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The impact of nodes distance on wireless energy transfer system

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Abstract

Wireless energy transfer (WET) reemerges as the method for transmitting electric power without the necessity to deal with cable losses and an aesthetically pleasing environment. The problem with WET is how to maintain magnetic induction as the distance gets further. This paper investigates the impact of nodes distance on the WET system. The experimental results show that the most effective distance among transmitter, nodes, and receiver are 4 cm. The measurement is taken with and without load. The without load application give that for node 1; the results are 6 V, 110 mA, and 2.85 mT for voltage, current, and magnetic flux, respectively. At the application of 2 nodes, the voltage is 6.8 V, the current is 0.124 mA, and the magnetic flux is 3.83 mT, and at three nodes installation, it is 7 V, 134 mA, and 3.83 mT. During the application of 3-Watt and 5-Watt lamp, at 4 cm distance, the power received is 1.66 W and 3.66 W at 3-Watt and 5-Watt lamp for one node, 1.84 W, and 3.84 for two nodes, and 1.93 W and 3.93 for three nodes. The experimental results show that the transmitted signal can be prolonged by installing nodes. Even though this study shows that 4 cm is the most effective, it is possible to increase up to 20 cm to power a 3-Watt lamp and 5-Watt lamp.

1. Introduction

Wireless energy transfer (WET) is not a novel method to transfer electricity from the source to the load, and this method is backed to 1888 when Heinrich Hertz experimented evidence of radio wave by using a spark gap radio transmitter and 1899 when Nikola Tesla showed the experiment in transmitting high AC voltage by using inductive and capacitive coupling method in Colorado [1]. The experiment was a success but poorly received by the community. However, the ever-advancing technology in Electrical Engineering results in the excessive usage of cables. The extensive use of cables creates disorder in terms of wire electricity. The energy transfer efficiency is also decreasing due to cable resistance. The problem of the massive requirement of cables installation can be overcome by designing a WET system. WET facilitate the non-physical conductor to transmit any electrical power.

Currently, people are coming back to investigate WET on small scales, such as for housing applications. The WET application for home appliances gives us the promise of a tidy and saver environment [2][3][4][5][6][7][8]. WET is divided into two methods: far-field, mid-range [9], and near field [3][10]. In far-field applications, the energy transfer can cover long distances by using power beaming through electromagnetic radiation. Near field is a non-radiative technique where the electricity is transfer in short distance by inductive coupling generated by a magnetic field of coils [7][8][11][12][13]. The widely used technique in daily and practical application is near field such as mobile charging or small-scale electronics devices [4]. Currently, the WET application is moving toward technology to support vehicle charging [14] and renewable energy [1][15][16], which are demanded due to the current increment of electric vehicles and renewable energy technology.

The problem with the near field is highly dependent on the distance between the transmitter and receiver coil. The effort to prolong the transmission is by adding a receiver or node [17][18][19][20][21][22][23][24][25][26]. The objective of this paper is to investigate the impact of node distance for the WET system. The experiment setup is using three nodes, installed at different distances. The output power transmitted and received will be analyzed to show the distance effect and finding the best distance to power the load.

2. Research Method

This paper presents the effect of varying distance in WET, and the proposed method is given by Figure 1, which shows the block diagram of the WET system considered in this research. This study proposes the method to prolong the emitted electromagnetic induction from the transmitter by installing nodes or repeater between transmitter and receiver.

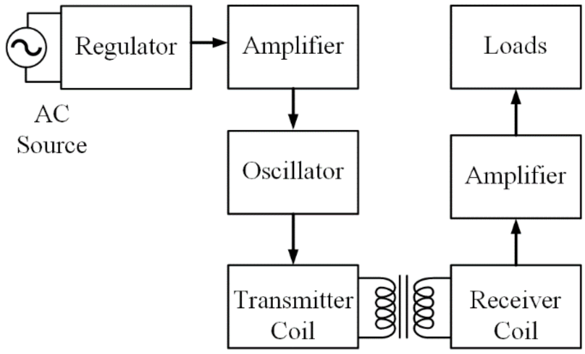
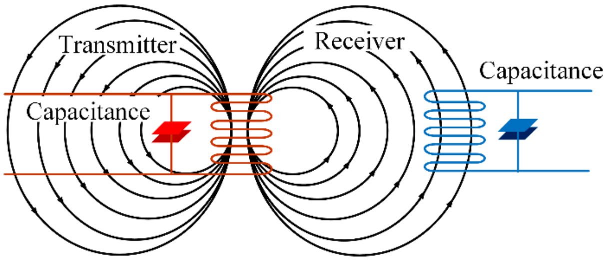


Figure 1. The Proposed Method Considered in this Study

(a) Bronze coil



(b) Magnetic induction illustration

Figure 2. The Bronze Coil and the Magnetic Induction Illustration

The primary material in this study is bronze coils winded N times shown in Figure 2(a) to generate magnetic induction between the transmitter and receiver illustrated in Figure 2(b). The number of windings is responsible for the amount of generated and transmitted voltage, as calculated by Equation 1.

$$V_L = N\frac{d\Phi}{dt} = \frac{\mu N^2 A}{l} \times \frac{di}{dt} \quad (1)$$

Where N is the winding numbers, A is the surface area (m^2), Φ is the magnetic flux (Wb), μ is material permeability, l is the inductor length (m), and i is the current. Equation 1 shows that the changing in the magnetic field ($\frac{d\Phi}{dt}$) is proportional to the changing of electric current ($\frac{di}{dt}$). The relation between the numbers of coils and the inductance (L) is given by $\mu N^2 A$, and the resulted current from installed capacitance is $C\frac{dv}{dt}$.

The mutual inductance (M) formed between transmitter (L_T), and receiver (L_R) is given by Equation 2.

$$M = L_T L_R, \quad (2)$$

and the inductance (L) is calculated by Equation 3.

$$L = N^2 \mu_0 \mu \left(\frac{D}{2}\right)\left(\left(\ln\frac{8D}{d}\right) - 2\right), \quad (3)$$

where μ_0 is the vacuum permeability ($4\pi \times 10^7$)(H/m), D is the diameter of loop coil (cm), and d is the conductor cross-section (m). The optimal resonance frequency (f_r) is determined by the capacitance (C) used in this study and calculated as Equation 4.

$$f_r = \frac{1}{2\pi\sqrt{LC}}, \quad (4)$$

and the coupling coefficient (k) is $\frac{M}{\sqrt{L_T L_R}}$. The coefficient k value is somewhere between 0 and 1, where 1 is the perfect coupling, and 0 means the transmitter and receiver coils are dependent on each other.

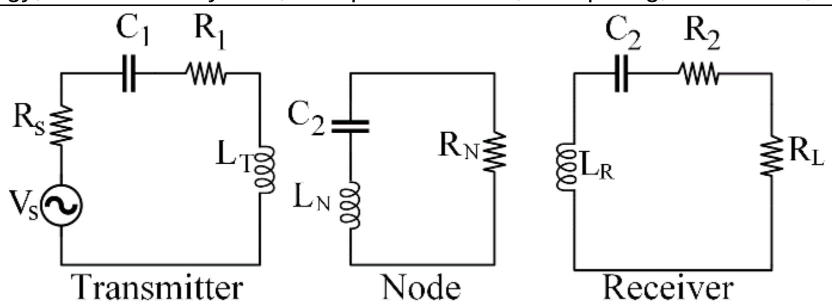


Figure 3. The Installed Node Model Considered in this Study

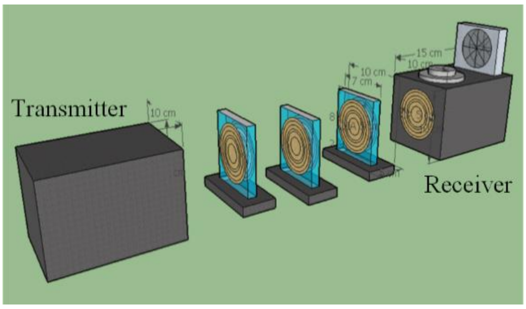
In order to enhance the transmitted signal from a transmitter, nodes are installed between transmitter and receiver, as modeled in Figure 3, where R_T is resistance in the transmitter, and R_R is the total resistance in the receiver. The voltage source (V_s) is given by Equation 5.

$$V_s = R_T I_T + j\omega k\sqrt{L_T L_N I_N}. \tag{5}$$

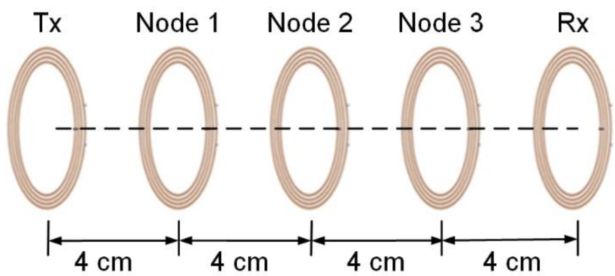
Where $R_T = R_s + R_1$ and $R_R = R_s + R_L$. The resistance in node shown in Figure 3 should be minimized to improve the transfer efficiency.

3. Results and Discussion

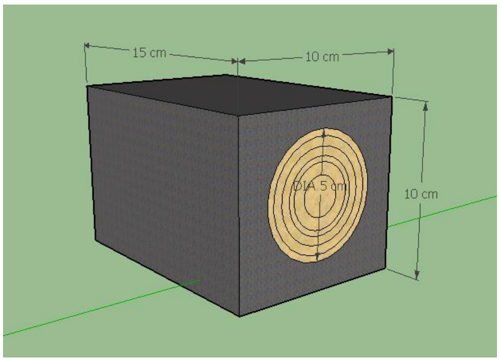
This paper discusses nodes application to prolong the transmitted signal from the transmitter to the receiver, where a load is installed. The experimental setup of this study is given in Figure 4(a), where the distances are given in Figure 4(b). Figures 4(c) and Figure 4(d) show the detail of the transmitter and nodes size. The distances among transmitters, nodes, and receivers are kept uniform, such as 4 cm, as shown in Figure 4(b). The distances are varied and investigated to show the effect on transmitted and received power, efficiency, and magnetic induction. Figure 4 shows the application of 3 nodes. For the application of 1 node, only one node is applied, and for two nodes, only two nodes are placed. Table 1 shows the specification of the components used in this study. The experiment is divided into three steps: the application of 1 node, 2 nodes, and 3 nodes, respectively.



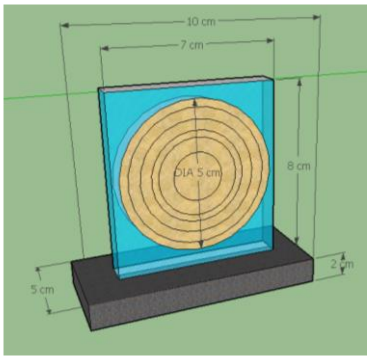
(a) The experimental setup



(b) The setting distances



(c) Detail of transmitter and receiver box size



(d) Node coils size

Figure 4. The Experimental Setting for Wireless Energy Transfer Considered in this Study

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Table 1. The Specification of Components Used in this Study

Specs	N (windings)	D (cm)	d(cm)	L(mH)	C(μF)	f(kHz)	V(volt)
Tx	23	1.1	3.2	5.714	682×10^{-6}	710.239	23.53
Node 1	23	1.1	3.2	11.428	682×10^{-6}	57.032	21.43
Node 2	23	1.1	3.2	17.142	682×10^{-6}	46.573	22.63
Node 3	23	1.1	3.2	22.856	682×10^{-6}	40.333	22.82
Rx	23	1.1	3.2	28.571	682×10^{-6}	36.075	23.42

The inductances in Table 1 are increasing respective to the more nodes application, where inductance in node 1 (L_1) is 0.011428 H, node 2 (L_1+L_2) is 0.017142 H, and node 3 (L_1+L_2+L_3) is 0.02856 H. Therefore, the inductance in receiver (L_1+L_2+L_3+L_R) is 0.028571 H, which is higher than inductance in transmitter. The increment of inductance reduces the frequency of each nodes and subsequently reduces the inductance in the receiver since the frequency is inversely proportional to inductance. Table 2 shows the transmitted voltage (V_{TX}), current (I_{TX}), and power (P_{TX}) from a transmitter (Tx) to Receiver (Rx), where I_s and P_s are the current and power from the source ($_s$).

Table 2. The Transmitted Voltage, Current and Power in Transmitter (Tx)

Distance (cm)	V_s (V)	I_s (A)	P_s (V)	V_{TX}	I_{TX}	P_{TX}
4	32	0.25	8	26	151	3.92
6	32	0.25	8	26	146	3.79
8	32	0.25	8	26	142	3.69
10	32	0.25	8	26	137	3.56
12	32	0.25	7.04	26	135	3.51
14	32	0.25	7.04	26	123	3.19
16	32	0.25	7.04	26	132	3.43
18	32	0.25	7.04	26	127	3.30
20	32	0.25	7.04	26	122	3.17

The experimental results of nodes application starting from 1 node, 2 nodes, and 3 nodes are shown in Figures 5 to 9, where VRx1, VRx2, and VRx3 are the voltage measured in the receiver due to the application of node 1, 2, and 3 respectively. IRx1, IRx2, and IRX3 are the currents, and B1, B2, and B3 are the magnetic inductions. Figure 5, Figure 6, and Figure 7 are the measurement results of voltage, current, and magnetic flux in the receiver without load application. Figure 5, Figure 6, and Figure 7 shows that the most effective distance among transmitter, nodes, and receiver are 4 cm, as indicated that in the distance 4 cm the voltage, current, and magnetic flux are at the highest measured. For node 1 at the distance of 4 cm, the voltage is 6 V, the current is 110 mA, and the magnetic flux is 2.85 μT. At the application of 2 nodes, the voltage is 6.8 V, the current is 0.124 mA, and the magnetic flux is 3.83 μT. For 3 nodes installation, the voltage is 7 V, the current is 134 mA, and the magnetic flux is 3.83 μT. The current, voltage, and magnetic flux are gradually decreasing as the distance increases, as shown in Figure 5, Figure 6, and Figure 7.

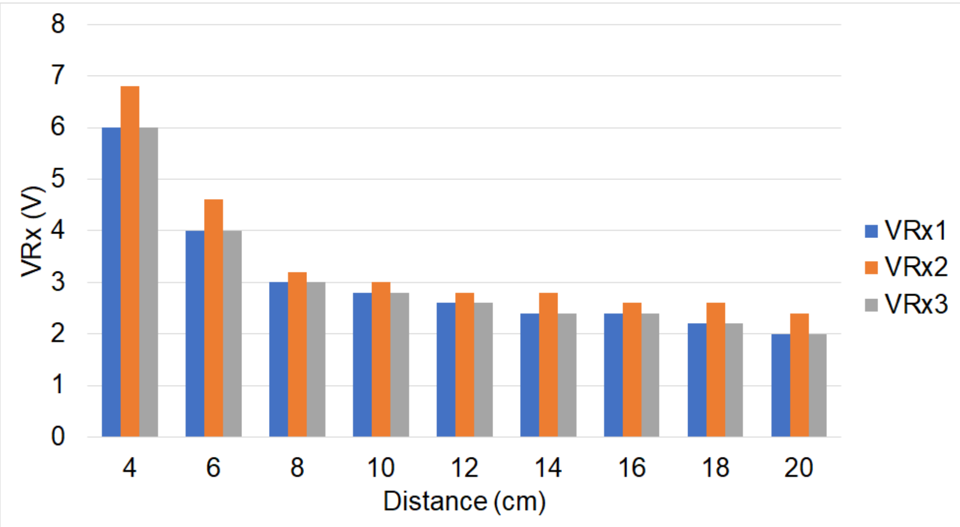

Figure 5. The Voltages Measured in the Receiver After the Application of Three Nodes

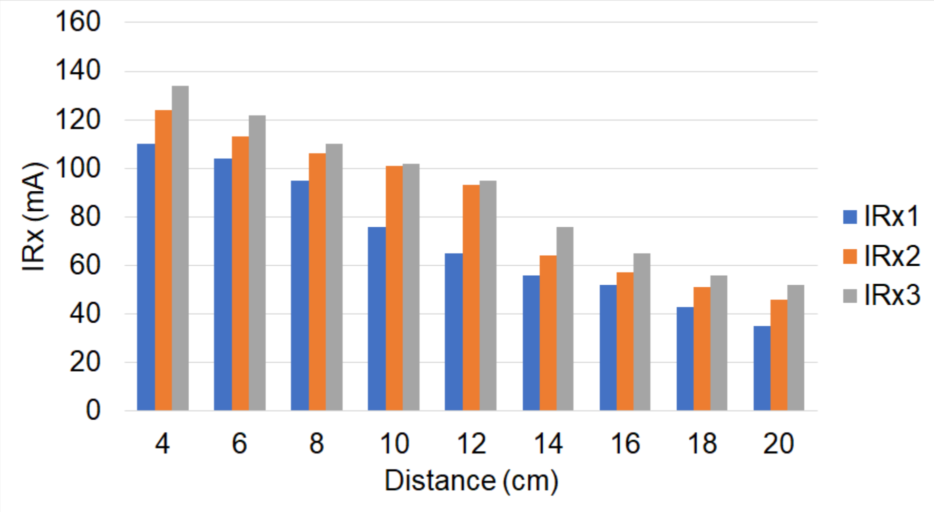

Figure 6. The Current Measured in Receiver After the Application of Three Nodes

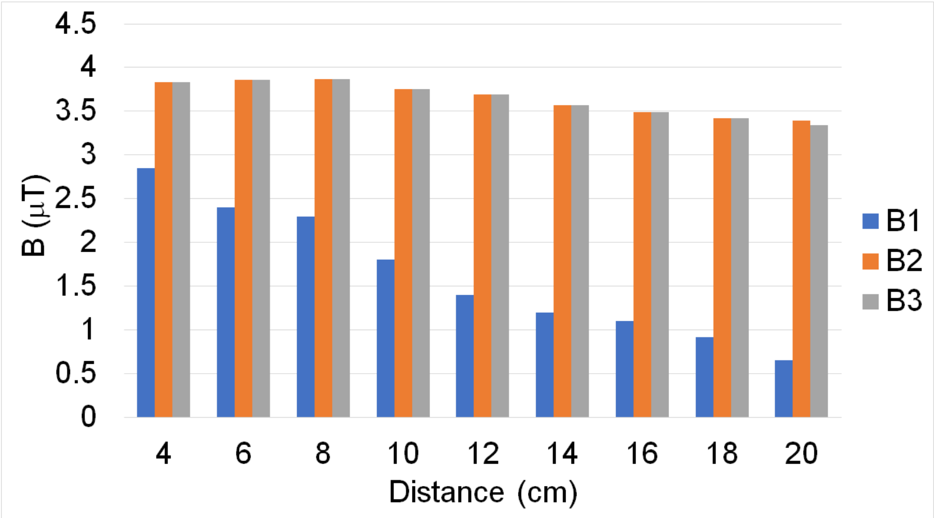

Figure 7. The Magnetic Fields Measured in the Receiver After the Application of Three Nodes

The next step is by installing two loads, a 3- and 5-Watts LED Lamps. The distance is varied from 4 to 20 cm, the effect of distances to the produced power is recorded in Table 3. The results of these experiment are shown in Figure 8 for 3-watt LED lamps, and Figure 9 for 5-watt LED lamps.

Table 3. The Received Power on the Receiver as the Distance Varied

Distance (cm)	P (Watt)					
	1 Node		2 Nodes		3 Nodes	
	3 Watt	5 Watt	3 Watt	5 Watt	3 Watt	5 Watt
4	1.66	3.66	1.84	3.84	1.93	3.93
6	1.41	3.41	1.51	3.51	1.80	3.80
8	1.28	3.28	1.33	3.33	1.50	3.50
10	1.21	3.21	1.30	3.30	1.32	3.32
12	1.16	3.16	1.26	3.26	1.28	3.28
14	1.13	3.13	1.17	3.17	1.21	3.21
16	1.12	3.12	1.14	3.14	1.18	3.18
18	1.09	3.09	1.13	3.13	1.14	3.14
20	1.07	3.07	1.12	3.12	1.13	3.13

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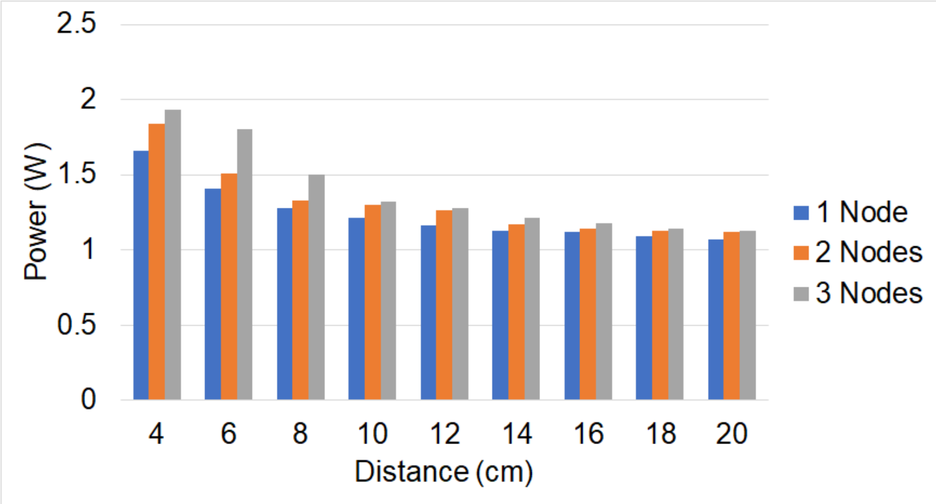

Figure 8. The Power Measured in the Receiver for the 3-Watt Load

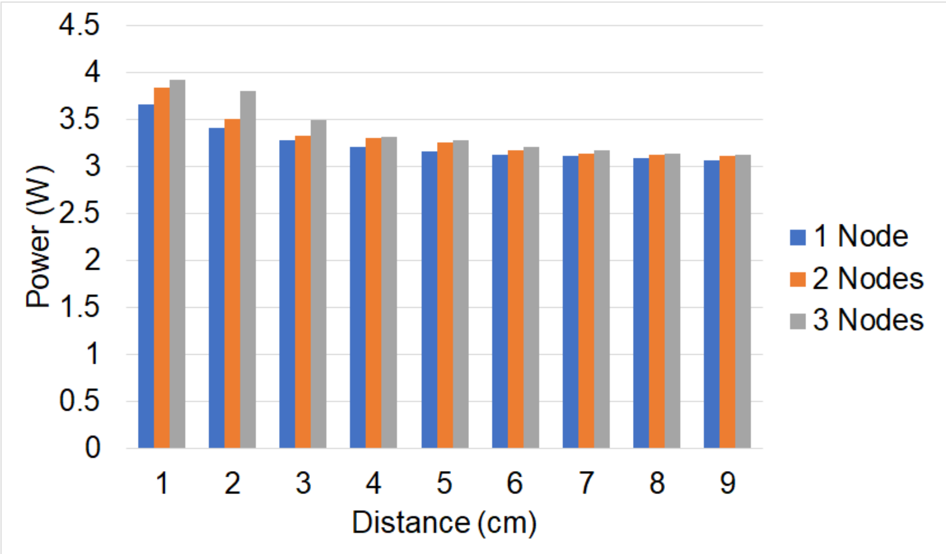

Figure 9. The Power Measured in the Receiver for the 5-Watt Load

One node application shows that the distance of 4 cm, the transmitted power is 3.92 W, and the highest power received is 1.66 W at 3-Watt lamp, and 3.66 W is indicated in a 5-Watt lamp, as shown in Table 3. Two nodes application increased the produced power measured on the load. It is 1.84 W for 3-Watt lamp, and 3.84 for the 5-Watt lamp. Three nodes application gives 1.93 W in the 3-Watt lamp, and 3.93 for the 5-Watt lamp.

The experimental results show that the possibility to prolong the magnetic induction between transmitter and receiver by installing nodes as the signal repeater. This study indicates that 4 cm is the best distance among transmitter, nodes, and receiver. Therefore, if one wants to transmit electric power, one should install a node every 4 cm to achieve the best result. However, Table 3 also indicates that the distances are not significantly reduced the received power, and it is possible to get the distance up to 20 cm to power a 3-Watt lamp and 5-Watt lamp.

4. Conclusion

The excessive usage of cable can result in cable losses and aesthetically unpleasant. WET is a non-contact electric power transmission to overcome this problem. Even though this method is not a new topic of research; however, currently, people are coming back to use it. This paper investigates the impact of nodes distance on the WET system. The experimental results show that the most effective distance among transmitter, nodes, and receiver are 4 cm. The without load application, it is indicated that for node 1, the results are 6 V, 110 mA, and 2.85 mT for voltage, current, and magnetic flux, respectively. At the application of 2 nodes, the voltage is 6.8 V, the current is 0.124 mA, and the magnetic flux is 3.83 mT, and at three nodes installation, it is 7 V, 134 mA, and 3.83 mT. During the application of 3-Watt and 5-Watt lamp, at 4 cm distance, the power received is 1.66 W and 3.66 W at 3-Watt and 5-Watt lamp for one node, 1.84 W, and 3.84 for two nodes, and 1.93 W and 3.93 for three nodes. The results show the possibility to increase the distance of the transmitter and receiver by installing nodes as the signal repeater. This study indicates that 4 cm is the best distance among transmitter, nodes, and receiver. Although 4 cm is considered the most effective distance, it is possible up to 20 cm to power a 3-Watt lamp and 5-Watt lamp.

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