A Development of Acoustic Energy Transfer System through Air Medium using Push-Pull Power Converter

Thoriq Zaid[1], Shakir Saat[2] Norezmi Jamal, Siti Huzaimah Husin, Yusmarnita Yusof, SK Nguang
Department of Industrial Electronics
Faculty of Electronic & Computer Engineering
Universiti Teknikal Malaysia Melaka
[1]thoriqzaid@gmail.com [2]shakir@utem.edu.my

Abstract: - This paper presents a development of Acoustic energy transfer (AET) system through air medium using push-pull power converter. The push-pull converter may operate under zero voltage switching condition at resonance frequency and capable to minimize switching losses. This paper investigates the performance of AET through the air by using ceramic disc ultrasonic transducer, specifically for low power applications. A multiple input-output transducer is also designed in this paper. The simulation and experimental works are carried out and the obtained results are analysed accordingly. Based on the experimental results, the 1.07mW output power is obtained at 40kHz operating frequency. The multiple transceiver design offers 100% efficiency of energy transmission which is 7.24mW output power.

Key-Words: - Contactless Energy Transfer, Acoustic energy transfer, Ultrasonic transducer, Push-pull converter

1 Introduction

Contactless energy transfer (CET) has emerged as an inventive new technology that creates possibilities to supply mobile devices with electrical energy without the connection of wire. Elimination of cables or connectors in most of CET applications has increased its reliability especially to a critical system such as in aerospace, biomedical, multi-sensors and robotics applications. Recently, various technologies of CET systems are developed and investigated. These technologies include the current technology of inductive power transfer (IPT), capacitive power transfer (CPT), and optical coupling energy transfer [1].

The IPT system is widely used in contactless energy transfer system technologies. It uses coupled of the electromagnetic field coil. The achievement of this IPT system has been proven in many applications such as in electric vehicles, mobile phones, and various types of battery charging system [2]–[4]. However, there is a major drawback of this electromagnetic coupling method, where the transmission distance is relatively limited, causing the efficiency to decrease rapidly with increasing distance. On the other hand, authors in [5] stated that the inductive power transmission in a larger space is very inefficient and not practical due to high conduction losses. Additionally, over a conductive medium, these systems cannot be possible to transfer power effectively.

On the other hand, CPT systems convey energy via high frequency resonant power electronic converter that is connected to two primary metal plates. CPT system has been successfully implemented in some miniature devices [6][7], however, they share the same problem as experienced in IPT, which is low efficiency over a large distance. Meanwhile, optical coupling energy transfer systems operate correspondingly to far-field electromagnetic and microwave energy transfer. The optical power beam and photovoltaic diodes are created by laser diodes and transform it into electrical power and therefore it is able to deliver a large amount of energy [7][8]. However, diffraction losses that occur internally in this approach lead to low efficiency when operating over a long distance.

Recently, acoustic energy transfer (AET) provides a new solution for transferring energy wirelessly which exploits vibration or ultrasound waves. AET is still in its early phases and has seen very little development as compared to its counterparts. Even though the other CET systems was established several years ago, but AET has still some advantages over them; as it propagates through vibration, it can transmit energy through a metal medium where IPT fails to achieve. The metal walls have a shielding effect which limits the coupling of electromagnetic fields and induces eddy currents in the metal resulting in high losses. However, an AET system would not face such difficulties due to the absence of electromagnetic fields. Several developments proved that AET can sustain its competency across a conductive propagation medium and obtain larger distance of transmission and applied in a miniaturized size [11]. Moreover, In biomedical application, presence of electromagnetic fields will cause side effects and it is controlled under medical regulation [10].

There are numbers of publication on AET that have been applied for biomedical applications, through-wall living tissue and metal applications. To the authors' knowledge, there are very few publications that discussed AET through air. In spite of this, authors in [11] proved that AET through air is possible to be achieved. Theoretical calculation of achievable AET through air has been discussed in [12].

This paper focuses on the development of AET through the air medium using ceramic disk transducer that is driven by a push-pull power converter. Basically, the first part of this paper discusses the introduction and overview of the wireless energy transfer system. In the second part of this paper will introduced the general system of AET and its element. The operation of AET using a push-pull converter is explained in Part III and proved by the simulation accordingly in Part IV. A multiple transceiver is also applied in this paper and its impact on the system performance is studied and conclude in the last part of this paper.

2 General AET System

A typical acoustic energy system consists of primary and secondary unit where both sides comprise of ultrasonic piezoelectric transducer and are separated by a transmission medium, as shown in Fig. 1. The main important elements that we can classify in this system are; power converter, rectifier, transmission medium and transducer. Power converter and rectifier will take part in transmitting and receiving energy using desired ultrasonic transducer. Meanwhile, the transmission medium determines how the wave propagates.

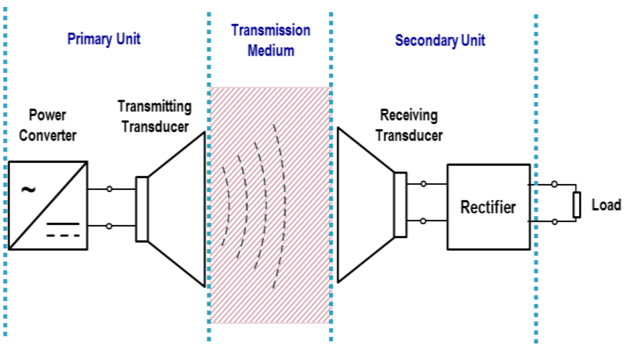

Fig. 1. A typical AET system that consists of 3 parts; primary unit, transmission medium and secondary unit.

AET system is based on sound waves or vibration and it is basically applied using an ultrasonic transducer. At the primary unit, power converter is used to drive the amount of power needed by the primary transducer. The primary transducer will transform electrical energy into pressure or acoustic wave. It generates waves in the form of mechanical energy and propagates through a medium. The primary transducer should be driven at a specific frequency and it is normally represented in a sinusoidal waveform to obtain the best performance that is matched with the propagation medium. In this paper, a push-pull power converter is used to drive the AC power to the transducer.

The secondary transducer is placed at a point along the path of the sound wave for the inverse process of converting back waves into electrical energy. It then can be used for powering up an electrical load.

Transmission medium is a part where the sound wave is being propagated between the transmitting and receiving transducers. There are some phenomena contribute to loss mechanism that affect the transmission; attenuation, diffraction and reflection of the sound waves [13]. Attenuation is reduction of signal strength during transmission and is measured in decibel. Diffraction refers to various phenomena which occurred when a wave encounters an obstacle. It is described as the apparent bending of waves around small obstacles and the spreading out of waves past small openings. Meanwhile, reflection is a change in direction that a wave experiences when it bounces off of a barrier between two kinds of media. An important idea that needs to be considered in determining the medium for transmission is material acoustic impedance. Acoustic impedance specifies how much sound pressure is generated by the occurrence vibration of the medium at a desired frequency. The medium which the wave propagates through will have its own acoustic impedance [14]. The characteristic acoustic impedance of a material is the product of its density and the velocity of propagation of sound in the material [15].

Piezoelectric materials could generate electrical energy from the pressure and mechanical energy from an electric field. Authors in [16] agreed that transducer material gives different damping effect. Therefore, the material of the transducer will give some effect to the system performance. Piezoelectric materials with high efficiency would be advantageous to be used. One of the types of transducer is a ceramic disk transducer. This type of transducer employs unique construction featuring higher sensitivity, wider bandwidth and smaller size as compared to conventional transducer. As shown in Fig. 2, the transducer utilized compound vibrator, which is a conical aluminum resonator with a connector bonded at the center of the piezoelectric elements of the bimorph type, consisting of oppositely polarized material in a sandwich construction.

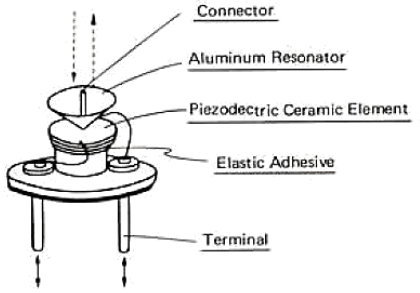

Fig 2: Topology of Ceramic-Film Ultrasonic Transducer

When an ultrasonic signal is applied to the compound vibrator, conical resonator begins to vibrate effectively because of its shape and drive the piezoelectric resonator at its central part according to the frequency of the signal. As a result, the compound resonator generates a high electrical signal from the piezoelectric resonator. Furthermore, formation of standing waves inside the case results in a higher electrical voltage. If the resonant frequency of this compound resonator corresponds to the frequency of the ultrasonic wave being applied, then the electrical voltage generated from the piezoelectric resonator is at a maximum level.

3 Power Converter Design

Power converter gives an important role to the system since it drives the sufficient voltage and current with specific frequency to transmit energy through ultrasonic transducer. The recent development in AET applied different types of power converter such as in [17] the authors applied DC power and microcontroller to generate pulse frequency. In [18], the resonance frequency is generated from a signal generator and amplified into the transmitter device.

3.1 Push-pull converter operation

Push-pull power converter is chosen because it is simple and low cost, besides does not need an additional controller to keep sustain in operation. At resonance frequency, the push-pull power converter operates under zero voltage switching (ZVS) condition, thus it reduces the switching losses during the operation. The push - pull converter is designed at the primary unit to deliver power to the transmitting transducer. This current fed converter should capable to deliver power to the transducer before the transducer propagates the energy in a form of waves to the secondary unit. Basically, the push-pull converter consists of a phase-splitting transformer, switches and resonant tank combined in a circuit as shown in Fig 3. The split-phase transformer comprises two inductor windings, L_a and L_b. The main purpose of this transformer is to split the received current into two parts, and smoothed the input ripple current. Thus, the current will start to oscillate when the force in energy form enters the resonant tank [19].

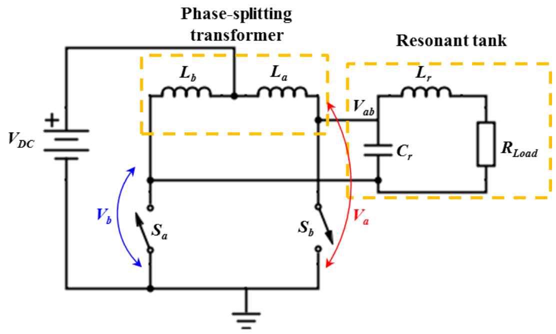

Fig. 3. Basic circuit of push-pull converter.

The two switching devices in the push-pull converter are driven from the voltage on the opposing pin. Normally, a typical switching device consists of a diode, resistor, gate capacitor and a Zener diode for both switches. The advantage of this system is, no external control circuitry is required to drive them. The zero voltage switching condition (ZVS) operation starts when the DC power is supplied to the input and triggered both of the switches. Ideally, the voltage across the switches should be same. ZVS operation ensures that one switch is activated while the other one is totally in off condition. Besides that, it can start up automatically without any control circuit. When the circuit is functioning, the voltage V_a across switch S_b will be off. This situation also similarly applies to the voltage V_b across switch SA. Both of this condition resulting to produce a sinusoidal signal of output voltage V_{ab} as shown in Fig. 4.

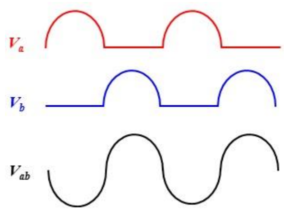

Fig. 4. Output signals of V_a, V_b and V_{ab}

The peak value of the output voltage V_{peak} of the push-pull converter can be calculated as:

$$V_{peak} = \pi V_{DC} \,, \tag{3}$$

and the output current (average), I can be expressed as:

$$I = \frac{V_{rms}}{\omega L_r} \,, \tag{4}$$

where Vrms is the rms value of the output voltage. The input of the power converter can calculate as follows

$$P_{in} = \frac{{V_{rms}}_{TX}^{\;\;2}}{Z_{TX}} \,, \tag{5}$$

where Z_{TX} is the transmitter's impedance. From [18], the total acoustic output power can be defined as

$$P_{acoustic} = \frac{[\int P_{rms} dA]^2}{[\int \rho c dA]} \,, \tag{6}$$

The maximum power is usually derived when the load resistor R_L is equal to the internal resistor of receiver device. The output power is defined by

$$P_o = \frac{{V_{rms}}_{RX}^{\;\;2}}{R_L} \,. \tag{7}$$

The efficiency of the energy transfer system can be calculated as follows

$$\eta = \frac{P_{acoustic}}{P_{in}} \times \frac{P_{output}}{P_{acoustic}} \times 100$$

$$= \frac{{V_{rms}}_{RX}^{\;\;2}/R_L}{{V_{rms}}_{TX}^{\;\;2}/Z_{TX}} \times 100 \,. \tag{8}$$

3.2 Push-pull converter design

The design of the push-pull power converter should consider several aspects such as frequency, type of waveform, voltage and current. The process is initiated by simulation design and analysis followed by experimental setup. The schematic circuit of this converter is shown in Fig. 5.

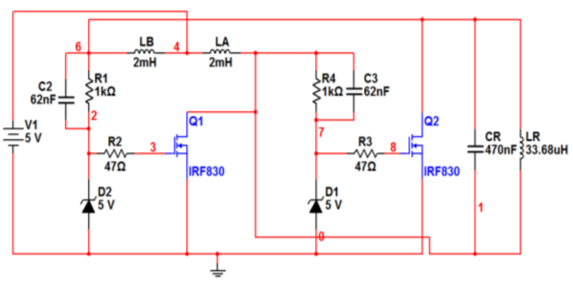

Fig. 5 : Push-pull power converter schematic circuit

TABLE I

Push-pull Converter Circuit Specifications

Parameters	Values
Operating Frequency, f	40 kHz
DC Voltage, V_{DD}	5.0V
Resonance Inductance, L_r	33.68uH
Resonance Capacitance, C_r	0.47uF

Table I shows the parameters of the push-pull converter circuit. In this paper, the operating frequency will be designated at 40 kHz. This is because the ceramic disk ultrasonic transducer that being used in this experiment is optimum at that particular value based on the initial testing of the transducer. The frequency of this power converter is obtained initially from the waveform generated by the simulation software. The most important parameter that determines the frequency calculation is the resonant inductor L_r and capacitor C_r as the formula, where

$$f = \frac{1}{2\pi\sqrt{L_r C_r}} \,. \tag{9}$$

4 Main Results

This section consists of simulation and experimental results, including the result of AET performance, which is tested in different conditions.

4.1 Simulation Results

The push-pull power converter circuit of Fig. 5 were simulated using Multisim simulation software. The result is shown in Fig. 6.

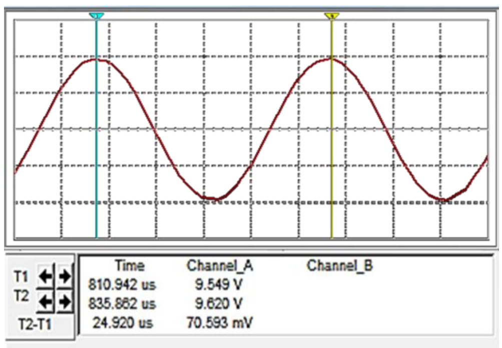

Fig. 6. Output waveform of push-pull converter simulation result

From the simulation result, we can calculate the frequency of the waveform as follows

$$f = \frac{1}{t} = \frac{1}{24.92} = 40.12\ kHz \tag{10}$$

The frequency obtained from the simulation is matched with the resonance frequency required by the transducer.

4.2 Experimental set up of AET System

The initial experiment is executed to find the optimum value of the transducer to transmit energy. The chosen ultrasonic transducer is 16mm Matsushita ceramic disk transducer. This transducer is connected to the function generator and oscilloscope. The function generator is used to generate some amount of power and frequency. The frequency value has been varied to see where the optimum value of the transducer based on the signal shown on the oscilloscope. The distance of both transmitting and receiving transducer is set to a constant value, 20.0mm. The results of the optimum frequency are shown in Fig. 7.

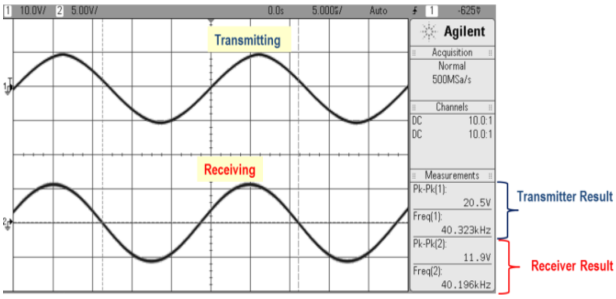

Fig. 7: Result of transmitting voltage from function generator

The results in Fig. 7 shows the waveform of the transmitting voltage where the maximum voltage is produced at a frequency of 40.32 kHz. The overall result of the variable frequency vs transfer voltage amplitude can be seen in Fig. 8.

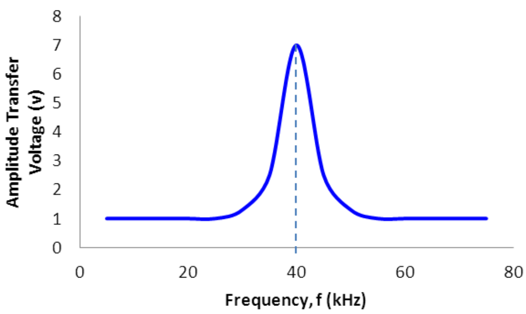

Fig. 8: Amplitude vs Frequency of the AET initial experiment

The result shows that, at this ≈40 kHz value, the energy can be transferred at maximum level. The changes made for even ±1 kHz of frequency would rapidly decrease the transferred voltage and affect the performance of the system. This experiment validated the theoretical explanation that the resonance frequency of the system should match with the transducer itself to obtain high efficiency of energy transfer.

4.3 The Performance of AET System with Single Transceiver

The experimental setup of the AET system is shown in Fig. 9. The DC input voltage that is supplied to the push-pull converter circuit is 5V and connected to the ultrasonic transducer as a transmitter. The secondary transducer is placed in opposite and perpendicular to the transmitting transducer with air gap of 2.0 cm. A simple bridge rectifier is used in the secondary unit to convert the received AC voltage to DC voltage. The arrangement of the power converter, transducers and rectifier is shown in Fig. 9. The transducer that has been used in this experiment is Multicomp ceramic disk ultrasonic transducer and the center frequency of this component is 40 kHz. Fig. 10 shows the experimental works of AET system.

Fig. 9: AET basic system using push-pull power converter transmits energy through the air medium.

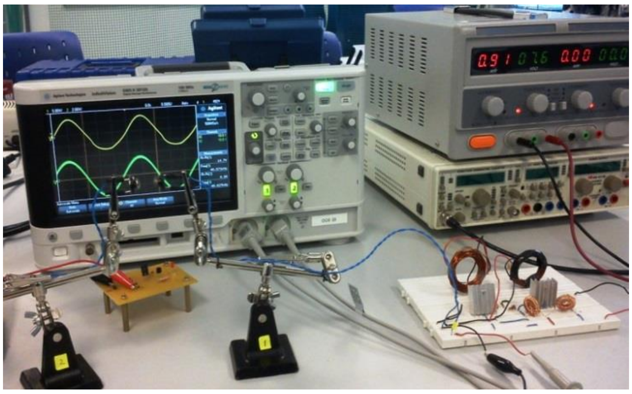

Fig. 10 : AET with push-pull converter work station

Based on the equation in (9), the frequency can be obtained by varying the value of the capacitor and inductor. In the experiment, there will be slight error where the value will be a bit different due to the external factors. It can be observed from Fig. 8 that the result is approximately similar to the simulation result shown in Fig. 11.

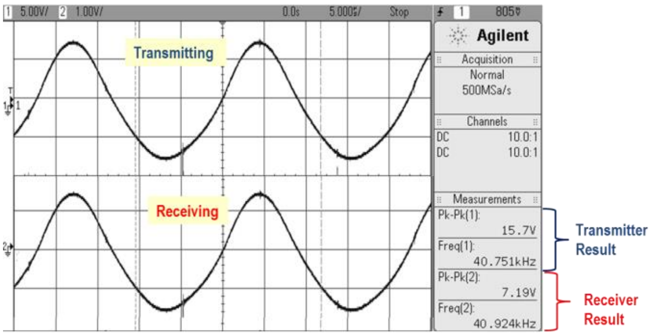

Fig. 11: Result of Push-pull power converter on AET

From the result in Fig. 11, the frequency obtained at the transmitter is 40.75 kHz, which is good condition to transfer power. The receiving signals also show that the transmitter and receiver can transfer energy even though only 45% of the Vpp voltage were received. The received voltage has been converted to the DC voltage using rectifier at different value of load and measured using a digital multimeter. The result is shown in Fig. 12.

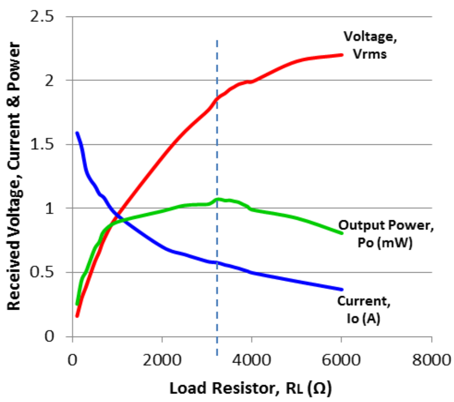

Fig. 12: The optimal power transfer ratio obtained by the varying the load resistance value. The most optimum value is at 3.3kΩ load resistances where 1.071mW power.

Fig. 13 shows the output power result when the distance of the air gap is increased. The alignment of the transducer's position is constant. In a certain limit, the output power will be decreased as the air gap distances increased.

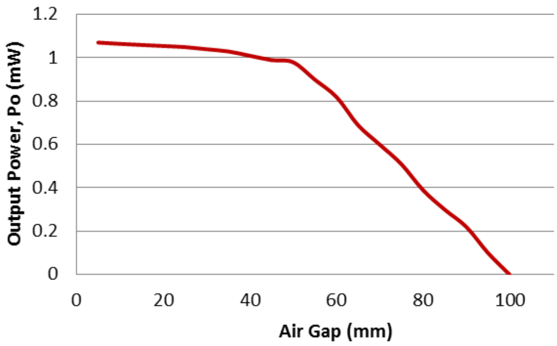

Fig.13: AET system with different air gap between transducers

Since the energy is transferred by wave propagation, the initial distance would not affect the performance of the system as long as the alignment of both transducers is not changed. Due to this fact, an AET system should be arranged where both transducers are opposite to each other in a straight line with constant alignment. Otherwise, the efficiency will drop off rapidly.

Other than that, when the wave is disturbed by any obstacle between both of the transducers, the performance of the energy transfer also decreases immediately. This is one of the wave phenomena which is called diffraction of waves. However, if both of the transducer are attached directly to the object (without gaps), we can obtain only a lower reduction of the signals. This is because, the wave is no longer propagates through air, but it transfers the ultrasound wave by the vibration through the medium (object).

The effect of heat in the inductor is not obvious as much as the increasing heat in a capacitor. Since, it is affecting the performance of the system, an additional experiment is executed to carry out the effect of heat to the capacitor of this push-pull converter. As the heat of capacitor, Cr is increased, the value of the capacitance will be decreased because of changes in the dielectric properties. Logically, based on the equation (9), the frequency will be increased as the consequent to the increased of capacitance.

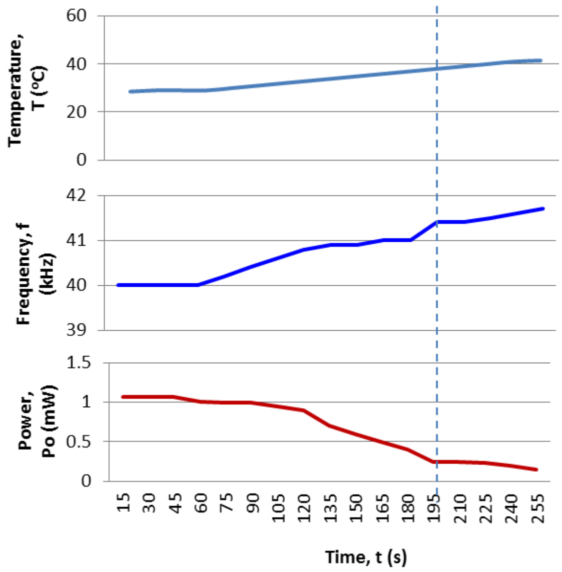

Fig. 14: The effect of capacitor's temperature to the frequency and the transferred power.

The result in Fig.14 shows the increasing of capacitor's temperature makes changes in capacitance value and thus affecting the frequency and finally decrease the possible power that can be transferred. From the graph, it is observe that the transferred voltage is decerease when the frequency is increased to 41kHz. At 41.5kHz, the voltage transfer is decreased to 0. The built up of heat made the operation time for perfect energy transfer is limited.

The power obtained is almost 1.07mW optimum. Even the achievement is quite low, it still higher than the previous development in [12] and proved that the AET system is working with this power converter design. The efficiency of the system is 14%.

4.4 Multiple Transceiver Results

The experiment also covers the study on the performance of the system with multiple input-output of the transducer. The arrangement of the system is shown as in figure 15.

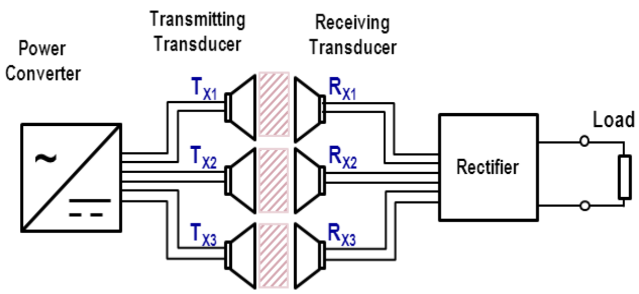

Fig.15: Multiple input-output AET system block diagram

All of the transmitting transducers connect to the power converter in parallel connection. This will make the transmitting transducer transmit equal power from the converter. The receiving transducer connected to the rectifier in series connection, thus the input of the transducer will get maximum value of power to the load. The schematic of the connection can be simplified as in Fig. 16:

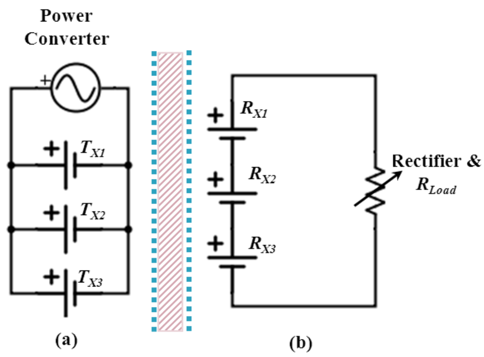

Fig.16: (a) Connection of multiple transmitters,Tx in parallel (b) Connection of multiple receivers, Rx in series

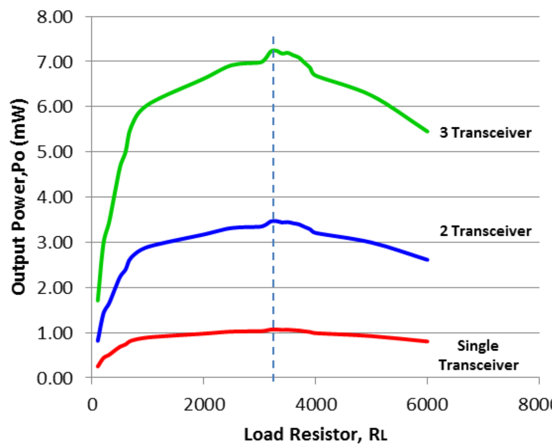

Fig.17: Result of multiple input-output AET system. The maximum power of the system is 1.07mW for single transceiver, 3.47mW for 2 transceivers and 7.24mW power for 3 transceivers.

The results in Fig.17 show that the output power is increased when multiple transceiver is used. This made the rectification efficiency of the system increased to 100% when 3 transceivers is used at 3.3kΩ load. This confirmed that AET system using multiple transceiver provides a better efficiency than the single transceiver.

5 Conclusion

This paper has presented a development of the AET system through the air medium using a push - pull converter. The performance of the system has been analyzed where there are some factors that affect the efficiency. To conclude this part, an AET system needs a focus beam with a constant alignment that operate with optimum frequency to optimize the energy transfer capabilities.

The single transceiver AET system is able to transfer 1.07mW power. However, the efficiency of the system was increased, when multiple transceiver is used. The output power of this multiple transceiver is 7.24mW. The future direction of the research is to implement the multiple transceiver to a better power converter circuit thus increase the input transmit power.

Acknowledgements

Sincerely to express appreciation to Universiti Teknikal Malaysia Melaka (UTeM) for fully funding this research work under PJP/2013/FKEKK(40C)/S01254 grant.

References:

[1] M. P. Kazmierkowski and a. J. Moradewicz, “Contactless energy transfer (CET) systems — A review,” in *2012 15th International Power*

Electronics and Motion Control Conference (EPE/PEMC), 2012, pp. Session 3–1–Session 3–6.

[2] H. H. Wu, A. Gilchrist, K. Sealy, P. Israelsen, and J. Muhs, "A review on inductive charging for electric vehicles," *2011 IEEE Int. Electr. Mach. Drives Conf.*, pp. 143–147, May 2011.

[3] J. Kim and F. Bien, "Electric field coupling technique of wireless power transfer for electric vehicles," *IEEE 2013 Tencon - Spring*, vol. 1, pp. 267–271, Apr. 2013.

[4] F. Musavi, M. Edington, and W. Eberle, "Wireless power transfer: A survey of EV battery charging technologies," *2012 IEEE Energy Convers. Congr. Expo.*, pp. 1804–1810, Sep. 2012.

[5] E. Waffenschmidt, H. T. Campus, and A. E. Eindhoven, "Limitation of inductive power transfer for consumer applications," *Power Electron. Appl. 2009. EPE '09. 13th Eur. Conf.*, pp. 1–10, 2009.

[6] A. M. Sodagar and P. Amiri, "Capacitive Coupling for Power and Data Telemetry to Implantable Biomedical Microsystems," *Neural Eng. 2009. NER '09. 4th Int. IEEE/EMBS Conf.*, pp. 411–414, 2009.

[7] H. Zheng, K. Tnay, N. Alami, and A. P. Hu, "Contactless Power Couplers for Respiratory Devices," *Mechatronics Embed. Syst. Appl. (MESA), 2010 IEEE/ASME Int. Conf.*, pp. 155–160.

[8] A. Sahai and D. Graham, "Optical wireless power transmission at long wavelengths," *2011 Int. Conf. Sp. Opt. Syst. Appl.*, pp. 164–170, May 2011.

[9] D. E. Raible, D. Dinca, and T. H. Nayfeh, "Optical Frequency Optimization of a High Intensity Laser Power Beaming System Utilizing VMJ Photovoltaic Cells," *Sp. Opt. Syst. Appl. (ICSOS), 2011 Int. Conf.*, pp. 232–238, 2011.

[10] G. Calcagnini, F. Censi, and P. Bartolini, "Electromagnetic immunity of medical devices: the European regulatory framework.," *Ann Ist Super Sanita 2007*, vol. 43, no. 3, pp. 268–276, Jan. 2007.

[11] I. Toshihiko, Y. Kanai, J. Ohwaki, and M. Mino, "Impact of A Wireless Power Transmission System Using An Ultrasonic Air Transducer for Low-Power Mobile Application," *Ultrason. 2003 IEEE Symp.*, vol. 2, pp. 1368–1371, 2003.

[12] M. G. L. Roes, M. a. M. Hendrix, and J. L. Duarte, "Contactless energy transfer through air by means of ultrasound," *IECON 2011 - 37th Annu. Conf. IEEE Ind. Electron. Soc.*, pp. 1238–1243, Nov. 2011.

[13] M. G. L. Roes, S. Member, J. L. Duarte, M. A. M. Hendrix, E. A. Lomonova, and S. Member, "Acoustic Energy Transfer : A Review," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 242–248, 2013.

[14] T. J. Lawry, K. R. Wilt, J. D. Ashdown, H. a Scarton, and G. J. Saulnier, "A high-performance ultrasonic system for the simultaneous transmission of data and power through solid metal barriers.," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 60, no. 1, pp. 194–203, Jan. 2013.

[15] K. Nakamura, *Ultrasonic transducers: materials and design for sensors, actuators and medical applications*. Woodhead Publishing, 2012.

[16] Y. Hu, X. Zhang, J. Yang, and Q. Jiang, "Transmitting electric energy through a metal wall by acoustic waves using piezoelectric transducers.," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 50, no. 7, pp. 773–81, Jul. 2003.

[17] A. Sanni and A. Vilches, "Powering low-power implants using PZT transducer discs operated in the radial mode," *Smart Mater. Struct.*, vol. 22, no. 11, pp. 1–12, Nov. 2013.

[18] S. Q. Lee, W. Youm, and G. Hwang, "Biocompatible wireless power transferring based on ultrasonic resonance devices," *Proc. Meet. Acoust.*, vol. 19, pp. 1–9, 2013.

[19] H. H. Wu, A. P. Hu, P. Si, and D. Budgett, "A Push-Pull Resonant Converter with Dual Coils for Transcutaneous Energy Transfer Systems," *Ind. Electron. Appl. 2009. ICIEA 2009. 4th IEEE Conf.*, pp. 1051–1056, 2009.