International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 7, No. 3, September 2016, pp. 946~953
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v7.i3.pp946-953

Implementation of a MIMO System forWireless Power Transfer Using Acoustic Approach

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Article Info

Article history:

Received Nov 12, 2015
Revised Apr 7, 2016
Accepted May 8, 2016

Keyword:

Acoustic energy transfer
MIMO system
Ultrasonic transducer
Wireless power transfer

ABSTRACT

This paper presents a development of Acoustic energy transfer (AET) system through air mediumby implementing a Multiple Input-Multiple Output (MIMO) arrangement of transducers to transmit energy. AET system allows power to be transmitted without wire connection. The MIMO system is proposed in this paper to increase the efficiency of the transmitting power by multiplying the received power. The simulation and experimental works are carried out using a Class E power converter and the obtained results are analyzed accordingly. Based on the experimental results, the 18.57mW output power is obtained at 40kHz operating frequency when triple transducer is used. It contributes to 30.96% efficiency to the power transfer system.

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1. INTRODUCTION

Acoustic energy transfer (AET) is an emerging new method of 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 other Contactless Energy Transfer (CET) system like Inductive Power Transfer (IPT) or Capacitive Power Transfer (CPT). Even though the other CET system was established earlier years ago, AET has advantages in some traits. As it propagates through vibration, it can transmit energy through a metal medium where IPT and CPT fail 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 [1]. In biomedical applications, presence of electromagnetic fields will cause side effects and it is controlled under medical regulation [2]. Absence of electromagnetic fields has made AET more practical to be used in biomedical applications and can beapplied in a miniaturized size [1]. Other than that, acoustic velocity in human tissues used by medical imaging application produces a very small wavelength. This makes AET an attractive method to energize implanted micro-devices wirelessly and allowing reasonable directional transmission since the transducers of overall dimensions are used as few millimeters [3]. Although the AET system could transfer energy over longer distance, the power received at receiver quite low especially when air medium of transmission is used. Thus, this paper presents a development of a Multiple Input-Multiple Output (MIMO) arrangement of transducers to transmit energyto increase the efficiency of the transmitting power by multiplying the received power.

A typical acoustic energy transfer system consists of primary and secondary unit where both sides comprise of ultrasonic piezoelectric transducer and separated by a transmission medium, as shown in Figure 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.. The development of AET in biomedical through tissue and water achieved quite a good result as in [3]–[7]. There are also several research and development of AET through metal medium as in [8]–[11], but very few works discussed AET through air [12], [13].

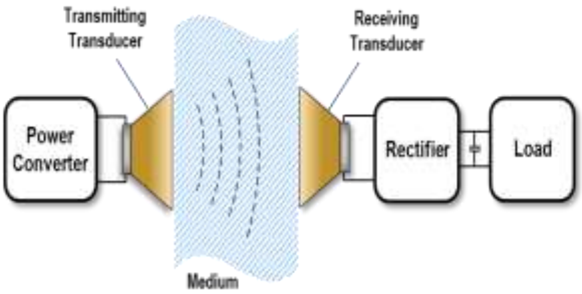


Figure 1. A general AET system that consists of 3 parts; primary unit, transmission medium and secondary unit

AET system is based on sound waves or vibration and 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 is normally represented in a sinusoidal waveform to obtain the best performance that is matched with the propagation medium[14]. In this paper, a Class E power converter is used as a power converter due to its simplicity and theoretically it can produce zero switching losses, besides its simplicity and only has a single switch component that need to be controlledas published in [15]–[17] for high frequency inductive CET.

The secondary transducer is placed at a point along the path of the sound wave for the inverse process of converting back into electrical energy. In other words, this acoustic wave is picked up by the secondary transducer at a specific frequency and converts the mechanical energy back to the electrical energy. It then can be used for powering up an electrical load. The sine wave is also produced at the secondary transducer.

2. ACOUSTIC ENERGY TRANSFER USING MIMO SYSTEM

Single input-output transducer has been developed in [18] shows a lack of output power received by the transducer, see Figure 1. Thus, this paper proposes a new arrangement of transducer position so that the received power can be multiplied using multiple-input multiple output (MIMO) transducer, see Figure 2. In other words, there are multiple transducers used on both side transmitter and receiver. The MIMO system is applied to increase the ability of the system to receive more power from one power source.

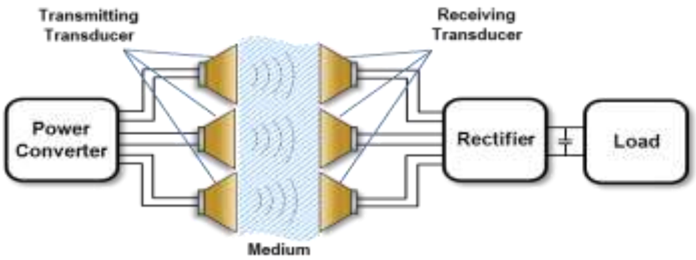


Figure 2. Multiple input-output AET system block diagram

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 shown in Figure 3(a) and 3(b).

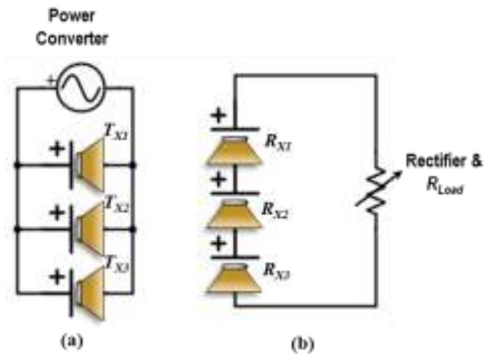


Figure 3. (a) Connection of multiple transmitters, Tx in parallel (b) Connection of multiple receivers, Rx in series

3. DESIGN of POWER CONVERTER

Power converter plays an important role to drive power to the circuit. In this paper, the Class E power converter is chosen to apply in the AET MIMO system. The Class E converter is chosen because it operation is based on the Zero Voltage Switching (ZVS) condition where the switching losses is minimized. Thus, the efficiency of the system can be increased.

3.1. Class E Converter Operation

Basically, the class e converter consists of PWM generator which is in this work we use a microcontroller, MOSFET driver and Class E amplifier circuit. Figure 4 shows the schematic circuit of the class E converter.

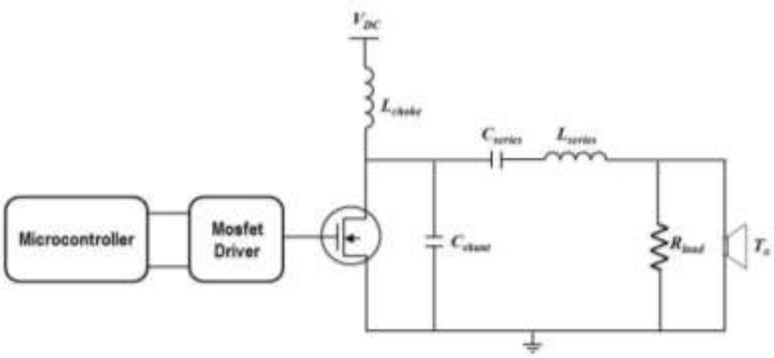


Figure 4. Class E converter schematic circuit

The microcontroller uses to generate the PWM pulse with specified frequency. The generated pulse connect to the MOSFET driver as a switching device to rapidly and completely switch the gate of the MOSFET of the Class E amplifier. The MOSFET operates as an on/off switch of the amplifier. The L_{choke} used to neglect its current ripple or acts as current source when the switch is off. This is to limit the input current to be a constant current. The shunt capacitor, C_{shunt} across the switch is to shape drain voltage and current waveform during on to off transition and a net series load inductance offer the required phase shift for the fundamental wave and behave as a harmonic open circuit [15]. Series capacitor, C_{series} and series inductor L_{series} act as a filter to reduce the harmonic effects at sine wave. It operates based on the zero-voltage switching (ZVS) and zero-derivative switching (ZDS) conditions at the on-state switch [19]. Since Class E converter circuit fulfills the ZVS/ZDS condition, thus, the power loss in Class E converter circuit can be minimized to zero during the switching operation [15], thus increses the efficiency of the energy transfer.

Based on the analysis in [20] and applied accordingly in [21] [22], the load resistance can be determined as RL= 0.5514 ($V_{DD}^2/P_{O)}$. The shunt capacitor, C_{shunt}across the switch can be calculated as C_{shunt}= 0.1971/ωR_L. Moreover, the series capacitor, C_{series}can be determined as C_{series}= 0.1062/ωR_L.The value of series inductor, L_{series} is the summation of resonant inductor, L_{res} and series loading inductor, L_{ext}, whereL_{series}=L_{ext}+L_{res}. Thus, the resonant inductor, $L_{res}$and excess series inductance, L_{ext}can becalculated as L_{res}= 10.62(R_L/ω) and L_{ext}=1.153(R_L/ω).

3.2. Class E Converter Design

The specifications and parameter of the Class E converter circuit are shown in Table I. In this paper, the Class E converter circuit is designed based on the requirement of the transmitter which must satisfy the following specifications: input voltage, V_{in}=9V, maximum output power is assumed, P_o=100mW, duty cycle, D=50%, operating frequency, 40kHz ±0.5 and quality factor, Q of a series resonant circuit is 10. The specification needed is applied to the formula and obtained the value as in Table I. In addition, the circuit design for Class E converter circuit as shown in Figure 5 based on the ideal case where the internal resistance in the MOSFET and all passive elements were ignored.

Table 1. Class E Converter Circuit Specifications

Parameters	Calculated
Operating Freqency, f	40.0 kHz
Rated Power, P	100mW
Quality Factor, Q	10.0
DC Voltage, VDD	9.0V
Switch Duty Cycle, *D*	0.5
Choke Inductor, L_{choke}	35.0mH
Shunt Capacitor, C_{shunt}	1.8nF
Series Capacitor, C_{series}	0.9nF
Series Inductance, L_{series}	20.9mH
Load Resistance, R_L	446.0Ω

Figure 5 shows the schematic diagram of the Class E circuit that has been designed in this work. The LTSpice software is used in this work. All the values used are the same as givenin Table I. The gate of the MOSFET will be driven by the PWM signal that is generated by the microcontroller. The microcontroller used in this work is PIC 16F819. The PWM is designed to produce a 40kHz ±0.5 frequency and this is the operating frequency of this system. The results will be discussed next.

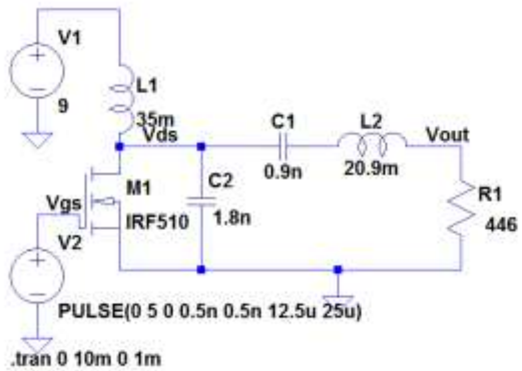


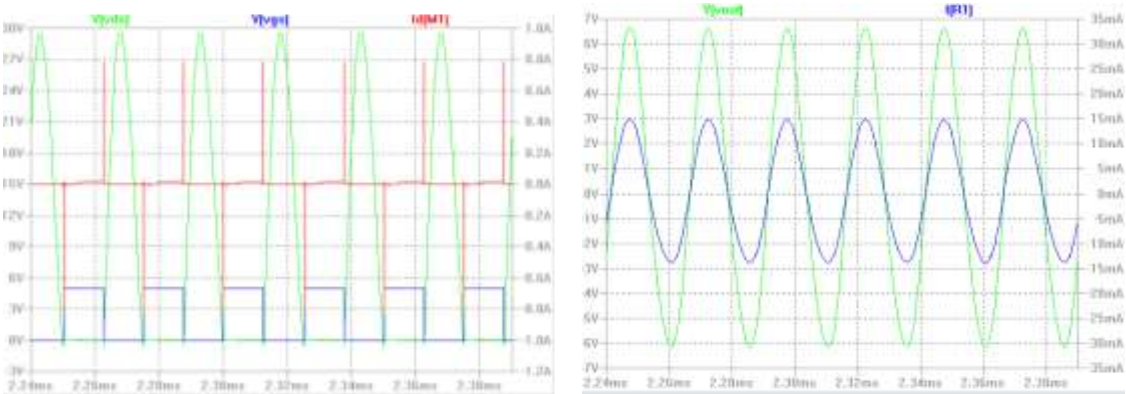
Figure 5. Class E converter design circuit

4. RESULTS AND ANALYSIS

This section consists of simulation and experimental results of the Class E converter and the output of the energy transfer based on the parameter value set in Table 1 The type of MOSFET that isused is IRF510 while the MOSFET driver is TC4422 type. The class E converter circuit simulations are obtained first to determine the ZVS condition of the converter. Both simulation end experimental results will be presented in this section.

4.1. Class E Simulation Results

Figure 6(a) shows the half sinusoidal waveform of the drain-to-source voltage, $V_{DS,}$ the gate-to-source voltage, $V_{GS}$and current drain, I_D. Due to the charges stored in the shunt capacitor, the V_{DS} value increases to almost 3.0 times greater. Meanwhile, the square waveform of gate-to-source voltage, V_{GS}, is specified as 5V. This is because, in the OFF state transition, the current will flow through C_{shunt} and produces the voltage across the capacitor and V_{DS}. Thus, the C_{shunt} shapes the drain-to-source voltage.



(a) (b)

Figure 6(a). The output waveform of V_{GS} V_{DS} and I_D (b) The output waveform of V_O and I_O

The results show that the ZVS condition is obtained successfully. Meanwhile, Figure 6(b) shows the output waveform of the Class E converter simulated for output voltage, V_O and output current I_O. The maximum output voltage obtained is 6.5V and the maximum output current is 15 mA. Thus, the output power obtained is 97.5 mW. This simulation results confirmed that the proposed requirements are satisfied and therefore can be proceed withthe experimental work.

4.1 Experimental Result

The DC input voltage that is supplied to the PIC microcontroller is 5.0V while the Class E amplifier is powered by 9.0V then connected to thetransmitting transducer. The secondary transducer is placed in opposite and perpendicular to the transmitting transducer with air gap of 20.0mm as a medium. Both transducers that have been used in this experiment is Multicomp ceramic disk transducer where the center frequency of this component is 40 kHz. A simple bridge rectifier is used at the secondary unit. Figure 7 shows the arrangement of a MIMO system where multiple transducer is used on both sides.

(a) (b)

Figure 7. The arrangement of the AET MIMO system where all the receiving transducer connected to the (a) single load and (b) multiple load

These arrangements of transducer are made to differentiate the output and analyze how the performance of the receiving power of this system by using different numbers of load. The air gap is constant at 20.0mm for both experiments. All the input and output of the transmitter and receiver are captured using an Agilent digital oscilloscope and also measured using a Tektronixdigital multimeter. The experimental setup of the overall system is shown in Figure 8.

Figure 9(a) depicts the result of the ZVS condition of the Class E circuit and it is obvious that the ZVS is achieved well. This will ensure the minimization of the switching loss. As in the simulation, when the switch is off, the current flow through shunt capacitor, C_{shunt}, and produces the voltage across it. Thus, it shapes the drain-to-source voltage, V_{DS} which is $37.4V_{pp}$. The peak drain current and drain peak voltage is displaced in time during the ZVS condition, thus it will cause the zero power of switching losses. The frequency obtained is 39.68kHz and still in the range of the transducer's operating frequency.

Figure 9 (b) shows the result of the output voltage, Vo at the transmitter using 460Ω load resistor. Thus, the output power obtained at the transmitter side is 59.98 mW. This is the maximum power can be transferred based on the designed. Then, the transmitter is ready to transmit power, though single or multiple transducers as arranged in Figure 7. The rectifier circuit is tested with different value of resistor (load) and results obtained are shown in Figure 10.

Based on the results shown in Figure 10, the output power received using a single transceiver is 4.2mW which is 7.02% efficiency. When double transceiver is used, the output power obtained is 11mW which contributes to 18.32% efficiency. The highest output power obtained is when triple transceiver is used where the efficiency reach to 30.96%. These values are the maximum output power obtains in each part when the load resistor is 3.3kΩ. The achievement is perform better and obtained higher result compared to the development in [18] which using similar types of transducer. From these results, it is confirmed that the efficiency of the system is increased when the MIMO arrangement of the transceiver is applied to the system. Of course, it can befurther increased if more transceiver is used. This is because when multiple transmitters are used, it will transmit the same power to every transducer. However, in receiver they received the same power at every receiving transducer. This arrangement made the receiver multiply the received power from a single source of power supply.

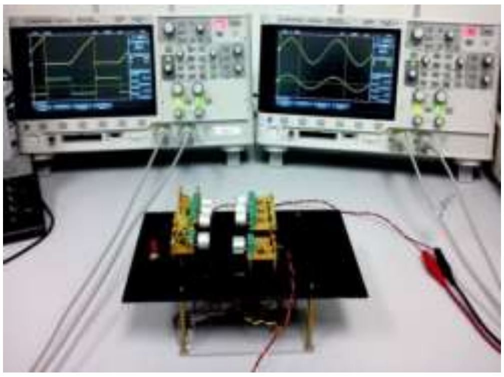


Figure 7. AET MIMO system experimental setup

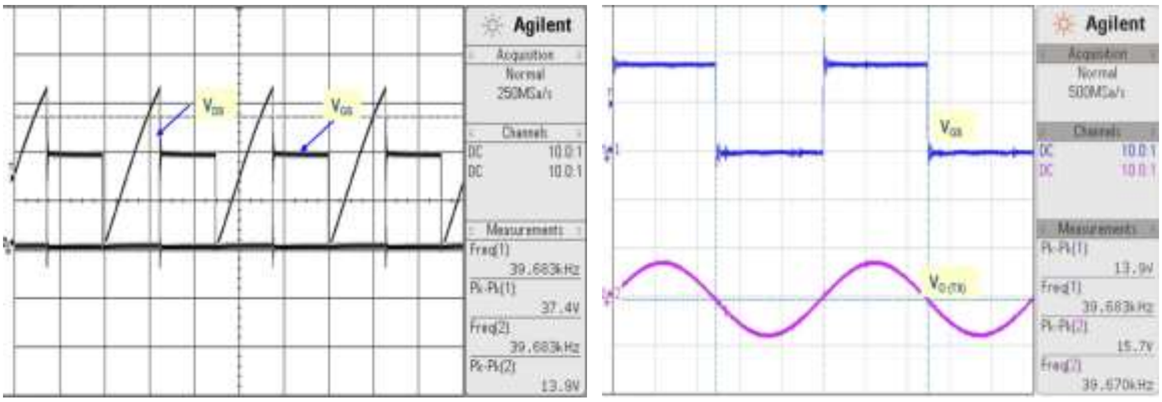


Figure 9. Experimental result of the (a) ZVS Class E Converter (b) Output voltage of Class E Converter

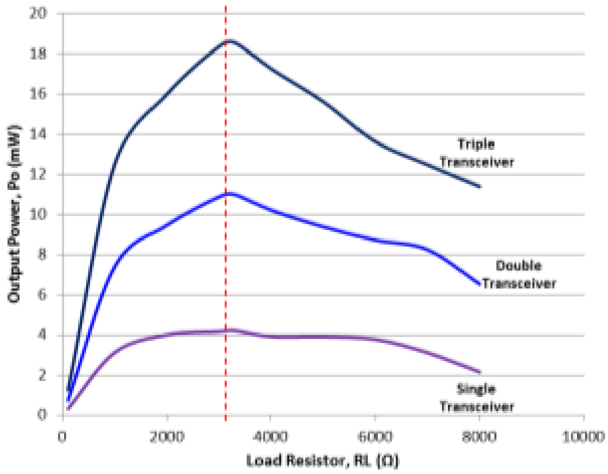


Figure 10. Output power obtained by different numbers of transceiver using different value of the load resistor

5. CONCLUSION

This paper has presented an analysis of the Class E converter that being applied to an AET system through the air medium using a MIMO arrangement of transducers. This type of transducer's arrangement is proving can increase the efficiency of the power transfer. As a result, the triple transducer reached 30.96% efficiency rather than a double and single transceiver used where the efficiency is below than that. Therefore, to increase the efficiency, the AET system needs a focus beam with a constant alignment that operates with optimum frequency to optimize its capability to energy transfer.Other than that, the rated power of the designed power converter is possible to be increased, thus more power can be transferred and receives.

ACKNOWLEDGEMENTS

Sincerely to express appreciation to UniversitiTeknikal Malaysia Melaka (UTeM) for fully funding this research work under PJP/2013/FKEKK(40C)/S01254 and RAGS/2013/FKEKK/TK02/06/B00035 grant.

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