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WIRELESS POWER TRANSFER USING EVANESCENT SIGNALS FOR MOBILE CHARGING

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Abstract— With Wireless electricity (Witricity), transfer of power across large air gaps have been achieved to power both small and large equipments. Evanescent coupling using magnetic resonance allows power transfer with high efficiency. In this paper, analysis has been done on the various technologies using equivalent circuits which are a familiar format of electrical engineers. Magnetic resonance has been used to transfer power to a mobile phone at a vertical distance of 15cm from a table top. The source antenna coil was powered using a DC-AC oscillator coupled to a power amplifier. The device antenna coil was connected to rectifier and a regulator to power the mobile. An operating power gain of 19.23% was realized.

Index Terms—Wireless power transfer, evanescent coupling, magnetic resonance

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1 Introduction

A Surge in interest towards wireless power is happening in recent years with a range of high power applications like vehicle battery charging, medical implanted batteries for heart and cochlear implants, Wireless charging systems with transmitter resonators embedded in car parks, and along roadsides would allow more frequent charging and could bring long journeys closer to reality and allow car manufacturers to produce smaller batteries. The high frequency energy from transmitter resonator is rectified and stored in batteries which are electric double layer capacitors. In devices like pacemakers and cochlear implants, the battery alone accounts for as much as half the volume of the device it drives. These batteries have finite lives and when they wane, surgical process has to be redone. Wireless charging has eliminated the costs involved in re-implanting the batteries. The complications and infections caused by percutaneous wired connections have been replaced by the free range resonant electrical energy delivery system in [1]. For high power applications the antenna sizes are too large .Low end applications involve charging of electric tooth brush, house hold toys, mobile phones and moving robots Wireless powering can also be done in utility devices for charging lighting gadgets for domestic applications as has been demonstrated in[2].

The breakthrough in these developments was due to the successful experiment at the Massachusetts Institute of Technology in 2007[3]. The researchers developed a wireless electricity system which enabled wireless power transfer of 60W with a coupling efficiency of 40% at a distance of 2m which is three times the diameter of the transmitter resonator.

This technology overcomes the need of all the equipment for electricity transmission by contact like cables, plugs, adapters and sockets. The high frequency system uses the near field range of the electromagnetic spectrum for transmission of alternating current. This field uses the reactive field which is inherently non-radiative. Far field method of realizing wireless power using directional transmission employing high gain antennas using micro waves have been tried for long range transmission with efficiencies of more than 90%[4]. The use of lasers for line of sight transmission [5] is also used to increase coupling efficiency of wireless power. Sophisticated tracking and alignment equipment are needed to maintain point to point connection in dynamic environments. The power density decreases inversely with distance from the source and thus the received power is very much lesser in magnitude compared to the transmitted power [6].The major disadvantage of far-field techniques are that the electromagnetic fields are highly radiative and cannot be used to achieve mid- range power transfer.

Inductive coupling using transmitter and receiver antennas has been the traditional way of realizing wireless power. The coupling between the antennas has to be tight to achieve reasonably good efficiency. When the distance between the antennas increases, more and more magnetic field will miss the receiver antenna coil. The efficiency of electromagnetic induction drops when there is slight misalignment between the antennas. The coupling between the coils can be enhanced using magnetic resonance which uses coupling of modes in time [7]. The time dependence of two weakly coupled resonators having amplitudes a_1 and a_2 and coupling coefficients k_{12} and k_{21}

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can be expressed in terms of the differential equations as

$$\frac{da_1}{dt} = j\omega_1 a_1 + jk_{12}a_2 \tag{1}$$

$$\frac{da_2}{dt} = j\omega_2 a_2 + jk_{21}a_1 \tag{2}$$

When the coupling is lossless, energy conservation imposes a restriction on k_{12} and k_{21}.

$$d/dt|a_1|^2 + |a|^2 = a_1 d/dta_{11}^* + a_1^* d/dta_1 + a_2 d/dta_2^* + a_2^* d/dta_2 \tag{3}$$

$$a_1^* k_{12} a_2 + a_1 k_{12}^* a_2^* + a_2 k_{21} a_1 + a_2 k_{21}^* a_1^* = 0 \tag{4}$$

The relationship between the coupling coefficients is related by

$$k_{12} + k_{21}^* = 0 \tag{5}$$

Magnetic resonance coupling has been used to power up multiple receivers in [8]. The use of additional resonators acing as repeaters increases the power transfer capability of the system and the operating distance can be increased [9].

In this paper, we analyze the various methods of tuning the source and device coils to resonance. We also experimentally demonstrate a wireless power transfer system to charge a mobile phone under distance variations.

2. EVANESCENT COUPLING IN ANTENNAS

The source antenna is omnidirectional which transmits equally in all directions. When an oscillating magnetic field is applied to the source antenna an oscillating electric field is developed around the elements of the antenna. These time varying electric and magnetic waves travel from the source antenna as a transverse electromagnetic wave. On reception, the moving electromagnetic wave exerts force on the device antenna elements causing oscillating currents in it. Two or more antennas are coupled together so that the evanescent field generated in the near field by one element exhibits exponential decay much before it reaches the other element. The propagating evanescent wave is either predominantly electric or magnetic.

Evanescent coupling is realized in antennas using the three possible methods such as untuned source antennae with untuned device antennae, unturned source with tuned device antennae and tuned source antennae with tuned device antennae. Untuned source antennae with untuned device antennae represent an ideal case with the device coil having reasonable resistive losses and source coil having negligible resistive losses. The effect of the presence of a coupled device coil on the source coil is additional impedance $(\omega M)^2/(R_D^2 + (X_D)^2)$ is added in series with the source antennae. With a quality factors of the coils determined by $Q = \omega L / R$ the resistance and inductance components of the source antennae are $\omega L_s k^2 Q_D$ and $L_s(1-k^2)$, where k is the coefficient of coupling between the antennas.

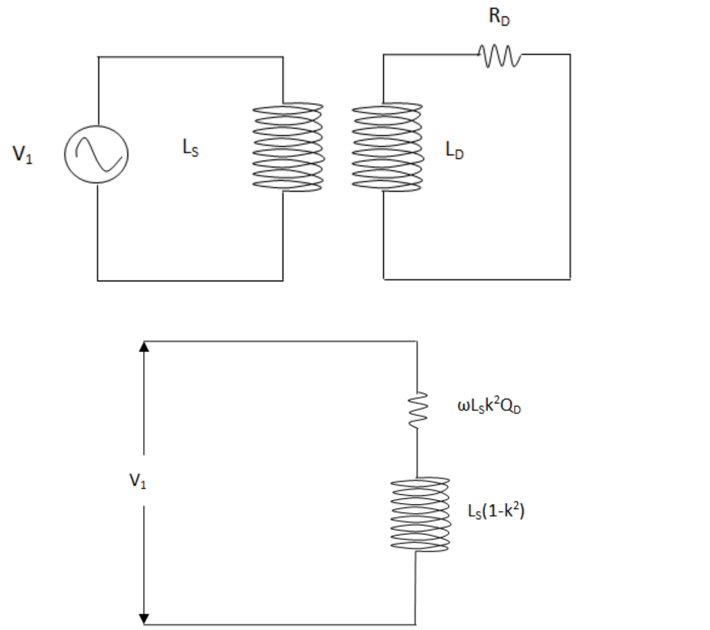
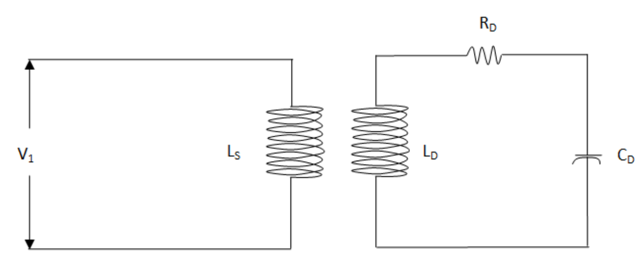


Fig.1 (a) Untuned source antennae coupled with an unturned device antennae having appreciable loss resistance (b) The equivalent circuit

The second topology of tuned device antennae uses capacitor tuning in the device coil. The coupled resistance and inductance component to the device coil are: $R_{eq} = (\omega M)^2 R_s / R_s^2 + (\omega L_s)^2$, $L_{eq} = -(\omega M)^2 Ls/(R_s^{\ 2} + (\omega L_s)^2)$ respectively



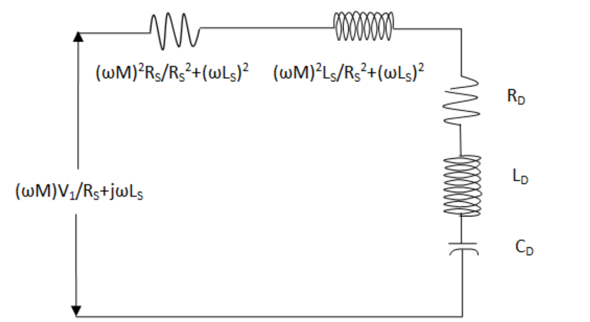


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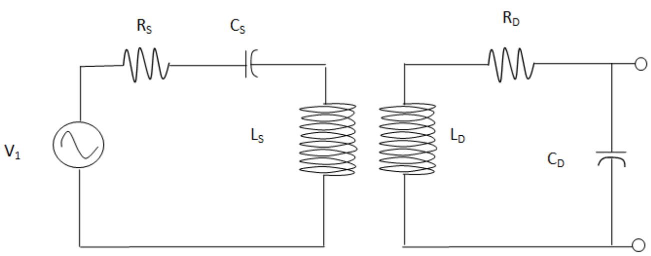
Fig.2(a). Untuned source antenna coupled with a tuned device antennae (b). The aaproximate equivalent circuit.

The widely used method of achieving evanescent coupling is by tuning both the source antennae and device antennae to the same resonant frequency. The source and device antennae coils have associated self-inductances of L_S and L_D respectively. These coils have inherent resistances of R_S and R_D. Since the source coil radiates energy to the receive coil through a low permeability path such as air and the strength of the field diminishes as inverse the square of the distance from the source [10], a capacitor C_S is included in the source circuit to achieve coupling between the coils. Similarly a capacitor is incorporated in the device circuit C_D to enhance coupling. The transmit/source coil is powered from a high frequency AC source. The two coils behave as antennas which exhibits resonance using the inherent parasitic capacitance and the installed capacitance. The efficiency of resonant coupling is greatly influenced by mutual coupling between the coils. The system dynamics in the frequency domain show the source and device network parameters and the effects of frequency on the two coils. When $\omega L_S > 1/\omega C_S$, the coupled resistance to the device antennae is represented as $R_{eq} = (\omega M)^2 R_s / \; R_S^2 + (\omega L_s - 1/\omega C_s)^2$ and the coupled inductance to the device antennae is represented as.

$$L_{eq} = -(M\omega)^2 L_s / (R_s^{\;2} + (\omega L_s - 1/\;\omega C_s))^2$$



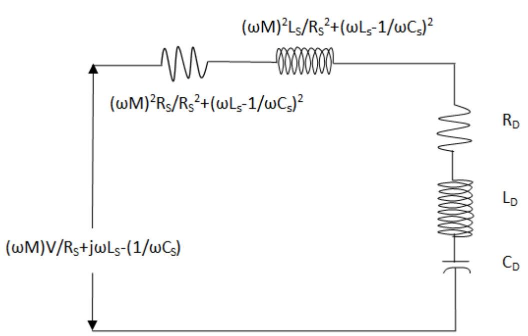


Fig3(a). Untuned source antenna coupled with a tuned device antennae (b). The aaproximate equivalent circuit.

3. CIRCUIT ANALYSIS IN THE FREQUENCY DOMAIN

The behavior of the coupled resonate system consisting of tuned source and device antennae is presented in the frequency domain. Since the coupled system is a combination of two second order circuits, the different parts of the circuit resonate at different frequencies which are related to their fundamental frequencies. When the source antennae are driven by an external source, the energy transferred to the circuit is moved between the energy storage elements according to each antenna's constitutive relations.

The impedances in the source and device antennae coils represented as Z_s and Z_D are defined for the circuit elements in series.

$$Z_S = R_S + j\omega(L_S - 1/C_S) \quad (6)$$

$$Z_D = R_S + j\omega(L_{sD} - 1/C_D) \quad (7)$$

The system transfer function which relates the input of the system $V_i(s)$ to the output $V_0(s)$ can be derived in the frequency domain by writing the Kirchhoff's voltage law equations for the source and device coils. The receive coil uses Faraday's and Lenz's laws to find the emf induced. This emf is in the form of a coupled inductance.

$$V_i(s) = I_S Z_S + j\omega M I_D \quad (8)$$

$$-j\omega M I_S = I_D Z_D \quad ((9)$$

Finding I_D from equation (9) and substituting in (8) we get,

$$I_s = V_1 / Z_S + \omega M)^2 / Z_D \quad (10)$$

$$I_D = -j\omega M I_S / Z_D \quad (11)$$

$$I_D = = -j\omega M V_1 / Z_S Z_D + (\omega M)^2 \quad (12)$$

When the device coil is coupled to the source coil there is an effect of additional impedance on the series path. The additional impedance is. $\omega M)^2 / Z_s$ .The device coil having voltage induced in it by the source coil loads the transmit coil to oppose the creation of flux by Lenz's law. This appears as a voltage drop in the transmit loop acting as an additional impedance. When the source and device coils are far apart the coupling between the coils $k = 0$. Each of the source and device coils has their self-resonant frequency determined by the circuit characteristics. When the source and device coils are brought closer, the source and device coil inductors tend to couple. When the coupling k increases, coupled inductances grow. The flux linking the receive coil increases as k increases. Leakage inductances serve as energy storing elements and do not link or share flux with other circuit. The equations governing L_s and L_D to L_M be given below:

$$M = -k\sqrt{L_S L_D} \quad (13)$$

$$L' = L_S + M \quad (14)$$

$$L'' = L_D + M \quad (15)$$

The leakage inductances L' and L'''' becomes zero ask increases to unity. The output voltage on the secondary coil is measured across the capacitance C_D .This voltage can be represented as:

$$V_0 = I_{2}/j\,\omega C_D = -MV_i / C_D(Z_S Z_D + (\omega M)^2) \quad (16)$$

The transfer function V_0/V_i can now be represented replacing the frequency term ω with the general Laplacian frequency operator s.

$$V_0/V_i = -M/C_D[R_s+sL_s+1/jsC_s][R_D+sL_D+1/sC_D] + (sM)^2 \quad (17)$$

Since the circuit is modeled as a series circuit, the conditions of resonance are incorporated as

$$V_0/V_i = --k\sqrt{L_s L_D}/C_D[R_s+sL_s+1/jsC_s]\,[R_D+sL_D+1/sC_D] + (sM)^2 \quad (18)$$

The terms in the denominator are expanded and ordered by their degree in s. The transfer function can now be represented as follows:

$$V_0/V_i = --k\sqrt{L_s L_D}\; C_S s^2/(1-k^2)C_S C_D L_S L_D s +$$

$$(R_S L_D C_D C_S + R_D L_S C_S C_D)s^3 +$$

$$(R_S R_D C_S C_D + L_S C_S + L_D C_D)s^2 + (R_S C_S + R_D C_D)s + 1 \quad (19)$$

Since the circuit is modeled as a series circuit, the conditions of resonance are incorporated as

$$\omega_S = 1/\sqrt{L_S C_S} \quad (20)$$

$$\omega_D = 1/\sqrt{L_D C_D} \quad (21)$$

Equations (20) and (21) are the self-resonant frequencies of the source and device coils. Their quality factors, which is the ratio of energy stored in the system to energy lost per cycle can be defined as

$$Q_S = \omega_S L_S / R_s \quad (22)$$

$$Q_D = \omega_D L_D / R_D \quad (23)$$

The coil inductances are measured using Wheeler's formula this is computed as follows:

$$L = a^2 N^2 / 9a + 10b \quad (24)$$

where a is the radius of the coil and b is the height of the coil in inches.These parameters are introduced by dividing the numerator and denominator by $1/L_S L_D C_S C_D$. This gives

$$V_0/V_i = -s^2\omega_D^2/1-k^2)s^4 + (\omega_S/Q_S + \omega_D/Q_D)s^3 + (\omega_D^2 + \omega_S^2) + \omega_s\,\omega_D/Q_S Q_D)s^2 + \omega_s\,\omega_D(\omega_s/Q_D + \omega_D/Q_s) + \omega_S^2\omega_D^2 \quad (25)$$

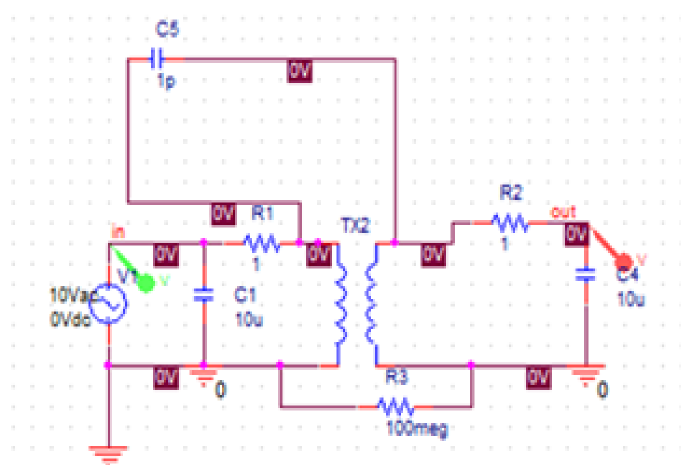
The factor $k\sqrt{L_D/L_s} = M(d)\sqrt{L_D/L_s}$ shows that ratio of inductances of the receive and transmit coils acts as a voltage divider between the receive and transmit coils. Equation (25) describes the system response. Alternatively equation (25) can also be written as

$$V_0/V_i = -M(d)/L_s / 1-k^2)s^4 + (\omega_S/Q_S + \omega_D/Q_D)s^3 + (\omega_D^2 + \omega_S^2) + \omega_s\,\omega_D/Q_S Q_D)\,s^2 + \omega_s\,\omega_D(\omega_s/Q_D + \omega_D/Q_s) + \omega_S^2\omega_D^2 \quad (26)$$

The characteristic polynomial of the system is represented by the denominator. This equation also gives an account of the voltage gain of the system. Since wireless power transfer systems operate at a resonant frequency where the primary and secondary circuits are tuned together, such that $\omega_S = \omega_D = \omega_R$ the output voltage depends on mutual inductance between the source and device coils which vary with distance.

4. SIMULATION AND VERIFICATION

The source and the device circuit was simulated using a near field formulation of the wireless power transfer system in ORCAD PSPICE as shown in Fig.4(a). The source and device circuits are taken as identical antennas of self inductances of 10µH. Assuming a lossless system with parasitic capacitances of 10µF, and link capacitance of 10µF, the variation of voltage across the device coil with frequency is shown in Fig .4(b).



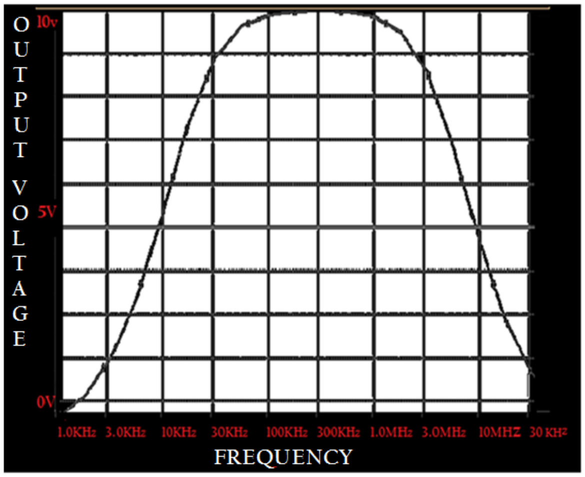


Fig.4 (a) Simulation of the wireless power transfer system using ORCAD PSPICE. (b). Variation of output voltage with frequency

Experimental setup consists of a source/transmitter antennae coil of 4 turns wound around a circular bobbin placed on a table top having diameter of copper wire of 1.291mm. The self-inductance of the source coil was measured as 21.6µH.The device antennae coil consisted of 35 turns of wire wound around a circular base to fit in at the bottom of the mobile. The diameter of copper wire was 0 .573mm.

The source coil was powered using a DC-AC oscillator coupled to a Class AB power amplifier. The DC-AC oscillation was produced using a standard Colpitts oscillator, where the feedback to the transistor circuit is taken from a combination of two capacitors in series as in Fig.5.

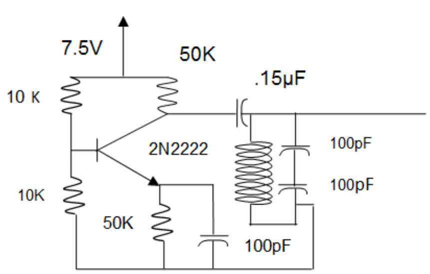


Fig.5. DC-AC oscillation produced by a Colpitts oscillator

The AC oscillation produced by the Colpitts oscillator was fed to a Class AB power amplifier made up two FET's connected back to back to amplify both half cycles of the AC power supply. The AB amplifier circuit is presented in Fig.6.

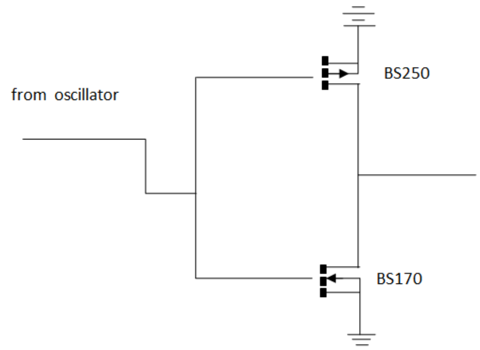


Fig.6. The power amplifier to the coupled circuit.

The device antennae were connected to a bridge rectifier circuit whose output was coupled to a capacitor of 100µF to provide a stable operation of the circuit as in Fig.7. The regulated DC output voltage of 6 V was obtained using a zener diode rated at 6.2V.

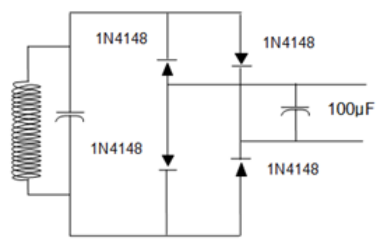


Fig.7. The device antennae circuit coupled to a bridge rectifier and capacitor.

Both source coil and the device coil tuned together at a resonant frequency of 953.2 KHz. The operating power gain expressed as $\frac{\mathrm{Re}[V_0 I_0^*]}{\mathrm{Re}[V_1 I_1^*]} = 19.23\,\%$. It was observed that the mobile phone was able to wirelessly charge at a vertical distance of 15 cm from the table top. The experimental set up is shown in Fig.8.

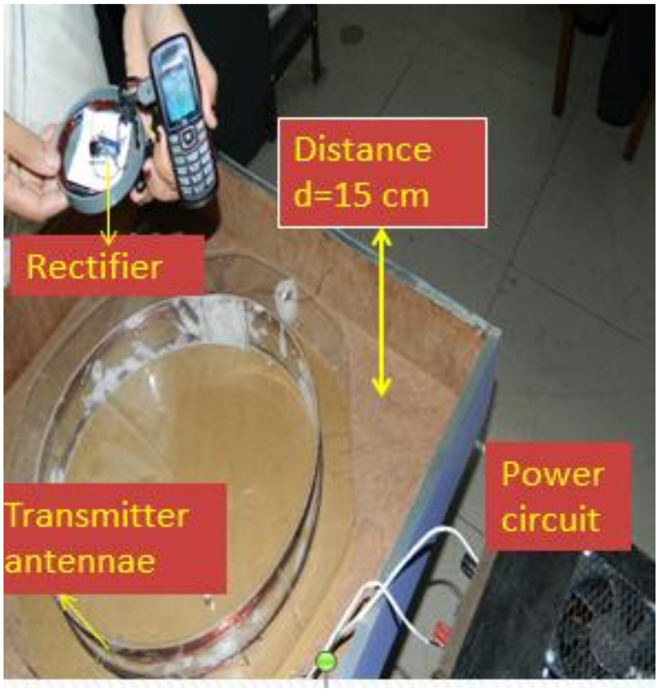


Fig.8. Mobile phone receiving evanescent signals from the electromagnetically energized table top.

The open circuit voltage across the device antennae varying with distance from the table top is shown in Fig.8

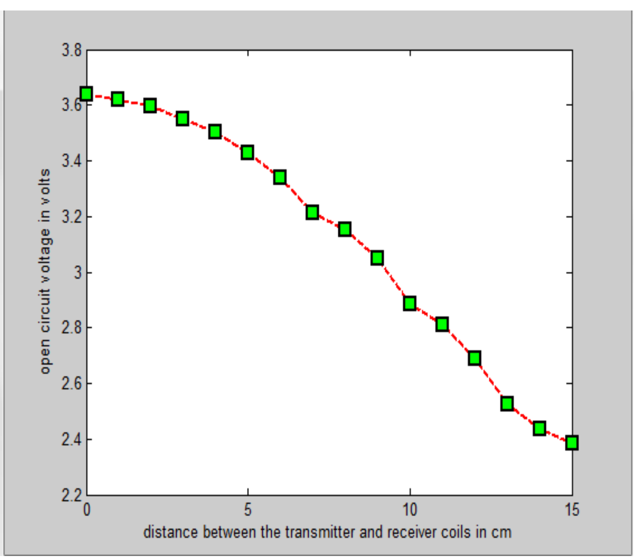


Fig.8. Open circuit voltage across the device antennae varying with distance from the table top.

CONCLUSIONS

The experimental realization of the wireless power transfer system demonstrated in this work can be extended to the powering of other utility devices like TV sets toys and other gizmos in living rooms. Enhanced powering mechanisms using resonant converters coupled to Class E Transmitters and sliver plated coils can be tried for source coils concealed in concrete for powering device coils of wireless gadgets in future.

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