The Experimental Analysis of Low-Power Acoustic Energy Transfer System using Class E Converter

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***Abstract*—This paper presents a development of acoustic energy transfer (AET) system through air medium for low power application using Class E converter. AET system transmits energy in a form of wave through a couple of transducer that is driven by the power converter. The primary circuit of AET uses a Class E converter circuit to drive the non-linear load, which theoretically produces zero switching losses. To ensure that the power can be transmitted efficiently, an optimum frequency was generated by the power converter. The frequency was generated from pulse width modulation (PWM) using microcontroller. In this work, the maximum output power that can be transferred was 4.20mW at 39.68kHz frequency.**

***Index Terms*—Acoustic Energy Transfer; Contactless Energy Transfer; Class E Converter; Ultrasonic Transducer.**

I. INTRODUCTION

Recently, a new form of contactless energy transfer (CET) called Acoustic Energy Transfer (AET) is proposed using generated sound waves through a couple of ultrasonic transducer to convey energy. Instead of using electromagnetic field as inductive CET, AET operates through sounds wave with specific frequency. Although it is still new, this method has its own merit and advantages compared to the other developed CETs. AET performs better when the distance between transmitter and receiver is large [1]. As it propagates through vibration, it can transmit energy through a metal medium where inductive CET and capacitive CET fail to achieve. Other than that, since the sound waves have a smaller wavelength, the transmitter and receiver in AET system can be smaller than several orders of magnitude for a given directionality of the transmitter [1],[2]. AET has been developed in several applications with different types of medium. The development of AET in biomedical through tissue and water has achieved good results as in [1], [3]–[6]. There are also several research and development of AET through metal medium as in [7]–[10], but very few works discussed AET through air [11], [12].

A good CET system is driven by a good power converter. Nowadays, there are several classes of power amplifiers available such as Class A, Class AB, Class C, Class D and Class E. In previous work on AET system [13], the push-pull converter has been used and analyzed. Although the push-pull provides a good Zero Voltage Switching (ZVS) result, it lacks stability, especially when the heat is increased. The class E converter circuit is proposed in this work because theoretically it can produce zero switching losses, besides its simplicity. Further, it only has a single switch component that needs to be controlled. This is why some researchers attempt to use class E converter as published in [14]–[16] for high frequency inductive CET. In AET system, besides requiring a sufficient power produced by the power converter, the operating frequency plays an important role to produce high efficiency energy transfer. The frequency should be optimum, stable and match with the frequency of the transducer. Thus, the class E circuit will be integrated with pulse width modulation (PWM) from microcontroller since it is more reliable in generating a stable frequency.

This paper focuses on the development of AET system using a class E converter through the air medium. It starts with an overview of AET system, followed by class E circuit design. The simulation and experimental works were carried out and the obtained results was analysed accordingly. The last section of this paper presents a brief conclusion and future recommended for this research work.

II. AET SYSTEM OVERVIEW

A typical acoustic energy system consists of primary and secondary unit where both sides comprise ultrasonic piezoelectric transducer and are 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. The transmission medium determines how the wave propagates.

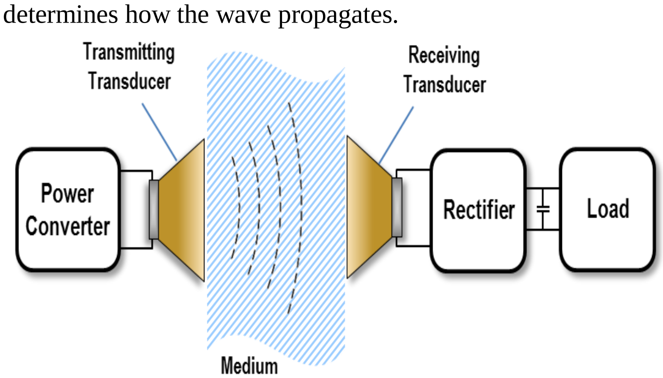

Figure 1: A general AET system consists of 3 parts; primary unit, transmission medium and secondary unit.

A. Acoustic Energy Transfer System

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 class E 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 the loss mechanism that affects the transmission; attenuation, diffraction and reflection of the sound waves [2]. Attenuation is a reduction of signal strength during transmission and measured in decibel. Diffraction refers to various phenomena which occurr 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 of vibration of the medium at a desired frequency. The medium, which the wave propagates through will have its own acoustic impedance [10]. The characteristic of acoustic impedance of a material is the product of its density and the velocity of propagation of sound in the material [17].

B. Power Converter Design

Figure 2 shows the schematic circuit of the class E converter for transmitter in AET system. Basically, this power converter consists of PWM generator, which is the microcontroller, MOSFET driver and Class E amplifier circuit. The microcontroller uses to generate PWM pulse with specified frequency. In this work, the frequency that needs to design is 40 kHz ±0.5. The generated pulses are then connected to the MOSFET driver as a switching device to rapidly and completely switch the gate of the MOSFET of Class E amplifier. The MOSFET operates as an on/off switch of the amplifier. The L_{choke} neglects its current ripple or acts as a 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 the drain voltage and the current waveform during the on and off transition, and a net series of load inductance offers the required phase shift for the fundamental wave and behaves as a harmonic open circuit [14]. 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 [18]. Since the Class E converter circuit fulfills the ZVS/ZDS condition, the power loss in Class E converter circuit can be minimized to zero during the switching operation [14], thus increases the efficiency of the energy transfer.

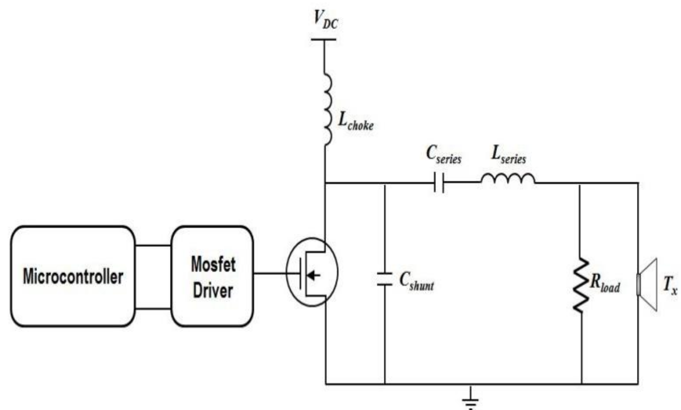

Figure 2: Class E converter schematic circuit

The Class E converter circuit is designed based on the requirement of the transmitter. Thus, it must satisfy the following specifications: input voltage, V_{in}=9V, maximum output power is assumed, P_o=100mW, duty cycle, D=10, operating frequency, 40kHz ±0.5. Based on the analysis in [19] and applied accordingly in [20][21], the load resistance can be determined as follows :

$$R_L = 0.5514 \frac{{V_{DD}}^2}{P_o}. \tag{1}$$

The shunt capacitor, C_{shunt} across the switch can be calculated as follows:

$$C_{shunt} = \frac{0.1971}{\omega R_L}. \tag{2}$$

Moreover, the series capacitor, C_{series} can be determined as follows:

$$C_{series} = \frac{0.1062}{\omega R_L}. \tag{3}$$

The value of series inductor, L_{series} is the summation of resonant inductor, L_{res} and series loading inductor, L_{ext}, where:

$$L_{series} = L_{ext} + L_{res}. \tag{4}$$

Thus, the resonant inductor, L_{res} and excess series inductance, L_{ext} can be calculated as follows:

$$L_{res} = 10.62 \frac{R_L}{\omega} \tag{5}$$

$$L_{ext} = 1.153\frac{R_L}{\omega}. \quad (6)$$

Table 1 shows the value of circuit design of the Class E amplifier for an AET system based on the stated equation.

Table 1
Class E Amplifier Parameter

Parameters	Values
Operating Frequency, *f*	40.0 kHz
Rated power, *P*	100mW
Quality Factor, *Q*	10.0
DC Voltage, V_{DD}	9.0 V
Choke Inductor, L_{choke}	50mH
Shunt Capacitor, C_{shunt}	1.8nF
Series Capacitor, C_{series}	1.0nF
Series Inductance, L_{series}	20mH
Load Resistance, R_L	430Ω

III. Results & Discussion

This section consists of simulation and experimental results based on the parameter values set in Table 1. The type of MOSFET used is IRF510, while the type of MOSFET driver used is TC4422. The class E converter circuit simulations were obtained first to determine the ZVS of the power converter between the drain voltage and gate voltage, drain current and voltage waveform. Both of the simulation and experimental results are presented in this section.

A. Simulation Results

Figure 3 shows how the circuit constructed the simulation purpose where it consisted of the PIC microcontroller, MOSFET driver and Class E amplifier circuit. Before running the simulation, the program codes for PWM were embeded to the microcontroller. Figure 4 shows the half sinusoidal waveform of the drain-to-source voltage, V_{DS}. Due to the charges stored in the shunt capacitor, the V_{DS} value increased to almost 3.0 times greater. Meanwhile, the square waveform of gate-to-source voltage, V_{GS}, was specified as 5V. This is because, in the OFF state transition, the current flowed through C_{shunt} and produced the voltage across the capacitor and V_{DS}. Thus, the C_{shunt} shaped the drain-to-source voltage.

The simulation in Figure 4 shows that the time of one cycle wave was 24.98µs. Thus, it can be determined that the frequency of this wave was 40.03 kHz. Figure 5 and Figure 6 show the simulation of the voltage and current at output load.

The output voltage obtained was 6.9V, while the current was 14.0 mA. Thus, the simulated output power obtained was 96.6mW power. This value was close to the calculated value which is 100mW power.

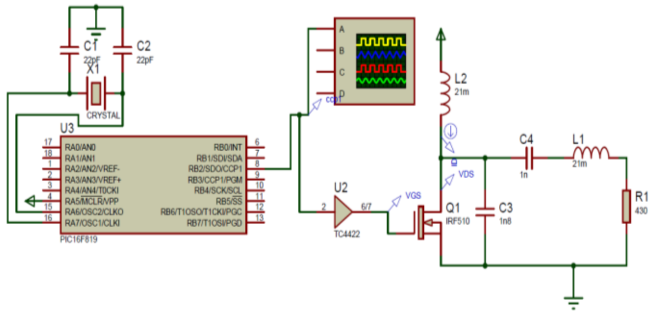

Figure 3: Class E Converter circuit constructed in the simulation software

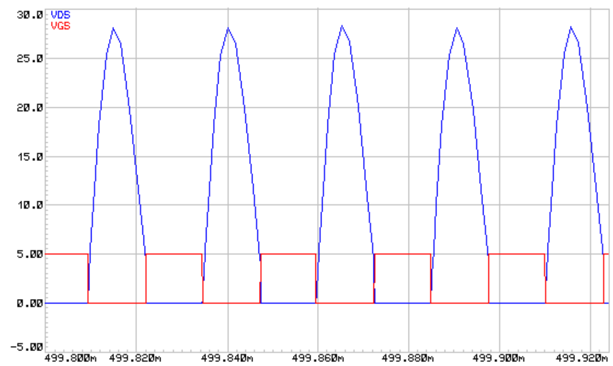

Figure 4: Simulation of the V_{DS} and V_{GS} meet the ZVS condition of the Class E amplifier

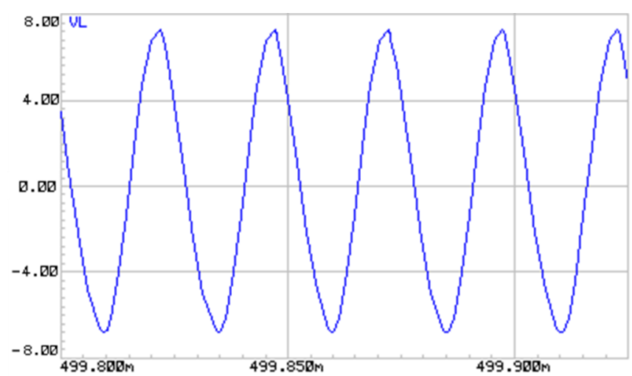

Figure 5: Simulation of the output load voltage in Class E amplifier

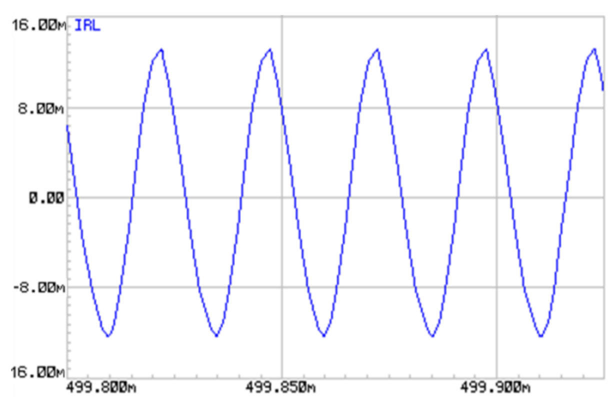

Figure 6: Simulation of the output load current in Class E amplifier

B. Experimental Results

The experimental setup of the AET system is shown in Figure 7. The DC input voltage supplied to the PIC microcontroller was 5.0V, while the Class E amplifier powered by 9.0V was then connected to the transmitting transducer. The secondary transducer was placed in opposite and perpendicular position to the transmitting transducer with air gap of 2.0 cm as a medium. Both transducers used in this experiment were the Multicomp ceramic disk transducer, where the center frequency of this component was 40 kHz. A simple bridge rectifier was used in the secondary unit. Figure 8 shows the experimental works of AET system.

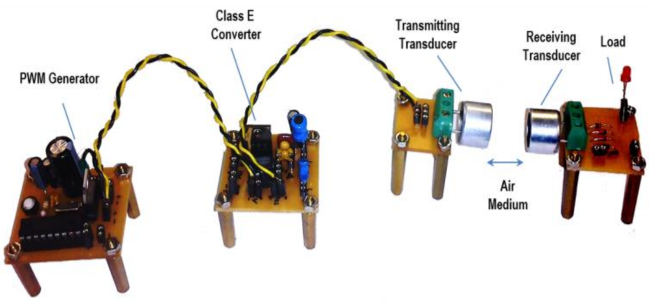

Figure 7: AET system using Class E converter through the air medium.

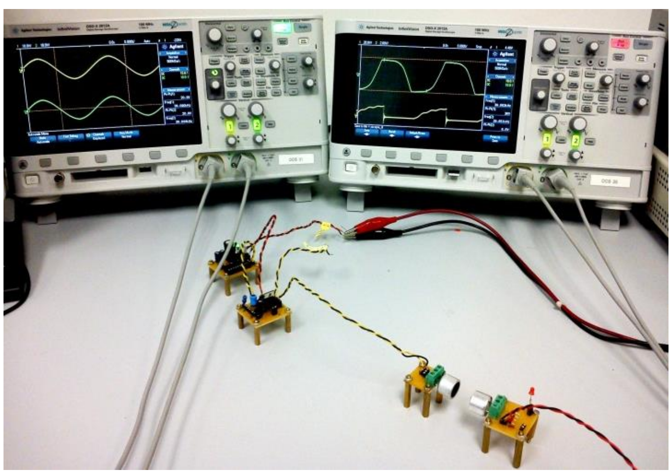

Figure 8: AET with Class E converter experimental workstation.

Figure 9 depicts the experimental waveform for zero voltage switching (ZVS) of the Class E circuit. It was found that the circuit satisfied the Class E switching conditions. As in the simulation, when the switch was off, the current flowed through shunt capacitor, C_{shunt}, and produced the voltage across it. Thus, it shaped the drain-to-source voltage, V_{DS} which was 37.4V_{pp}. The peak drain current and drain peak voltage was displaced in time during the ZVS condition, causing the zero power of switching losses. The frequency obtained was 39.68 kHz and still in the range of the transducer's operating frequency. Figure 10 shows the result of the transmitted power where the transmitter and receiver can transfer energy even though only 45% of the Vpp voltage was received.

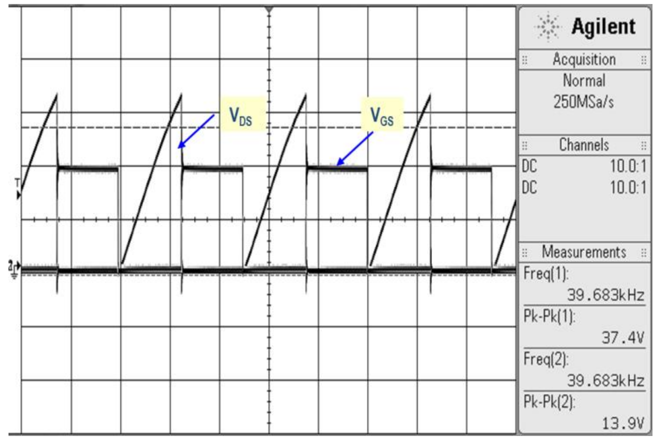

Figure 9: Experimental results of the ZVS Class E Converter

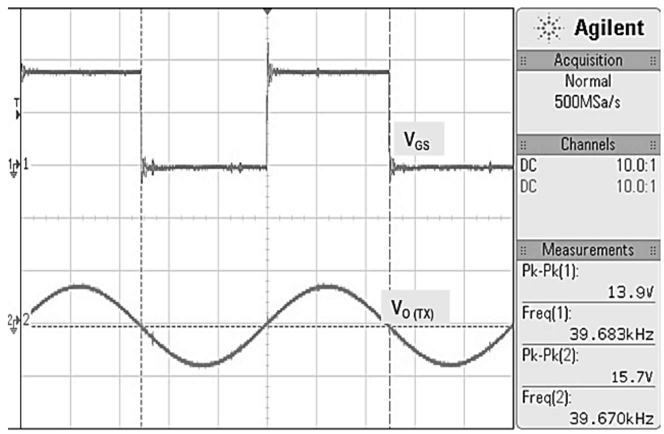

Figure 10: Waveform of the transmitted power by the transducer

The results in Figure 11 show the output power transferred at the receiver when the value of resistor was varied by different value at 20.0mm constant air gap. The highest power obtained was almost 4.21mW optimum, where the output load was 3.3kΩ output load. At this stage, the output voltage obtained was10.5Vpp and output current was 1.12 mA.

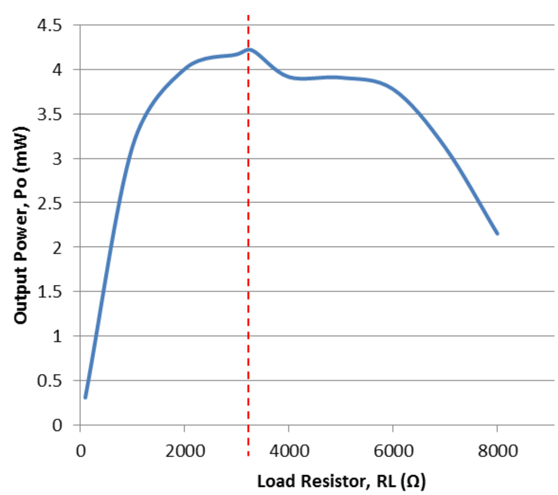

Figure 11: The optimal power transfer ratio obtained by the varying the load resistance value. The most optimum value is at 3.3kΩ load resistances where 4.21 mW power received.

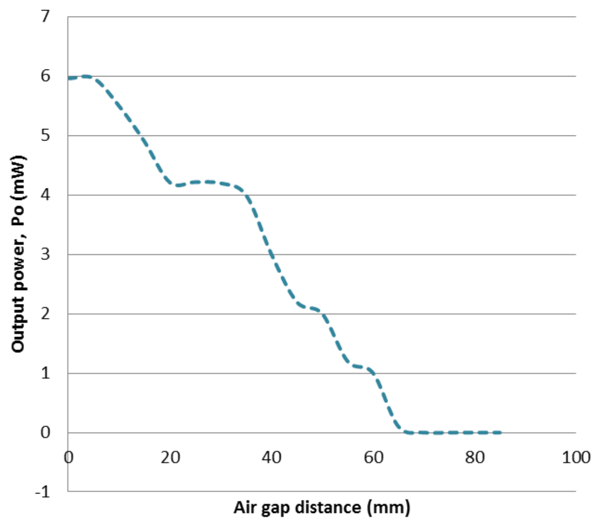

Figure 12: Air gap effect to the output power received at receiver

Figure 12 shows the output power when the air gap was varied at a constant alignment. The output power decreased when the air gap distance was increased to reach the limit, where the transmitting ultrasonic waves could not reach the receiver. The results also showed that the maximum distance an AET system through air using Class E converter that could be applied was 60.0 mm. This achievement was much better than the other CET methods, where the drawbacks were the distance between the transmitter and the receiver. AET system proves that it could transmit power over 3 times greater than the diameter of the transceiver.

IV. CONCLUSION

This paper has presented an analysis of the Class E converter applied to an AET system through air medium. The performance of the system has been analyzed, where there are some factors that affect the efficiency. The PWM Class E converter is more stable and suitable to apply in AET system compared to push-pull converter. In addition, to increase the efficiency, AET system needs a focus beam with a constant alignment that operates with optimum frequency to optimize the energy transfer capabilities. The AET systems are able to transfer 4.21mW power at 20.0 mm air gap with constant alignment. Even in instances where the achievement is quite low, it is still higher than the previous development in [13]. This result has proven that the AET system works well with this power converter design. The future direction of the research is to implement the multiple transceiver using this kind of power converter to increase the input transmit power.

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