

Wireless Power Transmission in Wireless Sensor Network- A solution to the power constraint

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Abstract— One of the major facts in Wireless Sensor Network (WSN) is its power constraint. In many critical cases, like sensors in hot oil pipe-lines may require urgent data from a selected node while the node is not waking up due to unhealthy battery life. Inductive coupling phenomena between two coils can easily solve it by wirelessly charging the previously placed coil inside that sensor. Wireless Power Transfer can be the solution on this concern. There are many alterable and unalterable factors that can govern the efficiency of Wireless Power Transfer. High Radio Frequency in lower coil radius with simple magnetic radiation mechanism can successfully transmit the power within a short distance at low cost. After pre-tuning resonant frequency, the optimum power transfer is possible through a constant efficiency in a short distance between nodes. Multi hop nodes can easily share the power from the source as well. A sensor can be placed anywhere when necessary, in that case the primary supply must be questionable and can be solved through the renewable energy.

Index Terms— Coupling coefficient, Impedance mismatch, Mutual inductances, Neumann's formula, Resonance, Wireless Power Transfer and Wireless Sensor Network

1 INTRODUCTION

Modern days are coming wrapped with a soft bound of simplicity and an awesomeness of fabulous technology.

Wireless Power Transfer (WPT) used in a charging unit [1] brings the beauty in heathers as a little hope for the possibilities of far field coupling mechanisms. Starting with a conventional theory of Faraday's Law of Magnetic induction along with simple calculation of Neumann's formula can lead the prospective technology to low cost commercial goods through simple circuit construction. In this paper, we focused on the simple, low cost construction of a charging system providing a concept of using renewable energy in a mostly power constrained application (e.g. Sensors). Using Magnetic coupling in a resonant circuit is widely used for its beneficiary significance of wirelessly power transfer capabilities. From the last decade a huge work has been done in progress of WPT, Different methods has brought into the operations of WPT understanding the coupling between subsequent transmissions of wireless power. Besides the small equipment charging, WPT electrical vehicles as well as electric trains and robots are also capable of charging wirelessly [2-9].

According to the practical analysis, it is clear that the design is suffered for some common reasons. In [10], describes the practical dependences of end to end efficiency of magnetically coupled resonators. Achieving a good coupling coefficient with a large air gap depends on many important features. Impedance matching [11] is one of the great issues. In [12-16], these papers focus on the improved efficiency analysis depending on the coupling coefficient relating with air gap. In [17], they propose a power distribution analysis by matching the impedance between the multi-coils. The paper [18], focuses on WPT consider-

ing the coil misalignment cases and successfully determine the effect over efficiency with an experimental verification. Into the WPT, basic problem can be indicating as the separation of coils where the electrical power is transferring along with the manageable efficiency. According to the recent study, WiTricity was proposed the theoretical implementation in 2007. The efficiencies are above approximately 50% within the distance of 2m [19]. In [17], they have calculated the imaginary value of the reactive powers which is then balanced by other reactances present in the circuit. According to the calculation, for a single receiver (Secondary coil) will experience a greater reactive power if the impedance mismatch factor is not wisely handled.

From recent works on WPT, We can introduce the method of wireless power transfer in three typical methods. (i) Coupled mode method (ii) Band-Pass Filter Method [20] and (iii) Equivalent circuit model. (Figure: 1) In [21], authors have calculated and proposed a band pass filter representation which is being analyzed considering the range between the pass bands, In [22], A method of introducing an intermediate coil between the transmitting and receiving coils is proposed where this concepts can be installed for a long transmission of WPT, also in [10], there method was a frequency tuning method for the optimum efficiency. (It can be proved theoretically by following to the solution of Helmholtz equation [23] relating angular frequency and magnetic field intensity). In the following papers [17, 24], authors have proposed a power division method by matching the impedance between coils. In this paper we have done the WPT with an experimental as well as simulation analysis using weakly coupled ($k=0.011$) inductive coil using the Neumann's formula equation (1).

Major concern is given to the impedance mismatch factor as well as the coil alignment cases for getting maximum distances.

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2 WIRELESS POWER TRANSFER CHALLENGES

2.1 Introduction

Wireless power transmission has an enormous prospect on commercial and domestic uses. Power transmission on electric vehicle is studying widely and come to a successful throughput in this field. The basic problems on this type of transmission are the separation distances between the coils, coupling phenomena, resonant frequency, quality factor, coils radii, coil alignments etc. Different types of method used to determine the efficiency and maximum separation distance.

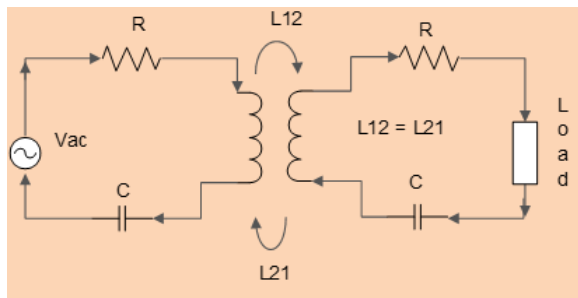


Fig. 1: An equivalent circuit model of inductive coupling circuit.

Also a new method of distribution power in receiving coils is discussed in [24]. Although the methods are very similar and the exact analysis of impedance inverters but the main problem is neglecting cross coupling between the multi receivers, which is not ignorable, while a sufficient numbers of receiver will be used along with multi repeaters. Another major problem is, the model is depends on coupling co-efficient and every time the tuning required for changing distance between transmitter and receiver coils, so that for a practical implementation, auto tuning capabilities are required. In this paper, (Fig: 2) renewable energy is being stored into a DC battery to supply for the RF oscillator circuit after proper biasing (RF amplifier circuit is required and used).

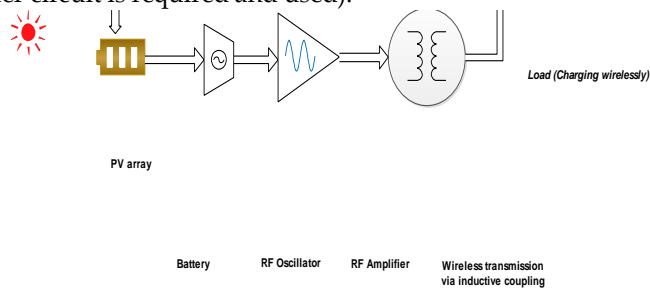


Fig. 2: Basic block diagram of WPT.

An equivalent circuit model is analyzed and calculated the parameters for impedance matching as well as proper resonance. The application is primarily designed for the wireless sensor networks, as the sensors are low consumed power and at the same time energy constrained. But the similar analogy can be established into the other charging systems for the rat-

ed or pick up current.

2.2 Issue on WSN

Considering the applications, Wireless Sensor Network suffers the continuous power constraint. Different types of mode and distribution of clustering technique has brought with the concern of power management in a small sensor. Wireless Sensor Network (WSN) is a robust technology based on Wireless Networking without any infrastructure. The back bone of WSN belongs to the Wireless Ad hoc Network, following IEEE 802.15.4 Low rate WPAN Standard [25]. Unlike wired or wireless infrastructure based network, which can be categorized by different topology, WSN structure is very much depends on application based. Basic advantage of WSN is its feasibility of working in rough environment. The Sensor nodes (which is on average known as 'mote') are typically consists of a microprocessor, digital radio, sensing unit and power supply [26]. In case of power assumption issue in WSN, many algorithms have been studied depend on application of establishing WSN. For an example, the idea of on demand schemes [27], scheduled rendezvous schemes [28, 29], asynchronous wakeup schemes [30] or the idea of selective communications or any type of wake/sleep schemes [31-33] are performed successfully for low power stability and cost. According to some of short discussion over Wireless Sensor Network it is clear that, an entire system is facing a short and limited capacity due to the power supply only. Fig: 3, is illustrating a new concept of distribution of power through WPT to the sensors where there is no other way of contact with the sensors after establishing. Using the multi receiver it is possible to transmit power through the intermediate nodes [34].

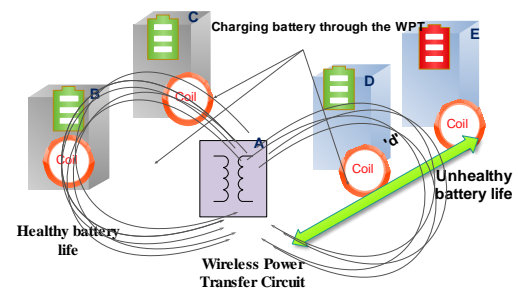


Fig. 3: Conceptual model of WPT in WSN.

2.3 Proposed Model

For the maximum efficiency, usually the typical steps are Impedance matching, Loss-less property of resonators,

resonant frequency, Power generated at the primary coil, coupling co-efficient and Mutual inductance etc. Selection of perfect load impedance for the available transmitted power from the primary coil is also important for the practical analysis. Now, the Neumann's Formula can be derived from the fundamental Biot-Savart's Law,

$$L_{12} = \frac{\mu_0 N_1 N_2}{4\pi} \oint_{C_1} \oint_{C_2} \frac{dl_1 dl_2}{R} \quad (1)$$

where, L12 is the Mutual inductance, N1 and N2 is the coil turn number primary and secondary coils respectively, dl1 and dl2 are the differential length of coils primary and secondary side respectively and 'R' is the separation between two coils). Mutual inductance (L12) between coils can easily be achieved by the above formula again the relation between coupling coefficient and the mutual inductance can be found as;

$$M_{12} = k_{12} \sqrt{L_{TX} L_{RX}} \quad (2)$$

Where, k12 is the coupling coefficient, M12 is the mutual inductance; L1 and L2 are the inductance in Primary and Secondary side respectively. Coil designed is being done by,

$$L_0 = N^2 \mu_0 r \left(\ln \left(\frac{8r}{a} \right) - 1.75 \right) \quad (3)$$

Where, 'L0' is the desired resonant coil inductance, 'N' is the turn number, 'r' is the coil radius and 'a' is the pitch of coil. Choice of taking equal amount of inductance both primary and secondary sides will make an easy way to determine the impedance matching in both sides. That is, we will now focus on the resistive and capacitive impedances. Unless tuning the capacitance, it is required to tune the resonant frequency so that the coil on both sides will resonate at same frequency and the efficiency will be high.

Fig. 4: An equivalent circuit model of a Wireless Power Transfer circuit.

Neumann's formula derived from the conventional Biot-Savart's law is a key to measure the mutual inductance. Efficiency for using two coils can be derived as,

$$\eta = \frac{P_{RX}}{P_{TX}} (100\%) = \frac{V_{ind}^2}{4R_{TX} R_{RX} I_{TX}^2} (100\%) \quad (4)$$

Here, η is the efficiency of power transmission, 'P_{RX}' and 'P_{TX}' is the power at receiving and transmitting side. Here, induced voltage on the secondary side can be designed as,

$$|V_{ind}|^2 = \left| \frac{j\omega\pi\mu_0 N_{TX} N_{RX} I_{TX} a^2 b^2}{2R^3} \right|^2 = \frac{\omega^2 \pi^2 \mu_0^2 N_{TX}^2 N_{RX}^2 I_{TX}^2 a^4 b^4}{4R^6} \quad (5)$$

Where, 'V_{ind}' is the induced voltage at the secondary side. 'a' and 'b' is the coil radius of primary and secondary sides respectively, ω is the resonant angular frequency. It can be stated from the faradays law of magnetic induction. Finally the efficiency becomes,

$$\eta = \frac{\omega^2 \pi^2 \mu_0^2 N_{TX}^2 N_{RX}^2 a^4 b^4}{16R_{TX} R_{RX} (d^2 + a^2)^3} (100\%) \quad (6)$$

Now, this formula only gives a complete concept of the factor depends on the efficiency. Clearly, η depends on the factors derived on coil's parameters and resonance as well as impedances. For any fixed coils, we can write that,

$$\eta = K \omega^2 / R_{TX} R_{RX} (d^2 + a^2)^3 \quad (7)$$

$$K = \frac{\mu_0^2 \pi^2 N_{TX}^2 N_{RX}^2 a^4 b^4}{16}$$

Where, Multiplying factor,

Again considering the impedance matching factor, we can take, R_{TX} = R_{RX} = Z, so that, efficiency depends only on resonant frequency, separation distance and the impedance mismatch. In this paper I tried to focus on the simple mechanism to find out the simplest and easiest way of calculation the efficiency considering the environment of a sensor.

$$\eta = \frac{K \omega^2}{Z(d^2 + a^2)^3} = \frac{K}{R^2 + X_L X_C + jR(X_L - X_C)(d^2 + a^2)^3} \quad (8)$$

So that, for any fixed distance,

$$\eta = \frac{K_1}{R^2 + X_L X_C + jR(X_L - X_C)} \quad (9)$$

$$K_1 = \frac{K}{(d^2 + a^2)^3}$$

Where, Multiplying factor,

Now, at resonant, X_L = X_C so that efficiency will become,

$$\eta = \frac{K_1}{R^2 + X_L X_C} \quad (10)$$

Where, X_L = ωL₀ and X_C = 1/ωC₀. And the resonant

frequency,
$$\omega_0 = \frac{1}{\sqrt{L_0 C_0}}$$

From the relation, it is understood that for any change of mismatching resonant frequency with a lower amount will take effect of serious degradation at the efficiency though for high 'Q'. If the deviation of the actual frequency versus

resonant frequency becomes wider than its cutoff frequency than there will be no power transmission through the entire system.

Impedance matching is evident in WPT, the circumstances of impedance mismatching will degrade the maximum efficiency can be discussed further with a simple

network, where, $\eta = |S_{21}|^2 \times 100\%$

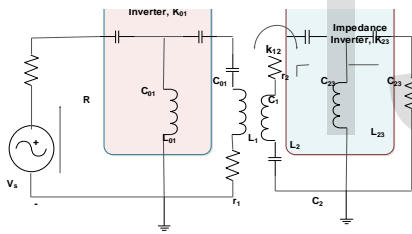
$$S_{21} = \frac{2j\omega_0 L_M Z_L}{\omega_0^2 L_M^2 + (Z_L + Z_2)^2} \quad (11)$$

Where, S_{21} is the transmission efficiency from primary side to the secondary sides, Z_L is the load impedance, Z_2 is the matched impedance in the secondary sides, L_M is the mutual inductance and ω_0 is the resonant angular frequency.

So that for the maximum case it can be shown that,

$$\omega_0^2 L_M^2 + Z_L^2 - Z_2^2 = 0$$

Thus the need of impedance matching could realize from the equation and also, LM can be chosen easily from this equation. From the mutual inductance, coupling coefficient could be studied easily, In this paper, the mutual inductance is found using Neumann's formula and found 0.16μH and the coupling coefficient is found 0.011 (Here, we took an arbitrary data to focus on applying the mentioned method for a distance of



2cm).

Thus, coupling co-efficient κ_{12} can be found from the conventional formula on equation (2) where mutual inductance is known by the Neumann's formula.

Fig. 5: Impedance matching equivalent circuit diagram.

From figure-5, an impedance matching inverting is designed which is virtually considered for the impedance matching calculation of load and to show the coupling between primary and secondary coils. Measured current (I_1 and I_2) can be expressed as,

$$I_1 = \frac{2(Z_L + Z_2)}{\omega_0^2 L_M^2 + (Z_L + Z_2)^2} \quad (12)$$

$$I_2 = \frac{2j\omega L_M}{\omega_0^2 L_M^2 + (Z_L + Z_2)^2} \quad (13)$$

Considering the configuration as a 'Butterworth response', low pass filter equation can be achieved which gives rise to the

following equations:

$$\kappa_{01} = \frac{K_{01}^2}{R_0 \omega_0 L_1} \quad (14)$$

$$\kappa_{23} = \frac{K_{23}^2}{R_L \omega_0 L_2} \quad (15)$$

$$\kappa_{12} = \frac{K_{12}}{\omega_0 \sqrt{L_1 L_2}} \quad (16)$$

Where, From above equation κ_{01} and κ_{23} are the coupling coefficient between L_{01} to primary coil and L_{23} to secondary coil respectively. κ_{12} is the coupling coefficient between the primary and secondary coils. R_0 and R_L are the input and output impedance (Which is considered same 'R'). C_1 and C_2 are the coupling capacitor for the coils to be resonance at the resonant frequency, ω_0 .

Now, Coupling coefficient κ_{12} is found, $\kappa_{12} = 0.011$, for the impedance inverter design we consider, $\kappa_{12} = \kappa_{01} = \kappa_{23} = 0.011$ and found the characteristics impedance, K_{01} and K_{23} are equal and same, 25.61Ω (cause, R_0 and R_L are considered same).

3 RESULTS AND DISCUSSION

In this paper, the proposed concept of mitigating the power constraint problem in Wireless Sensor Network come up with two coils surrounding each of the node. Two coils can conduct at the same time and transfer power continuously. Most power constrained node can send data to the cluster head by sending additional flag message and thus the power transmission will begin. Actual power will be cultivated from the renewable sources like solar power. After getting voltage from PV (Photo-voltaic) solar array, precisely +12 V is maintained through a voltage regulator. We used a current controlled amplifier to biasing the incoming voltage. When biasing is done, an RF oscillator circuit should be made with 13.56 MHz of resonant frequency. We used a 'Hartley oscillator' circuit to produce RF frequency of 13.56 MHz (Amplification of the output of RF oscillator circuit must be done with an RF amplifier circuit) which is not necessary to produce an extra burden for the sensor nodes (Typical RF used on the Sensors is 13.56 MHz). Impedance matching network is a pre-calculated for setting capacitance and resistance for the constructed coils (Primary and secondary). According to the objectives, sensors must be designed along with the two coils on both sides

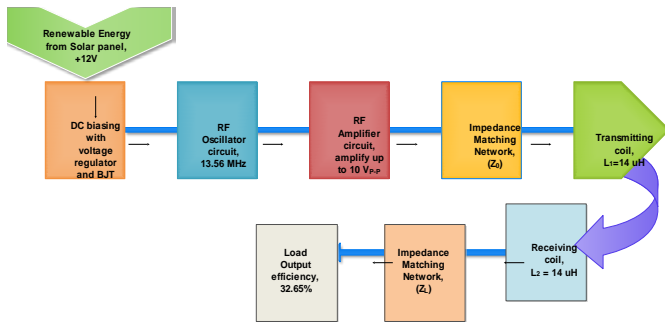


Fig. 6: Step by step methodology

We use the center tapped coil as a primary coil considering $N=10$ with a low coil radius (3.5 cm). Considering the low 'Q' (5.5) the simulation results found that primary coil is delivering constant current of 4 mA peak to peak and the oscillation is stable. The stability of the oscillation in the following figure (8) indicates the impedance matching on the primary and secondary sides.

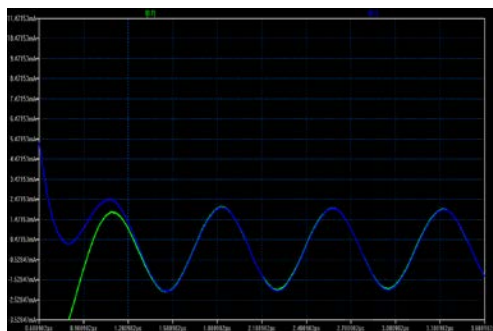


Fig. 7: Primary coil current I (L1) and I (L2) together after 1.5 μ s

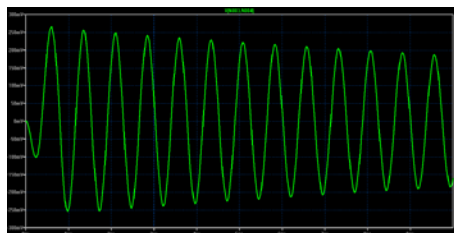


Fig. 8: Voltage found at resonant capacitance (damping condition).

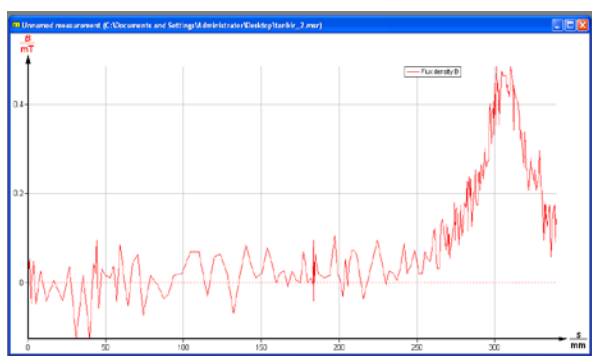


Fig. 9: Practical measurements of Magnetic Flux density

$$(N=10, a=0.035m)$$

Figure 9, is a practical approach taken after the calculation had been done. Results showing that the magnetic flux density generated by the short circuit operation of primary coil is 0.52 mT. This is standardized by the ISO and IEC 61000 standards for domestic and commercial uses. The efficiency versus distance curve gives an easy analytical result, which shows the parameter distance will vary the efficiency. In this paper, the physical construction of the prototype of wireless power transfer based on WSN is studied for the separation distance of the coils is 2cm. According to the following figure 7 and 8, we can see the condition for the efficiency to be decreased along with the increasing separation distance. Resonant frequency 13.56 MHz adjusted carefully after the construction of RF frequency, from the RF oscillator, a sensitive adjustment is necessary by changing the capacitance to achieve into the resonant frequency. It can be shown that how poorly the efficiency deviates due to detuning.

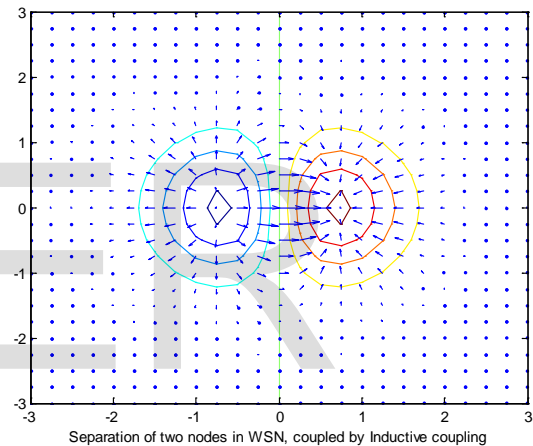


Fig. 10: Magnetic flux line sharing scenario

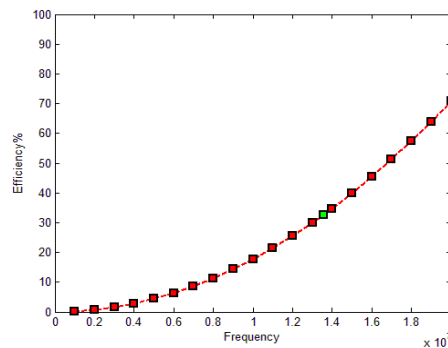


Fig. 11: Efficiency versus optimum frequency curve

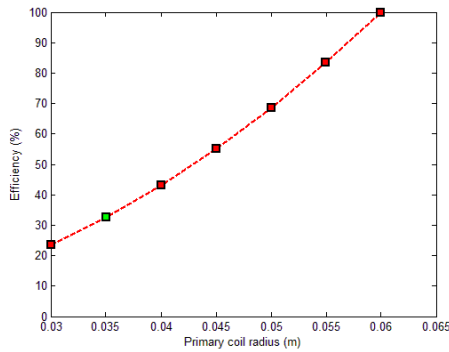


Fig. 12: Efficiency versus coils radius curve

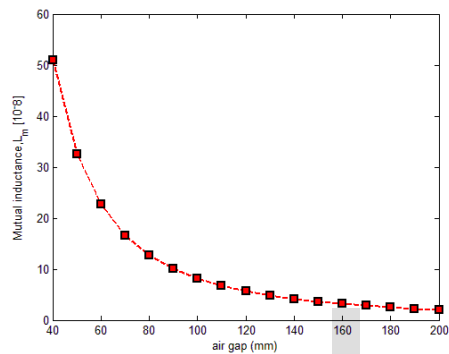


Fig. 13: Mutual inductance versus separation distance

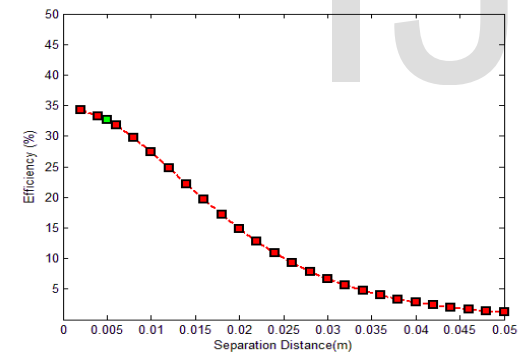


Fig. 14: Efficiency versus coil separation distance

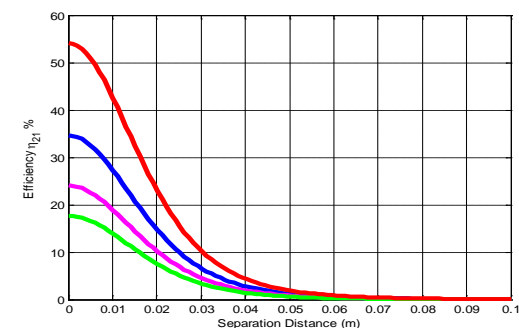


Fig. 15: Efficiency versus coil separation distances in different internal coil resistances, from top to bottom $R=40\Omega$, 50Ω , 60Ω and 70Ω

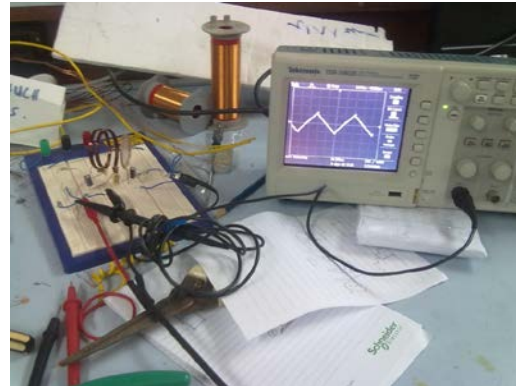


Fig. 15: An output of 20mV peak to peak is found at the receiver side for 2cm of separation distances.

In this paper, wireless power transfer into the WSN can be considered under some certain points of requirements. The feasibility of the transmission in worst case is considered for the entire experimental setup. But, some common facts must be maintained for optimum case. High quality factor 'Q' must take under the rough circumstances to get the narrow frequency width and high output for the critical frequency. In case of a small difference of resonant frequency ($\Delta\omega$), Efficiency drops rustically though the 'Q' factor is being chosen high. Impedance matching is calculated considering the 'impedance inverter' in both sides of the coupled inductors using 'Band pass method'. Selecting load for the paramount power transfer is one of the key features of WPT. Choice of selecting resistance confined the power at load. Coil misalignment in lateral and angular misalignment could happen for arbitrary set up of WSN nodes for the multi hop. The coupling coefficient k_{12} is in between 0~1 but for the low power assumption nodes require a strong coupling between them. Higher frequency will lead a good system performance but sensitive calibration.

4 CONCLUSION

A new model of circuit construction is illustrated and proved the transmission of wireless power through a small distance with only two RF amplifiers and conventional oscillator circuit. Our proposed method consists of simple algorithm and calculations with a cheap but efficient circuitry for commercial aspects. Simulation results demonstrate the similarity found by previously done practical works. A prototype was built to prove the new simplest method. But, tuning of resonant frequency through the variable capacitor was difficult and sophisticated. In future, a varistor could be introduced to replace the variable capacitor. Four coils transmission technique could be introduced for the further study for WSN.

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