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Optimization of Wireless Power Transfer Configuration for High Efficiency Achievement

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Abstract: This paper discusses the efficiency improvement of a wireless power transfer system based on parameters design optimization. Wireless power transfer system is designed to operate at higher frequencies in order to reduce the component sizing as well as power density improvement. Configuration of wireless power transfer system, i.e., transmitter and receiver coil are designed based on proper resonance frequency. The principle of the parameters design optimization is based on the single transmitter – multiple receiver coil configuration which reduce the system complexity and magnetic resonant method implementation which amplify the energy transferred between the coils. Simulation using ANSYS Maxwell and ANSYS Simplorer software show the system efficiency is at the peak at resonance frequency of 13.5571 MHz with a total power of 18 W delivered at a distance of 5 mm. Furthermore, efficiency of AC – DC converter and high frequency DC – AC converter considered for power conversions are 99.81% and 99.51% respectively. Therefore, maximum power transfer efficiency of the considered wireless power transfer system configuration is determined through this study.

Keywords: Wireless power transfer, resonance frequency, single transmitter – multiple receiver, magnetic resonant

1. Introduction

Nowadays, advancements in the field of wireless power transfer technologies have enabled various engineering applications towards the potential product implementation [1]. This technology development is significant to the future requirement which are more focusing on the mobility of appliances and devices. Conventional wired mobile phone charger seems irrelevant in this era due to user-friendly issues which reduce the user's mobility during charging process [2]. Currently, the wireless charger technology is not being practical as the phone need to be directly contact with the charging dock during charging process. This limitation basically still did not solve the user-friendly problem that become the trendiest issue in this era.

In order to solve this issue, a wireless power transfer system using magnetic resonant coupling mode is significant to be implemented towards mobile phone charger as there is no conventional power cable need to be connected during charging process. The proposed power transfer method allows wireless power transfer in a middle-range transmission distance such as a few dozen of centimetres at

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higher efficiency up to 80% [3]-[4]. To achieve an efficient wireless power transfer system, the configuration of transmitter and receiver design become the main focus in the wireless power transfer system. In this study, the circuit configuration is optimized by considering single transmitter and multi-receivers in the design. Thus, by optimizing the design of the transmitter and receiver, a higher efficiency of wireless power transfer system can be achieved. This method indirectly will solve the user-friendly issue besides improves the power transfer efficiency during the charging process. As stated in [5], wireless power transfer system is simple, safer and reliable for the power transfer system.

2. Wireless Power Transfer Structure

Proposed wireless transfer system consists of three (3) parts which are the input, processing and output. Power supply will act as the input to the system, whilst power converters as well as transmitter and receiver coils will play a significant role in transmitting the power to the load. At the output side, a DC load is connected in parallel with each receiving circuit. Figure 1 shows the block diagram of the wireless power transfer system.

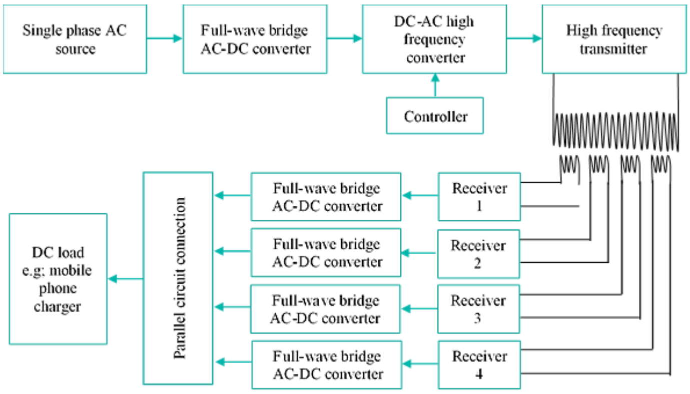


Figure 1: Block diagram of wireless power transfer system

2.1 Full-wave bridge AC – DC converter

Single phase AC – DC converter or rectifier is designed in form of full bridge rectifier in order to convert the 50 Hz AC supply into zero frequency DC supply. Basically, this converter consists of four (4) diodes for rectification process. The input voltage supplied to the rectifier is set to a value of 325.27 V (peak voltage). The rectified AC supply is supplied to the DC – AC converter in order to convert the zero frequency DC supply into 13.56 MHz AC supply. Figure 2 shows the topology of single phase full-wave bridge AC – DC converter used in this project.

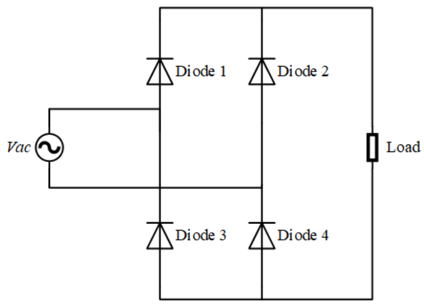


Figure 2: Full-wave bridge AC - DC converter

2.2 DC – AC high frequency converter

Single phase DC – AC converter or inverter is designed in the basis of H-bridge inverter. Basically, the circuit consists of four (4) switching devices in order to invert the direct signal into alternating signal. Four (4) metal oxide semiconductor field-effect transistor (MOSFET) are utilized as switching devices due to better performance compared to insulated-gate bipolar transistor (IGBT) for high frequency switching activity [6]. In this project, output voltage from the rectifier will become the input source for the inverter to produce a 13.56 MHz alternating signal. Figure 3 illustrates the topology of single phase DC – AC converter used in this project.

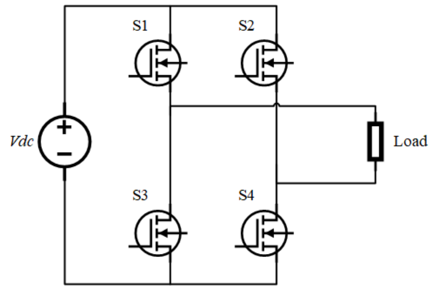


Figure 3: DC - AC converter

2.2.1 Generator for DC – AC converter

Operation of DC – AC converter require a proper switching pattern in order to execute the inverting process. In this project, Pulse Width Modulation (PWM) generator is applied by considering 13.56 MHz of switching frequency. From the pulses generated by PWM, the inverter will able to produce alternate square wave output voltage at the load. A 3-level inverter is considered in this project in order to allow optimum switching activity in the inverter due to the effect of dead time. Figure 4 shows the 3-level output voltage waveform produced by the inverter.

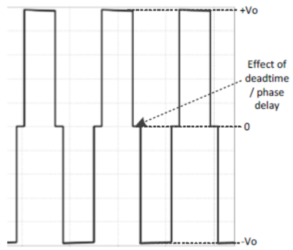


Figure 4: 3-level output voltage waveform

2.3 Transmitter system

Transmitter coil in this system is designed based on the comparative study reported in [7], where coupling efficiency between the coils are improved and maximized. Practically, receiver coils will be misaligned with the transmitter coil which reducing the coupling coefficient between the coils. This resulted to reduction of power transfer efficiency as power transferred are not successfully received by the receiver coils. Thus, a transmitter scheme consisting of a wider coil and proper orientation is designed in this system in order to reduce any possibility of energy losses during the power transfer process. Parameter of transmitter coil designed is tabulated as in Table 1.

Table 1: Parameter of transmitter coil

Specifications	Value
Material	Copper
Polygon segments	0 (Circular)
Polygon radius	2 mm
Start helix radius	10 mm
Radius change	4.05 mm
Pitch	0 mm
Turns	10

Single transmitter configuration provide lower complexity in the system as the number of switching circuit is reduced. This allow better control in the system besides reducing switching losses during the power conversion process. Therefore, higher efficiency and lower cost power transfer system is possible to be designed for practical application in the future. Design of transmitter coil constructed in ANSYS Maxwell is shown as Figure 5.

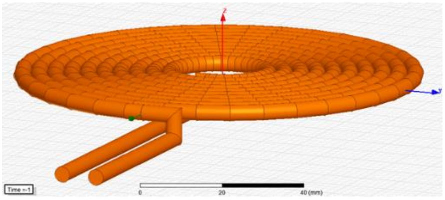


Figure 5: Transmitter coil

The resonance considered is focused towards the resonator system which must have a high quality factor for efficient energy transfer. High quality factor of electromagnetic resonators normally made from the conductive components which have relatively narrow resonant frequency widths [8]. On top of that, resonator system enable energy exchange between the resonators when are placed close to one another. The efficiency of energy exchange highly depends on each resonator and coupling coefficient of the transmitter and receiver designed. The equivalent circuit of resonator is shown as Figure 6.

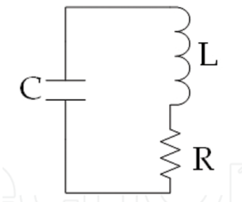


Figure 6: Resonator

Oscillation of energy occurs well at resonance frequency where energy is amplified as the impedances of circuit elements cancel each other. In a series resonance system, resonant frequency (f_r) is expressible as Eq. 1.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad \text{Eq. 1}$$

In order to set up resonant frequency of 13.56 MHz, value for each capacitor need to be determined based on the inductance obtained from each transmitter and receiver coil.

2.4 Receiver system

Receiver coils in this project are designed based on the concept of mobility degree as mentioned in [9]. In a multi-receiver system, power distribution depends on the load impedances and relative position of receivers to the transmitter [10]. Thus, multi receiver coil designed in this system allow higher mobility degree of load during power transferring process. Parameter of receiver coils design in this project is depicted as Table 2.

Table 2: Parameter of receiver coil

Specifications	Value
Material	Copper
Number of coil	4
Polygon segments	0 (Circular)
Polygon radius	1 mm
Start helix radius	5 mm
Radius change	2.05 mm
Pitch	0 mm
Turns	10

Designing receiver coils require proper coil coordination in order to optimize the received power from the transmitter. In this project, the receiver coils (grey) are arranged directly vertical above the transmitter coil as shown in Figure 7 below.

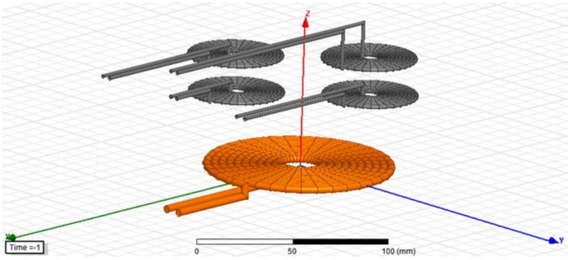


Figure 7: Coordination of transmitter and receiver coils

3. Results and Discussion

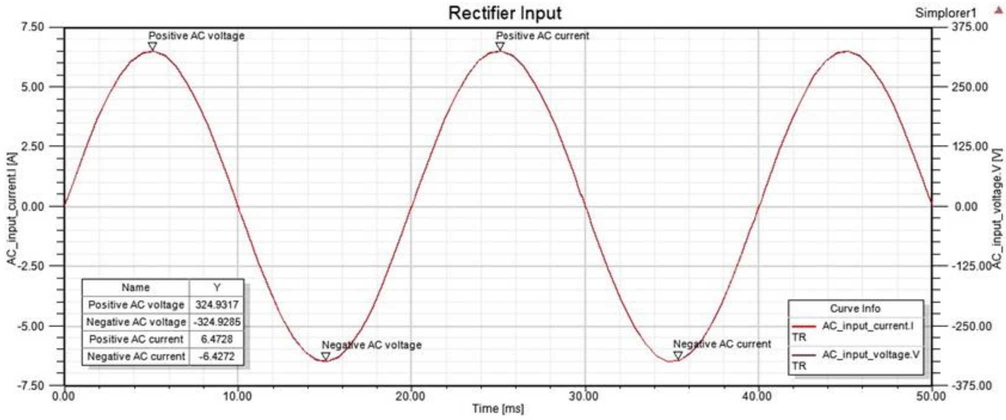
3.1 Simulation of AC – DC converter

Simulation of power circuit is done by using ANSYS Simplorer software. AC – DC converter is required in order to convert the 50 Hz of AC source from domestic supply into zero frequency DC supply. In this project, full-wave bridge AC – DC converter are equipped respectively at the input and output system to rectify the power supply. Simulation of AC – DC converter is required in order to ensure the validity of parameter in this system. Specifications of DC – AC converter designed in this system is depicted as Table 3.

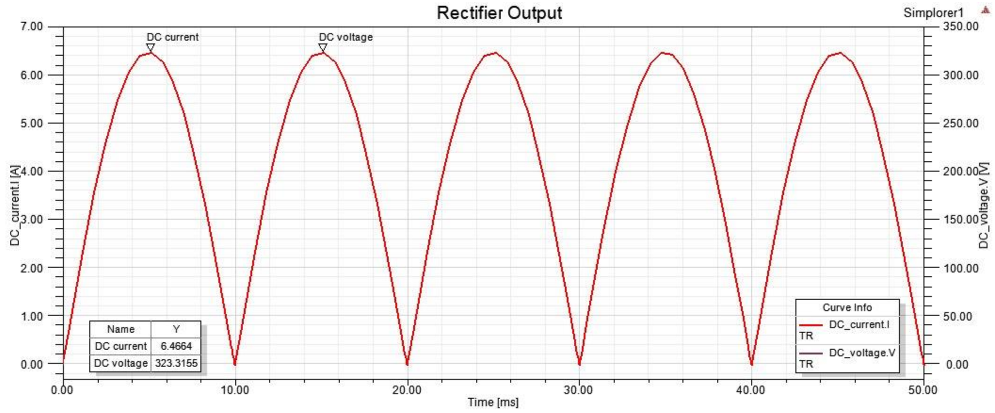
Table 3: Specifications of input AC - DC converter

Specifications	Value
Semiconductor	Diode
Input voltage, V_{in}	230 V
Supply frequency, f	50 Hz
Output resistor, R_{out}	500 Ω

Simulation results in Figure 8 showed the waveform obtained at the rectifier input is sinusoidal at a peak voltage and current of 323.93 V and 6.47 A, respectively. Meanwhile, rectifier output shows a waveform of positive pulses at amplitude of 323.32 V and 6.47 A. The reduction in voltage value from the converter shows energy losses occurred during the rectification process. Despite of energy losses occurred in this phase, the converter is still reliable to be implemented as the losses is only 0.19% from the overall performance.



(a)



(b)

Figure 8: Simulation results of AC - DC converter (a) Input (b) Output

3.2 Simulation of DC – AC converter

Wireless power transfer system require a high frequency AC supply in order to transmit power through the transmitter coil. Basically, DC – AC high frequency converter is required to produce a high frequency AC voltage which will be supplied into the transmitter coil. Operation of DC – AC converter require a proper switching technique in order to execute the power conversion process. In this case, Pulse Width Modulation (PWM) switching technique is applied to control the output of DC – AC converter as shown in Figure 9.

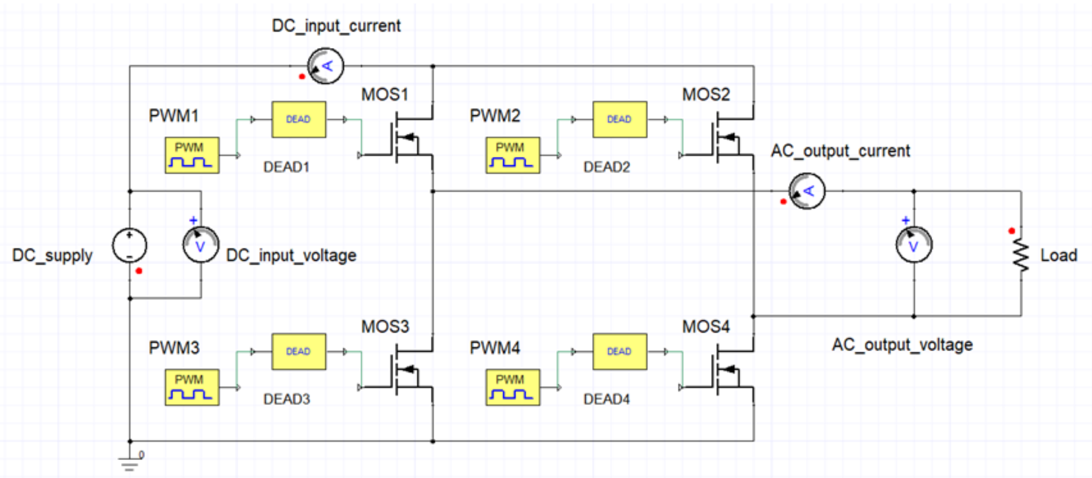


Figure 9: DC - AC converter circuit

In a conventional DC – AC converter, the output voltage depends on the size of load installed in the system. Variation of load size cause the performance of converter reduced due to improper pulses generated for the switching process. Thus, PWM technique applied in this converter design offers a significant solution to nullify the effect of load variations by adjusting the output voltage based on the switching frequency and pulse width according to the load size [11]. In order to produce higher power density output, switching frequency of the converter is set to 13.56 MHz with duty cycle of 0.5. Specifications of DC – AC converter designed in this system is depicted as Table 4.

Table 4: Specifications of DC - AC converter

Specifications	Value
Semiconductor	MOSFET
Duty cycle, D	0.5
Switching frequency, f_s	13.56 MHz
Input voltage, V_{in}	325.27 V
Supply frequency, f	50 Hz
Output resistor, R_{out}	500 Ω

Figure 10 showed the simulation output from PWM switching applied in the DC – AC converter. In practical, switching activity requires a short time delay in order to ensure all switching devices are completely dead during OFF phase. The effect of dead time in the circuit will produce a multi-level AC output which slightly can reduce the total harmonic distortion (*THD*) in the waveform. Figure 10 shows the three-level output waveform obtained due to the effect of dead time in the PWM switching.

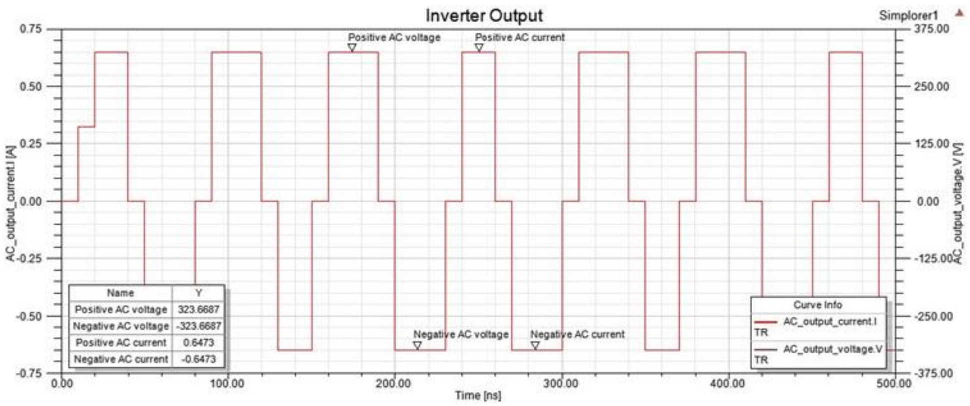


Figure 10: Output waveform of DC - AC converter

Results obtained from DC – AC converter simulation showed a three-level output waveform is produced due to effect of dead time in the switching scheme. Alternating peak voltage and current of 323.67 V and 0.65 A are obtained respectively as a load resistance of 500 Ω is connected in the circuit. High frequency switching applied in the system showed significant effect in the power converter performance as only 0.49% of voltage loss recorded. Thus, three-level DC – AC converter designed in this system is relevant to be implemented in order to achieve maximum performance in the wireless power transfer system.

3.3 Simulation of transmitter and receiver coil

Transmitter and receiver coil designed are simulated in the ANSYS Maxwell software. In this part, crucial parameter such as coupling coefficient (k), mutual inductance (M), self-inductance (L) and magnetic field distribution (B) are measured and evaluated from the simulation. Four (4) receiver coils made by copper are arranged directly vertical above a transmitter coil with a gap distance of 5 mm. Each transmitter and receiver coil are supplied with AC current source of 0.65 A and 2.40 A respectively as per obtained from the power circuit simulation before. Table 5 depicts the coupling data obtained from the simulation of transmitter and receiver coil.

Table 5: Coupling data of transmitter and receiver coil (5 mm)

Coupling coefficient, *K*		Mutual inductance, *M*		Self-inductance, *L*	
$TxRx_1$	0.0825	$TxRx_1$	163.8106 nH	TxTx	1.9321 µH
$TxRx_2$	0.0816	$TxRx_2$	161.7150 nH	Rx_1Rx_1	2.0406 µH
$TxRx_3$	0.0839	$TxRx_3$	168.9549 nH	Rx_2Rx_2	2.0349 µH
$TxRx_4$	0.0858	$TxRx_4$	170.3818 nH	Rx_3Rx_3	2.0966 µH
				Rx_4Rx_4	2.0429 µH

Referring to Table 5, coupling coefficient (*k*) of the transmitter and receiver coils showed a slightly low coupling ability due to various possible causes such as fringing flux formation due to eddy currents excited during power transfer process [12]. Other than that, low mutual inductance and self-inductance value depicts small amount of induced emf is generated between the coils. Despite of the low coupling ability, implementation of magnetic resonance could provide power transfer efficiency improvement as resonance frequency allow significant amount of power to be transferred over distance up to multiple times of the coil sizes [13].

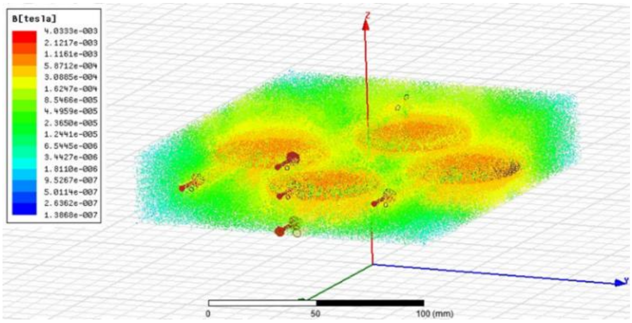


Figure 11: Transmitter and receiver coil magnetic field distribution

3.4 Simulation of receiving circuit

Simulation of the output system is also executed to test and verify the circuit topology. In this phase, parameter such as output voltage and output current are measured in order to evaluate the circuit performance and output waveform quality. On top of that, simulation of output system is crucial in order to pre-determine the circuit capability if being connected with various type of loads in the real applications. Specifications of the output circuit system is tabulated as shown in Table 6.

Table 6: Specifications of receiving circuit

Specifications	Value
Input voltage, V_{in}	230 V
Transformer turns ratio, *n*	46:3
Power converters	Full-wave bridge rectifier (diode)
Resonant frequency, f_r	13.56 MHz
Inductor, L_r	0.92 µH
Capacitor, C_r	150 pF
Output resistor, R_{out}	5 Ω

At the receiver, high frequency of 230 V AC voltage is stepped down to 12 V by an ideal transformer. Full-wave bridge AC – DC converter is also installed in each receiving circuit where AC supply is rectified into zero frequency DC output. Other than that, LC filter which also act as resonant tank for each receiving circuit is configured to 0.92 µH and 150 pF in order to maintain the resonant frequency of 13.56 MHz. Equipped with a resistor of 5 Ω, the circuit is expected to produce an output power of 30 W. Figure 12 shows simulation waveform from one of the receiving circuit in wireless power transfer system deployed in ANSYS Simplorer software.

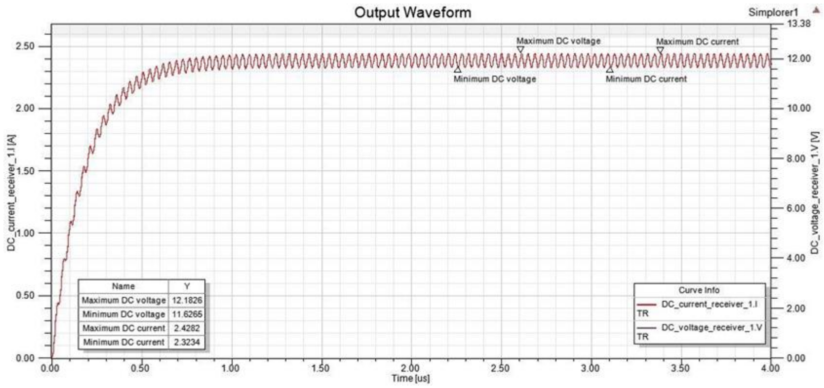


Figure 12: Output waveform of receiver circuit

Referring to Figure 12, output waveform of DC voltage and current are obtained at average of 12 V and 2.4 A, respectively, which producing an output power of 28.8 W. In this project, the output power produced by the receiving circuit is suitable to act as a fast-charging device towards the mobile phones. Other than that, ripple voltage and current of the output waveform are reduced to 4.7% and 4.4% respectively. Therefore, possibilities of damage or heating towards the mobile phones is reduced thus make this system is safe and efficient to be implemented as a mobile phone charger.

3.5 Simulation of overall wireless power transfer system

Simulation of overall wireless power transfer system is executed as transmitter-receiver configuration and power circuits are completely designed. In this part, the transmitter-receiver coils designed from ANSYS Maxwell are integrated together with the power circuits in the ANSYS Simplorer software. The co-simulation capability offered by ANSYS Maxwell and ANSYS Simplorer enables various types of simulation such as application of finite element analysis (FEA) towards variety of power electronic components which will ease the research and development process [14]. Figure 13 shows the exported block component of transmitter-receiver coils that connected with the power circuit constructed.

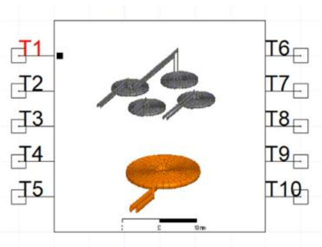


Figure 13: Transmitter-receiver block component

Referring to Figure 13, the exported block component of transmitter-receiver coils is integrated together in the full wireless power transfer system circuit. In this part, 5 mm gap distance between the transmitter and receiver coils is simulated based on specifications tabulated as in Table 7.

Table 7: Specifications of wireless power transfer circuit

Specifications	Value
AC input supply, V_{in}	230 V
Supply frequency, f	50 Hz
Inverter switching frequency, f_s	13.56 MHz
Resonant frequency, f_r	13.56 MHz
Resonance capacitor (transmitter), C_{tx}	71.30 µF
Resonance capacitor (receiver 1), C_{rx1}	67.52 µF
Resonance capacitor (receiver 2), C_{rx2}	67.70 µF
Resonance capacitor (receiver 3), C_{rx3}	65.71 µF
Resonance capacitor (receiver 4), C_{rx4}	67.43 µF
Transformer turns ratio, n	46:3
Output resistor, R_{out}	5 Ω

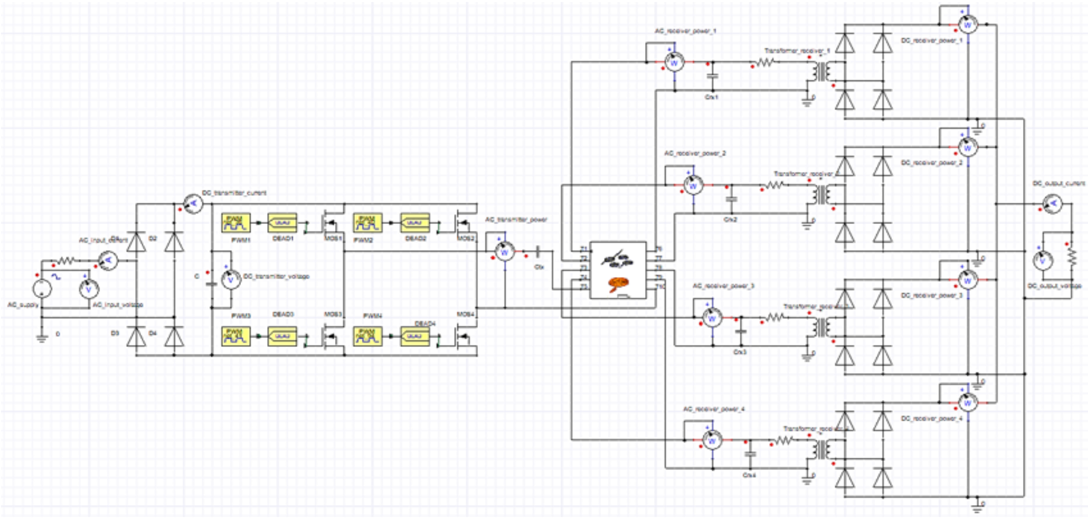


Figure 14: Wireless power transfer circuit

Simulation executed on the full wireless power transfer system showed a significant result regarding the output waveform obtained at the end load. Referring to Figure 14, the end load of the system is connected in parallel in order to maintain consistent voltage sources from the receivers. Based on the overall simulation, output waveform shown in Figure 15 showed average DC voltage of 9.5 V is received with flowing current of 1.89 A. This showed 20 percent of expected voltage is loss during the transfer process. Despite of losses recorded, the system is still capable to produce an output power of 18 W which is still enough to act as a fast charger for a mobile phone.

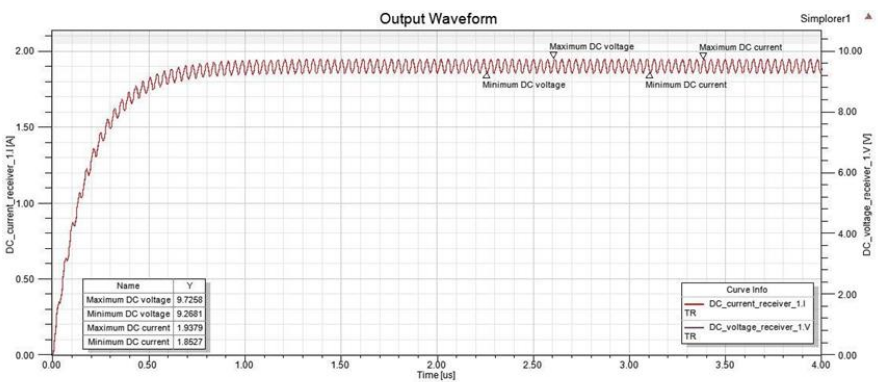


Figure 15: Output waveform of end load

In the other side, simulation of wireless power transfer system also verify the concept of magnetic resonance applied in this project. This is proved by the ratio of power received per power transferred as illustrated in Figure 16. Referring to Figure 16, the ratio of power received per power transferred showed the highest amplitude of 0.812 at frequency of 13.5571 MHz. This showed wireless power transfer occurs optimally at resonance frequency due to proper configuration of resonant tank in the circuit. On top of that, this also showed the single transmitter and multiple receiver configuration proposed in this project is able to improve the system efficiency as well as reducing the circuit complexity in the system. Thus, the proposed design in this project is proved to produce a wireless power transfer system with an efficiency up to 80% in overall.

Figure 16: Ratio of power received per power transferred at resonance frequency

4. Conclusion

In this paper, a single transmitter and multiple receiver configuration wireless power transfer system using magnetic resonant coupling method has been proposed and simulated. The simulation results obtained have shown an improvement in power transfer efficiency as well as circuit complexity reduction. The total efficiency of 81.2% obtained showed the optimization of wireless transfer system is achieved by implementation of magnetic resonant at resonance frequency of 13.56 MHz. Moreover, the output voltage ripple is reduced significantly to due to proper configuration of resonant tank which also act as LC filter for the wireless power transfer system. In overall, this wireless power transfer system configuration is suitable to act as wireless mobile charger as 20 W of power is produced by the system.

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References

[1] K. Kusaka and J. I. Itoh, “Reduction of reflected power loss in an AC-DC converter for wireless power transfer systems,” IEEJ J. Ind. Appl., vol. 2, no. 4, pp. 195–203, 2013.

[2] S. Lee, S. Kim, and C. Seo, “Design of multiple receiver for wireless power transfer using metamaterial,” Asia-Pacific Microw. Conf. Proceedings, APMC, pp. 1036–1038, 2013.

[3] A. K. Sah, “Design of Wireless Power Transfer System via Magnetic Resonant Coupling at 13.56MHz,” Proc. IOE Grad. Conf. 2013, vol. 1, no. May, pp. 202–210, 2013.

[4] Y. Tsuchida, S. Ito, and M. Fukui, “Development of magnetic resonant wireless power transfer system robust to position gap,” 2018 IEEE Int. Conf. Consum. Electron. ICCE 2018, vol. 2018-Janua, pp. 1–4, 2018.

[5] M. Masuda, “Electric field coupling type high power wireless power transfer with leakage electric field strucure,” 2018 Int. Power Electron. Conf. IPEC-Niigata - ECCE Asia 2018, pp. 88–93, 2018.

[6] C. Blake and C. Bull, “IGBT or MOSFET: Choose wisely,” EngineerIT, vol. 2018, no. April, pp. 37–39, 2018.

[7] U. Azad and Y. E. Wang, “Transmitter configuration to improve resonant coupling efficiency of a wireless power transfer system consisting of misaligned coils,” IEEE Antennas Propag. Soc. AP-S Int. Symp., vol. 1, pp. 848–849, 2013.

[8] A. Agcal, S. Ozcira, and N. Bekiroglu, “Wireless Power Transfer by Using Magnetically Coupled Resonators,” Wirel. Power Transf. Fundam. Technol., 2016.

[9] H. Lang, “Optimization of Wireless Power Transfer Systems with Multiple Transmitters and Receivers,” PhD dissertation, The Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, 2018.

[10] K. E. Koh, T. C. Beh, T. Imura, and Y. Hori, “Multi-receiver and repeater wireless power transfer via magnetic resonance coupling - Impedance matching and power division utilizing impedance inverter,” ICEMS 2012 - Proc. 15th Int. Conf. Electr. Mach. Syst., vol. 3, no. 1, pp. 1–6, 2012.

[11] N. Ramalingam, “Implementation of SPWM technique,” International Journal of Advanced Research in Biology, Engineering, Science and Technology (IJARBEST), Vol. 2, Issue 9, 2016.

[12] A. Abdolkhani, “Fundamentals of Inductively Coupled Wireless Power Transfer Systems,” Wirel. Power Transf. - Fundam. Technol., pp. 3–26, 2016.

[13] M. M. El Rayes, G. Nagib, and W. G. Ali Abdelaal, “A Review on Wireless Power Transfer,” Int. J. Eng. Trends Technol., vol. 40, no. 5, pp. 272–280, 2016.

[14] A. Brief, “AC Motor Drive Using Cosimulation,” ANSYS, Inc., pp. 1–4, 2014.