Comparative Analysis of Inverters for Low-Power Acoustic-Based Energy Transfer System

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ABSTRACT

The growing demand for efficient and reliable energy transfer systems has driven research into innovative solutions for low-power applications. This thesis focuses on the comparison analysis of inverters for low power application acoustic based energy transfer system. An acoustic energy transfer system is one of promising technology for wireless energy transmission in constrained environments especially in metal environments. The research evaluates the performance of different inverter topologies which are Class E ZVS Inverter and Class D Half Bridge Resonant Inverter by considering key parameters such as efficiency, power transmission, and adaptability to acoustic wave energy systems. Calculation and simulation results from both inverters were compared and Class E ZVS inverter has been chosen for further with experimental because the performance efficiency of Class E produces 98.6% compared to Class D which is 98.04%. The Class E inverter managed to produce better efficiency, power transmission at 40kHz and 470-ohm resistor as an inverter load. The experimental hardware of Class E inverter produces 64.2% as efficiency, as it undergoes tuning process where the tuning processes is critical to optimize the functionality of resonant circuits, ensuring they achieve the best and highest efficiency ii at transmitter. So, the power transmitted to the receiver have some drops due to their internal resistance, and components factor. The receiver will receive 7.36 V at 1cm distance while the target for this project is transmitting to 3cm distance with 6.43V. This shows that the goal of the project to transmit power to the receiving unit has been successfully implemented and it contributes to the progress in wireless power transmission technology.

INTRODUCTION

Contactless energy transfer, also known as wireless power transfer (WPT), transfers electricity from a power source to a load without the need for physical connections or connectors. The potential applications of this innovative energy transfer methods are gaining popularity in areas such as consumer electronics, electric automobiles, medical gadgets, and industrial automation. WPT is an innovative way to power electric devices, decreasing the need for batteries [1][2]. Researchers have extensively explored and developed contactless energy transfer devices. Acoustics is a contemporary wireless energy transmission technology that uses vibration or ultrasonic waves. A relatively recent technique for transmitting energy wirelessly that takes use of vibration, or ultrasonic [3][4] waves is called Acoustic Energy Transfer, or AET. AET is a generally new technology that transmits energy wirelessly using sound waves rather than touch. These technologies include those used today for optical coupling energy transfer (OPT),capacitive power transfer (CPT), and inductive power transfer (IPT) [2][5]. Any frequency higher than around 20 kHz, which is beyond human hearing, is referred to as ultrasonic. The AET system works based on wave propagation of ultrasound, which its operating

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frequency is from 20 kHz to 100 kHz using a couple of ultrasonic transducers [5][6]. Ultrasonic transducers also basically act as an energy transferring device as it will be used in transmitter and receiver for the AET system. The primary transducer transforms electrical energy into a pressure or acoustic wave. It generates waves in the form of mechanical energy and propagates through a medium. AET has promising applications in various fields, including medical implants, underwater communication, and sensor networks.

LITERATURE REVIEW

Wireless Power Transfer Transmission (WPT)

There are many advantages that wireless power transmission may offer make it appeal [2][5]. WPT is a technology that has seen significant advancements and is used in various applications ranging from consumer electronics to industrial equipment and even electric vehicles. With ongoing research and development, WPT technology will likely evolve and become more efficient, reliable, and versatile. There are a few types of WPT such as inductive coupling, capacitive coupling, microwave, and acoustic energy transfer [7]. Fig. 1 below shows the block diagram of wireless power transfer transmission system.

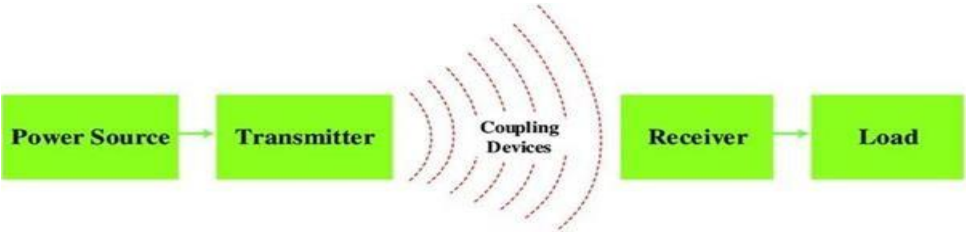

Fig. 1 The wireless power transfer transmission

IPT and CPT are the most common coupled WPT systems can offer up to MW. A magnetic field is used in electromagnetic induction to transfer energy between a transmitter and a receiver coil. Energy is transferred by an electromotive force (EMF) that is induced in the reception coil by an alternating current in the transmitter coil. Microwave power transmission transfers energy via the atmosphere using microwaves. Microwaves are created by a transmitter and then beamed to a receiver, which transforms them back into electrical energy. As for the application, long-distance power transfer, including that from space-based solar power systems, is the subject of investigation. Sound waves created by a transmitter are captured by a receiver and converted back into electrical energy. This acoustic energy transfer is specially used for medical services.

Acoustic Energy Transfer (AET)

Acoustic energy transfer (AET) is an original method of wireless energy transmission that makes use of vibration or ultrasonic vibrations. AET is still in its early phases and hasn't made much progress in compared to its competition. It can transmit energy via a metal medium while propagating through vibration, whereas inductive power transfer (IPT) cannot [6][8]. Significant losses occur in the metal due to eddy currents and the shielding effect of the metal walls, which stop electromagnetic fields from coupling. An AET system, on the other hand, would not have these problems since there are no electromagnetic fields present. The presence of electromagnetic fields in biological applications causes adverse side effects which are governed by medical regulations. Due to the lack of electromagnetic fields, AET is more practicable for use in biomedical applications and is used in a miniaturized scale [8][9]. Fig. 2 is the acoustic energy transfer system block diagram.

specific frequency to transmit energy through ultrasonic transducer. The type of power converter design should consider the system requirement. In AET system, the design of the power converter should involve the capability of the power converter to drive the primary transducer in a sinusoidal wave until it can transfer sufficient power to the secondary load. The need of matching resonance frequency between the transducer and power supply gives an intention in this thesis to design a suitable power converter for the system. The power converter should convert from DC to AC so that the output of the primary to generate signals. Other than that, the power converter also needs to be designed with minimal losses so that the efficiency of the system can be

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optimized. The recent development in AET uses different types of power converter such as in [15] applied DC power and microcontroller to generate pulse frequency. Meanwhile, the resonance frequency is generated from a signal generator and amplified into the transmitter device.

There are two available circuit methods to design a converter circuit for WPT system, which are the linear amplifier and the switch mode power converter. The example of linear amplifier circuits is of Class A, Class B, Class AB and Class C; while the switch mode power inverter is of Class D, Class E. Nevertheless, in terms of providing lower switching losses, the switch mode power converter is the best choice [16]. Therefore, there are several types of power converter that are possible to be used in developing the CET system: push-pull, Class D, Class E and Class F power converter. The following sub- section has briefly introduced them.

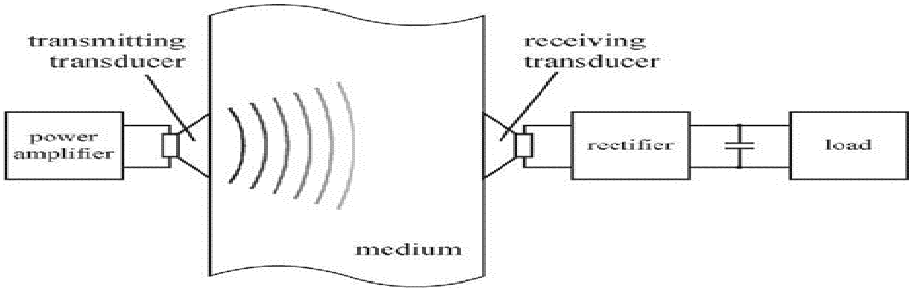

Fig. 2 The acoustic energy transfer block diagram

METHODOLOGY

Flowchart

At the primary side, power converters are used to supply the main transducer with the necessary quantity of power [3][6]. Primary transducer will transform to acoustic wave and travels through the medium [3][6]. This is because the ultrasonic air transducer converts an electrical signal to sound wave. The receiving transducer convert it back to usable electrical power. Most importantly, it employs sound or vibration as a channel for energy propagation. Ongoing advancements in transducer technology and system design may expand the use of AET in the future.

Power Converter

Power converter gives an important role to the AET system since it drives sufficient voltage and current with The flowchart in Fig. 3 describes the working process and steps that need to be followed in order to produce the best inverter and analyze the performance of the developed inverter.

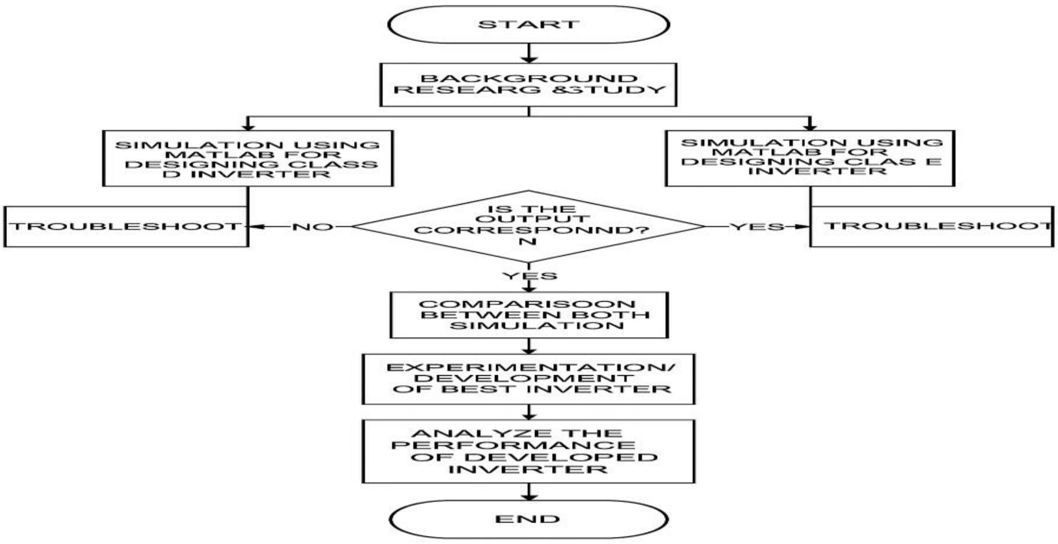

Fig. 3 The project flowchart

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The steps start with background research and study, design and simulation of the circuit for Class D inverter and Class E inverter. Simulation for both parts would be challenging as the circuit construction, component value and graph has to be analyzed and compared to each other. Which classes produces better power efficiency and better performance. Both classes will be troubleshooting once there are error or problems. Once settled, comparing both simulations, will be proceed with the one which better in terms of performance, and power efficiency. The experiment for hardware will be proceed with the better classes. After completion of the experiment, we can analyze the performance of the developed inverter. Lastly, the documentation has to be done, as all the project workflow is done and completed by following the flowchart progress.

Simulation Class D inverter

Fig. 4 below is a Simulink model of a Class D inverter circuit, created in MATLAB that based on the calculated values as in Table 1. Input voltage provides the DC input voltage to the Class D inverter circuit. Two MOSFETs are used in the circuit as electronic switches. They alternate between ON and OFF states to create a high-frequency pulse-width modulated (PWM) waveform. PWM generator generates a pulse-width modulated signal to drive the gates of the MOSFETs. The inductor helps to reduce current ripples and stabilize the current flow in the circuit while the capacitor smooths the output voltage by filtering high- frequency noise and providing a stable DC component. Resistor is the component where the filtered output power is delivered.

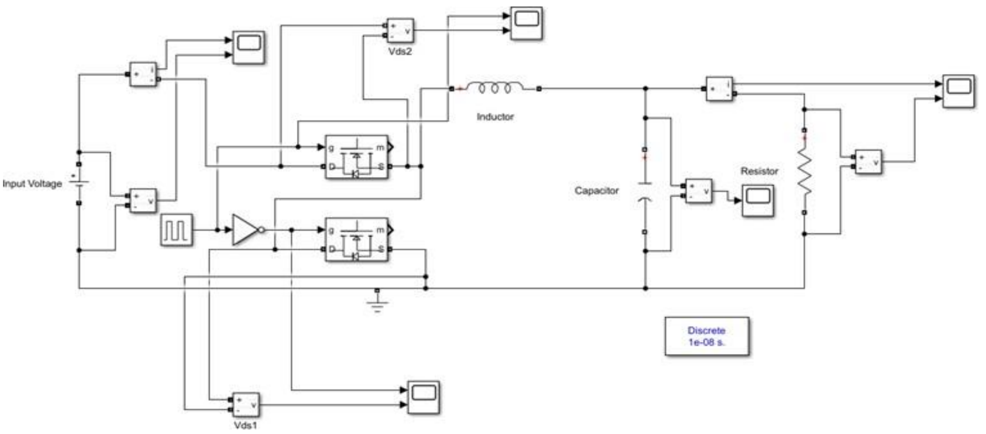

Fig. 4 Design of Class D inverter in MATLAB software

Table 1 Calculated value for designing optimum operation of Class D inverter.

$Maximum\ \ current, Im$(max)	43.80A
$Maximum\ capacitor\ voltage, Vcm$(max)	43.36V
$Maximum\ \ inductor\ voltage, Vlm$(max)	43.80V
$Output\ voltage, Vo$	43.36V

Simulation Class E inverter

The Simulink program in MATLAB simulation software could provide the designed process where the circuit was constructed and determined the exact value of component that needed to build the ideal circuit. Next, the simulation of the circuit could be done set up the correct setting of Simulink such as runtime of the simulation, power supply, frequency, duty cycle and others. Then, the measurement of performance obtained through scopes.

According to Fig. 5, the Class E circuit design in MATLAB software acts as a converter circuit which consists of choke inductor (L_f) and shunt capacitor (C_p). The choke inductor (L_f) is to reduce current ripple through the circuit while shunt capacitor (C_p) is to shape and modify the drain current and voltage waveform [10]. Class E circuit also consists of a series capacitor C_{series} and a series inductor L_{series} which the components used as a filter to reduce the effects of harmonic in waveform. Class E has many advantages over the other converter because it is simple passive purely and working operation has no overlap between current and voltage. The calculated values for Class E resonant inverter's components are tabulated in Table 2.

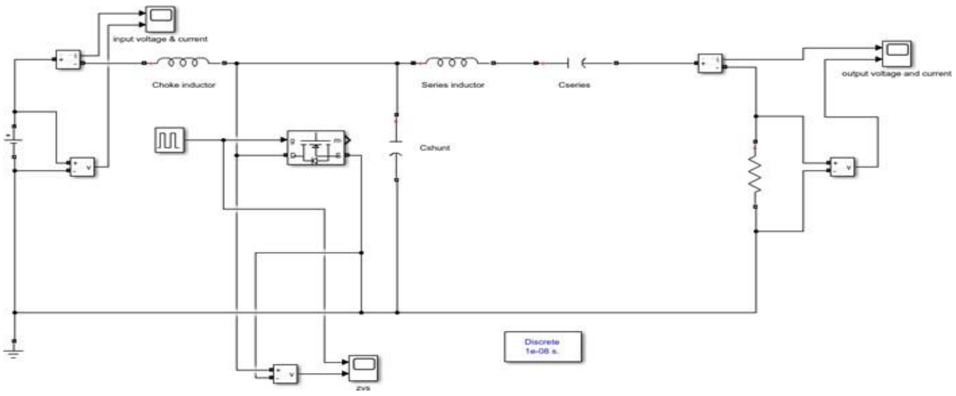

Fig. 5 Design of Class E inverter in MATLAB software

Table 2 Calculated value for designing optimum operation of Class E resonant inverter.

Inverter Parameters	Calculated Values
Input power, $P1$	$2.1W$
Input current, $I1$	$0.1A$
Operating frequency, $f0$	$40.41kHz$
Impedance, $Z0$	67.14Ω
Capacitor, C	$58.66nF$
Inductor, L	$0.26mH$

Inverter Parameters	Calculated Values
Voltage input, VDD	$40.36V$
Shunt Capacitor, $Cshunt$	$1.55nF$
Series Capacitor, $Cseries$	$1.45nF$
Amplitude of output voltage, Vrm	$22.61V$
Power Input, Pin	$2.00W$
Series Inductor, $Lseries$	$13mH$
Choke Inductor, $Lchoke$	$81mH$
Input current, I	$0.0495A$

RESULT

Analysis Between Class E and Class D inverter

The range and the optimum for input power, output power and efficiency for both Class E and Class D can be analyzed as in Fig. 6, Fig. 7 and Fig. 8.

Input Power, Pin (W)		
Resistor, Ω	Class E	Class D
50	0.62	0.69
100	1.14	0.75
200	1.56	0.98
300	1.74	1.36
400	1.89	1.75
420	1.97	1.83
470	2.06	2.04
500	2.08	2.14
600	2.01	2.52
700	1.94	2.88

Fig. 6 Analysis of Input Power Between Class E and Class D inverter

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Output Power, Pout (W)		
Resistor, Ω	Class E	Class D
50	0.53	0.69
100	0.98	0.75
200	1.36	0.98
300	1.58	1.35
400	1.77	1.7
420	1.92	1.81
470	2.03	2
500	2.02	2.12
600	1.9	2.48
700	1.83	2.83

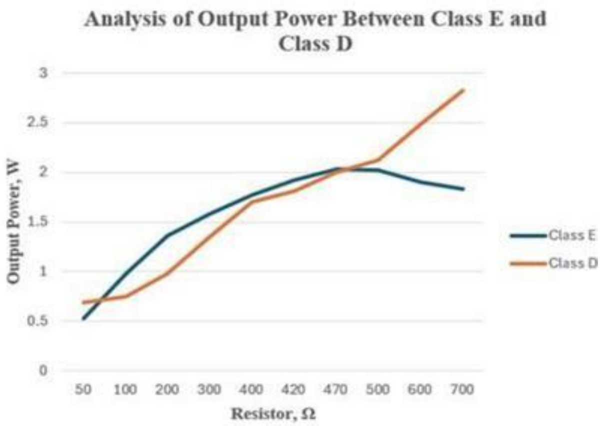

Fig. 7 Analysis of Output Power Between Class E and Class D inverter

Efficiency, η		
Resistor, Ω	Class E	Class D
50	86%	100%
100	86%	100%
200	88%	100%
300	91%	99%
400	94%	99%
420	97%	99%
470	99%	98%
500	97%	99%
600	95%	98%
700	94%	98%

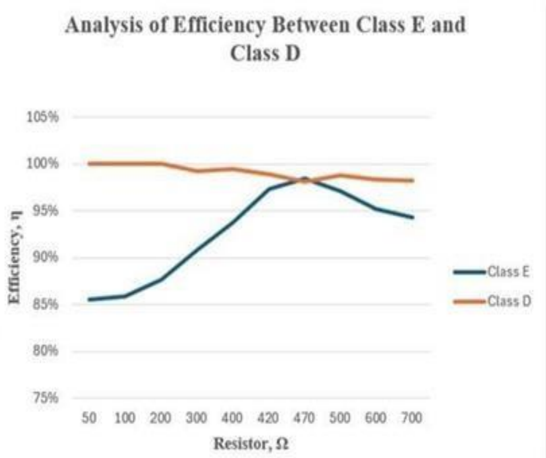

Fig. 8 Analysis of Efficiency Between Class E and Class D inverter

As to proceed with the hardware and which one to be selected, Class E resonant inverter will be chosen compared to Class D resonant inverter as the three main reasons stated below:

Higher Efficiency

Class E inverters achieve high efficiency by operating with zero voltage switching ZVS, which minimizes switching losses. In contrast, Class D inverters may experience higher switching losses due to hard switching, especially at high frequencies [13].

Simpler Circuitry

Class E inverters require fewer components, as their design eliminates the need for additional snubber or resonant circuits often required in Class D inverters designs to manage switching stresses [14].

Better Suitability for High-Frequency Operation

Class E resonant inverters are optimized for high- frequency operation due to their reduced switching losses and effective management of parasitic effects, which can degrade Class D inverter performance [15].

These are the reasons why the hardware has been chosen with the Class E resonant inverter compared to Class D resonant inverter.

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Experimental Hardware for Class E inverter

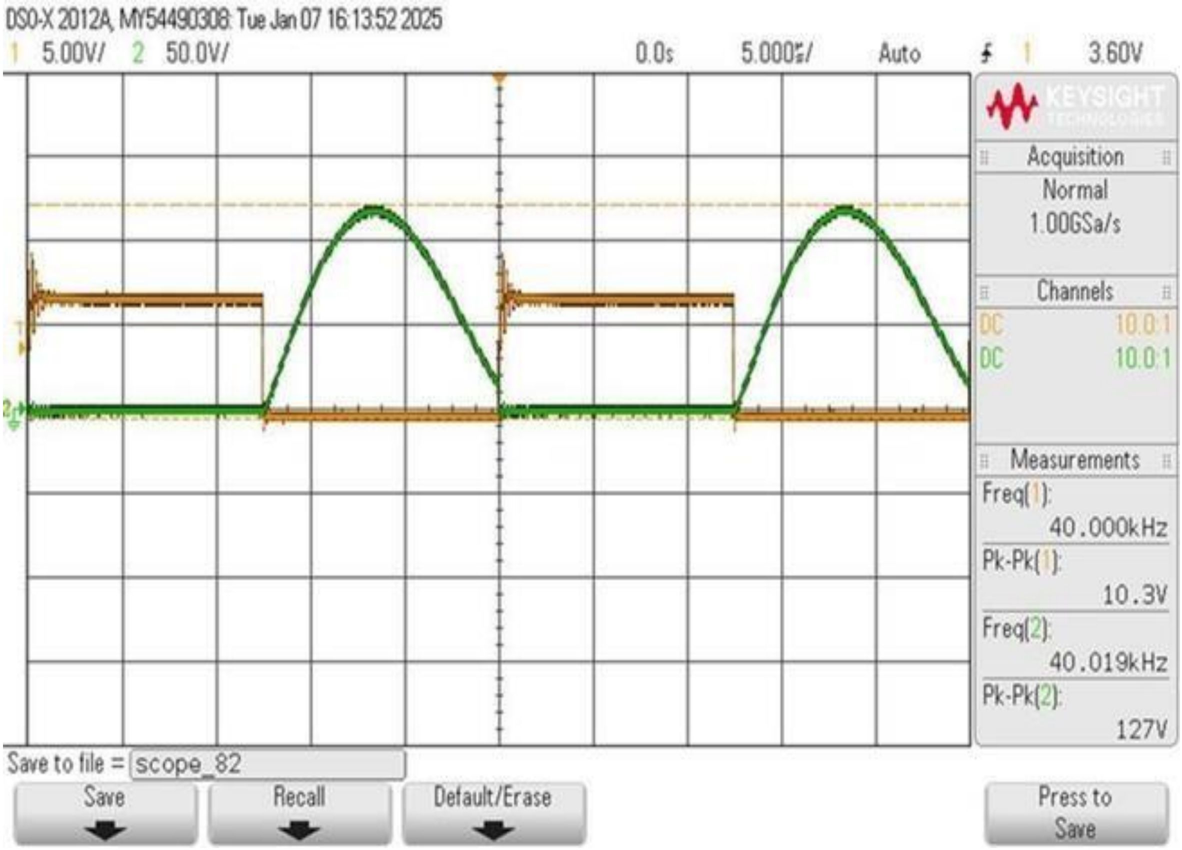

Fig. 9 Initial condition for Class E inverter

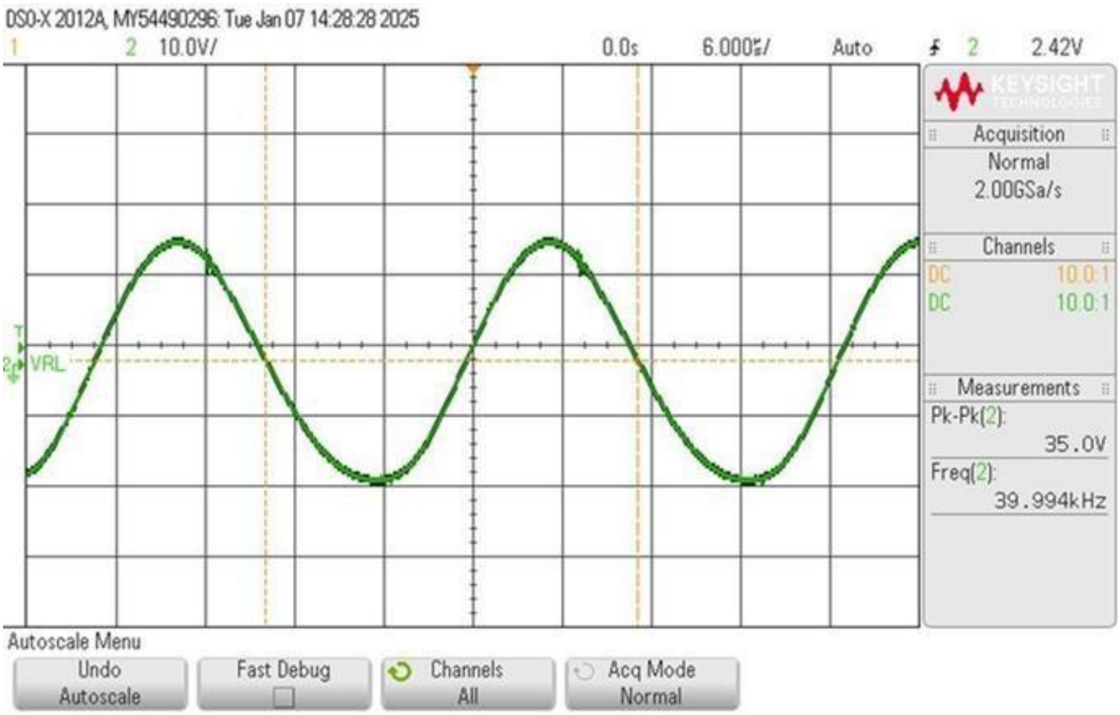

Fig. 10 Output waveform for the initial condition Class E inverter

Based on Fig. 9 and Fig. 10 the value for the V_{ds} is 127 V, output waveform is 35 V and the efficiency is very high which is 74.5 %. But the input power and output power are very low at 0.443 W and 0.33 W where it is not achievable to 2 W output power. So, it requires a tuning process to meet the best and optimum output power, efficiency and the V_{ds} graph.

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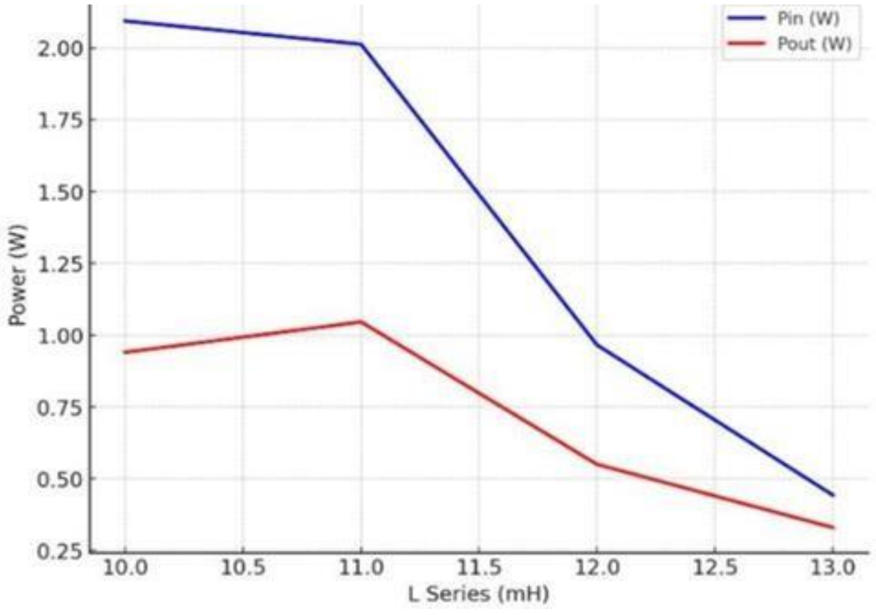

Fig. 11 L_{series} vs Power

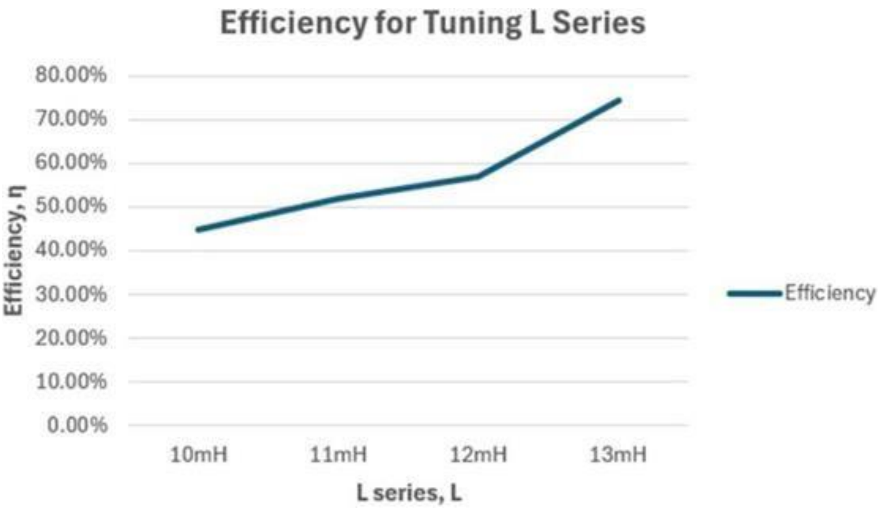

Fig. 12 Ls_{eries} vs Power

Based on Fig. 11 and Fig. 12 the efficiency increases but absolute power levels tend to drop as the Lseries value in this state is increased. This suggests that there is an ideal level at which trade-offs are possible, however they change depending on the system's needs. A lower inductance value could be recommended in cases where the greatest output power is the most crucial consideration. Higher inductance values may be chosen in applications where efficiency is more crucial.

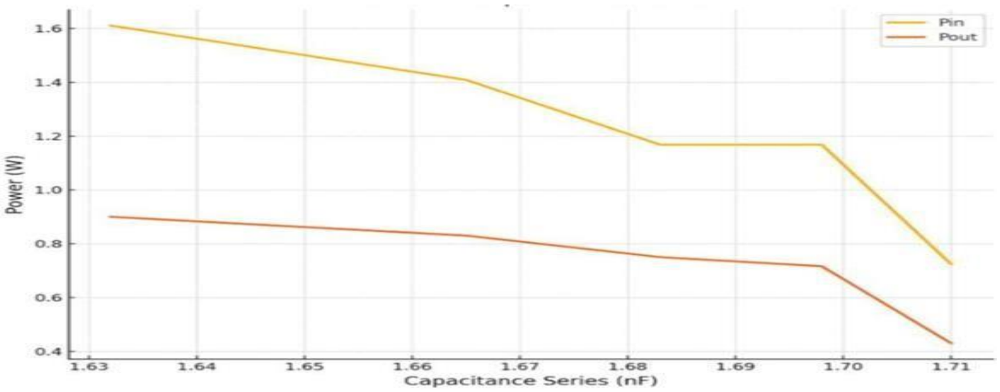

Fig. 13 Tuning of C_{series} vs Output Power

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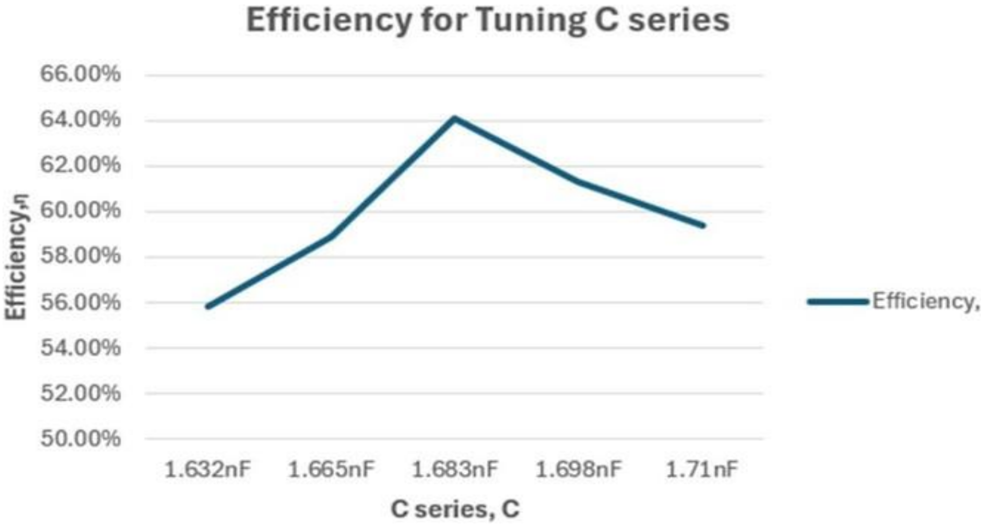

Fig. 14 **Cs**eries vs Efficiency

By referring to Fig. 13 and Fig. 14 the system appears to have a capacitance value of 1.683 nF. Any variation from this number results in a reduction in efficiency. The system's capacity is not eliminated by the efficiency drop brought on by the capacitance decreasing during rapid power fluctuations, but it is less effective. Therefore, it may be said that the working capacitance point should 1.683 nF as feasible to achieve the greatest efficiency.

Referring to Fig.15 and Fig. 16 in this system, increasing the C_{shunt} value leads to increased efficiency but lower absolute power levels (both input and output). Consequently, efficiency and power production are traded off. A smaller C_{shunt} value would be desirable if increasing output power is the main objective. A larger C_{shunt} value needs to be used if efficiency optimization is the top concern but the main certain is the efficiency, higher input and output power which is nearer to 2W and the V_{ds} graph is not interrupting or crossover the V_{ds} graph.

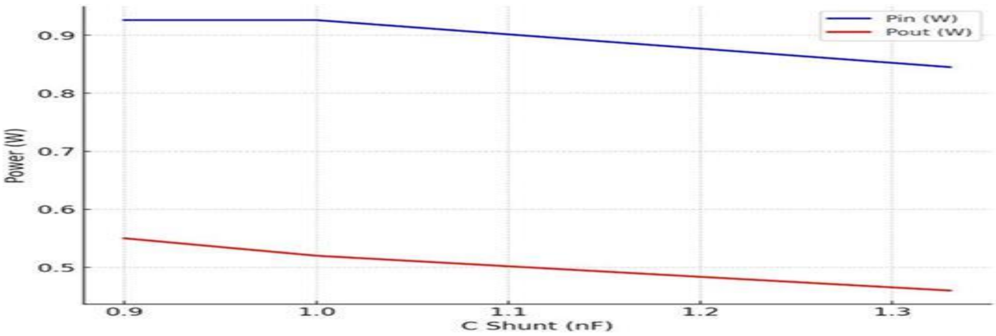

Fig.15 **C_{shunt}** vs Power

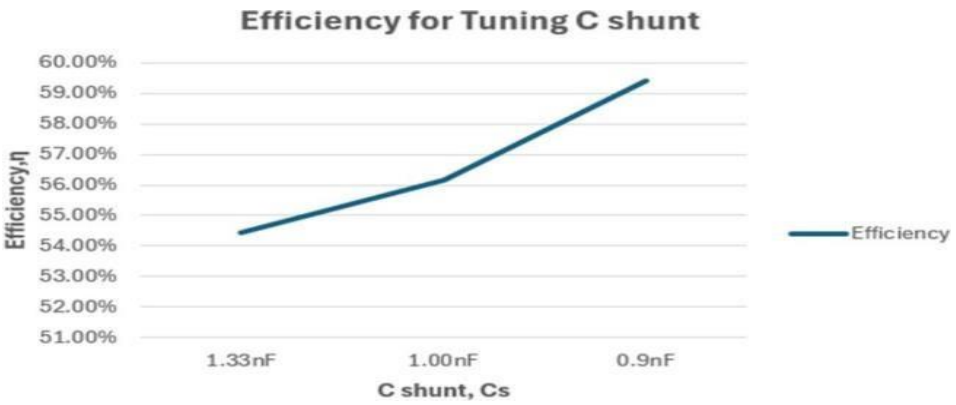

Fig. 16 **C_{shunt}** vs Efficiency

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So, the best efficiency, output power, and V_{ds} graph that could be produced is as in Table 3. where 3rd tuning is the best as it produces 64.2% where only tuning for L_{series} and C_{series} needed to achieve high output power. This is the maximum efficiency that can be gain from the hardware part.

All the comparison for Class E which are calculation, simulation and experimental will be classified and tabulated in the Table 3 below.

Table 3 Comparison between Calculation, Simulation and Experimental for Class E

Measurement	**Calculation**	**Simulation**	**Experimental**
P_{in}	2W	2.06W	1.15W
P_{out}	2W	2.03W	0.75W
V_{in}	40.36V	40.36V	40.31V
V_{out}	30.65V	30.9V	53.1V
I_{in}	0.0495A	0.05A	0.029A
I_{out}	0.065A	0.067A	0.04A
V_{gs}	-	10V	8.8V
V_{ds}	-	158.5V	129V
Efficiency	100%	98.6%	64.2%

Based on Table 3 above, the comparison shows significant variations between the experimental and theoretical (calculation and simulation) outcomes. The experimental implementation has significantly lower power output and efficiency due to significant losses. Besides, due to internal losses of the components itself, type of components selection and the circuit itself my affect the efficiency and output power. Differences in V_{out}, I_{in}, I_{out}, V_{gs} and V_{ds} indicate places where the theoretical models and the physical circuit vary because it shows practical constraints and losses that are not always considered in theoretical analysis, This study emphasis the significance of experimental validation in engineering design.

Transmitter and receiver part

Transmitter will transmit power via piezoelectric transducer and the receiver will receive the via piezoelectric transducer. The evaluation of the distance versus voltage is in Fig. 17 below.

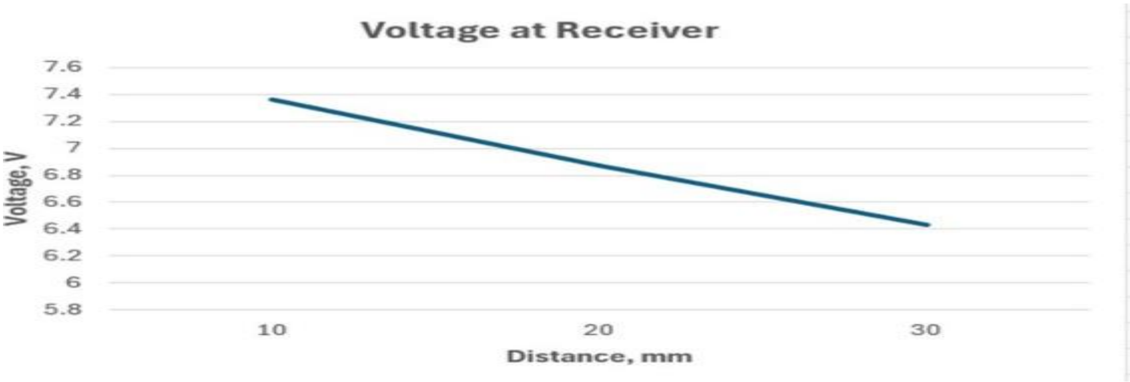
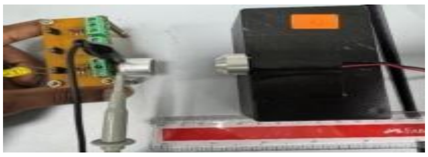


Fig. 17 Voltage at receiving part

Based on Fig. 17, the voltage received by piezoelectric transducer at the receiver shows the voltage decreases from 7.36 V which is 10 mm distance to 6.43 V at 30 mm distance. This shows that when the distance further away from transmitting transducer and receiving transducer, the voltage decreases. It also means that the power received by piezoelectric transducer is also low. For sure it will not receive the exact value of the transmitting value.

As for further overview for the experimental view of the distance between transmitter and receiver part can be seen in Table 4 below.

Table 4 Distance in Experimental Hardware

No	**Distance, mm**	**Experimental Hardware**
1.	10mm	
2.	20mm	
3.	30mm	

Based on Table 4, once the output power received by the receiver transducer, the LED light will blink, and it shows the power is transmitted and received by the receiver part.

CONCLUSION

In conclusion, the study investigates Class E resonant inverter and D inverter, focusing on their advantages and disadvantages. Both classes have been developed, with Class E resonant inverter achieving a 100% efficiency value and a simulation efficiency of 98.6%. Class D inverter, on the other hand, has an efficiency value of 95.23% and a simulation efficiency of 98.04%. A simulation comparison was conducted using a 470 Ω resistor, revealing that Class E resonant inverter have the best efficiency and output power. The second objective identified Class E resonant inverter and further development hardware for Class E resonant inverter. The tuning process, divided into L_{series}, C_{series}, and C_{shunt}, was used to determine the best output power and efficiency. The L_{series} achieved the best value of 11 mH, with an input power of 2.013 W and an output power of 1.045 W, and an efficiency of 51.9%. The C_{series} tuning resulted in an efficiency of 64.2% and an output power of 0.75W.

The receiver part received power from the transmitter, with a maximum distance of 10 mm between the transmitter and receiver part. The LED light illuminated to indicate power transmission. The study also demonstrated that the AET system can transmit power wirelessly, although the current technology is limited to low power applications. This progress will contribute to the development of AET systems as a technology for transmitting power wirelessly.

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