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Radio Frequency Based Wireless Battery Charging of Cellular Phones

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A B S T R A C T

The challenge of regularly charging the battery of cellular phones has brought about new and more convenient ways to realising cellular battery charging. The wireless power platform has been explored for years bringing about many dimensions to its realisation. In this research, developed a wireless charging of Li-Ion battery of a cellular phone using commercial-off-the-shelf components vis-a-vis Radio Frequency (RF) energy. A MAX2623 voltage controlled oscillator was used to generate RF signals at a frequency of 915 MHz. Through a series of amplifier stages, the signal is radiated using a half-wave dipole antenna. The signal is received by a remote receiver module made up of 5 dBi gain half-wave dipole antenna which is impedance matched to a bridge rectifier made of SMS3929 Bridge Quad Schottky low turn-on voltage diodes. The rectified output is received by a EH4205 low voltage booster which amplifies the input into two paralleled MAX 682 charge pumps. The paralleled MAX 682 charge pump delivers a constant output voltage of 5 V DC and current of 500 mA. Within a 4 m radius the receiver module can receive enough power for the realisation of wireless battery charging.

INTRODUCTION

Cellular phone usage and technology has become ubiquitous, as it has proven over time that its significant contributions to the globalisation concept are key to progress in modern communication. A major challenge to the use of these phones is the regular charging of their batteries and this has raised concerns in the mobile phone manufacturing industry as well as with users. Most people would not like to be tethered to the wall for several hours just to charge their phones, coupled with the fact that the current practice exhibits exposed wires, bulky cables, and bad environmental impacts [1, 2, 3]. With the fast pace at which technology is evolving, it is necessary to find alternate means of realising a more convenient way to charge the cellular phone. In this regard, it is evident that Radio Frequency (RF) as microwave energy source and part of the energy spectrum, can help in achieving a wireless means of transmitting some energy [2, 3]. Electromagnetic waves cannot propagate within a conductor; they are totally reflected when they strike a conducting surface. Radio waves are distinctively found at the lowest part of the electromagnetic spectrum and are of frequencies that fall within 3 kHz and 300 GHz.

Wireless Energy Transfer (WET) or Wireless Power Transmission (WPT) as a dynamic contactless charging technique entails the transmittance of electrical energy from a power source to an electrical load without connecting wires. Wireless transmission is useful in cases where interconnecting wires are problematic, hazardous, or impossible and typical applications include Electric Vehicles (EVs), biomedical implants, and portable electronics [4,5]. A wireless power system usually transmits energy from a transmitter to a receiver and the electric power is transmitted through an antenna, which converts the RF signal into an electromagnetic wave [5, 6]. The transmission medium for electromagnetic wave propagation is free space. The electromagnetic wave is intercepted by the receiving antenna which converts it back to a RF signal. Ideally, this RF signal is the same as that originally generated by the transmitter though, a part of this energy does not reach the receiver end. Factors affecting the electric power of propagated RF waves include antenna characteristics, system characteristics and signal loss [7, 8]. With wireless power transmission, power transfer efficiency and propagation distance are the more significant parameters [2, 4].

Six WPT technologies have been documented to date and each can be radiative or non-radiative [9]. The Laser Power Transfer (LPT) and Microwave Power Transfer (MWPT) are radiative, whilst Acoustic Power Transfer (APT), Capacitive Power Transfer (CPT), Inductive Power Transfer (IPT) and Magnetic Resonance Power Transfer (MRPT) are non-radiative [1, 9]. The LPT, MRPT and MWPT are able to achieve mid-range to far-range transmission distance with a smaller receiver radius [2, 9] and this could be suitable for remote battery charging especially the MWPT [1, 2]. More importantly, radio waves being useful in

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the MHz and GHz frequencies, can be propagated over very far fields [10].

The cellular battery is the powerhouse of the cellular phone. The Li-ion battery is a rechargeable battery best suited for mobile devices because of its small size, light weight and high performance. Its characteristics of high energy and high voltage (3.6 V) powerfully ensure these three key requirements. The three primary functional components of a lithium-ion battery are the positive and negative electrodes and the electrolyte. Generally, the negative electrode of a conventional lithium-ion cell is made from carbon (graphite). The positive electrode is a metal oxide, and the electrolyte is a lithium salt in an organic solvent. The electrochemical roles of the electrodes reverse between anode and cathode, depending on the direction of current flow through the cell [11]. Figure 1 shows the Li-ion battery of a Samsung cellular phone.

Figure 1. Li-ion Battery of a Samsung Cellular Phone

A number of research has been devoted to wireless power transfer in recent times. These include use of magnetic resonance coupling [12, 13, 14, 15], electromagnetic inductive coupling [16, 17] and capacitive coupling [18]. More importantly, Erol-Kantarci and Mouftah (2014) [19], considering Picocell base Ststions (PBSs) and dedicated Energy Transmitter Towers (ETTs) achieved RF-based WET in LTE-A heterogeneous networks. Khalifeh *et al*. (2021) [20] implemented and practically evaluated a RF-based wireless charging system for unsupervised clustered Wireless Sensor Networks (WSNs) using an off-the-shelf Powercast power charging and energy harvesting circuit. Kim *et al*. (2021) [21] researched on a smartphone-controlled wirelessly chargeable, battery powered, implatable soft, optoelectronic system for optogenetic applications.

Much of the research on WPT are devoted to WSNs, biomedical applications and EVs. Similar effort need be directed towards charging cellular phones whose use numerically could surpass the world's population in the next decade. This paper seeks to design a system whereby, a transmitter-generated RF signal at a set frequency is transmitted to a receiver circuit module located at a remote station and by virtue of some rectifier arrangements in the receiver module, the received radiation is converted from the AC into a DC signal for charging a battery using commercial-off-the-shelf components to achieve 5 V DC at 500 mA current output. The rest of the paper is structured as follows: Under methods in Section 2 are presented the theory of wireless battery charging, system design concept, data collection and analysis, development of the transmitter and receiver units as well as the overcharging unit and USB output. Bridge rectifier simulation results and discussion together with cost analysis are availed in Section 3. The research conclusions are provided in Section 4.

METHOD

Theory of Wireless Battery Charging

The basics of wireless power involve the transmission of energy from a transmitter to a receiver via an oscillating magnetic field. To achieve this, Direct Current (DC) supplied by a power source is converted into high frequency Alternating Current (AC) by specially designed electronics built into the transmitter. The alternating current energises a copper wire coil in the transmitter, which generates a magnetic field. Once a second (receiver) coil is placed within proximity of the magnetic field, the field can induce an AC in the receiving coil. Electronics in the receiving device then converts the AC back into DC, which becomes usable power for the charging of the battery. The effective power received at the receiving antenna can be calculated by the Friss transmission equation given by Equation (1) [10, 19, 20].

$$P_{rx} = P_{tx} G_{tx} G_{rx} \left(\frac{c}{4\pi D_r f_o}\right)^2 = \frac{\lambda^2 G_{rx} G_{tx}}{(4\pi D_r)^2} = \frac{A_{rx} A_{tx}}{(\lambda D_r)^2} P_{tx} \quad (1)$$

where, P_{rx} is received power, P_{tx} is transmitted power, G_{tx} is gain of transmitting antenna, G_{rx} is gain of receiving antenna, C is wavelength of transmission, D_r is distance between transmitting antenna and receiving antenna i.e. the signal propagation distance, f_o is frequency of transmission, λ is wavelength, A_{rx} is aperture area of the receiving antenna, A_{tx} is aperture area of the transmitting antenna. The power transfer efficiency or beam efficiency and the propagation distance are expressed by Equation (2) [10] and Equation (3) [22], respectively.

$$\eta = \frac{P_{rx}}{P_{tx}} = 1 - e^{-\tau^2} \quad (2)$$

$$D_r = \frac{\sqrt{60 P_{tx} D}}{\vec{E}_m} \vec{V} \quad (3)$$

where η is the power transfer efficiency, τ^2 is $A_{rx} A_{tx} / (\lambda D_r)^2$, D is the directional factor of the transmitting antenna, $\vec{V}$ is the vector of the signal attenuation factor, $\vec{E}_m$ is vector of the field strength at the distance D_r from the transmitting antenna in real conditions.

When the battery is first put on charge, the voltage shoots up quickly. The voltage of charging battery catches up when the battery is almost fully charged. Li-ion batteries are mostly charged to 4.2 V/cell with a tolerance of +/–50 mV/cell [11, 23]. Higher voltages increase the capacity, but the resulting cell oxidation reduces service life. The safety concern of charging beyond 4.2 V/cell is very important. Li-ion batteries cannot absorb overcharge, and when fully charged, the charge current must be cut off. A continuous trickle charge causes plating of metallic lithium, and this compromises safety. Therefore, in order to minimise stress, the lithium-ion battery voltage must be kept at the 4.2 V/cell peak voltage as short a time as possible. Once the charge is terminated, the battery voltage begins to drop, and this eases the voltage stress. Over time, the open-circuit voltage settles to between 3.6 and 3.9 V/cell. This charge characteristic is typical of all batteries. Figure 2 [23] gives the voltage and current

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signatures as lithium-ion battery passes through the stages for constant current and topping charge.

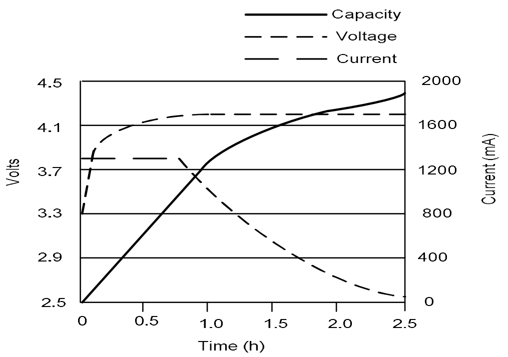

Figure 2. Typical Charge Characteristics of a Li-Ion Battery

The battery State-of-Charge (SoC) is expressed by Equation (4) [23].

$$SoC_{t_f} = \frac{Q_c}{Q_d} = \frac{\int_{t_i}^{t_f} i(t)\,dt}{Q_d} \tag{4}$$

where, SoC_{t_f} is final battery SoC, Q_c is battery capacity returned during the charging process from t = t_i to t = t_f, Q_d is the actual capacity discharged, $i(t)$ is the charging current at a given time, t, t_i is initial charging time, t_f is final charging time.

Design Concept

The design concept of the wireless charging of cellular phone battery is given in Figure 3. The proposed wireless power battery charging system should be light in weight, user friendly and effective, made of a transmitter module powered by a 5 V DC supply, made of a receiver module capable of enabling the charging of a Li-ion battery of a cellular phone of at least 800 mAh capacity, and used within a signal transmitting radius of at least 3 m.

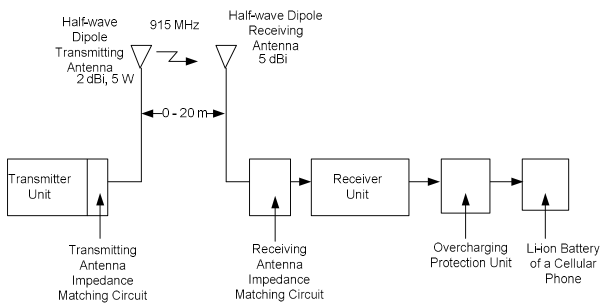

Figure 3. Design Concept of Radio Frequency based Wireless Charging of the Cellular Phone Battery

Data Collection and Analysis

In the design of the wireless power battery charging system, field data on the Li-ion battery and the standard charging devices for the various types of cellular phones are taken. The design is therefore made to reflect these parameters. Table 1 shows the rated voltage, current and power of cellular Li-ion batteries, while Table 2 shows the voltage and current rating of various USB charging points, respectively.

Table 1. Rated Voltage, Current and Power of Cellular Li-Ion Batteries

Phone Type	Rated Parameters of Battery		
	Voltage (V)	Capacity (mAh)	Power (Wh)
HTC Desire C	3.7	1230	4.55
Samsung Galaxy Advance	3.7	1500	5.55
Huawei HB5A2	3.7	1000	3.70

Table 2. Rated Voltage and Current of various USB Charging Points

Type of Charger	Voltage (V)	Current (mA)
Nokia	4.95	350
TECNO	5.00	200
Computer USB Port	4.92	Up to 2 A
RLG USB	5.00	450

From Table 1 it is seen that the maximum voltage which the various Li-ion batteries can deliver is around 3.7 V DC whereas Table 2 shows clearly that the average voltage value for charging these batteries is 5 V DC. It is also clear that the various charging points have different current ratings but almost same voltage rating. The charge capacities of the batteries in mAh indicate the amount of charge the batteries can store in an hour. If a 350 mA rated current charger is used to charge a battery with capacity 1500 mAh, it can only deliver a charge of 350 mAh in an hour as against the required 1500 mAh. This means that the charger would take more hours to fully charge the battery compared to a 900 mA rated charger which can deliver 900 mAh in an hour.

The Transmitter Unit

The block diagram of the proposed transmitter unit is given in Figure 4. The transmitter consists of a MAX 2623 Voltage Controlled Oscillator (VCO) that generates a sinusoidal RF signal in the range of frequencies that resides in the radio frequency band, 3 MHz to 3 GHz. The VCO operates at a frequency of 915 MHz. The frequency of 915 MHz is not used for mass communication, and therefore it will hardly interfere with other devices at low power levels. Since the output power of the voltage VCO is limited, an amplifier is required on the output. This signal at -3dB is supplied through Gali 6+ preliminary power amplifier to boost the -3 dB output of the VCO to 9 dB. At this stage the signal is further amplified by PF08109 dual band MOSFET power amplifier which is 50 Ω impedance-matched to a half wavelength dipole antenna. The antenna beams an output power of 5 W ready to be radiated to the receiver.

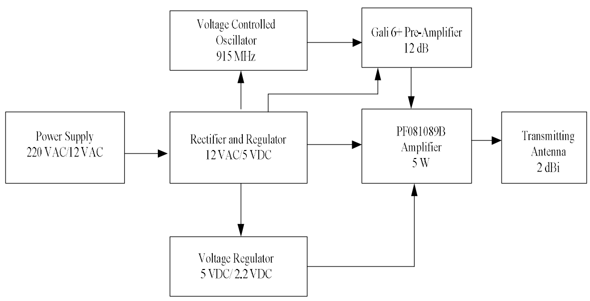

Figure 4. Block Diagram of the Proposed Transmitter Unit

Design of the Transmitter Circuit

A constant voltage of 1.32 V is maintained as tuning voltage for the VCO to operate at the frequency of 915 MHz. A 10 pF capacitor is connected in series with the PF08109B amplifier which determines the low frequency cut off of the amplifier circuit. The capacitor's value is chosen to suit the 915 MHz frequency that the amplifier circuit is used for. A bias resistor of 6 Ω is connected through the main VCC line of the amplifier to limit the current to the amplifier. An inductor (RFC) is connected in series with the bias resistor to isolate the bias resistor so that it does not appear in parallel with the output load of the amplifier, degrading the output match of the amplifier. The impedance of the choke at the lowest frequency of operation of the amplifier plus the value of the bias resistor should be at least 500 Ω. A capacitor is in conjunction with the series inductor to present a low impedance path to ground for any signal that manages to get past the RFC. The capacitor is connected at the junction of the bias resistor and the RFC to ground. A holding voltage of 2.2 V is input through pin 10 (V_{apc}) of the PF08109B amplifier to maintain the operation of the amplifier at 915 MHz. Figure 5 shows the transmitter circuit.

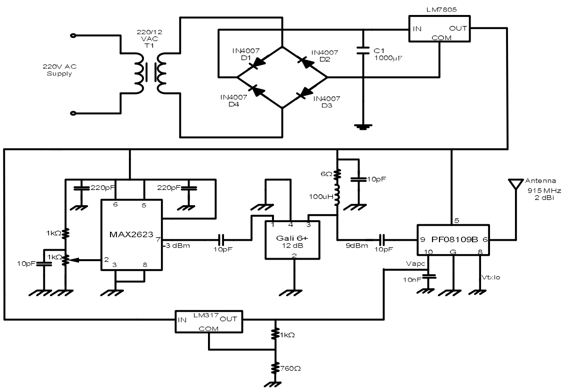

Figure 5. The Proposed Transmitter Circuit

The Receiver Unit

Figure 6 gives the block diagram of the receiver unit. The receiver unit consists of a half wavelength dipole antenna with 5 dBi gain. This antenna is impedance-matched to a full-wave bridge rectifier with low turn-on voltage SMS3929 Bridge Quad Schottky Diodes. The bridge rectifies the input AC voltage; a 100 pF capacitor connected in parallel with the bridge filters the rectified AC voltage and it is fed into a EH4205 micropower step up low voltage booster module. This booster steps up the very low voltages in millivolt to appreciable levels. An LM 7805 voltage regulator maintains a constant input of 5 V into two paralleled MAX682 charge-pumps. The full-wave bridge rectifier, voltage booster, voltage regulator and the MAX2623 charge pump together play the role of the cascaded Villard and Dickson voltage multiplier found in most wireless power devices.

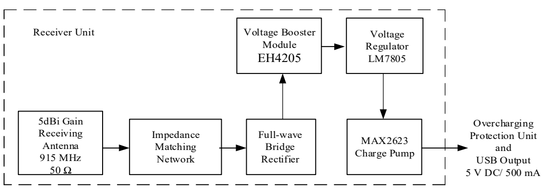

Figure 6 Block Diagram of the Proposed Receiver Unit

Design of the Receiver Circuit

The receiving antenna is impedance-matched through a 50 Ω impedance matching network to the rectification side. With the assumption that no power loss occurs as a result of impedance mismatch, the bridge rectifier made up of the four low voltage turn-on Schottky diodes rectifies the input voltage and current; the 100 pF capacitor connected in parallel serves as the filtering capacitor. The EH 4205 lies at the output of the bridge rectifier, the rectified signal is sent through a 1 kΩ resistor on the positive input to the EH 4205. Since the ouput of the EH 4205 module would vary depending on where the receiver is located from the transmitter; and in order to meet the input requirement of between 3.3 to 5 V DC of the MAX 682, LM7805 voltage regulator is placed at the output of the EH4205 module to maintain 5 V input into the MAX682 charge pump such that no matter how close the receiver is to the transmitter and how high input voltage is, the regulator would maintain a 5 V DC output. The MAX 682 charge pump, each has a voltage output rating of 5 VDC and a current of 250 mA. In order to achieve charging at a higher current, the two MAX 682 charge pumps are paralleled producing a combined output voltage of 5 V DC and current of 500 mA. An overcharging interrupting circuit is built at the output of the charge pump to cut-out charging voltage and current when the Li-ion battery has charged to 4.2 V. In this circuit a zener diode with voltage rating at 4.5 V is connected parallel to a NPN transistor. The diode turns on when the Li-ion battery charges to 4.2 V DC thereby switching on the transistor. The transistor once ON remains in that state until the battery voltage falls to below 4.2 V DC. A LED is connected parallel to the transistor to indicate the ON state of transistor which also means battery is fully charged. The output of the overcharge circuit is connected to the USB port. Figure 7 shows the circuit layout of receiver.

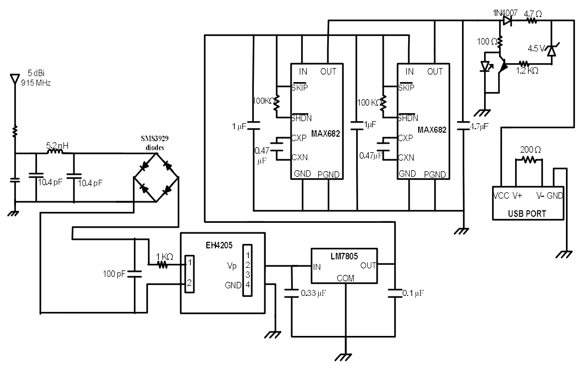

Figure 7. The Proposed Receiver Circuit

Overcharging Protection Unit and USB Output

The paralleled charge pumps maintain a constant 5 V DC and 500 mA current output which is supplied through an overcharging protection unit to prevent overcharging of Li-ion battery. A USB port is directly connected to the output of the overcharging protection unit to serve as the main port where available power can be tapped for the charging of cellular phone battery.

Overcharging Protection Circuit

The overcharging protection circuit is made up of 4.5 V zener diode, NPN transistor, LED resistors and 1N4007 diode. The diode is connected in series with a 4.7 Ω resistor to conduct

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current in one direction to the USB device. Figure 8 shows the overcharging protection circuit.

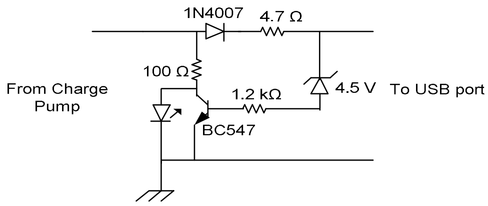

Figure 8. The Overcharging Protection Circuit

USB Port Output

The USB employed in this work is the USB 2.0 which can provide a voltage output of 5 V DC and can allow for a maximum current of 500 mA. Figure 9 shows the DC power-out USB port.

Figure 9. The DC Power-Out USB Port

Integrating the Charging System into the Receiver Circuit

The USB port serves as the charging point for the cellular phone battery. Figure 10 shows a four-terminal USB port with its labels. Table 3 gives the pin description and the cable colour code. In this design D+ and D- are shorted through a 200 Ω resistor.

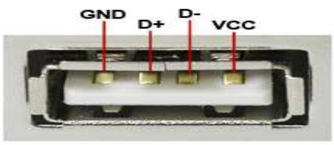

Figure 10. The USB Port Pins

Table 3. Pin Description of USB Charging Port

Pin Number	Name	Cable Colour	Description
1	VCC	Red	+5 VDC
2	D-	White	Data -
3	D+	Green	Data +
4	GND	Black	Ground

Simulation of Bridge Rectifier

A SPICE model of the SMS3929 Schottky diode was created using NI Multisim 13.0 workbench. The output rectified DC voltages and currents of the bridge circuit at various received power levels were measured. Figure 11 shows the SPICE model of the SMS3929 Schottky diode in NI Multisim 13 workbench and a snapshot of the SMS3929 Schottky diode bridge rectifier in NI Multisim workbench is shown in Figure 12.

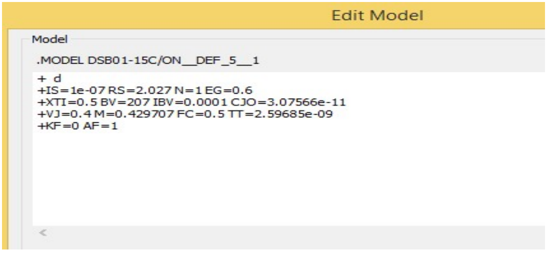

Figure 11 SPICE Model of the SMS3929 Schottky Diode in NI Multisim 13 Workbench

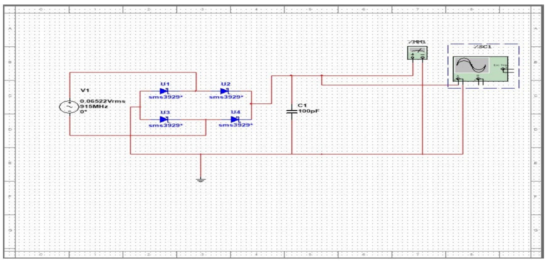

Figure 12 Snapshot of the SMS3929 Schottky Diode Bridge Rectifier in NI Multisim Workbench

RESULTS AND DISCUSSION

The simulation of the proposed wireless power charging system was centered on the bridge rectifier. With the assumption that maximum power is received and that there are no losses attributable to impedance mismatch, the following results are presented as well as the ensuing discussions.

Results of Simulation of Bridge Rectifier

Figure 13 presents the results of plot of received power, voltage and current (AC) against varying distance, as far as 20 m away from the transmitter module and Figure 14 presents the result of plot of the voltage and current (DC) against their corresponding distance points.

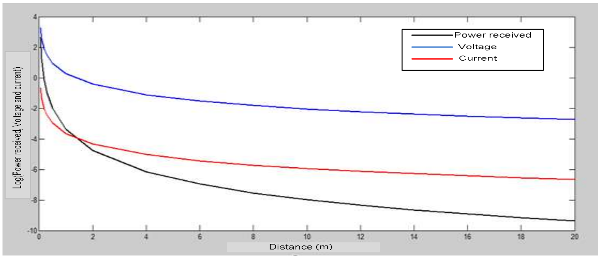

Figure 13. Received Power, Current and Voltage against Distance

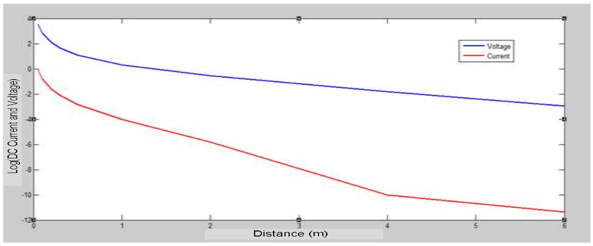

Figure 14. DC Voltage and Current against Distance

Discussions

Figure 13 showed clearly that the closest the receiver module is to the transmitter the more the received power, voltage and current. In other words, the farther away the receiver is from the transmitter, the lower the received parameters. The output of the bridge confirms the same characteristics as shown by Figure 14. It can be seen from Figure 14 that the rectified output current remains fairly low until at 4 m where it began to rise. This perfectly predicted the operating range of the transmitter-receiver module. It can thus be said that the controller of the circuit is the ouput of the bridge as it determines whether the minimum requirement of the booster module would be met or not.

Range of Use of the Wireless Power Charging Module

The bridge output voltage showed that at 4 m the output volatge was 165.35 mV and at 6 m voltage was around 50.835 mV and thus continues to decrease as the receiver goes farther away from the transmitter. The output of the EH4205 is maintained constant provided the minimum voltage requirement of the voltage booster is met. Minimum voltage rating of EH4205 module is 80 mV. It is therefore seen that a range of 4 m radius away from the transmitter produces the minimum requirement of voltage for charging the Li-ion battery.

Duration of Battery Charging

As seen from theory, the charging duration is dependent on battery capacity and the charging current. The proposed system can produce an output current of 500 mA DC, assuming a battery capacity of 1500 mAh, and ideally it should take 3 hours to charge. For a battery capacity of 2000 mAh, it can take a maximum of 4 hours to fully charge.

Cost Analysis

The cost analysis is summarised into Table 4. A total of GH¢ **2**10.00 is required by the proposed design.

Table 4. Component Cost Analysis of Proposed Design

SN	Item	Quantity	Unit Cost (GH¢)	Total Cost (GH¢)
1.	220/12 V AC Transformer	1	15.00	15.00
2.	Diodes	11	0.30	3.30
3.	Capacitors	19	0.30	5.70
4.	Voltage Regulators	3	9.00	27.00
5.	Resistors	11	1.50	16.50
6.	MAX 2623	1	6.00	6.00
7.	Gali 6+	1	7.50	7.50
8.	PF08109B	1	7.50	7.50
9.	Antennas	2	7.50	15.00
10.	NPN Transistor	1	1.50	1.50
11.	Inductors	1	1.50	1.50
12.	MAX682	2	18.00	36.00
13.	EH4205	1	60.00	60.00
14.	USB Port	1	7.50	7.50
Total Cost				**210.00**

CONCLUSIONS

The theoretical approach towards realising a wirelessly transmitted power for charging the battery of a cellular phone using commercial-off-the-shelf components showed that a constant DC output voltage of 5 V and a current of 500 mA is possible within a range of 4 m radius from the transmitter module. The receiver can intercept enough radiated power for the effective working and realisation of the intended purpose of charging a celullar battery. This wireless battery charging device can be employed in areas where the normal cellular battery charger cannot be used due to lack of sockets in proximity (at most 4 m radius according to this work) thereby creating the convenience of sitting not necessarily close to an electric socket to charge the cellular battery of one's phone. The device even though serves a good alternative for battery charging, it is limited to use with AC sources as the transmitter is powered from a 220/240 V AC source.

The issue of free space path loss and impedance mismatch must be taken into account in the actual implementation of the proposed wireless power battery charging system. The device would be best suited for indoor applications. The characteristics of these commercial-off-the-shelf devices employed in this work can be built into a microchip and incorporated into the battery charging compartments of the cellular phone.

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