Design and Implementation of a GSM-Based Wireless Power Transfer for AC/DC Loads*

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Abstract

This paper seeks to design and implement a Global System for Mobile Communication (GSM)-based wireless power transmitter and receiver circuits for the control of Direct Current (DC) and Alternating Current (AC) loads. The design is based on a self-resonating circuit, which converts DC to AC through a coupling coil. The results showed that power is effectively transferred wirelessly through resonance coupling technique. It was then concluded that the closer the separation distance, the higher the voltage transferred. This system can be actuated remotely and thus, has improved operational convenience.

Keywords: Wireless Power Transmission, GSM, AC/DC Load, Resonance Coupling

1 Introduction

Electrical power has become the number one energy source by which all activities depend with high rate of usage and demand in industries, homes, farms, etc. Electrical cables when used for a long time weakens and hence affects power transmission. As a result, conductive losses increase leading to eventual failures. The aged conductors sometimes do not handle surges very well, resulting in generation sparks, which may lead to fire outbreaks. This makes troubleshooting tedious and time consuming as faults in defective cables are difficult to identify. Also, ensuring connectivity of power remotely is presently difficult and expensive. The technology of wireless power supply may arrest the associated problems of conductor-based power transmission. Fig. 1 shows some application areas of wireless power transmission for mobile devices and medication applications.

Fig. 1 Usefulness of wireless Power Transfer (de Rooij, 2015)

Proximity and urgency in appliance control becomes a barrier where manual control of electrical gadgets is solely practiced. A GSM-based system best fits the task of having maximum control over appliances and industrial setups by SMS message commands relayed by a GSM system to a central controller for various load control anywhere via network access.

The rest of the paper is arranged as follows: the rest of this section presents a literature review of wireless power transfer while section two digs into the methodology used to achieve our design. Section three outlines the results, discussions and the mathematics involved in the wireless power transfer and section four draws out conclusions.

1.1 Concept of Wireless Power Transfer

Traditional power transmission has been via wired infrastructure for decades with various problems of difficulty tracing defective cables, sending power to remote areas etc. Since the inception of wireless transmission of energy, it has remained as a technology not developed enough for commercial use (Ahmed *et al*., 2003). Due to the evolving technology that includes electronics and portable gadgets that require electricity, it however, has become a popular topic in recent times, thereby generating new discoveries and research (Bhutkar and Sapre, 2009). Wireless transmission of energy may bring many recompenses and its use may sanction easier and convenient ways to transmit energy. Wireless power transmission could be conveniently used in areas such as mobile device charging, medical implants to reduce risk of infection, hazardous environment, etc. Wireless energy transfer brings home connector fatigue and extended battery life. Wireless power transfer can bring effectiveness in safety-critical environments

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such as explosive or corrosive atmospheres where electrical spark in the vicinity cannot be compromised, underwater, and when electrical connection is made or broken may pose a safety risk (de Rooij, 2015).

With the proliferation of mobile devices, wireless power transfer is imperative to offer convenience of charging the batteries without the annoyance of cumbersome cables, and inconvenience of plugging-in. Wireless power has the potency to extend the working life of the batteries by providing untethered power on demand (Rooij, 2015). Nikola Tesla (1888) developed the Tesla Coil which was one of the key elements to recreate wireless transmission (Ahmed *et al.*, 2003). Tesla in 1899 provoked one of the major steps by providing wireless energy to two hundred light bulbs and an electrical motor within a radius of twenty-six miles (Bhutkar and Sapre, 2009). The dearth of existence of any related available evidence confirming the possible success makes this just a theory (Budimir and Marincic, 2006).

1.2 Principle of Operation of Wireless Power Transfer

Wireless power system involves the transmission of energy from a transmitter to a receiver via an oscillating magnetic field. It essentially embroils two coils, as in a transformer, which has a transmitter and receiver coils. The transmitter coil is energised by Alternating Current (AC) to generate a magnetic field, which in turn induces a current in the receiver coil. This is achieved through Direct Current (DC) being supplied by a power source and converted into high frequency AC by specially designed electronics built into the transmitter. The AC 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 that receiving coil. The electronic circuitry in the receiving device then converts back the AC into DC, which becomes usable power.

The magnetic coupling of the primary transmitter infrastructure and the secondary on-board receiver takes place across an air gap using Electromagnetic Radiation (EMR) for power transfer. To achieve optimal power transfer at the resonance frequency and limit losses, transmitting and receiving coils must be precisely positioned and aligned with gap size restrictions. A closed circuit is additionally desirable to hold the magnetic flux and preclude stray magnetic field emissions. This closed circuit would preclude adverse operational effects (Rooij, 2015). Fig. 2 illustrates the principle of operation of the wireless power transfer.

As alluded above, power source A is converted into a high frequency AC by the transmitting electronics, which then flows through a transmitter coil (B) and generates an oscillating magnetic field. Energy from the magnetic field induces AC in the receiver coil (C) and is converted back into DC by the receiver electronics, providing power to the respective application.

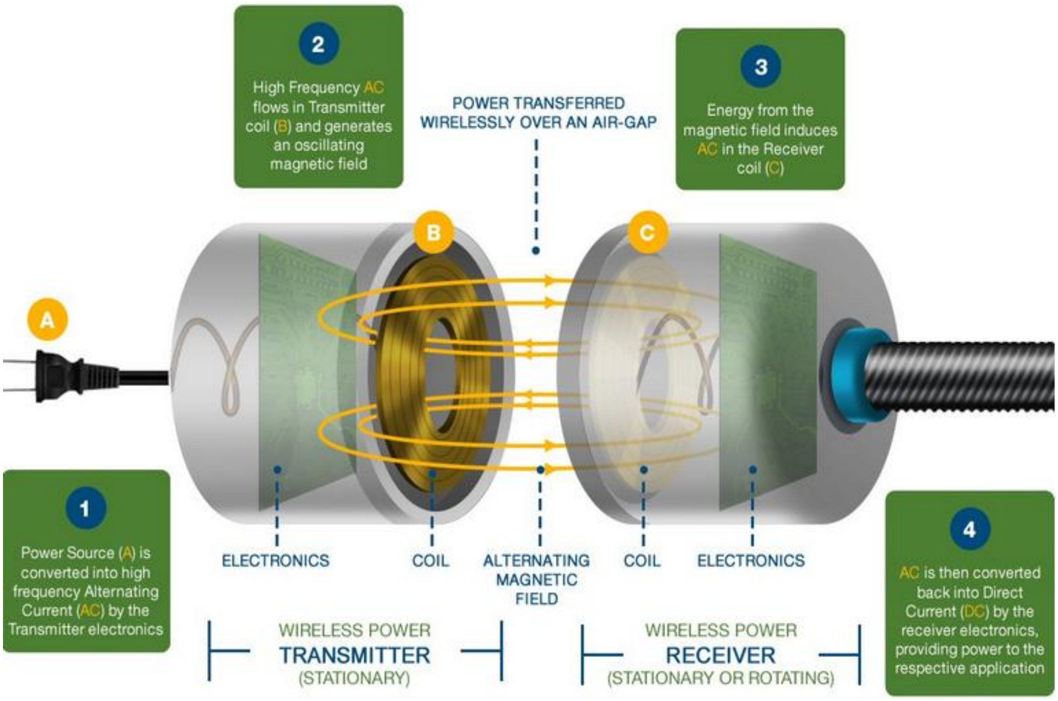

Fig. 2 Principle of Operation of Wireless Power Transfer (Muhamad and Sharma, 2015)

1.3 Techniques of Wireless Power Transfer

Methods of power transmission may be radiative (near-field) (Fig. 3) and non-radiative techniques (far-field). This paper focuses on near-field power transmission, which can be seen as the reactive field surrounding any electrically charged object. In static cases, the fields are simply electrostatic fields, and time varying electric and magnetic fields in non- static case used to induce current in nearby objects. Near-fields are highly efficient, as they do not radiate energy away from the source (Summerer and Barker, 2010).

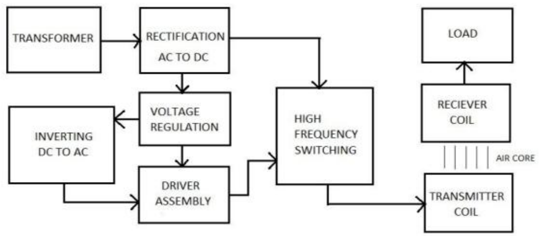

Fig. 3 Block Diagram of Near Field Wireless Power Transfer

Near-Field Wireless has three types; power Inductive Coupling (IC), Magnetic Resonance Coupling (MRC), and Capacitive Coupling (CC). This work is based on MRC but I present a brief discussion on all. In CC, power is transmitted by electric field between electrodes such as metal plates. The transmitter and receiver electrodes form a capacitor and an insulating material (dielectric) separates the two plates. An alternating voltage generated by the transmitter is applied to the transmitting plate. The oscillating electric field induces an alternating potential on the receiver plate by electrostatic induction, which causes an AC to flow in the load circuit. The amount of power transferred increases with the frequency and the capacitance between the plates. The capacitance between the plates is proportional to the area of the smaller plate and inversely proportional to the separation (Summerer and Barker, 2010).

IC consists of a transmitter coil L1 and receiver coil L2 with both coils forming a system of magnetically coupled inductors. Efficiency of the power transfer depends largely on the coupling (k) between the inductors and their quality (Q). The coupling is determined by the distance between the inductors (z) and the ratio of D2/D (Fig. 4) (Wageningen and Waffenschmidt, 2016). Fig. 4 shows typical arrangement of inductively coupled power transfer copied from Qi Wireless Power Consortium.

This technique offers wireless energy carried over a distance not longer than a few millimetres with high efficiency, and frequency used in inductive coupling is below some dozen megahertz. Inductive coupling is a low power transfer technique and has slow charging rate. To harness higher power transfer with lateral movement freedom, yet keeping high efficiency and without using ferrite core and subsequent charging multiple devices is a challenge (Karalis, 2008).

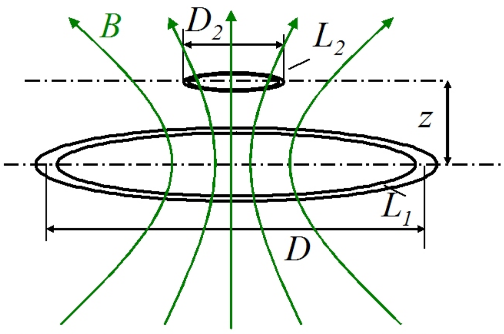

Fig. 4 Inductively Coupled Power Transfer (Wageningen and Waffenschmidt, 2016)

MRC transmits electrical energy between two magnetically-coupled coils that are part of resonant circuits tuned to resonate at the same frequency. Two high Q coils in a resonant transformer wound on the same core are used with capacitors connected across the windings to make two-coupled LC circuits in different devices. Transmitter coil in one device transmits electric power across an intervening space to a resonant receiver coil in another device. Resonant transfer works by making a coil ring with an oscillating current to generate an oscillating magnetic field (Prashansa *et al*., 2015). Comparatively, this is very effective in midrange transfer and can be omnidirectional (Kurs *et al*., 2007).

Magnetic resonances are viable for any application since it does not interfere with magnetic fields and gives a great effective connection between the transmitter and the receiver (Kurs *et al*., 2007). This theory was asserted through an experiment implemented using two self-resonant copper coils with one being transmitter that works as an electromagnetic resonator and other, a receiver. Setting resonant coils in this approach creates distributed inductance and capacitance to accomplish resonance and finally transfer energy wirelessly (Bhutkar and Sapre, 2009). The process of transferring energy between the two coils only occurs between the desired transmitter and receiver, avoiding any type of energy interference from other sources as a merit of using this technique on evanescent waves with same frequency. Power of transmission of the evanescent wave decreases with increasing distance until the efficiency is null. This avoids any interference but affects long distance transmission (Talamas, 2010). This is explained by attaching a light bulb into the resistive load while varying the distance of the source coil giving predictive results, then adjusting the right distance to get an optimal power output to get the light bulb to glow at a normal brightness. To establish the effectiveness of the transfer between the two coils, the current in the middle between the two coils is to be measured (Kurs *et al*., 2007). The flowing power was 400 W at an efficiency of 15%, which is very favourable. Advantage is power transmitted does not affect people or common objects like metals, wood or electronic devices even if they obstruct the line between the source and the device (Kurs *et al*., 2007).

However, the frequency may be affected if the objects are too near (a few centimetres) to the coils, which later will be rejected by the receiving coil affecting the efficiency of the transfer. The experiment saw two coils of the same sizes. Different sizes may also be used, albeit. Coils can be small sizes or shapes able to fit into portable devices without affecting the efficiency (Kurs *et al*., 2007). Balouchi *et al*., (2012) proposes that the biggest trend for the next few years will be a steady decline of induction coupling power transfer type from 80% to 10% and, a steady rise of magnetic resonance applications from 0% to 72% until 2020. Fig. 5 shows the trend of the various techniques of wireless power.

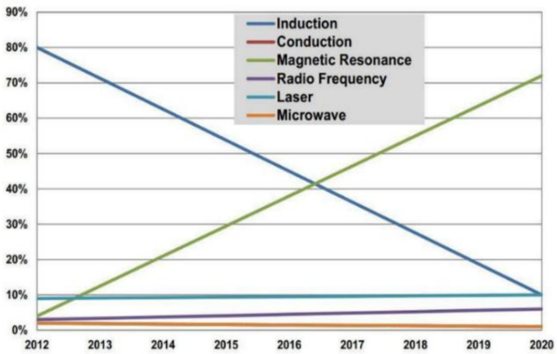

Fig. 5 Trend of Wireless Power Techniques (Balouchi *et al*., 2012)

Fig. 6 shows equivalent circuit of resonant inductive coupling applied in the carried out experiment.

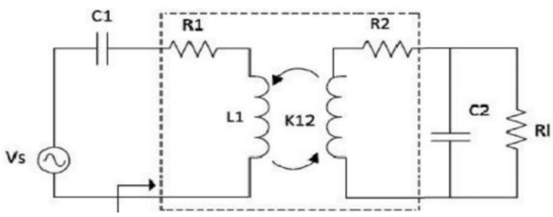

Fig. 6 Equivalent Circuit of Resonant Inductive Coupling Applied in the Carried Out Experiment

Resonance occurs when the input voltage and the input current are in phase. This corresponds to a purely real admittance, so that the necessary condition is given by:

$$\frac{\omega C - 1}{\omega L} = 0 \tag{1}$$

where ω is the resonant frequency, L is the inductance and C is the Capacitance.

The resonant condition may be achieved by adjusting L, C, or ω. Keeping L and C constant, the resonant frequency ω_o is given by:

$$\omega_o = \frac{1}{\sqrt{(LC)}} \tag{2}$$

$$\text{or } f_o = \frac{1}{2\pi\sqrt{(LC)}} \tag{3}$$

The distance at which the energy can be transferred is increased if the transmitter and receiver coils are resonating at the same frequency. This resonant frequency refers to the frequency at which an object naturally vibrates. (Muhamad and Sharma, 2015).

Literature so far strongly support wireless power transmission but the challenges with distance, remote actuation and cost have not been fully addressed. This system implements a GSM based wireless power transmitter and receiver circuits for the control of various loads.

2 Resources and Methods Used

2.1 PCB Design Process

A PCB with pre-designed copper tracks on a conducting sheet mechanically supports and electrically connects electronic components using conductive tracks, pads and other features etched from copper sheets laminated onto a non-conductive substrate. Pre-defined tracks reduce wiring and faults arising due to loose connections. The materials used in the PCB design were photo paper or art paper, laser printer, electric iron, steel wool, two plastic trays, copper clad, black permanent marker, etching solution (ferric chloride), and PCB drill machine. Print out of the PCB layout was done using the laser printer and A4 photo paper or art paper. The copper clad was cut with respect to size of the PCB layout and smoothened by vigorously rubbing steel wool on the surface of the board. Print out image was transferred onto a photo paper by ironing the glossy side of the paper onto the board. The printed board was immersed in cold water for close to ten minutes and gently removed. About three tea spoons of ferric chloride power was dissolved in a plastic box of water of which the PCB was dip into the Etching solution (ferric chloride solution,

$FeCl_3$) for approximately 30 minutes to remove unwanted copper from the PCB. Fig. 7 shows a schematic diagram of the wireless transmitter circuit.

2.2 System Hardware and Component Selection

A 40-pin ATmega32a Microcontroller was selected because it best fits into my design with the following pin count; two for power (pin 10: +5 V, pin 11: GND), two for oscillator (pin 12, 13), one for reset (pin 9), three for providing necessary power and reference voltage to its internal ADC, and 32 (4×8) I/O pins. ATmega32 is capable of handling analogue inputs. Port A can be used either as DIGITAL I/O Lines or each individual pin can be used as a single input channel to the internal ADC, plus pins AREF, AVCC & GND to make an ADC channel. ATmega32a MCU has three Inbuilt timer/counters; two 8 bit (timer0, timer2) and one 16 bit (timer1), one successive approximation type ADC in which total 8 single channels are selectable, three data transfer modules embedded in it i.e. two wire interface, USART, and serial peripheral interface, on-chip analogue comparator, 32 Kbytes of in-system self-programmable flash program memory, 1024 Bytes EEPROM, 2 Kbytes Internal SRAM, runs at a frequency from 1 to 16 MHz obtained from external Quartz Crystal, an R-C network, internal calibrated RC oscillator and 32 × 8 General Purpose working Registers. Atmega32 offers in-system programming via Serial Peripheral Interface (SPI), by parallel programming and programming via JTAG interface. JTAG boundary scan debugger was the adopted programmer. It was also ensured that SPI programming and JTAG are not disabled using fuse bits. Other hardware components used are; Crystal Oscillator which was used as a resonator, Decoupling Capacitor used to pass noise from the power source to the ground terminal while continuously supplying stabilised current to combat sudden changes in load current on ICs and other circuits and acted as a local source of energy for a short period. It was placed between power and ground lines to maintain low target impedance and to reduce the noise in power distribution network. The others are Ceramic Smoothing Capacitors used to suppress ripples that are generated after rectification to smooth-out signals to approach DC. It again stored excess voltage during high-voltage periods and released during low-voltage periods to eliminating fluctuations in voltage (Bhardwaj, 2011), IN4007 DIODE for reverse voltage protection; DC to DC step up, Toroidal (donut-shaped) cores Inductor to store energy as magnetic field and provide more inductance, for a given core material and number of turns (Rouse, 2005), LCD 2*16 used as electronic display module to display data and its economical, easily programmable, no limitation of displaying special and custom characters (Kushagra, 2012), LLM7805 (IC 7805) as a Voltage Regulator to restrict the voltage output to 5 V and draws 5 V regulated power supply.

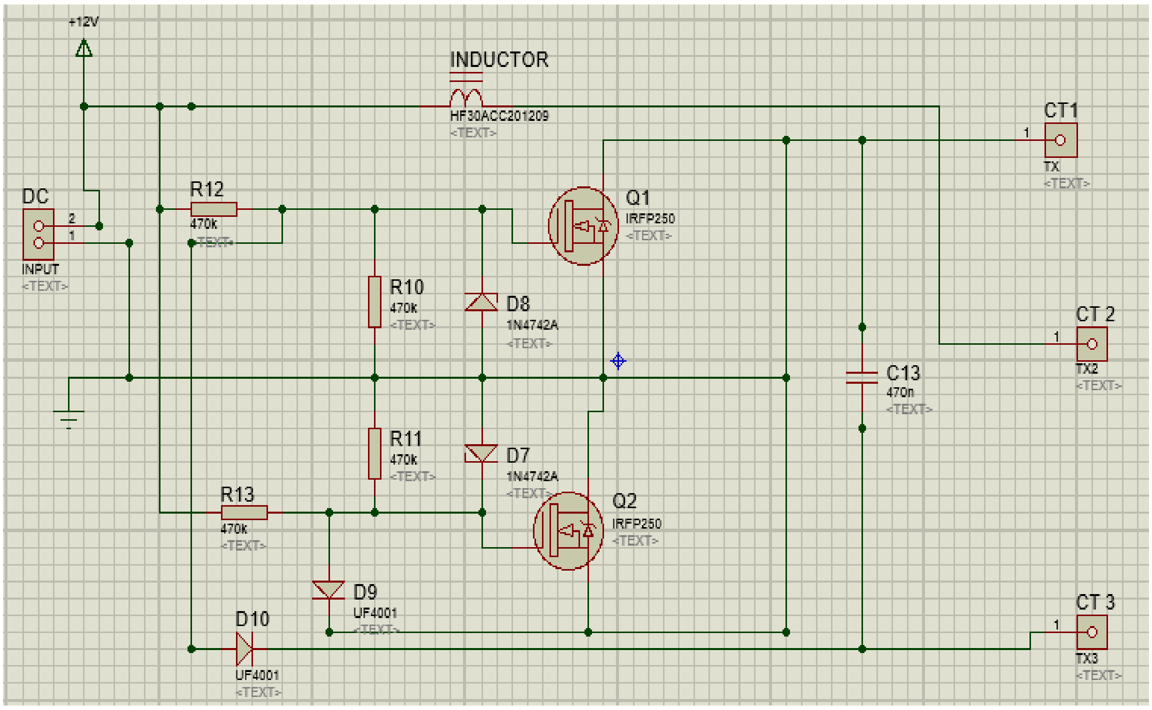

Fig. 7 Schematic Diagram - Wireless Transmitter Circuit

It is able to provide a constant steady voltage flow of 5 V for higher voltage input till the threshold limit of 35 V, LM1117 used as a series of low dropout voltage regulators with a dropout of 1.2 V at 800 mA of load current. It offers current limiting and thermal shutdown. Its circuit includes a zener trimmed band gap reference to as-sure output voltage accuracy to within ± 1% (Kushagra, 2012). Additional hardware that were used include MOC3021; an opto-coupler used for triggering TRIACS and is used with an LED diac type combination to indicate when logic high is given from micro controller to know that current is flowing in internal LED of the opto-coupler (Agarwal, 2016), solid-state relay (SSR) used as a switch and required relatively low control-circuit energy to switch the output state from OFF to ON and vice versa. Power gain in an SSR is substantial much higher than in an electromagnetic relay of comparable output rating since this control energy is very much lower than the output power controllable by the relay at full load. ULN2003LV is a low-voltage and low power upgrade of TI's popular ULN2003 family of 7-channel Darlington transistor array and was used to support low voltage relay and minimises on chip power dissipation. It supports 3.3 V to 5 V CMOS logic input interface. Others are TIP120 Transistor which was used as a substitute to NPN transistors and can switch up to 60 V at peak currents of 8A and continuous current of 5 A, with a DC gain of about 1000, IC 55 timer used as an Oscillator to produce a flip/flop type action (Bhatt, 2012), UF DIODE used as low forward voltage with an ultrafast reverse recovery, Light Emitting Diode (LED), XBee and XBee-PRO 802.15.4 OEM RF modules used as embedded solutions to provide wireless end-point connectivity to devices, Resistors to limit or regulate the flow of electrical current in an electronic circuit (Rouse, 2005), SIMCOM SIM300 modem was used to modulate and demodulates the GSM signals and in this particular case 2G signals. It is a Tri-band GSM/GPRS Modem and can detect and operate at three frequencies (EGSM 900 MHz, DCS 1800 MHz and PCS 1900 MHz). Default operating frequencies are EGSM 900 MHz and DCS 1800 MHz (Harikiran, 2012).

Fig. 8 GSM SIM 300

3 Results and Discussion

The design is based on the physics of inductiveness to transmit power wirelessly. The circuit was built around the following components; MOSFET (1RFEP250), polystyrene capacitor (MKP), Inductor, coupling coil (14-gauge copper), zener diodes, fast diodes and resistors. The circuit is a zero voltage switching which is self-resonating. The capacitor used prevents current at the primary from rising to point where the core saturates and part of L-C circuit used to achieve the best or required resonance in enhancing the coverage area of the transmitter. To obtain a high frequency, selected capacitor was low as possible but not below 1μF since the core may saturate below that value. The inductor used prevents AC in coil side from getting back to DC side; AC which passed through is stored as energy but on reluctance when not active, and released as DC. The inductor also forms part of L-C circuit used in modulating the resonance frequency.

Fast diodes were used to connect to the drains of the MOSFETS to prevent FETS from turning ON. The guide recovery time of fast diodes is enhanced by response of the fast diodes to the oscillation faction. To coerce the circuit to be driven at a minimum and maximum voltage of 12 V and 24 V respectively, zeners were employed. The transmitter circuit is interfaced to the main control unit and triggered using a transistor which drives a relay to handle the dedicated high power from the source.

The receiving end only gets activated when it is induced by the transmitter. For the transmitter to be active, the appropriate instruction is sent from a phone and upon reception of that message by the outboard GSM, the received message is pushed through the serial lines of the controller using USART standard of communication and data transfer. A comparison algorithm is then invoked when the correct start and stop bits are received. When the received message matches the coded instruction, PORT *A* of the controller declared as output receives a high (5 V) signal.

The corresponding pin then triggers the base of the transistor which, during the on-state produces *Ic* to energise the relay to close the switch between the supply source and transmitter circuit making it active. Any load connected to the receiving end gets activated instantly since it receives power wirelessly from the transmitter by induction. A low pass filter in the form of electrolytic capacitor allowed low frequency signals as DC to pass through ensuring that high frequency signals (AC) are sent to ground (GND). Superimposed high frequency which makes the DC signal a pulsating one is further smoothened by ceramic capacitor of value 0.1 µF to produce a perfect clean DC to the input side of the regulating device (LM7085) (Fig. 11). Mathematical Calculations for the Coil on the Receiver Circuit and the Resonance Frequency are follows as:

$$D = \frac{2\ x\ (length\ of\ wire)}{Number\ of\ turns\ x\ \frac{1}{2\pi}} \tag{4}$$

$$\Longrightarrow \mathrm{D} = \frac{4\pi \text{ x Length of wire}}{Number\ of\ turns} \tag{5}$$

where D is Diameter of coil in cm.

For example, if the total length of the coil in are 213*cm* and 274*cm*, D can be calculated as follows:

$$C = \frac{Length\ of\ wire}{Number\ of\ turns} \tag{6}$$

where C is the circumference.

From (6):

Circumference for 213*cm* coil = $\frac{213}{4} = 53.25\ cm$

Circumference for 274*cm* coil = $\frac{274}{4} = 68.50\ cm$

But Circumference, $\mathrm{C} = 2\pi \times \text{radius of coil (r)}$

We take diameter (D) = $2r = \frac{53.25}{\pi} = 16.95\ cm$ for 213*cm* coil

And diameter (D) = $2r = \frac{68.50}{\pi} = 21.80\ cm$ for 274*cm* coil

From (3); Resonance frequency $\mathrm{f_{res}} = \frac{1}{2\pi\sqrt{\mathrm{LC}}}$

Taking the inductance to be $200mH$ and the capacitance $2\mu F$

$$\mathrm{f_{res}} = \frac{1}{2\pi\sqrt{(200\times10^{-3})(2\times10^{--6})}}$$

$$\mathrm{f_{res}} = 252\ \mathrm{Hz}$$

An XBee module is interfaced to receive instructions based on SMS message to activate the router module to trigger AC load coupled to its control unit. The heat of the control unit processes data received serially to give the appropriate output in analog voltage form. The microcontroller accepts 5 V and 0 V (TTL) to properly function and has an external reset mechanism to manually reset the system if it fails to operate as intended. For the relay drive load, when a high signal 1 received on PIN1 of PORTA based on SMS message received from GSM module, the base of the transistor gets activated making it saturated hence the flow of collector current which energizes the coil of the relay to close the loop between the load and the AC supply source. The load goes off if low signal is received on the same PIN of PORT A due to the absence of collector current to keep the relay active in open state, hence load gets no operational voltage. The reverse biased diode across the relay coil is kept there to prevent any reverse voltage from relay coil getting back to the transistor (Lenz's law). The second load is controlled by a triac which is driven by an opto-coupler (MOC3021) used as isolation between power and driving circuitry. The triac conducts in both directions when triggered. The power output of triac depends on the firing angle. For the purposes of dimming AC loads, the triac's firing angle is manipulated by the driver to control the power output. If the triac is fired at an angle of 900, only 50% duty cycle of power is preceded. The opto-couple can be driven directly by the controller or transistor when its input receives a high signal from controller based on SMS message received. Internal LED (IR emitting type) gets activated thereby reducing the internal resistance which in turn triggers the gate of the triac into conduction. Resistor and capacitor configuration kept across the triac determines the relevance based on the type of load driven. When load is an inductive, capacitor-resistor configuration protects the left side of the circuitry from any reverse voltages or spikes from that load. Each Xbee communicates on a channel within a specified PAN ID group. A change on the pin of one module on the Xbee be it low or high is sensed on the other. PIN 3 of the controller is connected to 6th pin of Xbee which is a digital I/O PIN. The pin state is processed to either switch load on or off by the controller.

The following Figs. 9-11) are snapshots of wireless transmitter circuit, main control circuit and Xbee load circuit respectively. Figs. 12-14 are the flow charts showing the processes of the system's operation.

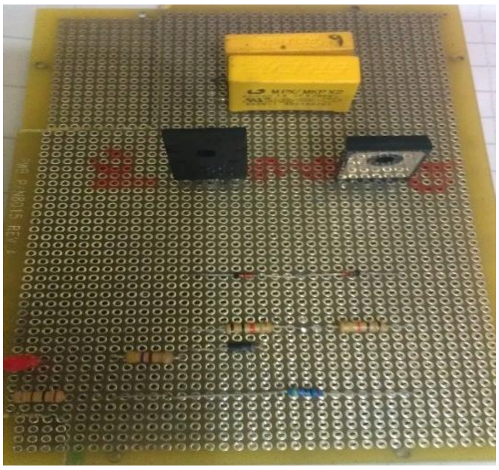

Fig. 9 Wireless Transmitter Circuit

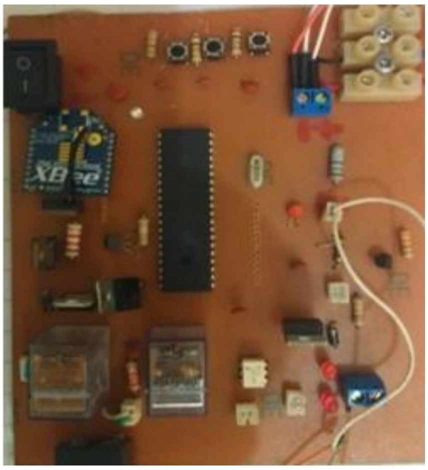

Fig. 10 Main Control Circuit

Fig. 11 Xbee Load Circuit

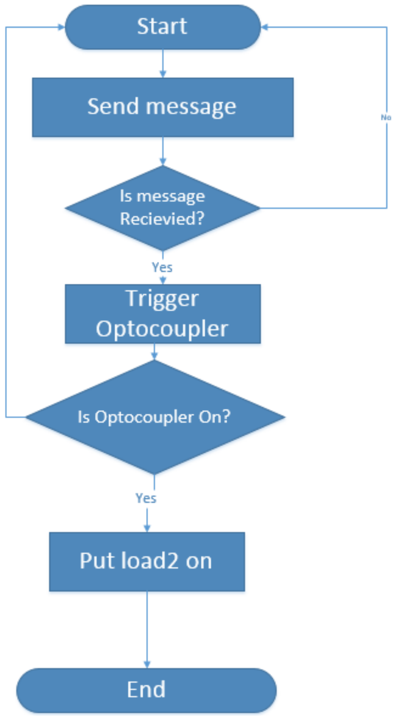

Fig. 12 Flow Chart for Putting on Load 1

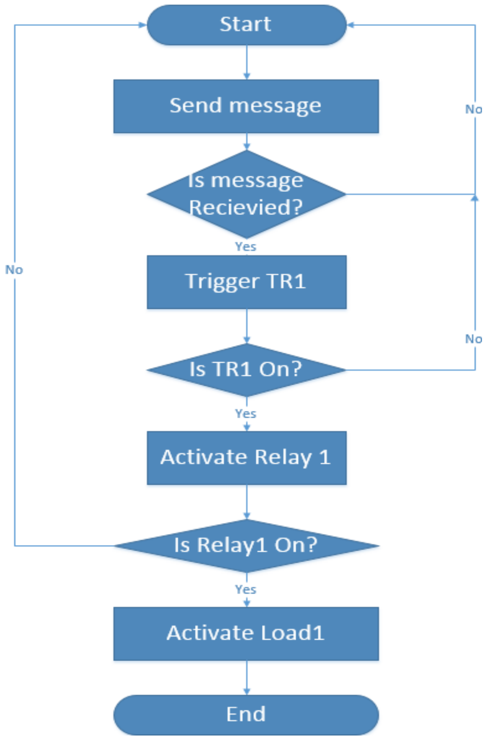

Fig. 13 Flow Chart for Putting On Load 2

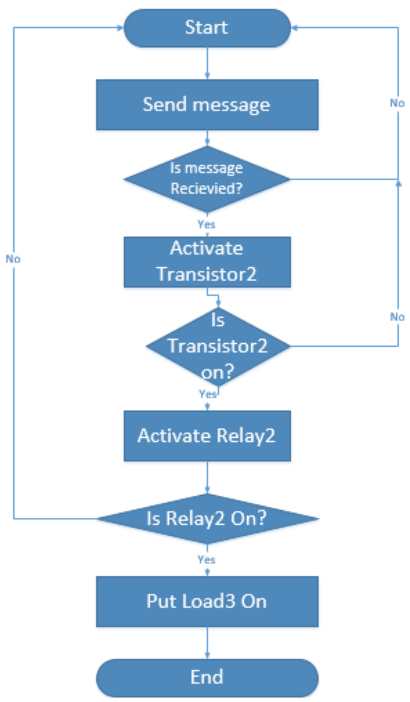

Fig. 14 Flow Chart for Putting On Load 3

4 Conclusions

It can be concluded that the wireless power transfer for AC or DC Load has been designed and implemented. Based on experimental results, wireless power transfer using resonance is dependent on the distance and the range of frequency. The wireless power transfer is not much affected by shielding materials such as the presence of hands, books and types of plastics. The result shows that the wireless power transfer is suitable to be implemented for resonant coils. With the introduction of the GSM module, our system can be triggered remotely and this improves the operational convenience of our system. Micro-power electronic devices can take advantage of this system.

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