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A Study on Transmission Coil Parameters of Wireless Power Transfer for Electric Vehicles

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Abstract: Electric vehicles (EVs) are becoming more popular as people become more concerned about global issues, such as fossil fuel depletion and global warming, which cause severe climate change. Wired charging infrastructure is inefficient because it requires the construction of one charging station for each electric vehicle. As a result, wireless power transfer via magnetic coupling, which is small, compact, and may be placed underground, is a promising technology for the future of charging electric vehicles. One of the disadvantages of wireless power transfer is that efficiency drops rapidly as air gaps grow larger, and it is particularly sensitive to other electrical characteristics such receiver unit capacitance. The purpose of this paper is to investigate the coil parameter, more specifically the outer diameter of wireless power transfer coil effects on the wireless power transfer efficiency at various air gaps and receiver capacitance values for EV applications. The simulations show that a larger outer diameter coil has a better power transfer efficiency at larger air gaps and a more stable range.

Keywords: Wireless power transfer, Electric vehicles, Air gap, Coil.

1 Introduction

Electric vehicles (EVs) have been becoming increasingly popular as the future mode of transportation since they are considerably more ecologically friendly than internal combustion engine vehicles. In addition, they do not require the use of gasoline to function, thereby reducing the release of greenhouse gases, such as carbon dioxide, into the environment, and help to mitigate global warming and climate change [1, 2]. However, there are several challenges that an EV faces that may limit its full potential.

The long charging duration of the vehicle is one of the main challenges as it is significantly longer as compared to the conventional refueling of internal combustion engine vehicle [3]. When EVs were first introduced, the wired charging technology took upwards of eight hours to complete the charging the battery to full capacity using DC Charging Level 1 [4]. In recent years, there have

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been some developments in the area of wired charging where an EV can be charged to almost full capacity within 30 minutes. Nevertheless, the duration is still not short enough to compete with the average refueling time of five minutes [4].

On the other hand, wired charging is not the only way to charge up an EV. There is another technology known as wireless power transfer where the load is not required to be connected to source through wires, rather the power is transferred and stored in battery through magnetic coupling [7]. Magnetic coupling occurs when a transmitting coil has alternating current flowing through and generates a magnetic field which induces a current flow in the receiving coil which flows towards the load [8, 9].

Wireless power transfer has certain advantages as compared to wired charging. In particular, wired charging needs long charging cables and consumers are prone to electrocution due to high power and voltages required to charge an EV [4, 6]. Aside from that, a specialized charging station for each EV must be installed above ground, which takes up a lot of space. A wireless charging pad, on the other hand, does not require much space to be constructed. In particular, it can be built underground beneath the vehicle, making charging incredibly convenient for consumers because the EV only needs to be parked above the transmitting pad. In addition, it may be considerably more durable than a dedicated charging station because it is totally enclosed, protecting it from the ever-changing environment [4, 5]. However, there are several limitations to wireless power transfer technology for EVs, such as the low efficiency at greater air gaps due to misalignments [10, 11]. Another challenge faced by wireless power transfer is the interoperability issues for different electric vehicles with different electrical parameters, such as capacitance and ground clearance issues [12]. Lastly, a wireless power transfer system capacity is greatly associated with size of transmitting and receiving pads. A larger pad increases the mass that an electric vehicle needs to carry [13].

The remaining part of this paper is organized as follows. In Section 2, the methodology including discussion of coil parameters and implementation of ferrite and aluminum plates are presented. Simulation results using ANSYS Maxwell 3D and ANSYS Simplorer and analysis are discussed in Section 3. The findings of this paper will be concluded in Section 4 along with some possible future works that can be carried out.

2 Methodology

2.1 Coil Parameters

There are certain aspects to consider before deciding on the size of the wireless power transfer coil, more specifically the outer diameter. The average ground clearance for majority of vehicles ranges from 100 mm to 200 mm [14].

Since the upper limit air gap required to transfer power wirelessly is 200 mm, the coil outer diameter should ideally be twice of this upper limit in order to establish a properly coupled pair of transmitter and receiver coil and improve the wireless power transfer efficiency.

The right side of Fig. 1 depicts a pair of loosely coupled coils, as the outer diameter of the coil relative to the air gap is nearly one to one. On the left side in Fig.1, a pair of tightly coupled coils with a one to three ratio of outer diameter to air gap is depicted. Note that the higher the ratio of outer diameter relative to air gap, the greater the coupling power between a pair of coils. From the SAE J2954 standard [15, 16], the established coil dimension is around 330 mm to 360 mm [17] which is less than twice of the upper limit of air gap. The outer diameter of the coil can be increased, and the limit will be discussed subsequently.

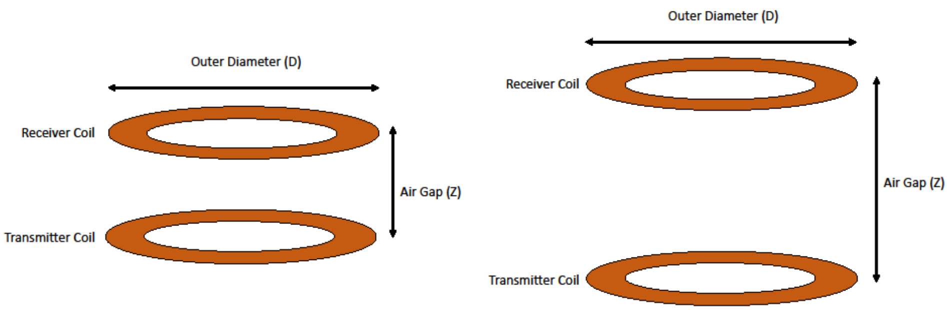

Fig. 1 – *Tightly coupled and loosely coupled coils.*

It is noted that the average width of a car is between 1700 mm and 1900 mm. The diagram of a car visualization is shown in Fig. 2. We assume that the width of a car is 1700 mm, and the width of the tires is 200 mm each. The true width of a car can then be calculated as shown:

$$\text{TrueWidth} = 1700\,\text{mm} - 2(200\,\text{mm}) = 1300\ \text{mm}\,.$$

Since the available space between the car tires is 1300 mm, it is probable to have a coil outer diameter limit of up to 1000 mm. However, there are some concerns over the effect of magnetic flux leakage into the surroundings that may put human in danger [18, 19]. To be on the safe side, this study will investigate the outer diameter of coil only up to 400 mm. At this length, the coils are coupled tightly as the ratio of outer diameter of coil to upper limit air gap of 200 mm is 2. The coupling coefficient will be improved for larger air gap of 200 mm with higher coupling power. Furthermore, in the case of a misalignment, the stability of power transfer efficiency will be superior to that of a coil with a lower outer diameter since a 5 mm misalignment will be substantially smaller to a coil with 400 mm outer diameter as opposed to 330 mm outer diameter.

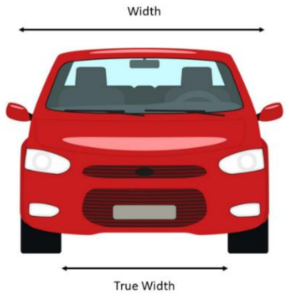

Fig. 2 – *Car visualization.*

In [20], it is shown that the number of turns of a coil providing optimized efficiency is between 10 and 20. In this paper, the number of turns of the coil is set as 15 as any above that would not increase the efficiency significantly. As the standard diameter of the coil is between 4 mm and 6 mm, in this paper, the wire diameter is set to be 4 mm. One last parameter is the spacing between each turn of the coil. It has been shown that the smaller the spacing between each turn of coil, the greater the mutual inductance, which is important to establish better coupling coefficient [20]. Hence, a spacing of 1 mm will be used in this paper.

The following presents the calculation of the coil parameters. The self-inductance of a coil can be calculated by [21]

$$L = \frac{r^2 N^2}{8r + 11w}, \tag{1}$$

where L is the self-inductance of the coil, N is the number of turns, r is the radius and w is the width. The coil radius can be calculated by

$$r = \frac{\frac{D_i}{25.4} + w}{2}, \tag{2}$$

where D_i is the inner diameter of coil. In (2), w is given by

$$w = \left(\frac{d}{25.4} + \frac{s}{25.4}\right)N, \tag{3}$$

where d is the wire diameter and s is the spacing between each turn.

In this paper, there are three coil outer diameter sizes that will be used and compared against each other, i.e., 250 mm – Coil 1, 330 mm – Coil 2, and 400 mm – Coil 3. The parameter settings of the three scenarios studied in this paper are summarized in **Table 1**.

Table 1
Parameters for Scenario 1, 2 *and* 3.

Parameters of Coil	Coil 1	Coil 2	Coil 3
Inner Diameter [mm]	100	180	250
Outer Diameter [mm]	250	330	400
Wire Diameter [mm]	4	4	4
Number of turns	15	15	15
Spacing [mm]	1	1	1
Self-Inductance [μH]	44.47	78.05	110.08

2.2 Ferrite plates

Ferrite plates have high magnetic permeability which helps to provide a lower reluctance path where the magnetic field generated in primary coil can travel to secondary coil to induce current more effectively. The ferrite plates are placed underneath the coil so that it will increase the strength of magnetic field at secondary coil, improving the coupling coefficient between the coils [22]. In [23], two different types of ferrite plate arrangement are studied where the ferrite plates are arranged in parallel and perpendicular to the circumference of the coil. The best arrangement is ferrite plates that are arranged perpendicular to the circumference of the coil which is shown in Fig. 3.

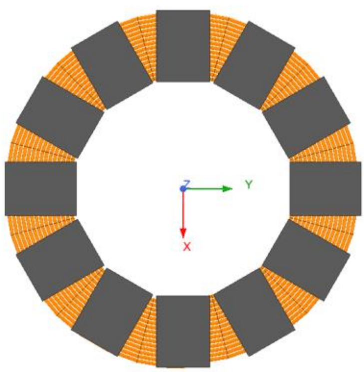

Fig. 3 – *Ferrite plates ideal arrangement.*

In addition, the higher the number of ferrite plates, the better the coupling coefficient [22]. Furthermore, coupling coefficient shows how strong the coupling power between transmitter and receiver coil. It ranges from 0 to 1, where 0 means zero mutual inductance and 1 means the best mutual inductance between coils.

2.3 Aluminum shielding

For wireless power transfer system, it is required to function with a set of resonant frequencies, usually in the range of kHz to MHz. At this frequency range, the magnetic flux leakage occurs. An aluminum shield is commonly implemented to help reduce this magnetic flux leakage by acting as an inductor to reduce the flux leakage [24].

3 Results and Discussion

ANSYS Electronics Desktop was used to run simulations for wireless power transfer efficiency results. The mutual inductance and coupling coefficient obtained in ANSYS Maxwell 3D are tabulated below in **Tables 2**, **3**, **4** and **5**.

Table 2
Simulation results for 250 mm *coil size.*

Air Gap [mm]	Mutual Inductance [µH]	Coupling Coefficient	Self-Inductance [µH]
100	6.411	0.152	41.77
150	2.881	0.069	41.77
200	1.349	0.032	41.77
250	0.627	0.015	41.77

Table 3
Simulation results for 330 mm *coil size.*

Air Gap [mm]	Mutual Inductance [µH]	Coupling Coefficient	Self-Inductance [µH]
100	17.390	0.232	74.55
150	9.572	0.128	74.55
200	5.457	0.073	74.55
250	3.133	0.042	74.55

Table 4
Simulation results for 400 mm *coil size.*

Air Gap [mm]	Mutual Inductance [µH]	Coupling Coefficient	Self-Inductance [µH]
100	28.430	0.273	104.02
150	16.686	0.161	104.02
200	10.004	0.097	104.01
250	5.959	0.058	104.01

Table 5
Simulation results for 400 mm *coil size with aluminum and ferrites.*

Air Gap [mm]	Mutual Inductance [μH]	Coupling Coefficient	Self-Inductance [μH]
100	51.188	0.321	159.15
150	28.965	0.184	156.78
200	17.126	0.110	156.22
250	10.284	0.066	155.91

From **Tables 2**, **3** and **4**, it can be seen that as the outer diameter of the coil increases from 250 mm to 400 mm, the mutual inductance and coupling coefficient increases. This shows that greater size of coil has a better coupling power as compared to smaller coil size. From **Table 5**, when the aluminum shield and ferrite plates are implemented, the mutual inductance and coupling coefficient improved which shows better coupling power. These data are then used to simulate the power transfer efficiencies using ANSYS Simplorer software.

3.1 Scenario 1

The power transfer efficiency plots for coil with outer diameter of 250 mm with resonant frequency of 85 kHz, at air gaps of 150 mm and 200 mm are shown below in Figs. 4 and 5, respectively. The plots in red, green, blue, orange, and turquoise show the power transfer efficiencies for receiver capacitance set at 10 nF, 15 nF, 20 nF, 25 nF and 30 nF, respectively.

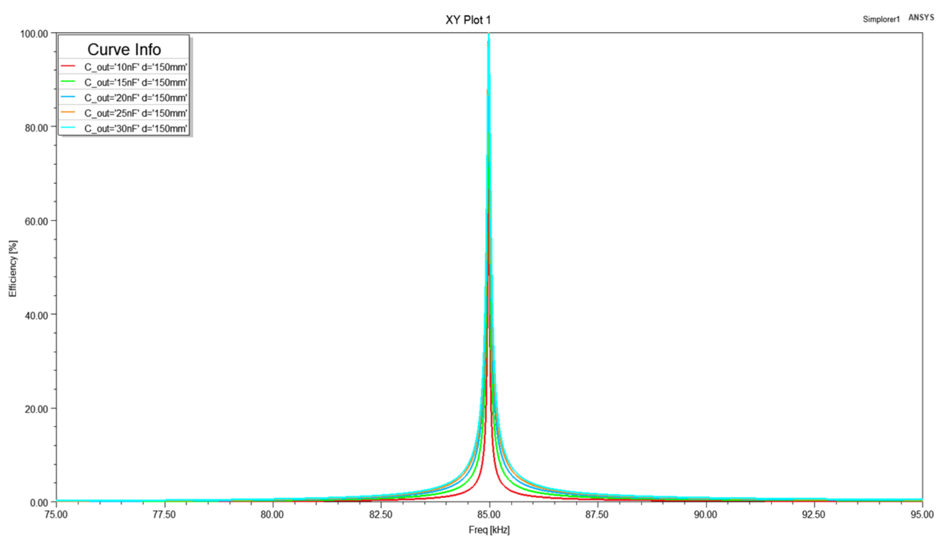

Fig. 4 – *Efficiency against frequency for* 250 mm *coil size at* 150 mm *air gap.*

From the Figs. 4 and 5, it can be seen that the plots of the power transfer efficiency for 250 mm outer diameter coil with different receiver unit capacitance is very slim. This means that the power transfer efficiency is not particularly steady; any slight change in electrical parameters causes the power transfer efficiency to decline dramatically at 150 mm and 200 mm air gaps.

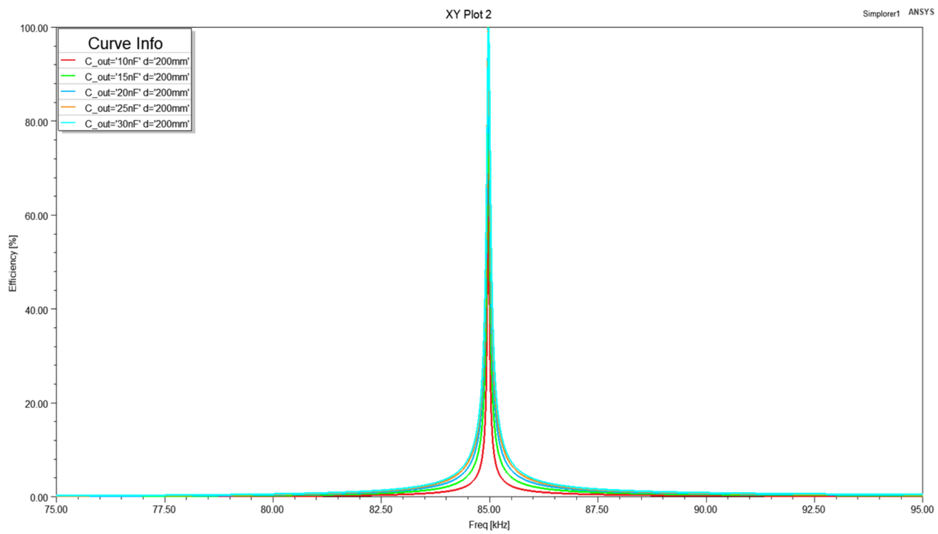

Fig. 5 – *Efficiency against frequency for* 250 mm *coil size at* 200 mm *air gap.*

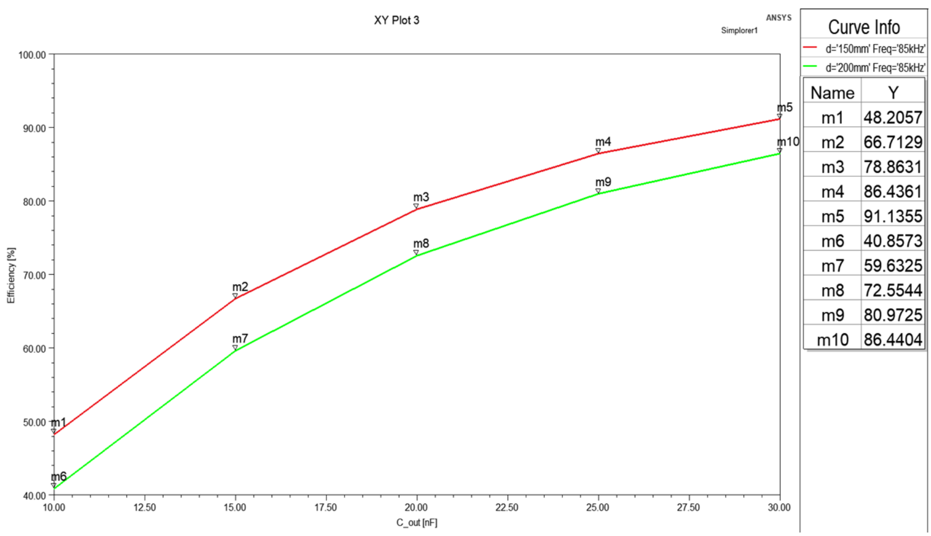

Fig. 6 – *Efficiency for* 250 mm *coil size with different receiver capacitance values at* 150 mm *and* 200 mm *air gap.*

The summary of power transfer efficiency plots for coil with outer diameter of 250 mm with different receiver unit capacitance values at 85 kHz are shown in Fig. 6. It can be seen that as receiver unit capacitance value decreases from 30 nF to 10 nF at 150 mm and 200 mm air gap, the power transfer efficiency drops from 86.44% to 40.86%.

3.2 Scenario 2

The power transfer efficiency plots for coil with outer diameter of 330 mm with resonant frequency of 85 kHz, at air gaps of 150 mm and 200 mm are shown below in Figs. 7 and 8, respectively.

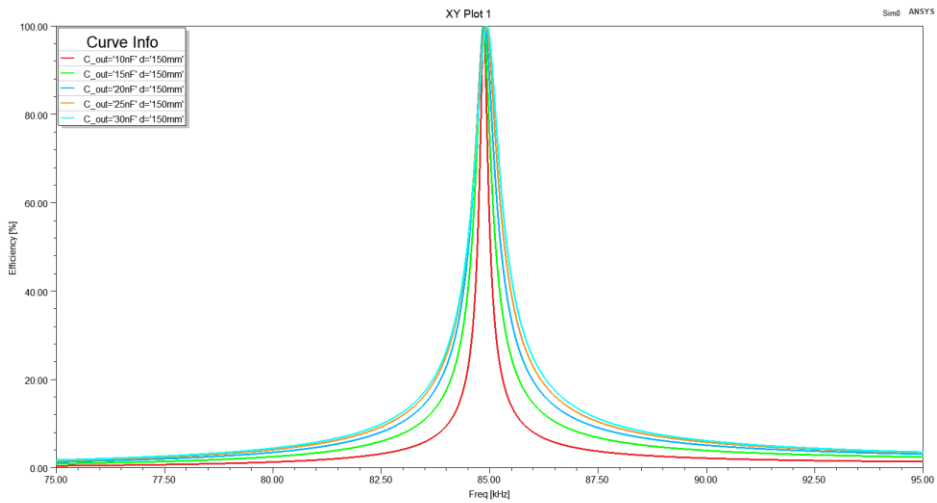

Fig. 7 – *Efficiency against frequency for* 330 mm *coil size at* 150 mm *air gap.*

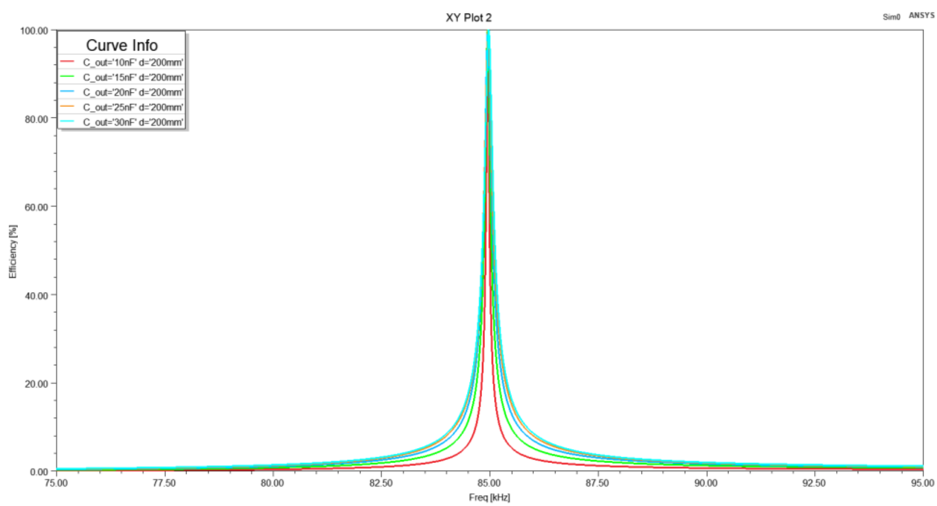

Fig. 8 – *Efficiency against frequency for* 330 mm *coil size at* 200 mm *air gap.*

The plot of power transfer efficiency for 330 mm outer diameter coil with different receiver unit capacitance values are shown to be acceptable but still quite slim for air gaps of 150 mm and 200 mm. This means that the power transfer efficiency is better.

The summary of power transfer efficiency plots for coil with outer diameter of 330 mm with different receiver unit capacitance values at 85 kHz are shown in Fig. 9. It can be seen that as receiver unit capacitance value decreases from 30 nF to 10 nF at 150 mm air gap, the power transfer efficiency drops from 97.35% to 55.42%. This is acceptable but far from ideal. Furthermore, at 200 mm air gap, the power transfer efficiency ranges from 50.54% to 95.67%.

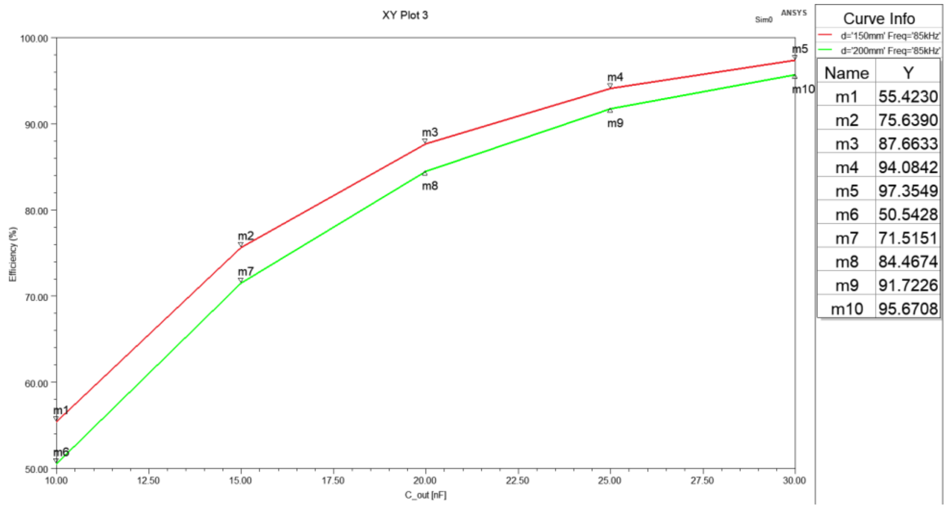

Fig. 9 – *Efficiency for* 330 mm *coil size with different receiver capacitance values at* 150 mm *and* 200 mm *air gap.*

3.3 Scenario 3

The power transfer efficiency plots for coil with outer diameter of 400 mm with resonant frequency of 85 kHz, at air gaps of 150 mm and 200 mm are shown in Figs. 10 and 11, respectively. The plot of power transfer efficiency for 400 mm outer diameter coil with different receiver unit capacitance values are shown to be much wider at air gaps of 150 mm and 200 mm. This means that the power transfer efficiency is more stable than with coil diameters of 250 mm and 330 mm.

The summary of power transfer efficiency plots for coil with outer diameter size of 400 mm with different receiver unit capacitance at 85 kHz are shown in Fig. 12. It is shown that as receiver unit capacitance value decreases from 30 nF to 10 nF at 150 mm air gap, the power transfer efficiency drops from 99.81% to 61.14%, which is still acceptable. At 200 mm air gap, the power transfer efficiency is slightly better (63.42% to 99.93%). This is because with 200 mm outer diameter, the magnetic field is denser at the edge so that it produces slightly better power transfer efficiency as compared to the one with 150 mm air gap.

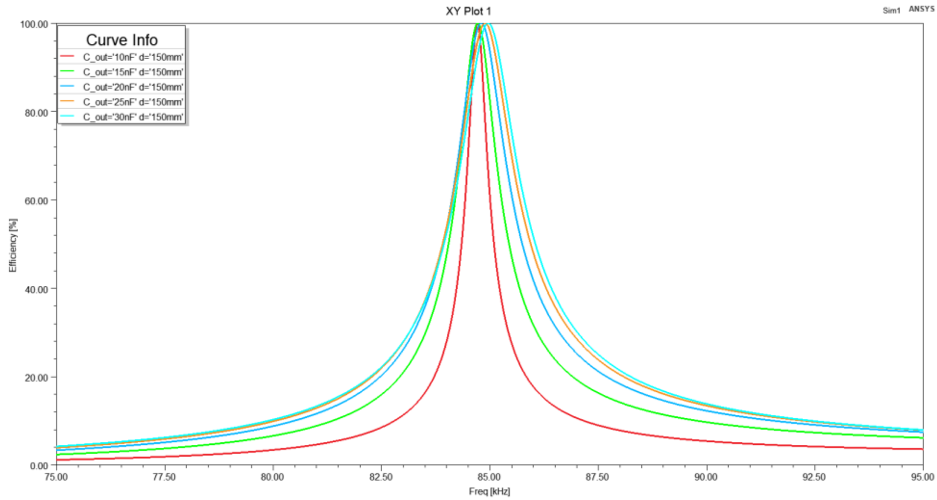

Fig. 10 – *Efficiency against frequency for* 400 mm *coil size at* 150 mm *air gap.*

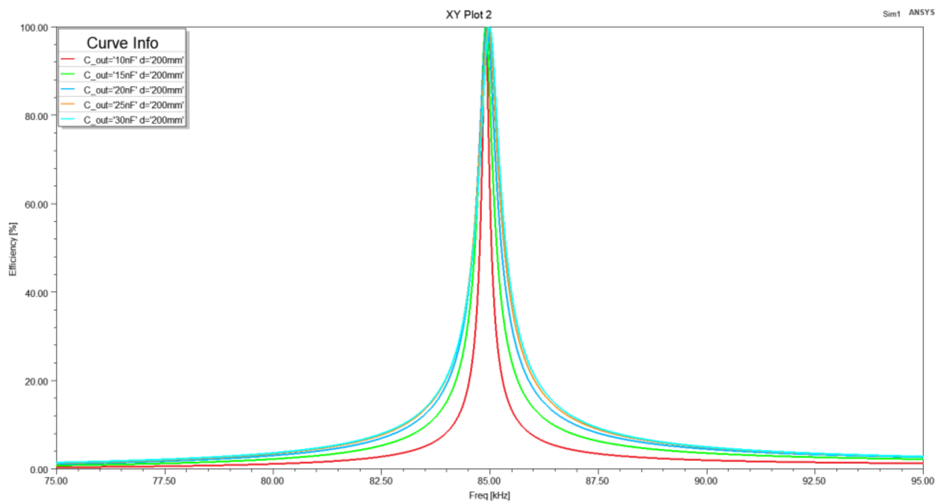

Fig. 11 – *Efficiency against frequency for* 400 mm *coil size at* 200 mm *air gap.*

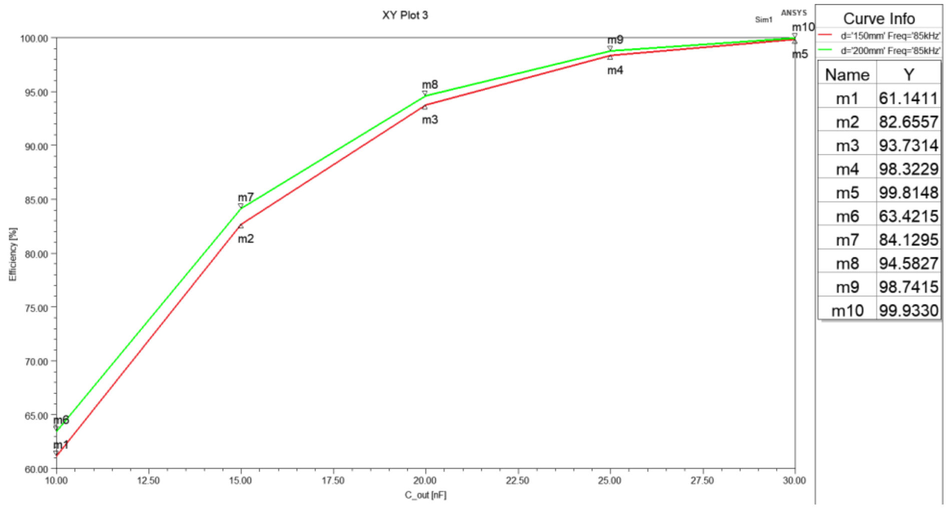

Fig. 12 – *Efficiency for* 400 mm *coil size with different receiver capacitance at* 150 mm *and* 200 mm *air gap.*

3.4 Scenario 3 with aluminum and ferrites results

The power transfer efficiency plots for coil with outer diameter of 400 mm implemented with ferrite cores and aluminum shielding with resonant frequency of 85 kHz, at air gaps of 150 mm and 200 mm are shown in Figs. 13 and 14, respectively.

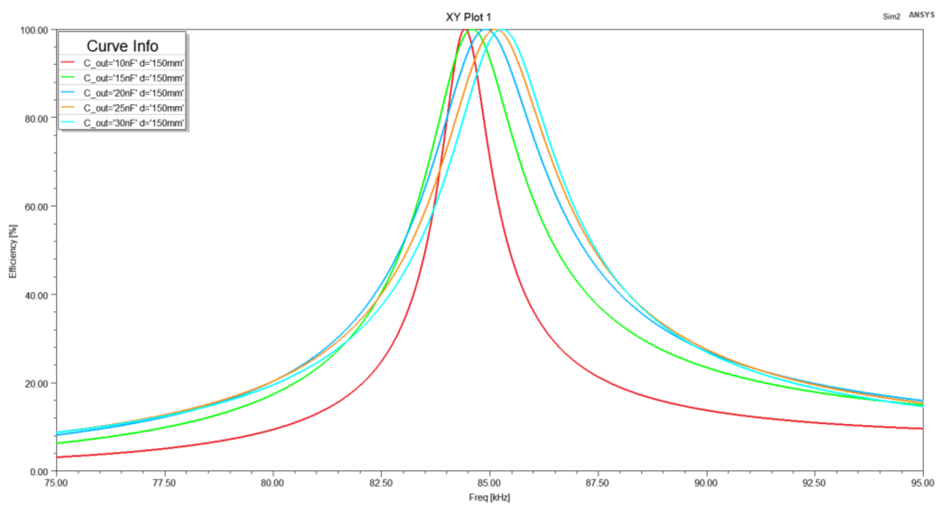

Fig. 13 – *Efficiency against frequency for* 400 mm *coil size with aluminum and ferrite at* 150 mm *air gap.*

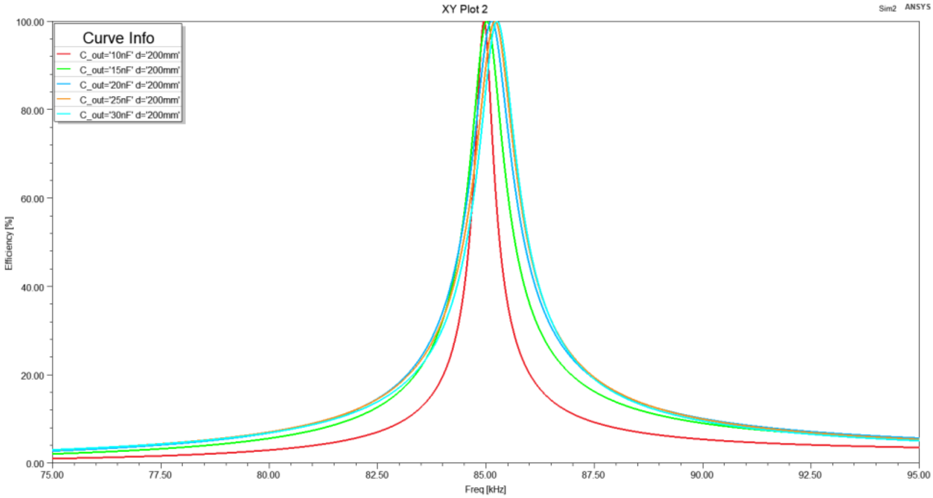

Fig. 14 – *Efficiency against frequency for* 400 mm *coil size with aluminum and ferrite at* 200 mm *air gap.*

The power transfer efficiency for 400 mm outer diameter coil with aluminum shielding and ferrite plates at different receiver unit capacitance are shown to be very wide. This means that the power transfer efficiency has a very stable range for air gaps of 150 mm and 200 mm.

The summary of power transfer efficiency plots for coil with outer diameter of 250 mm with different receiver unit capacitance at 85 kHz are depicted in Fig. 15.

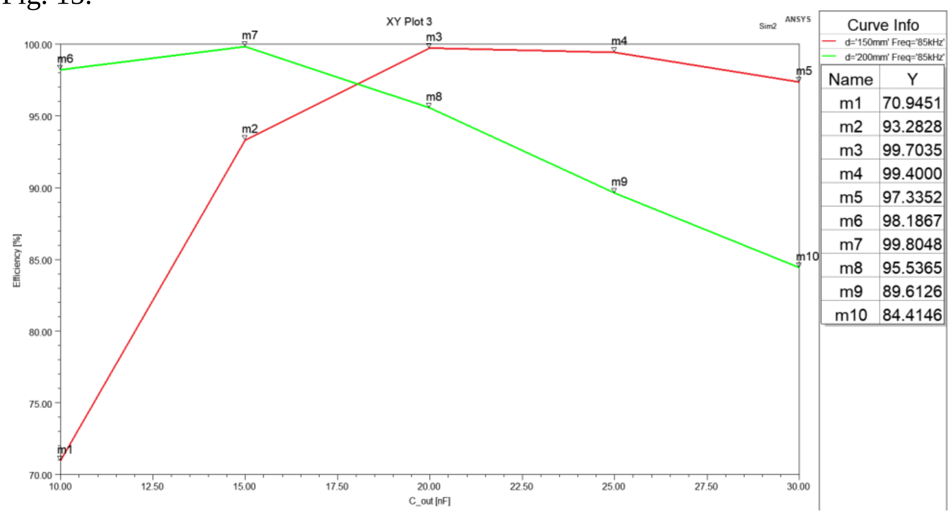

Fig. 15 – *Efficiency for* 400 mm *coil size with aluminum and ferrites for different receiver capacitance at* 150 mm *and* 200 mm *air gap.*

It is shown that as receiver unit capacitance value ranges from 10 nF to 30 nF at 150 mm air gap, the power transfer efficiency stays within the range of 70.95% and 99.70%, which is a very stable range. At 200 mm air gap, the power transfer efficiency is shown to be even more stable and promising where the range is from 84.41% to 99.80%.

3.5 Discussion

From Figs. 4, 7, and 10, it can be seen that as the outer diameter of the coil increases, the power transfer efficiency plot at 150 mm widens. This means that the power transfer efficiency is more stable given that the varying factors. When there is a change in parameters such as resonant frequency and different receiver unit capacitance values, the efficiency drops more gradually in Fig. 8 rather a sharp drop as shown in Fig. 4. Even at 200 mm air gap, the power transfer efficiency plot becomes wider as the coil outer diameter increases.

Table 6
Power transfer efficiency with 150 mm *air gap.*

Receiver Capacitance [nF]	Efficiency (%)			
	Coil 1	Coil 2	Coil 3	Coil 3 with ferrite and aluminum
10	48.21	55.42	61.14	70.95
15	66.71	75.64	82.66	93.28
20	78.86	87.66	93.73	99.70
25	86.44	94.08	98.32	99.40
30	91.14	97.37	99.81	97.34

Table 7
Power transfer efficiency with 200 mm *air gap.*

Receiver Capacitance [nF]	Efficiency (%)			
	Coil 1	Coil 2	Coil 3	Coil 3 with ferrite and aluminum
10	40.86	50.54	63.42	98.19
15	59.63	71.52	84.12	99.80
20	72.55	84.47	94.58	95.54
25	80.97	91.72	98.74	89.61
30	86.44	95.67	99.93	84.41

From **Table 6**, it can be seen that the coil with outer diameter size of 400 mm performs the best when the receiver capacitance is varied from 10 nF to 30 nF at 150 mm air gap. The efficiency ranged from 61.14% to 99.81% and 70.95% to 99.70% without and with ferrite and aluminum shielding, respectively.

From **Table 7**, at 200 mm air gap, the 400 mm coil efficiency is also proved to be better when the receiver capacitance is varied from 10 nF to 30 nF. The efficiency ranges from 63.42% to 99.93% and 84.41% to 99.80% without and with ferrite and aluminum shielding, respectively.

4 Conclusion and Future Work

The purpose of this paper is to present the simulation results for studying the effects of coil parameters in a wireless power transfer. A coil with greater outer diameter, such as 400 mm, is able to perform better than the one with smaller outer diameter at different air gaps and different receiver unit capacitance. The simulation results have shown that the coil with outer diameter of 400 mm is able to perform better at air gaps of 150 mm and 200 mm as compared to the one with 250 mm and 330 mm coils. Furthermore, the 400 mm coil has been proven to have better power transfer efficiency when the receiver unit capacitance value varies from 10 nF to 30 nF. This would prove to be useful in the real world for EV wireless charging application because the EVs from different car companies may have receiver coils with different capacitance values and air gaps. The transmitter coil would have a fixed capacitance value. This would help to improve the interoperability of wireless charging for different electric vehicles by maintaining stable efficiency with different parameters. In conclusion, a coil with a larger outer diameter performs better with an air gap of 150 mm to 200 mm and a higher receiver unit capacitance value.

There are some future works that could be done to further verify the feasibility of this 400 mm coil size. One of which is to carry out an experimental setup for this 400 mm coil as compared to smaller coil sizes and verify the real-world applications. Besides, the coil parameters and electrical parameters of 400 mm coil could be tuned and optimized. Lastly, the most important future work would be to measure the actual magnetic flux leakage of the 400 mm coil and determine whether it is safe for human to be in close proximity and study the limit of the coil size to be under the standard if magnetic flux leakage level.

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