonators such as the four coils wireless power transfer system. The high quality factor of the transmitter and receiver coils has been chosen to optimize the transfer efficiency of the system. Three number of turns are the ideal number of turns for the transmitter and receiver coils according to the simulation.

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REFERENCES

Badr, Basem M., et al. "Design of a wireless measurement system for use in wireless power transfer applications for implants." Wireless Power Transfer4.1 (2017): 21-32.

Bawa, Gaurav, and Maysam Ghovanloo. "Active high power conversion efficiency rectifier with built-in dual-mode back telemetry in standard CMOS technology." IEEE transactions on biomedical circuits and systems 2.3 (2008): 184-192.

Chandrakasan, Anantha P., Naveen Verma, and Denis C. Daly. "Ultralow-power electronics for biomedical applications." Annual review of biomedical engineering 10 (2008).

Hui, Shu Yuen Ron, Wenxing Zhong, and Chi Kwan Lee. "A critical review of recent progress in mid-range wireless power transfer." IEEE Transactions on Power Electronics 29.9 (2014): 4500-4511.

Imura, Takehiro, and Yoichi Hori. "Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula." IEEE Transactions on industrial electronics58.10 (2011): 4746-4752.

Mur-Miranda, Jose Oscar, et al. "Wireless power transfer using weakly coupled magnetostatic resonators." Energy Conversion Congress and Exposition (ECCE), 2010 IEEE. IEEE, 2010.

Liu, Fuxin, et al. "Modeling and optimization of magnetically coupled resonant wireless power transfer system with varying spatial scales." IEEE Transactions on Power Electronics 32.4 (2017): 3240-3250.

RamRakhyani, Anil Kumar, Shahriar Mirabbasi, and Mu Chiao. "Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants." IEEE Transactions on Biomedical Circuits and Systems 5.1 (2011): 48-63.

Samad, Noorul A., et al. "Design of a wireless power supply receiver for biomedical applications." Circuits and Systems, 2006. APCCAS 2006. IEEE Asia Pacific Conference on. IEEE, 2006.

Si, P., et al. "Wireless power supply for implantable biomedical device based on primary input voltage regulation." Industrial Electronics and Applications, 2007. ICIEA 2007. 2nd IEEE Conference on. IEEE, 2007.

Slaughter, Mark S., and Timothy J. Myers. "Transcutaneous energy transmission for mechanical circulatory support systems: history, current status, and future prospects." Journal of cardiac surgery 25.4 (2010): 484-489.

Wang, Bob, Aiguo Patrick Hu, and David Budgett. "Autonomous synchronous rectifier for heart pump applications." Industrial Technology (ICIT), 2013 IEEE International Conference on. IEEE, 2013.

Waters, Benjamin H., et al. "Powering a ventricular assist device (VAD) with the free-range resonant electrical energy delivery (FREE-D) system."Proceedings of the IEEE 100.1 (2012): 138-149.

Waters, Benjamin H., Joshua R. Smith, and Pramod Bonde. "Innovative free-range resonant electrical energy delivery system (FREE-D system) for a ventricular assist device using wireless power." ASAIO Journal 60.1 (2014): 31-37.

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