Wireless Power Transmitter Apparatus for Low-Voltage DC Power Transmission Applications

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Abstract: Wireless power transfer (WPT) technology and applications have become popular in recent years. This is a re-emerging technology that allows a convenient, simple, easy use of electrical energy delivery from a power source to an electrical load within a medium distance in the absence of any electrical cord. This paper presents a wireless power transmitter apparatus that has the capability to propagate wirelessly a low voltage to a load coupled at a wireless power receiver output module. The voltage to be transmitted coming from 2.5 – 3.5 V at a maximum current of 2A DC power source. It differs from typical developed wireless power transmission systems which usually transmit high voltage from either DC or AC power sources. The proposed apparatus was developed applying the magnetic induction concept, working at the operating frequency of 110kHz at a maximum transmission distance of about 10mm. Maximum power transfer is achieved at 5W with 5V constant output voltages and the maximum output current is up to 1.4A. These specifications are suitable for electronic device power charger applications. The experimental results show the developed apparatus has a peak power transfer efficiency of around 70% and complies with the international standard requirement for interoperability.

1 INTRODUCTION

Over years ago, wireless power transfer systems have been developed by adopting electromagnetic concepts either mutual induction or resonance methods. Nowadays, this technology is re-emerging and appealing to researchers and developers applying it in many applications from electronic devices to electrical vehicle systems.

The WPT systems enable an electrical load to obtain electrical energy that propagates wirelessly from energy sources over a distance (Costanzo *et al*., 2014, Garnica *et al*., 2013). This concept confirmed by Heinrich Hertz experiment in 1888 (wikipedia.org). His results were proof experimentally the existence of electromagnetic radiation for the first time. He used parabolic reflector and induction coil to emit high-frequency electric power generated by an oscillator over a tiny air gap. Over years, this system has improved the overall system efficiency, therefore various applications adopted this technology to offer the user more convenience and better experience.

Comparing with the conventional plug-in charger, WPT offers a more compatible and attractive alternative because it can recharge all electricity operated devices using a single power source within an average–sized room. Moreover, the contactless feature of WPT also raises their freely and easily to move, and reliability with low cost as it uses minimal of insulation material and wire for the cables (Barman *et al*., 2015). This technology has a prospect to be a standard for wireless power transmission. The first industry standard for mobile devices inductive charging released by the Wireless Power Consortium (WPC) (Johns, 2011), which is called “Qi” (pronounce “chee”) (WPC, 2011).

In the literature, several wireless power transfer works based on inductive electromagnetic coupling have been developed and realized. In (Cao *et al*.,

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2014), the authors presented WPT system for portable electronic device. The system is composed of transmitter (Tx) and receiver (Rx) modules, and has power efficiency of 65%. Tx and Rx coils were developed using Fe-based soft magnetic composites sheet to improve power transfer efficiency. The Tx module is powered by 20V, 20W DC to provide more than 5W at output power of Rx module.

A 36W WPT system for LED lighting applications is presented by Chen *et al*. (Chen *et al*., 2013). The Tx module powered with 34V DC to provide 35.9W across a 30Ω load at Rx output module. It has 82% power delivery efficiency with the distance range of 5mm. A class E amplifier was applied in Tx module.

Her *et al*. developed a WPT system that involve the green energy concept. PIC16F1937 microcontroller was applied on Tx module to generate 125kHz PWM (Her *et al*., 2012). The developed system is used to charge a PRC Li-Polymer 360mAh battery with power delivery efficiency of 43.4%. Tx module is powered by 8V, 320mA DC to achieve output power of 3.73V, 298mA at Rx output module.

On chip Tx module for WPT system that comply with Qi standard specification is presented by Berger *et al*. (Berger *et al*., 2016). The module was proposed to maximize the power efficiency. It is developed to provide maximum output power at 5W for 3.3V battery charger application. The developed chip is characterized by three kind of peak receiver efficiencies; 72% for passive mode rectifier control at an output power of 1.4W, 82% for semi-active mode rectifier control at an output power of 1.4W, and 88% for fully active mode rectifier control at an output power of 1.4W.

A full-bridge resonant inverter for WPT system is presented by Galizzi *et al*. (Galizzi *et al*., 2013). The bridge is coupled with Tx part and has various supply in range of 2 – 3 V to control total power transfer. It has a peak efficiency of 70% and work with certified WPT standard such as Qi standard.

Nataraj *et al*. present a DC–DC WPTs simulation model (Nataraj *et al*., 2017). The model was developed using Multisim. The simulation worked with the operating frequency range of 10Hz to 1kHz and an Tx input signal of 5V DC. Their simulation shows the output voltage is increased proportionally with the load resistance.

A wireless powered sensor chip is introduced by Yoo *et al*. (Yoo *et al*., 2010). The sensor consumes 12uW that is harvested energy surrounding using a health monitoring chest band with 54.9% efficiency. It works based on inductive coupling of WPT and an Adaptive Threshold Rectifier (ATR).

A wireless power receiver with dual mode transmission methods is presented by authors by Satyamoorthy *at el*. (Satyamoorthy *at el*., 2014). The receiver works in the 110 to 205 kHz (inductive mode) and 6.78MHz (resonance mode) frequency bands. It provides 5W output to comply with Qi standard and achieves a peak efficiency at 84% in inductive mode and 82% in resonant mode.

As mention in the literature above, some WPT systems based on magnetic induction have been developed for various applications. Some methods also presented in order to improve and revise the performance and functionality. In a couple of recent years, many applications begin to change over to WPT technology in order to transmit the power because of some benefits offered this technology. Although many WPT applications have been developed, however, in some application cases, a low voltage from DC power source needs to be transferred wirelessly to the load, but the load needs a voltage higher than the voltage provided by the power source.

This paper presents a wireless power transfer apparatus which capable to transmit a low DC voltage wirelessly to an electrical load that couples with wireless receiver module. The voltage to be transmitted coming from 2.5 – 3.5 V at a maximum current of 2A DC power source. Then, the receiver can provide a stable output voltage at 5V and a maximum current up to 1.4A. The developed apparatus complies with the international standard requirement for interoperability. The proposed apparatus also differs from typical developed wireless power transmission systems which usually transmit high voltage from either DC or AC power source. Some WPT applications in medical implantable also supply a low voltage to be transmitted to the load but the load also consumes voltage almost same as the voltage transmitted by the transmitter.

2 MATERIALS AND METHODS

2.1 Basic Design Concept

The proposed apparatus is design based on electromagnetic induction principle. The concept is described in Maxwell's equations is composed of Ampere's circuital and Faraday's induction laws (Ban *et al*., 2013). Ampere's circuital law introduces the relation between magnetic fields and the electric current, while the Kelvin-Stokes theorem is equivalent to Ampere's circuital law and written in either integral form or differential form. Ampere's circuital law is a line integral of magnetic field around an arbitrary closed curve *c*. The electric current passes through a surface *s* which in turn bounded and enclosed by curve *c*. The total current *i* passes through the surface *s* enclosed by *c* is proportional to the magnetic *B* field around a closed curve *c* (Sadiku, 2015):

$$\oint_c \mathbf{B}.\,\mathrm{d}\mathbf{l} = \mu_0 \oint_s \mathbf{J}.\,\mathrm{d}\mathbf{s} = \mu_0 \sum \mathrm{i} \tag{1}$$

where μ_0 is the magnetic constant, and *J* is the free current density.

Due to symmetry, the magnetic field lines perform concentric circles in planes perpendicular to the wire. The direction is the right-hand curl fingers if the wire is wrapped by them with the thumb in current direction. Suppose that the closed curve *c* is a circle of radius *r* centered on straight wire. The magnetic flux density can be expressed in line integral as follow (Sadiku, 2015):

$$\oint_c \mathbf{B}.\,\mathbf{dl} = 2\pi \mathrm{r} \mathrm{B} = \mu_0 i \tag{2}$$

$$\mathrm{B} = \frac{\mu_0 \mathrm{i}}{2\pi \mathrm{r}} \tag{3}$$

Actually, Faraday's law describes the phenomenon is called electromagnetic induction. An electromotive force (emf) is induced in any closed circuit using a time-varying magnetic flux through the circuit. Faraday's law of induction uses the magnetic flux Φ through a hypothetical surface *s* whose boundary is a wire loop *l*. The magnetic flux is defined by a surface integral (Hayt *et al*., 2012):

$$\Phi = \oint_s \mathbf{B}.\,\mathrm{d}\mathbf{s} \tag{4}$$

The induced emf ε is proportional to the rate of change of the magnetic flux (Hayt *et al*., 2012):

$$\varepsilon = -\frac{\mathrm{d}\Phi}{\mathrm{dt}} \tag{5}$$

Lenz's law expresses the direction of the induced current caused by the emf, which indicates that the magnetic field produced by the induced current opposes the original change in magnetic flux.

The magnetic field generated by one coil is coupled with other coils. The first coil (coil_1) has N_1 turns which carries a current i_1 and emits a magnetic field vector B_1. The magnetic field lines pass through the coil_1 will then also pass through the coil_2. The magnetic flux through coil_2 due to i_1 is expressed by Φ_{21}. Thus, there will be an induced emf associated with the changing magnetic flux in the second coil by varying i_1 with time (Hayt *et al*., 2012):

$$\varepsilon_{21} = -\mathrm{N}_2 \frac{\mathrm{d}\Phi_{21}}{\mathrm{dt}} = -\frac{\mathrm{d}}{\mathrm{dt}} \int_{\mathrm{coil2}} \mathbf{B}_1 \,.\, \mathrm{d}\mathbf{A}_2 \tag{6}$$

2.2 Wireless Power Consortium (WPC) Standard

There are three essential points which is defined by the WPC regarding standard of inductive charging of mobile devices; the power transmitter, the power receiver, and the communications protocol between the two devices (Wei *et al*., 2009). Low power for wireless power transfer is defined transmitting the power in the range of 0 to 5 W, and the distance between the two coils typically is 5mm (Johns, 2011). The power transmission uses two planar coils to emit electric energy from the power transmitter to the power receiver based on the inductive coupling method.

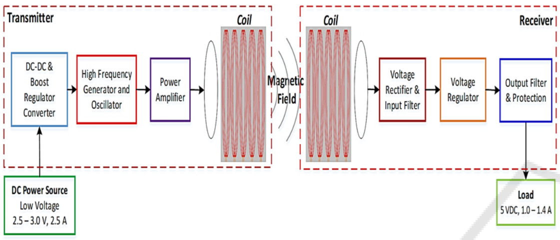
The WPC was founded in 2009, and at least 80 international companies joined as members at that time. The year the consortium was established the first international standard on wireless power for mobile devices of to 5W released. According the wireless power consortium, the key low-frequency specification for wireless power transmission is (WPC, 2011):

- Architecture: magnetic induction
- Antenna structure: planar
- Coupling: tightly coupled
- Operating frequency: 110 – 205 kHz.

2.3 Proposed Design

The proposed WPT transmitter apparatus was designed to transmit wirelessly 2.5–3.5 V DC to an electrical load that couples with a wireless receiver module. The maximum current source is 2A provided by a DC power source. In general, a WPT transmitter apparatus is used to propagate high voltage from either DC or AC power source to an electric load. Therefore, the proposed apparatus differs from the typical WPT application.

Overall, the proposed WPT system is shown in Figure 1. It is composed of Tx apparatus (Figure 1(a)) and Rx apparatus (Figure 1(b)). The proposed WPT system adopts an inductive coupling method and is compatible with the standard wireless power consortium. The proposed Tx apparatus was equipped with a front-end DC–DC and boost regulator converter circuit. This circuit provides suitable voltage for a frequency and oscillator circuit. A power amplifier circuit is excited by a signal from the frequency and oscillator circuit to generate a stable high-power electromagnetic wave. Finally, this electromagnetic wave is emitted by the Tx coil to the Rx apparatus.



(a) (b)

Figure 1: Block diagram of the proposed apparatus:(a) transmitter; (b) receiver.

A wireless Rx apparatus is also designed to conduct a performance test of the proposed wireless Tx apparatus. The wireless Rx apparatus main circuit includes a rectifier, filter, and voltage regulator as shown in Figure 1(b). It can provide a stable 5V output voltage at a maximum output current of up to 1.4A.

3 DESIGN AND RESULTS

The apparatus prototype has been developed according to the block diagram shown in Figure 1. It consists of two parts; the coil and electronic circuitry.

3.1 Coil Design

In coil design of WPT system, the magnetic field is essential because it has key role to create inductively coupling between Tx and Rx modules. The magnetic fields generate self-inductance of each coil and mutual-inductance between the two coils. Several coil parameters such as geometry, type and size of wire, number of turns, self-inductance and mutual-inductance are necessary to consider in coil design. Those coil parameters can maximize coupling coefficient between two coils.

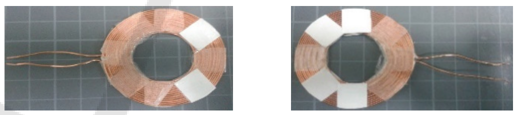
The proposed apparatus utilizes a flat spiral air core coil. It was chosen to maximize the Q-factor, efficiency, power handling, and the related magnetic field generated by the transmitter coil (Mitcheson *et al.*, 2004). The flat spiral air core coil self-inductance can be described by Harold A. Wheeler's approximations formula (Mohan *et al.*, 1999, Wheeler, 1928):

$$L = \frac{N^2.A^2}{30.A - 11.D_i} \tag{7}$$

$$A = \frac{D_i + N.(W + S)}{2} \tag{8}$$

where D_i is the coil inner diameter (inch), W is wire diameter (inch), N is the turn total number, S is the turn spacing (inch) and L is the inductance (microHenries (µH)).

Tx coil was designed having N= 17, number of turns is 1, inner diameter (D_i) is 25mm, turn spacing (S) is 0mm, wire diameter (W) is 0.64mm, outer diameter (D_o) is 49.89mm and the wire length (Wl) is 191.97cm. The coil inductance is 13.9µH that was calculated using Equations 7 and 8. Due to manual manufacturing, Tx coil is characterized by 13.7µH of inductance (L) and an outer diameter (D_o) of 49.36mm. It was built using AWG22 wire that has small diameter (0.64mm diameter and 0.0646mm insulating layer) and can be used for carrying a maximum current of 7A. Figure 2(a) shows Tx coil geometry.



(a) (b)

Figure 2: Coil: (a) transmitter; (b) receiver.

Rx coil was characterized by 14.02µH of inductance (L), an outer diameter (D_o) of 49.50mm, and 192.5cm in wire length (Wl). The coil parameter and diameter were designed same as Tx coil to maximize coupling efficiency. Figure 2(b) shows Rx coil geometry.

3.2 Wireless Power Transmitter Apparatus

Figure 3 shows the integrated Tx coil and wireless power transmitter PCB (80 × 17 mm) prototype. Part A is a DC–DC and boost regulator converter was applied using a high efficiency step up converter chip (MT3608), input and output capacitor filters (22µF), an inductor (22µH) to avoid saturation current, and a diode (SS34) to limit peak current.

The output voltage is given by Equation (9):

$$V_{out} = V_{Ref}\, x\, (1 + \frac{R_1}{R_2}) \quad (9)$$

where V_{Ref} is the internal reference voltage in Volt, R1 and R2 are the resistances in Ohm (Ω), and Vout is the output voltage in Volt. Typical V_{Ref} is 0.6V. With R_1=23,46kΩ (adjusting by potentiometer) and R_2=2.2kΩ, the boost regulator converter provides output voltage of 7V at maximum current 2.5A from input voltage source (Vs) of 2.5 – 3.0 V.

A radio frequency power supply chip (XKT–412), resistors of 8.2kΩ and 47kΩ, and a capacitor of 1nF built a high frequency generator (part B). Square waves with frequency of around 70kHz was generated by the radio chip. The signals have voltage of 7V and a maximum current of 1A.

A power amplifier circuit (part C) was built by a wireless power transmitter chip (T5336) and a capacitor of 47µF/16V. This circuit generates controllable high–frequency power signal with voltage gains of four times. Its output voltage is around 32 Volts.

The operating frequency/oscillator (part D) was controlled by the voltage difference between the DC voltage and the T5336 output. The oscillator circuit was built of LC tank, TX coil (13.9µH), and capacitors bank of 39nF. The capacitor bank defines the operating frequency of proposed TX of around 110kHz. This frequency complies with WPC standard operation frequency between 100 – 205 kHz.

The operating frequency was obtained by Equation (10):

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (10)$$

where f is the oscillation frequency (Hertz (Hz)), L is the coil inductance (Henry's (H)), and C is the capacitance (Farad (F)).

The circuitry and Tx coil built on PCB (80 × 20 mm).

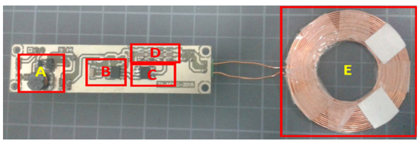


Figure 3: Wireless power transmitter apparatus prototype.

3.3 Wireless Power Receiver Apparatus

The Rx coil (13.9µH) on wireless Rx apparatus will absorb a high–frequency oscillation wave from wireless Tx apparatus. A voltage rectifier and input filter circuit (part A) converts into a DC voltage. A voltage rectifier was built by a capacitor of 27nF and a diode of SS34. While input filter built by a capacitor of 10µF/25V, and resistors of 10kΩ and 6.2kΩ.

The core of Rx apparatus (part B) is a wireless power receiver chip (T3168) and voltage adjustment (a voltage divider circuit composes of 6.2 kΩ and 2kΩ resistors).

The output filter and protection (part C) was built using a diode of SS34 and an inductor of 22µH (feedback protection), and a capacitor of 10µF/16V as an output filter.

The wireless Rx apparatus generates output voltage at 5V and a maximum current up to 1.4A. Figure 4 shows the integrated Rx coil and wireless power receiver PCB (80 × 17 mm).

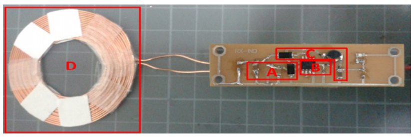


Figure 4: Wireless power receiver apparatus prototype.

4 EXPERIMENTAL AND DISCUSSION

4.1 Experimental Method

The experiment was conducted to examine the developed wireless Tx apparatus performance. The experiment configuration is composed of a 2.5 – 3.0 V, 2.5A DC power supply, wireless power Tx apparatus, wireless power Rx apparatus, two multimeters, and an Oscilloscope as shown in Figure 5.

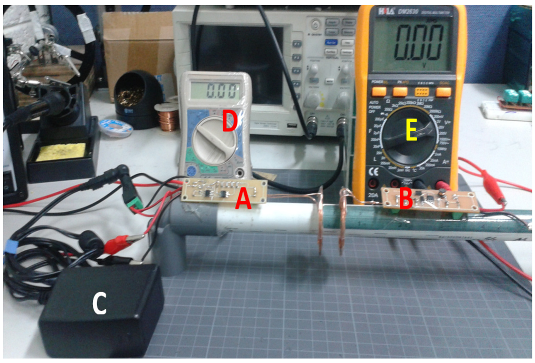


Figure 5: Experimental setup. A is wireless power Tx apparatus, B is wireless power Rx apparatus, C is DC power source, D and E are multimeters.

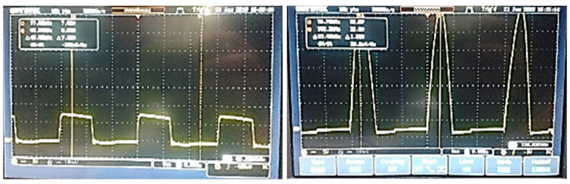
The wireless power Tx and wireless power Rx coils are configured at vertical alignment. The wireless power Tx apparatus, which powered by DC power supply, emitted power wirelessly to the wireless power Rx apparatus coupled with either a resistor or smartphone as an electric load. Multimeters measure input power of wireless power Tx apparatus and output power of the wireless power Rx apparatus output. An Oscilloscope capture and record the electromagnetic wave generated by wireless power Tx apparatus.

The experiment will perform with configuration of open load circuit, short circuit, and closed circuit crossed the wireless power Rx apparatus output terminal. A 4Ω resistor is used as an electric load. In between range from 0 to 2 cm, the gap between Tx and Rx coils is changed by the 0.5cm step. The current, voltage, and power crossed the wireless power Tx apparatus input terminal and the wireless power Rx apparatus output terminal were measured respectively. Moreover, the power delivery efficiency also obtained using input/output power measurement results.

The experimental also conducted to evaluate the developed wireless power transmitter apparatus compliance with the standard. A standard wireless receiver charger module which couples with a smartphone and a smartphone with standard wireless receiver charger module built-in are used to perform this experiment

4.2 The Characteristic Performance

The generated waveform by the radio frequency power supply chip (XKT-412) and the wireless power transmitter chip (T5336) conjunction with an Oscillator part are shown in Figure 6. The recorded operating frequency is around 110kHz.

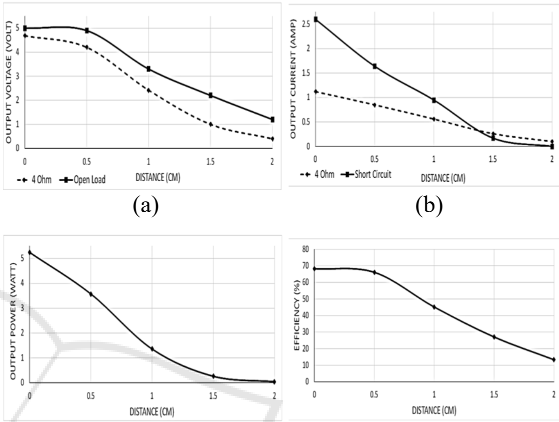


(a) (b)

Figure 6: Generated waveforms; (a) the radio frequency power supply chip waveform; (b) operating frequency waveform.

Figure 6(a) shows 7V square waves with frequency of about 68kHz generated by radio frequency power supply chip (XKT–412). XKT–412 chip input voltage is a step-up output power of the DC–DC and boost regulator converter (MT3608) part. This power is a suitable input power driving for XKT–412 chip to generate a square wave signal for the wireless power transmitter chip (T5336). Figure 6(b) shows T5336 chip and oscillator wave output. The waveform is a sinusoidal wave with an amplitude of 32 Volt and the frequency (operating frequency) of about 110kHz. This operating frequency compliance with the WPC standard.

Figure 7 shows the developed wireless power apparatus performance characteristic.



(a) (b)

(c) (d)

Figure 7: The developed wireless power characteristics; (a) the output voltage characteristic; (b) the output current characteristic; (c) the output power characteristic; (d) the efficiency characteristic.

The experiment result revealed that maximum output voltage, current and power on the wireless power receiver output are obtained at the smallest distance (tightly coupled) between Tx and Rx coils whatever the load configuration (open circuit, short circuit, 4Ω). Those will be decreased gradually with the increase in the distance between the Tx and Rx coils because of the high transmission coupling loss as shown in Figures 7(a), 7(b) and 7(c).

The output power was measured at the wireless power receiver output terminal crossed a resistor of 4Ω as shown in Figure 7(c). The power chart shows the peak efficiency is around 70% which is obtained at the maximum power delivery of 5.2W as shown in Figures 7(d) and 7(c).

4.3 Battery Charging Testing

This experiment goal is to evaluate the developed WPT apparatus compliance with the WPC standard. Figure 8 (A is device under charge, B is wireless power Tx apparatus, C is wireless power Rx apparatus) shows the developed WPT apparatus charged a smartphone battery (3.8V Li–ion battery 5.7Wh). A 2.5–3.0 V, 2.5A DC power supply was connected to the developed wireless power Tx apparatus, and the developed wireless power Rx apparatus was coupled with the device under charge (smartphone). This experiment result shows the device under charge can be charged with suitable power.

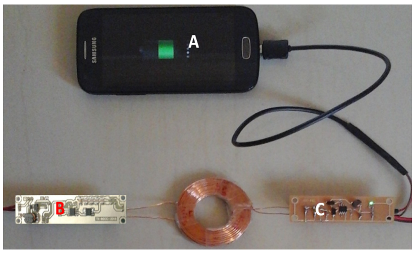


Figure 8: The battery charging experiment setup first configuration.

Figure 9 shows other battery charging experiments. The developed wireless power Tx apparatus (Figure 9(a)) was connected with a 2.5–3.0 V, 2.5A DC power supply. A smartphone couples with WPC standard wireless Rx charger module (Figure 9(b)) was charged by the developed wireless power Tx apparatus as shown in Figure 9(c).

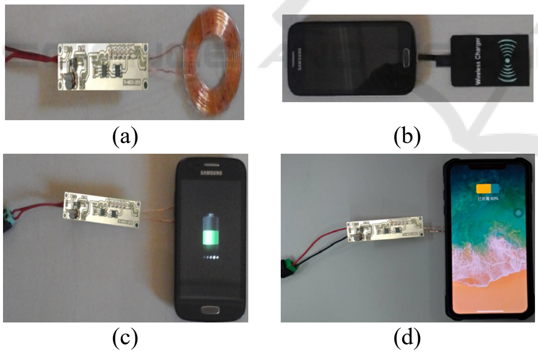


Figure 9: The battery charging experiment setup second configuration: (a) developed Tx module; (b) cell phone couple with standard wireless Rx charger; (c) charging process with standard wireless Rx charger; (d) charging process with built-in standard wireless Rx module.

While Figure 9(d) shows the developed wireless power Tx apparatus charged a smartphone with built-in wireless power Rx module. The experiment results show the developed wireless power Tx apparatus works properly and it complies with WPC standard.

The charging performance test of the developed apparatus was conducted using a 3.8V, 5.7Wh Li-ion rechargeable battery. The charging voltage of the battery under test is shown in Figure 10. In 15 minutes, the battery under test voltage reached a maximum and the charging test was stopped due to the battery voltage remained constant. Actually, the charging process can be remained to achieve maximum battery power capacity.

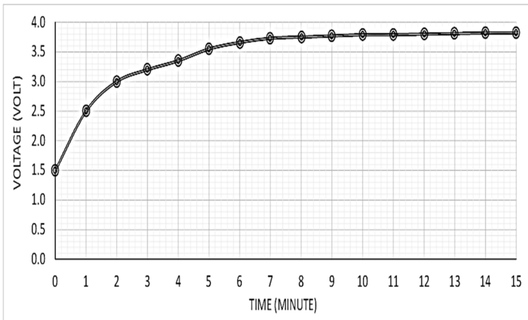


Figure 10: The Typical Charging Curve using the Developed Apparatus.

5 CONCLUSIONS

The WPT design provides high design freedom in achieving interoperability. In this research, a wireless power transmitter apparatus prototype was developed and implemented based on the magnetic inductive coupling and complies with WPC standard. There are various electrical dependent devices on the market and specific applications have the potential to use this apparatus.

According to the experimental results, the developed wireless power transmitter apparatus can work to meet the interoperability of various applications that comply with international standard either commercially or functionally. Its operating frequency is 110kHz with a maximum transmission distance of about 10mm. It achieves maximum power transfer at 5W with voltage to be transmitted coming from 2.5 – 3.5 V at a maximum current of 2.0A DC power source. From an efficiency point of view, it has a peak power transfer efficiency of around 70%.

The coil design needs more attention in the design process to improve the power transfer efficiency.

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