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Wireless Power Supply for Portable Devices

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***Abstract*—** As consumer electronics, smartphones, biomedical implants, electric vehicles etc. become more pervasive, there needs to be a paradigm shift for overcoming regular charging and to lessen the dependency on batteries. Wireless Power Transfer (WPT) is poised to surmount traditional charging methods and usher in a new era of IoT (Internet of Things) devices. However, the current state of WPT is riddled with proximity issues, poor efficiency, mediocre transmission distances, excessive heat-up and design complexions. This research aims to enhance the efficiency and the effective transmission distance. A WPT system has been designed based on a mixed, LCC topology along with a highly-efficient Class-E Power Amplifier as the source. The overall transfer-link efficiency attained for the designed WPT system is 90.026%. A multi-dimensional coil hierarchy can further be adopted for the designed WPT system for achieving spatial freedom. Furthermore, several tests have been conducted to test the system's overall feasibility and to enhance its performance even more.

***Index Terms*—**wireless power transmission, class-E Power Amplifier, GaN FET, 13.56 MHz, Magnetic Resonance Coupling, Oscillator, Intermediate Coils.

1. Introduction

One of the major driving forces that has brought about accelerated development of society, as well as enhanced the overall state of life, is Energy. The sudden increase in the advancement of science and technology, has enabled the world to become more affluent with a vast variety of portable consumer electronics, biomedical, vehicular and industrial devices. This unanticipated surge of portable devices has given rise to a new array of challenges; The foremost issue being, the high level of dependency on batteries for operational purposes. Battery technology has pretty much failed to keep up with the ever-dynamic consumer electronic industry, with the advances becoming almost stagnant.

With the advent of power electronics, wireless power transfer (WPT) or wireless charging technology has quickly progressed and is gaining popularity due to its simplicity & efficiency. Most current generation WPT systems, rely on Inductive Coupling as a means for efficiently charging devices. But vastly degrading efficiency, as a result of misalignment and angular placement, defeats the entire essence of going wireless [1]. Moreover, these inductive based WPT systems tend to suffer from intrinsic winding losses that leads to slow charging times and excessive heat dissipation.

The other type of WPT technique for efficiently transmitting over large distances is based on RF-Radiation, which as the name suggests is not suitable everywhere and poses a safety hazard, for users with biomedical implants. However, research conducted by MIT has painted magnetic resonant coupling to be quite an effective solution, due to its high-power transfer efficiency, covering a span of several meters (medium range). This new entrant has the potential for possibly commercializing midrange wireless power transfer systems [2].

Although magnetic resonance has a substantial edge when it comes to transmission distance, in contrast to electromagnetic induction, this technology has inherent limitations, which are most visible when there is even a slight variation in the operating parameters. Furthermore, a small difference in these parameters & resonance frequencies, will significantly impact the transmission performance and lead to frequency splitting for changing coupling co-efficient [3].

Whilst creating such WPT systems, the source used for powering the entire system often goes overlooked. However, according to a number of researches, the overall efficiency of the system can be enhanced by improving the transmission side of the WPT system [4]. Thus, a Class-E Power Amplifier (PA) has also been designed to be incorporated into the system, to improve its overall efficiency. A Class-E PA has been specifically selected due to its extreme switching and operational capabilities, allowing the PA to reach a theoretical operational efficiency of 100%. For this research, a GaN FET has been utilized because of its high switching rates and to reduce the overall size of the proposed WPT system [5].

2. WPT System Design & Construction

2.1 Block Diagram

As can be observed from Fig. 1, the block diagram of the entire system is separated into two main parts, the transmission side (left) and the receiving side (right). At the transmission side, it is apparent that the Class-E Power Amplifier acts as the source, which powers up the entire system and eventually leads to charging the device attached. After the amplification, the power coil transfers the energy to the transmitter coil. The transmitter coil, which is tuned to operate at the resonance frequency, magnetically transfers power to the receiving coil.

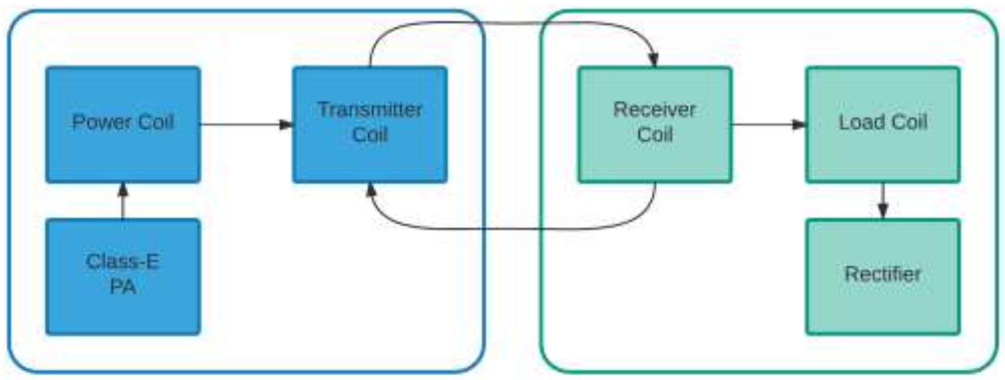

Fig. 1: Operational Block Diagram of the WPT System

At the receiving end, the power transmitted is accepted by the receiving coil through the phenomenon of Magnetic Resonance Coupling; It too is set to operate at the resonant frequency. The receiving coil then further transfers the power to the final load coil. The load coil can either be directly hooked to a device (load) or it can be attached to a rectifier first. The rectifier smoothens out the received voltage, which is then supplied to the attached device for a more consistent charging experience.

2.2 Class-E Power Amplifier

The Class-E PA has been selected to power the proposed WPT system. A typical Class-E Amplifier configuration includes a transistor that acts as a switch, which is further attached to an RF choke (L1) at the drain, an LC resonator (L2 & C2) connected in series and a resistive load (R1) as shown in Fig. 2. As a means for making the circuit more compact, many researches tend to exclude the shunt capacitor (C1), attached in parallel, but this significantly impacts the efficiency [5]. Since most portable devices such as smartphones, usually require only about 12W and 2.4A for fast-charging purposes, the supply & drain voltages have been set to 5V.

For this research, a high efficiency Gallium Nitride (GaN FET) based switching-mode transistor has been opted for, instead of the more traditionally used silicone MOSFET. By incorporating a Gallium Nitride (GaN) enhancement mode FET in the Class-E PA, the power density provided is significantly enriched, as it tends to operate at higher temperatures and considerably high switching frequencies. Furthermore, it is also capable for providing amplification, for a multitude of varying loads at the highest efficiency [4].

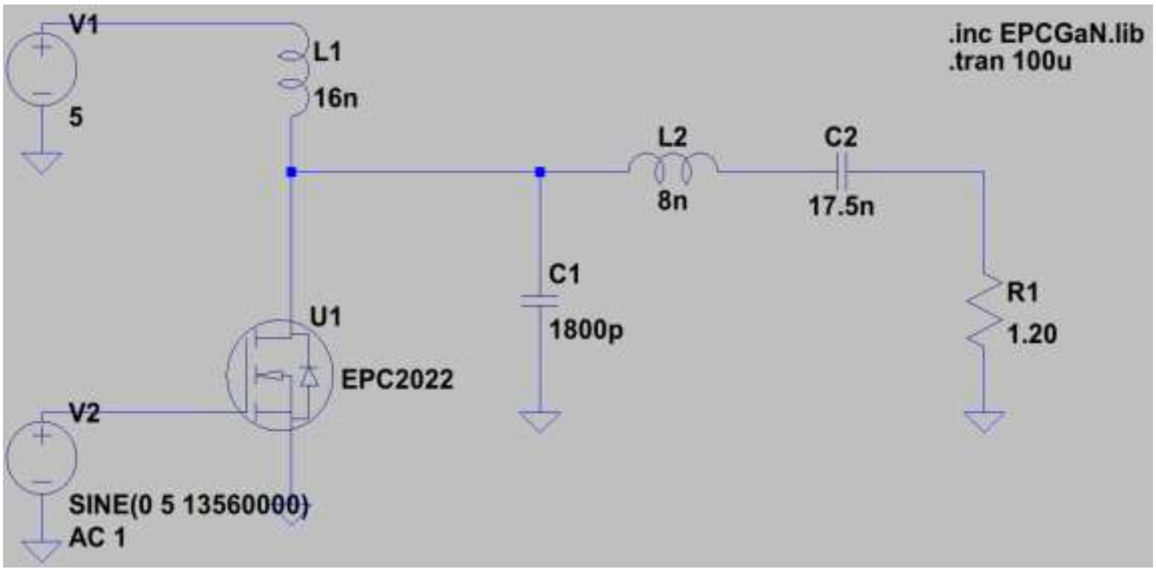

Fig. 2: Designed Class-E PA with GaN FET attached.

All of the component values are derived by making use of certain formulae, which are provided below [5]:

$$R1 = \frac{0.577Vdc^2}{P_{out}} \quad (1)$$

Where the load resistance can be calculated by setting an output power (12W) and supplying an input gate voltage of 5V. Using the R1 value obtained, the rest of the components are calculated accordingly:

$$C1 = \frac{1}{5.447\omega R} \quad (2)$$

$$L1 = \frac{1.525R}{\omega} \quad (3)$$

However, the LC Resonator values are calculated by including the proposed WPT's Q-factor, using the following formulae [5]:

$$C2 = \frac{1}{\omega QR} \tag{4}$$

$$L2 = \frac{1}{\omega^2 C2} \tag{5}$$

The values for each component was calculated using these formulas and all of the design parameters for the Class-E PA are provided in Table 1.

Table 1: Design Parameters for the Class-E Power Amplifier.

Components	Values
Frequency	13.56 MHz
V1	5V
V2	5V
L1	16.23nH ≈ 16nH
C1	1795.65pf ≈ 1800pf
L2	17.466nf ≈ 17.5nF
C2	7.887nH ≈ 8nH.
R1	1.20Ω

2.3 4-Coil WPT System

The proposed Wireless Power Transfer (WPT) System has been designed to further enhance the efficiency and the distance of transmission. Observing Fig. 3, the system designed is unlike other traditional WPT systems, in the way that it utilizes the 4-Coil regime for it to function. This system performs on the basic principles of magnetic resonance, with the added benefits of the intermediate, Tx & Rx coils [3]. Furthermore, the design topology has been tweaked from the conventional series-series to the mixed LCC topology.

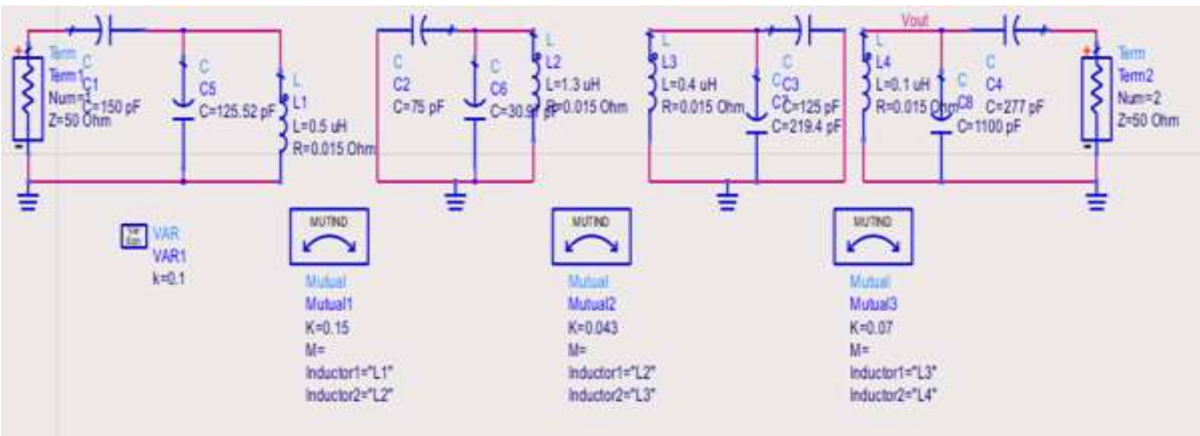

Fig. 3: Proposed 4-Coil SCMR WPT System.

The transmission stage is comprised of both the power coil and the transmitter coil. After the power is amplified, it is ready to be transferred that is carried out by the power coil, which is essentially two capacitors connected in parallel to an inductor. The capacitors attached, work in conjunction with the inductor, as a means for providing a simpler solution to impedance matching. The power coil is linked to the transmitter coil magnetically that is represented on the schematic (Fig. 3), as the coupling co-efficient (k), which has been set to 0.15, for the linkage between coils 1 & 2 (power & transmitter).

Here the value of 'k' not only represents, how tightly the coils are linked to one another but also acts as a function of distance between the power coil and the transmitter coil. Generally, the coupling co-efficient value diminishes when the distance is increased [4]. Due to the magnetic link present, the power is transferred to the transmitter coil. The Tx coil also functions on the same principles as the power coil and has been attached in a similar fashion. Being set at the resonant frequency, it is able to efficiently transmit the evanescent power-carrying waves to the receiving side.

The values for all the RLC components have been premeditated to operate at the selected resonance frequency of 13.56 MHz. The following calculations have been performed, based on the design parameters (Table 2), and are calculated using the following formulas.

Wheeler's Formula for calculating the value of the coil:

$$L = \frac{N^2 + R^2}{2.54(9R + 10H)} \tag{6}$$

where, L = inductance (uH)

N = number of turns of wire

R = radius of coil (cm)

H = height of coil (cm)

Since the resonant frequency has already been set at the source, the following formula may be used to determine the capacitance value:

$$f_r = \frac{1}{2\pi\sqrt{L(C1 + C2)}} \tag{7}$$

where, Fr = resonance frequency

L = inductance (uH)

C1 = series capacitance (pF)

C2 = parallel capacitance (pF)

Furthermore, the receiving end is comprised of the receiver & load coils, respectively and are arranged in the aforementioned manner. However, the link (k) between the transmitter and receiving coil has been set to 0.043, as can be seen from Fig. 3. This has been done for further increasing the actual distance between the power and load coils, as well as to overcome frequency splitting and improve the overall efficiency of the entire system [4].

Table 2: Design Parameters for the WPT System.

Coil (inductor)	N (turns)	R (cm)	H (cm)	L (uH)	F (MHz)	C1 (pF)	C2 (pF)
Power	2	5	3.3	0.5	13.56	150	125.52
Transmitter	3	6	4.4	1.3	13.56	75	30.97
Receiver	1.67	6	4.4	0.4	13.56	125	219.4
Load	1	3.7	2	0.1	13.56	277	1100

3. Working Principle

The operational working principle of the proposed WPT system is shown in Fig. 4. When a DC voltage is supplied to the Class-E Amplifier, it goes through the choke inductor (L1) and supplies a constant DC current to the GaN FET (EPC 2022) used. This transistor operates as switching mode amplifier and allows an AC current to flow through the transistor, when it is switched on. When the transistor switches OFF, the current is then rerouted to the load, producing a voltage. In an ideal scenario, this transition is seamless with a theoretical efficiency of 100%. However, power dissipation at harmonic frequencies, negates the efficiency, which is why an LC resonator is incorporated to regulate such harmonics. In the end, the amplified power is provided to the load and in this case, to the power coil for further transmission [5].

After being injected with the amplified power, the power coil begins to oscillate at the resonant frequency, to transfer the power to the intermediary Tx coil. When certain frequencies are applied, many objects tend to vibrate, producing greater amplitudes than at other frequencies, this phenomenon is known as resonance [6]. Thus, for this entire system the resonant frequency is set at 13.56 MHz.

The transferred power from the power coil is fed in to the intermediate Tx coil, which itself is already vibrating at the resonant frequency, due to the aid of impedance matching capacitors. Impedance matching is a necessary framework for efficient Wireless Power Transfer, as it optimally tunes the coils on both the transmitting and receiving ends, to resonate at a particular frequency, for maximum exchange and minimal losses [2].

The Tx coil then further transmits the power to the Rx coil magnetically. Both of these coils are the intermediate coils that have been inserted to make the WPT system more efficient. These coils are free from source internal resistances & other parasitic losses, leading to an improvement in the overall Q-factor [3]. The receiver coil again oscillates to finally transmit the power to the load coil. After having received the power transmitted all the way from the amplification and power coil stage, the load coil is connected to the portable device (load). It can alternatively be connected to a rectifier first, that will ensure a steady amount of current is provided to replenish the device.

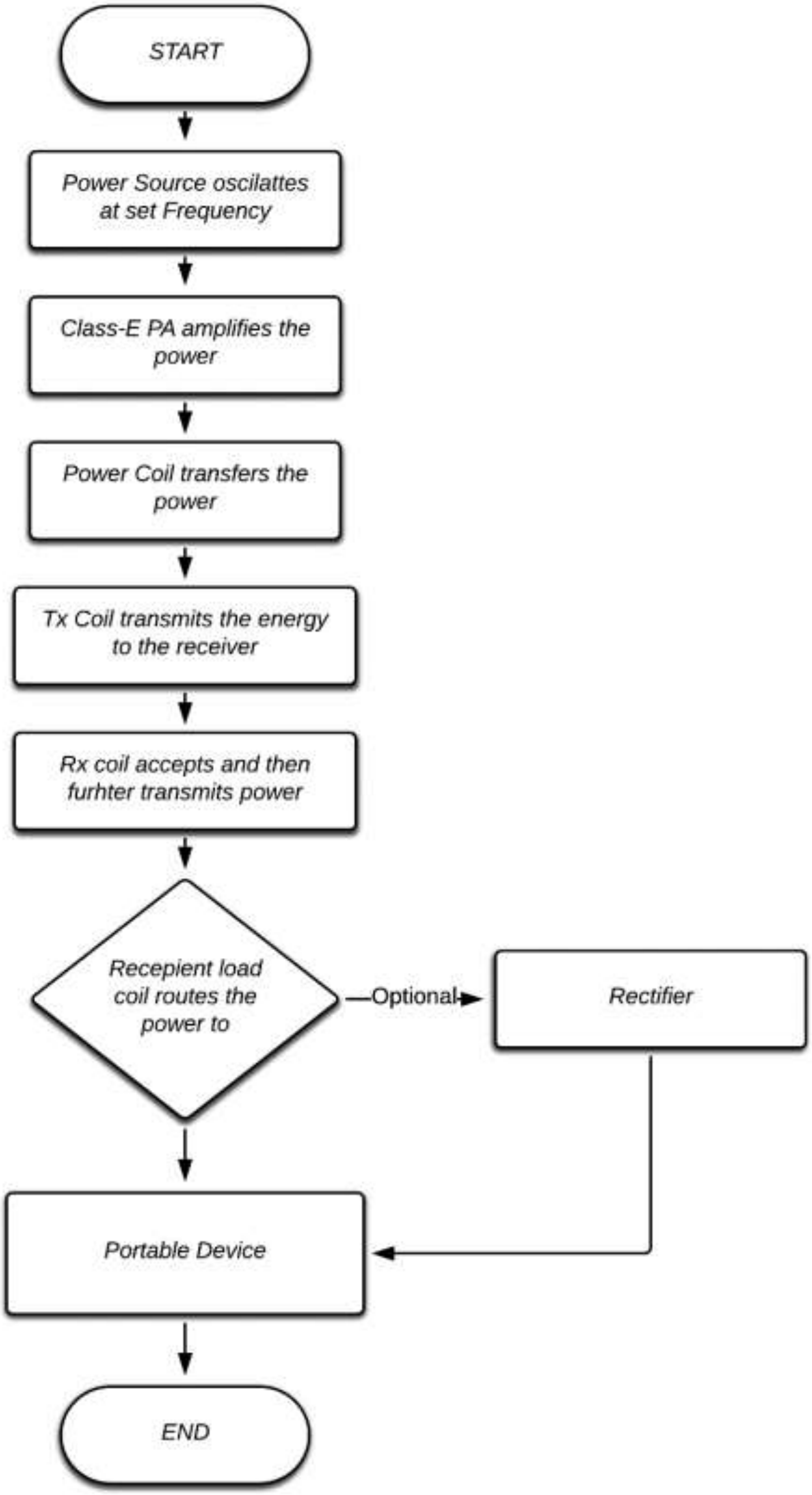

Fig. 4: Operational Principle Flowchart of designed WPT system.

4. Simulation Results

4.1 Class-E Power Amplifier

The Class-E Power Amplifier has been designed using LTspice due to a lack of a GaN FET in ADS. The PA has been setup as shown in Fig. 2 and its transient behaviour is analysed. As can be observed from Fig. 5, the voltage at the output is around 7.3V, with the current across the load being 6.2A. A drain input voltage of 5V has been provided and the drain current that exists is 9.4A, as can be evident from Fig. 6. Hence, the total efficiency of the designed Class-E Power Amplifier obtained is 95.75%, which is a bit lower than the theoretical efficiency of 100%.

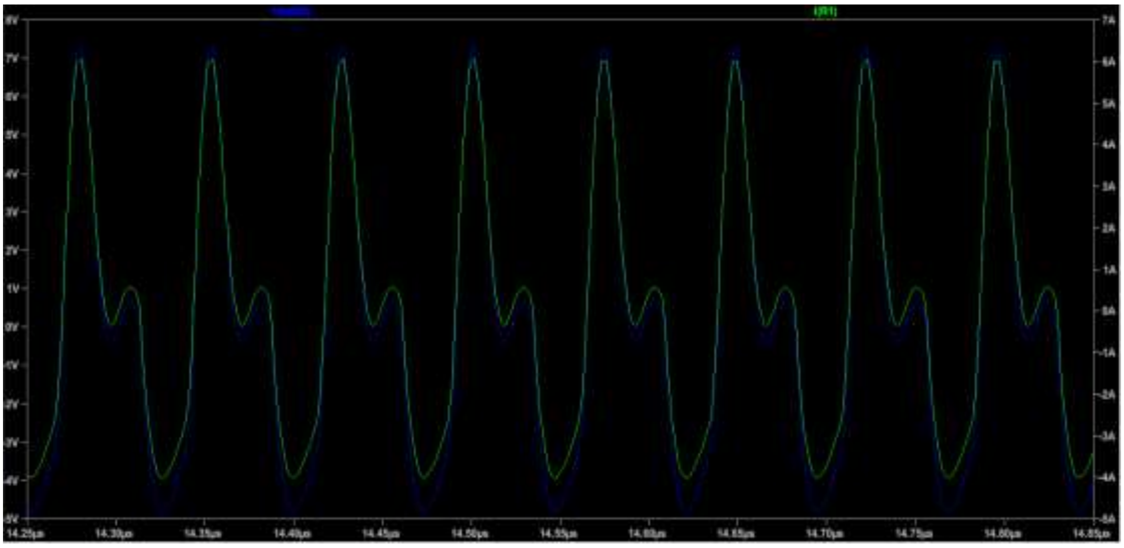

Fig. 5: Output voltage & current waveforms for the Class-E PA

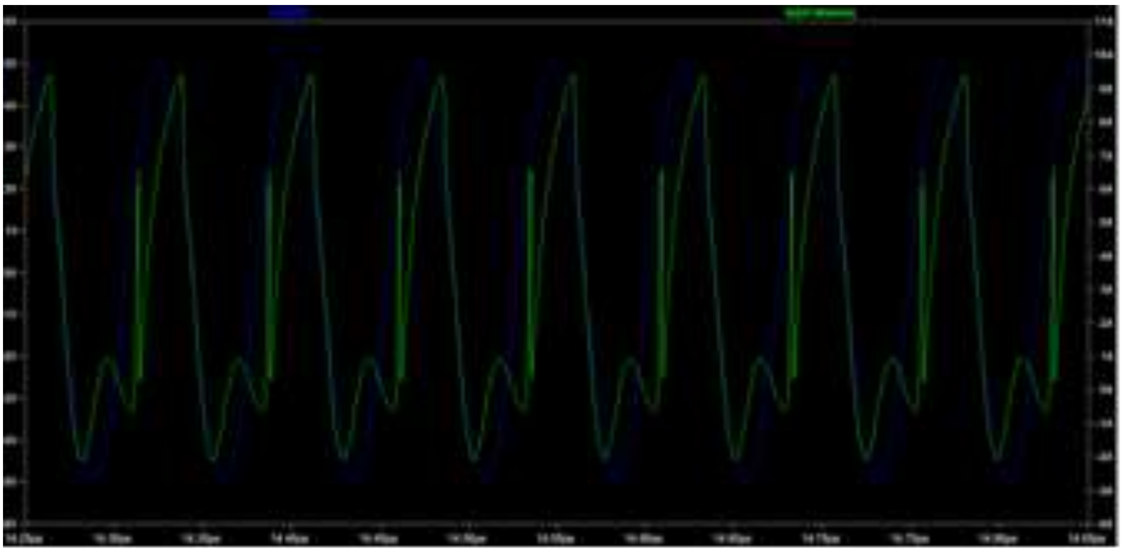

Fig. 6: Drain current & gate voltage with respect to time for the Class-E PA.

4.2 Wireless Power Transfer System

The WPT system has been setup with the S-Parameters terminations for testing the transfer-link efficiency of the system and the results are shown in Fig. 7 through Fig. 9. As can be observed from Fig. 7, the S11 magnitude obtained for the designed WPT system is just 0.252 and should be relatively low for an efficient system. The S21 parameter obtained is quite important as it signifies the ratio of the receiver's receiving power divided by the transmitter's transmitting power and hence, the total power that can be transferred [3]. Fig. 8, illustrates the value of S21, which is 0.949, with 1 being the maximum amount of power transferred. Finally, as can be observed from Fig. 9, by performing the S-parameters simulation, the overall transfer-link efficiency of the designed WPT system is 90.026%.

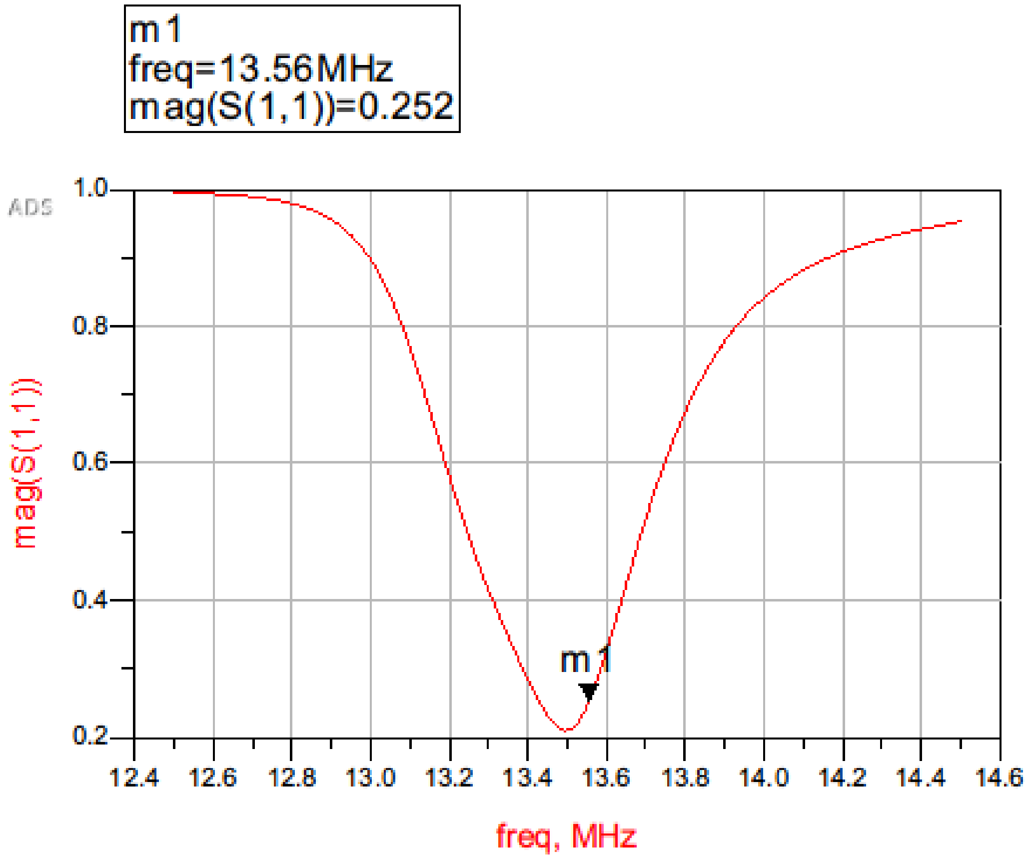

Fig. 7: S11 Magnitude result of the designed WPT system.

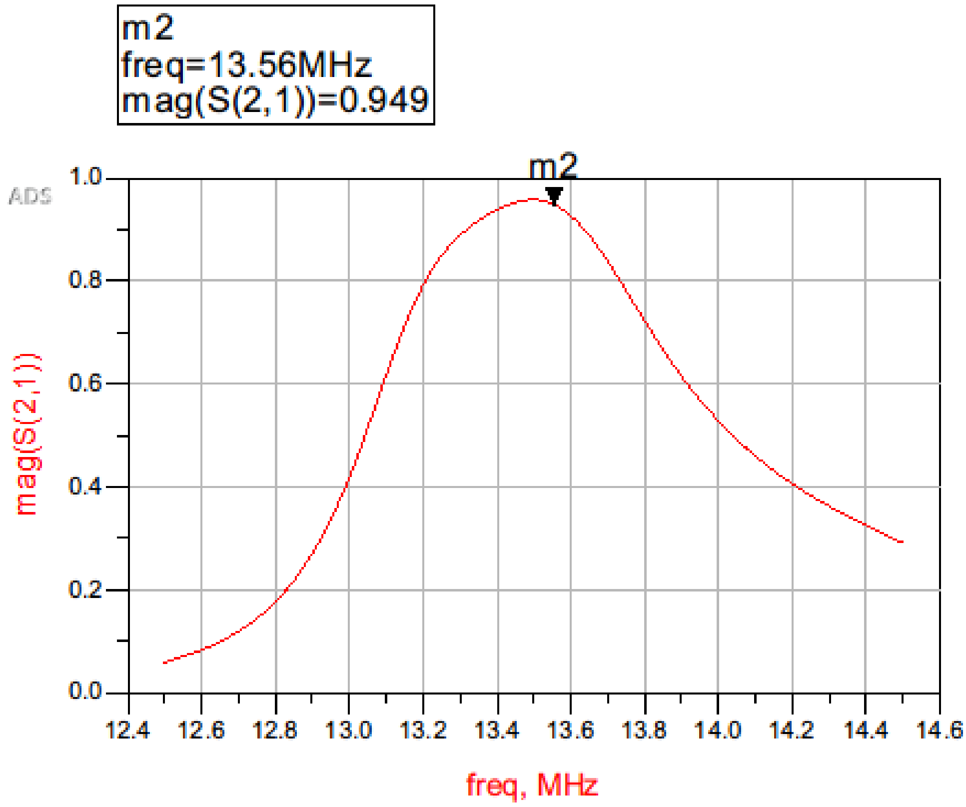

Fig. 8: S21 Magnitude result of the designed WPT system.

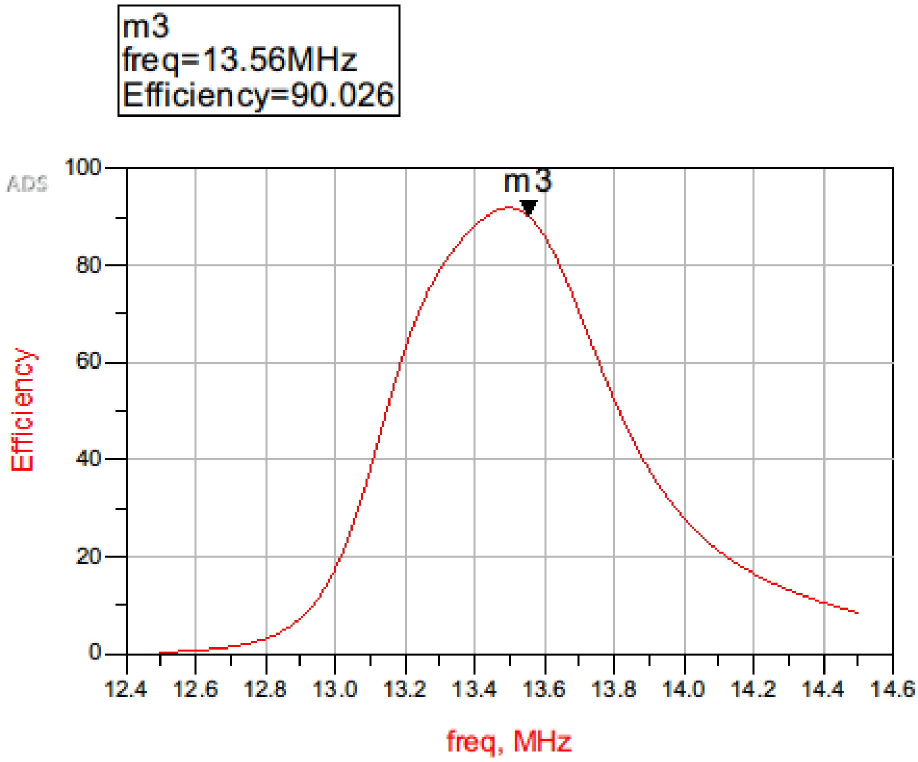

Fig. 9: Transfer-link efficiency of the designed WPT system.

5. Testing & Evaluation

In order to assess the overall performance and efficiency of the designed WPT systems, a number of tests were carried out, which are as follows:

5.1 Type of Topology

One of the most vital design changes that adversely affects the performance and link transfer efficiency of WPT systems, is the type of topology used. Conventionally, most inductive-coupling based charging systems make use of the series-series or LC compensation topology [4]. However, for the final design a mixed LCC type compensation topology was used and its performance was evaluated with the series-series one.

Table 3: Performance comparison data between different types of topologies.

Topology	S11	S21	Efficiency
Series-Series	0.973	0.184	3.371%
Mixed LCC	0.252	0.949	90.026%

As can clearly be observed from Table 3, using the traditional series-series topology without changing the design parameters, greatly degrades the entire performance of the system, when compared to the mixed LCC topology.

5.2 Effects of the Coupling Co-efficient

Fundamentally, the existing amount of coupling for an inductive system can be expressed as a fraction number between 0 and 1. Where $0.5<k<1$ represents a tightly coupled system and $0<k<0.5$ signifies a loosely coupled system. This is one of the most important factors that effects the transfer-link efficiency and determines the overall performance of the WPT system [2]. The coupling co-efficient is effectively determined by two factors, which is the distance between coils and their relative sizes [3].

Table 4: Performance evaluation for varying Coupling Co-efficient (K)

Coupling co-efficient Value	S21 Magnitude	Transfer-Link Efficiency
K23 = 0.03	0.864	76.229%
K12 = 0.1	0.861	73.464%
K34 = 0.1	0.891	79.959%

As can be seen from Table 4 above, reducing the distance between the transmitter and receiver (k23 = 0.03), whilst keeping k12 & k34 fixed, the efficiency of the system decreases significantly and the frequency spectrum becomes narrower. Furthermore, reducing the value of k12 to 0.1, the efficiency of the system is drastically impacted and frequency splitting occurs. Frequency splitting is a phenomenon at which the efficiency of a system, peaks at both below & above the resonant frequency [4]. Finally, when coupling between the receiver coil & load coil (k34) is increased to 0.1, while keeping k12 & k23 fixed, the efficiency decreases and the effects of frequency splitting are reduced.

5.3 Effects of using different System Types

A 4-Coil WPT system was designed so as to enhance the efficiency and increase the coverage area (distance) of the system [3]. The same system was recreated as a 2-Coil & 3-Coil system and its effects were analysed in detail as shown in Table 5.

Table 5: Efficiency comparison between 2-Coil, 3-Coil and the designed WPT system.

System Type	k	S21	Efficiency
Two-Coil	0.5	0.707	49.974%
Three-Coil	0.5	0.810	65.589%
Designed 4-Coil	0.043	0.949	90.026%

It can clearly be seen that even after substantially reducing the distance between the coils for the 2 & 3-Coil WPT setup, the power transfer ratio and the transfer-link efficiency takes a hit, leading to poor efficiency.

6. Conclusion

A wireless power supply for powering portable devices was designed and its performance was tested. A 4-Coil design WPT, with mixed LCC topology and highly efficient Class-E power amplifier was designed in this research. The 4-Coil design was incorporated to benefit from the added intermediate coils, which not only aid in increasing the transmission distance but also to mitigate source internal resistances. This type was later evaluated against existing solutions and proven to be the most suitable. A well-balanced link was achieved between the coupling co-efficient that increased the distance without hampering the efficiency. Furthermore, the designed Class-E PA was able to achieve an efficiency of 95.75%, a little short of the theoretical 100% efficiency. By using the mixed LCC topology, along with all of the design factors, the WPT system with a power transfer of 0.949 and an overall transfer-link efficiency of 90.026% was achieved. The addition of intermediate coils, allows the design to be more modular and the size of the receiver coil can further be reduced, for powering biomedical implants.

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