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# Wireless Charging of Electric Vehicle While Driving

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**ABSTRACT** Static wireless charging is becoming popular all over the world to charge the electric vehicle (EV). But an EV cannot go too far with a full charge. It will need more batteries to increase its range. Dynamic wireless charging is introduced to EVs to capitally increase their driving range and get rid of heavy batteries. Some modern EVs are getting off this situation. But with Dynamic WPT the need of plug-in charge and static WPT will be removed gradually and the total run of an EV can be limitless. If we charge an EV while it is driven, we do not need to stop or think for charging it again. Eventually, in the future the batteries can be also removed from EVs by applying this method in everywhere. Wireless charging needs two kinds of coils named the transmitter coil and the receiver coil. The receiver coil will collect power from the transmitter coil while going over it in the means of mutual induction. But the variation of distance between two adjacent coils affects the wireless power transfer (WPT). To see the variation in WPT, a system of two Archimedean coils of copper is designed and simulated for vertical and horizontal misalignment in Ansys Maxwell simulation software. The transfer power for 150 mm air gap is 3.74 kW and transfer efficiency are gained up to 92.4%. The charging time is around 1 hour and 39 minutes to fully charge its battery from 0 state for a 150mm air gap for an EV with 6.1 kW power may take. Also, a charging lane is designed for dynamic charging. Then the power transfer is calculated from mutual inductance when the EV is driven on a charging lane. From the load power, it can be calculated how further an EV can go with this extra power.

**INDEX TERMS** Electric vehicle, wireless power transfer, dynamic charging, efficiency, charging lane.

## I. INTRODUCTION

Electric Vehicles have started their journey when General Motors made the world's first electric vehicle during 1996. But, with the initiation of Chevrolet and Nissan, manufacturers of EV have started a magnificent journey through the technology, and the acceptance of users for it causes no harm to the environment. Also, stepping into EV is considered as to take a significant step towards protecting the environment, enhancing transportation durability and diminishing fuel dependency. With this great advantage, many automobile manufacturers have started to make immense investments to bring improvement in the technology of the electric automobile [1], [2]. Wireless Charging System (WCS) is working on the theory of Mutual induction is a phenomenon introduced by Sir Nikola Tesla in 1887 where an induced emf is caused in the second coil known as receiver coil can create electrical energy with a given current in the first coil known as transmitter coil [3].

The current development in this sector by the automobile companies and the research institutes show that within the next ten to twenty years charge while driving (CWD) infrastructure can be stationed for widespread use. That is why many companies have been looking at ways to not only extend the range of EVs by wireless charging but also to make the charging process seamlessly automatic. [4] Paper design

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and S-S (series- series) WPT system with a 40 kHz to 85 kHz resonant frequency. They found that the WPT system is in better use for light-duty EV applications. But, one of the big challenges facing EV makers is the issue of dynamic charging. Since wireless charging of EV is introduced, two methods are very effective for WPT. They are capacitive wireless power transfer (CWPT) and resonant inductive power transfer (RIPT). Some researches show that efficiency and power density are much higher in inductive charging than capacitive charging [5]. Also, inductive parameters significantly depend on the dimension of the coupling coils [6]. Many researchers are working on how maximum power can be transferred to the receiving pad and increase the overall efficiency of EVs in dynamic conditions. But the efficiencies of most work are under 90 percent for RIPT also [7]. The other factor which is affecting the overall efficiency is misalignment while driving the EV. The efficiency will be decreased with increase in misalignment between the transmitter coil and receiver coil [8], [9]. [10] paper the coupling co-efficient decreases from 0.2 to 1.6 for 20% mis-alignment between the coils compared to misalignment free condition. Different types of shielding material can be used for magnetic field alignment and leakage flux reduction. It has been seen that ferrite object restricts the magnetic fields and will not cause any harm to the neighbor objects [11]. Shapes of ferrite also depend on the coil. They can be Circular, circular striated, square, rectangular, T-core, U-core, E-core, Double U, and striated blocks [12].

WCS of EVs can be overcome the challenges associated with range anxiety, battery inadequacy, and wasted space for the large battery size. Despite that, lower power transfer, heavy structure, electromagnetic compatibility, more charging time and lower efficiency are the challenges that dynamic WCS have to face. However, dynamic WCS has been researched to overcome the shorter range of anxiety with a constant charging facility. This system allows the battery storage device to be charged when the EV is in motion. In this case, a fewer volume of battery storage is needed by the vehicle. Wireless Charging Units (WCUs) are placed on the road so that when a vehicle is driven over the WCUs, catches power by using mutual induction for wireless charging, which is known as dynamic charging. By enhancing EVs transit range, it can solve the limited issue range. But there are two main obstacles in dynamic WCS, horizontal misalignment and large air-gap between the charging lane and the EV. The efficiency of power transfer mainly relies on the coil alignment and air-gap distance within the coils. The power transfer among two coupling coils increases when the distinct distance among the coils decreases [13]. There are different types of coil structures such as circular pad (CP), circular rectangular pad (CRP), double-D pad (DDP), double-D quadrature pad (DDQP) bipolar pad (BPP), etc. [14]. Using DD and QDQ coil it is shown that the inductive system maintains maximum efficiency whether it is perfectly aligned or misaligned in the position of coils [15]–[18]. Regarding the small vehicle, there is a variation of the average air-gap distance between 150 to 300 mm [19]. So, simulation and calculation between these ranges are discussed in this work. But it can increase for larger vehicles.

In this work, dynamic WPT in the mean of mutual induction is discussed elaborately. Then modeling of the transmitter coil and the receiver coil and simulation for WPT are shown by Ansys Maxwell software. Ansys Maxwell is a modeling and simulation software which analyze in electromechanical components common to wireless charging, electric machines, transformers and many more. Therefore, verify the output data with the help of mathematical expression. Also, load power and efficiency are calculated here. Finally, how much power an EV can collect from the charging lane while it is driven over it and how extra distance it can travel with this consumed power is calculated.

There are many research works regarding simulation and calculation of transmitter coil and receiver coil of WPT. But there is no work till now which showed how much power we can get in dynamic WPT. And how far we can go with this extra power.

## II. WIRELESS POWER TRANSFER

### A. WPT SYSTEM

In a generic WPT system for EV, high-frequency ac power is supplied in the transmitter end and transfer the power to the receiver end over a specified distance. As RIPT is the most effective WPT for EV so, it is discussed here briefly and the whole structure is designed based on RIPT.

### B. RESONANT INDUCTIVE POWER TRANSFER

IPT method can transfer power by the inductive coil. It is the most efficient process for WPT in the static method where the receiver coil is in the centered position over the transmitter coil. But if we think of dynamic charging then the receiver coil is movable as shown in Fig. 1 and can barely collect the magnetic flux from the transmitter coil. Hence a capacitor is used on the transmitter side and as well as on the receiver side known as a compensation network to resonant the transmitter coil and the receiver coil [20]. This method is called the RIPT method. RIPT method is the most efficient - among all technologies to transfer power wirelessly in short-range [21]. There are four compensation networks in the RIPT method, series- series (s-s) compensation, series-parallel (s-p) compensation, parallel- parallel (p-p) compensation, and parallel-series (p-s) compensation. In this work, s-s compensation is used because, in the s-s compensation network, maximum power is transferred to the receiving pad [22], [23]. Also, RIPT has a higher switching frequency compared to IPT [24].

### C. CHARGING METHOD

Low-frequency ac power from the grid is converted into a high frequency (hf) ac through ac-dc converter and dc-ac inverter. To ensure maximum power transfer to the receiving end, s-s compensation topology is used in the transmitter coil and the receiver coil. The transmitting pad

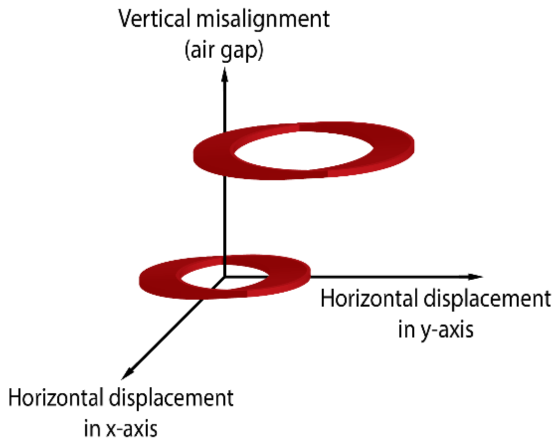


**FIGURE 1.** Transmitter coil and receiver coil misalignment.

is typically mounted beneath the surface of the road and the receiving pad is mounted underneath the vehicle [25]. The receiver pad is usually mounted lower from the frame of the EV to help to catch more magnetic flux. The high-frequency AC is then converted into DC by using an AC/DC converter and sent to the battery bank. The battery management system (BMS) communications and power controller are used to ensure stable operation and avoid any safety issues. The whole process of charging method from grid to vehicle (G2V) is shown in Fig. 2.

Here, the main work is focused on the transmitter coil and the receiver coil as it is the most important part of the whole system assuming the other parameters ideal. Varying the properties of these two coils can bring improvement in the overall efficiency.

### D. EQUIVALENT CIRCUIT DIAGRAM

In this work, 70A current is used because there is no abrupt voltage drop in the resonance case until the input current is 70A [26]. Also, the increase in input current will increase the overall efficiency. The resonant frequency is set to 85 kHz. An equivalent circuit diagram for the RIPT system is shown in Fig. 3. In the receiver end, an AC/DC is converter is used to convert the high-frequency ac to dc output. $C_1$ and $C_2$ are resonant capacitors of transmitting pad and receiving pad respectively.

The circuit simulation is done in LTspice circuit simulation software. In this software, direct mutual induction representation is not possible. So, an equivalent circuit diagram is drawn in Fig. 4 and hence simulated for the load current.

## III. COIL DESIGN

### A. TRANSMITTER COIL AND RECEIVER COIL

There are different shapes of coil used in WPT systems. Among them, the circular coil is the most effective structure in high-frequency wireless transfers [27] as there are no sharp edges. So, the eddy current is kept to minimum [12]. The high magnetic field produced by the coil causes better performance in the WPT system [28]. The proposed transmitter coil and the receiver coil are shown in Fig. 5.

**TABLE 1.** Specification of the transmitter coil and the receiver coil.

| Name | Transmitter coil | Receiver coil |
|---|---|---|
| Number of Turns | 18 | 18 |
| Inner coil radius | 140 mm | 140 mm |
| Outer coil radius | 232.5 mm | 232.5 mm |
| Radius change | 5.3 mm | 5.3 mm |
| Radius of conductor | 2.34 mm | 2.34 mm |
| Pitch | 0 | 0 |

### B. COIL SPECIFICATIONS

Many parameters affect the performance of circular coil such as outer radius, inner radius, pitch, number of turns, the radius of conductor [29]. The parameter set for the transmitter coil and the receiver coil is shown in Table 1. In this work, the size of both coils is the same.

### C. EQUIVALENT EQUATIONS

#### 1) CALCULATION OF SELF-INDUCTANCE OF COILS

Once an Archimedean spiral coil is built, then it is difficult to modify the coil. So, accurate modeling is important for an Archimedean spiral coil. And the calculation of inductance for an Archimedean coil is different from a normal circular coil.

Wheeler expression which is shown in (1) can be used for calculating the self-inductance of the transmitter coil [30]. Before that, from Fig. 6 the following parameters of the coils can be obtained-

The outer diameter of the coil, $D_{out} = 232.5$mm
The inner diameter of the coil, $D_{in} = 140$mm
Radius change per turn, T = 5.3mm
Diameter of wire, $D_{wire} = 2.34$mm
Number of turns, N = 18
Self-inductance,

$$L = \frac{a^2N^2}{8a + 11c} \tag{1}$$

where 'a' is the center of the coil to the center of the pitch of the coil and 'c' is the pitch of the coil.Since the geometry of the transmitter coil and receiver coil are the same, the self-inductance of each coil will also be the same.

After solving the (1), the value of self-inductance is obtained at 176.624$\mu$H. This value is evaluated for both self-inductance of transmitter coil, $L_1$ and receiver coil, $L_2$. Length of the wire of the coil, $l = \frac{\pi N(D_{out}+D_{in})}{2} = 21.06$m

#### 2) CALCULATION OF MUTUAL INDUCTANCE OF COILS

Mutual induction, M is the most important parameter of this work. Because from the mutual inductance the power transfer can be calculated to the receiving end and further work is depending on this value. Mutual induction depends on the magnetic field between the coils and any change in the

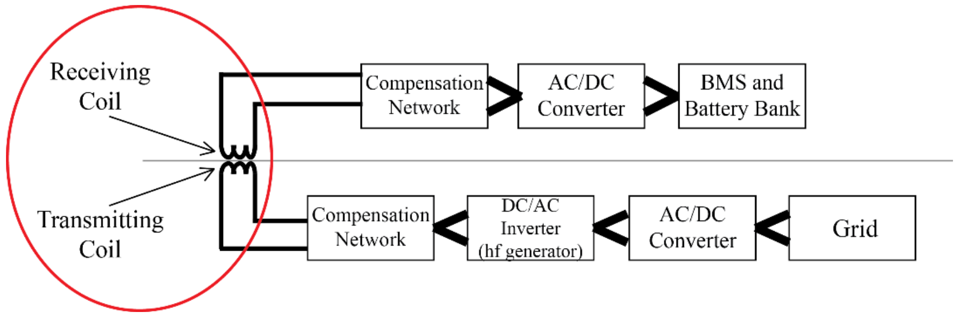


**FIGURE 2.** Block diagram of grid-to-vehicle (G2V) wireless charging system for an EV.

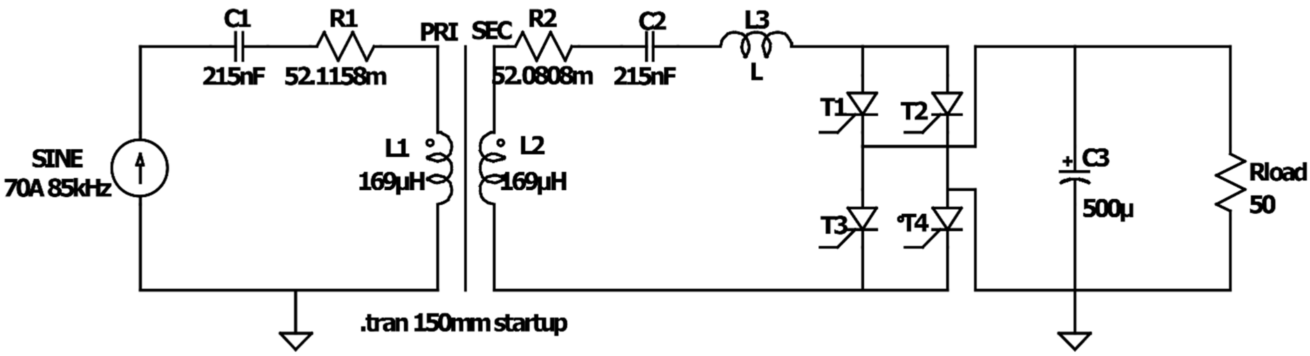


**FIGURE 3.** Circuit representation for RIPT system.

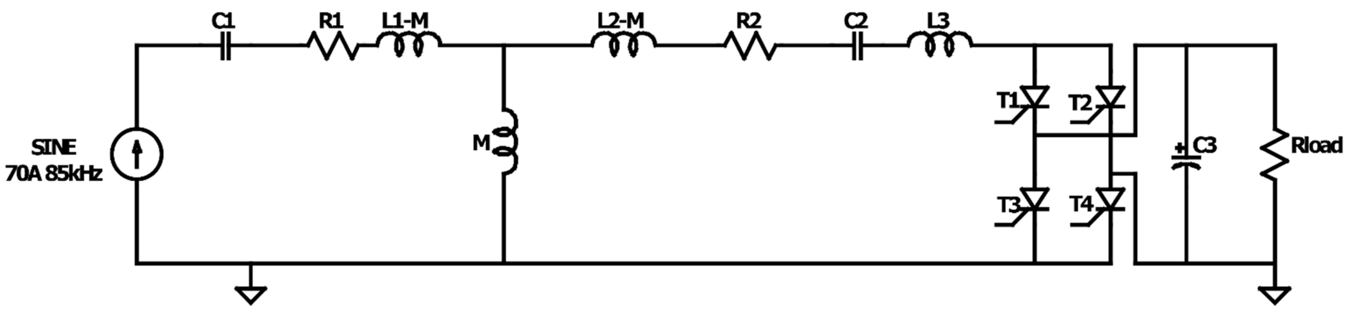


**FIGURE 4.** Equivalent circuit diagram for given self-inductance and mutual inductance.

vertical and horizontal displacement varies its value [31], [32]. For the calculation of mutual induction, let $R_t$ and $R_r$ represents the radius of the current filaments in the transmitter and receiver coils as shown in Fig. 7. Here, the subscripts 't' and 'r' are integers from 1 to 18 i.e., the turn each of coil such that $R_1$ represents the radius of innermost turn and so on. Let $N_t$ and $N_r$ are the numbers of turns of the transmitter coil and receiver coil and D be the vertical displacement between the coils.

Then, the RMS value of the magnetic flux density $B_0$ can be derived by the (2). The total magnetic flux density in the receiver coil from the summation of the magnetic flux density of each turn is represented by-

$$B_0 = \frac{\mu_o}{4\pi} I_{Trms} \sum_{t=1}^{N_t} \frac{2\pi R_t^2}{(R_t^2 + D^2)^{\frac{3}{2}}} \tag{2}$$

Here, $I_{Trms}$ is the RMS value of the input current in the transmitter end.

Mutual inductance, $M$ in the innermost turn, $N_r$ of receiver coil can be calculated from flux density, that is:

$$M = \frac{B_0 A_r}{I_{Trms}} \tag{3}$$

where, $A_r$ is the area of only conduction path of receiver coil. Putting the value of (2) to (3) M can be obtained.

$$M = \frac{\mu_o}{2} \pi R_r^2 \sum_{t=1}^{N_t} \frac{2\pi R_t^2}{(R_t^2 + D^2)^{\frac{3}{2}}} \tag{4}$$

The total mutual inductance between the transmitter coil and receiver coil can be finally found for each turn of transmitter and receiver end and thus give the final equation of

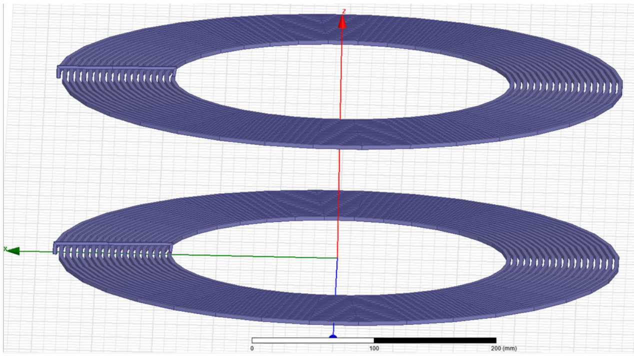

**FIGURE 5. Transmitter coil and receiver coil.**

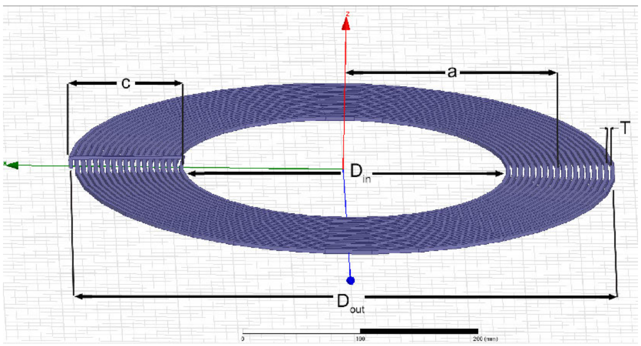


**FIGURE 6. 3D representation of an Archimedean coil.**

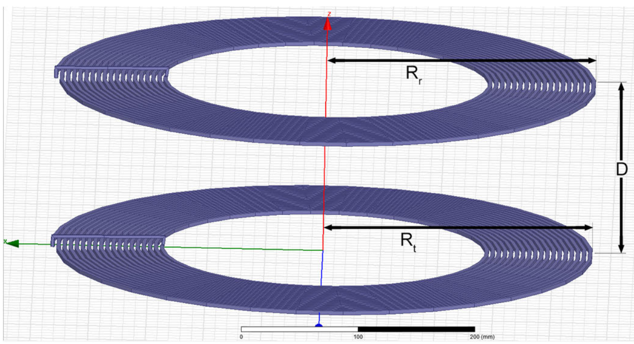


**FIGURE 7. Transmitter and receiver coil at a displacement 'D.'**

mutual inductance, $M$. With the help of (9), the mutual inductance of two coils can be calculated for any displacement between the coils.

$$M = \frac{\mu_o}{2}\pi \sum_{r=1}^{N_r} R_r^2 \sum_{p=t}^{N_t} \frac{2\pi R_t^2}{(R_t^2 + D^2)^{\frac{3}{2}}} \tag{5}$$

### 3) CALCULATION OF COUPLING COEFFICIENT

The fraction of magnetic flux produced by the current in one coil that links with the other coil is called coupling coefficient, k. The value of k is between 0 and 1. If k = 1, then the flux produced by one coil is completely linked with another coil. It is also called magnetically tightly coupled. If k = 0, then the flux produced by one coil does not link at all

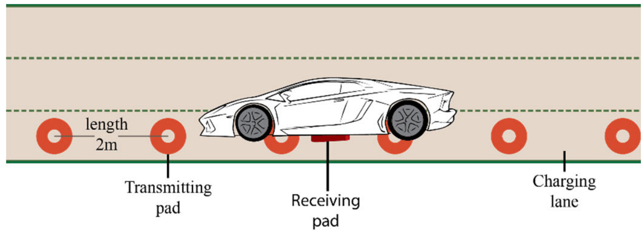


**FIGURE 8. Scenario layout of the position of transmitting pad for dynamic charging.**

with another coil. It is also called magnetically isolated. The total area occupied by the winding in Archimedean coils has a strong influence on the magnetic coupling coefficient [29]. From [26] the coupling coefficient can be easily found.

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{6}$$

Here, $L_1$ and $L_2$ are self-inductances of the transmitter coil and receiver coil respectively which is from Equation (1).

### 4) CALCULATION OF CURRENT AND VOLTAGE

The output current can also be found with the help of mutual inductance:

$$I_2 = \frac{MI_1}{L_2} \tag{7}$$

Here, the input current $I_1$ is 70 A. So, the input voltage can be derived with the help of $L_1$.

$$L_1 = \frac{V_1}{dI_1/dt} \tag{8}$$

where, $V_1$ is the input voltage of the transmitter coil. From this equation-

$$V_1 = L_1.dI_1/dt \tag{9}$$

The output equation of output voltage is as same as this equation.

### 5) LOAD POWER AND EFFICIENCY CALCULATION

The equation of load power and efficiency can get from [33], [34]. To determine the load power, $P_l$ angular frequency, $\omega$ is calculated. For RIPT, angular frequency of both transmitter coil and receiver coil are the same [35].

$$\omega = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{10}$$

$$P_l = \frac{\omega^2 M^2}{(R_t + R_r)^2} I_1^2 R_l \tag{11}$$

Here, $R_l$ is the load resistance. Typical EVs have a Li-ion battery which has around 2.25 Ω internal resistance [36]. $R_t$ and $R_r$ internal resistance of transmitter coil and receiver coil respectively.

The efficiency of WPT depends on the transmitting pad and receiving pad, the resonant frequency, the distance between the coils, and the mutual inductance collectively [11].

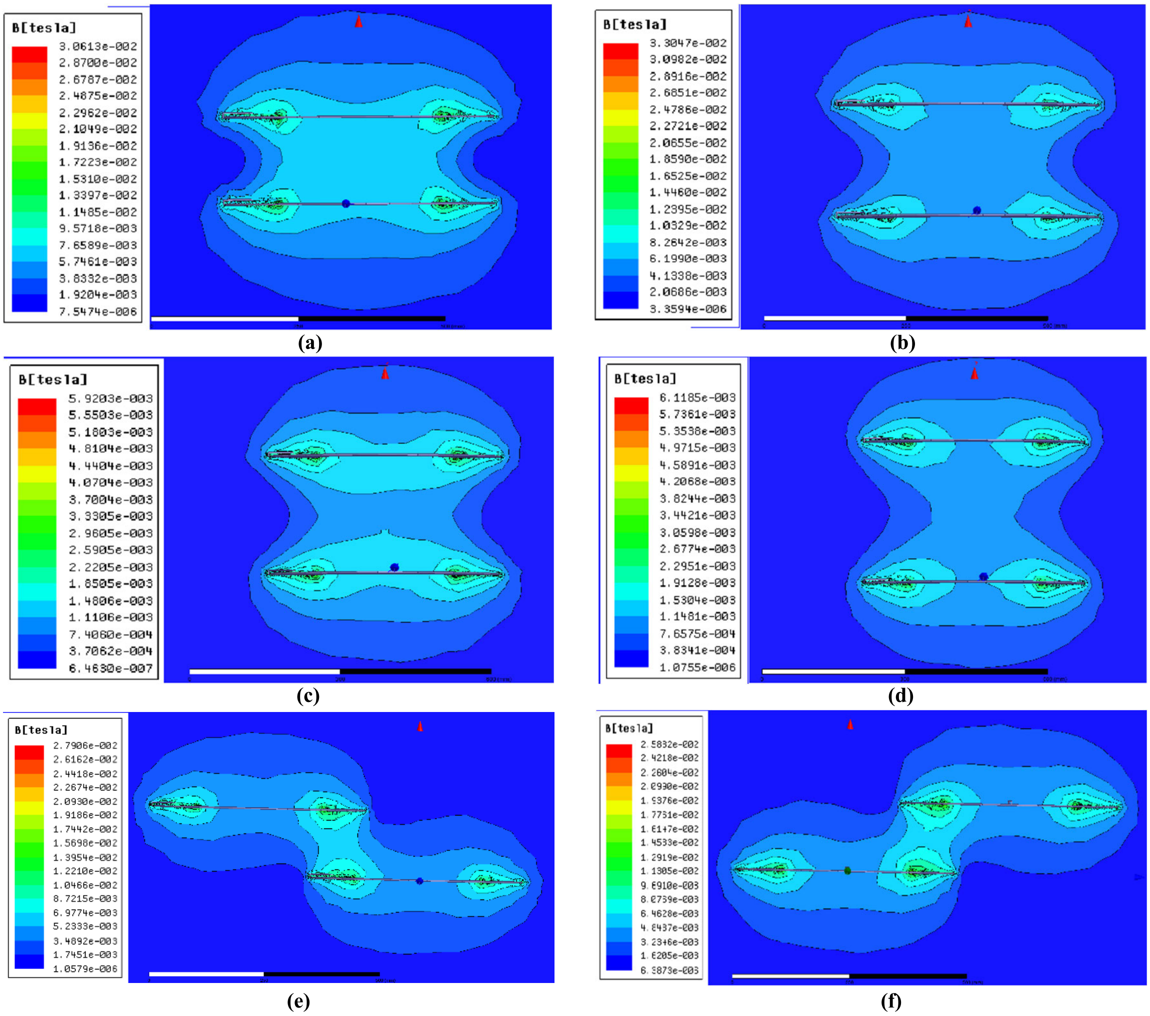


**FIGURE 9.** **Variation in magnetic flux density for (a) 150mm (b) 200mm (c) 250mm and (d) 300mm air gap between the coils and (e) x-axis displacement for 150 mm air gap and (f) y-axis displacement for 150 mm air gap.**

The overall efficiency, $\eta$ of the system can be calculated by (17). Where, $R_s$ is the inner radius of coils.

$$\eta = \frac{\omega^2 M^2 R_l}{(\omega^2 M^2)(R_t + R_r) + (R_s + R_t)(R_t + R_r)^2} \quad (12)$$

### 6) DYNAMIC WPT CALCULATION ADOPTING TO SPEED VARIATION

For a Renault Twizy EV the Dynamic WPT will be measured for a certain charging track and will also be examined how far this EV will go with this extra power.

Specifications of Renault Twizy-
Battery- 6.1 kWh
Electric range- 90 km (56 mi)
Curb weight- 450 kg (992 lb)
Seat capacity- 2 persons
Battery weight- 100 kg (220 lb)

Neglecting the y-axis displacement, the x-axis displacement of the transmitter coil to the receiver coil is (350+350) mm = 700 mm in both positive and negative directions. Between this position, the coils are inductively coupled as shown in Fig. 11(a).

For 20 km/h speed it will go 1 mm in, $\frac{60*60}{20*10^6} = 1.8*10^{-4} sec.$
and will take $1.8*10^{-4}*700 = 0.126$ sec.
to cross a transmitter coil in coupled mode.

So, transmitter coil crosses the receiver coil in $(0.126/2) = 0.063$ sec. for only one direction (positive direction/ negative direction). In this period, the load power will rise from 0 to 3.74 kW from (9) as the transmitter coil enters into the receiver coil from 350 mm to its center. The load power while reach in the middle of the transmitter coil for $1.8 * 10^{-4} sec.$ is $1.87 * 10^{-4}$ W with the stated speed. Therefore, the equation of load power for crossing individual coil is,

$$P_t = \int_0^{0.063}\int_0^{P_l} 1.8*10^{-4} xy^2 dxdy$$
$$\int_0^{3740} 1.8*10^4 * xydx = 1258.88y^2$$

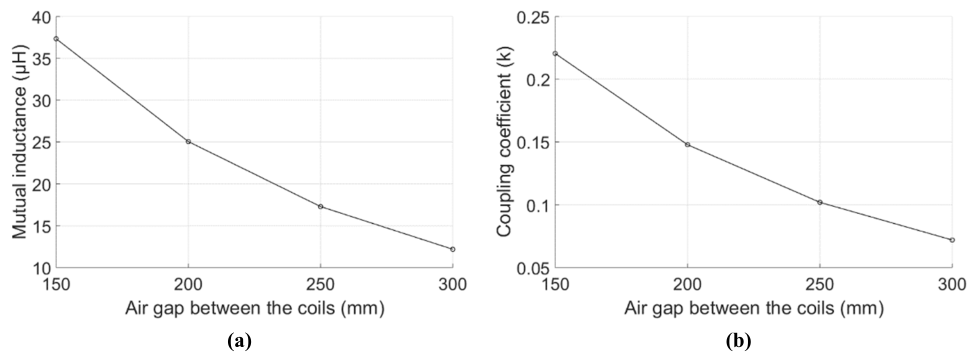


**FIGURE 10.** Reduction of (a) mutual inductance and (b) coupling coefficient with the increase in the air gap.

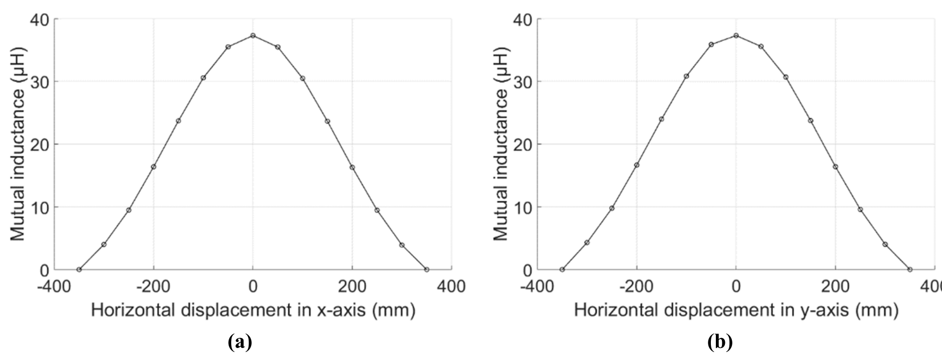


**FIGURE 11.** Variation of mutual induction with the change in horizontal displacement in (a) x-axis and (b) y-axis.

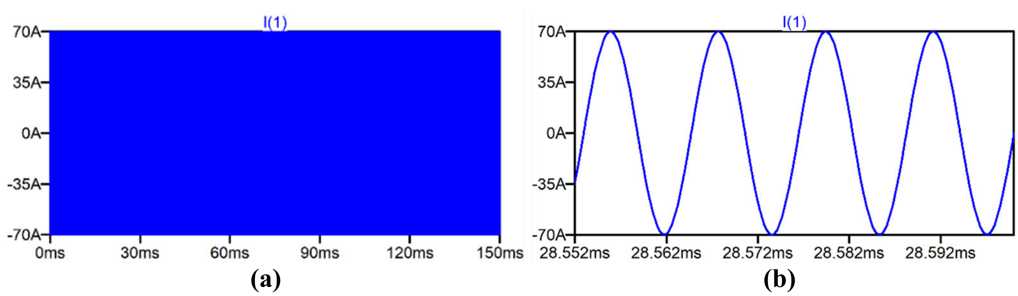


**FIGURE 12.** (a) The waveform of input current, $I_1$ and (b) Large scale view of input current, $I_1$.

$$= \int_0^{0.063} 1258.884y^2dy$$

$$\int_0^{0.063} 1258.884y^2dy = 0.10492 \tag{13}$$

After solving this equation, the total load power for only one transmitter coil while the receiver coil is moving will be $(0.10492*2)\mathrm{W} = 0.20984$ W. A track of a 3 km charging lane is proposed for WPT. If the distance between the transmitter coils is 2m then 500 transmitter coils will be implemented for 1 km of the track as shown in Fig. 8.

## IV. RESULTS AND DISCUSSIONS

After the mutual induction simulation, the simulated data of Fig. 9 is generated which is showing the variation of magnetic flux with the increase in the air gap. The region for the magnetic flux density of the transmitter coil is getting smaller with an increase in distance between the coils. As a result, the region for magnetic flux density which receives the receiver also getting smaller. After measuring the self-inductance and mutual-inductance of the transmitter coil and the receiver coil it is found that the calculated value and the simulated value are almost the same which showed Table 2.

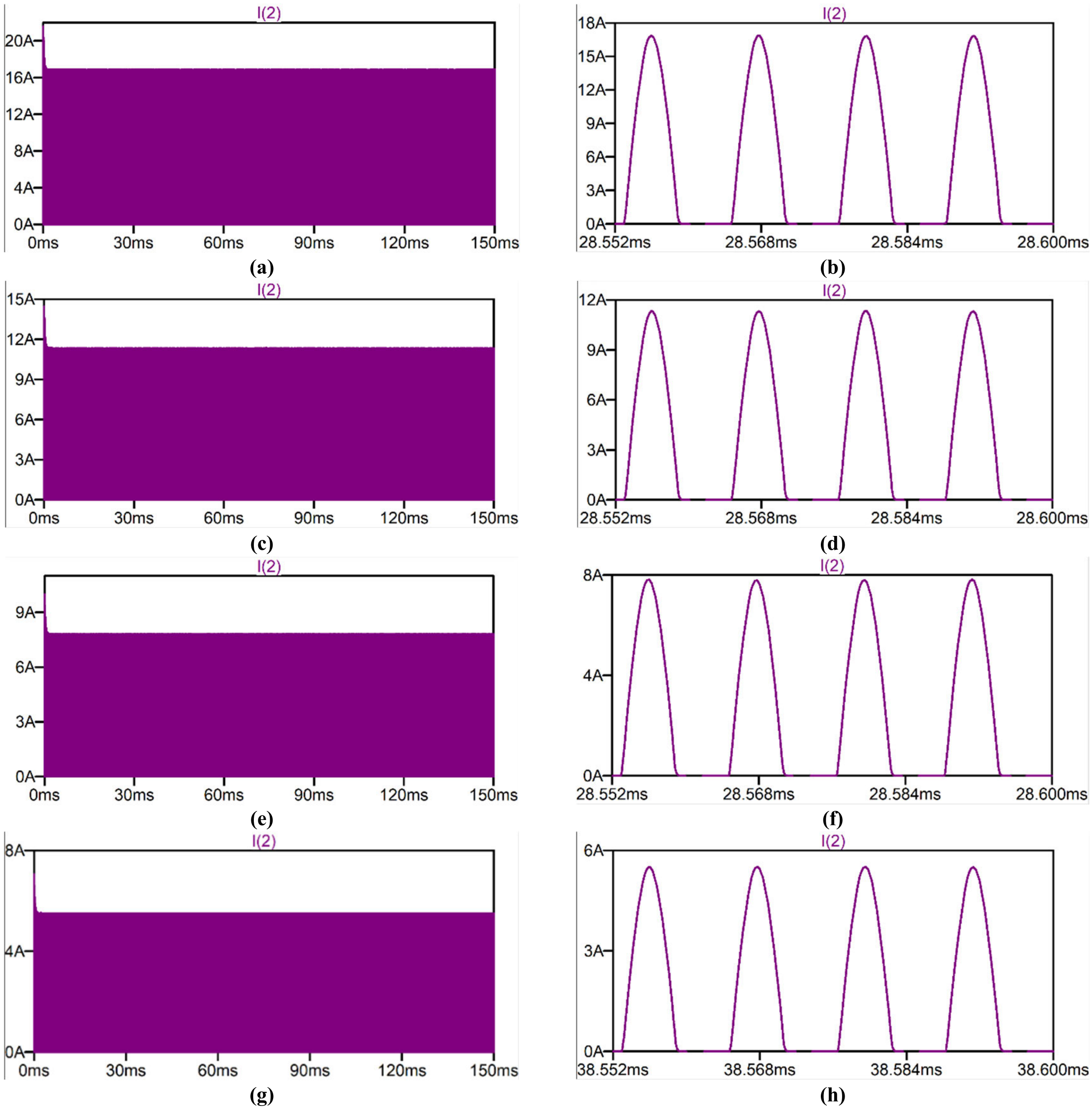


**FIGURE 13.** The waveform of load current, $I_2$ for (a) 150 mm, (b) 200 mm, (c) 250 mm, and (d) 300 mm air gap. Large scale view of load current for (e) 150 mm, (f) 200 mm, (g) 250 mm, and (h) 300 mm air gap.

**TABLE 2.** Calculated value and simulated value of the self-inductance of the transmitter coil and the mutual-inductance for 150mm air gap.

| Inductance | Calculated | Simulated |
|---|---|---|
| Self-Inductance($L_1$) | 176.624 µH | 169.844 µH |
| Mutual- Inductance(M) | 38.892 µH | 37.33368 µH |

Figure 10 shows the graphical representation of mutual inductance and coupling coefficient for 150mm-300mm air gap between the transmitter coil and the receiver coil. It can be easily seen from this figure that mutual inductance and coupling coefficient is decreasing with the increase in air gap. From Fig. 11, it can be seen that the mutual inductance is in peak value when there is no displacement. But, with the increase in displacement whether in positive or negative axis the mutual inductance decreases and becomes zero at approximately 350 mm displacement from the center. It occurs for both x-axis and y-axis displacement.

Fig. 12 shows the waveform of 70A input current with 85 kHz resonant frequency. And Fig. 13 shows the load current for the simulated four values of the air gap. It shows how current will decrease through the power transfer coil and load. These values are obtained by simulating the circuit of Fig. 4 for given self-inductance and mutual inductance.

The load power for the 150 mm air gap is 3.74 kW. And other respective values are shown in Table 3 for different air gap between transmitter coil and receiver coil. Therefore, the EV with 6.1 kW power may take 1 hour and 39 minutes to fully charge its battery from 0 state for a 150mm air gap if it is fully aligned to its transmitting pad. Fig. 14 shows the efficiency is much higher for 150mm and abruptly decreasing with the increase of air gap between the coils.

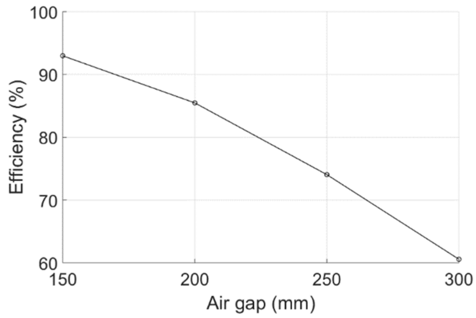


**FIGURE 14.** Decreasing efficiency with the increase in air gap.

**TABLE 3.** Calculated value of load power with the change of air gap.

| Air Gap (mm) | Load Power (kW) |
|---|---|
| 150 | 3.740 |
| 200 | 1.564 |
| 250 | 0.745 |
| 300 | 0.370 |

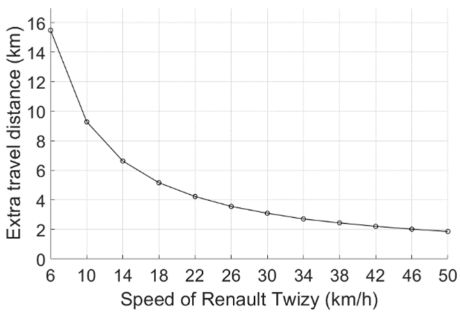


**FIGURE 15.** Extra travel distance gain concerning speed for 150 mm air gap between the coils.

By putting the obtained value from Equation (18) into equation (17) we can calculate the power transfer to the receiving end while the EV is moving in the track with no y-axis displacement and 150 mm air gap.

From this above result, it is showed how power decreases with the variation in the air gap and horizontal displacement. Fig. 15 shows how far it can travel from this extra power consumed by the battery through the receiver for the 150 mm air gap of Renault Twizy EV to the transmitter coil placed in the charging lane. It is natural that for the same air gap and no displacement in the y-axis the consumed power depends on the speed of the EV.

## V. CONCLUSION

Research on WPT is getting popular these years. This work compares the most famous WPT technologies and develops an effective one known RIPT. The RIPT method is used for resonating the transmitter coil frequency and receiver coil frequency. It shows how air gap and misalignment affect the WPT while the EV is driven in the charging lane. Firstly, WPT is simulated in the Ansoft Maxwell 3D simulation software to see the reduction in mutual inductance for air gap and horizontal displacement between the coils in x-axis and y-axis. Then verify the output data using mathematical equations. Equations for self-inductance, mutual inductance, coupling coefficient, voltage, and current are discussed here. The calculation for load power and efficiency for the 150mm air gap is shown. From the load power, the time for the full charge of the battery of an EV can be easily determined. Hence, a model is established to see the power transfer for different speeds and finally how far the EV can go with this consumed power. But, how efficiently the receiver pad can catch the power from the transmitter pad is also depends on the speed of the EV. Shielding materials like ferrite planner and aluminum plates can be used to transfer more power to the receiving end. This work helps to understand the wireless charging of EVs in the track for high resonant frequency in the means of RIPT and can be extended for future work in this field.

The main purpose of this work is to show the calculation of wireless power transfer of an EV while it is in motion based on vertical and horizontal misalignment. Misalignment of coils are also designed and simulated for getting a clear and broad knowledge about dynamic WPT.

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