Wireless Power Transfer between Air-core and Toroidal Inductor based on Environmental Conditions and Orientation

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***Abstract*—Present day research and development of wireless power transmission has evolved a lot from the work of Nikola Tesla in early 1900's. Therefore, this study seeks to evaluate and examine the WPT system, wherein employing toroidal inductors as the receivers and air core inductors as the transmitters. This is performed by analyzing the effect of different orientations and environmental conditions that may impinge the DC voltage output, therefore revealing how transitions in the factors would affect the efficacy of power transmission. Particularly, the deviations of the primary symmetry axes for the two inductors and the ambient medium are investigated for their influence.**

Furthermore, it was observed that when the copper wire impacts the aluminium reflector of the plasma ball within the quarter of a millimeter NMAC gap is generated which plays a key role in the performance of the WPT system. These procedures were run in a series where the elements were adjusted aiming to determine the optimum combinations of the factors and their influence. Thus, the study adds to the current literature by offering an overall analysis of the WPT performance in different situations, assessing the performance of WPT against the other technologies and suggesting improvement for the WPT systems. This study aims at enhancing real life designs of WPTs by researching the influence of ambient circumstances as well as accurate placement in increasing the efficiency of power transfer.

***Index Terms*—Wireless power transfer, toroidal inductor, air-core inductor, environmental conditions, power transfer efficiency.**

I. INTRODUCTION

The present technology of WPT emerged from the notions of wireless power transfer from the early 1900 around Nikola Tesla's creation [1]. This notion of wireless power transfer has motivated current study and monetary investment to Tesla in the form of specified application such as charging of portable electronics and energy supply to electric automobiles [2]. The vital necessity for dependability and usability in energy sources has been preserving this sector's growth [3].

WPT systems featured; inductive coupling, resonant inductive coupling, and microwave power transmission. Resonant inductive coupling is nonetheless exceedingly effective across moderate distances and consequently has a very large potential [4]. Toroidal inductors are beneficial utilized in WPT applications because they self-couple strongly and have minimal field dispersion combined with the fact that they may be coiled to enhance inductance [5]. The major aim of this work is to investigate the use of the toroidal inductor structure as the reported component in the WPT system with the air-core structure of the transmitter [6].

However, improvement of WPT systems poses obstacles owing to efficiency, reduction of losses aspects, and operational variations with different loads [7]. Some of the conclusions found in earlier research include the direction of the bed, coils, and room condition [8]. However, to address these problems in depth and to pick the optimal values of the above-discussed factors that create a high-performance WPT in real-life applications, this research intends to fill these gaps [9].

II. MATERIALS AND METHODS

A. Method

When copper wire connects with the distance under 1.2 mm and holded stable in optimal distance with 0.08 -1mm range with the aluminum refelection (Fig, 3 permanented on plasma ball may make ion electric flow ignited outside the environment. Hence, that's dubbed sparked gap. This sort of electric flow go via Transmitter for expending magnetic power to Receiver. The DC signal,what exported via Receiver, will on the match on triangle and sew tooth . Without a spark gap, the pan will gather frequency from plasma ball solely, which is frequency oscillations in the environment in 20-50kHz. Therefore, the DC Voltage signal is unstable went from 4.02V to 7.25V, seem like complicated type .

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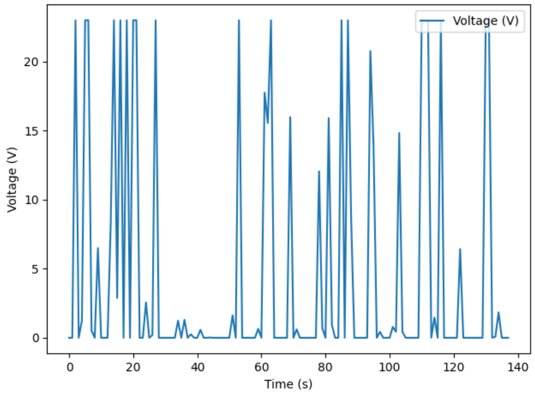

Fig. 1. DC Voltage output with spark gap

B. System Components

In this experiment, the WPT system comprises two main parts:

- **Generator Section:** In this experiment, we employed energy from Ion current ,which is ignited on the plasma ball's aluminium metal reflector (Fig. 4) using copper wire linked with air-core inductor. In the air-core inductor depicted in Fig. 2, this current forms a magnetic field to transport energy to the toroidal inductor in Fig. 3. Depending on the parameters of the experiment the ground wire is inserted into different fluids (normal water, salty water or air) [10].
- **Reception Section:** An assembly takes up the frequency produced by the plasma ball. This frequency is further added to the frequency of the alternating current after the toroidal inductor (Fig. 2) has been passed through. Wave filtering is done using an LC resonant circuit while converting AC to DC is done using a bridge rectifier in this experiment for data clarity [11].

Fig. 2. Air-core Inductor_Generator part

C. Circuit Schematic for Test Cases

The circuit schematic (Fig. 5)shows the send and receive components for the majority of tests. The test cases focus on modifying the degree of the axis via the toroidal inductor and the central axis of the air core inductor [12].

- Degree 0 presents the angle between the axis via the toroidal inductor and the central axis of the air core inductor equal 0. (Fig. 6)

Fig. 3. Toroidal Inductor_Receiver part

Fig. 4. Toroidal Inductor_Receiver part

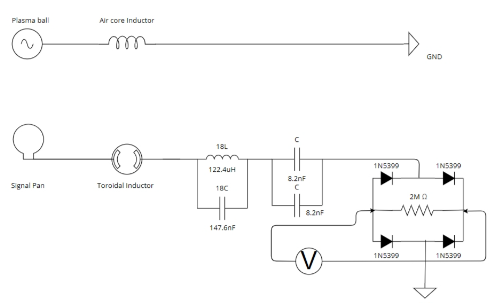

Fig. 5. Overall circuit schematic combines Transmitter and Receiver

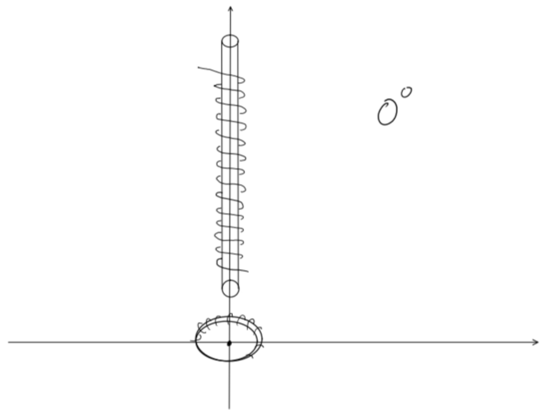

Fig. 6. Schematic of Degree 0 case

- Degree 45 indicates the value of angle between the axis via the toroidal inductor and the central axis of the air core inductor related 45 degree. (Fig. 7)

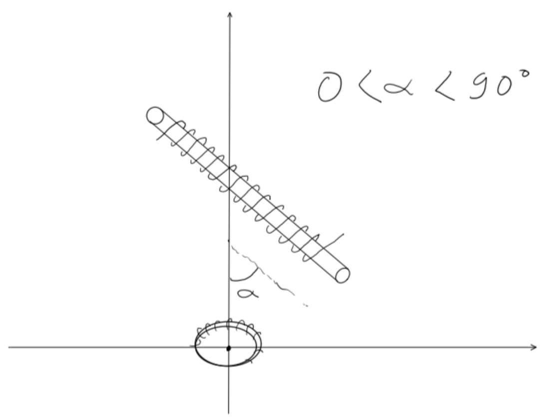

Fig. 7. Schematic of Degree 45 case

- Test case of Degree 90 furnish a square corner between via the toroidal inductor and the central axis of the air core inductor. (Fig. 8)

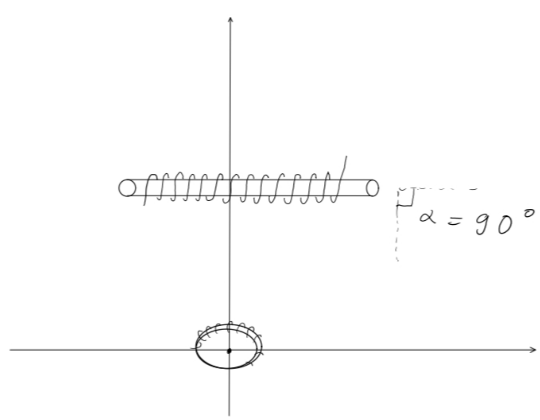

Fig. 8. Schematic of Degree 90 case

1) Schematics of particular condition Case:

- Degree 45 with Toroidal inductor parallel with Parallel-Series Resonant Half-Bridge Converter (Fig. 9)

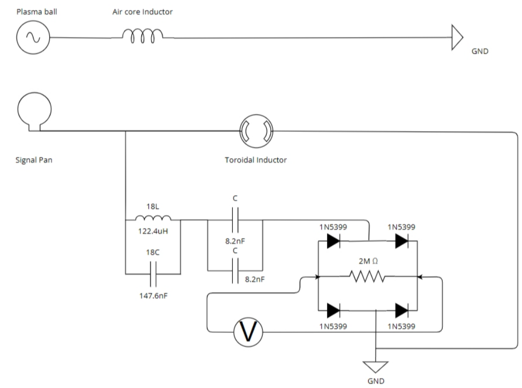

Fig. 9. Circuit diagram of Parallel-Series Resonant Half-Bridge Converter

- Toroidal Inductor parallel only Half-bridge Rectifier (Fig. 10)

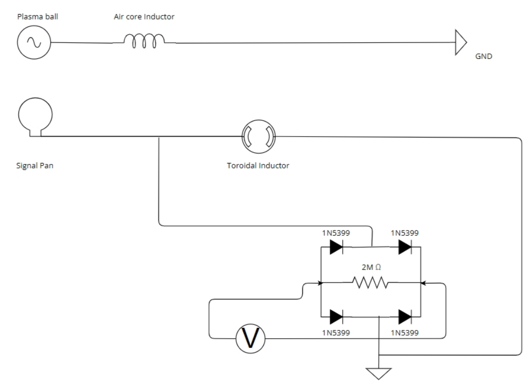

Fig. 10. Circuit diagram of Parallel-Series Resonant Half-Bridge Converter

- Degree 45 Resonance circuit parallel with Half bridge Rectifier (Fig. 11)

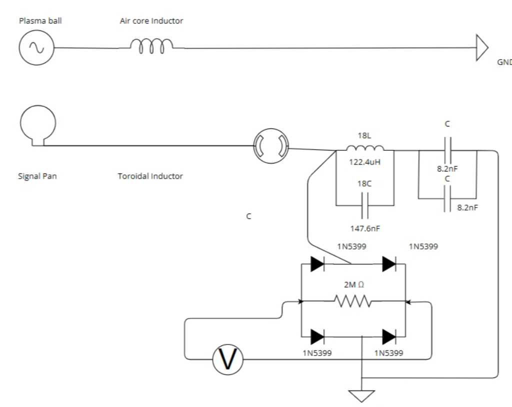

Fig. 11. Circuit diagram of Parallel-Series Resonant Half-Bridge Converter

D. Measurement Technique

The experiment requires positioning the toroidal inductor in three separate orientations relative to the air-core inductor: These sorts of hues include the basic colours, 0, 45 and 90 degrees. The ground wire is tested in various fluids: normal water, saline water and air [13]. Every configuration is performed a number of times, so that the results are standardized throughout the process. The efficiency of the power transmission is assessed with the assistance of a digital oscilloscope and a multimeter [14]. The resulting DC voltage is measured and utilized to calculate out the WPT system efficiency under the various situations stated in [15].

E. Parallel-Series Resonant Half-Bridge Converter

The LC resonant circuit is tuned to the plasma ball's frequency, typically ranging from 20Hz to 50Hz. The optimal value is set at the center of this range. The circuit consists of 18 sub-circuits, each with an inductor ($L = 6.8\mu H$) in parallel with a capacitor ($C = 8.2nF$) linked in series. The 18th sub-circuit has two capacitors linked in parallel and in series with the other sub-circuits.

The resonant frequency f of the LC circuit is given by:

$$f = \frac{1}{2\pi\sqrt{L_T C_T}} \tag{1}$$

where L_T and C_T are the total inductance and capacitance, respectively. For our configuration:

$$f = \frac{1}{2\pi\sqrt{18 \times 6.8\mu H \times 18.5 \times 8.2nF}} = 36,935\,\text{Hz} \tag{2}$$

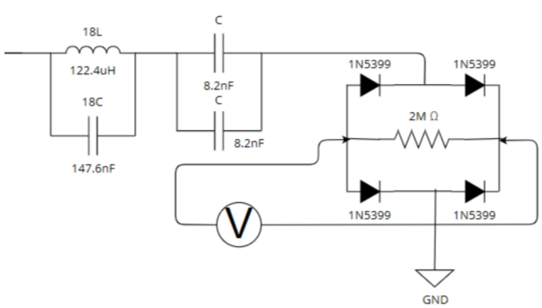

Fig. 12. Circuit diagram of Parallel-Series Resonant Half-Bridge Converter

F. Specification of Components

The experimental setup consists of an air-core inductor (82 turns) (Fig. 1), a toroidal inductor (60 turns) (Fig. 2), and a signal pan connected to a 36.9k Hz LC circuit. A diode bridge (1N5399 2A 1000V) is used for collecting DC voltage data. The experiment was conducted under various orientations and environmental conditions. Theories of inductive coupling and mutual inductance were applied to analyze the data. Statistical analysis was performed to determine the significance of the results.

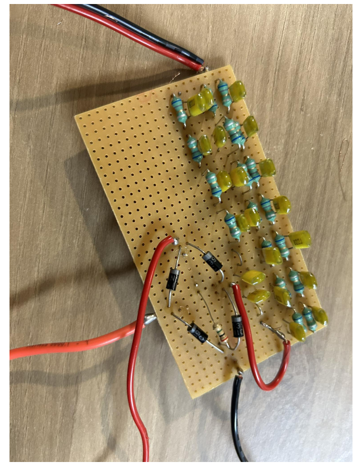

Fig. 13. Prototype Circuit of Parallel-Series Resonant Half-Bridge Converter

III. Results

A. Experiment 1

*1) **Energy Transfer Calculations**:* To estimate the quantity of energy changed from the air-core inductor to the toroidal inductor, it is required to take into consideration the coupling coefficient k of the two inductors coupled with the efficiency of the coupling. The transferred energy may be computed if one knows mutual inductance M and currents via the inductors.

2) Stucture of Inductor:

- An air core inductor 1 is created by winding 80 rounds of insulated copper wire around a PE plastic pipe. This component plays a crucial role in power production.
- A toroidal inductor is created by winding 63 rounds of insulated copper wire around an iron core. This component plays a crucial role in power reception.
- An air core inductor 2 is constructed by wrapping 62 rounds of insulated copper wire around a PE plastic pipe. This component plays a key part in power production.

3) Inductance and Mutual Inductance: Given the inductances:

- Air-core inductor 1 $L_1 = 10.1\,\mu$H
- Toroidal inductor $L_2 = 8.9\,\mu$H
- Air-core inductor 2 $L_3 = 7.83\,\mu$H

a) Toroidal with Air-core inductor Energy Transfer: The mutual inductance M relies on the coupling coefficient k , which goes from 0, no coupling to 1, completely connected the two circuits. It may be argued consequently that in a practical point of view, the coupling coefficient is likely to rely on the distance of the inductors and their arrangement.

For inductors 20-30 cm apart, the coupling coefficient might be around 0.1 to 0.3. Let's use an average value $k = 0.2$.

The mutual inductance M is calculated as:

$$M = k\sqrt{L_1 L_2} \tag{3}$$

Substituting the values:

$$M = 0.2\sqrt{10.1 \times 10^{-6} \times 8.9 \times 10^{-6}} \tag{4}$$
$$= 0.2 \times \sqrt{89.89 \times 10^{-12}} \tag{5}$$
$$= 0.2 \times 9.48 \times 10^{-6} \tag{6}$$
$$\approx 1.9 \times 10^{-6}\,\mathrm{H} \tag{7}$$

*4) **Energy Transfer Calculations**:* The energy stored in the air-core inductor 1 (E_1) can be used to estimate the energy transferred to the toroidal inductor (E_2). The energy transferred depends on the mutual inductance and the currents in the inductors.

Assume:

- Current in the air-core inductor $I_1 = 0.5\,\mathrm{A}$
- Current induced in the toroidal inductor I_2 is calculated using mutual inductance

The energy stored in the air-core inductor is given by:

$$E_1 = \frac{1}{2}L_1 I_1^2 \tag{8}$$

Substituting the values:

$$E_1 = \frac{1}{2} \times 10.1 \times 10^{-6} \times (0.5)^2 \tag{9}$$
$$= \frac{1}{2} \times 10.1 \times 10^{-6} \times 0.25 \tag{10}$$
$$= 1.26 \times 10^{-6}\,\mathrm{J} \tag{11}$$

The current induced in the toroidal inductor (I_2) can be approximated by the mutual inductance M and the rate of change of current in the primary inductor (I_1):

$$I_2 \approx \frac{M\frac{dI_1}{dt}}{L_2} \tag{12}$$

Assuming a sinusoidal variation of I_1 with angular frequency ω:

$$\frac{dI_1}{dt} \approx \omega I_1 \tag{13}$$

Substituting the values, with $\omega = 2\pi \times 36.6 \times 10^3$:

$$\frac{dI_1}{dt} \approx 2\pi \times 36.6 \times 10^3 \times 0.5 \tag{14}$$
$$= 115.2 \times 10^3\,\mathrm{A/s} \tag{15}$$

Then,

$$I_2 \approx \frac{1.9 \times 10^{-6} \times 115.2 \times 10^3}{8.9 \times 10^{-6}} \tag{16}$$
$$= \frac{218.88 \times 10^{-3}}{8.9 \times 10^{-6}} \tag{17}$$
$$\approx 24.6\,\mathrm{A} \tag{18}$$

The energy stored in the toroidal inductor:

$$E_2 = \frac{1}{2}L_2 I_2^2 \tag{19}$$

Substituting the values:

$$E_2 = \frac{1}{2} \times 8.9 \times 10^{-6} \times (24.6)^2 \tag{20}$$
$$= \frac{1}{2} \times 8.9 \times 10^{-6} \times 605.16 \tag{21}$$
$$= 2.69 \times 10^{-3}\,\mathrm{J} \tag{22}$$

b) 2 Air-core inductors energy contact: With the comparable duties as prior. We have

$$E_{1'} = \frac{1}{2} \times 10.1 \times 10^{-6} \times (28.52)^2 \tag{23}$$
$$= 4.107 \times 10^{-3}\,\mathrm{J} \tag{24}$$

with value $k = 0.28$. Hence, we dealing with

$$P_{1'constant} = \frac{E_{1'}}{120} = 34.225 \times 10^{-6} W \tag{25}$$

This $P_{1'constant}$ will be utilized for determine the Error% of WPT with 2 air-cor inductor scenario on this experiment

*5) **Measured Data**:* The experiments were conducted under various environmental conditions to measure the efficiency of the WPT system. The data collected included the voltage and current readings at both the transmitter and receiver ends. The power received was calculated using the formula:

$$P_{\text{out}} = \frac{V_{\text{out}}^2}{R_{\text{load}}} \tag{26}$$

where $R_{\text{load}} = 2M\Omega$.

*6) **Data Analysis**:* The received power was analyzed to determine the efficiency of the WPT system under different orientations and environmental conditions. The results showed significant variations in efficiency based on these factors. The Error % was calculated using the formula:

$$\text{Error } \% = 1 - \left(\frac{P_{\text{out}}}{P_{\text{constant}}}\right) \tag{27}$$

where $P_{\text{constant}} = \frac{E_2}{120 senconds} = 2.24 \times 10^{-5}\,\mathrm{W}$.

*7) **Experimental Results**:* The key results from the studies undertaken are shown below in table format:The key results from the studies undertaken are shown below in table format: (Table I)

The findings demonstrated a higher association between the toroidal inductor's location and the efficiency of the WPT system. Undoubtedly, the 0-degree orientation gave the greatest levels of power transmission, partly owing to the alignment of the magnetic fields between the inductors [16]. Conductive salty water boosts the functioning of a ground wire, and with efficiency being enhanced [2].

Power Output and Efficiency Analysis The power output (P_{out}) and error percentages were measured under various conditions to determine the efficiency and stability of the wireless power transfer (WPT) system. The selected cases for detailed analysis are:

- Degree 45 with Toroidal Inductor parallel only Half-bridge Rectifier:
  This arrangement delivered the highest power of $13.68\mu W$ with percentage error of 0. 39%. From these

data, WPT system has high power production and small error, which indicate the system credibility and efficiency.

- Degree 45 with Transmitter's ground dipped in Salt water and Receiver's ground dipped in water:
  This arrangement generated a power output of $11.87\mu W$ and error percentage of 0. 47%. The improved grounding condition proved to give greater stability and magnify the situation that led to a steady and smooth supply of electricity.
- Degree 45 with 2 Air-core Inductor:
  From this setup, the power output was calculated to be $12.72\mu W$, error % = 0. 63%. The usage of two air-core inductors boosted the power transmission capacity with an equal ratio of the gain obtained in stability and efficacy.

B. Experiment 2

Aside from the addition of a capacitor to ensure signal stability at the DC output stage, the design of this experiment closely resembles that of Experiment 1.

*1) **Component Modification**:* The purpose of incorporating a capacitor and connecting it in parallel with the load resistor is to implement a filtering mechanism in a bridge rectifier, which serves to correct the voltage ripple [17]. Allow me to explain the process:

- **Ripple Reduction:**The capacitor charges in the time of the rectified voltage growing and discharges when the rectified voltage lowers. This process of charging and discharging closes the gaps in the corrected waveform and consequently lowers the ripple [18].
- **Enhanced Stability:** By eliminating high-frequency components, the capacitor improves the stability of the DC voltage, which is advantageous for delicate electronic components [19].
- **Enhanced Efficiency:**A cleaner output of DC estimated by the presence of fewer ripples power all the components that are downstream of the inverter consequently boosting their efficiency and reliability by virtue of decreasing noise and interference issues in the circuit [20].
- **Optimized Performance:**In the application where the pure and steady power is expected, for instance in the communication system and precision instruments a capacitor in the rectifier circuit is necessary [21].

The value of the capacitor could possibly be estimated using the formula for the cutoff frequency of an RC filter:

$$f_c = \frac{1}{2\pi RC}$$

Solving for C:

$$C = \frac{1}{2\pi \cdot 2 \times 10^6 \cdot 36.9 \times 10^3} \approx 2.16 \times 10^{-12}\text{F} \approx 2.16\text{pF}$$

where:

- f_c is the cutoff frequency,
- R is the load resistance,
- C is the capacitance.

Hence, by updating component base on RC filter, there is new parallel-serie resonant half-bridge converter schematic for this circumstance (Fig. 14) [22].

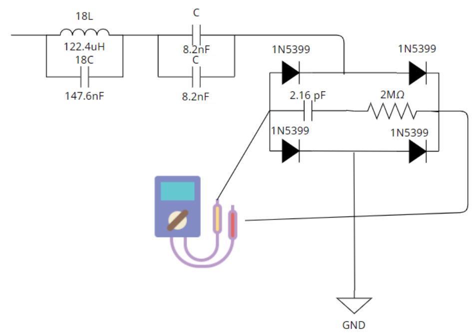

Fig. 14. Circuit diagram of New Parallel-Series Resonant Half-Bridge Converter

2) Experiment Analysis: In new circuit's structure, there is a pattern of fluctuations that are quite big broken by relatively minor oscillations. The signal has intermittent flares up which shows the transitory phenomena; nonetheless, the stability is favored across the span of observation. There low noise which means that the measuring settings or filter employed in its evaluation make it a trustworthy metric. These relative steady and readily modifiable features make osciloscope signal beneficial for the subsequent processing and interpretation. (Fig. 15) [23]. where:

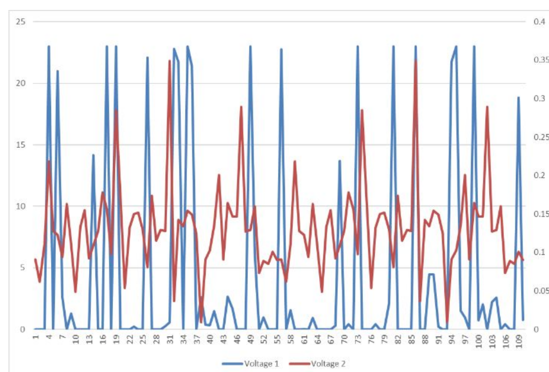

Fig. 15. Comparation of Old-New Parallel-Series Resonant Half-Bridge Converter output signal

- $Voltage1$ is the old structure,
- $Voltage2$ is the new one,

We can simply compute the Power via each 30 second period, impossible change combined in data below (Table II)

C. Summary

Compare to power output, simply demonstrate that applying RC filter provide better and smoother DC signal owing to without this. Trading off quantity of Voltage for being steady DC input, as far as equiqment protection, this is going to be a best option for WPT between ai-core and toroidal inductor dependent on rotation and enviromentally state [24].

IV. Discussion

The control room data corroborate the theory that the location of the toroidal inductor and the ground wire fluid conductivity greatly impact the WPT system efficiency [6]. These results are in accordance with earlier research which pointed out the need of appropriate alignment of magnetic fields, and proper grounding via conductive channel to enable greater efficiency of WPT [25].

More study might query how inductor kinds and material being utilized effects WPT efficiency. Also, the investigation of the impacts of other environmental parameters like temperature and humidity might be helpful for practical application in the future [8].

V. Conclusion

The researches of this article reveal that the location of the toroidal inductor and the kind of fluid used in the ground wire are characteristics which have a considerable impact on WPT systems [26]. The chosen strategies were the 0-degree orientation and the employment of salty water as it showed to produce the best efficiency [16]. These conclusions enrich the existing research on WPT technology and give realistic advice for boosting the efficacy of WPT systems for diverse applications [9]. However, a technological enhancement which has not been brought to an optimal level in this research is the insertion of a capacitor in the stabilization of current output in the DC stage. Subsequent studies should take this into consideration as part of the design in order to better the constancy of the output detected in the DC. Moreover, investigating how the location of the central axis of the system in connection to the signal stability by testing the system under various situations may possibly offer more information on the increase of WPT efficiency.

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TABLE I

WPT SYSTEM AVERAGE POWER UNDER DIFFERENT CONDITIONS

Condition	$0-30s\,(\mu W)$	$30-60s\,(\mu W)$	$60-90s\,(\mu W)$	$90-120s\,(\mu W)$	$P_{\mathbf{out}}\,(\mu W)$	**Error %**
Degree 0	4.63	2.18	6.92	16.91	7.66	0.66
Degree 45	7.57	5.00	13.26	1.91	6.935	0.69
Degree 45 with Toroidal inductor parallel with Parallel-Series Resonant Half-Bridge Converter	8.93	12.10	4.79	6.71	8.13	0.64
Degree 45 with Toroidal Inductor parallel only Half-bridge Rectifier	14.21	12.20	5.36	22.95	13.68	0.39
Degree 45 Resonance circuit parallel with Half bridge Rectifier	2.07	8.85	11.29	11.48	8.42	0.62
Degree 45 with Transmitter's ground dipped in Salt water	3.28	13.71	7.20	8.41	8.15	0.64
Degree 45 with Transmitter's ground dipped in Salt water and Receiver's ground dipped in water	27.3	1.10	10.09	8.98	11.87	0.47
Degree 45 with Transmitter's ground dipped in water	11.11	7.76	0.68	4.70	6.06	0.73
Degree 45 with Transmitter's ground dipped in water and Receiver's ground dipped in salt water	9.20	16.11	4.66	13.47	10.86	0.52
Degree 45 with 2 Air-core Inductor	10.94	23.41	8.08	8.43	12.72	0.63
Degree 90	2.98	4.01	3.65	5.69	4.08	0.82

TABLE II

WPT SYSTEM AVERAGE POWER UNDER DIFFERENT CONDITIONS WITH C= 2.16PF

Condition	$0-30s\,(\mu W)$	$30-60s\,(\mu W)$	$60-90s\,(\mu W)$	$90-120s\,(\mu W)$	$P_{\mathbf{out}}\,(\mu W)$	**Error %**
Degree 0	4.12	1.94	6.17	15.06	6.82	0.7
Degree 45	6.74	4.45	11.82	6.18	7.29	0.68
Degree 45 with Toroidal inductor parallel with Parallel-Series Resonant Half-Bridge Converter	7.96	10.77	4.27	5.98	7.25	0.68
Degree 45 with Toroidal Inductor parallel only Half-bridge Rectifier	12.66	10.86	4.78	20.41	12.17	0.46
Degree 45 Resonance circuit parallel with Half bridge Rectifier	1.85	7.89	10.06	10.22	7.50	0.67
Degree 45 with Transmitter's ground dipped in Salt water	2.92	12.22	6.41	7.50	7.26	0.68
Degree 45 with Transmitter's ground dipped in Salt water and Receiver's ground dipped in water	24.31	0.98	9.00	8.00	10.57	0.53
Degree 45 with Transmitter's ground dipped in water	9.91	6.92	0.61	4.19	5.4	0.76
Degree 45 with Transmitter's ground dipped in water and Receiver's ground dipped in salt water	8.19	14.35	4.15	12.01	9.68	0.57
Degree 45 with 2 Air-core Inductor	9.75	20.83	7.20	7.51	11.32	0.67
Degree 90	2.65	3.57	3.25	5.07	3.64	0.84