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Simple Design of Transmitter Circuit and Optimization Design of Receiver Circuit for Wireless Power Transfer

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Abstract. Two important parts of wireless power transfer are transmitter circuit and receiver circuit. Previous research has been completed which use CMOS H-Bridge in transmitter and full wave rectifier in receiver. This paper presented simple design of transmitter circuit and optimization of receiver circuit in rectifier circuit with transient analysis and Fast Fourier Transform (FFT) from LT spice software. The simple transmitter circuit used an integrated circuit (IC) NE555 with push-pull as oscillator circuit and LC resonant, while the receiver circuit used LC resonant, rectifier circuit, CLC filter for smoothing direct current (DC) output and 500 Ohm as load. The circuit design had resonant frequency of 250 kHz on both of transmitter and receiver, which comply with Power Matters Alliance (PMA) standard. The optimization of rectifier circuit had been done by comparing output of power load when it used basic rectifier (full wave), voltage doubler (dickson circuit and Villard circuit) and voltage multiplier (cockcroft-walton circuit). The results showed the receiver with Dickson circuit as rectifier has the highest efficiency compared to other rectifier circuits with efficiency of 10.93 % when it used coupling coefficient of 0.99, because Dickson rectifier has resonant frequency that is closest to 250 kHz and the highest level power, compared to other rectifier circuits.

1. Introduction

Research topic about Wireless Power Transfer (WPT) is highly increased recently. WPT can be used in several functions depending on the power, such as the use on low power charging-battery of implantable medical devices and the use in high power charging-battery of electric vehicles [1]. WPT has two categories: (1) Near-field transfer which well-known as non-radiative technique, and (2) far-field transfer which well-known as radiative technique [2,3]. The near-field transfer happens when the resonating frequency of the electromagnetic field is comparatively low (Hz - MHz) and the transfer range is comparatively short, inversely to far-field transfer which transferring power by a beam of electromagnetic source [2,3].

The resonant frequency from WPT circuit regulated in different three standards, that is the Alliance for Wireless Power (A4WP), the Wireless Power Consortium (WPC), and the Power Matters Alliance (PMA) or Rezence [4]. WPC and PMA use frequency ranges 110~205 kHz and 205~300 kHz, respectively, while A4WP use frequency 6.78 MHz ± 15 kHz carrier frequency [5,6].

A lot of researches was already done in WPT circuit with near-field categorized, it can be seen in **Table 1** [7–10]. The common WPT circuit consists of two important parts, transmitter and receiver. The transmitter circuit consists of oscillator circuit such as power amplifier (PA) or royer oscillator and resonant tank (LC tank). The receiver consists of resonant tank (LC tank), rectifier circuit (full wave or basic rectifier, voltage doubler or voltage multiplier) and load.

Table 1. Recent oscillator and rectifier circuit for research in WTP circuit

	Transmitter Circuit	Receiver Circuit	Resonant Frequency
Aldhaher et al	Class E Power Amplifier	Class E Rectifier	800 kHz
Irawan et al	Royer Oscillator	Full Wave	145 kHz
Ranum el al	Power Generator	Voltage Doubler	10 MHz
Schuetz et al	Direct Digital Synthesis (DDS)	Full Wave	13.56 MHz

State of the art of this paper, we proposed a simple design for transmitter circuit part which using an integrated circuit (IC) NE555 timer with astable multi-vibrator and push-pull transistor circuit and optimization in the receiver circuit. The transmitter circuit is different from previous research which was used CMOS H-Bridge and the receiver circuit was used full wave rectifier [11]. In the receiver circuit, the optimization of rectifier was used to define which rectifier that can give the highest efficiency. Furthermore, WPT circuit design had fixed resonant frequency at 250 kHz, which meet the requirement of PMA standard. In this paper, multifunction and free software namely LT spice software simulation tool was used for circuit design with command K1 Lt Lr .99, which had function to set coupling coefficient (k) between inductor LC tank of transmitter (L_t) and inductor LC tank of receiver (L_r) from 0 to 0.99 with increment 0.05. In addition, there was air gap between L_t and L_r. Furthermore, FFT was used to get resonant frequency of circuit design. the coupling coefficient similar to the fraction of magnetic flux resulted by L_t which flows through L_r and ranges from 0 to 1. Maximum coupling is obtain for transmission efficiency [12].

2. Circuit Design

2.1. Transmitter Circuit

The NE555 IC timer is famous and low-cost IC which can generate various waveforms, such as integrated square waveform and triangular waveform [12]. The NE555 IC timer also can be used in astable and mono stable mode [13].

The astable multivibrator mode, named astable a result of the output of NE555 IC timer is regularly inconstant between low and high. The transmitter circuit using NE555 IC timer in astable multivibrator mode to make square wave with sharp transition between low and high voltage. Furthermore, push-pull transistor was used to make the square waveform to sinusoidal waveform, so the LC tank resonate in sinusoidal waveform. The transmitter circuit design can be seen on **Figure 1**.

Input voltage of NE555 IC timer and push-pull transistor were using direct current (DC) with value 5 volt, as shown on **Figure 1**. The value of component in astable multivibrator mode was calculated by period and frequency (number of cycles per second) formula (equation 1 & 2) [13]. Furthermore, the value of LC tank was generated from resonant frequency (equation 3 & 4) [14]. The output frequency of NE555 IC timer was same as the resonant frequency of LC tank, with value frequency close to 250 kHz.

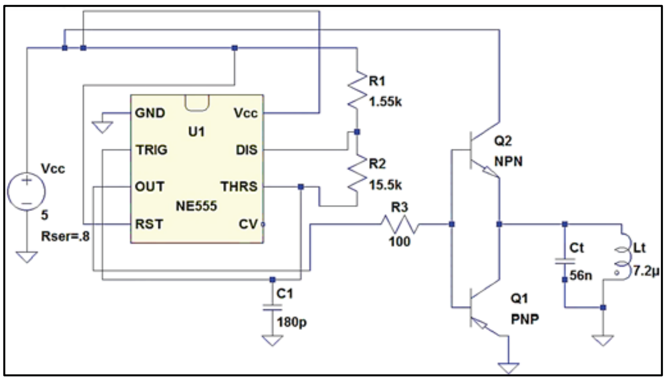

Figure 1. Proposed transmitter circuit using LTspice

$$\mathbf{f} = \frac{1.44}{(R_1 + 2R_2)\times C_1} \tag{1}$$

$$\mathbf{T} = 0.693\times(R_1 + 2R_2)\times C_1 \tag{2}$$

$$\omega_t = \frac{1}{(L_t\times C_t)^{1/2}} \tag{3}$$

$$f_t = \frac{1}{2\pi\omega_t} \tag{4}$$

Where,
f = frequency of NE555 IC timer (hertz)
R = resistor (ohm)
C = capacitor (farad)
T = period of NE555 IC timer (second)
$\boldsymbol{\omega_t}$= angular frequency transmitter of LC tank (radiant per second)
$\mathbf{f_t}$ = frequency transmitter of LC tank (hertz)
$\mathbf{L_t}$= inductor transmitter of LC tank (henry)
$\mathbf{C_t}$= capacitor transmitter of LC tank (farad)

2.2. The Receiver Circuit
The receiver circuit consists of LC tank, rectifier, CLC filter and load. The LC tank resonant frequency 250 kHz and the value component of LC tank calculated by equation (5 & 6) [14].

$$\omega_r = \frac{1}{(L_r\times C_r)^{1/2}} \tag{5}$$

$$f_r = \frac{1}{2\pi\omega_r} \tag{6}$$

Where,
$\boldsymbol{\omega_r}$= angular frequency receiver of LC tank (radiant per second)
$\mathbf{f_r}$ = frequency receiver of LC tank (hertz)
$\mathbf{L_r}$ = inductor receiver of LC tank (henry)
$\mathbf{C_r}$ = capacitor receiver of LC tank (farad)

If the alternating current (AC) voltage from LC tank would be used in charging direct current (DC) battery, it must be converted to direct current (DC) after LC tank part by using rectifier circuit. A lot of research has interest about rectifier circuit in energy harvester, but small has interest of the use of

WPT. Therefore, this paper describes the optimization of rectifier part, in order to get highest output of DC for WPT application. The rectifier circuit has two categories, basic rectifier (full wave rectifier) and voltage doubler (cockroft-walton, dickson charge pump and villard). The optimization of using 4 different circuits from basic rectifier and voltage doubler circuit is presented on **Figure 2**.

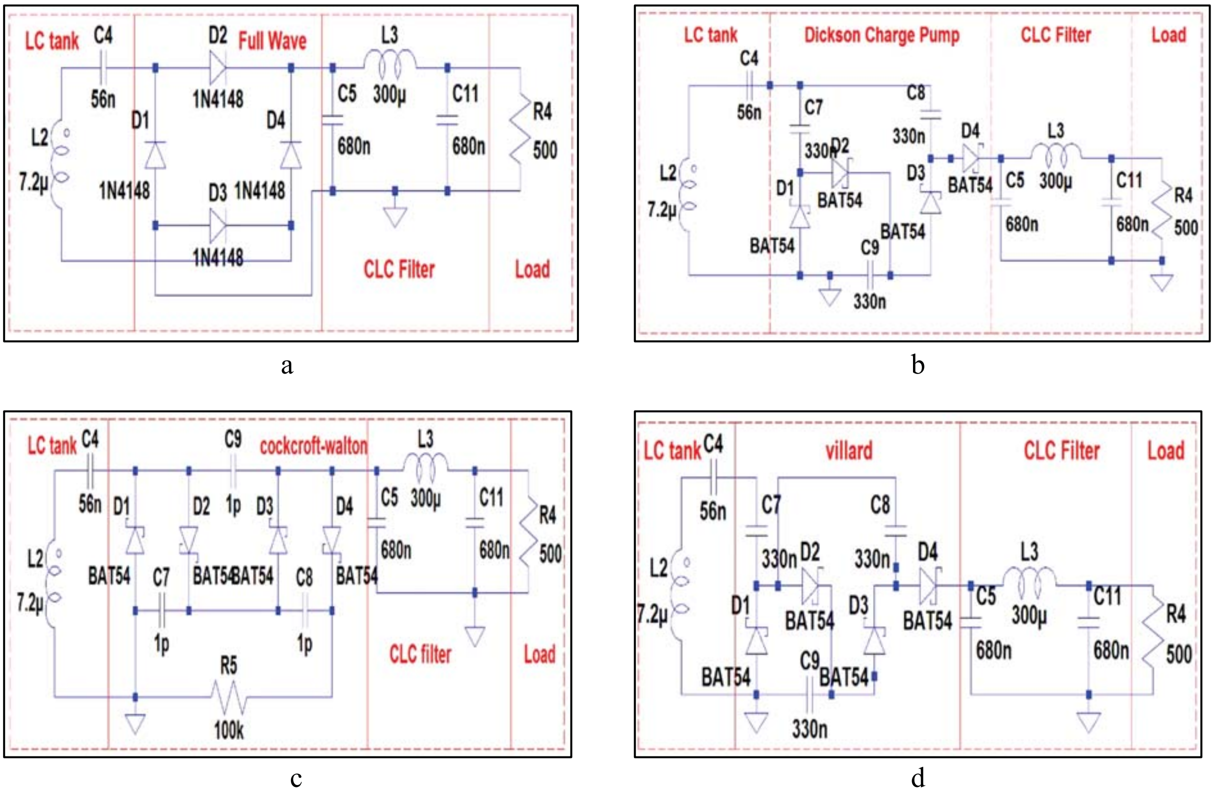

Figure 2. The receiver circuit for wireless power transfer use different rectifier circuit : a) full wave rectifier ; b) dickson rectifier ; c) cockroft-walton rectifier ; d) villard rectifier

3. Results And Discussions

3.1. Result of the Simulation

The simulation were conducted by using transmitter with IC NE555 timer and receiver circuit with full wave, Dickson, cockroft-walton and villard rectifier circuit, which resulting resonant frequency, voltage and current both of Lt and L_r.

Figure 3 show the closest and the farthest resonant frequency of circuit design in L_t and L_r when k of 0.99. The red and blue line on those images refer to f_t and f_r, respectively. The rectifier circuit with Dickson rectifier has resonant frequency of 254.9 kHz, which is the closest to 250 kHz and the highest-level of power in dB unit among rectifier circuits. Furthermore, full wave rectifier has resonant frequency of 257 kHz, which is the farthest resonant frequency and the lowest power in dB unit among rectifier circuits. The low-level power from full wave rectifier has an effect to the efficiency of WPT circuit.

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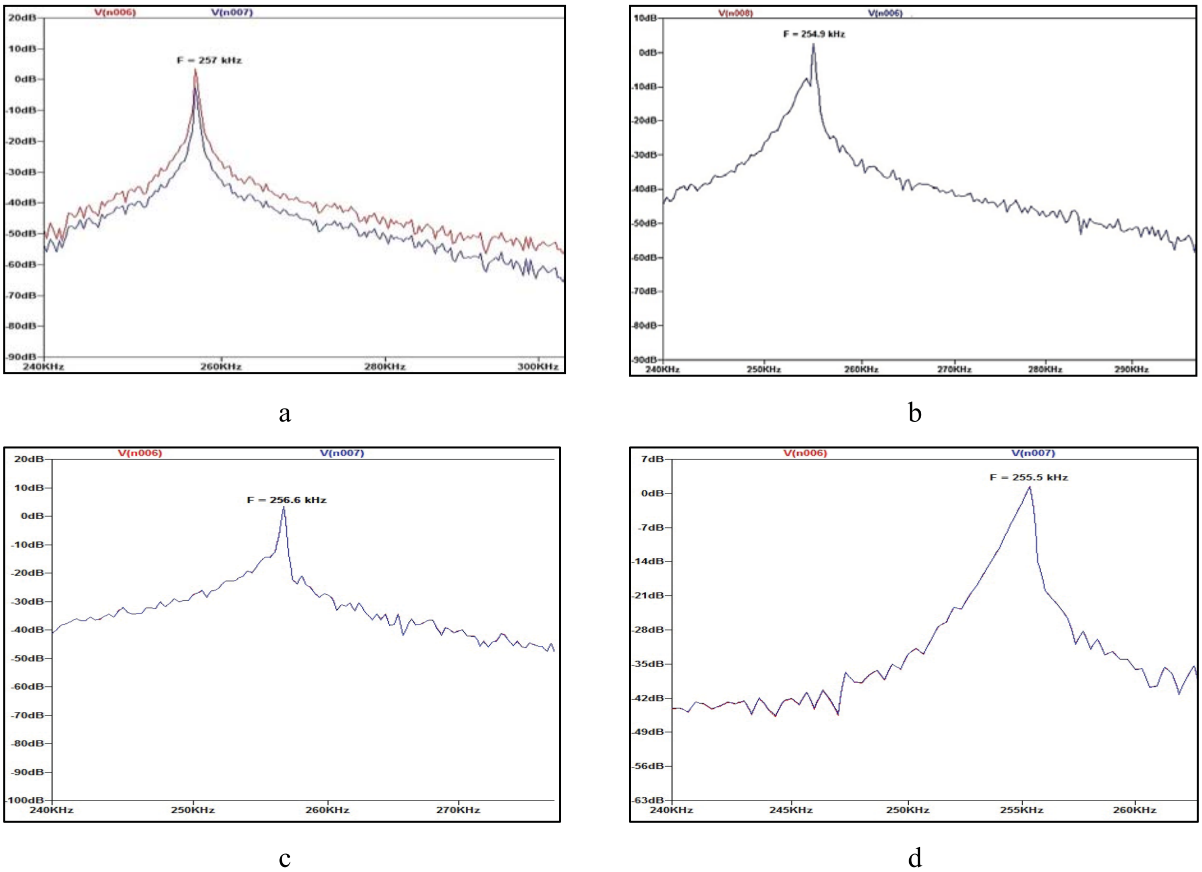

Figure 3. Result resonant frequency which use different rectifier : a) full wave rectifier ; b) dickson rectifier ; c) cockcroft-walton rectifier ; d) villard rectifier

The resonant frequency and level of the power can effect to voltage and current measured in load. The red, blue, pink, green lines on **Figure 4** refer to voltage in Lt, current in L_t, voltage in load, and current in load, respectively **Figure 4** show that the full wave rectifier only generated 0.7 mV in load, while Dickson rectifier resulted 4.2 V in load.

3.2. Efficiency (η)

Efficiency (η) of the circuit design can be calculated by using voltage and current from simulation both of Lt and of load. Efficiency (η) can be calculated by equation 7 [14]. Efficiency (η) of the circuit design can be seen in **Figure 5**. The result of η was based on different rectifier, as Dickson rectifier had the highest result of $\mathbf{P_r}$ and $\mathbf{P_t}$. **Figure 5** shows the maximum of circuit design that used Dickson rectifier could generate when it was using k of 0.95.

$$\boldsymbol{\eta} = \frac{\boldsymbol{P_r}}{\boldsymbol{P_t}} = \frac{\boldsymbol{V_r i_r}}{\boldsymbol{V_t i_t}} \qquad (7)$$

Where,
$\boldsymbol{\eta}$ = efficiency (%).
$\mathbf{P_r}$ = power receiver (watt).
$\mathbf{P_t}$ = power transmitter (watt).
$\mathbf{V_r}$ = voltage receiver (volt).
$\mathbf{i_r}$ = current receiver (ampere).

$\mathbf{V_t}$ = voltage transmitter (volt).
$\mathbf{i_t}$ = current transmitter (volt)

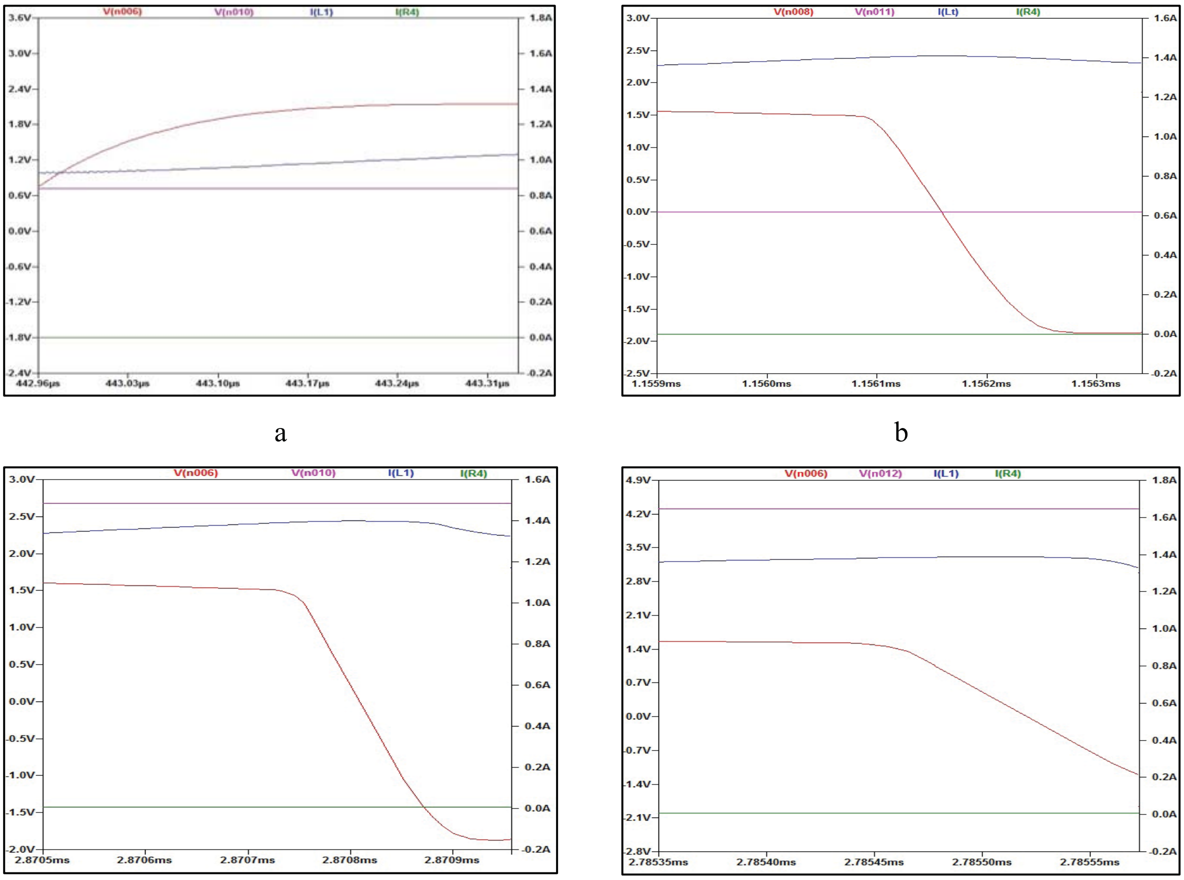

Figure 4. Result V_t, i_t, V_r and i_r which use different rectifier : a) full wave rectifier ; b) dickson rectifier ; c) cockcroft-walton rectifier ; d) villard rectifier

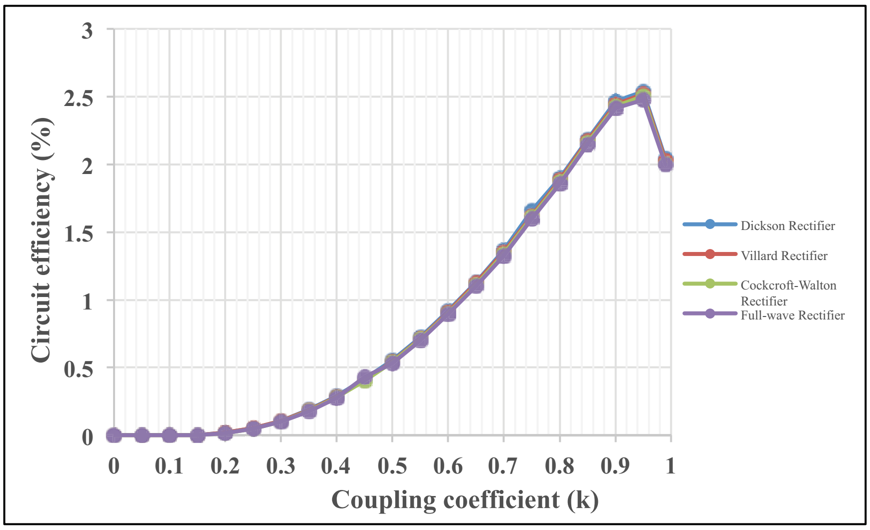

Figure 5. Efficiency of design circuit when using different rectifier

4. Conclusion and Future Work

The simple design circuit with optimization of receiver circuit for WPT was successfully designed. Although the circuit design had resulted lower efficiency than those of previously reported researches, the optimization resulted that Dickson rectifier was able to generate resonant frequency that was closest to 250 kHz, which complied with PMA standard. Furthermore, when the circuit design was using Dickson rectifier, it resulted the highest efficiency of 2.53 %and k of 0.95.

The aim of this research was to make real simple circuit design by using IC NE555 timer in transmitter and to optimize the receiver circuit, so the real distance can be measured and the other effects which can disturb the efficiency (η) will be understood.

Acknowledgments

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