"Wireless Power Transmission across Different Mediums Using Silicon Steel Core and Copper Conductors"

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Abstract
In an initial exploration, an effort was undertaken to execute WPT by utilizing circuits resonating at the standard utility frequency of 50 Hz. The primary goal the purpose of this study is to devise a technique for conveying electrical power through various mediums. By conducting an equivalent circuit analysis, a formula for the theoretical transmission efficiency was formulated, taking into consideration both copper and core losses. Notably, there's a substantial alignment between the values obtained from experimentation and those calculated theoretically. Itwas observed that the efficiency of transmission is significantly influenced by the configuration of the magnet pole pieces. This work sheds insight on the complex interaction between magnet pole component design and overall power transmission efficiency. An investigation is being carried out Power was transferred over a distance using various media for a rectangular flared shape, with air serving as the medium. This transmission efficiency was 56% at a distance of 0 cms. As the distance rose and for misaligned conduction, the efficiency decreased.

Keywords: Mediums, Utility frequency, Magnetic resonance, silicon steel core, copper wire, WPT

I. Introduction

The ultimate objective of this research is to create a way to recharge the batteries of robots that are used in environments that are inaccessible to people, such radioactively contaminated locations. This is an urgent issue that has become increasingly critical in the aftermath of the Fukushima nuclear disaster. To protect workers from contamination, energy would have to travel through massive concrete walls with steel frames [1].
Wireless power transfer (WPT) can be accomplished using three main techniques: radio waves, magnetic resonance, and electromagnetic induction. Many studies have been done utilizing resonant energy transfer and various methods since it was first established by the WiTricity project [2–3]. Nagano Japan Radio Co. Ltd. was able to transmit 1 kW of power at a high frequency of 13.56 MHz over a 300 mm distance with an 88% efficiency by using magnetic resonance [6]. Utilizing a 95 kHz power source, Pioneer Co. Ltd.'s electromagnetic induction device effectively transferred 3 kW over 150 mm with an 80% efficiency [7].
The WiTricity system is extremely straightforward, and research has moved in the direction of designing components like inverters and control strategies [8–10]. Concrete reflects and absorbs electromagnetic waves in proportions that are determined by the material's conductivity and dielectric constant. When it comes to reinforced concrete, which has a steel frame, These impacts are more evident and make megahertz frequencies a challenging frequency for energy transmission [11]. In Japan, equipment operating at frequencies higher than 10 kHz and power levels more than 50 W is subject to legal regulations. A straightforward workaround is to use a low frequency, like the common utility frequency, to get around these restrictions. Over thirty years ago, the University of California's Partners for Advanced Transit and Highways cooperation conducted research on low-frequency electromagnetic induction power transfer to electric vehicles. Over a 100 mm distance, an efficiency of 60% was attained with a 400 Hz power supply[12]. The methods created at that time haven't been significantly improved, though, as there hasn't been much demand for these low-frequency systems, and There have been no attempts to abuse the commercial power grid frequency since the WiTricity system was built. Using rectangular magnet pole piece designs, the efficiency of resonant power transmission through various media Was examined in the current study at the utility frequency of 50 Hz. Evaluations of the effects of various media were also conducted.

II. Circuit analysis:

Figure 1 depicts the WPT system's circuit diagram. For each of the findings in this study, the secondary condenser C2 was connected in parallel with the load (PP mode). It is also possible to use the PS mode configuration, which connects C2 in series. In the PS mode, the system acts as a continuous potential source, whereas the PP mode requires a constant current source. It was established that the transmission efficiency in PS mode was nearly identical to that of PP mode. When charging a lithium-ion battery, the ability to convert between constant current and constant potential mode with a single condenser connection is useful.

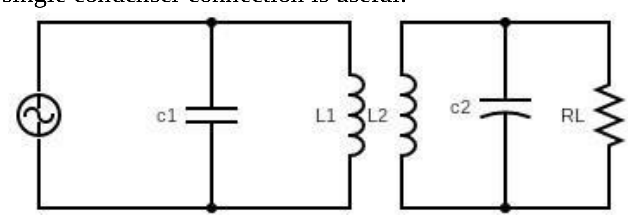


Fig 1 Circuit Diagram of WPT

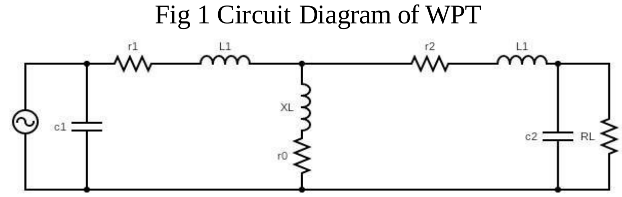


Fig 2 Equivalent Circuit Diagram of WPT

In Fig. 2, the similar circuit to that in Figure. 1 is also simple. In this case, the primary winding resistance is r1, the primary leakage inductance is jx1, the primary capacitance is -jxc1, the secondary winding resistance is jx2, the secondary leakage inductance is -jxc2, the core loss is jxl, the mutual inductance is jxl, and the load having resistance is R_l. When C_2 is coupled to a resonance frequency ω0, the following equation applies.

$$x_{c2} = \frac{1}{c_2 \omega_0} = x_L + x_2 \qquad (1)$$

Use Eq. (2) to determine the circuit's total impedance if C1 is absent. Because the reactance components are more important than the resistance components, the resistance components were disregarded.

$$Z = \left(\frac{x_L}{x_l + x_2}\right)^2 R_L + j\left(\frac{x_1 x_L + x_1 x_2 + x_2 x_L}{x_l + x_2}\right) \qquad (2)$$

Equation (3) describes the conditions under which the imaginary fraction of becomes zero when C1 is linked.

$$x_{c1} = \frac{1}{c_1 \omega_0} = \frac{\left\{\left(\left(\frac{x_L}{x_l + x_2}\right)^2\right) R_L\right\}^2}{\left(\frac{x_1 x_L + x_1 x_2 + x_2 x_L}{x_l + x_2}\right)} + \left(\frac{x_1 x_L + x_1 x_2 + x_2 x_L}{x_l + x_2}\right) \qquad (3)$$

We developed an analysis approach based on Tohi et al.'s, in which the copper loss of the WPT is considered, to obtain an equation for the theoretical maximum transmission efficiency [15]. The transmission efficiency of the corresponding circuit represented in Fig. 2(b) when copper and core losses are considered.

$$\eta = \frac{R_L I_L^2}{R_L I_L^2 + r_c I_o^2 + r_{L1} I_1^2 + r_{L2} I_2^2} \qquad (4)$$

If the two coils have a turn ratio of 1:1, the current relationships can be stated as follows:

$$I_1 = \alpha I_L, \ \alpha = \frac{x_l + x_2}{x_l} \qquad (5.1)$$

$$I_0 = I_1 - I_2 \qquad (5.2)$$

$$I_2 = I_L \sqrt{1 + \left(\frac{R_L}{x_{c2}}\right)^2} \qquad (5.3)$$

$$I_0^2 = I_L^2 \left[\alpha^2 + 1 + \left(\frac{R_L}{x_{c2}}\right)^2 - 2\alpha \sqrt{1 + \left(\frac{R_L}{x_{c2}}\right)^2} \cos\Phi\right], \quad \cos\Phi = \frac{x_{c2}}{\sqrt{R_L^2 + x_{c2}^2}} \qquad (5.4)$$

Substituting Eq. (5) into Eq. (4) yields

$$\eta = \frac{R_L}{R_L + r_1\alpha^2 + r_2\left(\frac{R_L}{x_{c2}} + 1\right)^2 + r_c\left\{\alpha^2 + 1 + \left(\frac{R_L}{X_{c2}}\right)^2 - 2\alpha\sqrt{1 + \left(\frac{R_L}{x_{c2}}\right)^2} \cos\emptyset\right\}} \qquad (6)$$

When the inductances of both coils are almost similar, the value of 1/α approaches the coupling coefficient (k). The following is the RL value that minimizes copper loss. [16]

$$R_L = x_{c2}\sqrt{\propto^2 \frac{r_1}{r_2} + 1} \qquad (7)$$

Therefore, taking into account copper and core losses, the maximum transmission efficiency is:

$$\eta_{\max} = \frac{1}{\frac{r_c \propto^2\left(\frac{r_1}{r_2} + 1\right) - 2\propto\sqrt{\propto^2 \frac{r_1}{r_2} + 2\cos\emptyset + 2}}{x_{c2}\sqrt{\propto^2 \frac{r_1}{r_2} + 1}} \quad 1 + \frac{2r_2}{x_{c2}}\sqrt{\propto^2 \frac{r_1}{r_2} + 1}} \qquad (8)$$

In this case, k and Q1 and Q2, the two coils' quality factors, are defined as follows:

$$Q_1 = \frac{\omega_0 L_1}{r_1}, \ Q_{21} = \frac{\omega_0 L_2}{r_2}, \ K = \frac{M}{\sqrt{L_1 L_2}}, \ M = \frac{x_L}{x_2 + x_L} L_2 \qquad (9)$$

Thus, we can rewrite the maximum transmission efficiency of Eq. (8) as follows:

$$\eta_{max} = \frac{1}{1 + \frac{2r_2}{x_{c2}}\sqrt{1 + \frac{1Q_2}{K^2 Q_1}} + \frac{r_c\left(\alpha^2 + 2 + \frac{1Q_2}{K^2 Q_1} - 2\alpha\sqrt{\frac{1Q_2}{K^2 Q_1}} + 2\cos\emptyset\right)}{1 + x_{c2}\sqrt{\frac{1Q_2}{K^2 Q_1}} + 1}} \qquad (10)$$

Since Eq. (11) is true in all circumstances, Eq. (12) illustrates how to approach Eq. (10).

$$\frac{1}{k^2}\frac{Q_2}{Q_1} > 1 \qquad (11)$$

$$\eta_{max} \sim \frac{1}{1 + \frac{2}{k\sqrt{Q_1 Q_2}} + \frac{2r_c(k + k^{-1} - 1)}{Q_2 r_2}} \qquad (12)$$

From Eq. (12), three conclusions can be drawn: 1) A large value of the product of k and Q provides high efficiency; 2) a big value of the product of r2 and Q2 (i.e., ωL2) likewise requires high efficiency; and 3) copper and core losses increase as k drops, i.e., as transmission distance grows. Core loss did not need to be taken into account when assessing a high-frequency system without a magnetic core. When working with silicon steel, it is especially vital to take core loss into account.

III Experiment

The magnet pole components used in this silicon steel plates of a thickness of 0.35 mm were used in the study. They were cut into rectangular, double flare, and single flare shapes by an electric discharge machine. Three different forms, P1 (rectangular), P2 (double flare), and P3 (single flare), were investigated. The curved areas followed a quadratic function to determine the right form of a magnet pole. This study employed rectangular forms.

At 50 Hz, no pole piece saturation was seen up to a flux density of 0.7 T. The coils were wound with a two-millimeter diameter single-strand enamel-covered copper wire. These prototypes were designed with an assumed operational voltage of 200 V and a current of 10 A. The transmitter and receiving circuits both used the same type of coil. The weights of a single coil are shown in Table 1.

Table 1 : Prototype silicon steel core details

Parameters	Transmitter Side	Receiver side
Schematic Shape	Rectangular	
Weight	8kg	9kgs
Magnetic area	252X110 mm	
Self inductance of the coils	78.5mH	80mH
Number of turns	375	525
Gauge of Copper wire	1.42mm(17Gauge)	1.42mm(17Gauge)
Winding resistance	0.36Ohms	0.38Ohms
Quality Factor	40	42.4

We determined transmission power efficiency by examining the equivalent circuit of a 50-Hz WPT system. An actual WPT device was used to conduct an experiment to determine the transformer constants, or the characteristics of the comparable circuit utilized in the computation.

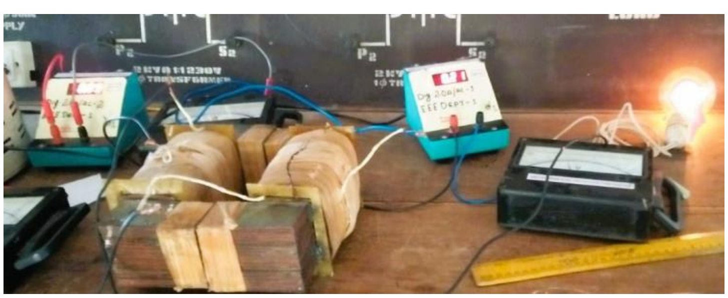


Fig 3: Experiment set up of WPT

Figure 3 displays photographs of the experimental setup. Acrylic plates are used to form an air gap between the receiver and the transmitter. Several media, including air, wood, plastic, glass, and iron, were placed in an air gap during transmission simulation investigations. The chosen area was discovered to be sufficiently greater than the spread of the observed magnetic field. Table 2 lists the different mediums' thicknesses.

Table 2: Various Medium measurements

	Length in Cms	Breath in Cms	Thickness In mm	Density kg /m^3
Glass	38	26	6	2500
Wood(ply)	35	19	8	500-600
Wood(Solid)	30	30	13	376-382
Tiles	30	20	7	2380-2450
Iron	49	12	1	7800
Plastic	32	18	10	1

We repeated the experiment and used silicon steel stamping and copper winding on both sides. The steel stamping measures approximately 100 x 252 mm in dimension, with a 150 mm window spacing element. The stamping's rectangular C-shaped core has a thickness of 0.38mm.

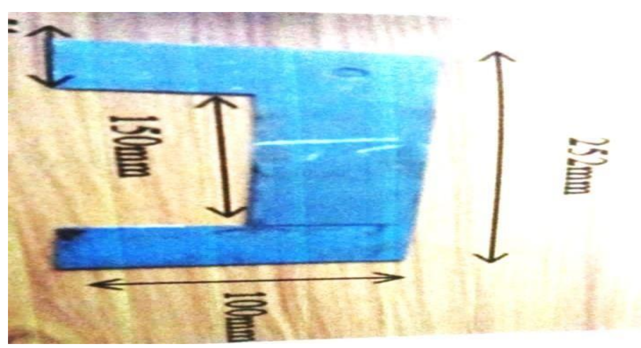


Fig 4: the C shape silicon steel Stamping

Transformer core stampings include no more than 4% silicon. Silicon steel is used in transformer cores due to its high magnetic permeability and intrinsic magnetic characteristics. Up to a flux density of 0.7 T, the pole pieces did not reach saturation at 50 Hz. A gauge of 25 0.5 mm copper wire was used to wind the coils. The assumed operating voltage and current for these prototypes were 200 V and 6 A, respectively. The transmitter and receiver circuits both used the same coil. Table 1 lists the weights for a single coil.

The wire-free power transfer experiment, which employs silicon steel stamping with a c-shaped core, features a copper winding wrapped at gauge 25 on both the transmitter and receiver sides. Performing the experiment without a load provides as validation. The voltage and distance are measured on the transmitter side, and the experiment is repeated to ensure proper alignment.

A wired power transmission experiment is executed using silicon steel and copper wire on both sides For different distances and mediums. The same experiment is performed to check for misalignment across different materials, and The findings are reported for further investigation. The experiment is performed at 0, 1, and 3 cms under normal conditions without the usage of any medium, and then repeated at a distance of 2 cms with various mediums such as air, glass, plastic, wood, tiles, iron, and plastic mediums of varying thicknesses. The results are likewise observed for 100% and 50% misalignment, respectively, utilizing different mediums, as presented in Figure 5.

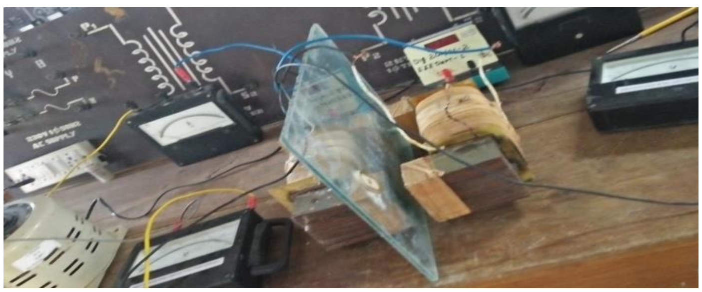


Fig 5 Experimental set up of WPT using silicon Steel using Glass as medium

Copper coils are coiled and insulated on the bobbin, and silicon steel stampings with a 0.38 mm C-shaped structure are used for wireless power transfer. In order to test the prototype module's output for different media, as illustrated in Fig. 6, a load is connected to the receiver side of a 200 watt light bulb to see if power can be delivered. Power could be given on the receiver side during load conduction over a variety of media and distances when the supply was delivered at the transmitter side. Between the transmitter and the receiver, the medium is of air, wood, plastic, glass, tiles, and an aluminum frame with varied thickness and area. The experiment was conducted with a misalignment of 50% to 100%. The findings of the experiment reveal that power was transferred to the load side during all conductions. The results are collated for analysis.

Fig 6 Experimental set up of WPT using silicon Steel using Glass as medium under load conduction

IV Results & Discussions

The experiment is carried out with copper wire wound on both sides of silicon steel stampings that serve as transmitter and receiver. The findings are tabulated for several configurations during the no-load condition, load conduction, altering distance, using different mediums, and misalignment for 50% and 100% of the duration. The results obtained by altering the distance without load conduction. The statistics show that as the distance grows, the voltage communicated falls while the current on the transmitting side increases. Figure 7 shows voltage as a function of distance.

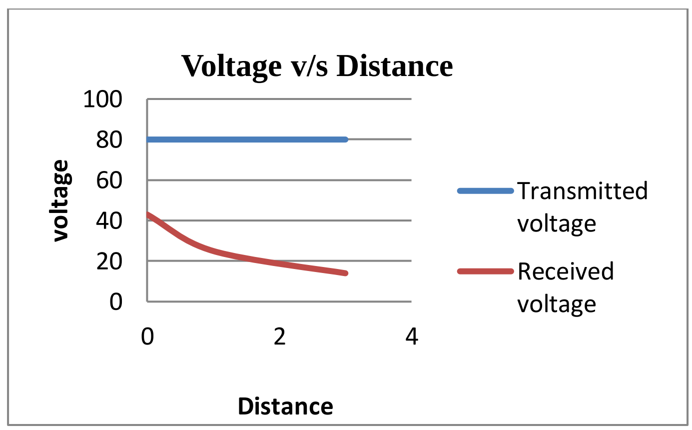


Fig 7(a) Silicon steel experimental setup without load conduction (Step Down)

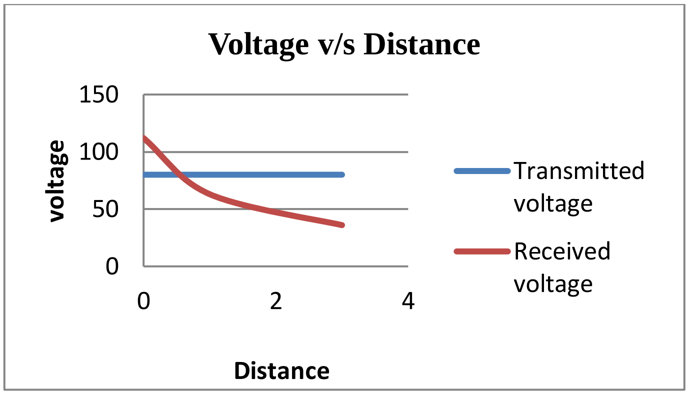


Fig 7 (b) Silicon steel experimental setup without load conduction (step up)

Figure 7 a & b displays the findings obtained from adjusting the distance with no load conduction. The data demonstrate that as the distance increases, the voltage transferred decreases and the current on the transmitted side increases in step up principle. Voltage is displayed in relation to distance.

With no load conduction, 50% misalignment, and 100% misalignment, with a distance of zero centimeters and a transmitted voltage of 60 V. The data are summarized and shown in Figure 8. In the analysis without misalignment during the air medium, The voltage received is around 27 volts at zero centimeters with alignment, and at three and one centimeters, it is approximately 10 and 16 volts for 50% misalignment, and 9 and 12 volts for 100% misalignment. As the distance increases, so do the transmitted current increases and Voltage decreases.

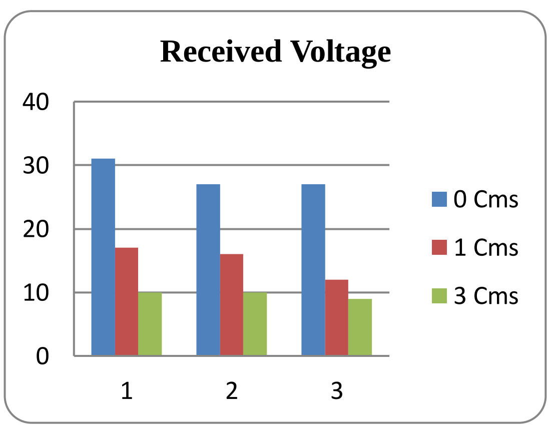


Fig 8: Graphically Representation under no load condition, Misalignment with differentMediums

Power is transferred to the receiving side via a load conduction experiment. Figure 9 shows the transmission outcomes for various media with and without misalignment. When the transmission voltage is fixed at 160 volts, the received voltage is roughly 200 volts, with 56% efficiency when air is used as the medium, as opposed to glass, wood, tiles, iron, or plastic. A 200-watt bulb was connected to the receiver side, and electricity could be sent by keeping the distance D=0 cms. The efficiency is low, and the secondary voltage ranges from 63% to 83% of the supplied voltage, as illustrated in Fig. 9 with no misalignment. The findings of the experiment indicate that when there is a 50% or 100% misalignment, the received voltage is 192 volts and 106 volts, with an efficiency of 55.71% and 45.48% when air is used as the medium. In contrast, whether there is a 50% or 100% misalignment, the received voltage ranges between 56% and 73% of the transmitted voltage, with comparatively low efficiency in both circumstances. We may conclude that air is a high-efficiency medium able to transmit electricity in all configurations.

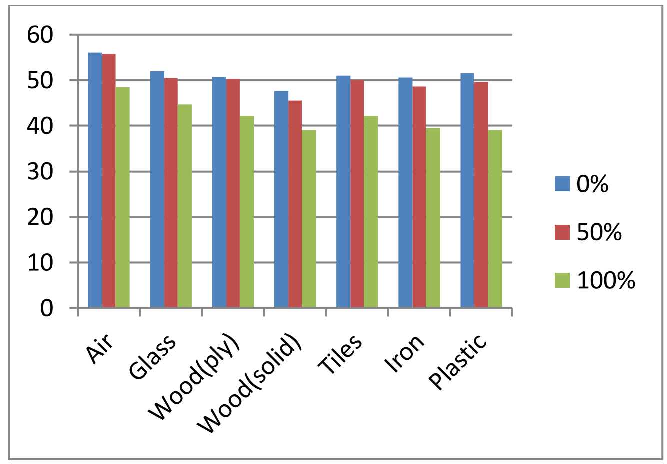


Fig 9: Efficiency both with and without misalignment for various media under load conditions.

Under no load conduction, the experiment is carried out with a fixed distance of 2 cm and a fixed transmitted voltage of 60 volts for various media with and without misalignment. The received voltage is displayed in fig. 9. According to the tabulated statistics, the received voltage is only roughly 25% of the transmitted voltage when there is no misalignment, compared to 50% and 100% in Misalignment: the transmitted current is the same for all mediums and the figures are calculated, but the received voltage is between 25% and 16% of the received voltage.

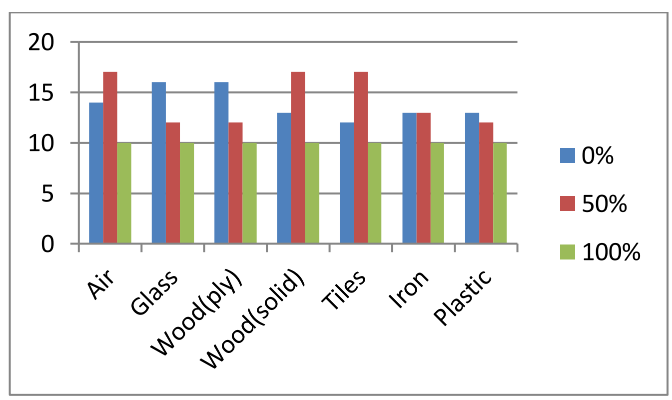


Fig 9 : Graphically Representation under no load condition, Misalignment with different Mediums

The experiment uses air as a medium and is carried out under load conduction with and without misalignment. Figure 10 shows the efficiency at different distances. The results show that at zero millimeters, the efficiency is 56%, 55.71%, and 48.48% respectively, for no misalignment, 50% misalignment, and 100% misalignment. However, if the distance is adjusted while the transmitted voltage remains constant, the received voltage drops and the efficiency decreases. We can conclude that, using air as a medium and a distance of 0 cms, Load conduction allows for more efficient power transfer to the receiving side.

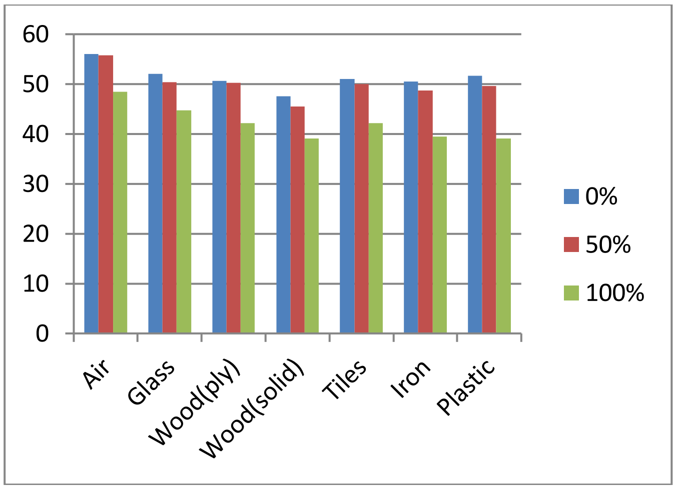
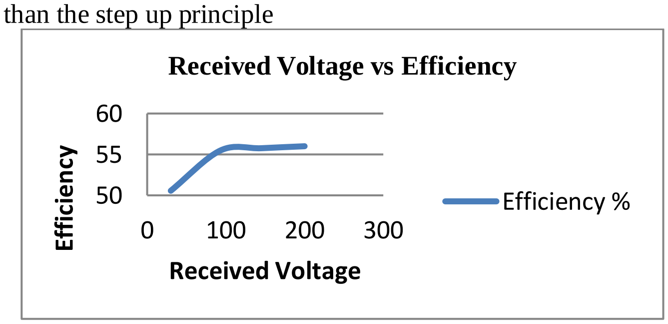
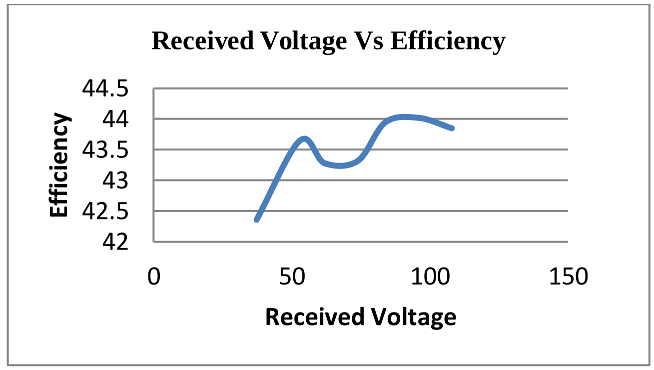


Fig 10: Efficiency under load condition with and without Misalignment for different Mediums

Figure 11 shows the efficiency. The investigation found that when employing the step up approach, efficiency increases as input voltage and received voltage increase. The step down principle, on the other hand, reduces receiver side voltage while increasing efficiency by more than 100%. Figure 11 shows the results of load conduction by altering the transmitted voltage using the step up and step down principle. According to the analysis, power could be transferred during load conduction using the step-up concept, but not to the receiver side using the step-down principle since the efficiency is lesser than the step up principle



Results under load condition for Variable Voltages (Step Up)



Results under load condition for Variable Voltages (Step Down)

Fig 11: Efficiency for different Voltages under load condition

V Comparison of Experimental Results with Silicon Steel Core

The experiment was executed with success utilizing Silicon steel as the core and copper winding on both sides of the transmitter and receiver. Based on the findings, the power was supplied to the load and the efficiency was around 56% during no misalignment conduction with a distance of 0 cms, whereas in other configurations the efficiency was lower, as stated in the above data.

Copper wire is utilized on both the transmitter and receiver sides of the experiment, while silicon steel is employed. The outcomes for every parameter are

Reviewed and reported in the following tables. The experiment has been finished, and Table 3 displays the findings for various distances and misalignments. According to the analysis, the efficiency is good at zero centimeters with 0% misalignment, but at fifty percent misalignment, the efficiency is 55.71%, and at one hundred percent misalignment, the efficiency is extremely 48.48%. According to the analysis, efficiency decreases in all instances when there is a change in the distance between the transmitter and the receiver, as illustrated in the table. The prototype module works well at zero distance and is very efficient during load conduction.

Table 3: Comparative Analysis of efficiency with distance and misalignment

Misalignment %	0	50	100
Distance in Cms	Efficiency in %	Efficiency in %	Efficiency in %
0	56	55.71	48.48
2	43.66	40.87	33.74
4	35.21	30.51	24.21
6	22.12	20.67	16.94

The step-up conduction method is used in the experiment to simulate load conduction through theuse of air as a medium. The voltage on the transmitter side is varied, and the received voltage is tabulated in table 4. The efficiency is calculated for each voltage as indicated in the table, and the analysis shows that efficiency increases as transmitted side voltage increases. The transmitted side's maximum voltage is 160 volts, and the associated efficiency is roughly 56%.

Table 4: Comparative Analysis of efficiency with transmitted voltage and received voltage

Load = 200Watts Bulb , Medium =Air , step Up		
Transmitted Voltage Volts	Received Voltage Volts	Efficiency %
40	30	50.56
80	93	55.48
120	145	55.76
160	200	56

When the step-up principle in load conduction is used to analyze efficiency during misalignment with a fixed voltage on the transmitting end, the efficiency levels are measured. The findings are grouped in table 5 based on the analysis performed. For example, when there is no distance 0 centimeters and air serves as the medium with zero percent misalignment, the efficiency is approximately 56 %. However, as misalignment increases, efficiency eventually decreases. According to the investigation, a 100% misalignment reduces efficiency dramatically to 48.48 %. This clearly shows an inverse link between misalignment and system efficiency.

Table 5: Comparative Analysis of efficiency with distance and misalignment

Misalignment	0%	50%	100%
Distance in Cms	**Efficiency**	**Efficiency**	**Efficiency**
0	56	55.71	48.48
2	43.66	40.87	33.74
4	35.21	30.51	24.21
6	22.12	20.67	16.94

The step-up conduction approach is utilized in the experiment to simulate load conduction utilizing air as the medium. The voltage on the transmitter side is changed, and the received voltage is shown in Table 6. The efficiency is calculated for each voltage as shown in the table, and the results demonstrate that efficiency increases as the transmitted side voltage rises. The transmitted side's maximum voltage is 160 volts, and the efficiency is around 56%.

Table 6: Comparative Analysis of efficiency with transmitted voltage and received voltage

Load = 200Watts Bulb , Medium =Air , step Up		
Transmitted Voltage	**Received Voltage**	**Efficiency**
40	30	50.56
80	93	55.48
120	145	55.76
160	200	56

When the step-up principle in load conduction is used to analyze efficiency during misalignment with a fixed voltage on the transmitting end, the efficiency levels are measured. Table 7 summarizes the findings drawn from the analysis. For example, when the distance is zero centimeters and air serves as the medium with zero percent misalignment, the efficiency is approximately 56%. However, as misalignment increases, efficiency eventually decreases. Based on the inquiry, a 100% misalignment reduces efficiency dramatically to 48.48%. This clearly shows an inverse link between misalignment and system efficiency.

Table 7: Comparative Analysis of efficiency with transmitted voltage, received voltage & misalignment under load

Load = 200Watts Bulb, D=0 Cms						
Medium	Transmitted Voltage Volts	Received Voltage Volts	Transmitted current Amps	Received current Amps	Efficiency %	Misalignment %
Air	160	200	0.89	0.5	56	0
Air	160	192	1	0.5	55.71	50
Air	160	106	2.38	0.36	48.48	100

Table 8: Comparative Analysis of transmitted voltage, received voltage & misalignment under No load

No-load, D=0 Cms				
Medium	Transmitted Voltage Volts	Received Voltage Volts	Transmitted current Amps	Misalignment %
Air	64	35	0.02	0
Air	64	32	0.04	50
Air	64	14	0.14	100

In the analysis based on Table 8, the evaluation was carried out under conditions of no load at a distance of 0 cm, with air as the transmission medium. Throughout the investigation, the transmitted voltage remained constant, and the received voltage data was reported in a table for various levels of misalignment. The findings show a continuous trend in which voltage drops with increased misalignment. Notably, when there is 100% misalignment, the received voltage registers around 14 Volts, as opposed to 0% misalignment, which records 35 Volts with a stable input voltage of 64 Volts. This data demonstrates a clear relationship between misalignment levels and the associated decrease in received voltage, emphasizing the effect of alignment accuracy on efficiency.

VI Conclusion:

Obtaining a large Q factor at low frequencies is difficult, which is why low-frequency techniques have been avoided until recently. However, when silicon steel is employed as the magnetic core, transmission efficiency is maximized at extremely low frequencies. To the best of our knowledge, this is the first time this outcome has been published. We considered total transmission efficiency and determined that 50 Hz is the best option. Our system can be easily plugged into a wall outlet.

WPT with evanescent tail coupling between two resonant circuits was studied. Although the premise is similar to that of WiTricity, the frequency used is the standard utility frequency. Higher frequency systems do not require magnetic cores, hence their weight and transmission distance are superior to those of our system. However, utilizing the utility frequency, it was discovered that power could be delivered efficiently through a variety of media including air, wood, plastic, glass, and tiles. Power was transferred in various mediums by changing parameters during load and noload conduction, and the results were recorded. A workable system of this type is likely to find uses in disaster-prone regions such as nuclear power plants, electrical vehicles, and household applications.

Analysis has been completed for the hardware experiment utilizing silicon steel with copper wire. According to the analysis, the efficiency is good at the distance of 0 cms, with 0% misalignment and air serving as the medium. The experiment was successfully carried out using silicon steel as the core and copper winding on both sides of the transmitter and receiver. According to the results, the power was delivered to the load and the efficiency was around 56% during no misalignment conduction with a distance of 0cms, whereas in other configurations the efficiency was lower, as stated in the above data.

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