Modeling of Wireless Energy Transfer Circuit and Implementation of Wi-tricity System Control using Infrared and PIC Microcontroller

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***Abstract*—A prototypes to prove and demonstrate the concept of Wireless Energy Transfer (WET) is proposed in this paper. The prototype is a simple structure consist of a transmitter as an electromagnetic resonator and a receiver to which the device to be powered is attached. It also implements with an ON/OFF control system using the Infrared (IR) module and Programmable Integrated Circuit (PIC) microcontroller. As a whole, experimental result proved that the distance between two coils is inversely directional to the level of current and voltage in the receiving coil. The strength of the magnetic field produced depends on the number of turns of both coils and input current plays an important role in determining the maximum distance between transmitter and receiver part. From the experiment, the receiver has the voltage of 10V for input current 3A, 5.213 V for input current 1A and 3.067 V for input current 500 mA at 0 distances. Besides that, the coil radius with 6 cm able to transmit 10 V to the receiver at zero distance while only 5.18V is transferred to the receiver for transmitter coil with radius 3 cm.**

Keyword - Wireless energy transfer, Magnetic field, Voltage, Distance, PIC microcontroller

I. INTRODUCTION

Wireless Energy Transfer (WET) or wireless power is the transmission of electrical energy from a power source to an electrical load without interconnecting wires. Wireless transmission is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible. The process is based on the power transfer distance and efficiency, which WET uses magnetic resonant coupling is preferred in many daily and industrial applications [1], such as wireless chargers for smartphones [2], electric vehicles [3]–[5], and biomedical implants [6]–[9].

Magnetic fields and inductive coupling have been studied since the discovery of transformer by Hans Oersted and Michael Faraday. In 1886, Westinghouse Company developed a first commercial AC transformer. A complete mathematical understanding of the coupled circuits used to make the transmitter and receiver was first published by Frederick Terman in 1935. The idea of using a microwave power transmission was put forward by William C. Brown in 1961. In 1973, world first passive RFID system demonstrated at Los-Alamos National Lab . In 1988, a power electronics group led by Prof. John Boys at The University of Auckland in New Zealand, developed an inverter using novel engineering materials and power electronics and concludes that inductive power transmission should be achievable. A first prototype for a contact-less power supply is built [10].

In 2007, a physics research group, led by Prof. Marin Soljačić, at MIT confirm the earlier (1980‟s) work of Prof. Boys by the wireless powering of a 60W light bulb with 40% efficiency at a 2 meters distance using two 60 cm-diameter coils [10]. In 2010, Haier Group debuts the world's first completely wireless LCD television at CES 2010 based on Prof. Marin Soljacic's research on wireless energy transfer and Wireless Home Digital Interface (WHDI) [11]. Back in 1899, Nikolai Tesla had built a resonant transformer called as Tesla coils, achieved a major breakthrough in his work by transmitting 100 million volts of electric energy wirelessly. He was able to light 200 lamps, 26 miles away from his lab to light up a bank and run one electric motor. He claimed that can transfer electrical energy at 95% efficiency, but the technology had to be shelved because the effects of transmitting such high voltages in electric arcs would have been disastrous to human and electrical vicinity [12]. By the early 2000s and recent research activities in WET including various forms of planar wireless charging systems, the formation of the Wireless Power Consortium in 2008 and the launch of the wireless power standard “Qi, it has been reported that over 500 products have been certified as Qi-compatible by 2014 [13]-[18].

II. MODELING THEORY

A. Resonance Frequency

In physics, resonance is the trend of a system to oscillate at larger amplitude at some frequency than at others. At this frequency, even small periodic forces can produce large amplitude oscillations. Resonances occur when a system is competent to store and easily transfer energy between two or more different storage modes. However, there are some losses from cycle to cycle, called damping. When damping is small, the resonant frequency is equal to a natural frequency of the system, which is a frequency of unforced vibrations. Magnetic coupling occurs when two objects swap energy through their oscillating magnetic fields. Resonant coupling occurs when the natural frequency of the two objects are the same.

B. Resonance with Inductor and Capacitor

When an inductor or capacitor is placed in series or parallel they will have a resonant frequency which is determined by the design equation below. Resonance occurs when the reactance of an inductor balances the reactance of a capacitor at some given frequency. In such a resonant circuit where it is in series resonance, the current will be maximum and offering minimum impedance. In parallel resonant circuits the opposite is true. LC resonant circuits are useful as notch filters or band pass filters. Since the inductive reactance and the capacitive reactance are of equal magnitude, $\omega L = 1/\omega C$, so

$$\omega = \frac{1}{\sqrt{LC}} \tag{1}$$

where $\omega=2\pi f$

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

where $\omega=2\pi f$, in which f is the resonance frequency in Hertz, L is the inductance in Henry, and C is the capacitance in Farads when standard SI units are used.

C. Resonance Energy Transfer

Resonant energy transfer or resonant inductive coupling is the short distance wireless transmission of energy between two coils that are highly resonant at the same frequency. The equipment to do this is sometimes called a resonant transformer. This type has a high Q and always used an air cored coil to avoid iron losses is a lot of transformers. The coils may be present in a single piece of equipment or in split pieces of equipment. Resonant transfer works by constructing a coil ring with an oscillating current. It occurs when AC voltage has been supplied through a coil which generates an oscillating magnetic field. Because the coil is greatly resonant, some energy placed in the coil lost away relatively slowly over very a lot of cycles, but if a second coil is brought near to it, the coil can pick up most of the energy before it is lost, even if it is some distance away [4].

D. Resonance Coupling

Non-resonant coupled inductors, such as transformers, work on the principle of a primary coil generating a magnetic field and a secondary coil attach as much as possible of that field so that the energy passing through the secondary is as similar as possible to that of the primary. This condition that the field be covered by the secondary results in very short range and usually requires a magnetic core. Over larger distances the non-resonant induction method is highly inefficient and wastes the lots of the energy in resistive losses of the primary coil. Using resonance can help efficiency significantly. If resonant coupling is used, each coil is capacitive loaded so as to form a tuned LC circuit. If the primary and secondary coils are resonating at a general frequency, it turns out that significant energy may be transmitted between the coils over a range of a few times the coil diameters at reasonable efficiency.

E. Inductor Basic

An inductor is a passive electrical device working on electrical circuits for its property of inductance. Inductance is an outcome which results from the magnetic field that forms around a current carrying conductor. Current flowing throughout the inductor produces a magnetic field that is having a related electromotive field which opposes the applied voltage. This counter electromotive force is generated which opposes the change in voltage applied to the inductor and current in the inductor resists the change but does increase. This is identified as inductive reactance. It is reversible in phase to capacitive reactance. The inductance can be improved by looping the conductor into a coil which creates a bigger magnetic field.

F. Quality Factor of Inductor

The quality factor is a value of the quality of a resonant system. Resonant systems react to the frequency close to their natural frequency stronger than they respond to other frequencies. The quality factor indicates the quantity of resistance to resonance in a system. Systems with a high quality factor resonate with better amplitude at the resonant frequency than systems with a low quality factor. In a circuit, inductors have a series resistance produced by the copper or other electrical conductive metal wire forming the coils. The series resistance changes the electrical current flowing through the coils into heat, hence causing a loss of inductive quality. This is where the quality factor is born. The quality factor is a relative amount of the inductance to the resistance.

$$Q = \frac{\omega L}{R} \quad (3)$$

where ω is resonance frequency, *L* is inductance and *R* is internal electrical resistance of the coil. Higher quality factor indicates a lower rate of energy loss relative to the stored energy of the oscillator. Oscillators with higher quality factors have low damping so that they can ring longer. Sinusoidal has driven resonators having higher quality factors resonate with greater amplitudes, but have a smaller range of frequencies around that frequency for them to resonate. High quality oscillators oscillate with a smaller range of frequencies and are more stable [5].

G. Multilayer air core inductor

Air core inductor is an inductor that does not depend upon a ferromagnetic material to reach its specified inductance. This covers the cases in which there really is just air inside as well as windings upon a different insulator such as plastic or glass. Air core inductors are free of the iron losses which affect ferromagnetic cores. As frequency is increased, this is very important to get higher quality factor, greater efficiency and less distortion. Air core coils can be designed to perform at frequencies as high as 1 GHz. Most ferromagnetic cores are likely loss above 100 MHz The common formulas for calculating the approximate inductance of the multilayer air core inductor is:

$$L = \frac{0.8r^2N^2}{6r + 9L + 10d} \quad (4)$$

where L is the inductance (µH), r is the radius of the coil (inch), l is the physical length of coil winding (inch), N is the number of turns and d is the depth of coil (inch).

H. Concept of Wi-tricity

Fig. 1 shows the block diagram of WET system. The power supply is to supply the AC power source to the system. The oscillator which is connected parallel to the power supply is used to supply high input frequency to the transmitter coil. Transmitter coil is the resonant antenna driven by an AC generator while the receiver coil is grounded resonant antenna directly powering the load. The rectifier circuit is built to convert the AC output source at the receiver part into a DC source in order to power up the DC device [6].

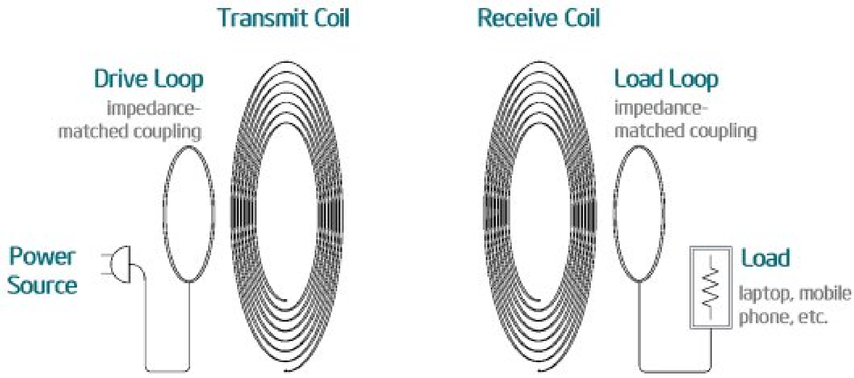

Fig 1. Block diagram of WET system

I. Control System Design

The infrared proximity sensor is used to sense the presence of the load on the power pad. When infrared detects the object, it reflects a signal to the photodiode sensor. This action causes the voltage increase in the input of the comparator. A comparator is a device that compares two voltages or currents and switches its output to indicate which is larger. When the input current of voltages is larger to the reference voltage, the comparator will send a "1" to the input of microcontroller and vice versa. After that, the microcontroller will process the input signal and trigger the transistor relay circuit to on the supply source to the transmitter based on the programming that burn into the microcontroller. All this process is shown in Fig. 2.

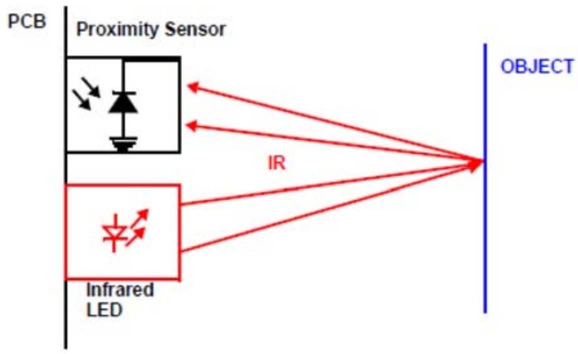

Fig. 2. IR proximity sensor working principle

III. DESIGN PROCESS

A. Construction of Transmitter and Coil

Coils were made using a plastic circle coil former and enameled copper wire with number of turn is 280. Diameter of copper wire is 16AWG. Two ends of the coil are connected with the series of $7.6pF$ and $50fF$ capacitor. Then, the resonance frequency of the LC tank is calculated in order to find out the source frequency that supply to the both transmitter and receiver coil as shown in Fig. 3 and Fig. 4 respectively.

Fig 3. Coil connected in parallel with capacitor and in series with 12V step down transformer

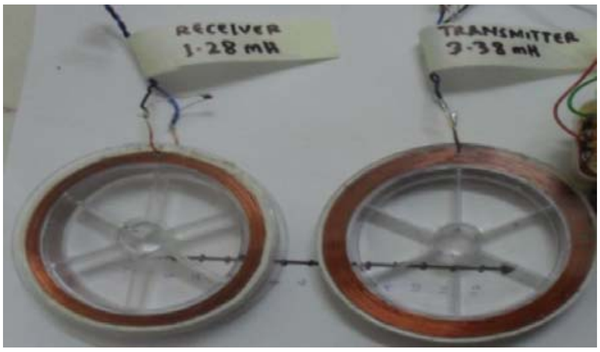

Fig. 4. Transmitter and receiver coil

B. Radial Inductor as Receiver Coil

In Fig 5, radial inductor 800 mH is used to replace the receiver cooper wire coil. Previous step is followed to determine the resonance frequency to match with transmitter coil. This component is better because normal inductors have higher resistance and other losses. Furthermore this component is compact and doesn't occupy large space.

Fig. 5. Radial inductor

C. Control System Design

The Wi-tricity system control consists of four circuits which are voltage regulator circuit, microcontroller circuit, IR module with comparator circuit and transistor relay circuit as shown in Fig. 6, Fig. 7 and Fig. 8 respectively . Voltage regulator circuit is designed to automatically maintain a constant voltage level at 5V to supply to microcontroller circuit. Microcontroller circuit is designed to process the output signal of the comparator. IR module and comparator circuit is designed to sense the presence of the object and transistor relay is designed to trigger the transmitter coil in order to transmit the energy to the receiver load.

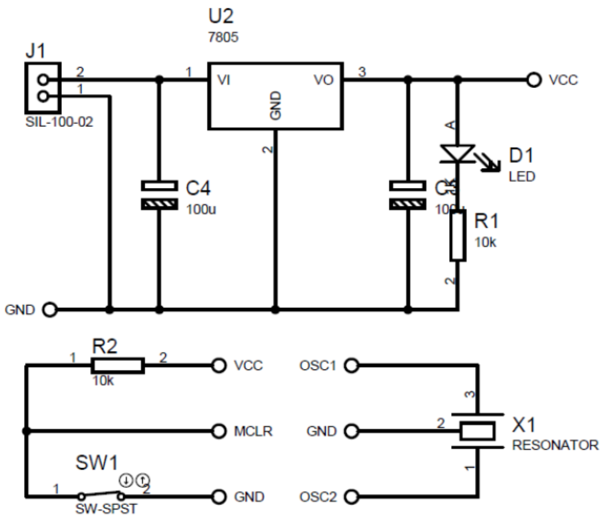

Fig. 6. Voltage regulator schematic circuit

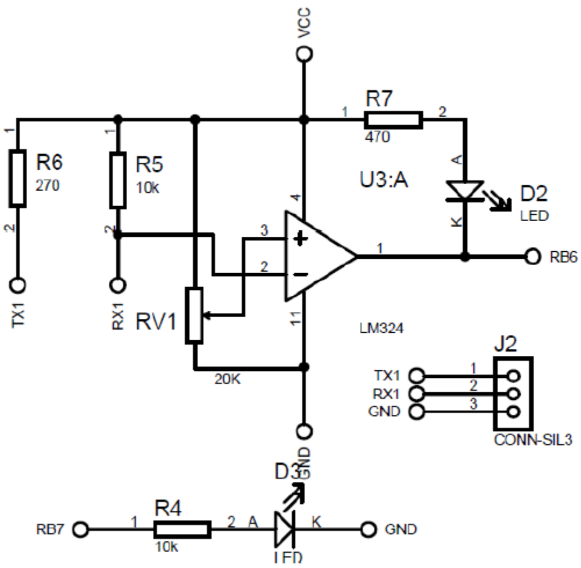

Fig. 7. IR module and comparator schematic circuit

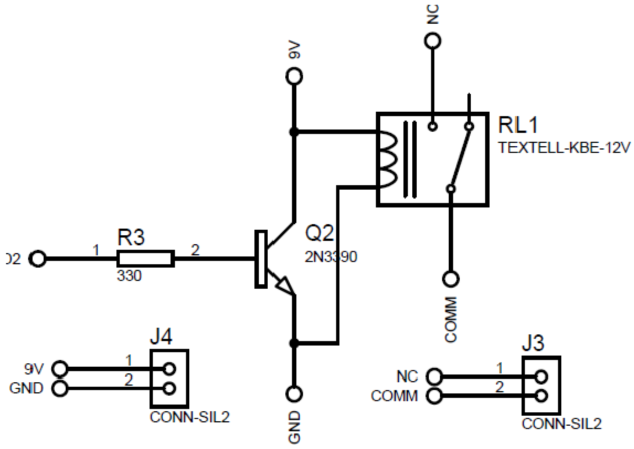

Fig. 8. Transistor relay schematic circuit

D. CCS programming

PIC 18F4550 is the microcontroller that being used in this project for transmitter coil input switching control. The coding is designed based on the scenario when the IR sensor detects the presence of the receiver coil, the output comparator will send a signal into the microcontroller to tell the system to trigger ON the transmitter coil. Pin port B6 is used as the input to receive the output signal from the comparator while the pin port B7 and D2 are the output that used as the indicator and triggered the transistor relay circuit. The flow chart of IR sensor programming control is shown in Fig. 9 [19],[20].

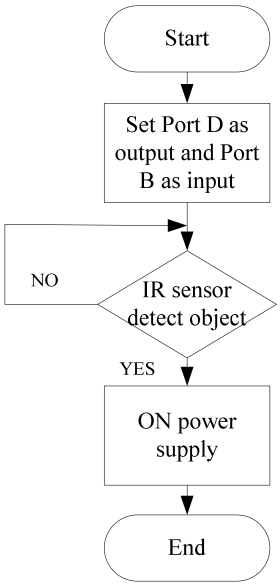

Fig. 9. Flow chart IR sensor programming control

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A. Cooper Wire Coil for Transmitter and Receiver

Based on Fig. 10, the system consists of two resonators which are transmitter coil and receiver coil. The transmitter and the receiver contain of same resonance frequency where the transmitter coil that linked to the oscillator is coupled inductively with the receiver coil and supply the power to the output loop. The transmitter coil is connected to high frequency AC power while the receiver coil is connected to the output load. The energy is transferred from the transmitter coil to receiver coil wirelessly relying on high frequency magnetic resonance based on two coupled LC circuits with the same resonant frequency. In other word, the coupled LC circuits is called impedance matching network [9]. The transmitter coil is manufactured with a number of turns,N = 187, radius of the coil, r = 1.457 inch, the physical length of coil winding l= 0.63 inch and a depth of coil,d = 0.315 inch. So that, the value of the inductor, L at the transmitter coil is 3.381mH. The same method is applied to the receiver coil. The receiver coil is manufactured with N = 112, r = 1.457 inch, l = 0.63 inch and d = 0.217 inch. The value of the inductor, L at the receiver coil is 1.284 mH. From eq. (2), the frequency for the transmitter is 126.44 kHz with the value of series capacitor is 100 nF and 471pF. In order to obtain magnetic resonant coupling, receiver part must also operate at the same frequency with transmitter circuit. Using eq. (2), the value of the capacitor that must be used is 1.24 nF. Systems with a high Q factor resonate with greater amplitude (at the resonant frequency) than systems with a low Q factor. The resonance frequency of the transmitter is 126.44 kHz and the inductor is 3.38 mH so that the quality factor of the transmitter coil using eq. (3) is 994.5 and Q factor for receiver circuit is 535.2.

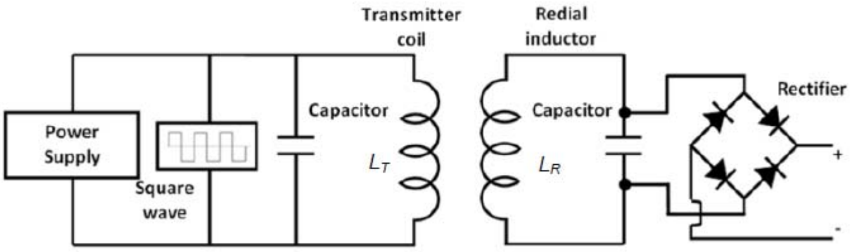

Fig. 10. Block diagram of prototype

Fig. 11 shows the relationship between source frequency and voltage at the receiver. The voltage of the receiver coil increased as the control signal increased and reach the maximum voltage when the control signal is adjusted to around 123kHz. The voltage started decreasing as after 123kHz. This phenomena shows energy transmission reaches its maximum when the two coupled LC circuits resonating at the resonance frequency.

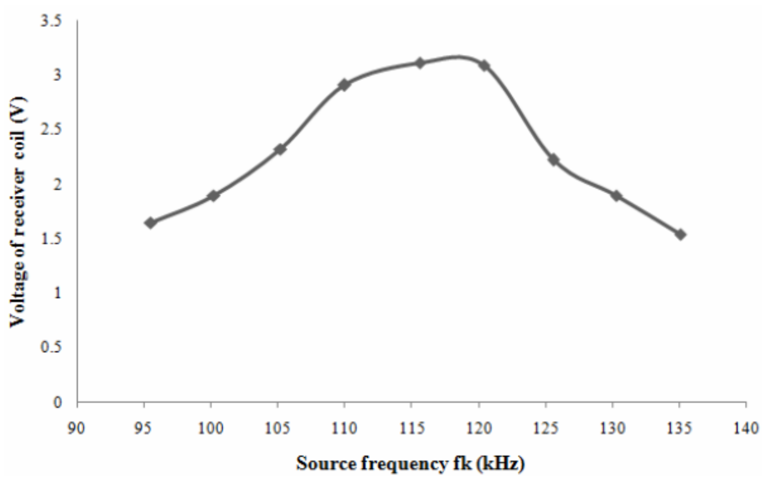

Fig. 11. Voltage of receiver versus Source frequency

B. Radial Inductor as Receiver Element

Based on the Fig. 12 and Fig. 13 show the impact on the voltage and current of the receiver coil caused by different transfer distance. It is obvious that the longer of distance between the two coils, the lower the voltage and the current of the receiving coil.

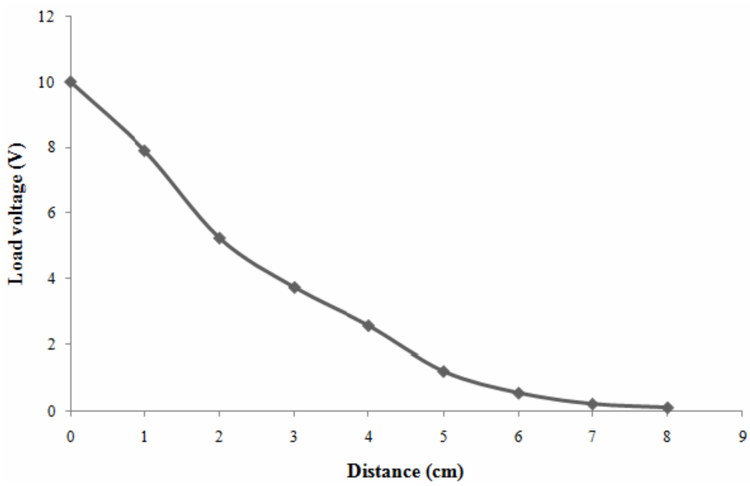

Figure 12. Load voltage versus Distance

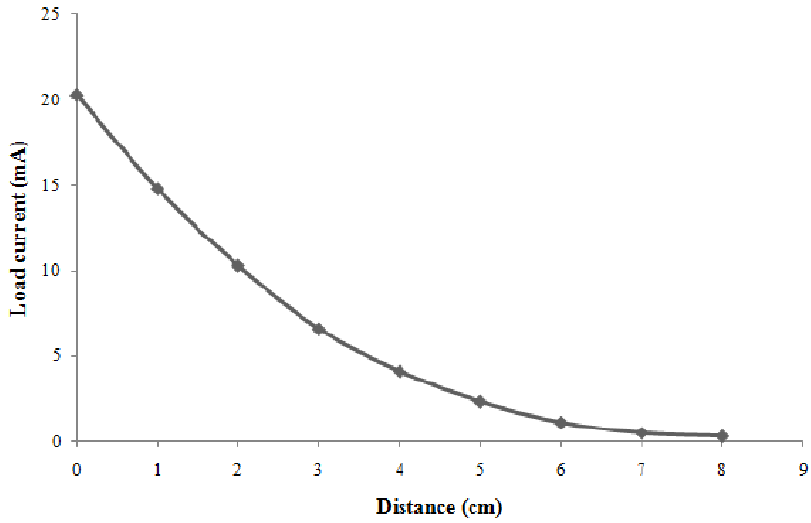

Figure 13. Load current versus Distance

High number of turn and current produce stronger magnetic field, thus give higher output voltage. Overall the output voltage is inversely proportional to the distance as shown in Fig. 14 and Fig. 15 respectively. Note that the input current controls the strength of the magnetic field. Fig. 16 and Fig. 17 shows the effect of power efficiency to distance with different number of coils. The efficiency was increased as coil radius increased.

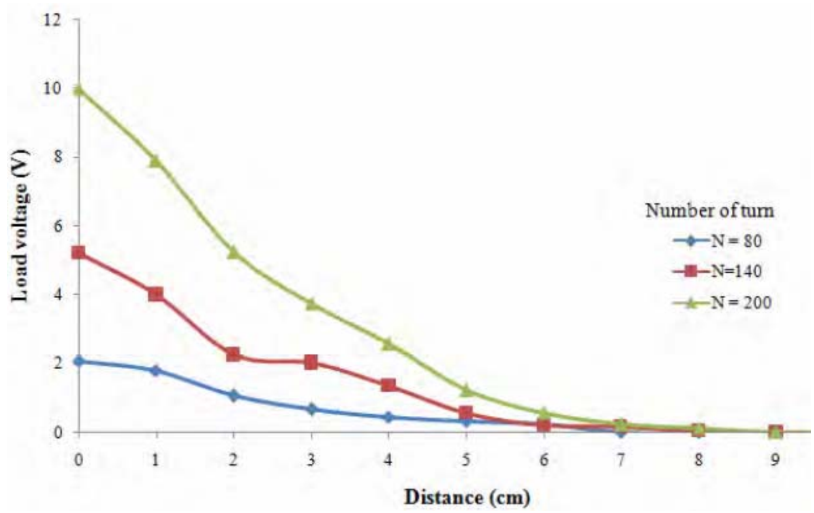

Fig. 14. Load voltage versus Distance (different number of turns) at receiver

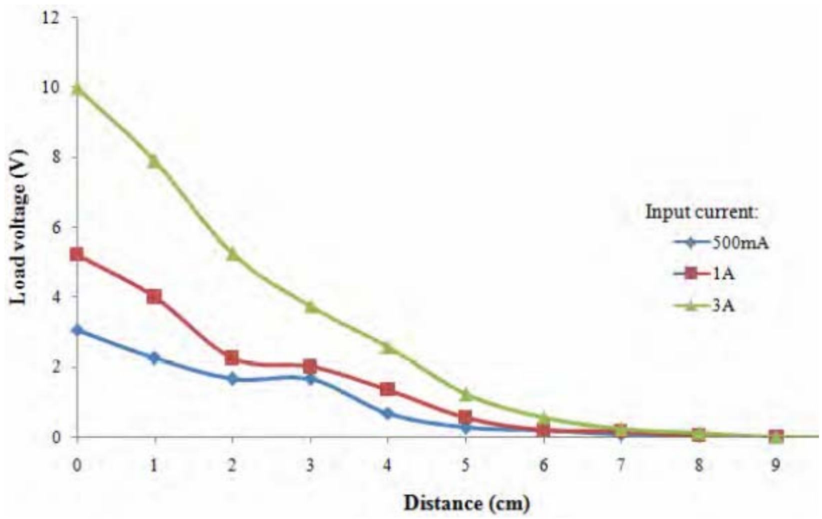

Fig. 15. Load voltage versus Distance (different input current) at receiver

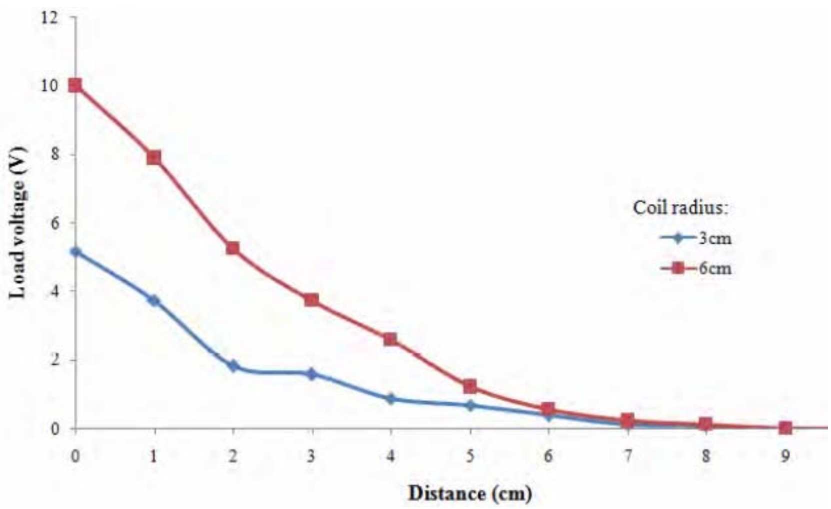

Fig. 15. Power efficiency versus Distance (different coil radius) at receiver

C. IR Proximity Sensor as System Controller

Based on the observation in Fig. 16, when the object is detected by infrared sensor, the system energized the relay and triggered ON the power supply, when the object is away from the power base, the relay is reenergized the power supply is OFF.

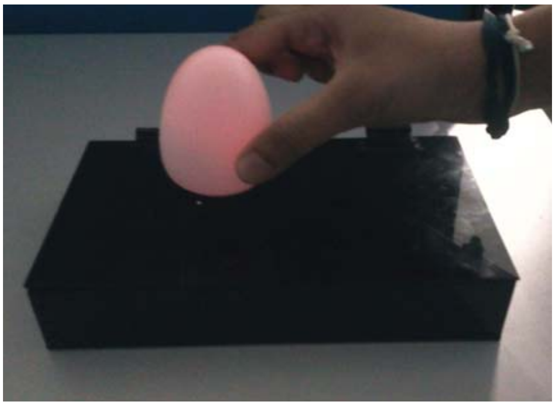

Fig. 16. Load receive transmitted power from source if presence in the active range of IR proximity sensor

V. CONCLUSION

The prototype of the Wi-tricity system control is built successfully and the characteristic of the WET efficiency has been investigated using PIC microcontroller and IR module. It proved that this kind of technology has the potential to improve and magnetic resonance coupling is the most feasible method in WET. Not The can be transmitted without the presence of control signal by using the radial choke inductor as the receiver. The impact on the voltage and current of the receiver coil caused by different transfer distance is investigated and shows that the longer of distance between the two coils, the lower the voltage and the current in the receiving coil. The strength of the magnetic field depends on the number of turns of the copper wire at the transmitter coil and receiver coil and the input current to the transmitter coil.

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