Wireless Power Transfer using Ferrite Core for Different Mediums

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Abstract

In an initial investigation, an attempt was made to perform WPT using circuits resonating at the normal utility frequency of 50 Hz. The fundamental objective of this research is to create a method for transmitting electrical power across multiple media. An analogous circuit analysis was used to develop a formula for theoretical transmission efficiency that accounts for both copper and core losses. Notably, the experimental and theoretical values are substantially aligned. The arrangement of the magnet pole components was shown to have a considerable impact on transmission efficiency.

This research provides light on the intricate relationship between the total power transmission efficiency and the design of the magnet pole components. There is an ongoing inquiry. Air was used as the channel for transferring power in the form of a rectangular flare. In a magnetizing medium with litz wire in the transmitter and reception coils, the transmission efficiency was 73% at a distance of 0 cms. In a hybrid mode, the efficiency was 31.84% with copper wire on the transmitter side and litz wire on the receiving side. In contrast, the efficiency in Litz wire on both side 49.66% & copper wire on both side 41.22%.

Keywords: Mediums, Utility frequency, Magnetic resonance, Ferrite core, litz wire, copper wire, WPT

I. Introduction

The ultimate goal of this research is to develop a method for robot battery recharging in places where humans are unable to reach them, such as radioactively polluted areas. This is a pressing matter that has grown more important in the wake of the Fukushima nuclear accident. Energy would need to pass through enormous concrete barriers with steel frames in order to shield workers from pollution [1].

Three primary methods are available for achieving wireless power transfer (WPT): electromagnetic induction, magnetic resonance, and radio waves. Since the WiTricity project initially proved resonant energy transmission, several research have been conducted using a variety of techniques [2–3]. Through the use of magnetic resonance, 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 [6]. Pioneer Co. Ltd.'s electromagnetic induction device transported 3 kW across 150 mm with 80% efficiency using a 95 kHz power source [7].

The WiTricity system is very simple to use, and research has advanced toward the design of parts such as control methods and inverters [8–10]. The conductivity and dielectric constant of concrete govern how much electromagnetic radiation it reflects and absorbs. Megahertz frequencies present a challenge for energy transmission because of these effects, which are particularly pronounced in reinforced concrete with a steel frame [11]. Legal restrictions apply to equipment in Japan that operates at frequencies higher than 10 kHz and power levels higher than 50 W. Using a low frequency, such as the common utility frequency, is an easy fix.

to circumvent these limitations. The Partners for Advanced Transit and Highways collaboration at the University of California has out studies on low-frequency electromagnetic induction power transmission to electric cars more than thirty years ago. A 400 Hz power source was able to achieve 60% efficiency over a 100 mm distance [12]. Though there hasn't been much demand for these low-frequency systems and no efforts to exploit the commercial power grid frequency since the WiTricity system was constructed, the techniques used at the time haven't been greatly improved.

The effectiveness of resonant power transmission via diverse media was evaluated using designs for rectangular magnet pole pieces. was investigated at the utility frequency of 50 Hz in the current study. Rectangular ferrite cores with copper wire wrapping on the transmitter and receiver sides and litz wire were used to evaluate the effects of different media.

II. Circuit analysis:

The circuit design for the WPT system is shown in Figure 1. The secondary condenser C2 was linked in parallel with the load (PP mode) for every research finding. The PS mode arrangement, which links C2 in series, provides an additional option. While the PP mode necessitates a constant current supply, the PS mode uses the system as a continuous potential source. It was found that the PS mode's transmission efficiency was almost the same as the PP mode's. The capability to switch between constant current and constant potential mode with just one condenser connection is helpful while charging a lithium-ion battery.

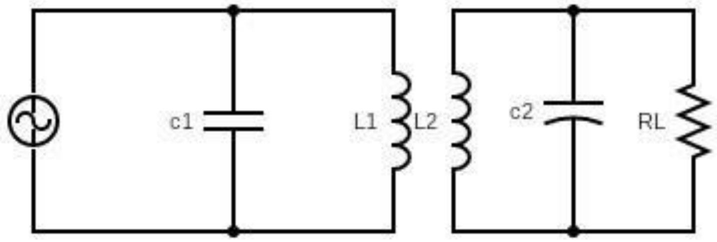

Fig 1 Circuit Diagram of WPT

The same circuit shown in Figure 4.3(a) in Figure 2 is likewise straightforward. This example shows that the load having resistance is R_l, the core loss is jX_L, the mutual inductance is JXL, the secondary winding resistance is jX_2, the secondary leakage inductance is $-jXC_2$, the primary capacitance is $-jXC_1$, and the primary winding resistance is r_1. This equation holds when C_2 is connected to a resonance frequency ω_0.

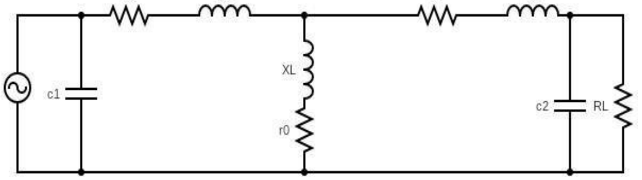

Fig 2 Equivalent Circuit Diagram of WPT

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

If C_1 is not present, use Eq. (2) to get the overall impedance of the circuit. The resistance components were ignored as the reactance components are more significant than the resistance components.

$$Z = \left(\frac{x_L}{\underline{x_l+x_2}}\right)^2 R_L + j\left(\frac{x_1x_L+x_1x_2+x_2x_L}{x_l+x_2}\right) \qquad (2)$$

The circumstances in which the imaginary fraction of, when C_1 is connected, reaches zero are outlined in equation (3).

$$x_{c1} = \frac{1}{c_1\omega_0} = \frac{\left\{\left(\left(\frac{x_L}{x_l+x_2}\right)^2\right)R_L\right\}^2}{\left(\frac{x_1x_L+x_1x_2+x_2x_L}{x_l+x_2}\right)} + \left(\frac{x_1x_L+x_1x_2+x_2x_L}{x_l+x_2}\right) \qquad (3)$$

Our method to study, which we based on Tohi et al.'s, takes into account the WPT's copper loss in order to derive an equation for the theoretical maximum transmission efficiency [15]. The transmission efficiency of the circuit depicted in Fig. 2(b) after accounting for core and copper losses.

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

The current relationships, assuming a turn ratio of 1:1 between the two coils, are as follows:

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

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

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

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

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

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

The value of 1/α approaches the coupling coefficient (k) when the inductances of the two coils are nearly identical. The RL value that minimizes copper loss is as follows. [16]

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

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

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

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

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

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

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

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

$$\frac{1}{k^2}\frac{Q_2}{Q_1} > 1 \tag{11}$$

$$\eta_{max} \sim \frac{1}{1+\frac{2}{k\sqrt{Q_1Q_2}}+\frac{2r_{c(k+k^{-1}-1)}}{Q_2r_2}} \tag{12}$$

Three inferences may be made from Eq. (12): 1) High efficiency is provided by a large value of the product of k and Q; 2) high efficiency is also required by a large value of the product of r_2 and Q_2 (i.e., ωL_2); and 3) copper and core losses rise as k decreases, i.e., as transmission distance increases. Core loss did not need to be considered when evaluating a system with no magnetic core that operates at high frequencies.

III Experiment

The magnet pole components used in this investigation were formed from a solid 10 x 5 cm Ferrite core. They were formed into the shapes depicted in the figure using an electric discharge machine. Three distinct shapes, denoted as (rectangular), (double flare), and (single flare), were taken into consideration. However, we employ a rectangular shape in our experiment. For the purpose of conducting the experiment, we utilize copper wire and litz wire that are wounded on both sides. Prior to actually doing the experiment, we first utilize copper -copper on both the transmitter and receiver sides and litz – litz on both sides. We carried out the experiment for each of the three scenarios using distinct media, using litz wire on one side and copper wire on the other.

Up to a flux density of 0.7 T, no saturation of the pole pieces was seen at a frequency of 50 Hz. The coils were wound using copper wire with a gauge of 25(0.5 mm) and single-strand enamel covered litz wire with a diameter of 24 gauges 0.5 mm. The assumed working voltage and current of 200 V and 6A, respectively, were used in the design of these prototypes. The transmitter and reception circuits both employed the same kind of coil

We calculated the transmission power efficiency by analyzing the 50-Hz WPT system's equivalent circuit. A real WPT device was utilized to conduct an experiment to ascertain the transformer constants, or the characteristics of the equivalent circuit employed in the calculation. A frequency response analyzer (FRA5097, NF Co. Ltd.) and a programmable AC power source (EC1000SA, NF Co. Ltd.) can be used to test the transformer constants. An inductor with a closed-loop core is required to measure the magnetic permeability; this can be added to WPT devices.

A specific kind of multi strand wire or cable called Litz wire is used in electronics to transmit alternating current (AC) at radio frequencies. The wire's purpose is to minimize losses from the skin effect and proximity effect in conductors operating at frequencies up to around 1 MHz.[1] It is made up of numerous thin wire strands that have been individually wrapped in insulation and twisted or woven together in accordance with a number of meticulously outlined patterns[2][better source needed], which frequently involve multiple levels (wires that have already been twisted together are twisted into smaller groups, which are twisted into larger groups, etc.). These winding designs have the effect of equating the percentage of the total length over which each strand is outside the conductor. By equating the current distribution among the wire strands, this lowers the impedance.

Litz wire is used in switching power supply, induction heating equipment, and high Q inductors for low frequency radio transmitters and receivers. The weights of a coil are shown in Table 1.

Table 1 : Prototype Ferrite core details

Parameters	Description	
Schematic Shape	Rectangular	
Magnetic pole area	10X5 Cms	
Number of turns	Copper	Litz
Primary	1200	260
Weight	790gms	790gms
Secondary	750	225
Weight	660gms	760gms
Gauge	Copper	Litz
Primary	27 (0.2mm)	24(0.5mm)
Secondary	25(0.5mm)	24(0.5mm)

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

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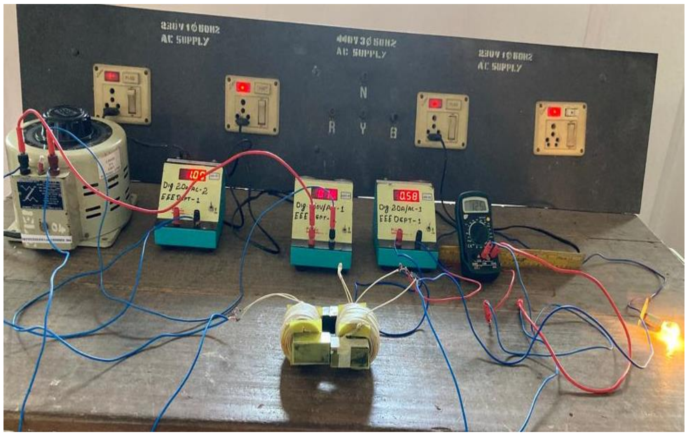

Fig 3 Experimental Setup for WPT System with litz wire on both side while Magnetizing

The experiment utilizing a ferrite core with litz wire on both sides is seen in Fig. 3. Air, wood, concrete, glass, plastic, and magnetizing were among the media in which the load was possible to provide power and transfer it from the source to the recipient side. The results met expectations.

Fig 4: Experimental Setup for WPT System while Magnetizing and converting AC voltage to DC

voltage by using Ferrite Core with Copper wire on both sides

The experiment is seen in Fig. 4; copper wire was utilized on both sides of a ferrite core. Power was able to go from the source to the receiver side, and the load was able to deliver in a variety of media, such as wood and magnetizing.

Fig 5: Experimental Setup for Hybrid WPT System

The experiment, depicted in Fig. 5, was carried out with a ferrite core and copper and litz wire on the transmitter and reception sides. Power might go from the source to the recipient while magnetizing a range of substances, including air, wood, concrete, tiles, glass, plastic, and magnetizing.

Table 2 lists the different mediums' thicknesses.

	Length in Cms	Breath in Cms	Thickness In mm	Density kg /m^3
Glass	38	26	6	2500
Wood(Solid)	30	30	13	376-382
Tiles	30	20	7	2380-2450
Concrete	49	12	1.5	2400
Plastic	32	18	10	1

IV Results & Discussions

The prototype module is used for the experiment, and it has a solid ferrite core with copper wire on sides, litz wire on the transmitter and reception sides, and copper wire Litz wire on transmitter and receiver side respectively. Several media, including air, wood, concrete, tiles, glass, and plastic, were used in the experiment during the load conduction. The efficiency for different configurations is computed, and the results are presented in the figs. 6, 7, and 8. The results for various configurations and mediums utilizing the litz wire on both sides are recorded in the tables 3, 4, and 5.

Table 3: Results of Different Mediums using Litz wire on both sides

Medium	Transmitted Voltage Volts	Transmitted Current Amps	Transmitted Power Watts	Received Voltage Volts	Received Current Amps	Received Power Watts	η %
Magnetizing	16	0.98	15.68	13	0.88	11.44	49.66
Air	20	2.45	49	12	0.32	3.84	20.94
Wood	24	2.36	56.64	17.7	0.80	14.16	33.99
Concrete	22	2.98	65.56	17.16	0.88	15.1	25.7
Tiles	22	2.99	65.78	18.73	0.84	15.73	28.3
Glass	23	3.0	69	18	1.35	14.3	26.96
Plastic	21	2.22	46.62	17	1.09	18.53	34.65

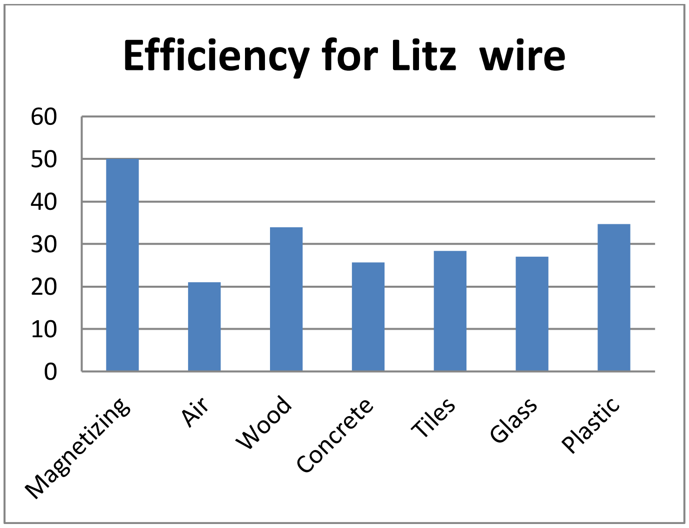

Figure 6: Efficiency of Different Mediums using Litz wire

Table 4: Results of Different Mediums using copper wire on both sides

Medium	Transmitted Voltage Volts	Transmitted Current Amps	Transmitted Power Watts	Received Voltage Volts	Received Current Amps	Received Power Watts	ɳ %
Magnetizing	100	0.69	69	24	2.44	58.56	41.22
Wood	100	0.92	92	17.5	1.58	27.65	31.01

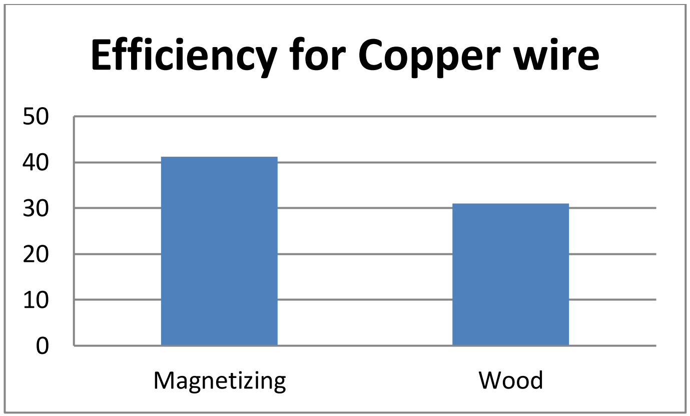

Figure 7: Efficiency of different mediums using copper wire

Table 5: Results of Different Mediums using litz and copper wire

Medium	Transmitted Voltage Volts	Transmitted Current Amps	Transmitted Power Watts	Received Voltage Volts	Received Current Amps	Received Power Watts	ɳ %
Magnetizing	70	0.30	21	25	0.63	15.75	31.84
Air	74	0.91	67.34	22	0.61	13.46	33.1
Wood	80	1.23	98.4	35	0.98	34.44	33.29
Concrete	90	1.93	173.7	30	1.73	52.11	31.24
Tiles	80	1.35	108	31	0.87	26.97	32.48
Glass	70	0.59	41.3	30	0.57	17.34	33.16
Plastic	81	1.24	100.44	45	1.11	50.22	34.48

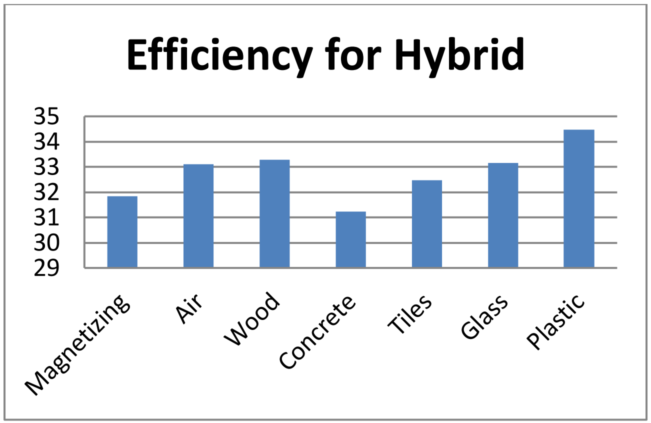

Figure 8: Efficiency of different mediums using litz and copper wire

The power was successfully transferred to the load side during the experiment conducted during load conduction, and the results are compared for all the mediums using various winding configurations, such as copper and litz wire on the transmitter and receiver side and litz wire on both sides. Based on the comparison of results, the magnetizing medium has a higher efficiency than the other mediums. The efficiency comparison results are displayed in Table 5.20 and are illustrated graphically in Figure 5.20. Ultimately, we can say that during load conduction, power was able to transfer using the ferrite core for various mediums and winding configurations. However, power transfer was not possible when the distance between the transmitter and receiver fluctuated, nor when there was a misalignment.

Table 6: Results of different Mediums

Medium	ɳ % for Litz	ɳ % for Hybrid	ɳ % Copper
Magnetizing	49.66	31.84	41.22
Air	20.94	33.1	
Wood	33.99	33.29	31.01
Concrete	25.7	31.24	
Tiles	28.3	32.48	
Glass	26.96	33.16	
Plastic	34.65	34.48	

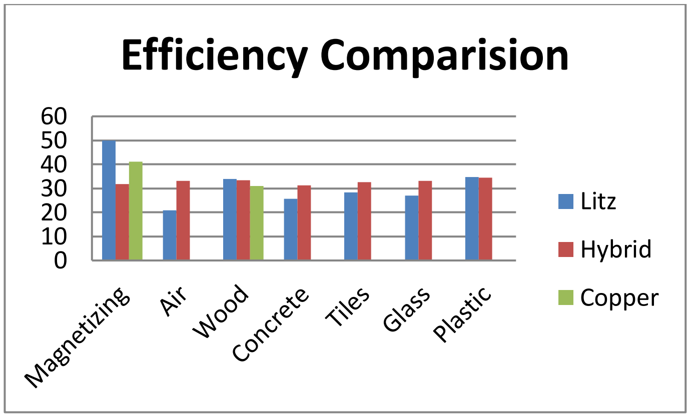

Fig 9 Comparison of results in different mediums

Prototype modules are used in an experimental context to validate theoretical analysis. The testing findings and comparison of the various connection types are displayed in Table 7. WPT coils are built in accordance with the design specifications. The ferrite core is used in the experiment, and copper and litz wire are used on both the transmitter and reception sides.

Comparisons between Litz-Litz, Litz-copper, and copper-copper have been made. however, for litz-litz and litz copper analysis, the efficiency percentage error is around 36.30% where as for litz-copper & Copper-Copper the % error is around 22.75%.

Table 7: % Error Analysis

Parameters	**Litz-Litz**	**Litz-Copper**	**Copper-Copper**	**% Error from Copper-Copper & Litz-Copper**	**% Error from Litz-Copper & Litz-Litz**
Transmitted Voltage Volts	16	70	100	30	77.14
Received Voltage Volts	13	25	24	4.16	48
Transmitted Power Watts	15.68	21	69	69.56	25.33
Received Power Watts	11.48	15.75	58.86	73.24	27.11
Efficiency %	49.99	31.84	41.22	22.75	36.30

The analysis focused on determining the percentage error between litz-litz and litz-copper wire configurations. The results revealed an error rate of 36.30%, whereas the % error between copper-copper and litz-copper is around 22.75% This assessment aimed to provide a clearer understanding of the comparative performance of litz and copper wire setups when integrated.

V 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 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 ferrite core with litz-litz, copper copper and copper-litz 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 ferrite as the core and copper and litz winding on both sides of the transmitter and receiver. Design a prototype hardware model with a rectangular ferrite core with litz and copper on both sides for use in various mediums such as magnetism, air, wood, plastic, tiles, and concrete. The experiment successfully transferred power to the load or receiving end, and the efficiency of the magnetizing medium is approximately 31.84% in the hybrid mode (using Litz and copper wire on the transmitter and receiver sides), 41.22% in the magnetizing medium using copper wire on both sides, and 49.66% in the magnetizing medium using litz wire on both sides. Where as in other configurations the efficiency was lower, as stated in the above data.

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