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Development of Class D Inverter for Acoustics Energy Transfer Implantable Devices

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ABSTRACT

The working principle of half-bridge Class D Parallel-Resonant Inverter (PRI) as power amplifier is presented in this paper. Simulation of the model is carried out using Proteus. In order to verify the simulation results, an experimental verification is done. This inverter used to excite PZT transducers at suggested resonant frequency of 416 kHz with power level transferred through Acoustics Energy Transfer (AET) concept at about 80 mW. As experimental outcome result, the system managed to transfer energy of 66 mW to the receiver side.

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1. INTRODUCTION

Implantable medical devices are being added to the market every year enormously in order to assist and serve a better health care of human being. Those devices are designed to be inserted into the patient's body for monitoring and/or therapeutic purposes such as pacemakers, defibrillators, heart-assists devices or implanted insulin pumps. All of these devices require power supply in order to function effectively. Majority of modern implanted devices consume low power (in range of hundreds of mW) [1], but then still required up to 10 W of power in some specific cases. The continuous supply of stable and reliable power sources is the key problem in developing those implantable devices [1], [2], [3] and [4]. Recently, various technologies for powering implantable devices have been developed whether with a connection cable to the device or based on penetration of energy through the tissue without any connections or wirelessly. The history of implantable devices was comprehensively elaborated in [5]. Meanwhile in [1] - [4] and [6] indicated that the current trend of powering implantable devices are toward to wirelessly or telemetry method. This is due to the needs of reducing or eliminating the tedious processes of changing the batteries that may occur such as trauma to the patient due to open surgery.

2. ACOUSTICS ENERGY TRANSFER (AET) CONCEPT

Impracticality the use of battery and physically wired for the implantable devices inspires this research to be carried out. The application of ultrasound or vibration as the medium of energy transmission especially in situations where no EM fields are allowed, and high directionality of the power transfer in combination with small system dimensions is required [7] and [8]. Currently, one of the Wireless Power

Transfer (WPT) technologies known as the Inductive Power Transfer (IPT) gained a huge attention from the researcher, with recent publications on system delivering energy up to 2 m at high efficiency [9],[10] and [11], but due to the magnetic coupling technique, IPT is not suitable for transferring the power across metal objects and can cause large eddy current losses [12], [13] and [14]. In order to overcome these limitations, another technologies of WPT is invented, namely Capacitive Power Transfer (CPT) is used since an electric field can penetrate through any metal shielding environment. The CPT not only can transmit through metal and shielded body, but also has good anti-interference ability of magnetic field [8], [13], [14], and [15]. However, till recent, CET systems have only been used for very low power delivery applications [8], [12], [14] and [15]. CPT is used far less often due to the limitation of distance that can be crossed with it. This is a direct consequence of the inverse proportionality of the capacitance with the distance, requiring high voltages and frequencies for the transfer of a certain amount of power.

Another principle for WPT is far-field EM or microwave energy transfer is seldom used. Instead of the nonradiative used in inductive and capacitive cases, a radiative EM field functions is used as the energy transfer medium. Rectification of these high-frequency waves at the pick-up unit can be achieved at high efficiency of 80% - 90% [16]. Generation of the microwaves, on the other hand, is much more difficult, particularly when a solid-state RF generator is used. Optical energy transmission uses same principle as far-field EM and has low efficiency whereby 40% and 50% of energy is lost [13] and [14]. All the previous described technologies drive us to implement Acoustics Energy Transfer (AET) as the medium of energy transmission in this research.

2.1. Acoustic Energy Transfer System

Considered as a new approach of transferring energy, AET uses acoustic waves to carry energy through the propagation mediums towards an implanted receiving transducer that positioned within the radiation lobe of the transmitting transducer. Figure 1 illustrates the basic structure of AET that consists of a transmitting side and receiving side. At the transmitter side, the power amplifier produces an ac output waveform from a dc voltage supply. A resonant circuit that consists of L-C network generates signal from particular frequency and as input to the transmitting transducer. The transmitting transducer will converts electrical signal into a pressure wave that propagate through a medium. A receiving transducer is positioned at a point along the path of the sound wave for the inverse process of converting the motion caused by the sound wave into electrical energy. A rectifier and a capacitor provide a usable steady dc voltage that drives a load. The medium can be anything ranging from air to human tissue or a solid wall; in principle, any material that will propagate a pressure wave can be applied to act as a transmission medium.

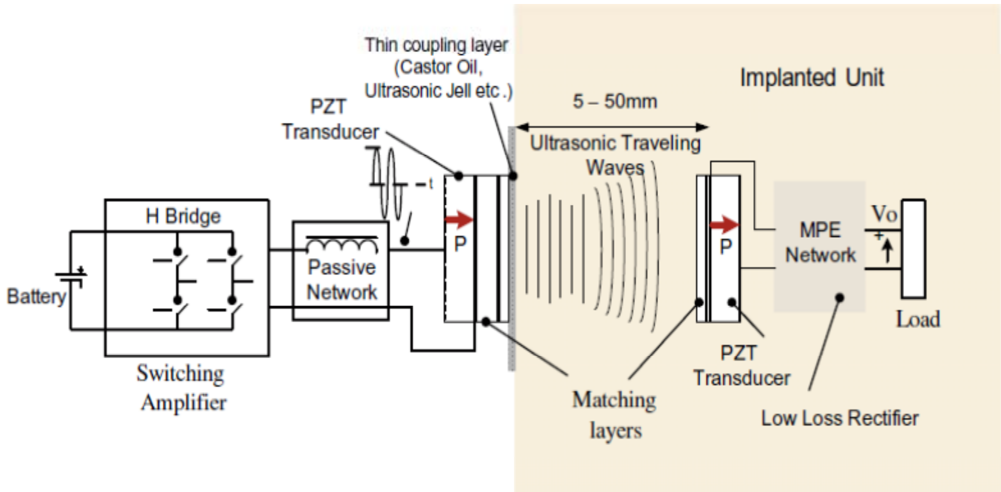

Figure 1. Acoustics Energy Transfer System [4]

2.2. Power Amplifier Circuit

The power conditioning phase of an AET system is one of the important aspects that determine the overall efficiency of an AET. The most desirable feature is to drive the device at the exact operating frequency without exciting harmonic modes at the transmitter side. On the receiver implanted unit, the circuit should interface with the transducer so as to extract maximum power. The power conditioning circuit on the both sides must have efficiency greater than 80% as they affect the overall efficiency of the energy transfer. This paper will focus on performance of the transmitter power amplifier circuit, namely Class D Parallel-Resonant Inverter to produce a frequency of 416 kHz used to excite the PZT transducer so that the proposed 80 mW power can be transferred to the receiver implanted unit.

The Class D inverter is one of the high-frequency and high-efficiency resonant power sources, which has been applied to dc/dc resonant converters, radio transmitters, and electronic ballasts for fluorescent lamps [17], [18], [19] and [20]. Its high dc/ac power conversion efficiency is achieved by the zero-current switching (ZCS), which enables its operation at frequency of several hundred kilohertz [21]. Furthermore, this resonant inverter with sinusoidal waveforms achieves low switching losses due to the phase displacement between the voltage and current through the transistors [22]. The full working of Class D that used in the research is extensively explained in [23], In order to design the transmitter side, which focuses on half-bridge Class D parallel-resonance inverter, the theoretical value of each components is obtained through calculation. The equations related were explained in details in [23]. The calculation based on the standard circuit shown in Figure 2.

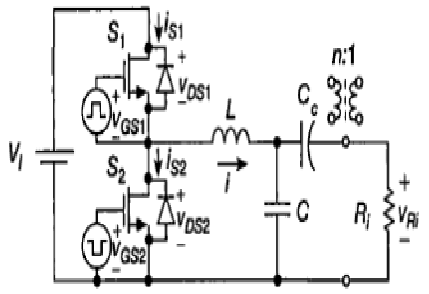

Figure 2. The standard model of half-bridge Class D parallel resonant inverter[23]

Assume a typical value of the inverter efficiency η_I = 95%, some relevant equations as below:
The DC supply power of the circuit is

$$P_1 = \frac{P_{Ri}}{\eta_1} \text{ W} \tag{1}$$

Thus, the DC supply current is

$$I_1 = \frac{P_1}{V_1} \quad \text{A} \tag{2}$$

Assuming $f = f_r$ = 416 kHz at full power, the corner frequency is

$$f_o = \frac{f_r}{\sqrt{1 - \frac{1}{Q_L}}} \quad \text{Hz} \tag{3}$$

The AC load resistance

$$R_i = \frac{V_{Ri}^2}{P_{Ri}} = \frac{2V_1^2 \eta_I^2}{\pi^2 P_{Ri}\left(\left[1-\left(\frac{\omega}{\omega_o}\right)^2\right]^2 + \left[\frac{1}{Q_L}\left(\frac{\omega}{\omega_O}\right)\right]^2\right)} \quad \Omega \tag{4}$$

The characteristic impedance of the circuit can be obtained as

$$Z_o = \frac{R_i}{Q_L} \quad \Omega \tag{5}$$

Thus, the elements of resonant circuits are

$$L = \frac{Z_o}{\omega_o} \text{ Henry} \tag{6}$$

and

$$C = \frac{1}{\omega_o Z_0} \text{ Farad} \tag{7}$$

The maximum value of the switch peak current is

$$I_{m(max)} = I_{SM(max)} = \frac{2V_1\sqrt{Q^2L+1}}{\pi Z_o} \quad \text{A} \tag{8}$$

The voltage stresses on the resonant components are

$$V_{Cm(max)} = \frac{2V_1Q_L}{\pi} V\ ,\ \ V_{Lm(max)} = \frac{2V_1\sqrt{Q^2L+1}}{\pi} V \tag{9}$$

As the load is in parallel with resonant capacitor as shown in Figure 2, the output voltage at the load can be obtained as

$$V_O = V_{Cm} \text{ V} \tag{10}$$

As the aim of this paper is to produce output power at *Ri*, the equation below use to calculate the output power required.

$$P_{Ri} = \frac{V_{orms}^2}{R_i} \quad \text{W} \tag{11}$$

3. RESULTS AND ANALYSIS

3.1. Simulation of the Class D Operation with Proteus

In order to verify the operation of the half-bridge Class D parallel resonant inverter and make the analysis of operation performance more convenient, the parameters of the inverter is calculated based on formula described in [23] and simulated using Proteus. Simulation model is shown as in Figure 3. The main data used in the simulation are as in Table 1.

Table 1. The calculated parameters value for inverter

Inverter Parameters	Symbol	Value
Dc Supply Power	P_1	84.21 mW
Dc Supply Current	I_1	23.4 mA
Corner frequency	f_o	453.89 kHz
AC Load Resistance	R_i	185.28 Ω
Impedance	Z_o	74.11 Ω
Resonant Inductor	L	25.9 µH
Resonant Capacitor	C	4.73 nF
Switch Peak Current	$I_{m(max)}$	83.2 mA
Voltage at resonant Capacitor	$V_{Cm(max)}$	5.73 V
Voltage at resonant Inductor	$V_{Lm(max)}$	6.17 V
Output power gained	P_{Ri}	88.6 mW

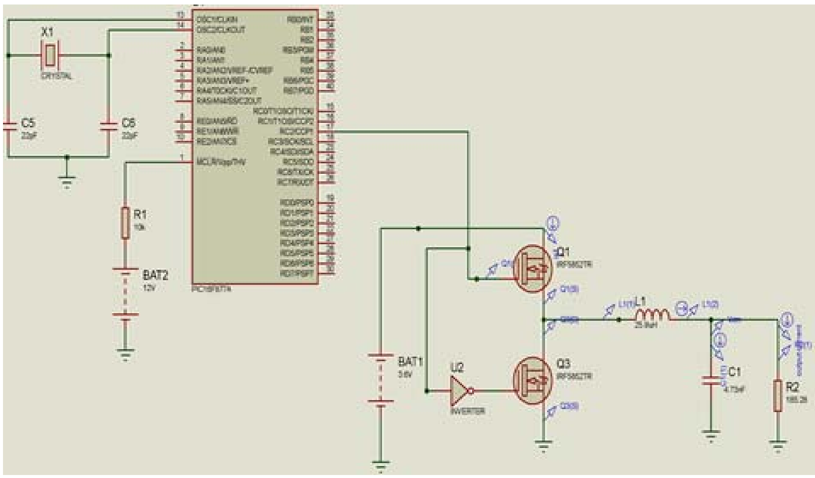

Figure 3. The simulation model of half-bridge Class D parallel resonant inverter

The Pulse Width Modulation (PWM) technique is chosen due to capabilities in the minimization of harmonics and switching losses in the inverter [24] and [25] that in turns will increase the efficiency of the inverter itself. On the other hand, PWM can be employed in order to obtain the required output voltage of the inverter [26].

The generation of PWM was done by using PIC16F877A with the coding simulation through mikroC PRO for PIC software. The generation of 5Vp square wave is produced by Pheriperal Interface Controller (PIC) with the resonant frequency of 416 kHz is successfully obtained and shown in Figure 4. This is the stable waveform that drives the turn-on and turn-off of the MOSFET IRF5852TR that is used as a switch in the design. The approach in using PIC as PWM generator makes the design process less complicated and simpler.

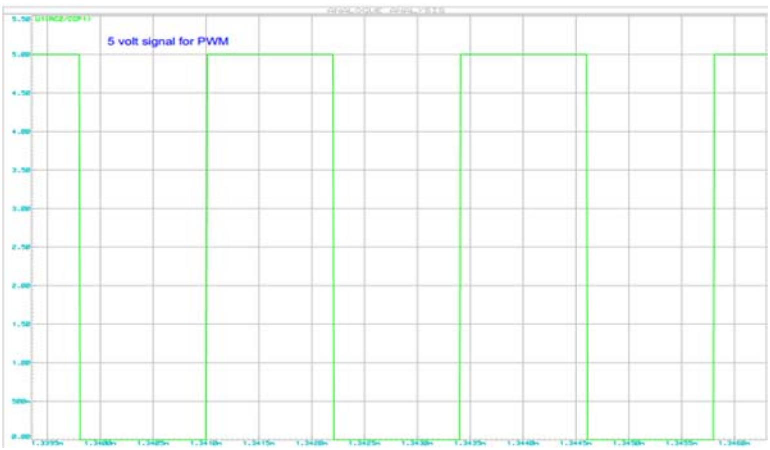

Figure 4. Simulation waveform of PWM

A 5Vp square wave input that drives the resonant circuit L-C-R_i is connected to the gate of S_1 meanwhile the inverted one is connected to the gate of S_2. The inversion is done in order to fulfill the out-of-phase condition between S_1 and S_2 and shown in Figure 5.

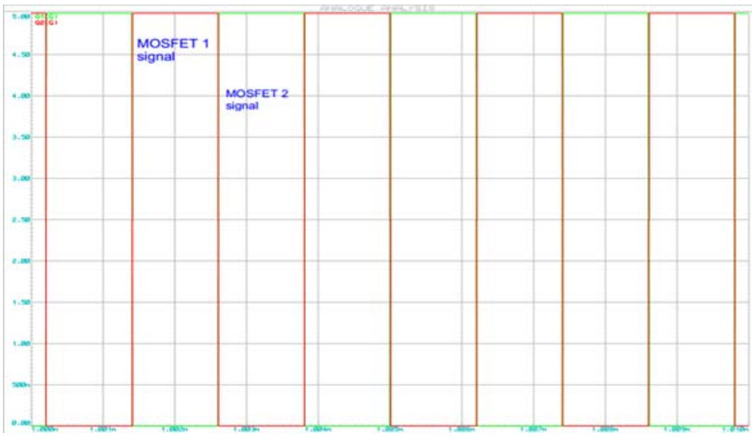

Figure 5. Simulation waveform for MOSFET gate signal

The output simulation waveform of the inverter expected to be pure sinusoidal and shown in Figure 6. As the switching frequency is 416 kHz, thus the cycle is 2.4 μS. From the graph, the simulated output power that is measured at the point of AC load resistor, R_i is V_o=V_{Cm}=5.6 V which is slightly different from the calculated value shown in Table 1. The difference is due to some parasitic resistance in the simulation software settings. Using equation $P_{Ri} = \frac{V_{orms}^2}{R_i}$, this design obtained 84.63 mW as output power compared to 88.6 mW as in the calculation.

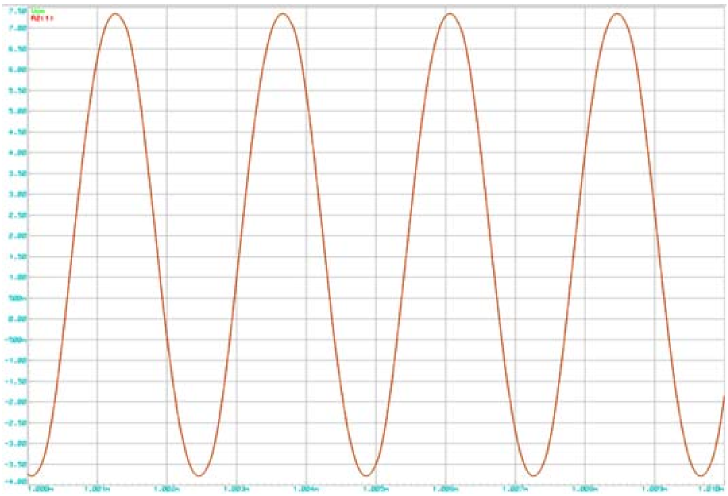

Figure 6. Simulation output waveform for inverter

3.2. Experiment and Analysis

Based on the simulation model as in Figure 2, an experimental setup is shown in Figure 7 with complete transmitting and receiving transducer sections. The PIC16F877A is used since the ability to generate PWM with the coding simulation through mikroC PRO for PIC software. The PZT transducers are applied as transmitting and receiving transducer in the AET system. In this experiment, the PZT transducers used manufactured by Multicomp with part number MCUSD11A400B11RS. The transducers are lossly coupled for this particular work. The power delivered can be affected by the medium of propagation and distance, rotational angle between the transducer. However, those scopes are not covered in this research.

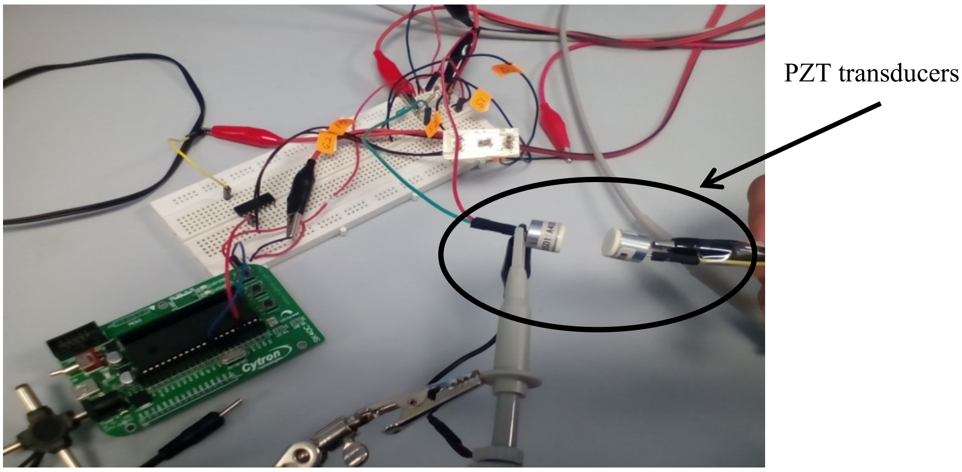

Figure 7. Experimental setup

The gate signal for MOSFET IRF5852TR is controlled by PWM signal as shown in Figure 8. There is a dead time in the waveform and can be effectively avoided by setting a guard period so that the MOSFET will turn on at the different time.

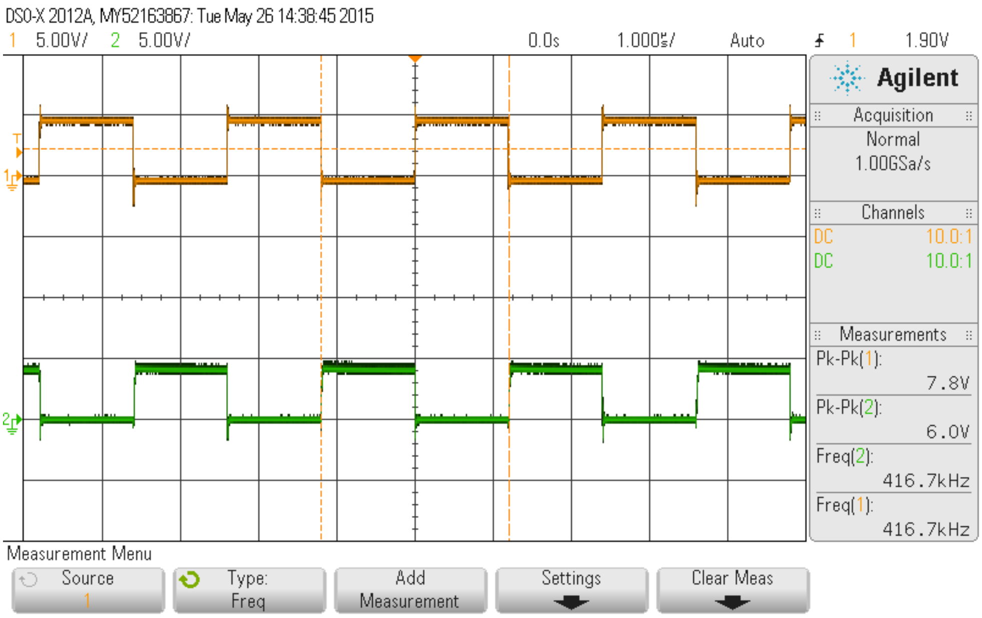

Figure 8. Gate signal for MOSFET

As the main objective of this research, the transferring power through acoustics technology for low power implantable devices is feasible and can be shown in Figure 9. The above waveform is measured at the transmitting transducer meanwhile the below waveform is measured at the receiving transducer. The system successfully maintained the switching frequency at 416 kHz as required. The output power through experimental setup is calculated using the same formula as in Section 3(a) and obtained as 66.11 mW at the transmitting tranducer. The performance efficiency of transmitter unit is 78.2% obtained by comparing the value of output power from transmitting transducer in the experiment (66.11 mW) to the simulation (84.63 mW). Meanwhile, the efficiency of transferred power is 53.1%, gained from comparing the output power at the receiving transducer to the transmitting transducer. The low efficiency of transferred power is due to the coupling technique and medium permeability effects as stated by [4], [7] and [27]. Those criterias are not taken into consideration while doing this research. Practically, it is essential to add an amplifier circuit at the receiver side in order to amplify the power according to the actual load requirement. The waveform at the transmitter and receiver side is not pure square and sinusoidal waveform respectively due to the presence of harmonics. This problem can be overcomed by introducing active filter that suitable with the inverter source topology as suggested in [26] in the next stage.

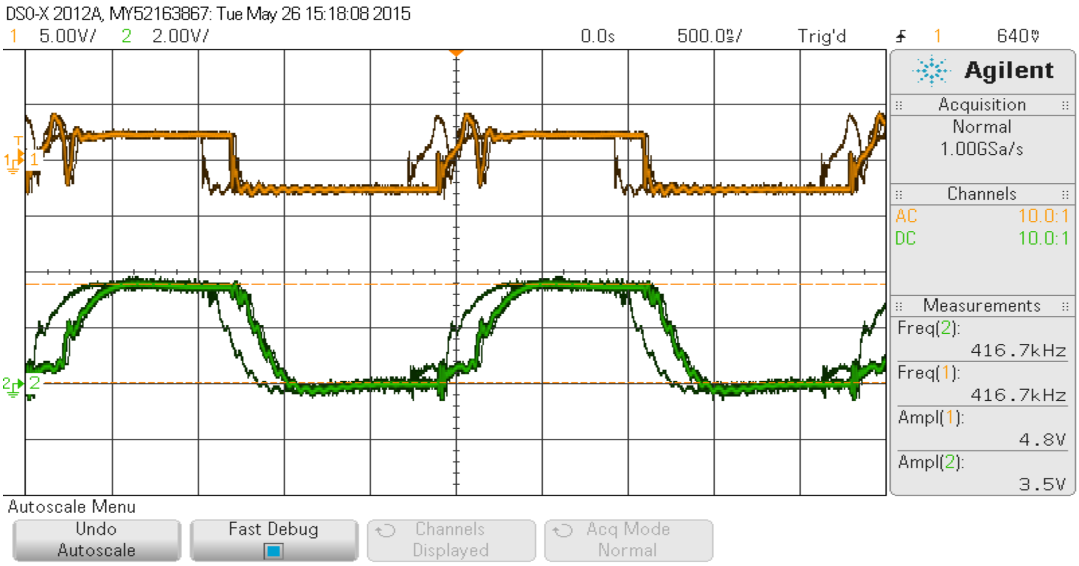

Figure 9. Power transfer waveforms

4. CONCLUSION

The main study in this research is to develop the Class D parallel resonant inverter as power amplifier in an AET system. The results obtained from calculated, simulated and experimented setup shown that the inverter can be used to excite the PZT transducers at the suggested resonant frequency of 416 kHz. It is feasible to transmit power wirelessly for low power implantable devices using an Acoustics Energy Transfer technology. The model developed is very useful for guiding the future AET system analysis and design. In the upcoming research for this particular work, the comparison study of using different materials such as through wall, metal and living tissues as a medium of propagation will be carried out.

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