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Design and Estimation Point Transfer for Dynamic Wireless Power Transfer Disc Coil for Electric Vehicle

***Abstract**. One effort research topic in the electric vehicle is wireless power transfer (WPT). The advantage of using WPT is allowing the electric vehicle to charge while running (dynamic wireless power transfer). This is because, the transfer power method not involve a plug-in process. Therefore, in this research, an estimation of the number of transfers point from electric vehicles will be made to find the required electrical energy transfer for electric vehicles. In addition, the estimation is calculated in one hour based on the classification of the light and heavy electric vehicle power based on SAE J2954 standard. In this research, the disc coil is developed for transmitter and receiver, then it followed by creating a couple magnetic based on series-series topology method. The resonance frequency in this study is set to be constant at 100 kHz. Meanwhile, a constant gap between the transmitter and receiver is set to be 9 cm. To illustrate the dynamic movement of vehicle, e velocity and the distance of the electric vehicle are also set to be constant at 3.6 km/hour and 0.3 m. As a result, in the heavy electric vehicle, 22 kW and 200 kW to generate an electric vehicle in one hour are required 4,552,440 and 41,386,517 transfer points respectively. For the light electric vehicle with the size 3.7 kW, 7.7 kW and 11.1 kW need 765,600 1,593,333 and 2,296,667 transfer points respectively.*

***Streszczenie.** Jednym z tematów badawczych w pojeździe elektrycznym jest bezprzewodowy transfer energii (WPT). Zaletą korzystania z WPT jest możliwość ładowania pojazdu elektrycznego podczas jazdy (dynamiczny bezprzewodowy transfer mocy). Dzieje się tak dlatego, że metoda zasilania transferowego nie obejmuje procesu podłączania. Dlatego też w niniejszych badaniach dokonane zostanie oszacowanie liczby punktów przesiadkowych z pojazdów elektrycznych w celu znalezienia wymaganego przesyłu energii elektrycznej dla pojazdów elektrycznych. Ponadto oszacowanie jest obliczane w ciągu jednej godziny na podstawie klasyfikacji mocy lekkich i ciężkich pojazdów elektrycznych w oparciu o normę SAE J2954. W badaniach tych opracowano cewkę dyskową dla nadajnika i odbiornika, a następnie utworzono parę magnetyczną w oparciu o metodę topologii szereg-szereg. Częstotliwość rezonansowa w tym badaniu jest ustawiona na stałą wartość 100 kHz. Tymczasem stała odległość między nadajnikiem a odbiornikiem ma wynosić 9 cm. Aby zilustrować dynamiczny ruch pojazdu, prędkość e i odległość pojazdu elektrycznego są również ustawione na stałe i wynoszą 3,6 km/h i 0,3 m. W rezultacie w ciężkim pojeździe elektrycznym do wytworzenia pojazdu elektrycznego w ciągu godziny potrzeba odpowiednio 4 552 440 i 41 386 517 punktów przesiadkowych o mocy 22 kW i 200 kW. Dla lekkiego pojazdu elektrycznego o mocy 3,7 kW, 7,7 kW i 11,1 kW potrzeba odpowiednio 765 600, 1 593 333 i 2 296 667 punktów przesiadkowych. (**projekt punktowej estymacji dynamicznego bezprzewodowego przesyłu mocy w oparciu o normę SAE J2954 zasilania pojazdu elektrycznego lekkiego i ciężkiego**).*

Keywords: Dynamic WPT; Disc Coil; Estimation Point Transfer; SAE J2954 standard
Słowa kluczowe: Dynamiczny WPT; cewka dyskowa; Transfer Punktu Oszacowania; Norma SAE J2954

Introduction

There are numerous researches on the development of electric vehicles. Majority research topics regarding to the electric vehicles is in the charging section. The electric vehicle charging strategy developed in the current era is a wireless system. This strategic system has advantages which allows the electric vehicles to charge while moving in the highway. In other word, this system is running without any plug-in [1-2]. In the research [3], describes the charging electric vehicles process with a source that is passed on to electric vehicles wirelessly vehicle to vehicle (V2V). This implementation is motivated by the limited charge area for electric vehicles. However, this kind of electric charging takes a long time because the electric power in the first vehicle will be channeled back to the second vehicle. A possible up-to-date solution is to charge electric vehicles while running wirelessly [4-5].

In the research in ref. [6] discusses the effect of coil shape on wireless power transfer. This research compares 3 shapes of coil geometry. The coils are helix coil, planar spiral coil, and square helix coil. The wireless transfer performance of each of these coil geometries are 84.65%, 78.67%, and 82.99% respectively. Moreover, in the [7] research explains about Wireless power transfer design uses a coil with a planar spiral geometric shape. In this study, it is called as a disc coil because it is like a disc. The wireless power transfer performance in this study reached from 80% to 97.42%.

In term of the topology of magnetic resonant coupling circuit, the series-series topology is suitable for implementing in the wireless power transfer (WPT) for electric vehicles. While The implementation of series-series resonance of the transmitter and receiver is very easy and can provide a constant current, the use of series-series resonance topology in transmitter and receiver can transfer a large currents and even large power. In addition, the reflected of impedance has only a resistive part, and it will not have any reactance impact on the transmitter circuit [8-9]. Based on their power, electric vehicles can be classified into 2 types, namely heavy electric vehicles and light electric vehicles. According to SAE J2954, heavy electric vehicles require an electrical power of 22 kW to 200 kW. Light vehicles require electrical power of 3.7 kW, 7.7 kW, 11.1 kW, 22 kW [10].

Based on the research exposure, this research proposes a wireless power transfer design with a coil disc shape. The resonance used is a series resonance at the transmitter and receiver. The power generated by electric vehicles by driving will be analyzed and calculated. The results of the analysis and calculations are used to determine the total point transfer points that can be applied to highways with regular straight motion.

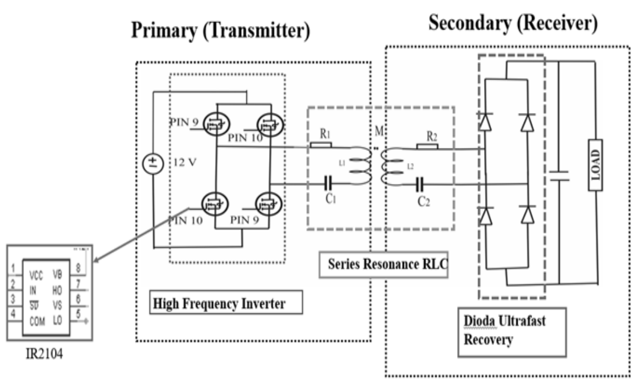


Fig. 1 Topology Series-series resonance

Material and Method

1. Series-Series Resonance Topology

Series-series resonance topology is a topology composed of resistive, inductive, and capacitive components connected in series. Series-series topology means that the transmitter and receiver parts are arranged in series. The resistive component of the WPT topology series is the internal resistive which is inside the coil.

The use of a series-series resonance topology for electric vehicles has several advantages. Although the installation is easy, it has a large currents and power. In addition, the reflected impedance only has in a resistive part and will not have any reactance impact on the transmitter circuit [9-13]. Figure 1 is a topological depiction of the WPT series resonance used in this model. The transmitter section consists of a source connected to transmitter coil resistance (R1), transmitter coil inductance (L1), and transmitter capacitance (C1) connected in series. The receiver section is also composed of receiver resistance (R2), receiver coil inductance (L2), reactance, and receiver capacitance (C2) connected to the load.

2. Disc Coil for Transmitter and Receiver

In this research disc coil for transmitter and receiver are identic, both in the size or even in the shape as seen in the Figure 2. The transfer quality of the WPT is influenced by the geometry factor. These geometric factors include coil shape, the number of turns, the distance between the coils, and the radius of coil [13-15]. While The disc coil is very suitable to be planted on the ground of highway and the bottom of vehicle, it has a high transfer efficiency, and it does not require extra space in the depth of road for their installing [6-7]. When a coil is wound in the form of a flat spiral or an inverted cone, the value of its inductance can be obtained by using the Archimedes spiral equation as follows [16]:

(1) $$L(\mu H) = \frac{A^2N^2}{8A+11Wd}$$

(2) $$A = \frac{Di+(Wd)}{2}$$

(3) $$Wd = (W+S)\times N$$

(4) $$(D_O) = Di + (2 \times N \times (W+S))$$

The variable L is the inductance of the coil in H. Variable A is the inner cross-section (inch). The number of turns of the coil is N. Di and Do are the inside and outside diameters (inch). The distance between the windings is S. The variables W, Wd are the wire width and the overall coil width in (inch).

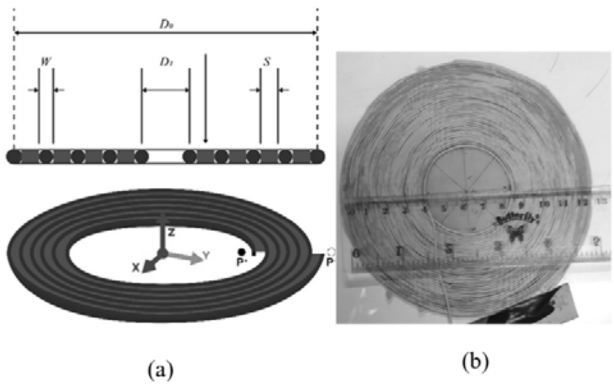


Fig. 2 Disc coil, (a). parameters, (b). prototype

The geometry factor greatly affects the quality of wireless power transfer [13-15]. One of the geometric factors is the shape of the coil. In this research, a disc coil will be used for transmitter and receiver of coil coupling.

The required frequency used in this study is 100 kHz or the second period. The maximum voltage (ε) and maximum current passing through coil are 60 V and 5 A. Then, required inductance value is as follows.

$\varepsilon = 60t$ V then, $\varepsilon = -L_1\frac{dI}{dt}$,

I =5t A, with frequency switching (fs) is 100kHz.

Then, $t = \frac{1}{100kHZ}$, $t = 10^{-5}$ s.

$L = \frac{60t}{d(5t)/dt} = 12t, = 12\times10^{-5} = 120$ µH

Therefore, the inductor required for the transmitter and receiver coil is selected as 120 µH. The next step is to design the disc coil. The disc coil that will be used is planned to use an inner diameter (Di) of 4.5 cm in mm which is 45 mm, a coil diameter (W) of 0.2 mm, and the distance between windings (s) is 0. All known variables will be calculated by the equation (1-4) as follows.

(Do) = Di + $(2 \times N \times (Wd+S))$
= 45 + $(2 \times 37 \times (0.2+0))$ = 59.8 mm

Wire length = $\pi \times N \times \left(\frac{Do+Dt}{2}\right)$ = 3.14 × 37× 52.4
= 6087.832 = 6.09 m

$(Wd) = \left(\frac{W}{25.4} + \frac{S}{25.4}\right) \times N = \left(\frac{0.2}{25.4} + 0\right) \times 37 = 0.29$ mm

$(A) \quad = \frac{\frac{Dt}{25.4}+W}{2} = \frac{\frac{Dt}{25.4}+0.29}{2} = 1.03$ mm

$L \quad = \frac{A^2N^2}{8A+11Wd} = \frac{1.03^2 37^2}{8(1.03)+11(0.29)} = \frac{1452.3721}{11.43} = 127.06$ µH

Based on disk coil design calculations, 37 turns are required to obtain 120 µH. The length of the coil required for 120 µH based on calculations, is 6.09 m. This coil will be arranged in series with the coupling capacitor. Figure 2 (b) depict the prototype of disc coil used in this research. The value of the transmitter and receiver coils is the same as 120 µH with no core material.

3. Coupling Capacitor and Ultrafast Diode

The coupling Capacitor is an important component in the magnetic resonance coupling method. Capacitors play an important role in making magnetic resonance to create a larger magnetic field [9,17]. It is known that the required inductance is 120 H. The frequency switching (f_s) used is 100 kHz and L = 120 µH. Therefore, the capacitor requirement can be calculated based on angular frequency (ω) as follows.

(5)

$$\omega = \frac{1}{\sqrt{LC}}$$

$$f_s = \frac{1}{2\pi\sqrt{LC}},$$

$$C = \frac{1}{4\pi^2 L f^2} = \frac{1}{10^{10}.3{,}14^2.4.10^{-6}.120} = 2.1\ .10^{-8}\ F = 21\ nF$$

Regarding to making resonance, 21 nF capacitor is required. However, available size in the commercial market is only 22 nF. Both of transmitter and receiver have the same value of capacitor, then it is connected with inductor in series-series topology circuit resonance. While the WPT system use a high frequency for switching, it needs ultrafast recovery diode, and this diode would convert a high frequency AC to DC wave, leading to changing a DC storage such as battery and supercapacitor.

Associated with designing of ultrafast diode rectifier, the thing that must be considered is the recovery time. According to the 100 kHz frequency, the period of this frequency can be calculated by one divided 100 kHz, then the result is 10^{-5} second. Based on the datasheet of diode, the MUR1560 is appropriate diode since it is capable to convert in DC wave that has a high performance due to very fast until at 60 ns time recovery. The maximum current in this diode is 15 A, and the maximum voltage is 600 V [17]. All components used in the study is shown in Table 1. Meanwhile, experimental setup can be seen in Figure 3.

Table 1. The component which require in WPT

Component	Value
L_1	119.05 μH
L_2	122.08 μH
C_1	22nF
C_2	22nF
R_1	0.73 Ohm
R_2	1.015 Ohm
C (internal coil 1)	20.48 nF
C (internal coil 2)	20.39 nF
f (resonance)	100 kHz
Diode	Mur1560
Battery Voltage	12.50 volt

4. Estimation of Power Transfer on Dynamic WPT Disc Coil

The estimation point transfer is used to calculate and estimate the number of points transfer for finding the electrical power needs of moving electric vehicles until fully charged. This estimated transfer point is based on SAE J2954 where electric vehicles are classified as light vehicles and heavy vehicles. The electric power requirements of light vehicles are 3.7 kW, 7.7 kW, 11.1 kW, and 22 kW. The need for heavy vehicles is from 22 kW to 200 kW [10].

Electric vehicle is tested with a constant in speed and the electric power gain is divided into 3 areas that shows in figure 3 and 4. The first area is the arrival area where this area can still transfer electric power even though it is not in proper electric charging center, and it is expressed as variable Pa. The second area is the area where electric vehicles stay away from the central point of electric charging that can still transfer electric power which is expressed in the variable Pb. The third area is the central area. The central area is the area that produces the maximum power, and it is expressed by the variable Pc. The total power transferred (Pt) wirelessly to a moving electric vehicle can be expressed in equation (6).

$$Pt = Pa + Pb + Pc \quad (6)$$

$$E = T \times \left(\sum Pa + \sum Pb + Pc\right) \quad (7)$$

The total energy transferred (E) wirelessly to a moving electric vehicle can be expressed in equation (12). The variable T is the time for electric vehicles to pass through the points Pa, Pb, and Pc with total testing the test track is 30 cm. Here, the central point is 15 cm or 0.15 m.

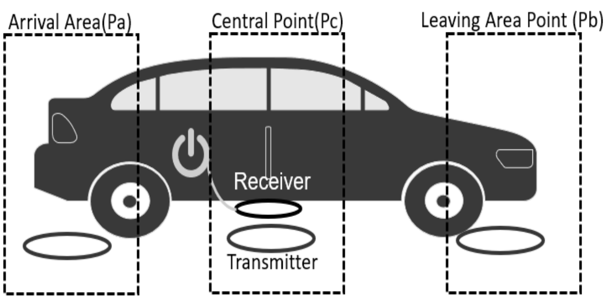


Figure 3. Classification transfer point

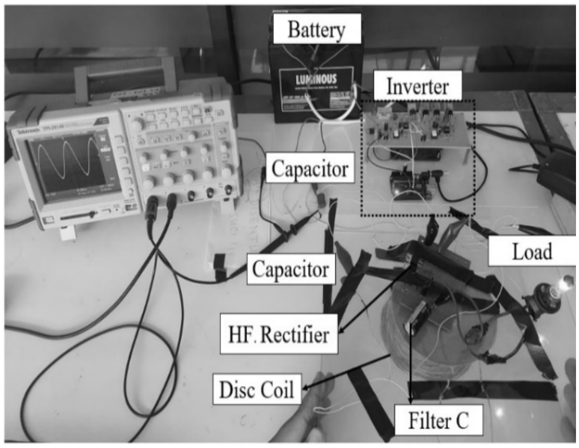


Fig. 4. Experimental test of disc coil WPT

Result and Analysis

The dynamic wireless power transfer disc coil test is carried out by simulating the movement of an electric vehicle as it passes through the transfer point. At the point of arrival (Pa) data will be collected on electrical power in this area. Electrical power data retrieval is also carried out at the point away from the transfer point (Pb) and at the central point (Pc). The height of the WPT was kept at 9 cm and tested with a constant speed.

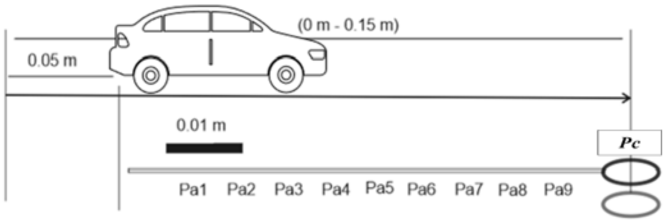


Figure. 5. The movement of electric vehicles at the arrival point (Pa) towards the central point (Pc)

1. Arrival Point (Pa)

The arrival area is the area where the electric vehicle has received an electromagnetic field before reaching the central point. This result can cause the electric vehicles starting to get electric power before they are at a central point precisely. The movement of electric vehicles from the arrival point (Pa) to the central point (Pc) can be illustrated in Figure 5. When the electric vehicle is in the first 0.05 m, the electric vehicle has not received an electromagnetic field so at that point the electric power has not been transferred. After entering the 0.06 m point towards the central point, the electric power begins to be transferred. When the vehicle closer to the central point, the electrical power transferred will be greater. The power gain rate reveals in the line graph in figure 6.

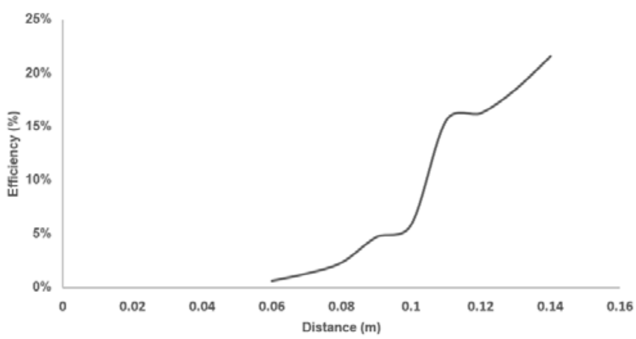


Figure. 6 Electric vehicle power received at the arrival point (Pa) to the central point (Pc)

The line graph illustrates the number of increasing the receiving power from starting point to central point. It can be seen that the graph witnessed a significant increase trend throughout distance from 0 to 0.15 m. this is because, the electric vehicle drives toward the central point (Pc.) that has highest power. it starts at 0.16 W with efficiency 1%, then it experience a significant rise at 5.6 W and 22% efficiency in 0.14 m distance. The detail data of power gain can be listed in Table 2 which has correlation in figure 6.

Table 2. The acquisition of electric vehicle power as long as in the arrival point

Distance (m)	Voltage (V)	Current (A)	Power (W)	Efficiency (%)
0.06	0.08	0.3	0.16	1%
0.07	0.168	0.5	0.336	1%
0.08	0.3	0.85	0.6	2%
0.09	0.61	1.17	1.22	5%
0.1	0.76	1.24	1.52	6%
0.11	2.02	1.8	4.04	16%
0.12	2.11	2.22	4.22	16%
0.13	2.4	2.07	4.8	19%
0.14	2.8	2	5.6	22%

2. Leaving Point (*Pb*)

Leaving area is the area where the electric vehicle still gets the electromagnetic field after left the central point. This is causing the electric vehicle still get electric power even though it is not at a central point. The movement of electric vehicles in the central point area (*Pb*) can be illustrated in the Figure 7. Electric vehicle can accept a power before through the point 11.

When the electric vehicle is running before 0.26 point, the proccess charging still be done, as this area has an electromagnetic field. While by the time the electric vehicle has entered in 0.26 m point and above, it does not produce any electrical power at all, and this incident indicate that an increasing of the distance which pass by the electric vehicle from central point, leading to the generating power to be smaller. The trend of power gain of leaving point (Pb) is showed in figure 8.

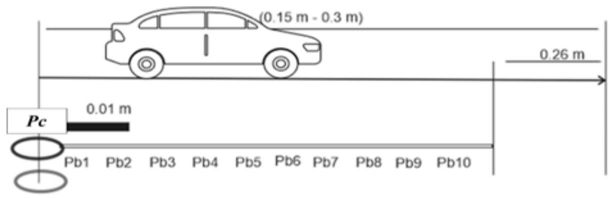
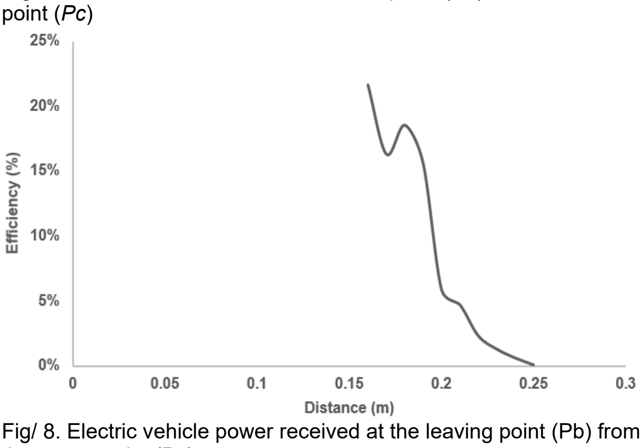


Fıg 7. Electric vehicle moves at the far point (*Pb*) from the centre point (*Pc*)



Fig/ 8. Electric vehicle power received at the leaving point (Pb) from the center point (Pc)

The drop inclination of electric power in the leaving area is explained in the line graph figure 8. The dropping trend is caused by the electric vehicle moving from central point (0.15 m) to the leaving point (0.25 m). It begins at 5.6 W, and follows by efficiency in 22%. In addition, it make up a dramatic decline at 0.16 W with 1% efficiency. The complete acquisition of electrical power points in the leaving area can be illustrated in Table 3.

Table 3. The Acquisition of Electric Power throughout in the Leaving Point

Distance (m)	Voltage (V)	Current (A)	Power (W)	Efficiency (%)
0.16	2.8	2	5.6	22%
0.17	2.11	2.22	4.22	16%
0.18	2.4	2.07	4.8	19%
0.19	2.02	1.8	4.04	16%
0.2	0.76	1.24	1.52	6%
0.21	0.61	1.17	1.22	5%
0.22	0.3	0.85	0.6	2%
0.23	0.168	0.5	0.336	1%
0.24	0.08	0.3	0.16	1%
0.25	0.011	0.04	0.022	0%

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3. Estimation Transfer Point of Dynamic WPT Disc Coil

The estimation of the transfer point is done by testing at the way where it is passed by electric vehicle at every point that the electric vehicle use. The power of the electric vehicle from the point of arrival (Pa) is obtained by adding points from Pa1 to Pa9 with a shift of 0.01 m. The total power generated from the point (Pa) is 22,496. The power of the electric vehicle at the point away from (Pb) is obtained by adding points Pb1 to Pb10 which produces 22,518 W of electricity.

When an electric vehicle passes through a central point (Pc), it produces 12,97590 W of electrical power. So that during the trip, it produces a total electric power of 57.9899 W. Moreover, the resulting energy equation is expressed as 57.9899T. The number of energy being transferred to electric vehicles with changes of speed can be seen in Table 4. The distance between electric vehicles is fixed at 0.3 m. Velocity is made in constant increments from 1 to 10 m/s. Despite of the speed of electric vehicle experienced an increase trend, the less electric energy is obtained. Hence, the velocity of electric vehicle is inversely proportional with the receving electric energy of vehicle that illustrates in figure 9.

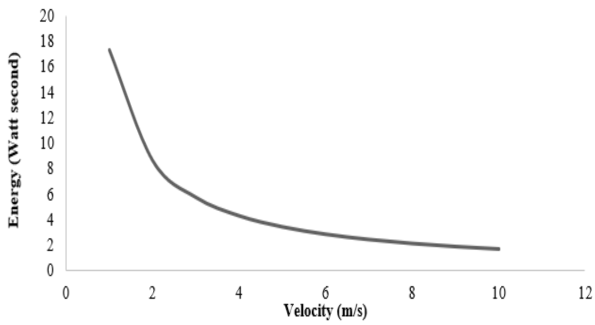

Fig. 9 The Comparison of speed with energy produced

The energy equation as previously discussed is used to see the effect of velocity on the energy transferred. In Table 5, by using the energy equation, the number of electrical energy transfer points (NT) which use to fulfill the electric vehicle in an hour can be known. It can be seen that the variable (E) is the energy requirement of an electric vehicle to drive the engine in an hour. The time required to search the needs of actual energy from electric vehicles is expressed as (T).

Table 4. The Result of The Energy Which is Produced by Dynamic WPT Coil Disc with Velocity Change

Distance (m)	Velocity (m/s)	Time (s)	Energy (W.s)
0.16	2.8	2	5.6
0.17	2.11	2.22	4.22
0.18	2.4	2.07	4.8
0.19	2.02	1.8	4.04
0.2	0.76	1.24	1.52
0.21	0.61	1.17	1.22
0.22	0.3	0.85	0.6
0.23	0.168	0.5	0.336
0.24	0.08	0.3	0.16
0.25	0.011	0.04	0.022

In addition, the total time (T) can be determined by using the energy equation 57.9899T which is equated with energy demand. Therefore, the (T) would be obtained with divided between the energy demand and 57.9899. Ultimately, after knowing the full time, the distance (S) that must be traveled by the electric vehicle can be found in order to cover the required electrical energy which is solved by multiplying the speed (V).

Table 5. The number of point transfer (NT) based on calculation

(*E*) (kWh)	*T* (Hour)	*S* (Km)	(*NT*)	V km/h)
3.7	63.8	229.68	765,600	3.6
7.7	132.78	478	1,593,333	
11.1	191.41	689	2,296,667	
22	379.37	1,365.73	4,552,440	
200	3,448.876	12,415.95	41,386,517	

In this case is kept in 3.6 km/hour by the full time (T). In this study one transfer point is 0.3 m or 0.0003 km. The number of transfer points can be found by dividing between the total distance passed by electric vehicle to fulfill energy for activating electric vehicle in an hour, and the distance of 1 transfer point.

Overall, regarding to the heavy vehicle in 22 kW, or even 200 kW, to drive an electric vehicle in an hour, needs at around 4,552,440 and 41,386,517 the number of transfer points respectively.

On the other hand, in terms of the light vehicles at 3.7 kW, 7.7 kW and 11.1 kW to activate the machine of electric vehicle in an hour, should create 765,600 (NT), 1,593,333 (NT) and 2,296.667 (NT) respectively.

Conclusions

The use of WPT disc coil is beneficial because it allows electric vehicles to charge while moving. Based on the analysis, it can be seen that electric vehicles can receive electric power before reaching the transfer point properly and after leaving the transfer point. When the electric vehicle is approaching the transfer point, the electric power generated is greater and decreases whenever it moves away from the transfer point. In addition, the faster electric vehicle is moving, the less electrical energy received. Based on the estimation test of the number of transfer points, electric power according to SAE J2954 with the capacity are 3.7 kW, 7.7 kW and 11.1 to drive in one hour it takes 765,600 points of transfer point (NT), 1,593,333 points and 2,296.667 points. According to SAE J2954, a heavy vehicle with an electrical power requirement of 22 kW, 200 kW to drive an electric vehicle in one hour requires a transfer point (NT) of 4,552,440 points and 41,386,517 points.

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