Improvement of power transfer efficiency of hexagonal coil arrays in misalignment conditions

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ABSTRACT

Wireless charging by transferring energy between two objects using electromagnetic fields commonly called Wireless power transfer is an alternative technology that is physically installed in an electric vehicle (EV) to charge. Parking alignment is a very important factor in driver behavior that affects power transfer efficiency (PTE). The proposed hexagonal coil array design in this experiment is to optimize PTE and receiver coil size. The experimental results show that PTE in the tangential boundary plane Misalignment increases by 5-10% when compared to coil array circles and increases by 82% when compared to single coil circles.

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1. INTRODUCTION

Wireless power transfer (WPT) technology is a promising approach of transferring energy from source to load without physical connection. This technology has been used for a variety of applications including biomedical implants, mining applications, underwater power supplies and electric vehicles with advantages among others not affected by ice, water or other chemicals [1], [2].

Nowadays the demand for high power applications is in an uptrend. Converters on both sides the primary and secondary essentially must be capable of handling the required power level [3]. However, the power capacity of traditional WPT systems was limited by the constraints of semiconductor devices [4]. Additionally, single transmitters and single magnetic couple-based receivers produced low reliability of WPT systems [5] due to only one energy transmission path [6], and may not meet the requirements for high-power applications such as public transport systems that require power to hundreds of KVA or more (up to MW scale) [7], [8]. WPT system applications required high transmission efficiency being despite in large lateral misalignment [9]. One of WPT application systems is the electric vehicle (EV) charging system [10]. WPT for EV applications is divided into: WPT static and dynamic charging [11]. For static scenarios, EV can be charged in a modified car park or garage [12], [8]. In dynamic WPT systems, EV are continuously filled in specific charging lines using railway grid [13], [1]. Battery size may be smaller and reduce capacity by up to 20% and shorter charging times [14].

Parking behaviour shows that only 5% of parked vehicles in alignment tolerance for WPT charging can reach 80% of PTE level. Perfect alignment achieves 95% of peak efficiency, but peak efficiency will decrease less than 50% in 15-20 cm misalignment [4]. The WPT technology challenging when efficiency [15], sharply drop down to zero if the distance between transmitter and receiver kept away [16], [5]. That's why many researches in recent years have focused on methods of improving the power transfer efficiency in the EV wireless charging system. The design and location of the coil structure may also affect PTE [17] in EV wireless charging [18], [3].

The misalignment between the transmitter and receiver coils causing the weak coupling thereby reducing efficiency. The existing WPT technology is highly sensitive to the angular and lateral coil misalignment [17]. Recent research with 7 array circle coil design for the transmitter and circle coil receiver can reduce load on EV without reducing the efficiency [2] shown in Figure 1. Misalignment in tangential boundary area causes a drop in efficiency [19]-[20]. The main issue in transfer efficiency due to misalignment and uncoupling between resonance primary coils/transmitter (Tx) with and secondary coil/receiver (Rx) [21]. In circular Coil Array, the efficiency level will decrease significantly in the tangential boundary area with 7 circular coil arrays, the efficiency drop is close to 0% [17] with the misalignment position on the central boundary and the tangential boundary is shown in Figure 2. This is become the basis for researchers to conduct studies on the design of other coil shapes in an array, in order to maintain the efficiency level of the tangential boundary. The proposed coil design is a hexagonal coil array.

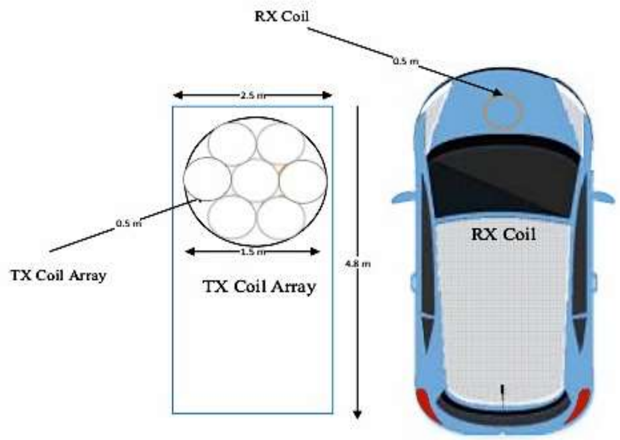


Figure 1. Seven array circle coil design for the transmitter and circle coil receiver

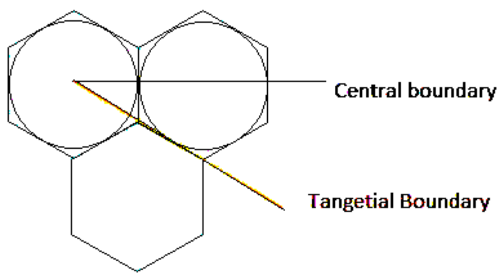


Figure 2. Central Boundary and tangential boundary

This study aims to analyze the energy efficiency when using hexagonal coil arrays in a larger misalignment position both in the central boundary especially in the tangential boundary [20]. With this proposed coil design make the size of the Rx coil smaller and if it’s applied on the EV will reduce the weight of the vehicle itself [1], [21]. Next sections of the paper are as follows. Section 2 shows the design of WPT system and data retrieval method based on misalignment central boundary and tangential boundary. Section 3 contains the experiment result and analyzes and conclusion given in Section 4.

2. RESEARCH METHOD
2.1. Inductive power transfer
IPT is based on several inductor whose magnetic flux exchanges with each other, where the trasmitter (Tx) coil by the number of turns N1 is driven by a voltage source (or current) and receiver (Rx) coil with the number of turns N_2 connected to the load. The mutual inductance between two circular loops separated by distance d with coil turns n1,n2, radius coil r1, r2, as shown in Figure 3, can be calculated using the Neumann equation [22] :

$$M = \frac{\mu \pi n_1 n_2^2 r_1^2 r_2^2}{\left[(r_1 + r_2)^2 + d^2 \right] \sqrt{(r_1 + r_2^2)^2 + d^2}} \quad (1)$$

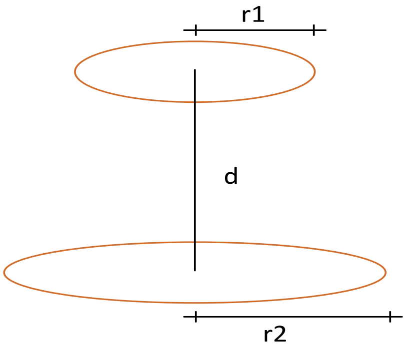


Figure 3. Two coil with distance d and radius r1 and r2 [23]

In the medium-distance IPT system power transfer efficiency hence required a high frequency. But when using high frequency, the impedance becomes more inductive [24], causing the power factor (PF) to be smaller. Additional capacitive are required which will cause the impedance to be purely resistive [12]. The addition of capacitors in the circuit causes the coils to resonate at the same frequency in two systems so that the power transfer becomes efficient [13]. Resonance is the tendency of systems (usually linear systems) to oscillate with greater amplitude at some frequencies than others. This is known as the resonant frequency of the system [11]. The quality factor (Q-factor) indicates the stored energy of the oscillator is relatively to the energy loss rate. In ideal series RLC circuit Q factor can be written as shown the following formula [14]:

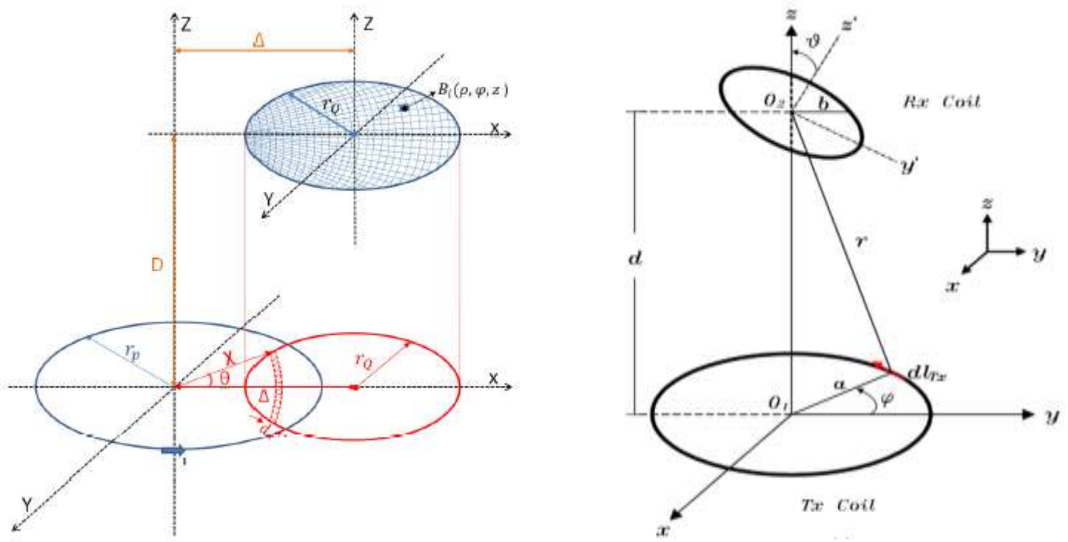
$$Q = \frac{1}{R\sqrt{\frac{L}{C}}} \quad (2)$$

efficiency of WPT system is given [15]:

$$\eta \max \approx \frac{(kQ)^2}{1 + \sqrt{\left(1 + (kQ)^2\right)}} \quad (3)$$

2.2. Alignment in WPT
Perfect alignment occurs when the transmitter coil and receiver coil are aligned at a distance d. The position of misalignment is an important factor that affects PTE as shown in Figure 4. Misalignment consists of two types:

a. Lateral misalignment: when a pair of transmitter coil and receiver coil in parallel position, the center has a horizontal distance Δ and vertical distance d as shown in Fig ure 4(a).
b. Angular misalignment: when the receiver coil Rx position is at an angle θ even though it is parallel to the transmitter coil Tx and aligned well as shown in Figure 4(b).



(a) Lateral (b) Angular

Figure 4. Misalignment [25]

2.3. System design

The design of the system consists of two parts: the transmitter circuit or the primary circuit consisting of a DC power supply unit, a 555 timer in a stable mode, a MOSFET, an LC primary resonance coil and a rectifier and a receiver circuit also called a secondary circuit which consists of secondary resonance coil, rectifier and load in the form [19]. The primary coil resonates at a frequency of about 22.2 kHz to transfer the induced voltage in the air [24]. When the secondary coil is placed close to the primary coil, due to an electric motion force inducing the secondary coil is then fed to the high frequency rectifier to repair the high frequency AC [26]. Then it was forwarded to the capacitor to filter the noise that occurs on the AC and obtained DC voltage of 12 V. System design can be seen in Figure 5.

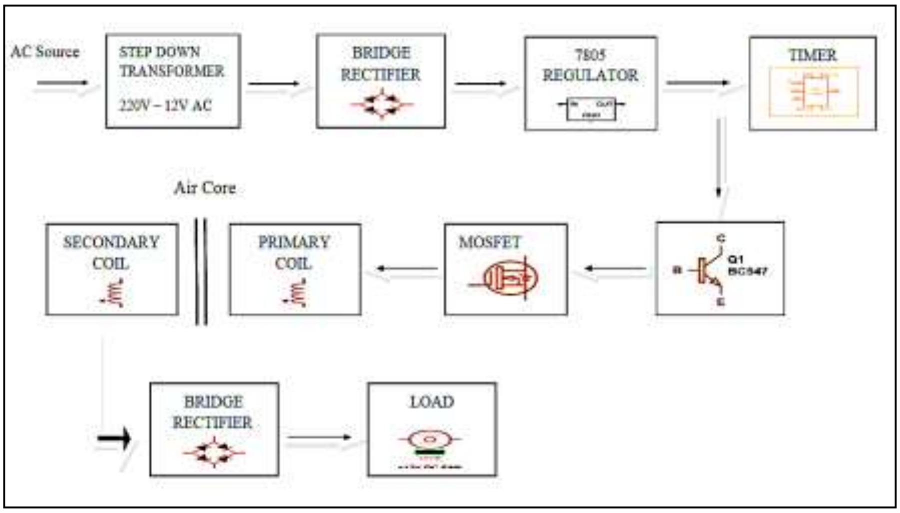


Figure 5. System design

2.4. Coil design

In order to solve the misalignment issue in tangential boundary [3] a new coil array is proposed in this experiment, which can achieve a higher PTE compared to the single coil benchmark and improve PTE in tangential boundary using 7 array circle coil [27]. Conducting this study in addition to the coil design proposed by the researcher [17], it first performs a reconstruction of the coil design [28] of the previous researcher on [8] as a benchmark for measuring and retrieving data [29]. This experiment use 3 coil designs:

a) Single-loop coils with diameter 15 cm in size as shown in Figure 6(a) for the primary and secondary coils respectively.
b) 7 Arrays Circle coils as reference coils [8] with a diameter of 5 cm as shown in Figure 6(b) as the primary coil and 1 circle coil with a diameter of 5 cm as a secondary coil.
c) Proposed coil 7 arrays hexagonal coil with 3 cm side size as primary coil as shown in Figure 6(c) and 1 hexagonal coil with 3 cm side size as secondary coil.

Single loop coil as a benchmark, which in general on EV uses one coil on the transmitter and one coil on the receiver.

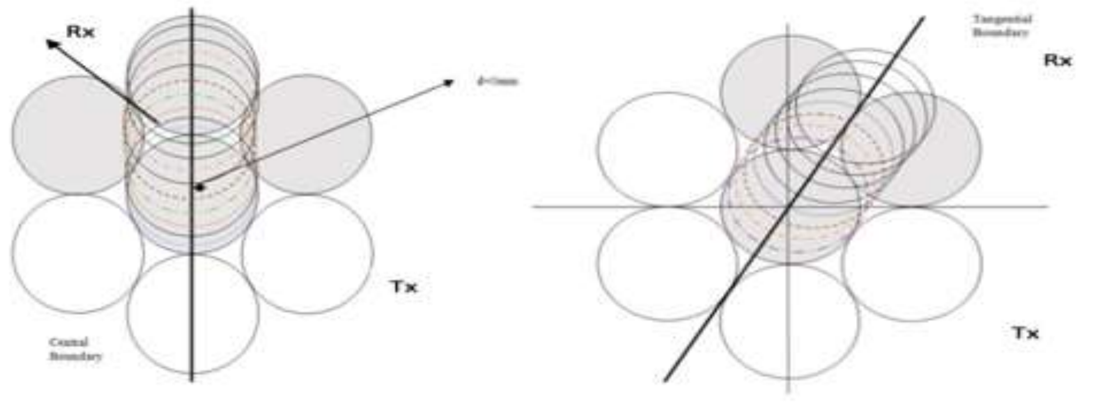
(a) Benchmark coil (b) 7 Array circle coil (c) 7 Array hexagonal coil

Figure 6. Coil design

2.5. Measurement method

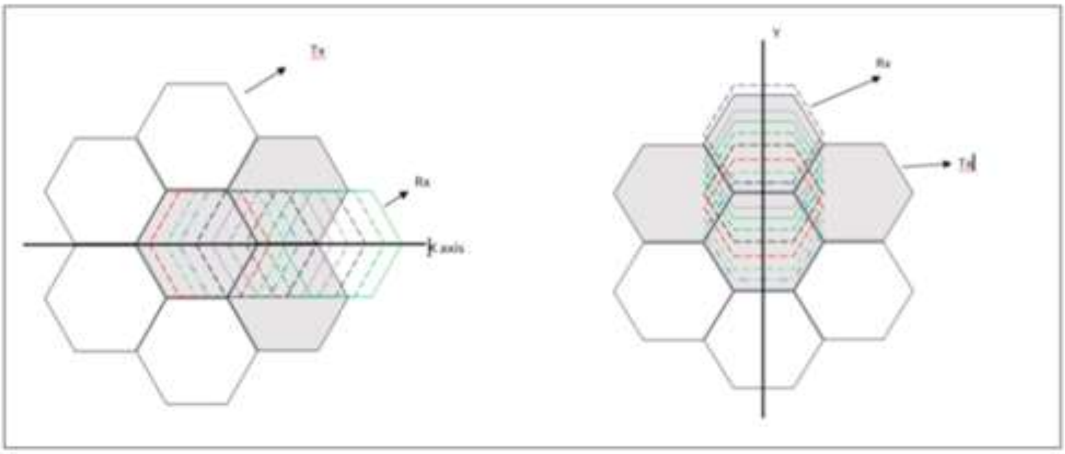
The system was tested by measure using some tool and its function. Reactance, capacitor and resistor was measured using an LCR meter. Voltage and current using multi meter [30]-[31]. The resonant frequency was measured using the oscilloscope. Table 1 gives the summary of dimensions and parameter for each experiment. In this works, Using our system design We measure the PTE of benchmark coil in X/Y axis [29]. Then, reconstruction of the experiment using coil design with 7 array circle coils and the measurements performed on the central boundary and tangential boundary positions [13] as shown in Figure 7. The measured parameters include the voltage and current on the side of the primary coil as well as the secondary coil side.

Figure 8 shows the measurement position of the secondary coil (Rx) to the primary coil (Tx) which is carried out at the center boundary and tangential limit for the arrangement of 7 hexagonal coils. Measurements are made between the primary coil which interacts directly with the secondary coil. It can be seen that the position of the tangential boundary is identical to the position of the center line of the X axis, so the measurement is carried out according to Figures 8(a) and 8(b). We assume all the misalignments that occur are lateral misalignments.

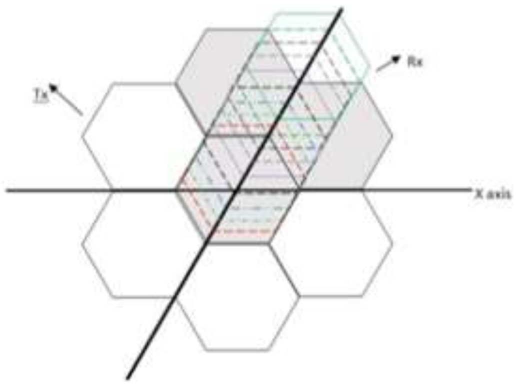


(a). Central Boundary (b). Tangensial Boundary

Figure 7. Measurement position in circle array 7 coils



(a). X axis (b). Y axis



(c). Tangensial Boundary

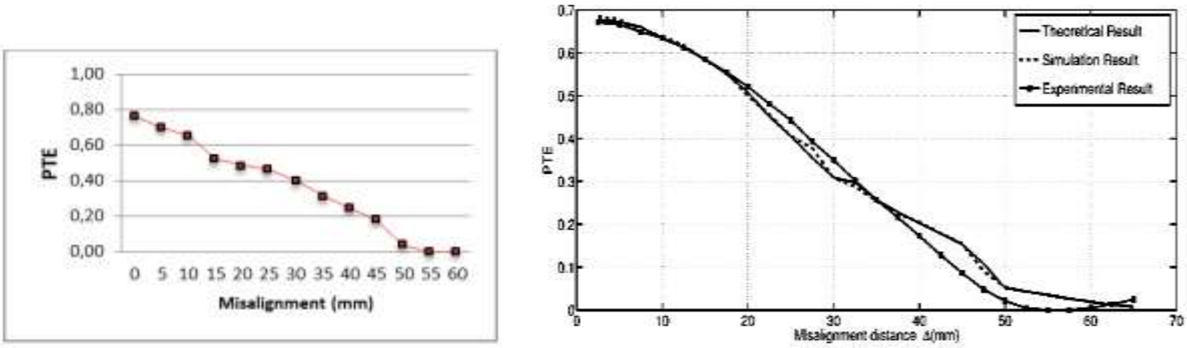
Figure 8. Measurement position in hexagonal array 7 coils

3. RESULTS AND DISCUSSION

Experiment refers to a reference model. An experimental reconstruction with parameters defined by the researcher where the reference results of the reconstructed model are shown in Figure 9(a) and we compare it to the reference coil in Figure 9(b). The efficiency drops by almost 50% when the angular misalignment is 2 cm and the efficiency is lost when the misalignment is more than 5 cm. We found that our experiments yielded almost similarities in trends.

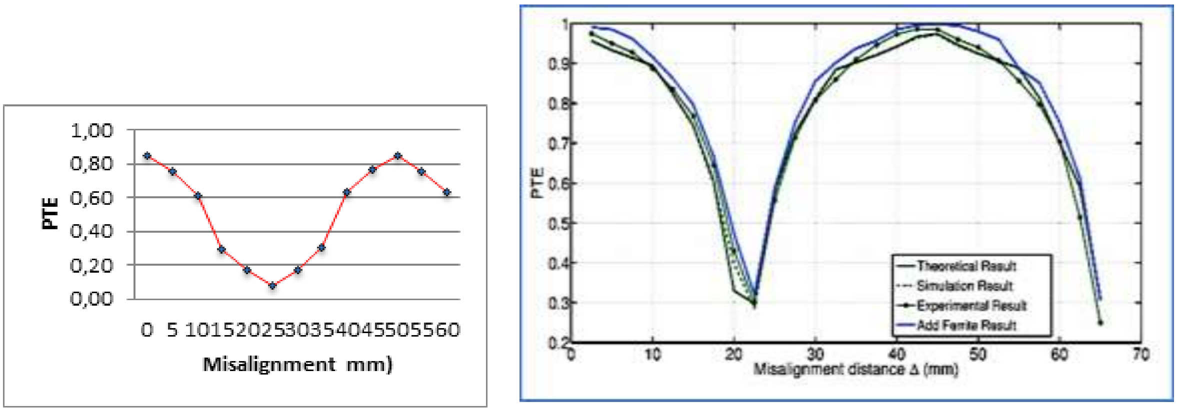
Experimental using 7 circle coil arrays, measurements were performed on the central boundary and tangential boundary positions with circle diameters of 5 cm. The result of measurement our 7 Array circles coils show in Figures 9 and 10 compare to measurement result by previous study, it has similarity in trend, both in central boundary and tangential boundary. In the reconstruction of the central boundary measurement, the results in Figure 11(a) show a sharp decrease in the misalignment position from 10 mm to 15 mm, where the lowest efficiency position occurs at 25 mm misalignment then rises to the alignment position closer to the closest circle. This happens because the mutual inductance depends on the distance of each coil as in (1).

In Tangential boundary reconstruction, the measurement results in Figure 11 show the same results until the misalignment position is 25 mm with the measurement center limit due to the same measurement position, but at the tangential boundary position there is an empty gap when the position is more than 25 mm and the efficiency decreases to 1%. then increased slightly to 10% when the misalignment position was 45 mm then decreased to 0%. The increase is experienced when the 35 mm position becomes 45 mm from the middle, because in this position there is an effect of mutual inductance by the arrangement of the secondary coil next to the primary coil.



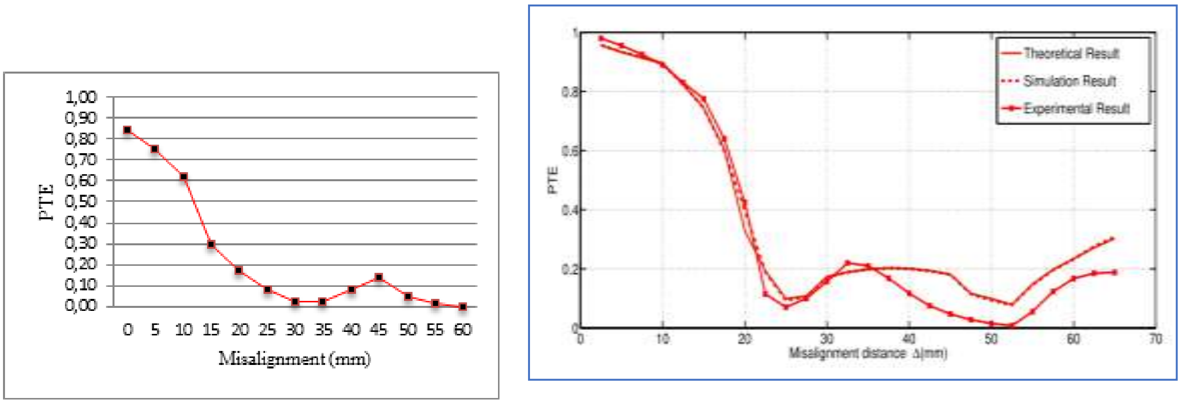
(a) Measurement by researcher (b) Measurement on previous study

Figure 9. Comparison result benchmark coil [17]



(a) Reconstruction result (b) Result central boundary previous study

Figure 10. Comparison result at central boundary



(a) Reconstruction in tangential boundary (b) Result Tangential boundary previous study

Figure 11. Comparison result at tangential boundary [8]

From the results of reconstruction above, the system design that we use produces measurements with a trend that is close to the reference both same as 7 array circle coils. So that the measurement with the proposed coil design illustrates the desired improvement. The comparison between 7 array circle coils and 7 array hexagonal arrays in Figure 12 shown that there is not significantly different in central boundary position refers to Y Axis and it gaves the same position as 7 array circle coils both in Y axis and Y axis.

Unlike the case with the measurement in the tangential boundary position when using 7 array circles coils, the measurement using 7 hexagonal coil arrays shows in Figure 13 that the efficiency at 30 mm misalignment position stable up to 55 mm misalignment position with efficiency level up to 2 times from circle coil array at the same position because when using hexagonal arrays coils, there is no empty gap between each coils and the influenced of the mutual inductances still in the scope of each array coils nearest the primary coils maintain the efficiency at the same level, proven by (1).

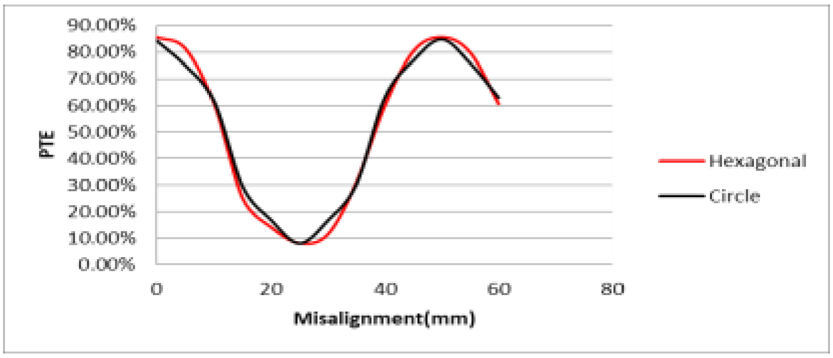


Figure 12. Comparison at central boundary

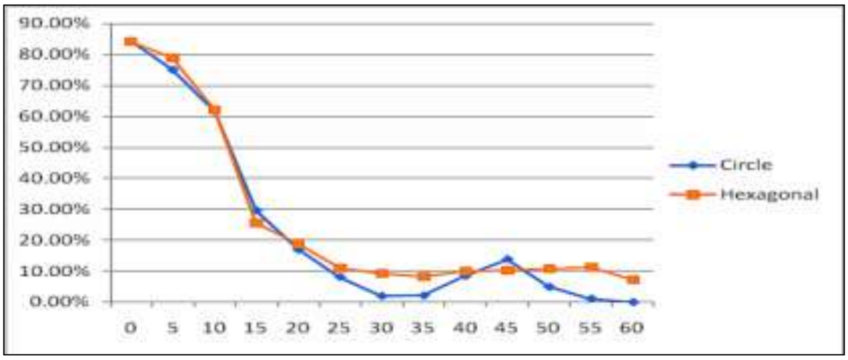


Figure 13. Comparison at tangential boundary

4. CONCLUSION

PTE strongly influenced by coil parameters such as its location, dimensions and geometry. This paper has introduced the main resonant coil design of hexagonal array types, to solve misalignment problems in circle array types and achieve higher PTE in boundary tangential position without reducing PTE in central boundary position. In practice related to EV, coil misalignment is unavoidable, as it is difficult for drivers to park their car accurately above a specified charging point or remain within the dynamic filling limit. The experimental results obtained an improvement of PTE observed at the tangential boundary position up to 10%. Furthermore, the array design can reduce the radius of the Rx coil and thus reduce the weight of the car. The comparison between 7 array circle coils with hexagonal arrays is not significantly different in central boundary. Drop in the PTE between coils along the tangential boundary can be optimized by using a hexagonal shaped coil without reducing the maximum misalignment distance between the coils. The coil design presented here only focuses on repairing the PTE associated with coil misalignment and ignoring the losses incurred by additional circuitry required in a complete EV charging system. For Future work, it need to design systems that produce higher power and hardware enhancements to work on the transmitter array positions simultaneously supply energy to the receiver coil without compromising input power requirements.

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